

Search for near-threshold multi-neutron resonances with (p,2p) reactions in neutron-rich nuclei at R^3B

**Suche nach Multineutronenresonanzen nahe der Schwelle
mit (p,2p)-Reaktionen in neutronenreichen Kernen bei R^3B**

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Darmstadt, May 19, 2025

Nikhil Mozumdar

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Abstract

In order to constrain the largely unknown multi-neutron interactions, it is necessary to measure the relevant observables sensitive to them. One such property is the possible existence of narrow resonances related to multi-neutron cluster structures and correlations [1, 2]. This can be investigated by studying multi-neutron resonances close to the corresponding neutron removal thresholds in neutron-rich light nuclei. Progress over the recent years have presented several evidences of such narrow resonances [3, 4, 5, 6], which provides an indication for the generalization of the Ikeda conjecture.

This thesis aims at the systematic study and characterization of such resonances, and is based on an experiment conducted at the R³B setup in GSI, within the FAIR Phase-0 program. Quasi-free scattering (QFS) reactions are studied in inverse kinematics where a radioactive ion "cocktail" beam is impinged on a 5 cm LH₂ target. The resulting reaction products are measured in the state-of-the-art setup using a large combination of detector systems providing information of the full reaction kinematics. This includes, in addition to detection of fragments, the measurement of the γ -rays and protons in the CALIFA calorimeter. Relevant to the current work, is the neutron detector NeuLAND, which thanks to its high resolution and granularity provides access to the detailed study of multi-neutron resonances.

Among the incoming nuclei in the cocktail beam, of particular interest is the case of ¹⁷B, populated via the QFS ¹⁸C(p,2p) reaction. This is because of a previous indication of a possible near-threshold state [7], which could be compatible with a multi-neutron "cluster" state.

The analysis has been carried out in a step-by-step process, starting with the investigation of the detailed structure of all available neutron-rich Boron isotopes in the mass range of $A \in [14, 17]$. This includes the identification of the bound and unbound states, with emphasis on states populated above the two-neutron emission thresholds. Analysis of the ¹⁸C(p,2p)¹⁷B reaction reveals a 1.64(2) MeV state, situated above the two-neutron separation energy ($S_{2n} = 1.38(21)$ MeV [8]) and decaying via γ -ray emission. A near-threshold state at $E_{rel} = 0.4$ MeV is also observed in the ¹⁵B+2n spectrum.

Finally the analysis is concluded with the study of the nn -distributions corresponding to the identified Fragment+2n resonances, investigating the correlations between the two neutrons emitted in the decay of these resonant states.

Zusammenfassung

Um die weitgehend unbekannten Multineutronenwechselwirkungen einzuschränken, ist es notwendig, die relevanten, auf sie empfindlichen Observablen zu messen. Eine solche Eigenschaft ist die mögliche Existenz schmaler Resonanzen, die mit Multineutronenclustern und Korrelationen zusammenhängen könnten [1, 2]. Diese können durch die Untersuchung von Multineutronenresonanzen in der Nähe der entsprechenden Neutronenseparationsschwellen in neutronenreichen leichten Kernen untersucht werden. In den letzten Jahren wurden mehrere Hinweise auf solche schmalen Resonanzen gefunden [3, 5, 4, 6], was eine Verallgemeinerung der Ikeda-Vermutung nahelegt.

Diese Arbeit zielt auf die systematische Untersuchung und Charakterisierung solcher Resonanzen ab und basiert auf einem Experiment, das am R^3B -Aufbau am GSI im Rahmen des FAIR Phase-0-Programms durchgeführt wurde. Dabei wurden quasi-freie Streureaktionen (QFS) in inverser Kinematik untersucht, bei denen ein radioaktiver Ionen-Cocktailstrahl auf ein 5 cm dickes LH_2 -Target trifft. Die resultierenden Reaktionsprodukte wurden in einem hochmodernen Aufbau gemessen, der eine große Kombination von Detektorsystemen umfasst und eine kinematisch vollständige Messung ermöglicht. Dazu gehört neben dem Nachweis von Fragmenten auch die Detektion von γ -Strahlung und Protonen im CALIFA-Kalorimeter. Besonders relevant für die aktuelle Arbeit ist der Neutronendetektor NeuLAND, der dank seiner hohen Auflösung und Granularität detaillierte Studien zu Multineutronenresonanzen ermöglicht.

Von besonderem Interesse unter den einlaufenden Kernen im Cocktailstrahl ist der Fall von ^{17}B , der über die QFS-Reaktion $^{18}C(p,2p)$ erzeugt wird. Dies liegt an einem früheren Hinweis auf einen möglichen Zustand nahe der Schwelle [7], der mit einem Multineutronen-Clusterzustand kompatibel sein könnte.

Die Analyse wurde schrittweise durchgeführt, beginnend mit der Untersuchung der detaillierten Struktur aller verfügbaren neutronenreichen Bor-Isotope im Bereich $A \in [14, 17]$. Dies umfasst die Identifikation gebundener und ungebundener Zustände, mit besonderem Fokus auf Zustände oberhalb der Zwei-Neutronenemissionsschwelle. Die Analyse der $^{18}C(p,2p)^{17}B$ -Reaktion zeigt das Vorhandensein eines 1,64(2) MeV-Zustands auf, der oberhalb der Zwei-Neutronenseparationsenergie ($S_{2n} = 1,38(21)$ MeV [8]) liegt und durch γ -Strahlung zerfällt. Ein Zustand nahe der Schwelle bei $E_{rel} = 0,4$ MeV wird ebenfalls im $^{15}B + 2n$ -Spektrum beobachtet.

Zuletzt wird die nn -Verteilung in dem identifizierten Resonanzsystem, bestehend aus dem Fragment und den zwei Neutronen, untersucht. Hierbei wird speziell die Korrelation zwischen den beiden Neutronen, welche bei dem Zerfall dieser resonanten Zustände emittiert werden, untersucht.

Contents

1. Introduction	1
1.1. Quasi-free scattering reactions	3
1.2. Nuclear Shell Model	5
1.2.1. YSOX Shell-Model Interaction	7
1.3. Resonant states	7
1.3.1. Invariant-mass method	9
1.4. Three-body resonant systems	10
1.4.1. Observables	10
1.4.2. Phase-space direct decay	11
1.4.3. Sequential decay	14
1.4.4. Direct decay with nn -FSI	14
1.5. Neutron-rich Boron isotopes	14
2. Experimental Setup	19
2.1. Beam Production at GSI	19
2.2. The R ³ B Setup	20
2.2.1. Incoming Beam Detectors	24
2.2.2. Target Area	25
2.2.3. Fragment Arm	26
2.2.4. Neutron Arm	27
2.3. Triggers	28
3. Calibration and Analysis	31
3.1. Ion Tracking	31
3.1.1. Incoming ID	31
3.1.2. Fragment Reconstruction	33
3.2. Protons and γ -rays	38
3.2.1. Quasi-free scattered protons	38
3.2.2. γ -ray analysis	40
3.3. Neutron Analysis	43
3.3.1. NeuLAND Calibration	44
3.3.2. Neutron Simulations	44
3.3.3. One Neutron Analysis	45
3.3.4. Neutron detection efficiency	47
3.3.5. Implementation of simulations to analysis	50
3.4. Two Neutron Reconstruction	52
3.4.1. Causality Method	53
3.4.2. "Two-wall" method	60

4. Spectroscopy of Boron isotopes	65
4.1. $^{16}\text{C}(\text{p},2\text{p})^{15}\text{B}$	65
4.1.1. $^{16}\text{C}(\text{p},2\text{p})^{15}\text{B} \rightarrow ^{14}\text{B} + 1\text{n}$	66
4.1.2. $^{15}\text{B}(\text{p},\text{pn})^{14}\text{B}$	69
4.1.3. $^{16}\text{C}(\text{p},2\text{p})^{15}\text{B} \rightarrow ^{13}\text{B} + 2\text{n}$	75
4.1.4. Cross Section	81
4.2. $^{18}\text{C}(\text{p},2\text{p})^{17}\text{B}$	85
4.2.1. Bound states	85
4.2.2. $^{17}\text{C}(\text{p},2\text{p})^{16}\text{B}$	87
4.2.3. $^{18}\text{C}(\text{p},2\text{p})^{17}\text{B} \rightarrow ^{15}\text{B} + 2\text{n}$	94
4.2.4. Cross Section	101
4.3. Summary	103
5. nn-analysis	105
5.1. $^{15}\text{B} \rightarrow ^{13}\text{B} + 2\text{n}$	106
5.2. $^{17}\text{B} \rightarrow ^{15}\text{B} + 2\text{n}$	108
5.3. $^{15}\text{B}(-1\text{p})^{14}\text{Be} \rightarrow ^{12}\text{Be} + 2\text{n}$	117
5.4. Summary	120
6. Conclusions and Outlook	125
Appendices	127
A. Experimental Runs and Downscaling factors	129
B. Fragment-n velocity alignment	131

List of Figures

1.1.	Examples of two Borromean systems with cluster states near the corresponding particle emission thresholds. Left: ^{12}C level scheme with the shown 0^+ Hoyle state corresponding to the $3\text{-}\alpha$ cluster system. Right: The Halo $3/2^-$ ground state of ^{11}Li , which can be considered as cluster state of a core and two-weakly bound neutrons, carries the imprint of the nearby two-neutron threshold. Image taken from [2].	2
1.2.	Schematic of $(p,2p)$ scattering process with the measured experimental angles with respect to the beam axis. Image taken from [26].	3
1.3.	Top: Dalitz plot corresponding to a simulated 3-body phase-space decay with resonance parameters of $E_r = 2$ MeV and $\Gamma_r = 1$ MeV. Bottom: Projections of the m_{fn}^2 (left) and m_{nn}^2 (right) distributions. .	12
1.4.	Top: Dalitz plot corresponding to a simulated sequential decay with resonance parameters of $E_r = 2$ MeV and $\Gamma_r = 1$ MeV through an intermediate resonance with parameters $E_{s,r} = 0.5$ MeV and $\Gamma_{s,r} = 0.05$ MeV. Bottom: Projections of the m_{fn}^2 (left) and m_{nn}^2 (right) distributions corresponding to the same sequential decay as above shown in black. The distributions are compared to those obtained for a sequential decay though another intermediate resonance with parameters $E_{s,r} = 1$ MeV and $\Gamma_{s,r} = 0.05$ MeV. .	13
1.5.	Top: Dalitz plot corresponding to a simulated direct decay including nn -FSI with resonance parameters of $E_r = 2$ MeV and $\Gamma_r = 1$ MeV. Bottom: Comparison of the projections of the m_{fn}^2 (left) and m_{nn}^2 (right) distributions corresponding to the decay with nn -FSI (in black) and 3-body phase-space decay (in Red).	15
1.6.	Left: γ -ray spectrum in coincidence with ^{17}B fragment (produced from ^{19}C incoming beam). The one-neutron separation energy S_n is shown by the gray band indicating the uncertainty. Right: $^{15}\text{B}+2n$ relative energy spectrum corresponding to true ^{17}B events (In blue). "Cross-talk" $^{15}\text{B}+2n$ distribution obtained for incoming ^{17}C beam (In red). Plots taken from [7].	17
2.1.	Schematic diagram of the existing GSI facility along with the FAIR facility under construction (in red on the right). Figure taken from [68].	20
2.2.	Scheme of the FRS setup. The dipole and quadrupole magnets are shown in green and red respectively. The focal planes are labeled from S1-S8. Figure taken from [69].	21
2.3.	Setup of the detectors at $R^3\text{B}$ for the present experiment. Figure courtesy of D. Körper.	22
2.4.	LH_2 Target Cell with surrounding FOOT detectors.	23
2.5.	A single FOOT module.	25
2.6.	Schematic design of the full CALIFA calorimeter. For the current experiment only a part of the Barrel and the IPHOS was available. Figure taken from [73].	26
2.7.	NeuLAND at $R^3\text{B}$ with 13 double planes. Figure taken from [75].	28
3.1.	Identification plots of incoming ions for the two settings. Top: Tuned for $A/Z \sim 3$. Bottom: Tuned for $A/Z \sim 2.7$. The incoming channels studied in the current analysis are highlighted	32
3.2.	Identification plots of outgoing ions with a cut on ^{18}C incoming Top: ToFD charge versus FOOT charge distribution with shown cut on charge $Z = 5$ to select outgoing Boron isotopes. Bottom: A/Z distribution versus ToFD X-distribution for the outgoing charge $Z = 5$	35

3.3. Outgoing transverse momentum distributions of different incoming isotopes obtained after implementation of strict cuts to reproduce a pencil beam. Comparison is shown with a Gaussian providing the best fit for all three cases.	36
3.4. Outgoing longitudinal momentum distributions of ^{16}C (left) and ^{18}C (right) obtained after implementation of cuts as discussed in text. Gaussian fits for both cases are also shown.	37
3.5. Angular distribution of azimuthal ϕ and polar θ angles of the two scattered protons from quasi-free scattering reactions. Top: Experimental angular correlation with selection on ^{18}C incoming and ^{17}B outgoing, requiring two proton clusters in CALIFA. Bottom: Angular correlations obtained with simulated QFS events using quasi-free event generator developed by L. Chulkov [84] and V. Panin [26].	38
3.6. Left: γ -energy background distribution for unreacted ^{16}C (in blue) and ^{18}C (in red) beams. Right: γ -energy distribution for $^{24}\text{F}(p,2p)^{23}\text{O}$ reaction, where no γ -ray is expected. The double exponential fit (in red) for the background is seen to reproduce the distribution accurately. The two exponential components of the total fit are shown in blue.	40
3.7. γ -ray spectrum obtained from ^{22}Na stationary source (in blue) compared to a simulation of monoenergetic sources (in red). The simulations include a combination of two monoenergetic sources at 511 keV and 1275 keV in order to reproduce the experimental distribution. The simulated red distribution is scaled to the photopeak integrals in the blue distribution to show the agreement in the widths. . .	41
3.8. Photopeak widths of known γ -rays from in-beam isotopes as a function of the photopeak centroids (blue data points). The expected response of the widths obtained from simulations is shown by the red curve.	42
3.9. Photopeak efficiency curves for detection of in-beam γ -rays as a function of the γ -ray energy for standard fixed cluster size (Left) and dynamic cluster size (Right). The photopeak efficiency distribution for boosted γ -rays is shown in blue. The red distribution shows the efficiency distribution with the requirement of proton detection and clustering, which effectively reduces the γ -ray detection efficiency. The gray band indicates the uncertainty in the estimation of the reduction.	43
3.10. Velocity distribution of particles detected in NeuLAND with the neutron velocity/ToF cut shown corresponding to the broad neutron peak in the range of $\beta = 0.64 - 0.94$. The peak at $\beta = 1$ corresponds to γ -rays produced from reactions at the target. A slower peak at $\beta \approx 0.5$ is also observed, attributed to secondary showers originating from the beam dump.	45
3.11. Top: Response matrix obtained from simulation for Fragment + 1n reconstruction where the x-axis is the input generator level relative energy and the y-axis is the reconstructed distribution after applying the reconstruction methodology. Bottom: Evolution of the experimental resolution as a function of the relative energy.	46
3.12. Fragment + 1n efficiency distribution including the acceptance. The shown distribution is obtained from the simulation of a uniform distribution in relative energy range of 0-10 MeV.	48
3.13. Top Left: $^{14}\text{B} + 1\text{n}$ relative energy spectrum from $^{16}\text{C}(p,2p)$ reaction. Bottom Left: ^{14}B γ -ray spectrum in coincidence with $^{14}\text{B} + 1\text{n}$ system with the identified γ -ray photopeak at 0.65 MeV. Right: Tentative level diagram of ^{15}B	49
3.14. Experimental 1-neutron detection efficiency distribution as a function of deposited energy threshold from two selection methods (see text) compared with the distribution expected from simulation. . . .	49
3.15. (Left) χ^2 distribution for the energy E_r and width Γ_r parameter for fit of the dominant resonance at $E_r \sim 1.6$ MeV in $^{14}\text{B} + 1\text{n}$ spectrum (Right)	51
3.16. Schematic of the 2-neutron interaction process in NeuLAND. The initial incoming neutrons are indicated with red arrows, with their incoming velocity defined as β_{01} . All secondary hits in NeuLAND is shown in blue along with the clusters. The "virtual" velocity β_{12} is also highlighted for a cross-talk event between two clusters shown with the blue arrow.	53
3.17. Relative spatial δr and temporal δt distribution as compared to the first hit in time for 1-neutron events. The shown distribution is obtained from the $^{19}\text{N}(p,2p)^{17}\text{C} + 1\text{n}$ channel.	54

3.18.	Right: Q_1 vs β_{01}/β_{12} experimental distribution with the causality cut shown with the black line. All hits on the right side of the line is removed. Left: Q_2 vs $1/\beta_{12}$ experimental distribution. A clear enhancement at $1/\beta_{12} = 1$ at low energies corresponding to secondary γ -rays is observed. The cut to remove this cross-talk is also shown in black. The shown experimental distributions are obtained from the $^{19}\text{N}(p,2p)^{17}\text{C}+1n$ channel.	55
3.19.	Left: Experimental hit multiplicity in NeuLAND for 1n events (solid circles) compared to simulation (blue histogram). Right: Reconstructed neutron multiplicity for 1n events using the "Causality" method from data (solid circles) compared to simulation (blue histogram). The shown experimental distributions are obtained from the $^{19}\text{N}(p,2p)^{17}\text{C}+1n$ channel.	55
3.20.	Response matrix for Fragment + 2n reconstruction for the "Causality" method.	57
3.21.	Left: Response matrix of the neutron-neutron relative energy. The cross-talk contribution can be observed at low $E_{\text{rel}}(nn)$ reconstructed over a large range of generated $E_{\text{rel}}(nn)$. Right: Response matrix of Frag + 1n relative energy component reconstructed for Frag + 2n events. The plots shown are obtained with the "Causality" reconstruction procedure.	57
3.22.	Left: $^{12}\text{Be} + 2n$ relative energy distribution from $^{15}\text{B}(-1p)$ reaction without implementation of the 2n reconstruction algorithm. Right: Same relative energy distribution after implementation of the "Causality" reconstruction algorithm. A peak at 250 keV is clearly visible after reconstruction.	58
3.23.	(In blue) Simulated 2-neutron efficiency distribution of the reconstructed relative energy for the "Causality" method (see text). The cross-talk contribution is also shown (in red).	59
3.24.	Evolution of the resolution as a function of the relative energy obtained from the simulation.	59
3.25.	Relative spatial δr and temporal δt distribution as compared to the first hit in time for 1-neutron events, taken from experimental data, with the cut shown for the "Two-wall" method. All hits below the line are removed. The shown distribution is obtained from the $^{19}\text{N}(p,2p)^{17}\text{C}+1n$ channel.	60
3.26.	Response matrix for Fragment + 2n reconstruction with the "Two-wall" method.	61
3.27.	Left: Response matrix of the neutron-neutron relative energy. Right: Response matrix of Frag + 1n relative energy component reconstructed from Frag + 2n events. The plots shown are obtained with the "Two-wall" reconstruction method.	61
3.28.	Simulated 2-neutron efficiency distribution as a function of the reconstructed relative energy for the "Causality" method (in blue) compared to the "Two-wall" method (in black).	62
3.29.	m_{nn}^2 distribution for 250 keV simulated resonances with FSI (in red) and phase-space (in black). Left: Events reconstructed with "Causality" method. Right: Events reconstructed with "Two-wall" method. A clear distinction in the shape can be observed in the "Two-wall" method.	63
3.30.	$^{12}\text{Be} + 2n$ relative energy distribution from $^{15}\text{B}(-1p)$ reaction after implementation of the "Two-Wall" reconstruction algorithm. A peak at 250 keV is clearly visible.	64
4.1.	Doppler corrected γ -ray spectrum corresponding to $^{16}\text{C}(p,2p)^{15}\text{B}$ reaction, fitted with a double exponential decay function. The two exponential distributions are shown in blue and the total fit of the background are shown in red. No significant peaks above the background are observed.	66
4.2.	Relative energy spectrum for $^{16}\text{C}(p,2p)^{15}\text{B} \rightarrow ^{14}\text{B}+1n$ channel.	67
4.3.	Left: γ -ray spectrum of ^{14}B in coincidence with the $^{14}\text{B}+1n$ system. Known γ -ray photopeak from the 1^- state of ^{14}B at $E_\gamma = 0.653(7)$ MeV can be clearly observed. The γ -ray response function is shown in green, the fitted background in blue and the total fit is shown in red. Right: $^{14}\text{B}+1n$ relative energy distribution in coincidence with the 0.653 MeV γ -ray photopeak. The spectrum shown is obtained after background subtraction (see text for details). The distribution is fitted with a single resonance.	68
4.4.	Relative energy spectrum for $^{16}\text{C}(p,2p)^{15}\text{B} \rightarrow ^{14}\text{B}+1n$ channel, fitted with three identified resonances.	68
4.5.	Doppler corrected γ -ray spectrum in coincidence with ^{14}B fragment following a QFS $^{15}\text{B}(p,pn)^{14}\text{B}$ reaction. A peak at $E_\gamma = 0.655(7)$ MeV is identified corresponding to the known 1^- state. The fitted photopeak is shown in green, the double exponential background in blue and the total fit in red.	70

4.6. Inclusive transverse recoil momentum distribution $P_{y,recoil}$ for the bound states populated via $^{15}\text{B}(p,pn)^{14}\text{B}$ reaction. A single $L=0$ component obtained from the DWIA calculations is observed to reproduce the full distribution.	70
4.7. Relative energy spectrum for $^{15}\text{B}(p,pn)^{14}\text{B} \rightarrow ^{13}\text{B}+1n$ channel fitted with four identified resonances. The resonance parameters are tabulated in Table 4.2.	71
4.8. Left: ^{13}B γ -ray spectrum in coincidence with the $^{13}\text{B}+1n$ system. Right: $^{13}\text{B}+1n$ relative energy distribution with a gate on ^{13}B photopeak (shown in left panel) with the background contribution subtracted, fit with resonance at $E_r = 2.98$ MeV.	72
4.9. Recoil transverse momentum distributions $P_{x,recoil}$ obtained from the energy gates in the $^{13}\text{B}+1n$ system corresponding to each identified resonance. The applied energy gates are highlighted in each plot. For all energy gates a single $L=1$ component obtained from the DWIA calculations can reproduce almost the full distribution.	73
4.10. Obtained level scheme for $^{15}\text{B}(p,pn)^{14}\text{B}$ reaction. The multiplet of excited states of ^{13}B is shown as a single state.	74
4.11. Relative energy spectrum for $^{16}\text{C}(p,2p)^{15}\text{B} \rightarrow ^{13}\text{B}+2n$ reconstructed with the "Causality method".	75
4.12. Relative energy spectrum for $^{16}\text{C}(p,2p)^{15}\text{B} \rightarrow ^{13}\text{B}+2n$ channel fit with 4 resonances.	76
4.13. γ -ray spectrum in coincidence with the $^{13}\text{B}+2n$ events. A clear peak can be observed around ~ 3.5 MeV.	77
4.14. Top Panel: $^{13}\text{B}+2n$ relative energy distribution showing the different cuts corresponding to the identified resonances. Bottom Panel: ^{13}B γ -ray spectra corresponding to the different gates in the relative energy distribution. The cuts have been color matched with the corresponding spectrum.	78
4.15. Level diagram for state obtained from $^{16}\text{C}(p,2p)^{15}\text{B}$ QFS reaction.	79
4.16. Left: Two-body $^{13}\text{B}+1n$ relative energy distribution corresponding to the energy gate $E_{rel} \in [0, 0.8]$ MeV for the resonance at $E_r = 0.7(25)$ MeV in the three body $^{13}\text{B}+2n$ spectrum. The distribution is fitted with the identified sequential (in pink) and direct decay (in blue) components. Right: m_{fn}^2 distribution corresponding to same cut fitted with components following the same decay mechanism.	80
4.17. Left: Two-body $^{13}\text{B}+1n$ relative energy distribution corresponding to the energy gate $E_{rel} \in [2, 3.2]$ MeV for the resonance at $E_r = 2.43(25)$ MeV in the three body $^{13}\text{B}+2n$ spectrum. The distribution is fitted with the identified sequential (in pink) and direct decay (in blue) components. Right: m_{fn}^2 distribution corresponding to same cut fitted with components following the same decay mechanism.	81
4.18. Comparison of experimentally obtained states for $^{16}\text{C}(p,2p)^{15}\text{B}$ (in red) to the states predicted by YSOX SM [33] with significant spectroscopic factors for proton removal reaction from ^{16}C (in blue). The corresponding proton removal spectroscopic factors are also shown. The states identified via multi-nucleon transfer reaction in [51] are also included for comparison (in green).	82
4.19. Top: γ -ray spectrum of $^{18}\text{C}(-1p)^{17}\text{B}$ without QFS conditions with a fitted Gaussian peak over a double exponential background. Bottom: Same plot but with a strict QFS condition and fitted with the same conditions. Both spectra are obtained for events with gamma multiplicity $N_\gamma = 1$	86
4.20. ^{16}B level scheme for the $^{17}\text{B}(p,pn)^{16}\text{B}$ reaction reported in [56]. The obtained results (in red) are shown in comparison to GSM, VS-IMSRG, AMD and SM calculations. The corresponding separation energies are highlighted in parentheses. Figure taken from [56].	88
4.21. Relative energy distribution for $^{17}\text{C}(p,2p)^{16}\text{B} \rightarrow ^{15}\text{B}+1n$ channel.	88
4.22. Fit of relative energy spectrum for $^{17}\text{C}(p,2p)^{16}\text{B} \rightarrow ^{15}\text{B}+1n$. Top: Plot in linear scale. Bottom: same plot but in logarithmic scale. The resonances and their corresponding parameters are listed in Table. 4.7.	89
4.23. Left: ^{15}B γ -ray spectrum in coincidence with the $^{15}\text{B}+1n$ relative system. The distribution is fitted with two γ -ray components with fixed energies taken from [52] ($E_\gamma = 1.327$ (green) and 1.407 (pink) MeV) and the double exponential background. Right: $^{15}\text{B}+1n$ relative energy distribution obtained with a gate on the ^{15}B photopeak region after background subtraction, fitted with the resonance at $E_r = 0.21$ MeV.	90

4.24. Tentative level scheme for $^{17}\text{C}(p,2p)^{16}\text{B} \rightarrow ^{15}\text{B} + 1n$ reaction. Assigned excitation energy of the $E_r = 0.21$ MeV state is tentative, since the decay to ^{15}B excited states is not constrained.	91
4.25. Comparison of level schemes of ^{16}B obtained from proton/neutron removal. Left: Level scheme obtained from quasi-free $(p,2p)$ reaction in the current work. Assigned excitation energy of the $E_r = 0.21$ MeV state is tentative, since the decay to ^{15}B excited states is not constrained. Right: Level scheme from [56] for quasi-free (p,pn) reaction. According to [56], the states at $E_x = 2.33$ MeV, 3.65 MeV and 4.75 MeV decay to the excited states of ^{15}B with negligible spectroscopic factors.	92
4.26. Top: Relative energy spectrum for $^{18}\text{C}(p,2p)^{17}\text{B} \rightarrow ^{15}\text{B} + 2n$ reaction reconstructed using "Causality method". Bottom: Same spectrum but corrected for with the neutron efficiency distribution along with other detection efficiencies.	93
4.27. Top Left: Direct decay fit of two-body $^{15}\text{B} + 1n$ relative energy distribution corresponding to an energy gate on the $^{15}\text{B} + 2n$ system in the range $E_{rel} \in [0, 0.6]$ MeV (shown in inset). Top right: m_{fn}^2 distribution corresponding to the same energy gate shown with a fit using the same direct decay component. Bottom: Level diagram of ^{17}B corresponding to the energy gate with the proposed decay mechanism.	95
4.28. Top Left: Fit of two-body $^{15}\text{B} + 1n$ relative energy distribution using a single sequential component, corresponding to an energy gate on the $^{15}\text{B} + 2n$ system in the range $E_{rel} \in [1.2, 1.6]$ MeV (shown in inset). Top Right: m_{fn}^2 distribution corresponding to the same energy gate, shown with a fit using the same sequential decay component. Bottom: Level diagram of ^{17}B corresponding to the energy gate with the proposed decay mechanism.	96
4.29. Top Left: Fit of two-body $^{15}\text{B} + 1n$ relative energy distribution with direct and sequential components, corresponding to an energy gate on the $^{15}\text{B} + 2n$ system in the range $E_{rel} \in [2.2, 3]$ MeV (shown in inset). Top Right: m_{fn}^2 distribution corresponding to the same energy gate, shown with a fit using the same decay components. Bottom: Level diagram of ^{17}B corresponding to the energy gate with the proposed decay mechanism.	97
4.30. Top Left: Fit of two-body $^{15}\text{B} + 1n$ relative energy distribution with several direct and sequential components, corresponding to an energy gate on the $^{15}\text{B} + 2n$ system in the range of $E_{rel} \in [4, 4.5]$ MeV (shown in inset). Top Right: m_{fn}^2 distribution corresponding to the same energy gate, shown with a fit using the same decay components. Bottom: Level diagram of ^{17}B corresponding to the energy gate with the proposed decay mechanism.	98
4.31. Obtained experimental level scheme for $^{18}\text{C}(p,2p)^{17}\text{B}$ (in red) compared to SM YSOX calculations [33] (in blue). The experimental $^{15}\text{B} + 2n$ contribution and corresponding parameters shown are obtained assuming single state placed at the cross section weighted centroid. For the SM calculations only states with significant spectroscopic factors are shown.	100
5.1. Top: Fit of $E_{rel}(nn)$ (left) and m_{nn}^2 (right) distributions corresponding to the resonance at $E_r = 2.43$ MeV in the $^{13}\text{B} + 2n$ channel. The fits include the sequential (in pink) and three-body phase-space direct decay (in blue) components. Bottom: $E_{rel}(nn)$ (left) and m_{nn}^2 (right) distributions for the same channel, fitted with sequential decay (in pink) and direct decay with nn -FSI (in green). The bottom plots clearly show a better agreement with the experimental data.	107
5.2. Left: Total cluster multiplicity vs Total deposited energy distributions for 1- neutron (in green) and 2-neutron (in blue) events. The cut separating the 1-neutron events from the clean 2-neutron events, used in the current analysis, is shown in red (see text). Right: The $1/\beta_{12}$ (virtual velocity between two clusters) velocity distribution for the causality method with and without the calorimetric cut.	109
5.3. Efficiency distribution as a function of the reconstructed relative energy for the "causality-calorimetric method" (in red) compared to the standard "causality method" (in black).	110

5.4.	Relative energy spectrum for $^{18}\text{C}(-1\text{p})^{17}\text{B} \rightarrow ^{15}\text{B} + 2\text{n}$ reconstructed using the "Causality method" without selection on the QFS protons. The region of the near-threshold peak around $E_r \sim 0.4$ MeV is highlighted.	111
5.5.	Relative energy spectrum for $^{18}\text{C}(-1\text{p})^{17}\text{B} \rightarrow ^{15}\text{B} + 2\text{n}$ reconstructed using "causality-calorimetric method" (see text) without selection on the QFS protons. The region of the near-threshold peak around $E_r \sim 0.4$ MeV is highlighted.	111
5.6.	Left: $^{15}\text{B} + 2\text{n}$ relative energy distribution without the QFS (p,2p) cut, with the near-threshold peak fitted with a simulated resonance following a Breit-Wigner distribution. Right: The same spectrum fitted with a linear distribution from 0 – 2 MeV to estimate the "background" and the significance of the observed peak.	112
5.7.	Left: $^{15}\text{B} + 2\text{n}$ relative energy distribution with QFS (p,2p) cut (in black) and without (p,2p) cut (in red). The distribution without the QFS condition is scaled to match the one with the QFS condition. Right: The ratio of the two relative energy distributions on the left.	112
5.8.	Left: Two-body $^{15}\text{B} + 1\text{n}$ relative energy distribution corresponding to the energy gate of $E_{\text{rel}} \in [0, 0.8]$ MeV in the three-body $^{13}\text{B} + 2\text{n}$ spectrum, reconstructed with causality-calorimetric method, fitted with identified sequential (in pink) and direct decay (in blue) components. Right: m_{fn}^2 distribution corresponding to the same energy gate, shown with a fit using the same decay components.	114
5.9.	Top: Fit of $E_{\text{rel}}(nn)$ (left) and m_{nn}^2 (right) distributions corresponding to an energy gate of $E_{\text{rel}} \in [0, 0.8]$ MeV in the three-body $^{13}\text{B} + 2\text{n}$ spectrum, reconstructed with the causality-calorimetric method. The fits include the sequential (in pink) and three-body phase-space direct decay components (in blue). Bottom: Fit of the same $E_{\text{rel}}(nn)$ (left) and m_{nn}^2 (right) distributions with components for sequential (in pink) and direct decay including nn -FSI (in green). The χ^2 values indicate a better fit when the direct decay component with nn -FSI is included.	115
5.10.	Relative energy spectrum for $^{18}\text{C}(-1\text{p})^{17}\text{B} \rightarrow ^{15}\text{B} + 2\text{n}$ reconstructed using "two-wall method" without selection on the QFS protons. The region of the near-threshold peak around $E_r = 0.4$ MeV is highlighted.	116
5.11.	Left: Two-body $^{15}\text{B} + 1\text{n}$ relative energy distribution corresponding to the energy gate $E_{\text{rel}} \in [0.2, 0.8]$ MeV in the three-body $^{13}\text{B} + 2\text{n}$ spectrum, reconstructed with the two-wall method, fitted with identified sequential (in pink) and direct decay components (in blue). Right: m_{fn}^2 distribution corresponding to same energy gate, fitted with components following the same decay mechanism.	116
5.12.	Top: Fit of $E_{\text{rel}}(nn)$ (left) and m_{nn}^2 (right) distributions corresponding to an energy gate of $E_{\text{rel}} \in [0.2, 0.8]$ MeV in the three-body $^{13}\text{B} + 2\text{n}$ spectrum, reconstructed with the two-wall method. The fits include the sequential (in pink) and three-body phase-space direct decay (in blue) components. Bottom: Fit of the same $E_{\text{rel}}(nn)$ (left) and m_{nn}^2 (right) distributions with components for sequential (in pink) and direct decay including nn -FSI (in green). The χ^2 values indicate a better fit when the direct decay component with nn -FSI is included.	118
5.13.	Relative energy spectrum for $^{15}\text{C}(-1\text{p})^{14}\text{Be} \rightarrow ^{12}\text{Be} + 2\text{n}$ reconstructed using "causality-calorimetric method" without selection on the QFS protons. The near-threshold resonance at $E_r = 0.24$ MeV is fitted with a simulated resonance following a Breit-Wigner distribution with an $L = 2$ neutron emission.	119
5.14.	Left: $^{12}\text{Be} + 2\text{n}$ relative energy distribution with QFS (p,2p) cut (in black) and without (p,2p) cut (in red). The distribution without the QFS cut is scaled to the one with the QFS cut. Right: The ratio of the the two relative energy distributions on the left.	119
5.15.	Top: Fit of $E_{\text{rel}}(nn)$ (left) and m_{nn}^2 (right) distributions corresponding to an energy gate of $E_{\text{rel}} \in [0, 0.4]$ MeV in the three-body $^{12}\text{Be} + 2\text{n}$ spectrum, reconstructed with the causality-calorimetric method. The distribution is fitted with a single direct decay component following phase-space kinematics (in blue). Bottom: Fit of the same $E_{\text{rel}}(nn)$ (left) and m_{nn}^2 (right) distributions with a direct decay component including nn -FSI (in green). A notable improvement in the χ^2 values is observed for the fits with the three-body phase-space direct decay component.	121

5.16.	Top: Fit of $E_{rel}(nn)$ (left) and m_{nn}^2 (right) distributions corresponding to an energy gate of $E_{rel} \in [0, 0.4]$ MeV in the three-body $^{12}\text{Be} + 2n$ spectrum reconstructed with the two-wall method. The distribution is fitted with a single direct decay component following phase-space kinematics (in blue). Bottom: Fit of the same $E_{rel}(nn)$ (left) and m_{nn}^2 (right) distributions with a direct decay component including nn -FSI (in green). A notable improvement in the χ^2 values is observed for the fits with the three-body phase-space direct decay component.	122
B.1.	Evolution of the alignment variables as a function of the velocity shift $\delta\beta$ applied to the fragment. . .	132

List of Tables

2.1. The relevant "ON-Spill" bits of the TPat along with the trigger conditions used for the current analysis.	29
4.1. Obtained resonances from the fit of $^{16}\text{C}(p,2p)^{15}\text{B} \rightarrow ^{14}\text{B} + 1n$ relative energy spectrum.	69
4.2. Obtained resonances from the fit of the $^{13}\text{B} + 1n$ relative energy spectrum.	71
4.3. Obtained resonances from fit of $^{13}\text{B} + 2n$ relative energy spectrum.	76
4.4. Experimental cross section σ_{exp} and spectroscopic factors (C^2S_{exp}) corresponding to the identified states from the $^{16}\text{C}(p,2p)^{15}\text{B}$ reaction. The spectroscopic factors are calculated by taking the ratio of the experimental cross section to the single particle theoretical cross section obtained from the DWIA calculation, i.e, $C^2S_{exp} = \sigma_{exp} / \sigma_{s.p.,th}$. The $C^2S_{exp,norm}$ is obtained by scaling the C^2S_{exp} by the reduction factor of 0.6.	83
4.5. Excitation energies and spectroscopic factors (C^2S_{sm}) of states predicted by YSOX SM calculations for proton knockout from ^{16}C . Only the states predicted with significant spectroscopic factors are shown.	83
4.6. Orbital occupation numbers for the ^{16}C g.s. and predicted ^{15}B states for proton knockout from ^{16}C , obtained from YSOX shell-model calculations. Only the states predicted with significant spectroscopic strength are shown.	84
4.7. Resonances obtained from the best fit of the $^{15}\text{B} + 1n$ relative energy spectrum. Assigned excitation energy of the $E_r = 0.21$ MeV state is tentative, since feeding the to ^{15}B excited states is not constrained.	89
4.8. Experimental cross section σ_{exp} and spectroscopic factors (C^2S_{exp}) corresponding to the identified states from the $^{18}\text{C}(p,2p)^{17}\text{B}$ reaction. The spectroscopic factors are calculated by taking the ratio of the experimental cross section to the single particle theoretical cross section obtained from the DWIA calculation, i.e, $C^2S_{exp} = \sigma_{exp} / \sigma_{s.p.,th}$. The $C^2S_{exp,norm}$ is obtained by scaling the C^2S_{exp} by the reduction factor of 0.6.	102
4.9. Excitation energies and spectroscopic factors (C^2S_{sm}) of states predicted by YSOX SM [33] calculations for proton knockout from ^{18}C . Only the states predicted with significant spectroscopic factors are shown.	102
4.10. Orbital occupation numbers for the ^{18}C g.s. and predicted ^{17}B states for proton knockout from ^{18}C , obtained from YSOX shell-model calculations. Only the states predicted with significant spectroscopic factors are shown.	103
A.1. Downscaling factor values for each TBit of the "ON-Spill" triggers corresponding to different runs along with the incoming beam setting.	129

1. Introduction

The 7.67 MeV 3- α Hoyle cluster state in ^{12}C was discovered over 60 years ago [9], marking a key milestone in understanding the nucleosynthesis of ^{12}C during helium burning in stars. It is named after Fred Hoyle who predicted the existence of this state in order to account for the abundance of ^{12}C [10]. The presence of this near-threshold resonant state, enhances the probability of formation of ^{12}C via the triple α -process [11, 12]. In this process, two α -particles first fuse to form an ^8Be nucleus in an unstable equilibrium. This is followed by the capture of another α before the decay of the ^8Be to produce ^{12}C . The presence of the Hoyle state enhances the capture cross section, where now the capture takes place through the Hoyle state, which subsequently decays to the ground state with the emission of a γ -ray of 7.67 MeV. Ikeda et al. [1] proposed a molecule-like α "cluster" structure for this state near the α -emission threshold. They further indicate that such α -"cluster" states are systematically present in the proximity of α -emission thresholds of light nuclei. Recently, a generalized formalism of this conjecture has been proposed in [2], which extends this idea to all particle emission thresholds. The authors propose that such clustering phenomenon is a characteristic feature of all near threshold states corresponding to any particle emission, as a consequence of coupling to the continuum of the decay channel in the open quantum system (OQS). These so-called clusters are generally formed by weakly bound Borromean systems. In the ^{12}C case, this corresponds to the unstable ^8Be cluster, while for a halo-nucleus like ^{11}Li , this correspond to the *di-neutron* cluster.

The *di-neutron* is considered to be the lightest neutron "cluster" composed of two correlated neutrons. Neutron clustering in the nuclear medium and its role in the evolution of the structure of neutron-rich light nuclei has been a topic of significant interest in the last few decades. The first instance of a di-neutron system coupled to a nuclear core was proposed for ^{11}Li by the authors of [13]. In the following decades, numerous experiments have reported evidence of correlated two-neutron emission in the resonant decay of neutron-rich light nuclei. These include strong neutron-neutron (nn) correlations in the decay of Fragment+2 n systems unbound in the ground state, such as in ^{13}Li [14], ^{16}Be [15] or in the excited resonant states, such as in ^6He [16], ^8He [17], ^{11}Li [18], ^{14}Be [19], etc. It is noted that, these strong nn -correlations have been observed mostly in neutron-rich light nuclei, since in this case the neutrons are decoupled from the core, which allow the nn -interaction to dominate the decay mechanism.

Recently, extremely strong nn -pairing correlations has been observed in the decay of core + 4 n nuclei [20]. These correlations manifest in the form of a strong nn -Final State Interaction (nn -FSI) at low nn relative energies, characterized by the nn scattering length $a_s = -18.63(40)$ fm [21]. The strong nn -FSI signature observed by the authors of [20] in the decay of the excited continuum of $^{18}\text{C} \rightarrow ^{16}\text{C} + 2n$, is a consequence of the fact that a significant portion of the decay proceeds via direct 2-neutron emission. This indicates that the neutrons are preferentially excited to the continuum as a pair. The presence of such strong nn -correlations can be interpreted as the two neutrons forming a cluster analogous to ^8Be in the ^{12}C case. This points towards the possible existence of near-threshold resonances corresponding to 2-neutron cluster structures. Therefore, if such clustering phenomenon exists, near-threshold states exhibiting a signature of nn -clustering should be observed in neutron-rich light nuclei near the dripline. In recent years, the development of advanced neutron detection systems has led to the observation of multiple near-threshold resonances decaying via direct 2-neutron emission in neutron-rich light nuclei. These

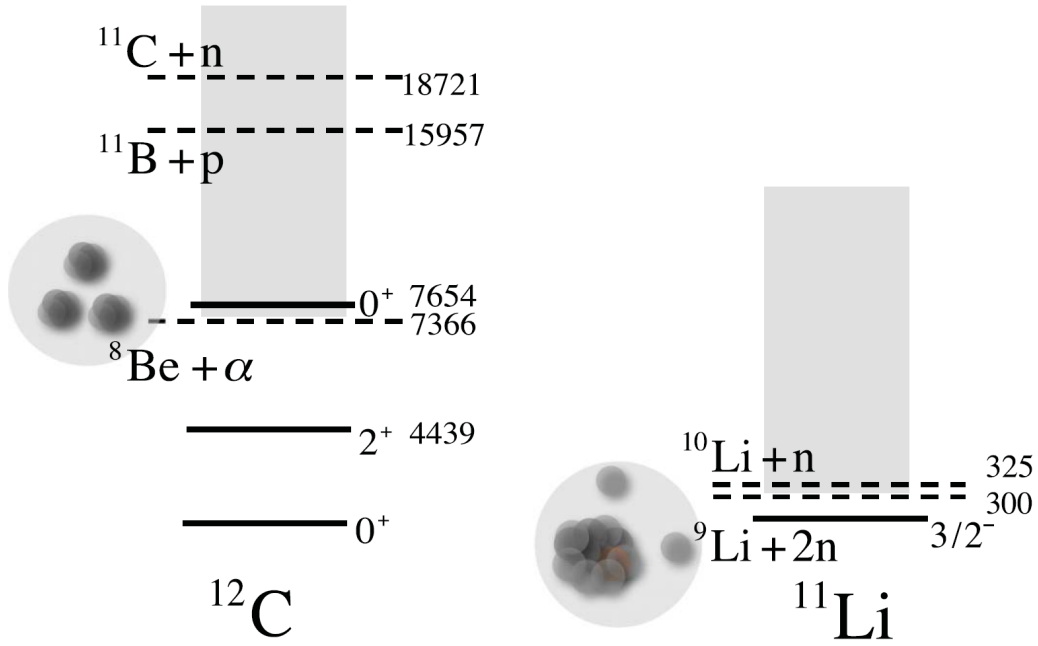


Figure 1.1.: Examples of two Borromean systems with cluster states near the corresponding particle emission thresholds. **Left:** ^{12}C level scheme with the shown 0^+ Hoyle state corresponding to the $3\text{-}\alpha$ cluster system. **Right:** The Halo $3/2^-$ ground state of ^{11}Li , which can be considered as cluster state of a core and two-weakly bound neutrons, carries the imprint of the nearby two-neutron threshold. Image taken from [2].

include near threshold resonances in ^{14}Be [3], ^{26}O [5][4], ^{28}F [6] and ^{29}F [22]. However, the study of the nn -correlations corresponding to most of these cases has not been explored in details.

For completeness, the recent progress in the study of correlated multi-neutron systems with higher multiplicities, specifically the correlated $4n$ system, is mentioned here. The first indication of a correlated $4n$ system was reported by F.M. Marqués et al. [23] in the breakup of ^{14}Be into ^{10}Be and 4 neutrons. More recently, a correlated four neutron resonant structure was reported in the work of M. Duer et al. [24] in the $^8\text{He}(p,p\alpha)4n$ reaction. Such correlation signatures also suggests the presence of clustering phenomenon in core+ $4n$ systems. A $4n$ resonance corresponding to the proposed ground state of ^{28}O has been reported in the work of [25]. However in this case, the resonance appears to decay sequentially via two pairs of neutron emission.

The objective of the current work is to study near-threshold resonances, decaying via $2n$ emission, populated with Quasi-free $(p, 2p)$ reactions in neutron-rich light nuclei. This includes the identification of such resonances and the characterization of their corresponding nn -distributions to understand the role that the nn -correlations play in these states. The use of $(p, 2p)$ reactions as a probe helps constrain the structural information corresponding to the identified states/resonances. In addition, other structural properties of dripline nuclei that may indicate clustering phenomena and the effects of continuum coupling are also investigated. One such property is the presence of γ -ray transitions from states above the multi-neutron emission threshold, analogous to the γ decay in the Hoyle state. The current work demonstrates a possible evidence of such a transition in the structure of ^{17}B , populated via the $^{18}\text{C}(p,2p)$ reaction.

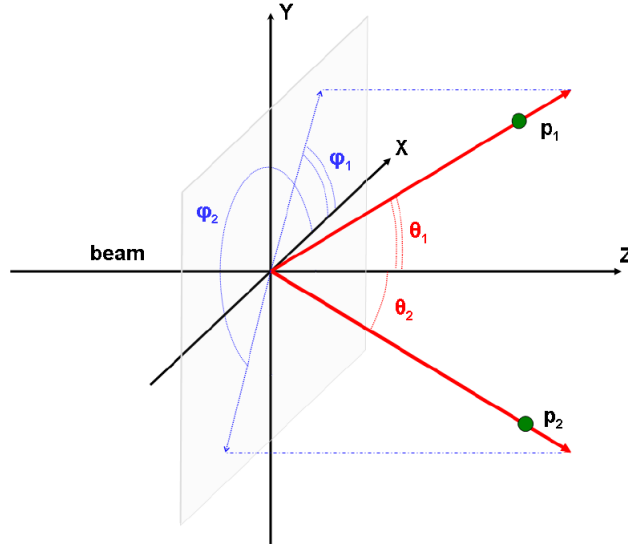


Figure 1.2.: Schematic of $(p,2p)$ scattering process with the measured experimental angles with respect to the beam axis. Image taken from [26].

1.1. Quasi-free scattering reactions

Over the last few decades, direct reactions have been extensively used to study the microscopic single particle structure of atomic nuclei. Direct reactions refer to the subset of nuclear reactions involving a single-step process, with an extremely small interaction time between the projectile and target ($\sim 10^{-22}$ s). These reactions include transfer and knockout reactions involving pickup or removal of nucleons. Since the reactions include interaction with a single nucleon or a cluster (e.g. α , ${}^2\text{H}$, ${}^3\text{H}$, etc.) in the nucleus, the remaining spectator nucleons retain their initial configurations. Therefore the cross section of the configurations populated in the final state corresponds to the overlap of its wavefunction with that of the initial state. This effectively enables the study of the detailed nuclear structure associated with the interacting nucleon(s) in the nucleus.

The present experiment utilizes a special subset of direct knockout reactions, known as quasi-free scattering (QFS) reactions, in order to study the nuclear structure. Quasi-free scattering refers to the knockout of a bound nucleon or a cluster inside the nucleus by an incident proton or electron via $(p, p'X)$ and $(e, e'X)$ reactions respectively, where X is the knocked out nucleon/cluster. The first experiments studying these reactions were performed in 1952 with a 350 MeV incident proton beam on a Lithium target [27], where a pair of protons were observed to be scattered with a relative angle of $\sim 90^\circ$. This was interpreted as a direct "quasi-free" scattering process between the incident high-energy proton and a proton within the nucleus.

Substantial advancements followed in the ensuing decades, deepening the understanding of the reaction mechanism. QFS emerged as a powerful tool for probing the single-particle structure of nuclei. The reaction can be qualitatively described as a high-energy incident particle knocking out a nucleon, with minimal subsequent interaction of both the ejected nucleon and the projectile with the residual nucleus, thereby, selectively probing the single-particle structure of the nucleus. The direct one nucleon knockout process was found to be the dominant contribution at intermediate energies (~ 200 to 1000 MeV). At these energies, the large momentum transfer at the initial interaction point corresponds to a highly

1. Introduction

localized interaction within the nucleus. Realistically, however, the mean free paths of the incident and scattered nucleons are comparable to the nuclear radius, making multiple scattering events in the entrance and exit channels non-negligible. These are accounted for in theoretical treatments through the use of distorted waves and complex optical potentials.

The formal theoretical framework for QFS was laid out in foundational reviews by Jacob and Maris [28, 29], and more recent developments are summarized in [30, 31]. Early QFS studies were performed in direct kinematics, using stable target nuclei bombarded by protons or electrons, limiting investigations to nuclei near the valley of stability. The advent of radioactive ion beam production via fragmentation, along with the use of hydrogen targets, has enabled the study of QFS reactions in inverse kinematics. In this case, the nucleus of interest acts as the incoming projectile impinging on a proton target. In the center of mass frame, the reaction is exactly equivalent to that of the direct kinematics. However, it has more challenges, since it requires the use of more sophisticated detection systems for the measurement and reconstruction of all observables. This technique has significantly expanded the range of nuclei that can be studied using QFS reactions, with the limits close to the driplines.

In the current case, proton probes are used to study the QFS reactions in inverse kinematics via (p, pN) reactions (where $N = p$ for protons and $N = n$ for neutrons). As discussed, in such scattering processes, the two emitted nucleons exhibit correlations, and their angular distributions display characteristic signatures resembling those of free nucleon-nucleon scattering. Figure. 1.2 shows the outgoing protons along with their angles following a pp scattering. For a free proton-proton scattering process at non relativistic energies ($\beta \rightarrow 0$), the scattering should follow co-planar kinematics (i.e., $\Delta\phi = 180^\circ$), and since both scattered protons have the same mass, the opening angle should be $\theta = 90^\circ$. At relativistic energies, however, the kinematics are modified by the increasing projectile momentum, and the scattering angle becomes smaller than 90° . In addition to this the proton in the nucleus is not truly free but bound, with finite separation energy and Fermi motion, which further shift the expected opening angle to lower values. Finally, the rescattering/absorption processes of the scattered proton can further distort the observed distributions.

The theoretical QFS cross sections presented in this work were calculated using the Distorted Wave Impulse Approximation (DWIA), as implemented by C. Bertulani [31]. The DWIA framework assumes a two-body interaction, such that variations in the distorted waves describing the incoming and outgoing nucleons due to medium effects do not significantly alter the two-body scattering matrix element. This permits the reaction amplitude to be factorized into two components, with a term reflecting the structure of the target nucleus, and the other representing the elementary two-body elastic scattering process.

These calculations rely on both the *eikonal* and *sudden* approximations. In the eikonal approximation, the projectile and ejectile are assumed to be slightly distorted in the direction perpendicular to the wave motion through the nuclear medium. This distortion depends on the *S-matrix*, which includes in its definition a complex optical potential and accounts for rescattering and absorption effects due to interactions with the nuclear environment.

The sudden approximation implies that the scattering event occurs over a timescale much shorter than that of the intrinsic nuclear motion. Consequently, the recoil momentum of the residual nucleus, $\vec{p}_{A-1}$, is nearly equal in magnitude and opposite in direction to the momentum $\vec{p}_N$ of the struck nucleon prior to knockout, i.e., $\vec{p}_{A-1} \cong -\vec{p}_N$ (thus, the notation "quasi-free" scattering). This means that the recoil momentum distribution provides information on the momentum distribution of the knocked-out nucleon. The nucleon bound-state single-particle wavefunction $\psi_{jlm}(\mathbf{r})$ determines this momentum distribution. Therefore, by comparing theoretical predictions which include exact kinematics of energy/momentum conservation – beyond the simple description given above – with experimental recoil momentum distributions, detailed

information about the bound-state wavefunction of the removed nucleon can be extracted [31]. An application of this method is discussed in section 4.1.2.

1.2. Nuclear Shell Model

The atomic nucleus is a many-body system of strongly interacting nucleons. Its theoretical treatment is based on solving an eigenvalue problem, corresponding to the solutions of the Schrödinger equation,

$$\hat{H} |\psi_n\rangle = E_n |\psi_n\rangle, \quad (1.1)$$

where $\hat{H}$ denotes the nuclear many-body Hamiltonian, $|\psi_n\rangle$ represents an eigenstate of the Hamiltonian and E_n the corresponding eigenvalue. The nuclear Hamiltonian for A nucleons has the general form given by,

$$\hat{H} = \sum_{i=1}^A \hat{T}_i + \sum_{i>j}^A \sum_{j=1}^A \hat{V}_{ij} + \dots, \quad (1.2)$$

where $\hat{T}_i$ is the kinetic energy operator of nucleon i and $\hat{V}_{ij}$ the two body nucleon-nucleon (NN) interaction between nucleons i and j . Additional terms, such as three-body or higher-order interactions, can be incorporated to account for other many-body effects. The Hamiltonian in this form is too complex and the Schrödinger equation cannot be solved exactly for nuclei with $A > 4$. Consequently, several "mean-field" approaches were developed, making the problem more approachable. One of the most common and widely used mean-field method is the nuclear Shell Model (SM).

In general, the two-body interaction, $\hat{V}_{NN}$, is found to be the most dominant contribution in the nuclear potential. Therefore, the Hamiltonian in Eq. 1.2 is restricted to include only the two-body potential operator. In the mean-field approximation, the two-body interaction is replaced by a mean-field potential $\hat{U}_i(r)$, which depends only on the position of the nucleon i with respect to this potential. As a result, the system of A interacting nucleons is described as A independent nucleons moving in a mean field. Accordingly, the Hamiltonian defined in Eq. 1.2 can be rewritten as,

$$\hat{H} = \sum_{i=1}^A \left(\hat{T}_i + \hat{U}_i(r) \right) + \left(\sum_{i>j}^A \sum_{j=1}^A \hat{V}_{ij} - \sum_{i=1}^A \hat{U}_i(r) \right) = \hat{H}_0 + \hat{H}_{res}, \quad (1.3)$$

where the $\hat{H}_0$ is the one-body operator corresponding to the mean-field potential and $\hat{H}_{res}$ corresponds to the residual interactions not accounted for by the mean-field. The simplest nuclear shell model, known as the Independent Particle Model (IPM), is based on the extreme approximation of $\hat{H}_{res} \rightarrow 0$. The mean-field potential $U(r)$ can take various forms. The most commonly used ones are the harmonic oscillator (HO) and the Woods-Saxon potential. In addition to this, in order to reproduce the good "magic numbers" corresponding to the shell structure, additional terms must be included. This includes a surface correction term proportional to ℓ^2 , and the spin-orbit (SO) term $\ell \cdot s$ corresponding to the coupling of the intrinsic spin s and the orbital angular momentum ℓ of the nucleons. The Single-Particle Energy (SPE) is defined as the expectation value of the IPM Hamiltonian $\hat{H}_0$ for a nucleon in a given single-particle state $|\phi_i\rangle$, given by $\epsilon_i^0 = \langle \phi_i | \hat{H}_0 | \phi_i \rangle$. The IPM is particularly successful in explaining the observed magic

1. Introduction

numbers and provides a good framework to interpret experimental data for stable nuclei near the magic numbers.

In the current work, the focus of the study is on nuclei near the dripline where the residual term $\hat{H}_{res}$, corresponding to the two-body interaction $\hat{V}_{NN}$, becomes important. It has been found that the correlations between the valence nucleons have the most dominant contribution on the shift of the SPE obtained from the IPM. This is implemented in the widely used Valence-Space Shell Model (VSSM) (or Interacting Shell Model) by defining a model space corresponding to a non-interacting inert core and interacting valence nucleons within a defined *valence space* above it. The contribution of the nucleons in the inert core remains the same as in the IPM case, while for the valence nucleons, additional two-body interactions are taken into account via $\hat{H}_{res}$, modifying the single-particle energies. The two-body interaction is defined in terms of the so called Two-Body Matrix Elements (TBME) which is given as, $\langle \phi_a \phi_b JT | \hat{V}_{NN} | \phi_c \phi_d JT \rangle$, where $\phi_a, \phi_b, \phi_c, \phi_d$ are used to label the single particle states, J is the coupled total angular momentum and T is the total isospin.

The NN interaction used to obtain the residual interaction can be derived using microscopic models or by following a phenomenological approach. The former can be implemented in the form of Meson exchange models which are based on general symmetry arguments which constrain the structure of the $\hat{V}_{NN}$ operator. Modern methods based on chiral effective field theory (χ EFT) implement a more systematic and theoretically consistent procedure to construct realistic NN potentials based on the symmetries of quantum chromodynamics (QCD). On the other hand, in the phenomenological approach, the valence-space effective interaction is derived by fitting the two-body matrix elements and single-particle energies to reproduce observed binding and excitation energies in nuclei with nucleons in the same valence orbitals. This procedure captures the effective interaction in the model space, but it does not provide insight into the fundamental nucleon-nucleon interaction. Based on the general operator structure and nature of interaction, the NN interaction can be divided into three components, namely, the *central*, *spin-orbit* and *tensor* terms.

The nuclear interaction can be further decomposed into monopole and multipole components [32]. The monopole part of the interaction corresponds to the weighted average of the two-body interactions between two nucleons occupying two specific orbitals. While the multipole interaction accounts for the remaining part of the NN interaction which includes pairing, quadrupole and other correlations, such as collective excitations and configuration mixing. The monopole matrix element for the two-body interaction is given as,

$$V_T^m(a, b) = \frac{\sum_J (2J+1) \langle \phi_a \phi_b JT | \hat{V}_{NN} | \phi_a \phi_b JT \rangle}{\sum_J (2J+1)}, \quad (1.4)$$

for $T = 0, 1$. Each matrix element $\langle \phi_a \phi_b JT | \hat{V}_{NN} | \phi_a \phi_b JT \rangle$ is a diagonal TBME in a JT -coupled, anti-symmetrized basis. The monopole term captures the average interaction strength between orbitals a and b , and governs the evolution of effective single-particle energies as orbitals are progressively filled. It provides the average shift in the mean field energy (SPE) of a nucleon in orbital a when adding nucleons to orbital b . This *effective* single particle energy (ESPE) is given by,

$$\epsilon_a = \epsilon_a^0 + \sum_b n_b V_T^m(a, b), \quad (1.5)$$

where ϵ_a^0 is the SPE of a nucleon in orbital a , $V_T^m(a, b)$ is the monopole matrix element defined in Eq. 1.4, and n_b is the number of nucleons occupying a given orbital b .

1.2.1. YSOX Shell-Model Interaction

In the current work, the experimental spectroscopic information has been compared with shell-model calculations, performed within the VSSM framework using the YSOX interaction [33]. The calculations were performed and provided by C. Yuan (Priv. Comm.). The YSOX shell-model interaction is based on an effective interaction built by implementing the monopole based universal interaction V_{MU} [34] in the full psd model space, assuming a ${}^4\text{He}$ inert core. The V_{MU} , introduced to capture monopole based shell evolution, consists of a long range central Gaussian interaction and the tensor force consisting of $\pi + \rho$ meson exchanges.

The Hamiltonian is constructed using interactions from V_{MU} + spin-orbit (M3Y [35]), SFO [36] and SDPF-M [37]. In particular, the $\langle psd | V | psd \rangle$ and $\langle pp | V | sdsd \rangle$ matrix elements derived from the V_{MU} + spin-orbit interaction are included. These matrix elements have the general form given by,

$$V = V_{\text{central}} + V_{\text{spin-orbit}}(\text{M3Y}) + V_{\text{tensor}}(\pi + \rho). \quad (1.6)$$

The obtained YSOX Hamiltonian is shown [33] to successfully reproduce the ground state energies, drip lines, excited states, electric quadrupole and spin properties of the nuclei within the psd valence space. By incorporating realistic central and tensor components, the interaction effectively captures the essential aspects of shell evolution. Moreover, the inclusion of the $\langle pp | V | sdsd \rangle$ matrix elements enables $2\hbar\omega$ excitations, allowing for mixing between $(0 - 1)\hbar\omega$ and $(2 - 3)\hbar\omega$ configurations, which is shown to be important for describing some of the physical properties.

The shell model described thus far treats the nucleus as a closed quantum system, predicting eigenstates within a purely bound configuration. In reality however, the nucleus is an open quantum system, with resonant states and a non-resonant continuum of scattering states existing beyond the particle separation thresholds. As the dripline is approached, the corresponding separation energies decreases and a significant amount of the spectroscopic strength is shifted to the continuum. Consequently, the bound system can couple to the unbound continuum, leading to modifications of both the bound states and the unbound states in the continuum. This coupling is particularly significant for near-threshold states—the primary focus of the current work—which are proposed to be strongly influenced by the continuum [2]. To address this, various theoretical frameworks have been developed over the years that explicitly incorporate continuum coupling [38, 39, 40].

1.3. Resonant states

Nuclei close to the driplines generally have very low particle emission thresholds. Consequently, these near-dripline nuclei do not have many bound excited states. For example, nuclei such as ${}^6\text{He}$, ${}^{11}\text{Li}$ and ${}^{14}\text{Be}$ do not have any excited states below their corresponding two-neutron separation energies. Beyond the driplines, even the ground states of the nuclei become unstable against particle emission. States populated above and close to the particle emission thresholds can manifest as unbound resonances. A summarized description of the formalism for the treatment of unbound resonant states, adopted from [7], is presented in this section.

Unbound resonant states generally have very short lifetimes τ ($\sim 10^{-21}\text{s}$), which implies that their energy is associated with a certain width, Γ , as a consequence of the Heisenberg's uncertainty principle given by,

1. Introduction

$$\Gamma \times \tau = \hbar. \quad (1.7)$$

Because of the short lifetimes direct measurement of the energy of such resonant states is extremely difficult. Consequently, indirect methods involving the measurement of the the decay products are employed to determine the energy.

Considering a one-neutron unbound system, an unbound resonant state can be described as a resonant scattering reaction of the unbound neutron with a bound nucleus core. In this case, the unbound neutron can be characterized as a plane wave $\phi = e^{ikz}$, with the wave number $k = \sqrt{2\mu E}/\hbar$, where μ and E corresponds to the reduced mass and energy of the neutron-core system respectively. For a neutron emitted with an orbital angular momentum ℓ , the effective spherical potential scattering the incoming plane wave is given by,

$$V_{eff}(r) = V_N(r) + V_\ell(r) = V_N(r) + \frac{\hbar^2 \ell(\ell + 1)}{2\mu r^2}, \quad (1.8)$$

where r is the relative neutron-core distance, $V_N(r)$ the attractive nuclear potential and $V_\ell(r)$ the ℓ -dependent repulsive centrifugal potential. From Eq. 1.8, it can be observed that this centrifugal barrier increases with the increase in ℓ . The barrier confines the neutron in the ℓ -dependent potential, therefore larger the ℓ , higher is the centrifugal barrier and longer the neutron exists within the potential. Therefore, for a system with angular momentum $\ell > 0$, resonant states are expected, with longer lifetimes and narrower widths associated with larger values of ℓ . However, for a neutron with $\ell = 0$, the centrifugal barrier term $V_\ell(r)$ vanishes, and thus there is no confinement of the neutron. Thus for $\ell = 0$, no resonant states are observed, but rather the situation may give rise to *virtual states* [41] if an increase in the cross section is observed towards lower relative energies.

In this scattering formalism of describing the resonant states, the core is treated as a hard sphere scattering target and the neutron as the incident particle. The differential cross section for a given partial wave with angular momentum ℓ , derived through a partial-wave analysis, is given by,

$$\frac{d\sigma_\ell}{dE} = \frac{4\pi}{k^2} (2\ell + 1) \frac{1}{1 + \cot^2 \delta_\ell(E)}, \quad (1.9)$$

where, δ_ℓ is the phase-shift of the partial wave ℓ of the neutron wavefunction induced by its interaction with the potential. As can be observed, the cross section σ_ℓ reaches its maximum value at a phase shift of $\delta_\ell = \pi/2$, corresponding to the resonant peak with energy E_r and width $\Gamma_{r,\ell}$. For a resonant system with $\ell > 0$, the δ_ℓ for all other ℓ will be negligible except the resonant ℓ component. δ_ℓ can be approximated as,

$$\cot \delta_\ell(E) = 2 \frac{E_r - E}{\Gamma_{r,\ell}}. \quad (1.10)$$

The shape of the phase shift gives rise to a *Breit-Wigner* distribution for the cross section corresponding to the resonance, which is given by,

$$\sigma(E)_\ell \propto \frac{\Gamma_{r,\ell}^2(E)}{(E - E_r)^2 + \Gamma_{r,\ell}^2(E)/4}. \quad (1.11)$$

This description enables characterization of the populated resonant states entirely in terms of the energy E_r and width $\Gamma_{r,\ell}$. The Breit-Wigner function defined in Eq. 1.11 is hence implemented into the fitting procedure to identify and characterize the resonances in the experimental data.

1.3.1. Invariant-mass method

As discussed, one of the main objectives in the current work is to study neutron-unbound states, which are populated in the continuum. Such resonances are generally extremely short-lived and decay instantaneously after being populated. These resonant states can be reconstructed from the information of the incoming ions and the outgoing reaction products resulting from the decay of the resonances formed during the reaction. Two methods are generally used in order to reconstruct such unbound resonant states, namely the *missing-mass method* and the *invariant-mass method*. At the R³B setup (section 2.2), the invariant-mass method is employed to reconstruct the unbound resonant states. This method requires the measurement of the complete kinematics of the reaction in order to reproduce the four-momenta of all outgoing decay products. As its name suggests, the invariant-mass method is Lorentz-invariant and thus provides the mass of the unbound state prior to decay, i.e., the mass of the unbound system in its center-of-mass frame.

Working in a system of natural units, for a particle with four momentum $P = (E, \vec{p})$, where E is its energy and $\vec{p}$ its 3-momentum, its mass m is given by,

$$m^2 = P^2 = E^2 - p^2. \quad (1.12)$$

For a system of N particles, the invariant mass is given by,

$$M_{inv}^2 = \left(\sum_i^N P_i \right)^2 = \left(\sum_i^N E_i \right)^2 - \left(\sum_i^N \vec{p}_i \right)^2, \quad (1.13)$$

where $P_i = (E_i, \vec{p}_i)$ is the four-momentum of the i th particle. The above equation can be rewritten as

$$M_{inv} = \sqrt{\sum_i^N m_i^2 + 2 \sum_{i<j}^N (E_i E_j - |\vec{p}_i| |\vec{p}_j| \cos(\theta_{ij}))}, \quad (1.14)$$

where m_i is the mass of the i th particle and θ_{ij} the angle between the momentum vectors of the i th and j th particles. The relative energy E_{rel} between the particles can now be derived from the invariant mass M_{inv} by subtracting the sum of the rest masses of the individual particles, i.e.,

$$E_{rel} = M_{inv} - \sum_i^N m_i. \quad (1.15)$$

Replacing M_{inv} from Eq. 1.14,

$$E_{rel} = \sqrt{\sum_i^N m_i^2 + 2 \sum_{i<j}^N (E_i E_j - |\vec{p}_i| |\vec{p}_j| \cos(\theta_{ij}))} - \sum_i^N m_i. \quad (1.16)$$

1.4. Three-body resonant systems

In this section, the decay kinematics corresponding to the three-body resonant systems will be discussed. In the case of a simple two-body decay, the possible correlations between the two particles (in this case Fragment+1n) in the system is constrained by only the energy and momentum conservation rules. In contrast, three-body decays can exhibit more complex correlations influenced by the decay mechanisms and final state interactions (FSI), in addition to those imposed by the energy and momentum conservation. The decay of three-body resonances can be broadly categorized into three main categories namely,

- Phase-space direct decay
- Sequential decay
- Direct decay with nn -FSI

Each of the decay mechanisms exhibit unique features in the corresponding three-body distributions which is discussed in the following subsection.

1.4.1. Observables

In order to characterize the three-body correlations following resonant decays, it is necessary to define observables that capture the complete information regarding these correlations. Over the years, several tools have been developed to study such three-body correlations in nuclear and particle physics. Of these, two notable approaches have been used extensively in the recent years to study Fragment+2n systems, namely, the Jacobi Coordinates [14] and Dalitz plots [15, 20]. In the current analysis the latter of the two has been employed.

Dalitz plots have been extensively used in particle physics for analyzing three-particle correlations [42, 43]. These are generally reconstructed with the particle energies (E_i, E_j) or the squared invariant masses of particle pairs (M_{ij}^2, M_{jk}^2), where $M_{ij}^2 = (P_i + P_j)^2$. In the current case, the Dalitz plots can be reconstructed with the two-body relative energy distributions corresponding to the three-body decay. The combination of these two-body relative energy distributions — which in the current case are the Fragment- n and the nn distributions — carry the complete information of the decay mechanism and associated correlations. The final surface distribution is confined to a kinematic boundary defined by the total Fragment+2n relative energy (E_{rel}) following energy-momentum conservation. In the case of a three-body phase-space direct decay, the Fragment- n and nn relative energy surface will consist of uniform distribution within the kinematic boundary. On the other hand, the presence of FSI or correlations will distort this uniform distribution and additional structures related to these correlations will be observed. A disadvantage of building the Dalitz plots with the two-body relative energies is that the energy boundaries depend on the total relative energy. Since the total relative energy changes from event to event, so does the boundary, which can make the interpretation non-trivial. To address this, a more accessible description was proposed in [19], where the reduced invariant mass was defined,

$$m_{ij}^2 = \frac{M_{ij}^2 - (m_i + m_j)^2}{(m_i + m_j + E_{rel})^2 - (m_i + m_j)^2}, \quad (1.17)$$

with,

$$M_{ij} = m_i + m_j + E_{ij}, \quad (1.18)$$

where E_{ij} is the two body relative energy between i and j . This confines the distribution from 0 to 1 for all events, regardless of the total relative energy. Therefore the Dalitz plots can now be built with two reduced invariant masses, i.e., m_{fn}^2 and m_{nn}^2 . Since the decay involves two neutrons, resulting in two Fragment- n pairs, the plots are filled twice for each event, once for each neutron.

To understand the reduced variable m_{ij}^2 more intuitively, the reduced energy ε_{ij} can be defined as

$$\varepsilon_{ij} = E_{ij}/E_{rel} \quad (1.19)$$

replacing ε_{ij} in Eq. 1.18,

$$M_{ij} = m_i + m_j + \varepsilon_{ij}E_{rel}, \quad (1.20)$$

with which the reduced mass can be written as

$$\begin{aligned} m_{ij}^2 &= \frac{(m_i + m_j + \varepsilon_{ij}E_{rel})^2 - (m_i + m_j)^2}{(m_i + m_j + E_{rel})^2 - (m_i + m_j)^2} \\ &= \varepsilon_{ij} \frac{2(m_i + m_j) + \varepsilon_{ij}E_{rel}}{2(m_i + m_j) + E_{rel}}. \end{aligned} \quad (1.21)$$

Since, the masses of the the involved particles, i.e., the fragment and the neutrons are much larger than the investigated relative energy E_{rel} , this implies $2(m_i + m_j) \gg \varepsilon_{ij}E_{rel}$. Therefore, the reduced invariant mass can be approximated as,

$$m_{ij}^2 \approx \varepsilon_{ij}. \quad (1.22)$$

This implies at low relative energies, the reduced invariant mass m_{ij}^2 corresponds approximately to the partial relative energy carried by the two-body ij system.

In the following, the evolution of the Dalitz plots corresponding to the different decay modes of the three-body resonances is discussed. It is pointed out here that the generator used for all neutron simulations in the current work was adapted and provided by A. Revel. It is based on the original generator developed by F. M. Marqués.

1.4.2. Phase-space direct decay

To identify correlations arising from interactions between the decaying particles, it is essential to first define the baseline correlation determined solely by energy-momentum conservation rules, which is described by the three-body phase-space. Direct decay refers to the type of decay where the two neutrons are emitted simultaneously. The neutrons in this case are indistinguishable and there is no decay through an intermediate state. As mentioned previously, in the case of direct decay following the three-body phase-space, the variables describing the decay uniformly fill the available phase-space. In the current case, the decay is described with the reduced invariant masses, m_{fn}^2 and m_{nn}^2 serving as the kinematic variables. Figure. 1.3 shows the Dalitz plot constructed using these variables for a simulation of a direct three-body phase-space decay. As can be observed the distribution is completely flat and uniform over the

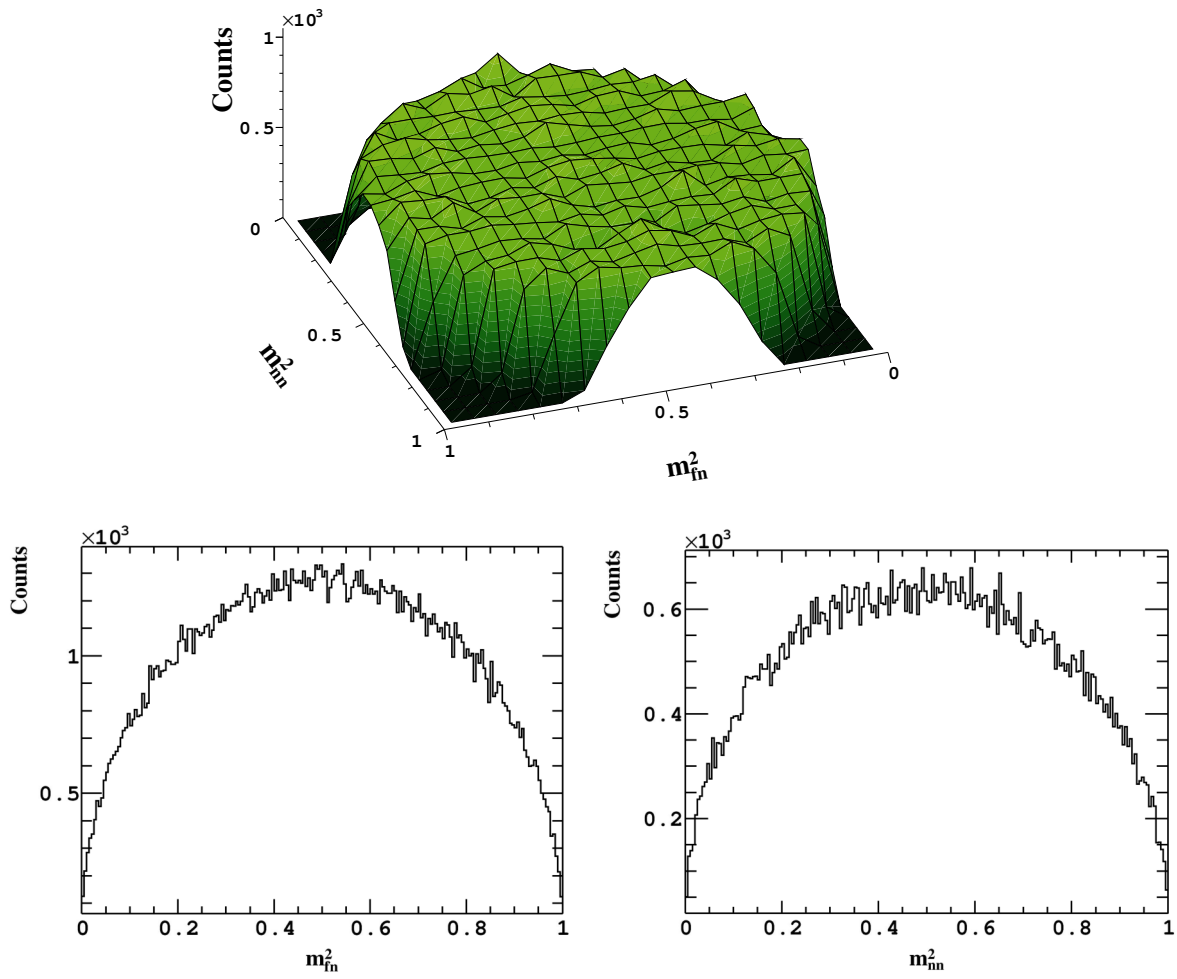


Figure 1.3.: *Top:* Dalitz plot corresponding to a simulated 3-body phase-space decay with resonance parameters of $E_r = 2$ MeV and $\Gamma_r = 1$ MeV. *Bottom:* Projections of the m^2_{fn} (left) and m^2_{nn} (right) distributions.

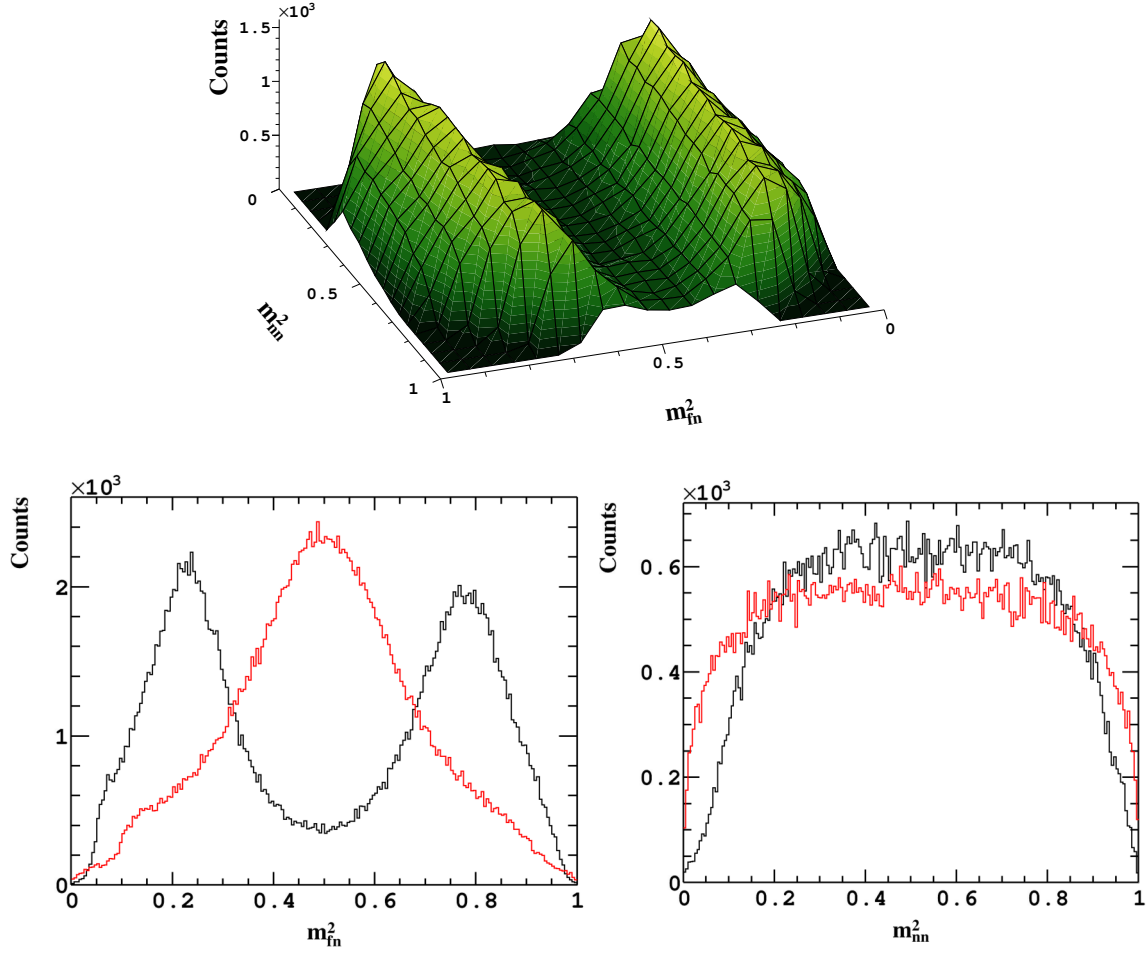


Figure 1.4.: **Top:** Dalitz plot corresponding to a simulated sequential decay with resonance parameters of $E_r = 2$ MeV and $\Gamma_r = 1$ MeV through an intermediate resonance with parameters $E_{s,r} = 0.5$ MeV and $\Gamma_{s,r} = 0.05$ MeV. **Bottom:** Projections of the m_{fn}^2 (left) and m_{nn}^2 (right) distributions corresponding to the same sequential decay as above shown in black. The distributions are compared to those obtained for a sequential decay through another intermediate resonance with parameters $E_{s,r} = 1$ MeV and $\Gamma_{s,r} = 0.05$ MeV.

1. Introduction

entire surface with no unique structures. For application in the analysis, a more quantitative approach is to study the projections of the Dalitz plot onto the two axes, which correspond to the individual m_{fn}^2 and m_{nn}^2 distributions. The projections are also shown in Fig. 1.3. Both distributions exhibit a bell shape from $m_{ij} = 0 - 1$, which reaches a maximum at $m_{ij} = 0.5$, and approaches 0 at $m_{ij} = 0$ and 1.

1.4.3. Sequential decay

Sequential decay refers to the situation where the decay proceeds through an intermediate state. It can be described as a two-step process, where the initial Fragment+2n system first emits a neutron at a specific excitation energy, populating an intermediate resonant state in the Fragment+1n channel. This Fragment+1n resonance then decays further by emitting a second neutron, with the energy and width of the intermediate state governing this decay. Therefore, in the case of sequential decays, the kinematics are determined by two-body phase-space decay applied twice, with additional constraints imposed by the energy and width of the intermediate state.

Figure. 1.4 shows the Dalitz plot and the corresponding projections along the two axes for a simulated sequential decay. As can be observed, the distribution is clearly different as compared to the phase-space direct decay. This is especially the case for the projected m_{fn}^2 distribution, which is characterized by ridge-like structures. The location of these structures depends on the energy of the intermediate state as compared to the energy of the initial state. To highlight this, two sequential decay simulations are shown in comparison. In the first case (shown in black in the projected distributions), the energy of the intermediate state is much smaller than the energy of the three body resonance. In this case, two symmetric wings are observed in the m_{fn}^2 distribution. Since the distribution is filled twice, once for each neutron n_1 and n_2 , the wings appear at $m_{fn_1}^2$ and $m_{fn_2}^2 \approx 1 - m_{fn_1}^2$ as a consequence of total energy conservation. In the second case (shown in red in the projected distributions), the intermediate state is located at half the excitation energy of the initial state. As a result, the ridges overlap and a single structure is observed at $m_{fn_1}^2 \approx m_{fn_2}^2 \approx 0.5$. The m_{nn}^2 distributions are filled following the phase-space defined by the sequential decay.

1.4.4. Direct decay with nn -FSI

In order to simulate direct decay including nn -FSI, a correlation factor is introduced into the phase-space direct decay simulations. This modifies the phase-space nn cross section to resemble the distribution expected from a system emitting neutrons with final-state interaction. The form of this correlation factor is discussed in chapter 5. The Dalitz plot and the corresponding projections along the two axes for the simulations of direct decay with nn -FSI are shown in Fig. 1.5. The projections are shown in comparison to the phase-space direct decay distributions. A clear difference can be observed in the m_{nn}^2 distribution as compared to the phase-space, with an enhancement towards the lower m_{nn}^2 values (i.e., lower nn relative energies), which is the typical signature of nn -FSI.

1.5. Neutron-rich Boron isotopes

Study of the evolution of the nuclear structure along a single isotopic chain helps reveal systematic trends in nuclear properties, providing insights into the underlying nuclear forces, shell structure, and

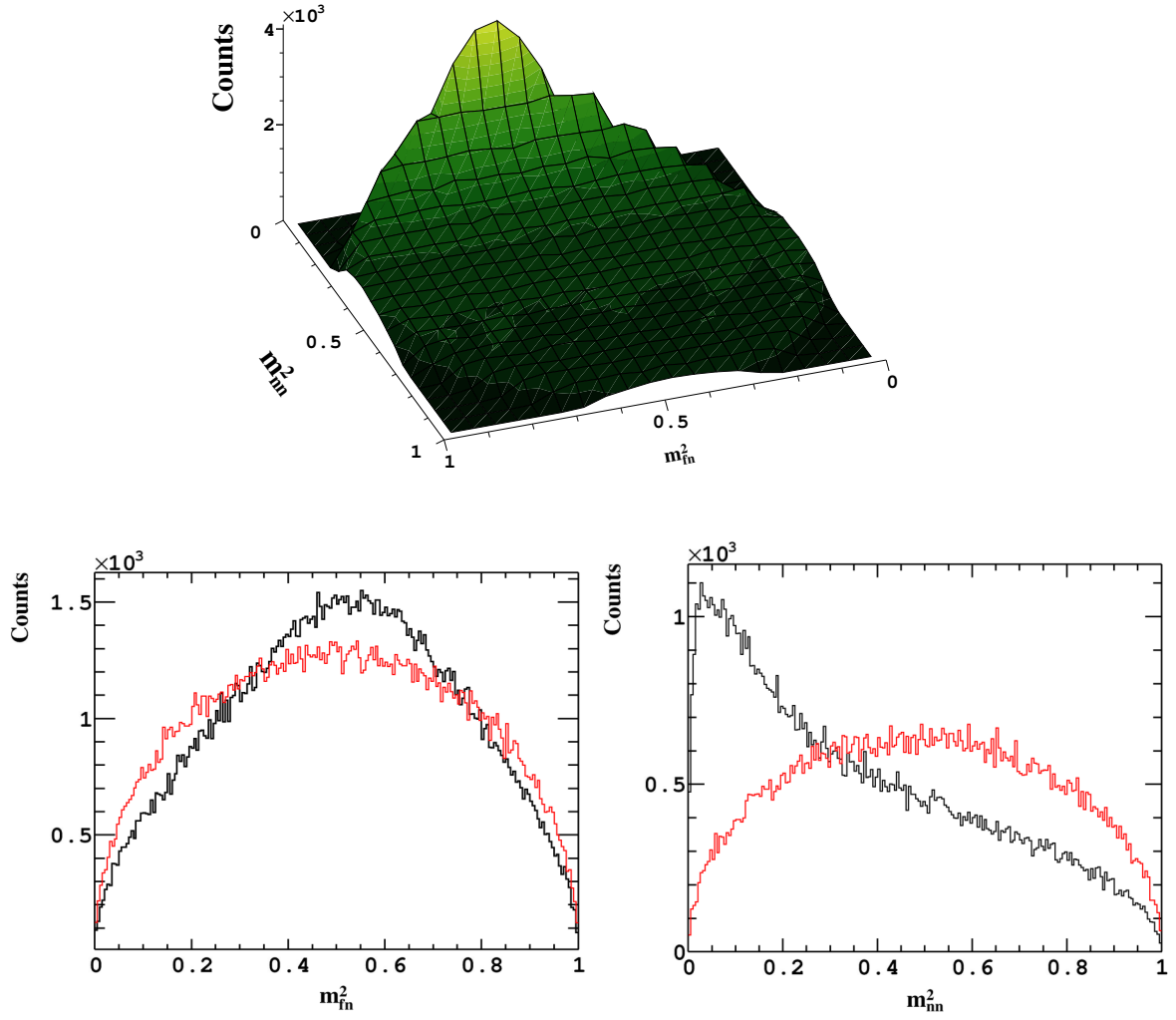


Figure 1.5.: *Top:* Dalitz plot corresponding to a simulated direct decay including nn -FSI with resonance parameters of $E_r = 2$ MeV and $\Gamma_r = 1$ MeV. **Bottom:** Comparison of the projections of the m_{fn}^2 (left) and m_{nn}^2 (right) distributions corresponding to the decay with nn -FSI (in black) and 3-body phase-space decay (in Red).

the impact of nucleon-nucleon interactions with varying neutron number. In particular, it contributes to explaining the emergence or disappearance of shell closures and appearance of exotic phenomena like halo formation. This is because, it provides a direct probe to the contribution of the monopole part of the effective nucleon-nucleon (NN) interaction, reflected in changes in the ESPE of the valence orbitals with the addition of neutrons.

The present work involves the study of neutron-rich Boron isotopes in the range $A \in [14, 17]$, where the valence neutrons primarily occupy the $0p_{1/2}$, $1s_{1/2}$ and $0d_{5/2}$ orbitals. Starting from ^{13}B , it has been shown that the neutron $N = 8$ shell closure (corresponding to the complete filling of the $0p_{1/2}$ orbital) is restored in the ground state (g.s.) of this nucleus [44, 45], following the abrupt breakdown of this magicity in the g.s. of its isotonic partner ^{12}Be , where the intruder sd configuration was shown to be dominant [46]. Thus, the further addition of neutrons to the ^{13}B core would lead to the filling of the $1s_{1/2}$ and $0d_{5/2}$ orbitals, with the relative occupancy depending on the evolution of the ESPE of these two orbitals. The filling starts with ^{14}B , which is the lightest bound $N = 9$ isotone. ^{14}B has been shown to have a strong $0s_{1/2}$ component in its g.s. [47, 48], which, due to its low separation energy ($S_n = 0.97(2)$ MeV [8]) is proposed to be a 1-neutron halo. In addition, several bound and unbound excited states have been reported for ^{14}B , populated via various reaction mechanisms [49, 48, 50]. In the current work, the structure of ^{14}B is investigated via the QFS $^{15}\text{B}(p,pn)^{14}\text{B}$ reaction, which should populate some of the previously identified states in addition to new ones. This reaction in particular also probes the g.s. neutron configuration of ^{15}B which has not been studied previously, offering insight into the subsequent evolution of the valence orbital ESPE. Bound and unbound states of ^{15}B are also investigated in the present work via the $^{16}\text{C}(p,2p)^{15}\text{B}$ reaction up to high excitation energies. Previous studies of ^{15}B states have been reported using multi-nucleon transfer reactions [51], fragmentation reactions [52] and inelastic scattering reactions [53].

The next isotope, ^{16}B , is one-neutron unbound and has been previously studied via various reaction mechanisms [51, 54, 55, 56]. Of particular interest, is the work reported in [56], where the ^{16}B states are populated via the $^{17}\text{B}(p,pn)^{16}\text{B}$ reaction, which provides the g.s. configuration of ^{17}B . In this case, the authors reported a dominant $0d_{5/2}$ configuration (~ 91 (7)%) in the ^{17}B g.s. This is contrary to the results from [57, 58, 59], which propose a two-neutron halo structure. In contrast, ^{19}B , the heaviest bound Boron isotope, has been identified as a prominent two-neutron halo, with a significant contribution from the $1s_{1/2}$ orbital in its g.s. [60]. Therefore, a significant shift in the relative ESPE of the $1s_{1/2}$ and $0d_{5/2}$ orbitals is expected between the two isotopes. To get a complete understanding of the evolution of the orbital strengths, this study should also include the other isotopes in the chain, i.e., ^{15}B and ^{21}B . As mentioned previously, the g.s. configuration of ^{15}B has been investigated in the current work through the $^{15}\text{B}(p,pn)$ reaction. In the case of ^{21}B , the two-neutron unbound g.s. has been previously reported in the work of [61] at 2.47 MeV above the two-neutron emission threshold. However, a detailed structural study was not presented due to limited statistics, highlighting the need for further experimental efforts to produce this isotope with sufficient intensity.

Finally, as previously discussed, one of the primary objectives of this work is to search for near-threshold "cluster" states close to the 2-neutron separation energy. With respect to this, the work of [7], indicates the presence of such near-threshold states in ^{17}B . The plots shown in Fig. 1.6, correspond to the γ -ray spectrum (left) and the $^{15}\text{B}+2n$ relative energy spectrum (right), obtained in coincidence with ^{17}B produced via a multi-nucleon knockout reaction from an incident beam of ^{19}C . In the γ -ray spectrum, two peaks were observed, with the first peak at $E_\gamma = 1.08$ MeV, which has been previously identified in inelastic scattering experiments [53, 62] and a second peak at $E_\gamma = 1.62$ MeV. Since ^{16}B is unbound, ^{17}B is a Borromean nucleus with a two-neutron separation energy of $S_{2n} = 1.38(21)$ MeV [8]. Therefore, the second γ -ray peak is 240 keV above the current value of S_{2n} , which however still has a very large uncertainty. In the γ -ray spectrum, the one-neutron separation energy (S_n) is shown with the gray band.

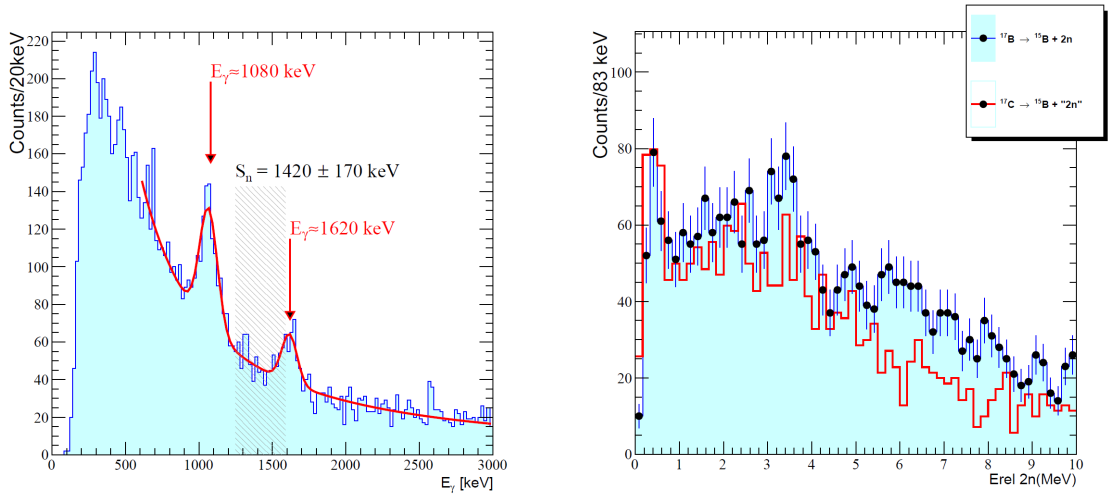


Figure 1.6.: *Left:* γ -ray spectrum in coincidence with ^{17}B fragment (produced from ^{19}C incoming beam). The one-neutron separation energy S_n is shown by the gray band indicating the uncertainty. *Right:* $^{15}\text{B}+2n$ relative energy spectrum corresponding to true ^{17}B events (In blue). "Cross-talk" $^{15}\text{B}+2n$ distribution obtained for incoming ^{17}C beam (In red). Plots taken from [7].

The $^{15}\text{B}+2n$ relative energy spectrum shown in the right panel (in blue), indicates the presence of a peak at around $E_{rel} = 0.4$ MeV. However, the authors also plot the one-neutron "cross-talk" spectrum obtained by reconstructing two neutrons from one-neutron events corresponding to the $^{17}\text{C} \rightarrow ^{15}\text{B} + 1n$ reaction, which is shown in red in Fig. 1.6 (right). This "cross-talk" spectrum also exhibits a peak at ~ 0.4 MeV, which, according to the authors, indicate that the 0.4 MeV peak observed in the "good" $^{15}\text{B}+2n$ spectrum is not real. In the present work, ^{17}B is populated via the $^{18}\text{C}(p,2p)$ QFS reaction, which should selectively populate some of the previously identified states in addition to new ones. The aim is to identify the near-threshold states observed in the work of [7] and characterize their structure and decay properties.

2. Experimental Setup

The experiment (s509, Spokesperson: O. Sorlin) presented in this work was carried out in the summer of 2022 in the state-of-the-art R³B setup at GSI, as part of the FAIR Phase-0 program. The acronym R³B stands for Reactions with Relativistic Radioactive beams. This setup is designed to provide information on the full reaction kinematics, including the details of the incoming isotopes and all reaction products on an event-by-event basis. This identification ensures accurate selection of the reaction channel with minimal background contribution, allowing for reliable reproduction of the physics observables.

In this chapter details on the experimental configurations will be provided. This includes a brief description of the beam production at the SIS-18 and FRagment Separator (FRS). This is followed by an overview of the R³B experimental setup used for the detection and identification of both reaction products and projectiles. Finally, a brief description of the triggering conditions applied during the measurements will be presented.

2.1. Beam Production at GSI

In the current experiment, a radioisotope "cocktail" beam of neutron-rich light nuclei was delivered to the R³B setup at Cave-C in GSI. These radioisotopes are produced and separated via the so-called in-flight technique [63, 64]. A schematic view of the GSI facility along with the FAIR facility currently under construction is shown in Fig 2.1.

The first stage involves the production and acceleration of a stable primary ion beam, the choice of which can range from ¹H to ²³⁸U. This begins with the injection of a low-energy stable isotope beam of choice from the MUlti-Cusp Ion Source (MUCIS) into the UNiversal Linear Accelerator (UNILAC) [65]. The ions are then accelerated to an energy of 11.4 MeV/A before being fed into the Schwer Ionen Synchrotron - 18 (SIS-18) [66]. The 18 refers to the maximum magnetic rigidity (in Tm) achievable by the setup. The beam extraction is done in the form of "spills" of a few seconds. In the current experiment, ⁴⁰Ar was chosen as the primary beam. It was accelerated to 600 MeV/A at the exit of SIS-18 and fed to the FRagment Separator (FRS) [67]. The beam intensity was 3¹⁰ particles/spill at the FRS production target with a spill length of 2.5 seconds.

The FRS is a high-resolution spectrometer with a momentum resolution of $\sim 2\%$, used for the production and separation of secondary radioactive ion beams. A schematic diagram of the FRS setup is shown in Fig 2.2. The production target was a 4009 mg/cm² thick Beryllium target, placed at the entrance to the FRS. The ⁴⁰Ar primary beam undergoes fragmentation at the target to produce a wide range of radioactive ions. The isotope selection at the FRS is done using the so-called $B\rho - \Delta E - B\rho$ method, where $B\rho$ is the magnetic rigidity for a magnetic field B acting on particle trajectories with curvature ρ , and ΔE correspond to the energy loss with a degrader. The FRS consists of a combination of four dipole magnets used for the $B\rho$ selection based on the mass-to-charge ratio A/Z . The relation between $B\rho$ and A/Z is given by,

2. Experimental Setup

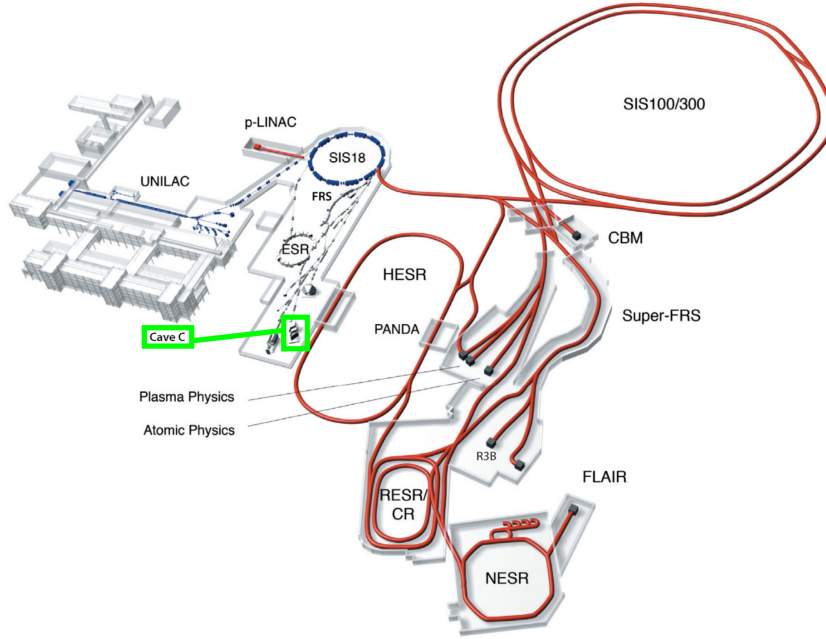


Figure 2.1.: Schematic diagram of the existing GSI facility along with the FAIR facility under construction (in red on the right). Figure taken from [68].

$$B\rho \propto \frac{A}{Z}\beta\gamma, \quad (2.1)$$

where β is the particle velocity and γ the corresponding Lorentz factor. In the current experiment, the incoming ions are light and therefore mostly fully stripped which implies $Q \approx Z$. In addition to the dipole magnets, the FRS also consists of several quadrupole and sextupole magnets for focusing and stabilizing the beam. In the present experiment, two $B\rho$ settings were used, which enabled the measurement of a large range of radioactive ions. Beam diagnostic is performed with detectors placed at each focal plane of the dipole magnets labeled as S1-S8 in Fig. 2.2. For the present analysis, only the central dispersive focal plane S2 is of interest, where a plastic scintillator was placed to measure the Time-of-flight (ToF) between the focal plane and the entrance of Cave-C, covering a flight path of $\sim 136\text{m}$. Typically, a wedge shaped degrader is placed at the S2 focal plane for further selection of the isotopes via the ΔE method. However in this experiment the aim was to obtain a "cocktail" beam with a range of isotopes with similar $B\rho$ within the FRS acceptance, and therefore no degrader was used.

2.2. The R³B Setup

The experimental setup at R³B is a flexible setup which can be adapted based on the physics case being probed. The layout of the setup along with the detectors used for the current experiment is shown in Fig. 2.3. The experimental setup at the time of the experiment was located at Cave-C in Experimental Hall-II. As mentioned above, the general design of the R³B setup enables kinematically complete measurements at relativistic energies. This includes complete information of incoming particles,

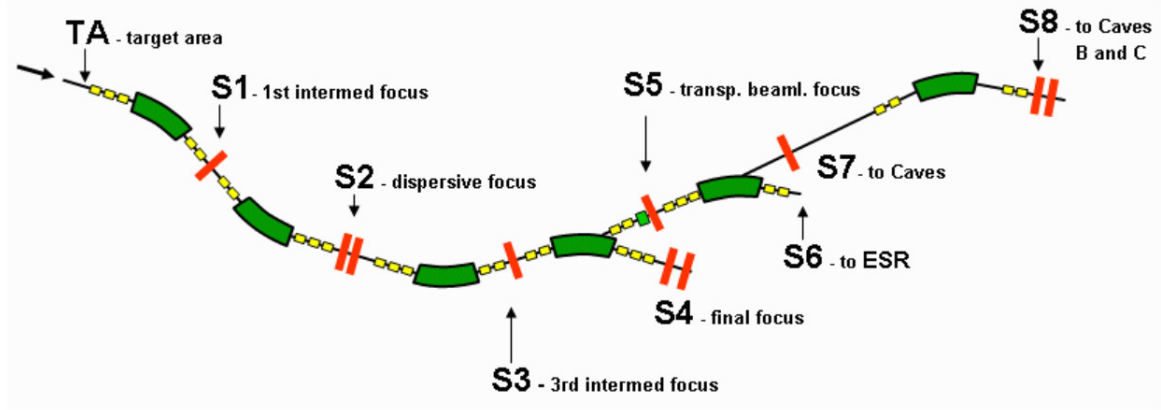


Figure 2.2.: Scheme of the FRS setup. The dipole and quadrupole magnets are shown in green and red respectively. The focal planes are labeled from S1-S8. Figure taken from [69].

as well as detection of the outgoing fragments in coincidence with produced γ -rays, protons, neutrons and other reaction products. The velocities, trajectories and energies of all detected particles are reconstructed on an event-by-event basis. In the current experiment, two $B\rho$ settings were used to cover a broader range of isotopes, centered around $A/Z \sim 2.7$ and $A/Z \sim 3$, with rates of 6 kHz and 1 kHz at the entrance of the setup, respectively. The focus of the experiment was on light ions, with the oxygen isotopes being the heaviest incoming ions.

Event-by-event particle identification (PID) for the incoming ions is especially important in the current case, since the incoming cocktail beam consists of a range of ions. To identify the incoming particles, it is necessary to determine their mass and charge. Rearranging Eq. 2.1,

$$\frac{A}{Z} \propto \frac{B\rho}{\beta\gamma}. \quad (2.2)$$

Therefore, to deduce the mass of an ion, it is necessary to know its $B\rho$, velocity, and charge. The $B\rho$ centroid is generally known from the FRS settings used to tune the beam. The velocity is extracted via a ToF measurement with knowledge of the flight path length. In this case the ToF was measured between a scintillator paddle placed at the S2 dispersive focus at FRS and the start detector LOS, which is another octagonal shaped plastic detector placed at the entrance of the cave. With a flight path distance of $d \sim 136$ m, the velocity is calculated as,

$$\beta = \frac{d}{(T_{LOS} - T_{S2})c}, \quad (2.3)$$

where T_{LOS} and T_{S2} are the times at the LOS and S2 detectors, respectively and c is the velocity of light.

The measurement of the charge Z is based on the principle of energy loss ΔE of the charged ions, which is governed by the Bethe-Bloch formula,

$$\Delta E \propto \frac{Z^2}{\beta^2}. \quad (2.4)$$

This can be rearranged to,

2. Experimental Setup

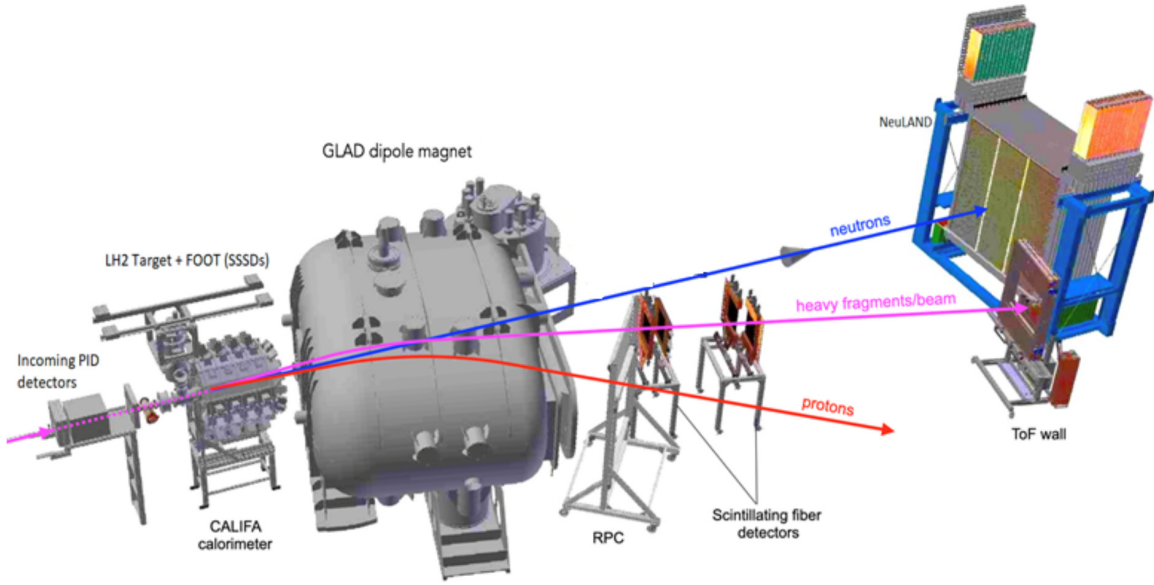


Figure 2.3.: Setup of the detectors at R^3B for the present experiment. Figure courtesy of D. Körper.

$$Z \propto \beta \sqrt{\Delta E}. \quad (2.5)$$

Therefore, measuring the energy loss ΔE helps determine the charge Z . In the current experiment, this is achieved using the charge sensitive gas ionization chamber MUSLi detector, as well as the start detector LOS. Because of the contribution of the velocity β , event-by-event velocity correction is done to maintain the proportionality.

In addition to the identification of the mass and charge of the incoming particles, the information on their trajectories can be obtained with the help of position sensitive detectors. In this case, Multi Wire Proportional Chambers (MWPCs) were used for this purpose. Here, the convention for the coordinate system used in the present experiment is introduced: the Z-axis is considered to be in the direction of the beam, the Y-axis points to the top of the beam and consequently the X-axis points to the left of the beam. Two MWPCs were placed upstream of the target, each providing X and Y position information.

The incoming beam was directed onto the reaction target to study QFS reactions. In the current experiment, a 5 cm liquid hydrogen (LH_2) reaction target was employed (see Fig. 2.4). The LH_2 target had a density of 0.0711 g/cm^3 , operated at a temperature of $\sim 20 \text{ K}$ and pressure of $\sim 950 \text{ mbar}$. The target cell is composed of Mylar and consists of an entrance and exit window of $120 \text{ }\mu\text{m}$ and $180 \text{ }\mu\text{m}$, respectively. The target cell is further encased in $5 \text{ }\mu\text{m}$ multi-layer insulating foils. The beam energy at the entrance of the target was $\sim 540 - 580 \text{ AMeV}$ depending on the incoming ion.

After the target, the beam carrying the fragments and the forward focused reaction products enter the large acceptance dipole magnet GLAD, which bends the particles based on their $B\rho$ values, as given in Eq. 2.1. Similar to the incoming ions, identifying the outgoing fragments requires determining their charge Z and mass A . For the charge, four Single Sided Silicon Strip Detectors called FOOT were placed right behind the target (and before GLAD). In addition to the charge, these detectors also provide position information which aids in reconstructing the outgoing trajectories of the fragments. The outgoing fragments then enter GLAD and are bent by the magnetic field into the fragment arm, which was centered

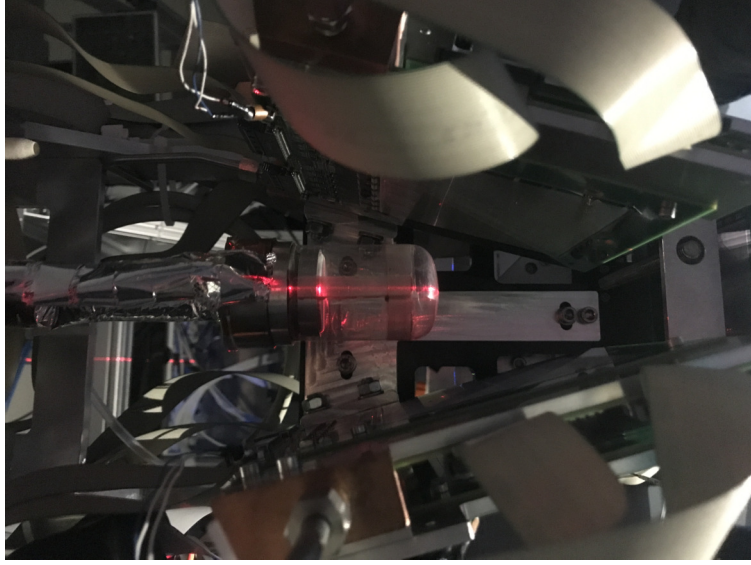


Figure 2.4.: *LH₂ Target Cell with surrounding FOOT detectors.*

at 14° (w.r.t the beam axis) in the current experiment. The fragment arm consisted of position sensitive scintillator fiber detectors and the Time-of-Flight Detector (ToFD), which is a wall made of scintillator bars placed at the end of the beam line. The position information before and after GLAD is used to reconstruct the $B\rho$, which when combined with the ToF information between LOS and ToFD provides the A/Z . The ToFD also provides the charge information of the outgoing fragments, which is used in combination to the Z provided by the FOOT detectors.

In addition to the outgoing fragments, other reaction products such as γ -rays, protons, neutrons, etc. are also emitted from the reaction processes depending on the excitation energies. Since the objective is to measure the full reaction kinematics, there are several detectors dedicated to the measurement of these reaction products. γ -rays and proton/neutrons scattered around the target area from the QFS reactions are detected by the CALIFA calorimeter surrounding the target. It is a highly segmented calorimeter composed of CsI(Tl) crystals, providing an angular coverage of 22° - 81.9° in theta (w.r.t the beam axis). Several FOOT detectors were also placed in the proton arms to detect the QFS protons, however the efficiency of these detector was found to be extremely low and thus not used in the subsequent analysis.

The forward focused protons as well as α -particles going through GLAD were detected in the proton arm which consisted of a Resistive Plate Chamber (RPC) detector. For the current work, this detector was not used. For further details on this detector please refer to [70].

The forward focused neutrons are primarily produced via evaporation from fragments having excitation energies higher than the neutron separation threshold. These neutrons, which are the main focus of the current work, were detected in the neutron detector NeuLAND. It was placed ~ 15.4 m downstream of the target at 0° to the beam, since neutrons are not affected by the magnetic field and travel forward. Most of the current work involves analysis using this detector, including the development of the algorithms to reconstruct the multiplicity and the four momenta of the detected neutrons.

2. Experimental Setup

2.2.1. Incoming Beam Detectors

LOS!ROLU

LOS is an octagonal shaped plastic scintillator of 3 mm thickness which is read out by 8 photomultipliers (PMTs) coupled to the side of the edges. LOS has a unique electronic setup in the sense that each PMT is read out by two independent systems for time and charge measurement. The time information from this detector is used for the ToF measurement of the incoming ions when used in combination with the S2 scintillator paddle. It also acts as the start of all ToF measurements within the Cave. It enables the extraction of the fragment ToF when used in coincidence with ToFD and similarly the neutron ToF when used with NeuLAND. Since this experiment consists of light ion beams, the LOS has sufficient resolution to provide the energy loss information too.

The LOS detector is generally operated with the ROLU (Rechts-Oben-Links-Unten) veto in anti-coincidence. The objective of the ROLU detector is to define the beam spot. It consists of four movable scintillator paddles of 5 mm thickness, each read out by 1 PMT. They are placed around the beam in such a way that a small rectangular area corresponding to the appropriate beam spot is left empty at the center. The minimum requirement to read out an event with a valid on-spill trigger condition is to have a signal in all 8 PMTs of LOS and no signal in any of the ROLU paddles (hence the LOS!ROLU). This forms the so-called minimum bias condition for an on-spill event (see section 2.3 for the trigger definitions).

Multi-Wire Proportional Counters (MWPC)

Two Multi-Wire Proportional Counters (MWPC) were used to identify the trajectories of the incoming ions. These detectors provide the absolute X and Y positions and are used as references for position calibration of other detectors. They were placed 268 cm and 149 cm upstream of the target. The first MWPC consists of 64 vertical and horizontal pads each of 3.125 mm width along with planes of horizontal and vertical tungsten wires of 5 μm diameter. The second MWPC also has 64 vertical pads of 3.125 mm width but 40 horizontal pads of 5 mm width and only one plane of horizontal wires of 50 μm diameter. This implies that the second MPWC has a similar resolution to the first in X direction but poorer resolution in the Y direction. The X direction resolution is $\sim 200 \mu\text{m}$ FWHM. The gas mixture enclosed inside the detector is composed of 84% Ar and 16% CO₂. The wires are separated from the readout pads by a distance of approximately 2.5 mm. During operation, a high voltage is applied to the wires, creating a strong electric field in the gas-filled active volume. When a charged particle passes through this volume, it ionizes the gas, producing electron-ion pairs. The electrons then drift towards the wires, where an avalanche is created. This avalanche induces a signal on the nearby readout pads, and the distribution of the induced charge across these pads provides the position information..

MUSIC For Light Ions (MUSLi)

MUSIC is an acronym for MUlti-Sampling Ionisation Chamber [71]. In the current experiment, the double ionization chamber Twin-MUSIC was employed in a modified configuration, enabling the detection of light ions. The Twin MUSIC in general consists of two chambers with a central cathode and two anode planes on both sides. Each anode plane is divided into top and bottom and further segmented into 16 anodes along the length of the detector. Frisch grids are placed 110 mm from the cathode and 3 mm from the anode planes. In the current experiment, only 1/4 of the detector was used. The charged ions

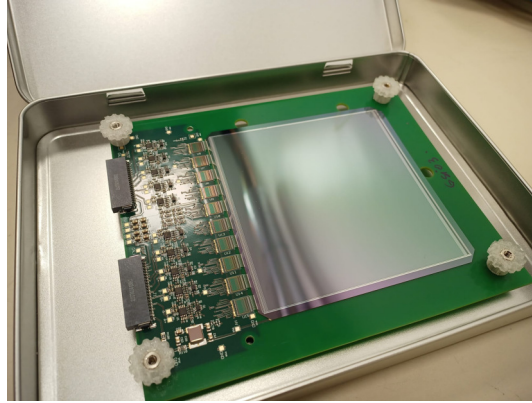


Figure 2.5.: A single FOOT module.

traversing through the detector were detected in the active volume of $110 \times 110 \times 400 \text{ mm}^3$, filled with a gas mixture of 79% CH₄, 20% Ar and 1% CO₂. When an incoming ion traverses the active volume of MUSLi, an ionisation track of electrons and positive ions is created in the detector. The electron cloud then drifts towards the anodes through the grounded frisch grid where the charge distribution is sampled as a function of the collection time. Consequently, in addition to measuring the charge, one can also, in principle, obtain the trajectory information along the detector, thanks to the granularity of the anodes and the information of the drift time.

2.2.2. Target Area

FOOTs

FragmentiOn Of Target (FOOT) detectors (see Fig. 2.5) are single sided silicon strip detectors. Each detector has an active area of $10 \times 10 \text{ cm}^2$ with a thickness of $150 \text{ }\mu\text{m}$ and strip pitch of $50 \text{ }\mu\text{m}$. Three adjacent strips are coupled together via capacitive coupling (1 readout strip, 2 adjacent floating strips), resulting in an effective strip pitch of $150 \text{ }\mu\text{m}$. They were placed after the target along the fragment trajectory and on the arms of the target in order to detect the protons from QFS reactions. The general tracking idea is to have the detectors oriented in X and Y directions consecutively, to ensure precise X-Y coordinate readout. Along the beam axis, one X-Y pair was placed within the vacuum chamber housing the target and one outside the chamber. Along the QFS proton trajectories, all detectors were placed within the chamber with two X-Y pairs along each arm.

In addition to the position information, the in-beam detectors were also used to obtain the charge of the outgoing fragments before GLAD, which was used in combination with the charge information from ToFD after GLAD.

CALIFA

CALIFA stands for CALorimeter for In-Flight detection of γ -rays and high energy charged pArticles [72][73]. As the thoroughly descriptive name suggests, it is a highly segmented calorimeter designed to measure γ -rays emitted via de-excitation of fragments and scattered charge particles around the target area, such as QFS protons. A schematic of the full CALIFA design is shown in Fig 2.6. At the time of the

2. Experimental Setup

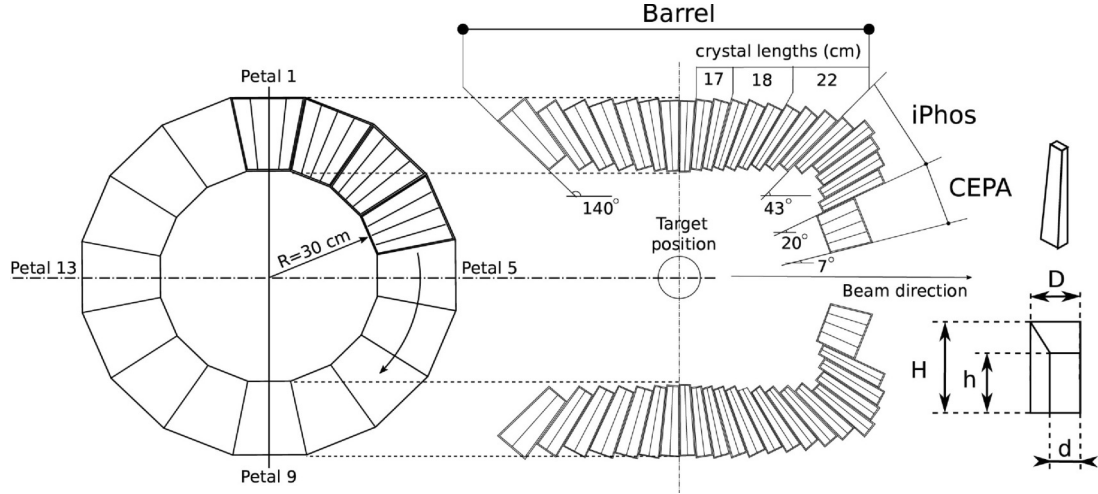


Figure 2.6.: Schematic design of the full CALIFA calorimeter. For the current experiment only a part of the Barrel and the IPHos was available. Figure taken from [73].

experiment, the detector was still under development, and therefore the complete geometry was not available. The current setting consists of 1504 CsT(Tl) crystals (called petals), each shaped in the form of rectangular prisms with varying angular coverage. The high segmentation allows for studies involving higher particle multiplicities and appropriate Doppler correction of the Lorentz boosted γ -rays. Each crystal is covered with reflective foil and read out by Large Area Avalanche Photodiodes (LAAPDs). The detector consists of two parts, namely, the Barrel with 1024 crystals providing a polar angular coverage of $43^\circ - 81.9^\circ$ (measured from the beam axis) and the EndCap consisting of 480 crystals for the IPHOS (Intrinsic PHOSwich) part, providing an angular coverage from $22.0^\circ - 43.2^\circ$.

Since most of the particles emitted from the reactions will be boosted into the forward directions, the EndCap should be able to detect both charged particles with high Linear Energy Transfer (LET) as well as γ -photons with low LET. In order to accommodate for this, each crystal in the IPHOS is read out by two sets of pre-amplifiers settings, corresponding to different gain configurations. The high-gain output is used for the γ -photons and other low energy signals while the low-gain output is used for charged particles. The Barrel uses only the high-gain output as mostly γ -rays are detected in this angular range, with minimal contribution from other charged particles. The readout consists of a charge-to-digital converter (QDC), which provides a digitized output corresponding to the measured deposited energy. The detector has a modular design where it can be opened into two sides, the left and the right, in order to allow for placement of the target chamber inside. This separation into the left and right sides is important since they provide separate trigger signals.

2.2.3. Fragment Arm

Fibers

In order to track the fragments after GLAD and consecutively obtain their $B\rho$, four scintillating fiber detectors were placed along the fragment trajectory at 14° . Each fiber detector consists of 512 fibers of 1 mm thickness with a square cross section providing a total active area of $50 \times 50 \text{ cm}^2$. They are read out on both sides by two Multi-Anode PMTs (MAPMTs) on each side. The advantage of having MAPMTs

over single PMTs is that they are less sensitive to the fringe field. The active area was covered with black tape to avoid external light background.

The orientation and alignment of the four detectors was optimized to get maximum possible acceptance. The first detector in the beam direction (Fiber32) was oriented to measure the X position and placed with the 14° line passing perpendicular to the center. The second fiber (Fiber30) was placed 25 cm further into the beam line, also centered at the 14° line but oriented to measure the Y position. The last two fibers (Fiber 31 and 33), oriented to measure the X-positions, were placed adjacent to each other 150 cm downstream from the first fiber, with the 14° line passing between the two detectors (see Fig. 2.3). This spread in acceptance down the beam line is necessary in the X-position measurement since it corresponds to the dispersive plane of GLAD.

Time-of-Flight Detector (ToFD)

The ToFD [74] is a scintillator wall placed at the end of the beam line. It is used to measure the charge and the ToF (w.r.t LOS) of the fragments. It consists of four walls, each having 44 scintillator paddles placed vertically. Each paddle has dimensions of $1000 \times 27 \times 5 \text{ mm}^3$. The paddles are read out on both sides by two PMTs coupled at the far ends. The paddles of consecutive planes are shifted in order to cover small gaps appearing between neighboring bars within a single plane. This allows for a final active area of $1200 \times 100 \text{ mm}^2$. The paddles were also wrapped in black tape for light tightness. Each paddle can also provide a precise Y-Position information by taking the time difference between the two PMTs. Additionally, the X-position distribution can also be extracted limited to the granularity of the paddle size ($\sim 27 \text{ mm}$).

2.2.4. Neutron Arm

NeuLAND

The New Large-Area Neutron Detector (NeuLAND) [75] is a high-resolution neutron spectrometer designed for identification of large neutron multiplicities with high detection efficiency. This is achieved thanks to its high granularity, excellent time resolution, and large active volume. The detector for the current experiment was placed 15.4 m downstream from the target centered at the 0° line. At the time of the experiment the detector was partially built with 13 double planes with the final design objective being a total of 30 double planes. The planes were placed alternating between horizontal and vertical orientations between consecutive planes, hence the terminology of double planes. Each plane consists of 50 paddles (or submodules) placed adjacent to each other, where the active volume of each paddle corresponds to $5 \times 5 \times 250 \text{ cm}^3$. Therefore the total active area of the detector corresponds to $250 \times 250 \text{ cm}^2$ with a total depth of 1.3 m. Each paddle was read out at the far ends by two PMTs and wrapped in reflector material and adhesive black tape for light tightness. The full paddle length is 270 cm, with 250 cm being rectangular and the tapered 10 cm ends serving as light guides to the PMTs. Each paddle can provide time and position information. The time information is based on the average time between the two PMTs, and is used to calculate the ToF from LOS by taking the difference between the LOS time and the paddle time. The position information depends on the orientation of the paddles. For horizontal paddles, the X-position is obtained from the time difference between the two PMTs, while the Y-position is derived from the fixed paddle position in the detector geometry, resulting in a Y-position granularity of 5 cm. This situation is reversed for the vertical bars.



Figure 2.7.: NeuLAND at R^3B with 13 double planes. Figure taken from [75].

The neutron detection principle is based on the light production from secondary charged particles after the initial neutron interaction in the active volume. The low probability of initial neutron interactions necessitates the requirement of a large active volume. With the present configuration, a maximum one-neutron detection efficiency of $\sim 78\%$ is obtained (see section 3.3.4).

2.3. Triggers

The R^3B setup primarily uses DRASI [76] based data acquisition system (DAQ). The data is stored event-by-event in the form of list mode data (LMD) files. For every event, a decision has to be made whether the data is satisfactory and worth writing to file. For this purpose, an efficient trigger logic is generally employed which is used to make a decision on whether the detector signals correspond to a physical event or not. If a valid trigger is detected, the event is saved to the data; otherwise, it is discarded. To implement this, the first step is to obtain a logic signal from some of the critical detectors, depending on whether a signal was seen above the detector specific threshold. A combination of these logic signals within a given time window form what is known as the trigger-logic. This trigger-logic is generally employed in the form of a 16-bit word known as the TPat (Trigger PATtern). Each bit of this trigger pattern requires a logic signal from a specific combination of detectors, the logic of which is decided prior to the experiment depending on its specific requirements. Whenever the logic for a Bit is fulfilled, it is set to true (binary 1) in its position in the 16 bit word of the TPat. Every event has its own recorded TPat. Multiple bits may be set to true in an event and the combination is what forms the final TPat of the event.

Bit Value	Description	LOS!ROLU	ToFD	CALIFA OR	CALIFA AND	NeuLAND
1	Minimum bias	x				
2	Fragment	x	x			
3	CALIFA P2P	x			x	
5	CALIFA OR	x		x		
6	Neutron	x				x

Table 2.1.: The relevant "ON-Spill" bits of the TPat along with the trigger conditions used for the current analysis.

For the current experiment, all 16 Bits were used and assigned a unique trigger condition. The first 12 bits were "ON-spill" triggers, i.e., triggers corresponding to beam arriving at the cave. These required coincidence with the "Beam-ON" signal arriving from SIS-18 in addition to the LOS!ROLU condition. The last 4 bits were "OFF-spill" triggers, which were used for detectors measuring cosmic and background data needed for calibration. Generally, for a trigger condition to be fulfilled and a bit to be set to true, multiple detectors must record a signal within a set time window. For example, for the "Fragment" bit to be set to true, it requires signals from "Beam-ON", LOS!ROLU and ToFD in coincidence. For this purpose, the detectors also need to be aligned in time by delaying the signal from the different detectors such that the coincident signals from these detectors arrive within a given time window of the event. In the current experiment, this time window was set to $8.5 \mu\text{s}$. Any signal in the detectors within this window was written as a single event. This could include multiple hits in the same detector within the same event, though within one event all detectors receive only one trigger signal.

In the current experiment, a unique "ON-Spill" triggering/TPat condition was used owing to the long deadtime of the FOOTs, which was $\sim 150 \mu\text{s}$. The deadtime of the DAQ is based on the OR of the "busy" signals (sent when a detector is in deadtime) of all the other detectors. A safe upper limit of this was estimated to be around $50 \mu\text{s}$. In order to not lose triggering rate due to the FOOT deadtime, the trigger bits of the TPat was separated into two sets: 1-6 in coincidence with FOOT and 7-12 with no FOOT in coincidence, but otherwise the same trigger conditions as the first 6. The logic works as follows; If a good ON-Spill trigger signal is received, the system first checks if all detectors including the FOOTs are not in deadtime and whether a good trigger condition is set. If its is a good event it is then recorded in the first 6 bits of the TPat depending on which bit logic is fulfilled and the FOOTs enter their $150 \mu\text{s}$ deadtime. After a short interval, still within the FOOTs deadtime, the DAQ can be ready again (i.e., when all detectors composing the OR signal for the DAQ deadtime are ready) to read another event, provided the event occurs at least $50 \mu\text{s}$ before the FOOTs deadtime ends. This ensures that the event can be fully read out and that the DAQ recovers from its deadtime by the time the FOOTs are ready again. Events arriving within the FOOTs' deadtime are recorded in bits 7–12. With this configuration, priority is given to the first six bits so that the system can read out as soon as the FOOTs are ready. In the current analysis, only events with TPat bits in coincidence with the FOOTs (i.e., bits 1-6) are used, although the other TPats could still be used to increase statistics..

The trigger conditions for the relevant "ON-Spill" trigger bits used in the current analysis are shown in Table. 2.1. The simplest trigger, which is the minimum condition for all "ON-Spill" trigger bits is the "Minimum Bias" condition, which is "Beam ON" + LOS!ROLU. This is in fact the definition of the the first trigger bit of the TPat, which implies that its always set to true for all "ON-Spill" data. CALIFA and NeuLAND were the main detectors measuring reaction channels and consequently formed the major part of the reaction triggers. For CALIFA, the trigger threshold for the crystals were set to above ~ 5 MeV in the Barrel region and above ~ 30 MeV in the low gain preamps of the IPHOS region (there is no trigger signal from the high gain preamps of IPHOS). The "CALIFA OR" trigger is set when *either* the left

2. Experimental Setup

or the right side of CALIFA records a valid trigger signal in any of its crystals. On the other hand, the "CALIFA AND" trigger (for "CALIFA P2P" bit value) is set when *both* sides see a valid trigger signal. For NeuLAND, a valid trigger signal is produced whenever there is a signal in at least two PMTs above the PMT specific threshold which is around ~ 600 keVee.

Here, the concept of downscaling is introduced. Since the reaction rate at the target is very low ($\sim 1\%$), the number of relevant reaction events is very small. Therefore, in order to reduce the deadtime of the DAQ and the storage space required, it becomes practical to reduce the number of events recorded, especially for events with predominantly unreacted event triggers. To do this, certain trigger bits are downscaled by a factor X , such that only every X th event in which the bit is set to true is recorded. As mentioned, for an event multiple trigger bits can be set to true in an event and each bit undergoes the downscaling check separately. For example, if in an event the "Fragment" and "Neuland" trigger bits were set but the "Fragment" bit was downscaled, then the event TPat would just record the "Neuland" bit as true. On the other hand, if the event just had the "Fragment" bit set and it was downscaled then the entire event would be discarded. Cross section measurements require counting both reacted and unreacted events, making it essential to have precise knowledge of the downscaling factors. The downscaling factors change for the current experiment between runs and are listed in Appendix. A.

3. Calibration and Analysis

In this chapter, the detailed analysis methods used in the current work are reported. The analysis has been carried out using the analysis and simulation software package R3BRoot [77], which inherits from the global FAIR analysis software package FairRoot [78]. It is primarily based on the ROOT analysis framework [79] for the data analysis, while incorporating the GEANT3 [80] and GEANT4 [81] toolkits for simulations.

As discussed in Chapter. 2, two settings of incoming ions were used in the experiment, and for each setting, data was collected across multiple runs. Reaction channels from both settings have been analyzed in the present work. The runs used in the analysis are listed in Appendix. A.

This chapter provides an overview of the important detector observables needed for the complete analysis, along with a brief description of the calibration procedures for the corresponding detectors. The final objective is to select out specific reaction channels and reconstruct the properties of all reaction products. Firstly, the identification of the incoming and outgoing nuclei, along with the reconstruction of their trajectories and velocities, is described. This is followed by a discussion on the identification of other reaction products, either emitted directly from the reaction such as QFS protons or emitted via de-excitation of the residual nucleus, for example, γ -rays and neutrons. Finally, this work introduces, for the first time, a methodology for reconstructing one and two-neutron events with NeuLAND at R³B.

3.1. Ion Tracking

3.1.1. Incoming ID

Since the current experiment uses an incoming cocktail beam of nuclei, it is essential to have accurate incoming particle identification (PID) to ensure good selection on the incoming isotope. The ideology behind the identification procedure has been outlined in section 2.2. To summarize, the methodology involves the determination of the mass-to-charge ratio A/Z and charge Z of the particles in flight. This is done for the incoming particles via a ToF measurement between the scintillator at the FRS focus S2 and the start detector LOS at the entrance of the cave. The calibration procedure for the A/Z identification involves the following steps:

- Determination of the flight path length using an isotope beam for which the $B\rho$ and A/Z are fixed, so that the velocity β is known. The ToF is then measured as a function of the velocity for multiple $B\rho$ values, and a linear fit according to Eq. 2.3 provides the nominal flight path length.
- Position calibration of the S2 scintillator to reconstruct the flight path more precisely on an event-by-event basis, thereby improving the resolution of the $B\rho$.

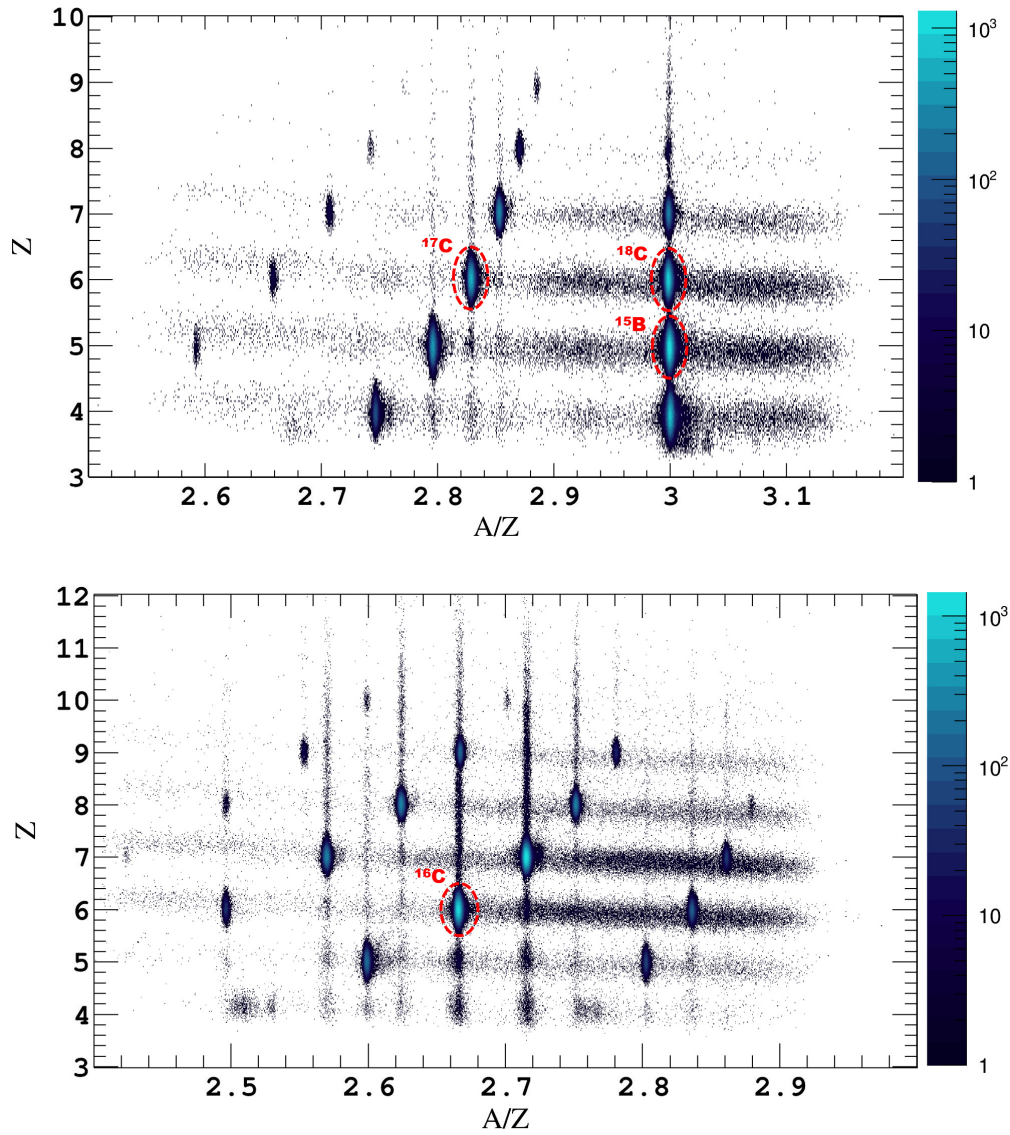


Figure 3.1.: Identification plots of incoming ions for the two settings. **Top:** Tuned for $A/Z \sim 3$. **Bottom:** Tuned for $A/Z \sim 2.7$. The incoming channels studied in the current analysis are highlighted

- The final step is to timewise correlate all hits with appropriate time windows. Since the event window is large, multiple hits may occur in the detectors within a single event window, making it crucial to match the correct hit. For the current analysis, only the hit triggering the event is used. This is true for all consequent detectors.

The ΔE measurement at the MUSLi and LOS detectors enables the charge Z identification as shown in Eq. 2.5. The calibration involves the estimation of the velocity correction function, which was obtained by using beams of known charge, energy and velocity. In this case too, the hits have to be correlated timewise to properly match the ToF of the incoming particle to the charge Z value from LOS and MUSLi respectively. The final A/Z versus charge Z plot for the two settings is shown in Fig. 3.1.

To identify the trajectories of the incoming ions, the two in-beam MWPC detectors placed upstream of the target are used. These detectors provide the absolute X- and Y-positions of the interaction point of the ions at the detector positions. By extrapolating the two interaction points recorded by the two detectors, the trajectories (angles) of the incoming ions can be reconstructed. The requirement for the calibration of these detectors involves determination of their absolute positions in the laboratory frame. With the determination of the $B\rho$ and the trajectories (angles) of the incoming ions, the absolute and the transverse momentum components of the ions can be reconstructed on an event-by-event basis.

3.1.2. Fragment Reconstruction

Since the objective is to measure the full reaction kinematics, one of the major steps is to reconstruct the reaction fragments. In order to identify the outgoing fragments (or unreacted beam), similar to the incoming case, it is necessary to determine the charge Z and mass-to-charge ratio A/Z of the outgoing ions, along with the beam trajectory. Here, a brief description of the reconstruction procedure and the calibration requirements from the corresponding detectors is provided.

For the charge selection, two detectors are used, namely the FOOT SSSDs along the beam-line placed just behind target and before the GLAD dipole magnet, and the Plastic wall ToFD, located at the end of the beam-line. The requirement to perform the charge selection at these two points along the beam-line ensures all losses in air and other materials (e.g. detectors) along the beam trajectory are properly accounted for. Therefore, this selection ensures that the ion with the same charge reaches the end of the beam-line from the target. The calibration of the silicon detectors involved a strip-by-strip subtraction of the pedestals and the energy correction for the inter-strip events. Details on the calibration procedure can be found in [82]. For the charge in ToFD, the calibration procedure requires the alignment of the ΔE peaks for all bars, a position dependent charge correction along the bars and the time alignment of the bars to select out the correlated hits. In the current analysis, only the first ToFD plane was used. An example for the ToFD charge versus the FOOT charge is shown in Fig. 3.2 (Top) for an incoming cut on ^{18}C .

After exiting the target flange, the ions enter the GLAD dipole magnet, which disperses them along distinct trajectories according to their $B\rho$ values. Referring to Eq. 2.2, since the velocities of all outgoing fragments are nearly identical, the primary difference in their $B\rho$ arises from their respective A/Z values. Therefore, if the magnetic field is well defined, one can identify the corresponding ions by reconstructing the unique trajectories. To do this, the requirement is to obtain the interaction points of the ions before and after the magnet, as well as to determine the accurate field map inside the magnet. For the position measurements, as discussed in the previous chapter, the in-beam FOOTs are used to reconstruct the interaction points before the magnet, while the fibers are employed after the magnet. An efficient method for using these inputs to obtain the corresponding trajectories — and consequently the $B\rho$ values — is to

3. Calibration and Analysis

apply the Multi-Dimensional Fit (MDF) method, based on the implementation of the TMultiDimFit class in ROOT [79]. In this case, the calibration requirement is to have a precise knowledge of the absolute positions of the involved detectors in the laboratory frame.

The tracking principle of the MDF method is to encode the track information into multiple functions of several input parameters. The output of these functions corresponds to observables that carry relevant information about the tracks of interest, such as outgoing angles, total momentum, etc. The input parameters are generally the trajectory information obtained from the corresponding detectors. Practically, this is done as follows; First, the correct detector geometries relative to the magnetic field are defined, along with an accurate magnetic field map. Next, a set of output observables is defined, which contains the relevant information about the ions passing through the magnetic field. These observables will be the output of the fitted functions. At this stage, the only parameter that is needed to be specified for the functions is their order, which, depending on the observable, can go up to 200. Then, reference ions (with fixed Z and A/Q) starting from the target position — which is defined as a Gaussian source with the target dimensions — are propagated through the magnetic field. These ions are generated over a large phase-space to cover the full experimental acceptance. The propagation of the trajectories involves calculating the motion of the ions with an initial momentum-to-charge ratio, traversing in small predefined steps through the magnetic field, while accounting for realistic effects such as energy loss. All of these trajectories are then fitted as a function of the input parameters, which are the extrapolated points of interaction at the corresponding detector positions. The output values of the functions in this case are already known since a predefined reference ion is propagated. Therefore, using these output values and the trajectory information, the coefficients of the fit functions are calculated. Finally, in the analysis of experimental data, the position information is obtained on an event-by-event basis from the detectors located before and after the magnetic field. For each event, this position information is fed into the previously determined functions, which provides a unique output of the trajectory observable.

For the current experiment, the chosen input parameters were,

- The X, Y and Z position information from the in-beam FOOT SSSDs placed right after the target and before the GLAD magnet
- The X and Z position information of Fiber 32 after GLAD
- the Y and Z position information of Fiber 30 after GLAD
- the X and Z position information of Fiber 31/33 after GLAD.

The relevant output observables for which the functions were created were,

- The momentum-over-charge ratio (P/Z) or equivalently the $B\rho$
- The outgoing angles in X and Y after the target but before GLAD
- The outgoing angles in X and Y after GLAD
- The flight path length inside the magnet.

Finally, due to imprecise measurement of the detector positions inside the cave and uncertainties in the field Map, an alignment procedure is necessary to get the correct absolute values of the observables. For this, a reference beam is chosen from the experimental data which traverses through all the relevant detectors. In the current experiment, the ^{16}C unreacted beam was used as this reference. All information of the reference beam is obtained from the detector information (for example the angles) or analytically calculated (for example the P/Z) from the incoming beam information. Then the detector positions are

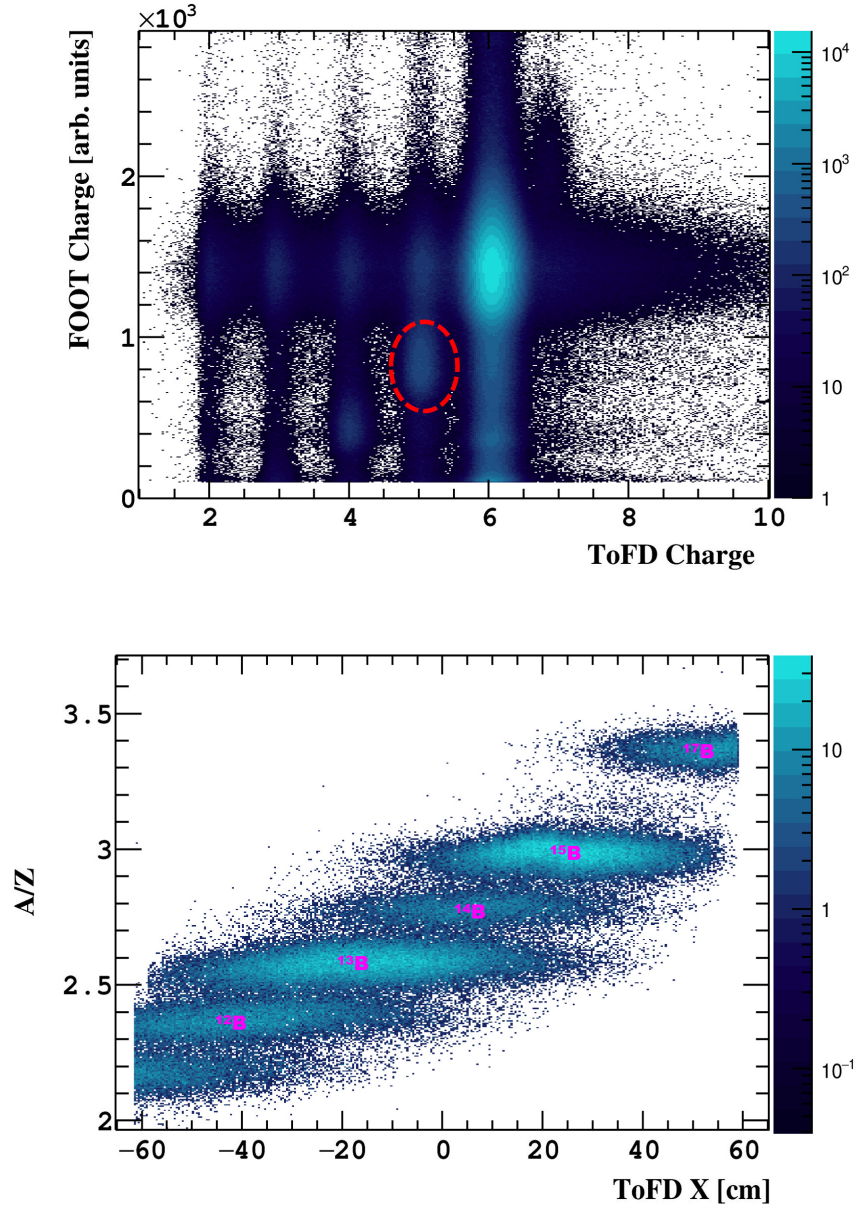


Figure 3.2.: Identification plots of outgoing ions with a cut on ^{18}C incoming **Top:** ToFD charge versus FOOT charge distribution with shown cut on charge $Z = 5$ to select outgoing Boron isotopes. **Bottom:** A/Z distribution versus ToFD X-distribution for the outgoing charge $Z = 5$.

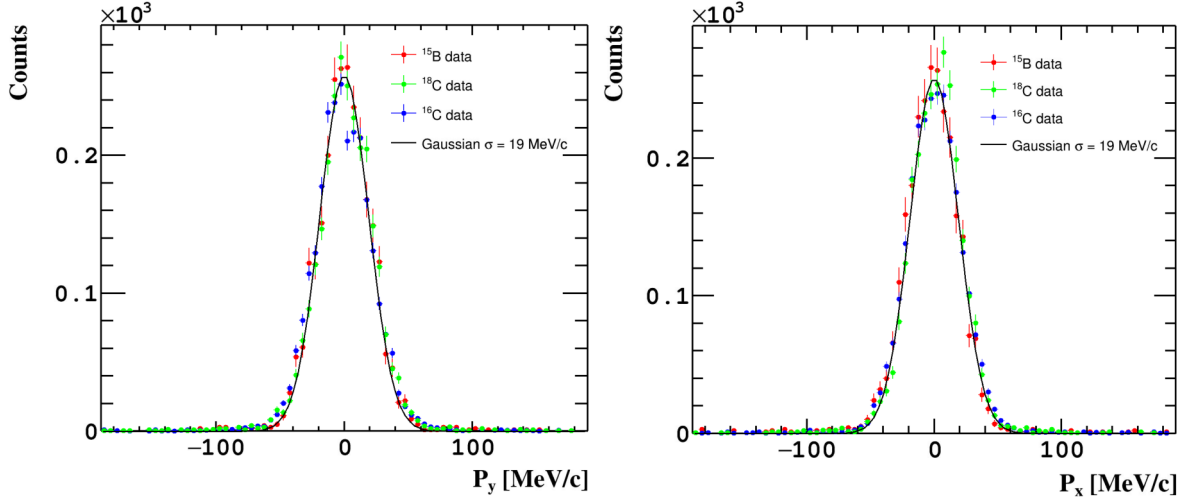


Figure 3.3.: Outgoing transverse momentum distributions of different incoming isotopes obtained after implementation of strict cuts to reproduce a pencil beam. Comparison is shown with a Gaussian providing the best fit for all three cases.

shifted until the observables obtained from the MDF process minimises to the ones obtained directly for this reference beam.

After obtaining the P/Z (or $B\rho$), the A/Z ratio can be derived using Eq. 2.2 with the velocity information. For this, either the ToF information from the ToFD detector or the incoming velocity after corrections for the energy loss, can be used. In the current experiment the latter is implemented.

In Fig. 3.2 (Bottom) an example of the reconstruction is shown for the outgoing Boron fragments obtained with an incoming cut on ^{18}C and an outgoing cut on charge $Z = 5$. The A/Z distribution is plotted against the ToFD X-positions.

Fragment Resolution

The final reconstructed fragment momentum has in it an intrinsic experimental resolution, which depends on a complex combination of the detector resolutions. When reconstructing the Fragment + x-neutron relative energy, it is necessary to estimate and include this resolution, as it significantly affects the observed widths of the resonances. In addition to this, for the analysis of the recoil momentum distributions, this resolution must be folded into the theoretical calculations. In principle, the resolution can be accurately estimated using realistic simulations including all in-beam detectors. However, given the complexity and computation time required to run such large simulations, it is not feasible to perform these for the large number of channels studied. Therefore, a simpler procedure is adopted to estimate the resolution from the experimental data. This procedure is adopted from [83].

The objective is to determine the transverse and total momentum resolution of the resultant fragments. The ideal configuration for this would involve using a pencil beam on an empty target, with negligible momentum and angular spread. However, such conditions are not realistic, and since no empty target runs were performed in the current experiment, the alternative is to apply strict cuts on the angles

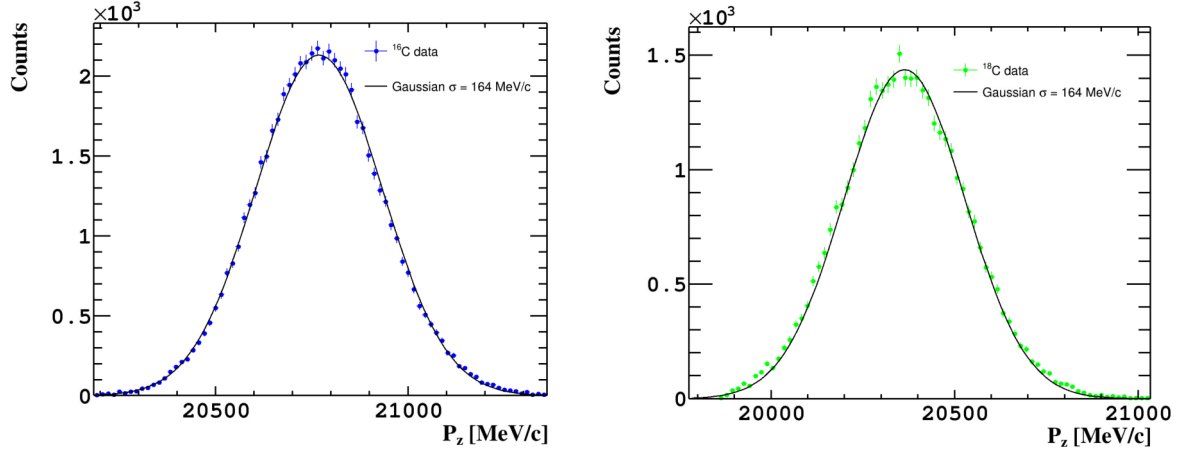


Figure 3.4.: *Outgoing longitudinal momentum distributions of ^{16}C (left) and ^{18}C (right) obtained after implementation of cuts as discussed in text. Gaussian fits for both cases are also shown.*

and momenta of the incoming beams to approximate a pencil beam. The angular and momentum distributions of the outgoing unreacted beam is then measured to obtain the momentum resolution.

In order to obtain the transverse momentum resolution the following cuts were applied on the incoming beam:

- Reaction centered at the target
- $|\theta_x - \langle \theta_x \rangle| < 1 \text{ mrad}$
- $|\theta_y - \langle \theta_y \rangle| < 1 \text{ mrad}$
- No condition on total incoming momentum P_{in}

The P_x and P_y distributions of three incoming isotopes namely ^{15}B , ^{18}C and ^{16}C are shown in Fig. 3.3 to be in good agreement with each other, with a resolution of $\sigma(P_x, P_y) = 19 \text{ MeV/c}$.

For estimating the resolution of longitudinal component, the following cuts are applied on the incoming beam:

- No selection on target
- No selection on angle
- $|P_{in} - \langle P_{in} \rangle| / \langle P_{in} \rangle < 0.1\%$

The P_z distributions for ^{18}C and ^{16}C are shown in Fig. 3.4. A Gaussian width of $\sigma(P_z) = 164 \text{ MeV/c}$ is observed to be consistent with both distributions. Subsequently, the fragment momenta in the simulations are smeared using the extracted momentum resolutions.

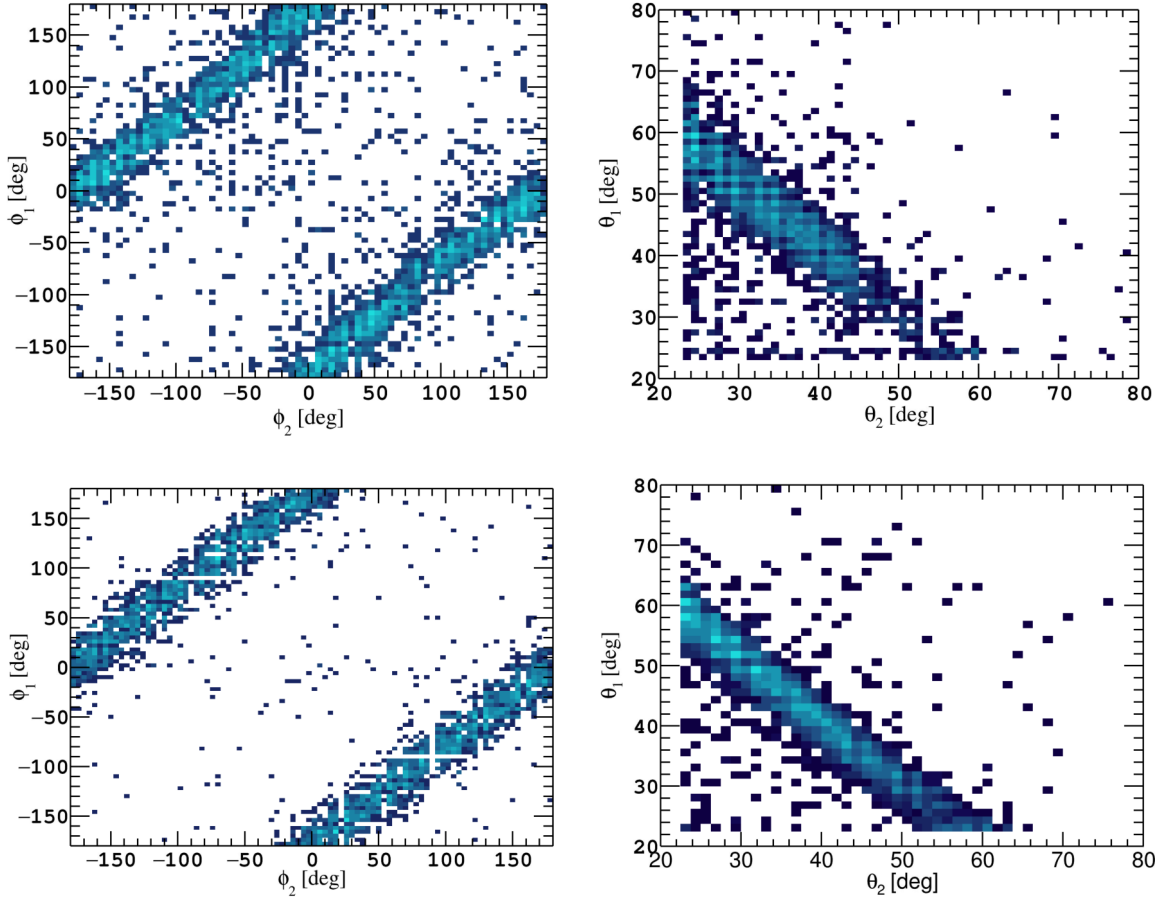


Figure 3.5.: Angular distribution of azimuthal ϕ and polar θ angles of the two scattered protons from quasi-free scattering reactions. **Top:** Experimental angular correlation with selection on ^{18}C incoming and ^{17}B outgoing, requiring two proton clusters in CALIFA. **Bottom:** Angular correlations obtained with simulated QFS events using quasi-free event generator developed by L. Chulkov [84] and V. Panin [26].

3.2. Protons and γ -rays

The CALIFA calorimeter is the main detector used to detect and measure particles emitted around the target region. This includes QFS protons (or neutrons) and γ -rays emitted from the de-excitation of the fragment nucleus. In this section, the reconstruction and identification procedure of these reaction products will be discussed.

3.2.1. Quasi-free scattered protons

As previously mentioned, the detection of scattered protons from the QFS reaction is done using the CALIFA calorimeter. The calibration process of this detector involves two steps. First is an energy calibration which is done using multiple stationary γ -ray sources of known energies, in order to convert the QDC value of the crystal outputs to energy units. This process also aligns the energy values of all crystals with respect to each other. Since only γ -rays are used for the energy calibration, it is very accurate at low energies (few MeVs) corresponding to the range of energies covered by the used γ -ray

sources. However, protons deposit much higher energies ($\gtrsim 20$ MeV) in the crystals, and in this range the calibration becomes inaccurate since the non-linearity of the response is not properly corrected.

Since the detector is highly segmented, whenever γ -rays or protons enter the detector, the interaction spreads across multiple crystals. Therefore, the next step in the calibration process is to cluster these localized interactions in nearby crystals and assign them as one interaction event. This process is called addback. In order to implement this, several algorithms have been proposed [85]. In the current work, the following approach is implemented; first the data is sorted according to the energy deposited in the crystals. Then starting from the highest energy crystal, a clustering process is performed by grouping neighboring crystals within a fixed opening angle relative to the first crystal. In the standard procedure, the clustering angle is kept constant for all clusters at ≈ 0.25 rad. However, a more detailed study presented in the work of [82] proposes a dynamic cluster size based on the primary particle producing the cluster, i.e., depending on whether it is a proton or γ -ray interaction. In order to do this (and more generally to select out the reaction products in CALIFA), it is necessary to identify and separate out proton clusters from the γ -ray clusters. In the current work, a pretty simplistic method is used; A threshold for the total cluster energy is defined at 20 MeV, such that clusters with energies higher than this are assigned as proton clusters and those below are assigned as γ clusters. Though more complex techniques to obtain the Particle ID exists [86], they have not been properly bench-marked and studied to the extent where they can be directly applied to the analysis. All clusters with total energy below 20 MeV have a cluster size of 0.14 rad and as soon as the cluster energy is ≥ 20 MeV (proton clusters), the cluster size is increased to 0.4 rad. In the present work, both the standard and dynamic clustering algorithms have been studied and implemented, with the results being largely interchangeable, except for changes in the relative γ -ray detection efficiency, as discussed in the next section.

To identify QFS reactions, the angular distributions between the obtained proton clusters are studied. An example for this is shown in Fig. 3.5, where the proton angular distributions are reconstructed with a selection on the incoming ^{18}C and outgoing ^{17}B fragment, requiring the reconstruction of two proton clusters in CALIFA. The co-planarity condition with the azimuthal angles is shown in Fig. 3.5 (Top left), where it can be clearly observed that the relative azimuthal angle $|\Delta\phi|$ between the two protons is centered at 180° . The angles of the scattered protons relative to the beam axis is also shown in Fig. 3.5 (Top right), where the relative opening angle between the two protons $|\Delta\theta|$ is observed to be centered at $\sim 81^\circ$. The angular distributions obtained from QFS simulations is also shown in Fig. 3.5 (Bottom) for comparison.

Finally, in the subsequent analysis, a selection cut is applied to the two protons detected in CALIFA to isolate the (p,2p) QFS reactions. As a consequence of this selection, a QFS reconstruction efficiency is induced in the data, which is the combination of the detection efficiency and proper identification of the protons with the cuts applied. The QFS cuts include two high-energy hits (≥ 20 MeV) in CALIFA, satisfying the co-planarity condition with $|\Delta\phi| = 180^\circ \pm 30^\circ$, along with an opening angle cut, the centroid of which varies depending on the nucleus and excitation energy being probed. The efficiency value is estimated with the help of QFS simulations with CALIFA using the QFS generator developed by V. Panin [26] and applying the same cuts to the simulation as in data. The efficiency value for the current cuts was estimated to be $\varepsilon_{QFS} \sim 0.50$. The estimation of the uncertainty associated with the efficiency is still ongoing and is not included in the present thesis.

In addition to (p,2p) reactions, a case of (p,pn) reaction is also presented in section 4.1.2. In this case, a proton and neutron pair should be detected in CALIFA. The selection cuts for the (p,pn) reaction is exactly the same as for the (p,2p) reaction described above, i.e., requiring two large energy hits (≥ 20 MeV) in CALIFA, co-planar condition and a selection on the opening angle.

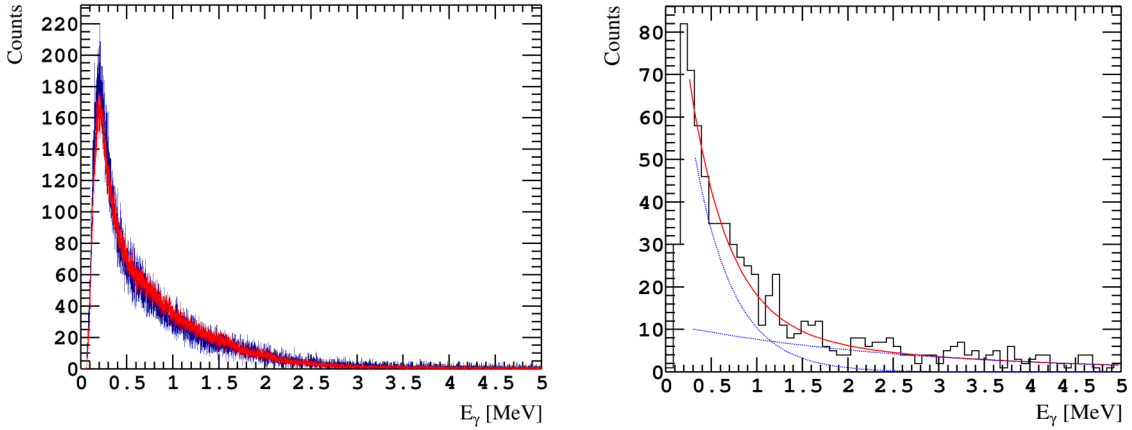


Figure 3.6.: *Left:* γ -energy background distribution for unreacted ^{16}C (in blue) and ^{18}C (in red) beams. *Right:* γ -energy distribution for $^{24}\text{F}(p,2p)^{23}\text{O}$ reaction, where no γ -ray is expected. The double exponential fit (in red) for the background is seen to reproduce the distribution accurately. The two exponential components of the total fit are shown in blue.

3.2.2. γ -ray analysis

In order to extract spectroscopic information of the bound excited states, detection and analysis of γ -rays is essential. Since the experiments are performed in inverse kinematics, the γ -rays are emitted from ions moving at relativistic velocities. Consequently, the γ -rays detected at the CALIFA calorimeter are Doppler boosted, and thus the deposited energy differ from the true γ -ray energy. To obtain the true γ -ray energy $E_{\gamma\text{true}}$, the detected γ -ray energy $E_{\gamma\text{detected}}$ should be Doppler corrected event-by-event using the measured velocity of the beam,

$$E_{\gamma\text{true}} = \gamma_{\text{beam}} E_{\gamma\text{detected}} (1 - \beta_{\text{beam}} \cos \theta_\gamma), \quad (3.1)$$

where γ_{beam} is the Lorentz factor of the beam and θ_γ is the angle of the emitted γ -ray with respect to the beam direction in the lab frame. In order to obtain the correct angle, it is generally advantageous to have the knowledge of the vertex point at the target where the reaction occurs, i.e., the point of emission of the γ -photon (assuming emission is instantaneous $\leq 10^{-15}$ s). This is particularly important when using an extended target, like the one used in the current experiment. However, due to the low vertex reconstruction efficiency with the FOOTs placed in the proton arms, this was not done in the current analysis, and all reactions were assumed to be on average at the center of the target. The overall effect of this was a slight degradation of the resolution, which remains manageable since the target length was only 5 cm. For a simulated boosted source emitting 1 MeV γ -rays, the Doppler-corrected width, σ , was estimated to be ~ 35 keV with vertex reconstruction, increasing to ~ 45 keV without it.

To properly characterize the γ -rays detected, it becomes necessary to constrain some of the detection parameters. This includes the response/resolution and the detection efficiency as a function of the γ -ray energy. This is done with the help of realistic simulations. In the following, details on how the simulations are bench-marked and used to obtain these properties are provided.

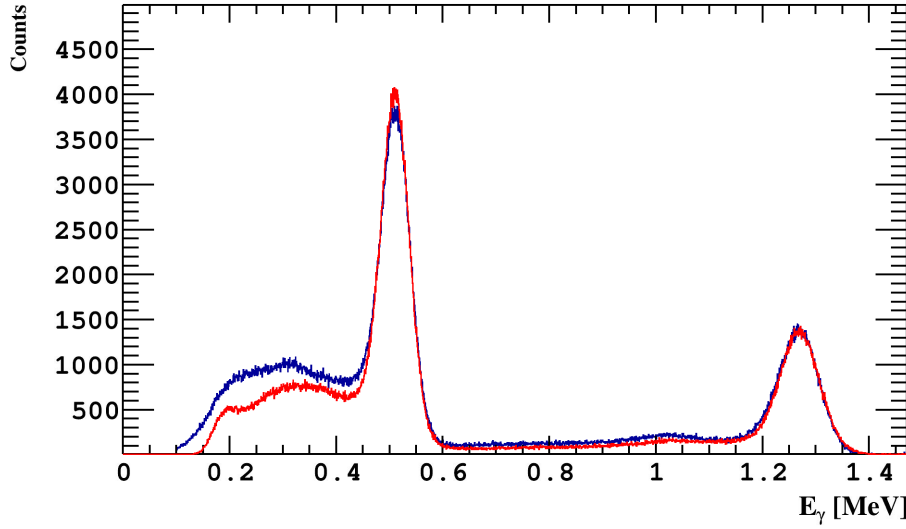


Figure 3.7.: γ -ray spectrum obtained from ^{22}Na stationary source (in blue) compared to a simulation of monoenergetic sources (in red). The simulations include a combination of two monoenergetic sources at 511 keV and 1275 keV in order to reproduce the experimental distribution. The simulated red distribution is scaled to the photopeak integrals in the blue distribution to show the agreement in the widths.

γ -ray Energy Response

The first step in order to identify γ -rays and separate them from the background, is to properly characterize the response function of CALIFA for detection of monoenergetic γ -rays. The response in general has two parts, namely the background contribution and the distribution corresponding to the interaction of true monoenergetic γ -rays with the detector. The shape of the background contribution can be estimated in two separate ways; The first is to obtain the energy distribution in CALIFA from unreacted beam data or for reacted isotopes with no bound excited states, which should then in principle contain only background contribution. This is shown in Fig. 3.6, where the distributions for the unreacted beams are shown on the left and for a reaction ($^{24}\text{F}(p,2p)^{23}\text{O}$) with no bound excited states on the right. However as can be observed from the distributions on the left that this background changes slightly with the change in the incoming beam. Therefore, to properly parameterize it, a second approach is adopted, which involves fitting the γ -ray spectrum with a double exponential function, which reproduces the background shape very well, as shown in Fig. 3.6 (Right).

To obtain the response for monoenergetic γ -rays, stationary γ -sources are used and compared to realistic simulations of these sources. Figure. 3.7 shows a comparison between the response of ^{22}Na source data (in blue) and that of simulations of similar monoenergetic γ -rays (in red) after addback. While the photopeak widths are very similar between the experimental and simulated data, the full response with the Compton edge is not completely reproduced. This discrepancy is not only in the shape of the Compton edge but also the relative amplitudes of the photopeak and Compton edge. Such a discrepancy could arise from inconsistency in the way thresholds are handled in experiment, which is not included in the simulations. Additionally, as discussed in [82], the overall integral of the full response is lower in the simulation which must be corrected for when calculating the efficiency.

The in-beam response is generally very different as compared to stationary sources since the γ -rays are emitted from ion sources moving at relativistic velocities. The Doppler correction generally changes the shape of the photopeak significantly. This is further enhanced by the fact that in the current experiment

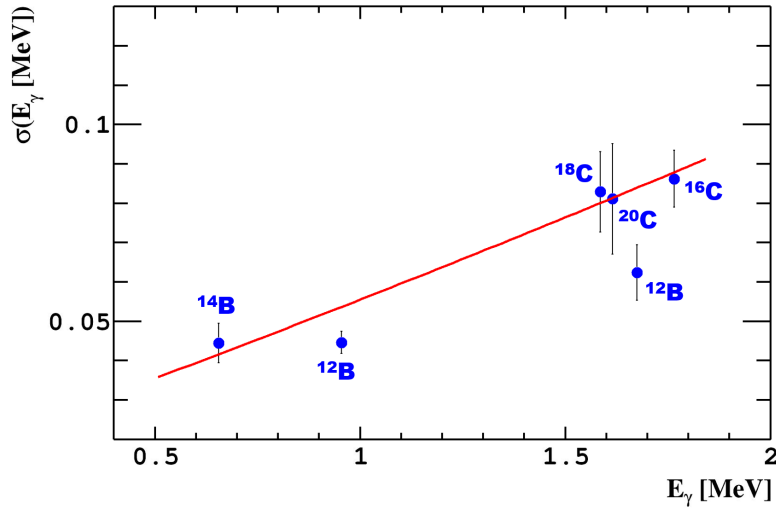


Figure 3.8.: Photopeak widths of known γ -rays from in-beam isotopes as a function of the photopeak centroids (blue data points). The expected response of the widths obtained from simulations is shown by the red curve.

the vertex point of γ -emission was not known accurately and consequently the Doppler correction was not perfect. In order to properly characterize the in-beam resolution, isotopes from the cocktail beam that emit well-known and documented γ -rays were identified. The $1\text{-}\sigma$ widths of the corresponding photopeaks were then plotted as a function of their centroids, as shown in Fig. 3.8. This distribution is then compared to the expected response from the simulation (red line Fig. 3.8), where a general agreement is observed within the uncertainties.”

γ -ray Efficiency

Since a part of the analysis involves extracting the cross section of the bound excited states decaying via γ -ray emission, it is necessary to obtain the corresponding γ -ray detection efficiency of CALIFA. Complete details of the analysis performed to extract the γ -ray detection efficiency is provided in [82]. Here, only an overview of the procedure used to obtain the efficiency distribution is provided.

The first step to characterize the efficiency is to use standardized stationary γ -ray sources and simulations. For the current work, γ -ray sources, namely ^{22}Na and ^{152}Eu were used. The absolute efficiency of the source measurements was estimated by taking the ratio of the detected counts to the expected counts from the known activity. This is then compared to simulations of similar sources in CALIFA. While the measurements showed a good overall agreement, a small discrepancy was observed between the total integrals of the simulated and experimental spectra, with the simulated integral being slightly lower. As a result, a correction factor of $C_{\text{source}} = 1.056(31)$ was applied to the final efficiency. Since the source efficiency measurements provide a good agreement with the simulations, it is assumed that the in-beam situation should also be reproduced to a good degree of accuracy in the simulations (after the C_{source} correction). This is a reasonable assumption since the main factors contributing to the efficiency are the geometrical acceptance and interaction process in the materials which are already taken into consideration for the case of the stationary sources. Therefore, in order to obtain the in-beam efficiency, simulations were performed with the corresponding in-beam γ -ray energies emitted from sources boosted to the beam velocities. The photopeak efficiency curves as a function of the γ -ray energy corresponding

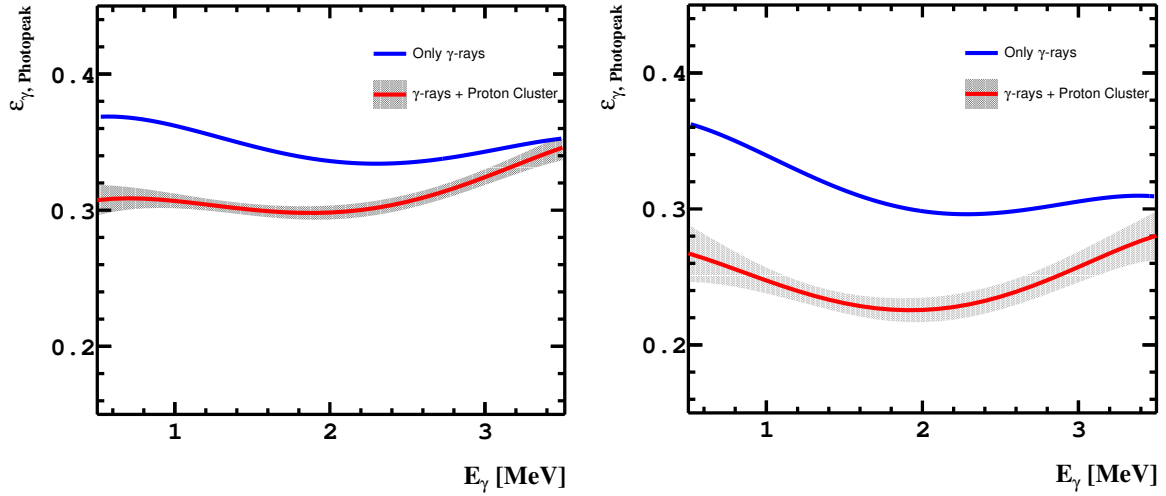


Figure 3.9.: Photoppeak efficiency curves for detection of in-beam γ -rays as a function of the γ -ray energy for standard fixed cluster size (**Left**) and dynamic cluster size (**Right**). The photoppeak efficiency distribution for boosted γ -rays is shown in blue. The red distribution shows the efficiency distribution with the requirement of proton detection and clustering, which effectively reduces the γ -ray detection efficiency. The gray band indicates the uncertainty in the estimation of the reduction.

to the boosted sources is shown in Fig. 3.9 (blue curves). However, in the real experiment, in addition to detecting γ -rays, CALIFA is also used to detect protons (neutrons) from the (p,2p) (or (p,pn)) reaction process. These protons further induce secondary showers in the vicinity of the primary interaction region. The detection of the protons and the subsequent clustering procedure, which is performed to addback all hits generated from these showers, reduces the effective area available for detection of γ -rays, especially in the forward direction. Consequently, this would further reduce the γ -ray detection efficiency. The estimation of this reduction factor has been performed by A. Barriere as reported in [82]. As discussed in section 3.2.1, two clustering algorithms have been implemented in the present work, the first based on a standard fixed cluster size and the other based on a dynamic cluster size depending on the particle type. The two algorithms have different detection efficiencies and show different magnitudes of reduction in efficiency due to the proton clustering as illustrated in Fig. 3.9, where the left panel corresponds to the standard cluster size and the right panel to the dynamic cluster size. The reduced photoppeak efficiency distributions are shown in red, with a gray band indicating the uncertainty in the estimation of the reduction. For the calculation of the cross-section in the current analysis, the dynamic cluster size has been implemented.

3.3. Neutron Analysis

NeuLAND is the primary detector used for the detection and measurement of neutrons emitted due to excitation of the fragments beyond their neutron separation threshold. Since the final analysis of the current work requires the reconstruction of the Fragment + neutron(s) relative energy, it is necessary to measure the four-momenta of the fragment and all evaporated neutrons. For the fragments, the reconstruction procedure has already been discussed in section 3.1.2. In this section, the neutron

3. Calibration and Analysis

analysis will be presented starting with a brief description of the calibration procedure followed by the reconstruction and validation procedure of the detected neutron(s).

3.3.1. NeuLAND Calibration

The NeuLAND calibration routine is based on the tracking algorithm of the ultra-relativistic cosmic-rays. The detailed procedure can be found in [75]. The basic principle is to use the cosmic-ray muons, which travel close to the speed of light through the detector and provide straight line correlated trajectories in the detector. Thanks to its high granularity, these cosmic muons can be tracked through the detector and extrapolation of the tracks provides the hit position along the bar length. This derived hit position is then compared to that obtained from the time difference between the two PMTs of the bar which is corrected with an offset to match the two. In addition, since the trajectories should be time correlated with single muon tracks, traveling at nearly the speed of light, the relative time differences between the bars can also be synchronized. The same calibration routine also gain matches the individual PMTs. This is possible since the track length of the muons along a bar is calculated from the trajectory, and the muons, as minimum ionizing particles (MIPs), deposit an energy of $2 \text{ MeV cm}^2 \text{ g}^{-1}$ [87] in the detector material. After alignment of the relative time within the detector, the next step is to provide an absolute time offset to the full detector. This is done by shifting the Time-of-Flight (ToF) peak corresponding to the γ -rays emitted from reactions at the target (see Fig. 3.10). Since the distance of the detector to the target is known, and the velocity of these γ -rays should corresponds to $\beta = 1$, the global ToF offset is easily established. Further fine tuning of the relative time between the bars was performed by aligning this γ -ray ToF peak for each bar. The final time resolution obtained for the full detector was $\sim 180 \text{ ps}$.

3.3.2. Neutron Simulations

The neutron simulations were performed within the GEANT4 framework implemented as a part of R3BRoot. The NeuLAND geometry with 13 double planes of scintillator bars was implemented mirroring the true detector configuration, and placed at the accurate position in the lab frame with respect to the target position. The neutrons were generated as a part of a phase-space decay for a Fragment + x-neutron system from a 5 cm target at the target position. The Fragment + x-neutron decay is generated in the Center of Mass (CoM) frame, following a relative energy distribution with the differential cross section having certain standard functional forms, such as the Breit-Wigner as discussed in section 1.3. After the decay, the particles are boosted to the relativistic beam energies in the lab frame. The generated system also incorporates the experimental angular spread, which includes contributions from the incoming beam spread and the internal momentum spread from the nucleon-knockout process in the QFS reactions.

The generated neutrons, moving with the beam velocity, can interact at the detector via various reaction mechanisms and can produce secondary particles. All interaction points in the detector both from primary (generated) neutrons and secondary particles that deposit energies above a predefined threshold are recorded. These recorded neutron interaction events at the detector level are then further "Digitized". Digitization refers to the further processing of the simulated data to include all experimental effects of detection and final production of an electronic signal. In this process, the total deposited energy in each bar is first converted into light yield using standard Birk's law. Following this, the amount of light reaching the PMTs and the time it takes for the light to reach the two PMTs is then calculated using experimentally determined values for the light attenuation and the effective speed of light in the bar. Further experimental effects, such as energy and time resolution are folded into the respective energy and time information. Finally, only "hits" in bars with total deposited energies above a certain PMT

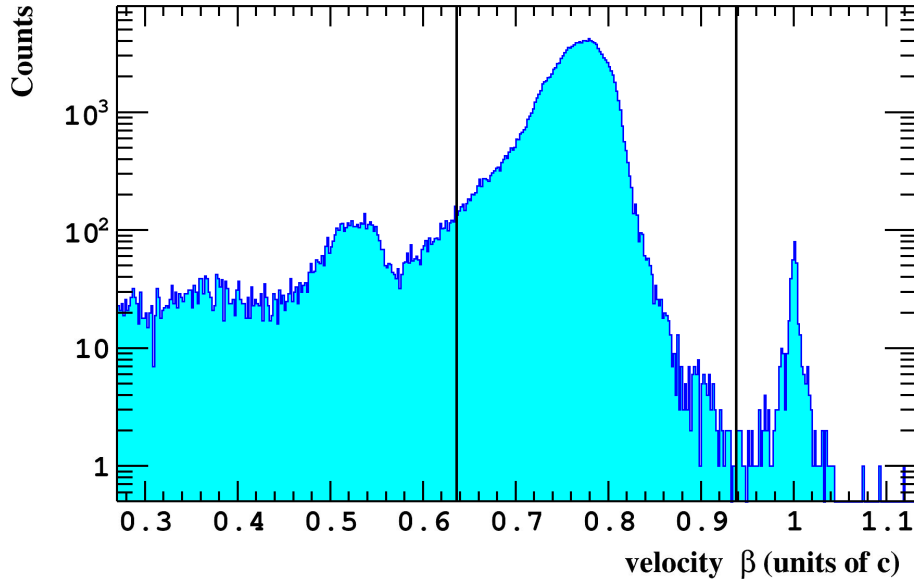


Figure 3.10.: Velocity distribution of particles detected in NeuLAND with the neutron velocity/ToF cut shown corresponding to the broad neutron peak in the range of $\beta = 0.64 - 0.94$. The peak at $\beta = 1$ corresponds to γ -rays produced from reactions at the target. A slower peak at $\beta \approx 0.5$ is also observed, attributed to secondary showers originating from the beam dump.

threshold equivalent to the experimental threshold are saved. The objective of this digitization procedure is to incorporate all experimental effects into the simulations and to enable the application of the same analysis algorithms to both simulated and experimental data.

For the neutron simulations several standard GEANT4 physics lists were used and compared. The QGSP_INCLXX physics list [88] was found to provide the best agreement with the experimental data, based on comparisons of basic quantities such as multiplicity and deposited energy. Consequently, the final analysis was performed using this physics list.

A final step needed in the simulations is to identify and include the fragment resolution, which impacts the resolution of the reconstructed relative energy spectra. The estimation procedure and the quantities obtained are discussed in section 3.1.2.

3.3.3. One Neutron Analysis

To make a clean selection of the neutron evaporation channel with neutrons detected in NeuLAND, several cuts are applied in the analysis to unambiguously identify the source and number of expected neutrons. These cuts include:

- A selection on the incoming ion, $^{A_{inc}}_{Z_{inc}}X$
- A QFS cut (section 3.2.1) to select the reaction mechanism
- A selection on the outgoing fragment corresponding to proton (neutron) knockout from the incoming ion along with x -neutron removal via evaporation, $^{A_{inc}-x-1}_{Z_{inc}-1}Y$ ($^{A_{inc}-x-1}_{Z_{inc}}X$)
- A selection on the ToF distribution in NeuLAND corresponding to the neutron ToF/velocity window (see Fig. 3.10).

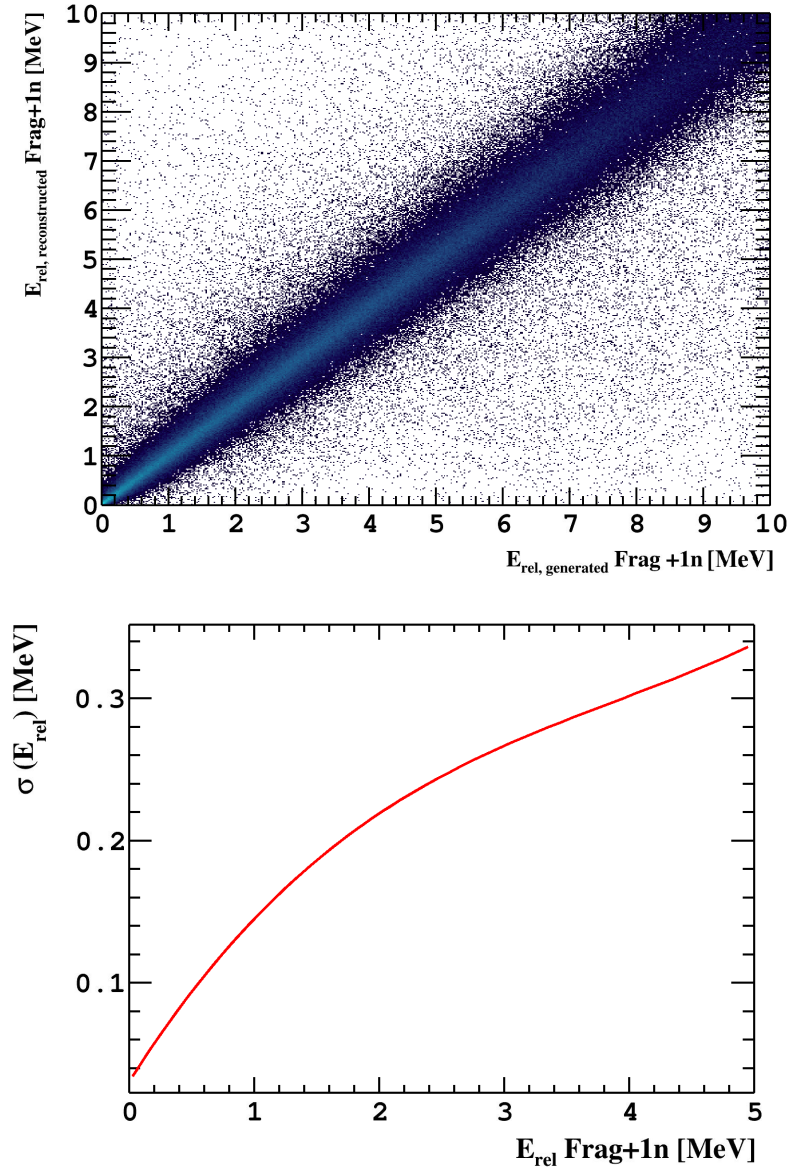


Figure 3.11.: *Top:* Response matrix obtained from simulation for Fragment + 1n reconstruction where the x-axis is the input generator level relative energy and the y-axis is the reconstructed distribution after applying the reconstruction methodology. *Bottom:* Evolution of the experimental resolution as a function of the relative energy.

- A selection on the deposited energy such that only hits above a certain threshold are used for the reconstruction. This selection reduces probability of selecting background events. For the 1-neutron case the threshold was set to 6 MeVee.

These cuts are general for the reconstruction of all neutron multiplicities and are applied in all subsequent analyses involving neutrons.

The reconstruction procedure for the 1-n channel is straightforward. All hits in NeuLAND are first sorted according to the time they were recorded in the detector. Following this, the first hit in time is taken as the first interaction point of the neutron with the detector. Accordingly, the position and time of this hit is used to reconstruct the four-momentum vector of the neutron. This is done by using the time information to calculate the ToF and the position information relative to the target to calculate the outgoing angles. Taking the first hit in time for the reconstruction is a reasonable assumption, backed up by realistic simulations wherein the same reconstruction process is applied. In the simulations, a Fragment + 1n system is simulated with a uniform distribution over a large relative energy range of ~ 0 -10 MeV. A strong correlation between the generated relative energy and the reconstructed relative energy based on the first-hit approach is shown in Fig. 3.11 (Top). It can be observed that the correlation slope is very close to unity. This implies that the reconstruction process accurately reproduces the initial relative energy. Such a distribution, which correlates the input relative energy to the reconstructed relative energy with appropriate effects of the efficiency, acceptance and resolution, is known as a response matrix. In order to reconstruct the experimental relative energy accurately, some further alignment procedures are necessary which have been outlined in Appendix. B. The change in the resolution as a function of the relative energy, extracted from the simulations which includes the experimental response, is also shown in Fig. 3.11 (bottom).

The 1-n channel reconstruction provides a good basis for standardizing and validating the neutron simulations. Furthermore, it also presents the first essential steps for the multi-neutron reconstruction algorithms by characterizing important features of the secondary showers produced from the primary neutron interactions. These points will be addressed in the following sections.

3.3.4. Neutron detection efficiency

In order to validate the simulations, it is essential compare relevant observables to experimental data. One such observable is the 1-neutron detection efficiency which will be discussed in this section. Validation of the efficiency is extremely important since it affects not only the cross section calculations but also the efficiency distribution corresponding to the multi-neutron reconstruction.

Figure. 3.12 shows the simulated 1-neutron efficiency as a function of the Fragment + 1n relative energy (E_{rel}) for neutrons with a kinetic energy of 560 MeV. The distribution is observed to be flat around $\sim 75\%$ below $E_{rel} \lesssim 4.5$ MeV, beyond which, the effect of the geometrical acceptance of NeuLAND starts to manifest and the efficiency decreases smoothly. This implies, in the region with maximal acceptance, i.e., $E_{rel1n} \leq 0$ -4.5 MeV, the flat efficiency value corresponds to the absolute detection efficiency of the detector. If neutrons are emitted from a system having most of its strength within this relative energy range, the probability to detect such neutrons will be $\sim 75\%$. Therefore, for the validation procedure, only systems having $E_{rel1n} \leq 4.5$ MeV is considered in order avoid including complex acceptance effects.

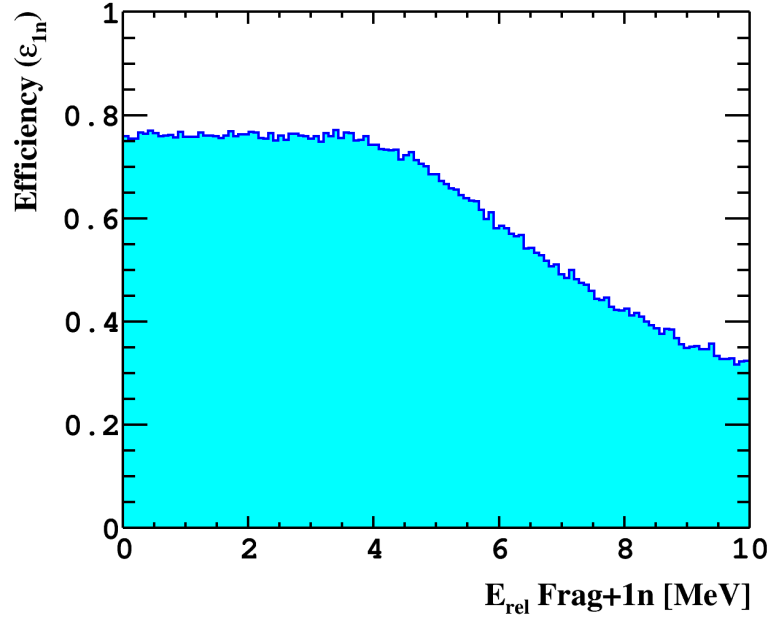


Figure 3.12.: *Fragment+1n efficiency distribution including the acceptance. The shown distribution is obtained from the simulation of a uniform distribution in relative energy range of 0-10 MeV.*

The basic ideology of the validation procedure is as follows: If the reaction mechanism, which produces the Fragment + 1n system is well established and selected, the ratio of the counts with and without the requirement of neutron detection in NeuLAND should give the 1-neutron efficiency ε_{1n} , i.e.,

$$\varepsilon_{1n} = \frac{N_{frag+1n}(\text{NeuLAND})}{N_{frag+1n}(\text{total})}, \quad (3.2)$$

where $N_{frag+1n}(\text{NeuLAND})$ is the number of events when a neutron is detected in NeuLAND in coincidence with the Fragment + 1n system, and $N_{frag+1n}(\text{total})$ is the total number of Fragment + 1n events. Equation. 3.2 can be implemented through various selection cuts. Here, the efficiency is obtained using two set of selection cuts which is discussed in the following.

The first approach is to count events where γ -rays are detected in CALIFA in coincidence with the Fragment + 1n system. The idea here is as follows — after neutron emission, the residual fragment produced with the neutron might be left in its ground state or an excited state. If left in the ground state, only the fragment will be detected. However, if it is left in an excited state it may decay via emission of γ -rays. These γ -rays will then be detected in CALIFA. This implies that for each event in CALIFA corresponding to such a decay, there should be a coincident hit in NeuLAND of the emitted neutron. However since the neutron efficiency is not 100%, not all hits in CALIFA will have a coincident hit in NeuLAND. Therefore, the ratio of the number of γ -rays in CALIFA in coincidence with NeuLAND, $N_{\gamma}(\text{CALIFA} + \text{NeuLAND})$, and the number of total γ -rays in CALIFA, $N_{\gamma}(\text{CALIFA})$, corresponds to the efficiency of NeuLAND. Thus, Eq. 3.2 is modified to,

$$\varepsilon_{1n} = \frac{N_{\gamma}(\text{CALIFA} + \text{NeuLAND})}{N_{\gamma}(\text{CALIFA})}. \quad (3.3)$$

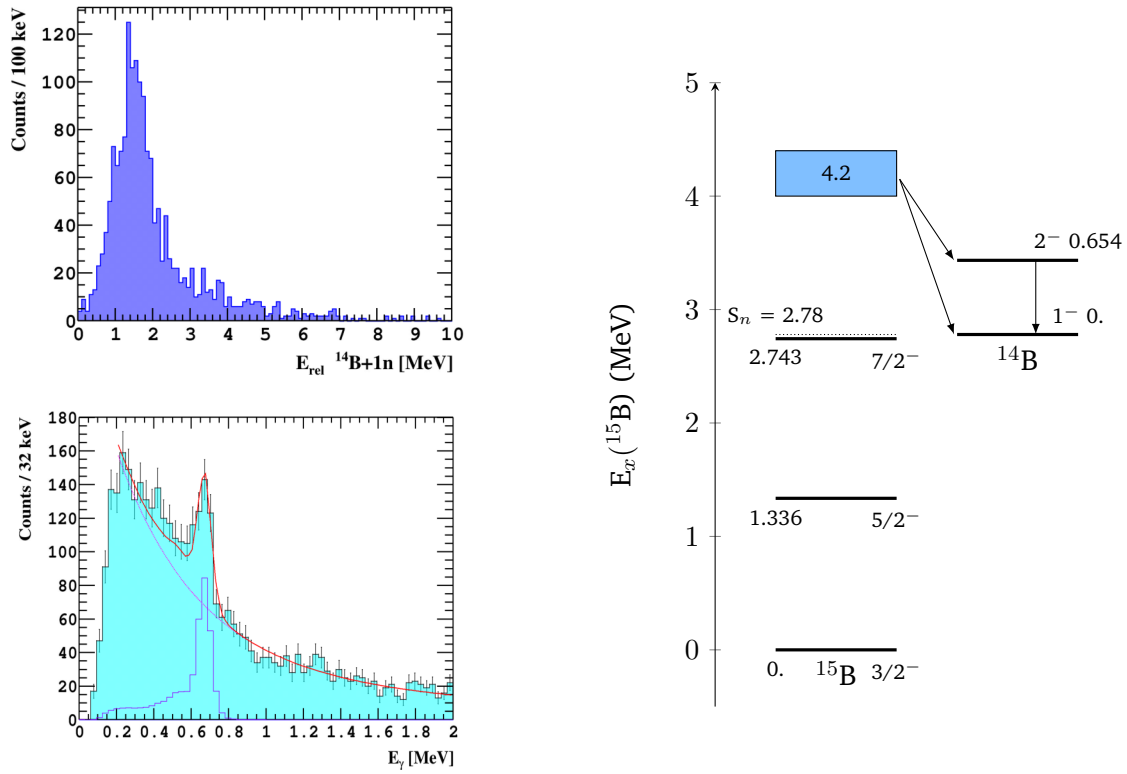


Figure 3.13.: *Top Left:* $^{14}\text{B}+1\text{n}$ relative energy spectrum from $^{16}\text{C}(p,2p)$ reaction. *Bottom Left:* ^{14}B γ -ray spectrum in coincidence with $^{14}\text{B}+1\text{n}$ system with the identified γ -ray photopeak at 0.65 MeV. *Right:* Tentative level diagram of ^{15}B .

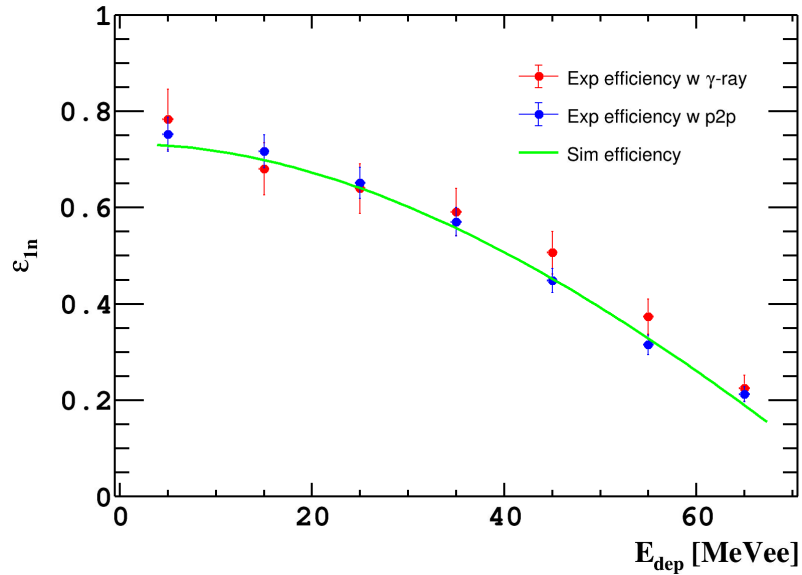


Figure 3.14.: Experimental 1-neutron detection efficiency distribution as a function of deposited energy threshold from two selection methods (see text) compared with the distribution expected from simulation.

The advantage of this method is that it is independent of the detection efficiency of CALIFA since it is a ratio of counts in the same detector for γ -rays of same energy. Furthermore, it is highly selective on the reaction mechanism, since, in addition to the fragment and the (p,2p) condition, the γ -ray is selected which can only be emitted from the residual fragment.

The experimental relative energy distribution for the $^{16}\text{C}(\text{p},2\text{p})^{14}\text{B}+1\text{n}$ channel is shown in Fig. 3.13 (Top left). As can be observed, most of the relative energy strength is below 4 MeV. The γ -ray spectrum in coincidence with the system, is also shown in Fig. 3.13 (Bottom left). The well known 1^- state of ^{14}B at $E_\gamma = 654$ keV [62] is clearly observed, indicating that some of the $^{14}\text{B}+1\text{n}$ system decays through the excited state of ^{14}B . The complete analysis of this channel will be provided in Chapter. 4. The integral under the photopeak is obtained for events with and without requiring NeuLAND in coincidence. The ratio of the counts obtained from the two conditions, as described in Eq. 3.3, yields the absolute detection efficiency value of NeuLAND. This process is repeated with different deposited energy thresholds in NeuLAND for both simulated and experimental data, to characterize the change in efficiency as a function of the threshold. The efficiency values obtained with this procedure are shown in Fig. 3.14 (in Red). A comparison to the expected distribution from the simulation is also shown (in green). As can be observed, there is a general agreement in the experimental and simulated efficiency centroids and their overall trend. However, the uncertainty in the experimental efficiency values is very large and predominantly statistical, due to the limited number of counts in the photopeak. To address this, an alternative set of cuts is proposed.

The objective of the second set of selection cuts is to identify clean (p,2p) events. To do this, the requirement is that there should be exactly two large energy clusters in CALIFA corresponding to the two protons and no low-energy clusters < 20 MeV. With this selection, the number of ^{14}B events with and without the requirement of having NeuLAND in coincidence can be obtained, in order to determine the efficiency ε_{1n} . In this case, Eq. 3.2 becomes,

$$\varepsilon_{1n} = \frac{N(\text{p2p} + \text{NeuLAND})}{N(\text{p2p})}. \quad (3.4)$$

The process is again repeated for different deposited energy thresholds and the final distribution is shown in Fig. 3.14 (in blue). With lower uncertainties, the agreement with the simulated data can be clearly observed.

3.3.5. Implementation of simulations to analysis

Once the Fragment + x-neutron relative energy spectrum is reconstructed, the next objective is to fit this distribution. If the Fragment + x-neutron system populates unbound states, they will appear as resonances in this relative energy spectrum. As discussed in section 1.3, such resonances generally follow a Breit-Wigner (BW) type distribution. The Breit-Wigner can be parameterized by the resonance energy E_r and the width $\Gamma_{r,ell}$, which further depends on the angular momentum ℓ_r of the neutron with respect to the fragment (though in most cases, due to the experimental resolution, the distributions are not sensitive to ℓ_r and the parameter is redundant). The full relative energy distribution could consist of multiple such resonances. The challenge is to identify the number of resonant states and to parameterize them. The full distribution at the end should be reproduced with the function,

$$f(E_x) = \sum_i w_i R_i(E_x), \quad (3.5)$$

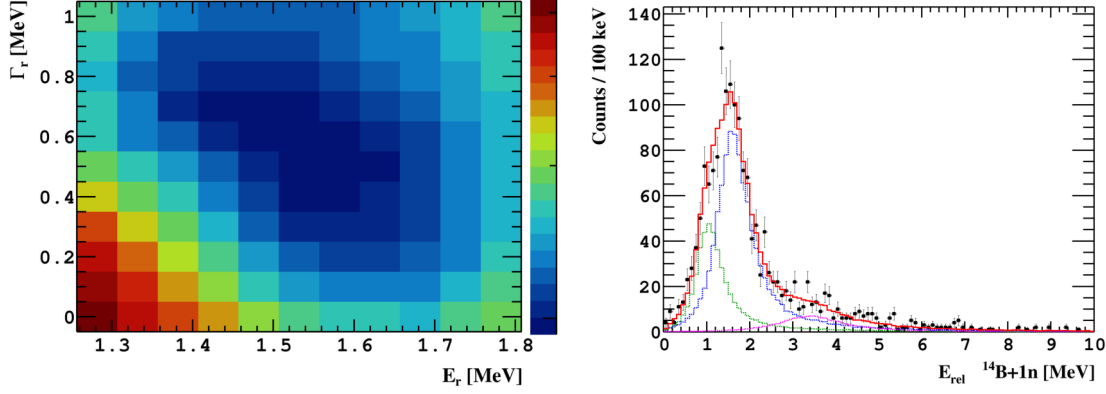


Figure 3.15.: (Left) χ^2 distribution for the energy E_r and width Γ_r parameter for fit of the dominant resonance at $E_r \sim 1.6$ MeV in $^{14}\text{B}+1\text{n}$ spectrum (Right)

where R_i is the i th resonance with weight w_i , and the weights satisfy the condition $\sum_i w_i = 1$. The resonances R_i are generated through simulations that convolute the input Breit–Wigner distributions with the experimental resolution and detector response. To get the best fit of the data, the resonances are simulated with varying energy and widths and added to the function $f(E_x)$. The final fit is estimated by minimizing the χ^2 with a given combination of resonances, wherein the χ^2 is given by,

$$\chi^2 = \left(\sum \frac{N(E_x) - \sum_i w_i R_i(E_x)}{\text{err}(N(E_x))} \right)^2, \quad (3.6)$$

where $N(E_x)$ is the number of counts in the relative energy distribution at a given relative energy E_x .

To illustrate an example, the case of $^{16}\text{C}(p,2p)^{14}\text{B} \rightarrow ^{14}\text{B} + 1\text{n}$ reaction is presented here. The $^{14}\text{B} + 1\text{n}$ relative energy distribution along with the fit is shown in Fig. 3.15 (right). Further details about this channel will be discussed in Chapter. 4. It is observed that the full distribution is described with the help of 3 resonances. The centroid values of all parameters — the energy E_r , width Γ_r and the amplitude — corresponds to their values at the minimum χ^2 . Additionally, the uncertainties of the individual parameters can be estimated by analyzing the spread of the χ^2 distribution with the variation in their values. Since there are multiple overlapping resonances, this is done for each resonance by fixing the energy and width of the other resonances. Figure. 3.15 shows the heat-map of the χ^2 for the variation in the energy and width of the resonance at $E_r \sim 1.6$ MeV. The uncertainty can be defined with the condition of $\chi^2 < \chi_{min}^2 + \delta\chi^2$, where $\delta\chi^2 = 1, 2, 3, \dots$ depending on the desired confidence level and the number of degrees of freedom [89]. In the presented fit, since the energy and width of the other resonances are fixed, only their amplitudes contribute as free parameters. Therefore, the fit has 5 degrees of freedom, which implies a good level of confidence is achieved by taking $\delta\chi^2 = 6$. The fit parameters in this case give $E_r = 1.63$ MeV with $\Delta E_r = 0.05$ MeV and $\Gamma_r = 0.55$ MeV with $\Delta\Gamma_r = 0.15$ MeV

A final comment about the fit function; in Eq. 3.5 the full relative energy distribution is described with resonant contribution only. However, there is an established practice of including a non-resonant contribution in addition to the resonances, to describe parts of the relative energy distribution where distinct resonances cannot be identified. There are various approaches to obtain the shape of the so called non-resonant part, some of which are described in [90]. In this case, Eq. 3.5 would be modified to include the non-resonant component in the sum. However, in the present analysis, no non-resonant contribution is included in the fits.

3.4. Two Neutron Reconstruction

High-energy neutrons impinging on NeuLAND can interact with the detector material via a large variety of reactions. These reactions can lead to the production of a wide range of secondary particles, which can then further interact in the detector and produce more particles. This collection of secondary particles from the primary neutron interaction can be referred to as the secondary shower. For such high-energy neutrons, the secondary shower for each neutron interaction can spread over a very large spatial and temporal distance in the detector medium. An estimate of this distribution can be obtained by examining one-neutron events. In these events, it is clear that only one neutron enters the detector, therefore, there should be only one hit in the detector corresponding to the primary neutron interaction, which is assigned as the first hit in time. All other subsequent hits are produced as a result of the secondary interactions. The spatial and temporal experimental distribution of all hits relative to the first hit in time for 1-neutron events is shown in Fig. 3.17. As can be observed, the distribution spreads over a large volume of the detector within a few nanoseconds. Now consider a two neutron emission reaction where a second neutron is emitted at the same time as the first neutron. If the total relative energy (E_{rel}) is very low, then the primary interaction point of the second neutron is very likely to overlap with the region of the secondary shower from the first neutron. As a result, it becomes very difficult to identify the precise interaction point of the second neutron, and, consequently, its four-momentum. This highlights the main challenge of the multi-neutron reconstruction algorithm. In the subsequent discussion, all the secondary hits from the primary neutron interaction will be referred to as "cross-talk" and the objective is to separate out the cross-talk from the primary neutron interaction points.

NeuLAND was designed with the concept of a "Calorimeter", which can with a high degree of accuracy provide the multiplicity of neutrons interacting in the detector. This calorimetric method of neutron identification has been highlighted in [75]. However, for the current analysis, it is necessary to properly suppress the cross-talk contribution while reconstructing the true 4-momentum of the neutrons, for which the calorimetric method is not very effective without its full design depth. The disadvantages of the calorimetric method are discussed in [91]. In fact, the current NeuLAND setup, operated as a calorimeter with all 13 double planes placed together as a single wall, makes cross-talk rejection even more challenging. This is effectively because of the lower relative distances between the primary and all secondary hits. The secondary particles can spread out over a large part of the detector volume within a few hundred picoseconds. This implies that a large number of secondary hits occur within the time resolution of the detector, which makes it difficult to separate out these hits through simple kinematic conditions. Therefore, there is a need for a separate dedicated algorithm for the cross-talk rejection, which has been developed and implemented for the first time for NeuLAND in the current analysis. Here, the reconstruction procedure is limited to only two-neutron systems, as higher multiplicities introduce additional complexity which is beyond the scope of the current work.

Over the years several cross-talk rejection algorithms have been developed for detector arrays similar to NeuLAND, for e.g. the ones reported in [68, 92, 93]. In the current work, majority of these were implemented and tested. Finally the method described in [93] was found to be the most suitable for the current NeuLAND setup. It should be noted, however, that this method — implemented for the NEBULA-NeuLAND demonstrator setup at the SAMURAI experiment in RIKEN — was developed for low-energy beams (< 300 AMeV). At higher incident beam energies, the emitted neutrons experience a stronger forward boost. This implies that for the same relative energy, the relative angles between the neutrons, as well as between the beam and the neutrons, are smaller. The advantage of this is that the acceptance extends to higher relative energies. However, the disadvantage is that the neutrons are much closer together, making it more difficult to separate them from cross-talk at lower relative energies.

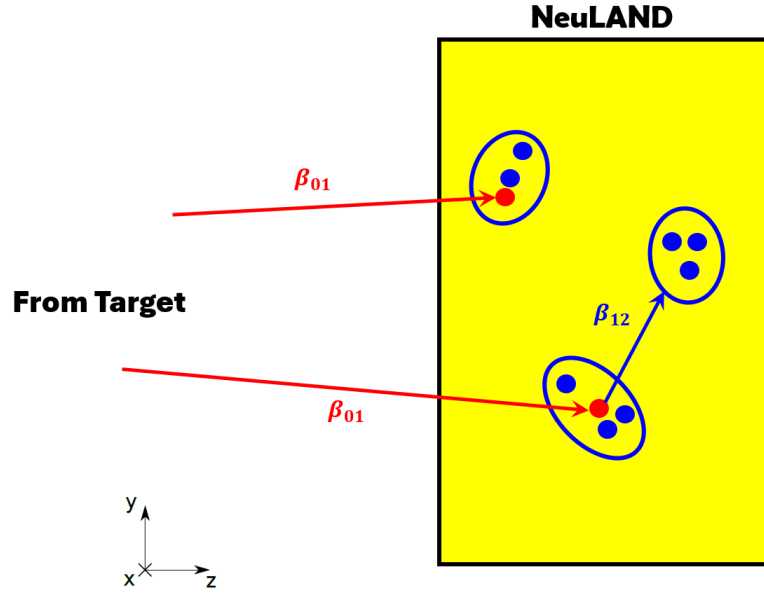


Figure 3.16.: Schematic of the 2-neutron interaction process in NeuLAND. The initial incoming neutrons are indicated with red arrows, with their incoming velocity defined as β_{01} . All secondary hits in NeuLAND is shown in blue along with the clusters. The "virtual" velocity β_{12} is also highlighted for a cross-talk event between two clusters shown with the blue arrow.

Consequently, the cross-talk rejection algorithm removes more events at lower relative energies, causing the two-neutron reconstruction efficiency to drop more steeply at these energies. It is also noted that the method applied in [93] was developed for the detector setup where the detector walls were separated by some distance which allows for cleaner kinematic cuts. As discussed above, in the current case NeuLAND is operated as a single wall and thus the kinematic cuts further enhance the effect of efficiency reduction at low relative energies. With this in mind, a second reconstruction algorithm was developed to obtain a less deformed efficiency distribution.

The development and validation of the reconstruction algorithms are based on the neutron simulations. The advantage of using simulations is that they not only provide the efficiency distribution but also the cross-talk contribution after the reconstruction. This is done by backtracking the reconstructed hits and comparing the accuracy of the reconstructed four-momenta and identifying whether they were produced from the same neutron or not. Although simulations play a central role in algorithm development, most of the selection cuts and conditions applied are derived from the one-neutron experimental data. As mentioned, this is especially useful since all other hits besides the first hit in time are attributed to cross-talk. Therefore, the distributions of these hits relative to the first hit in time essentially reflects the cross-talk distributions that needs to be removed.

3.4.1. Causality Method

This algorithm is largely based on the methodology described in [93]. The method combines the concepts of *clustering* and *causality*. *Clustering* refers to grouping together hits that are close in space and time within the detector into so-called clusters. *Causality* refers to removal of secondary hits which can be produced by a neutron after it is scattered from an initial interaction point in the detector. This means

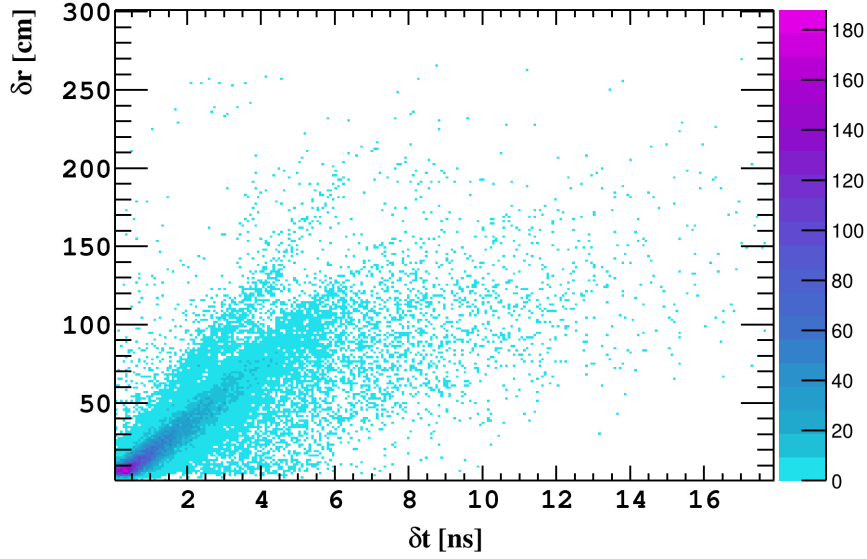


Figure 3.17.: Relative spatial δr and temporal δt distribution as compared to the first hit in time for 1-neutron events. The shown distribution is obtained from the $^{19}\text{N}(p,2p)^{17}\text{C}+1n$ channel.

that if the virtual velocity between the first and second interaction points in the detector is less than the velocity from the target to the first interaction point, there is a possibility that the second interaction point was produced by particles scattered from the first interaction point.

In the following, the methodology and principle of the reconstruction algorithm is described. The relevant cross-talk distributions are obtained from the one-neutron experimental data and compared to the simulated data. To define the cuts, the $^{19}\text{N}(p,2p)^{18}\text{C} \rightarrow ^{17}\text{C}+1n$ channel was used, since the one-neutron channel in this case has significant statistics and the distribution extends to high relative energies. The one-neutron cross-talk distributions, along with the cuts and conditions discussed below, is shown in Fig. 3.18.

- A ToF cut, similar to the one-neutron case as shown in Fig. 3.10, corresponding to realistic velocities of neutrons arriving in NeuLAND.
- The next step is to accept hits with deposited energies above a certain threshold which was set to > 7 MeV. All other hits below this energy were rejected. This is the Q -cut and it ensures that sufficient energy is deposited by the initial neutron interaction, such that the scattering process leads to a large change in the scattered neutron momentum, which can be later identified by the causality cut within the time resolution. Additionally, it removes background stemming from low-energy cross-talk. This threshold value can be slightly adjusted depending on the channel based on required statistics.
- The hits were then sorted according to the time they were recorded in the detector. The first hit in time already ensures the correct four-momentum reconstruction of one neutron. All other hits are processed relative to this hit.
- The hits are then clustered based on a predefined spatial and temporal clustering window. The time window used to cluster the hits was set to $\delta t = 3$ ns, while the spatial window was set to $\delta r = 20$ cm. To be more consistent, the current clustering algorithm is based on what is known as the *handshake* algorithm described in [91]. In this method, the first cluster is started by comparing all hits with the first hit in time, and any hit that satisfies the clustering condition is added to the

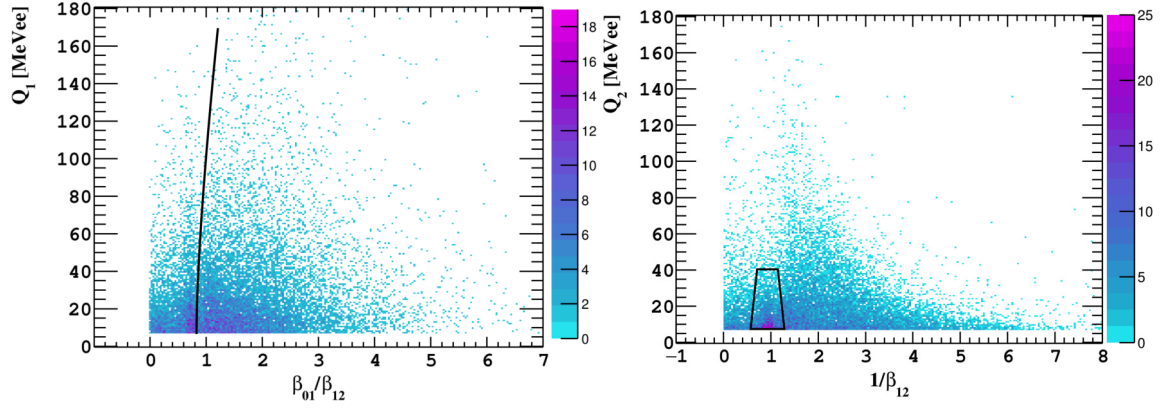


Figure 3.18.: *Right:* Q_1 vs β_{01}/β_{12} experimental distribution with the causality cut shown with the black line. All hits on the right side of the line is removed. *Left:* Q_2 vs $1/\beta_{12}$ experimental distribution. A clear enhancement at $1/\beta_{12} = 1$ at low energies corresponding to secondary γ -rays is observed. The cut to remove this cross-talk is also shown in black. The shown experimental distributions are obtained from the $^{19}\text{N}(p,2p)^{17}\text{C}+1n$ channel.

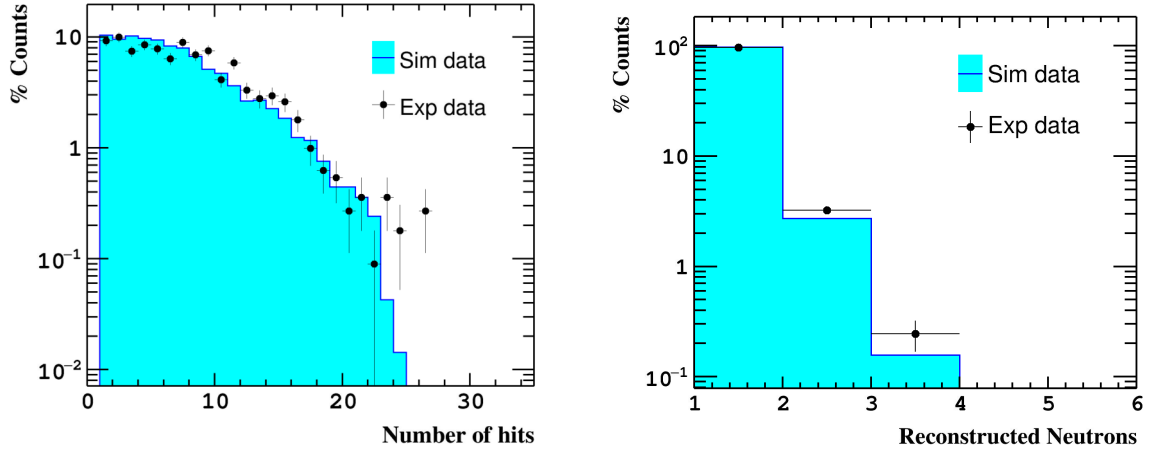


Figure 3.19.: *Left:* Experimental hit multiplicity in NeuLAND for $1n$ events (solid circles) compared to simulation (blue histogram). *Right:* Reconstructed neutron multiplicity for $1n$ events using the "Causality" method from data (solid circles) compared to simulation (blue histogram). The shown experimental distributions are obtained from the $^{19}\text{N}(p,2p)^{17}\text{C}+1n$ channel.

cluster. Subsequently, the remaining hits are compared to those already in the cluster, and any that meet the clustering condition are further added to the cluster. This process is repeated iteratively until no further hits satisfy the clustering condition. Then the first hit from the remaining list of hits starts the next cluster. This is repeated until there are no more hits left to cluster. This clustering process removes most of the cross talk from secondary charged particles with low range, especially protons which deposit most of their energy close to the first interaction point. Each cluster is characterized by the position and time value of the first hit in time within the cluster. The deposited energy attributed to the cluster was also that of the first hit in time. This was chosen over taking the sum of the deposited energy of all hits since the cuts were found to be cleaner with the former.

- The next step is to apply the causality condition on the clusters. As mentioned, this is done to remove hits where neutrons, after interacting at one point in the detector, scatter and interact at another point in the detector. For this purpose, two new parameters are defined: β_{01} , the velocity calculated using the ToF between the target and the cluster in NeuLAND; and β_{12} , the virtual velocity between two clusters, obtained from their relative time and position differences. The virtual velocity β_{12} , essentially defines the velocity a particle will need to travel between two clusters (see Fig. 3.16). All clusters are compared pairwise, and the ratio of the velocities, β_{01}/β_{12} , is plotted against the deposited energy of the first cluster, Q_1 , as shown in Fig. 3.18 (Left). The idea of the cut is simple; if the velocity of the scattered neutron is less than the velocity of the incident neutron, it is removed. That is, all clusters with $\beta_{01}/\beta_{12} > 1$ are removed. However, the time resolution of the detector is not perfect and allowances have to be made accordingly. The black line in the plot Fig. 3.18 (Left) describes the causality cut used on the velocity ratio as a function of the deposited energy Q_1 . The cut is slightly shifted below $\beta_{01}/\beta_{12} = 1$ to account for the time resolution and changes with the magnitude of the initial deposited energy Q_1 .
- The next cuts is defined is to remove cross-talk from secondary γ -rays, which can travel to large distances in the detector volume at the speed of light. To identify them, the clusters are again compared pairwise and the inverse of virtual velocity between two clusters, $1/\beta_{12}$, is plotted against the energy deposited by the second cluster, Q_2 , as shown in Fig. 3.18 (Right). A clear collection of counts around $1/\beta_{12} = 1$ at low Q_2 values can be observed corresponding to the γ -ray cross-talk. The cut used to remove these cross-talk hits is also highlighted.
- The final selection is to have exactly two neutrons in an event. If the event has more reconstructed neutrons, the event is rejected since it is not trivial to determine which hits correspond to the correct reconstruction.

In order to benchmark the reconstruction algorithm, it is first applied to 1-neutron events in the experimental data. The multiplicity for the 1-neutron events before and after the reconstruction is shown in Fig. 3.19. As can be observed, most of the events are reconstructed with only one neutron. Therefore, when a single neutron interacts in NeuLAND there is a very small probability to reconstruct it as a two neutron event.

To demonstrate the performance of the cross-talk suppression algorithm, similar to the 1-neutron case, a response matrix is obtained with the simulations. To do this, the reconstruction algorithm is applied to simulated Fragment + 2n events, generated assuming a phase-space three-body decay with a uniform distribution over a relative energy range of $E_{rel} \sim 0-15$ MeV. Following this, the response matrix is obtained by plotting the input relative energy against the reconstructed relative energy, as shown in Fig. 3.20. The strong correlation between the generated and reconstructed data indicates a good reconstruction over a large relative energy region. Most of the off diagonal events correspond to the cross-talk. Since

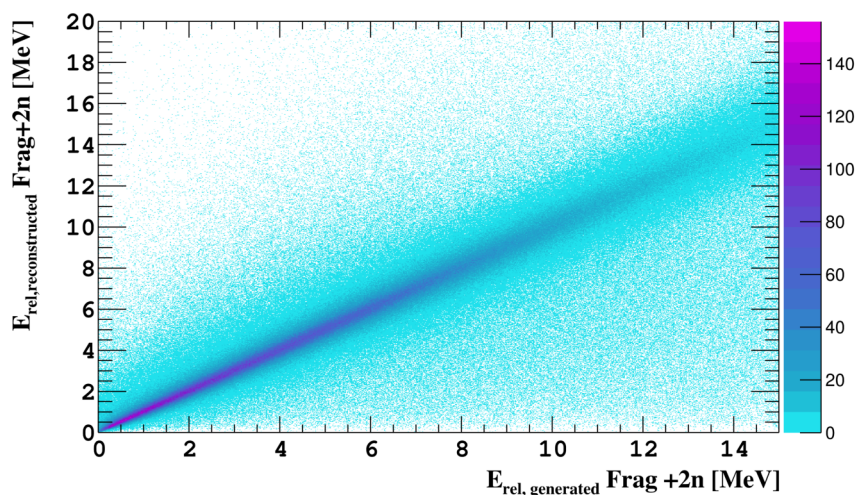


Figure 3.20.: Response matrix for Fragment + 2n reconstruction for the "Causality" method.

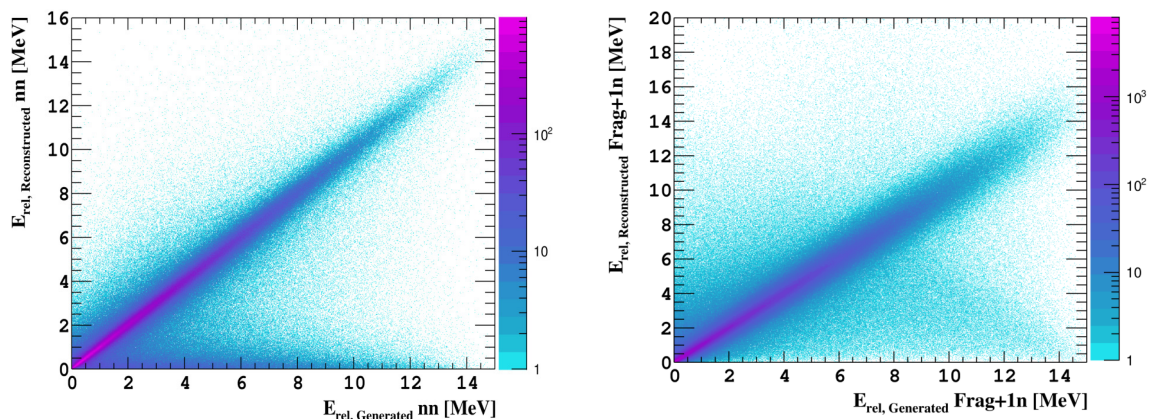


Figure 3.21.: **Left:** Response matrix of the neutron-neutron relative energy. The cross-talk contribution can be observed at low $E_{rel}(nn)$ reconstructed over a large range of generated $E_{rel}(nn)$. **Right:** Response matrix of Frag + 1n relative energy component reconstructed for Frag + 2n events. The plots shown are obtained with the "Causality" reconstruction procedure.

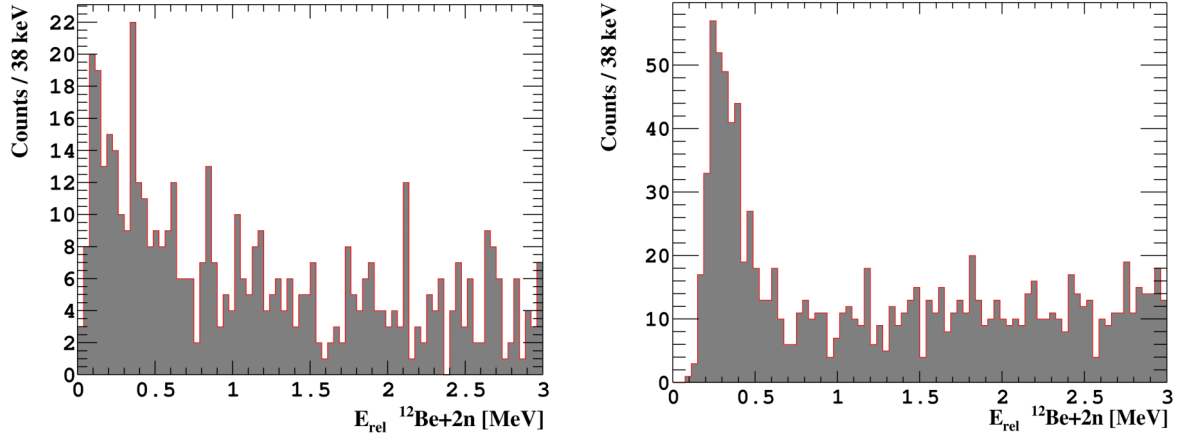


Figure 3.22.: *Left:* $^{12}\text{Be} + 2n$ relative energy distribution from $^{15}\text{B}(-1p)$ reaction without implementation of the $2n$ reconstruction algorithm. *Right:* Same relative energy distribution after implementation of the "Causality" reconstruction algorithm. A peak at 250 keV is clearly visible after reconstruction.

the current system involves a 3-body decay, it is also possible to check the validity of the reconstruction for each two-body subsystem. In Fig. 3.21, correlation matrices for the neutron-neutron (nn) and Fragment-neutron (Frag+1n) components of the relative energy are shown. A strong correlations is observed for most of the reconstructed events. However, a small non-diagonal component appears at low reconstructed nn relative energies, extending over a broad range of the input distribution. This is a typical signature of the cross-talk contribution in the reconstructed nn -relative energy distribution. One has to be especially careful here that the cross-talk is accounted for properly in order to distinguish it from the signature of the nn -FSI, which also appears at low nn -relative energies.

From the perspective of the experimental data, the measured relative energy distribution corresponding to the $^{15}\text{B}(-1p)^{14}\text{Be} \rightarrow ^{12}\text{Be} + 2n$ reaction, with and without the cross-talk suppression is shown in Fig. 3.22. After cross-talk rejection, the previously reported 2_1^+ state of ^{14}Be [3] at ~ 250 keV is clearly visible.

The efficiency distribution obtained from the simulations of the Fragment + $2n$ events, as a function of the reconstructed relative energy, is shown in Fig. 3.23. This distribution is a combination of the detection efficiency, acceptance and reconstruction efficiency taking into account the detector response. As can be observed, the total efficiency is heavily distorted by the cross talk suppression algorithm. The efficiency drops significantly at low relative energies since the relative distance between the two neutrons is very small and it becomes very difficult to separate the good hits from cross-talk. In general, it is not possible to completely eliminate the cross-talk contribution without sacrificing a significant amount of efficiency. Thus, a balance must be struck between maximizing the efficiency and minimizing the cross-talk contribution. For the current work, since the objective of the study is to identify near-threshold states, where the efficiency drops significantly, the cuts were chosen to be less strict to obtain sufficient statistics. The cross-talk contribution to the total efficiency as a function of the relative energy is also shown in Fig. 3.23 (in red). Care must be taken, however, as the true cross-talk contribution changes depending on the decay mechanism and correlation between the neutrons. In order to have a sufficient statistics at low relative energies, the allowed cross-talk percentage is around $\sim 15\%$ at 1 MeV relative energy.

The cuts described above are flexible and can be adjusted to be more or less strict depending on the channel and the expected relative energy distributions. This implies that the final efficiency value and the corresponding cross-talk contribution also change slightly.

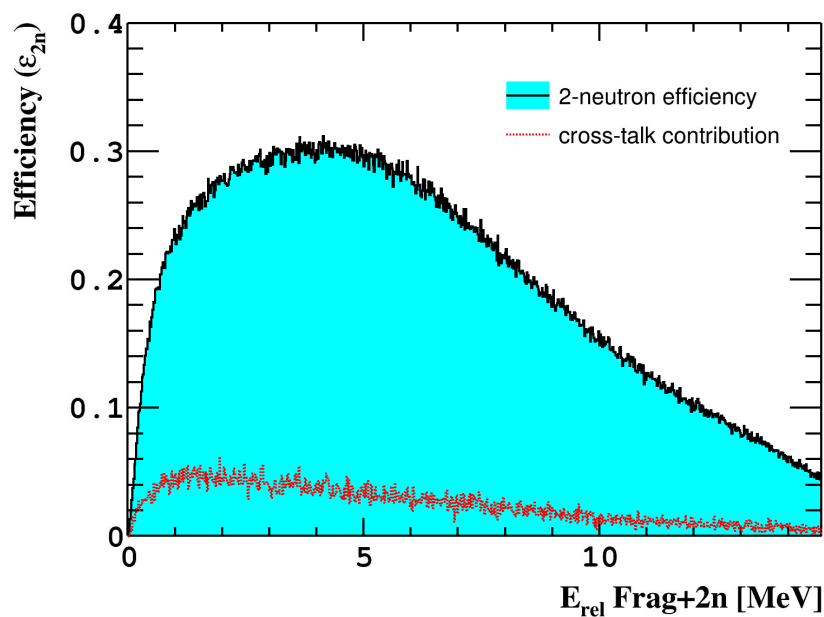


Figure 3.23.: (In blue) Simulated 2-neutron efficiency distribution of the reconstructed relative energy for the "Causality" method (see text). The cross-talk contribution is also shown (in red).

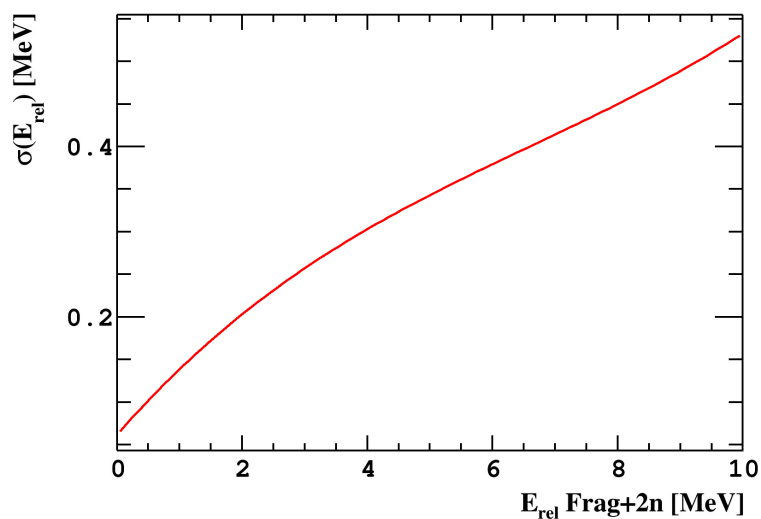


Figure 3.24.: Evolution of the resolution as a function of the relative energy obtained from the simulation.

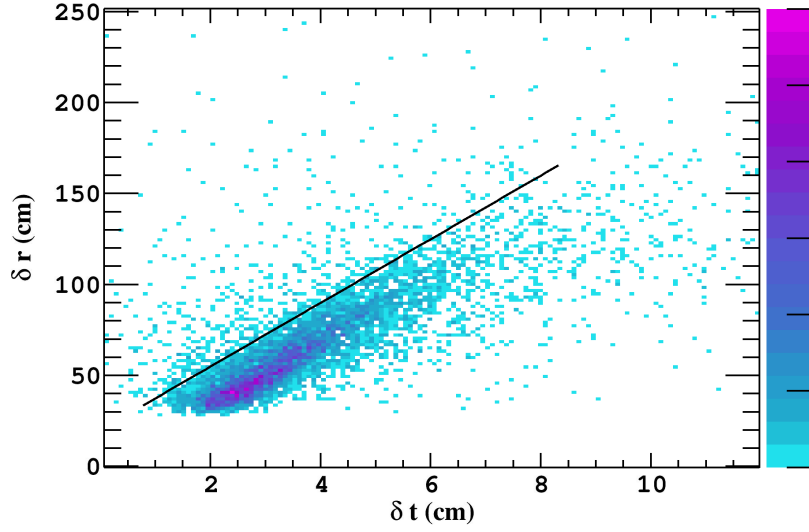


Figure 3.25.: Relative spatial δr and temporal δt distribution as compared to the first hit in time for 1-neutron events, taken from experimental data, with the cut shown for the "Two-wall" method. All hits below the line are removed. The shown distribution is obtained from the $^{19}\text{N}(p,2p)^{17}\text{C}+1n$ channel.

The resolution curve as a function of the relative energy can also be extracted from the simulations, which includes the detector response and is convoluted with the experimental resolution. This is shown in Fig. 3.24.

3.4.2. "Two-wall" method

Though the method mentioned above provides sufficient efficiency at higher relative energies, it has the disadvantage of a sharp drop at low Fragment + 2n relative energies below 1.5 MeV. Furthermore, the efficiency for the two-body neutron-neutron (nn) relative energy distribution also decreases significantly at low nn relative energies. This is especially disadvantageous for the current analysis, where the focus is to study the nn -FSI, which effectively manifests at low nn relative energies. The problem is illustrated in Fig. 3.29. The left panel shows two superimposed m_{nn}^2 ($\approx E_{rel}(nn) / E_{rel}(\text{Frag}+2n)$) distributions for a simulated resonance at $E_{rel}(\text{Frag}+2n) = 250$ keV, reconstructed using the causality method. One distribution corresponds to 3-body phase-space decay, while the other is simulated including nn -FSI. The drop at low nn relative energy makes it difficult to distinguish between the two. With this context, there was a need for a method which prevents such a large relative drop of efficiency at low nn relative energy values.

The cuts and conditions used for this method is as follows:

- A ToF cut, corresponding to realistic velocities of neutrons arriving in NeuLAND.
- Accepting hits with deposited energy > 10 MeVee
- The first hit in time defines the first neutron interaction point and, as before, is used to reconstruct the four-momentum of the first neutron.
- The next step is to accept hits only from detector regions that are separated by at least three double planes from the first hit in time, hence the name "two-wall method".

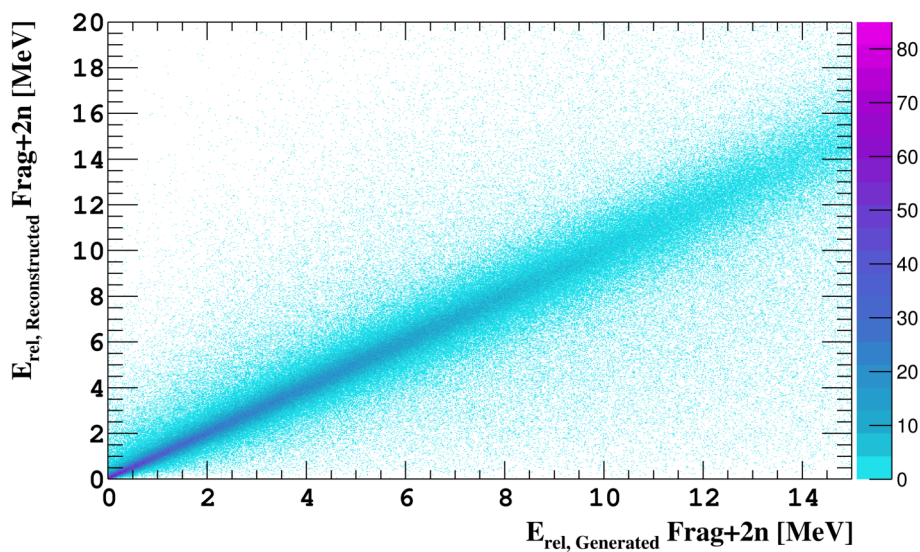


Figure 3.26.: Response matrix for Fragment + 2n reconstruction with the "Two-wall" method.

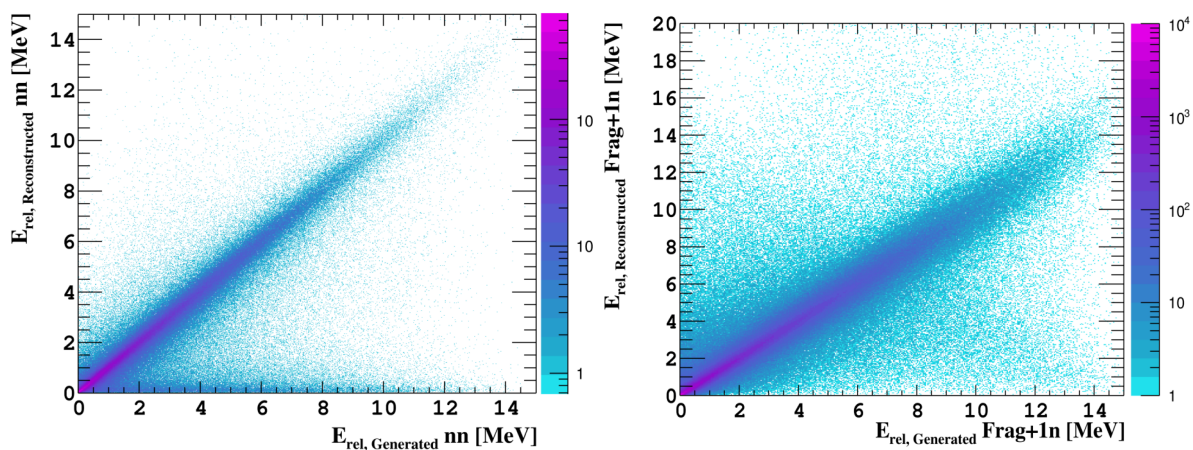


Figure 3.27.: **Left:** Response matrix of the neutron-neutron relative energy. **Right:** Response matrix of Frag + 1n relative energy component reconstructed from Frag + 2n events. The plots shown are obtained with the "Two-wall" reconstruction method.

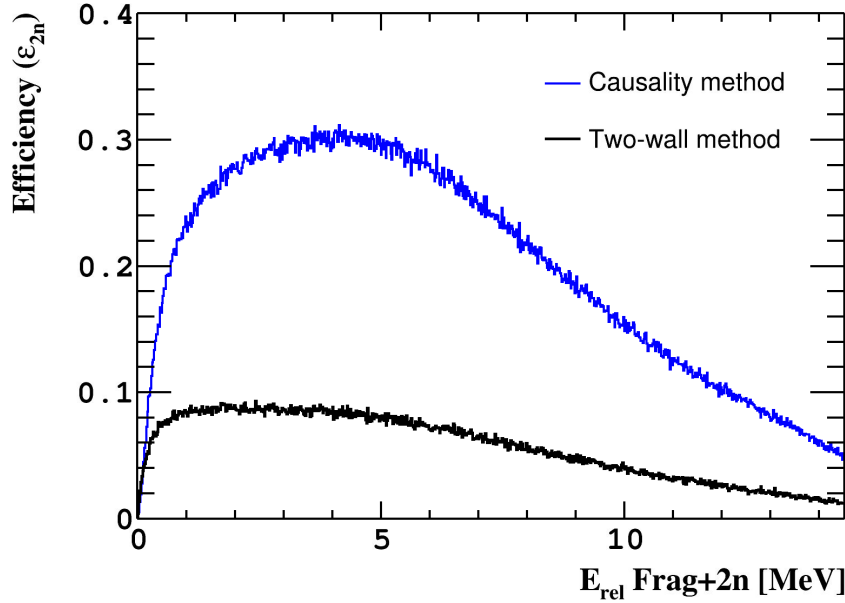


Figure 3.28.: Simulated 2-neutron efficiency distribution as a function of the reconstructed relative energy for the "Causality" method (in blue) compared to the "Two-wall" method (in black).

- From the remaining hits, all hits having deposited energy < 30 MeVee are removed to eliminate the low-energy cross-talk. Compared to the previous method, all secondary low-energy hits are removed here regardless of their velocity distribution, ensuring that the kinematic cuts used later leads to a less biased final efficiency distribution.
- The final step is to remove all hits within a defined space-time cut relative to the first hit in time as illustrated in Fig. 3.25. This cut, as shown, is determined based on the experimental one-neutron distribution.
- The first hit in time among the remaining hits, after applying the cuts, is used to reconstruct the four-momentum of the second neutron.

As before, to demonstrate the performance of the algorithm, a response matrix is obtained by plotting the generated and reconstructed data from the simulations. A strong correlation is observed in Fig. 3.26. The two-body correlation matrices are also shown in Fig. 3.27. Additionally, the experimental relative energy distribution for the $^{15}\text{B}(-1\text{p})^{14}\text{Be} \rightarrow ^{12}\text{Be} + 2\text{n}$ reaction, reconstructed with this method is also shown in Fig. 3.30. A distinct peak at $E_{\text{rel}} \sim 250$ keV is observed.

The resulting Fragment + 2n efficiency distribution of the reconstructed relative energy for this method, is shown in Fig. 3.28, and is compared to the "Causality" method. Although the overall efficiency is much lower, the distribution is flatter, and the drop is observed to occur at a much lower relative energy. In this case, the cross-talk contribution at 1 MeV is $\sim 10\%$.

To highlight the effectiveness of this method for the nn analysis, a comparison of the m_{nn}^2 distributions for a simulated 250 keV resonance, with and without nn -FSI, is shown in Fig. 3.29 (right). In the "Two-wall" reconstruction case, a qualitative difference in the shape can be observed. This enables the proper estimation of whether the nn -subsystem exhibits an FSI signature at low relative energies. Such an analysis with the 250 keV resonance in the $^{15}\text{B}(-1\text{p})^{14}\text{Be} \rightarrow ^{12}\text{Be} + 2\text{n}$ channel will be discussed in Chapter. 5.

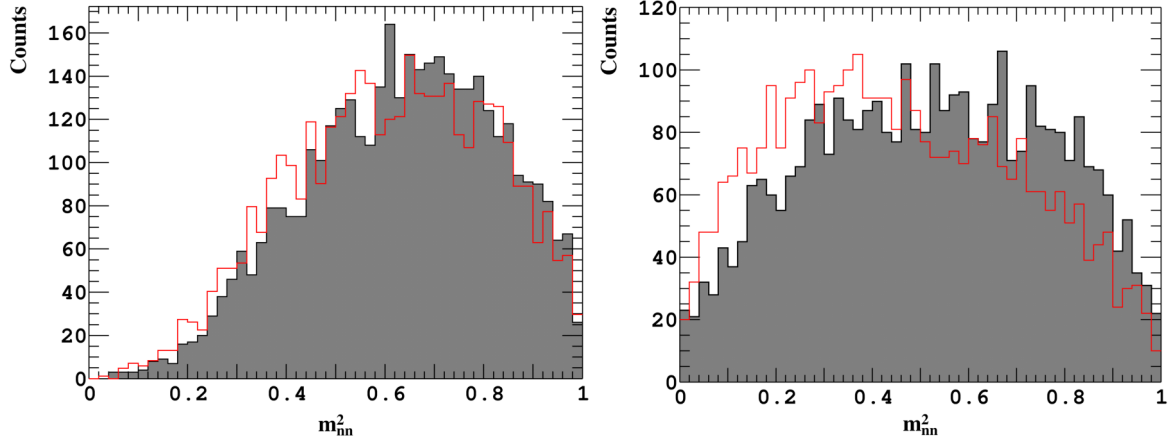


Figure 3.29.: m_{nn}^2 distribution for 250 keV simulated resonances with FSI (in red) and phase-space (in black). **Left:** Events reconstructed with "Causality" method. **Right:** Events reconstructed with "Two-wall" method. A clear distinction in the shape can be observed in the "Two-wall" method.

As is apparent, due to the significantly lower efficiency, the final statistics in the relative energy spectra reconstructed using this method are much lower and, for most channels is insufficient. For such cases, the causality method is much preferred, especially at higher relative energy. Eventually, both methods have been employed for the final analysis, and based on the requirements of the analysis one or the other is preferred. This is done by taking into account the trade-off between the efficiency and the response of the two methods. For the nn -analysis of the near-threshold resonances, additional modification of the causality method is implemented, which is discussed in Chapter. 5.

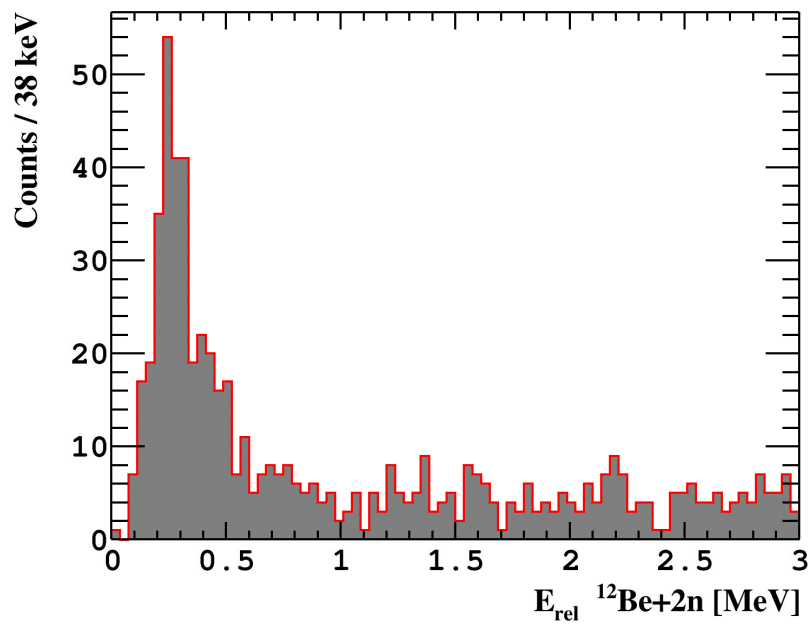


Figure 3.30.: $^{12}\text{Be} + 2n$ relative energy distribution from $^{15}\text{B}(-1p)$ reaction after implementation of the "Two-Wall" reconstruction algorithm. A peak at 250 keV is clearly visible.

4. Spectroscopy of Boron isotopes

In the current work, the objective is to search for multi-neutron near threshold resonances in neutron-rich nuclei and study the interplay of the nn -FSI on the formation of such resonant states. Among the nuclei populated in the current experiment, ^{17}B is of particular interest due to prior indication of a near threshold state in this nucleus [7] (see section 1.5). In this chapter, results on the structure of ^{17}B — populated via the QFS $^{18}\text{C}(p,2p)$ reaction— is presented. This study is based on the spectroscopy of bound and unbound states. The study of the nn -correlations corresponding to the resonant systems will be discussed in the next chapter.

To provide a comprehensive picture of the Boron isotopic chain, the structure of several Boron isotopes have been investigated and presented in this chapter. The discussion begins with results from the $^{16}\text{C}(p,2p)^{15}\text{B}$ reaction. This includes the identification of the populated bound and unbound states of ^{15}B . To investigate the 2-neutron unbound system and the ground state configuration of ^{15}B , analysis of the $^{15}\text{B}(p,pn)^{14}\text{B}$ reaction is also included. This is followed by the results for the $^{18}\text{C}(p,2p)^{17}\text{B}$ reaction. The unbound $^{15}\text{B} + 2n$ system populated in this reaction could decay via the intermediate ^{16}B resonant states. Consequently, the structure of ^{16}B is also explored through the $^{17}\text{C}(p,2p)$ reaction.

4.1. $^{16}\text{C}(p,2p)^{15}\text{B}$

Several previous experimental studies investigating the structure of ^{15}B have been reported [51, 52, 53, 62]. Bound excited states of ^{15}B have been measured in the work of [52] and [53]. The former populated ^{15}B states through the fragmentation of ^{36}S on a ^9Be target, while the latter used inelastic scattering of ^{15}B on carbon target. Two γ -ray transitions were identified at $E_\gamma = 1.327(12)$ MeV and $1.407(20)$ MeV. Detailed spectroscopy of the γ - γ coincidences by the authors of [52] suggests a cascade decay, where the 1.407 MeV γ -ray corresponds to the transition from the second excited state to the first excited state, while the 1.327 MeV γ -ray is emitted in the transition from the first excited state to the ground state. The authors of [52, 53] tentatively assigned a spin of $5/2^-$ to the first excited state at $E_x(^{15}\text{B}) = 1.327$ MeV and a spin of $7/2^-$ to the second excited at $E_x(^{15}\text{B}) = 2.734$ MeV by comparing the level scheme with theoretical shell-model (SM) and antisymmetrized molecular dynamics (AMD) calculations. The authors of [51] reports multiple excited states of ^{15}B beyond the neutron separation threshold ($S_n = 2.78(3)$ MeV [8]), populated via multi-nucleon transfer reaction.

In the present work, ^{15}B states populated via QFS proton removal in the $^{16}\text{C}(p,2p)^{15}\text{B}$ reaction are reported. As discussed previously, QFS reactions are very selective and are an excellent tool to probe single particle states in exotic nuclei. If a proton is knocked out, only those states corresponding to the proton configurations should be observed. Furthermore, at low excitation energies, the spin-parities of the states should correspond to the configuration of valence protons. The valence protons in ^{16}C occupy $0p_{3/2}$ or $0p_{1/2}$ orbitals, and consequently, removal of these protons should populate $3/2^-$ and $1/2^-$ states. Therefore, the $5/2^-$ and $7/2^-$ states identified in [52, 53], should not be populated in the current experiment.

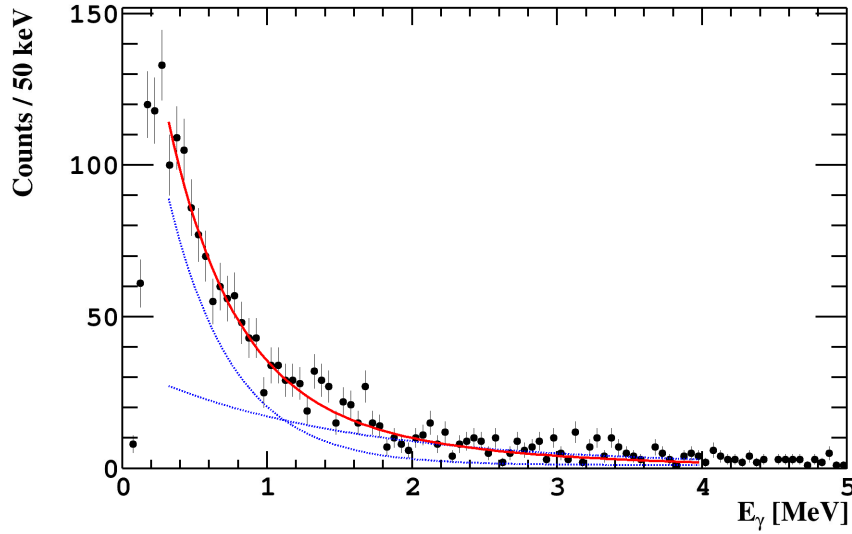


Figure 4.1.: Doppler corrected γ -ray spectrum corresponding to $^{16}\text{C}(p,2p)^{15}\text{B}$ reaction, fitted with a double exponential decay function. The two exponential distributions are shown in blue and the total fit of the background are shown in red. No significant peaks above the background are observed.

Figure. 4.1 shows the Doppler corrected γ -ray spectrum, corresponding to events selected with outgoing ^{15}B isotopes and an incoming ^{16}C beam with strict QFS proton cuts. The spectrum shown is plotted with a maximum γ -multiplicity of $N_\gamma = 3$ in CALIFA. The background is fitted with a double exponential as described in section 3.2.2. No distinct peaks are observed in the spectrum, and the full distribution can be completely reproduced with the background fit. This is in agreement with the assignment of $5/2^-$ and $7/2^-$ to the two bound states observed in the previous experiments [52, 53].

In the following subsections, the analysis of the unbound states populated beyond the neutron separation threshold is presented. The analysis is based on 1-neutron and 2-neutron invariant-mass spectroscopy. As mentioned, several unbound states have been observed in the work of [51]. The objective is to confirm the states previously identified and characterize them, as well as to identify additional states not observed previously.

4.1.1. $^{16}\text{C}(p,2p)^{15}\text{B} \rightarrow ^{14}\text{B}+1n$

States populated above the neutron separation threshold at $S_n = 2.78(3)$ MeV [8] will generally decay via neutron emission. Such resonant states can be reconstructed in the current setup with the invariant-mass method (section 1.3.1). The reconstructed $^{14}\text{B}+1n$ relative energy spectrum corresponding to the $^{16}\text{C}(p,2p)^{15}\text{B} \rightarrow ^{14}\text{B}+1n$ reaction, with the selection on QFS protons is shown in Fig. 4.2. A single structure peaking at $E_{rel} \approx 1.6$ MeV can be observed. In principle the full distribution can be reproduced with a single Breit-Wigner fit. It should be noted, however, that the $^{14}\text{B}+1n$ system can decay either to the ground state or the excited state of ^{14}B . In the case of the former, the excitation energy is defined as,

$$E_x(^{15}\text{B}) = S_n(^{15}\text{B}) + E_r(^{14}\text{B} + 1n), \quad (4.1)$$

while for the latter it is defined as,

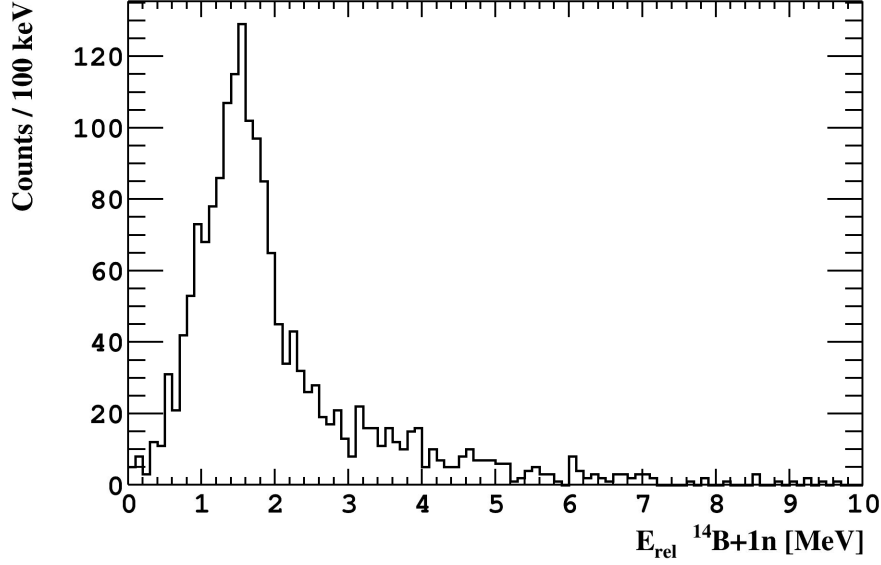


Figure 4.2.: Relative energy spectrum for $^{16}\text{C}(p,2p)^{15}\text{B} \rightarrow ^{14}\text{B}+1n$ channel.

$$E_x(^{15}\text{B}) = S_n(^{15}\text{B}) + E_r(^{14}\text{B} + 1n) + E_x(^{14}\text{B}), \quad (4.2)$$

where $E_x(^{14}\text{B})$ is the energy of the excited state of ^{14}B . A single bound excited state of ^{14}B has been previously identified at $E_\gamma = 654$ keV [62, 48, 94] and assigned a spin-parity of 1^- . The γ -ray spectrum in coincidence with the $^{14}\text{B}+1n$ events is shown in Fig. 4.3 (Left). A clear peak at $E_\gamma = 653(7)$ keV is observed, indicating that a portion of the $^{14}\text{B}+1n$ system decays through the excited state of ^{14}B .

In order to identify the component in coincidence with the γ transition, an energy gate is applied on the γ -ray spectrum ($\sim E_\gamma \in [0.55, 0.76]$ MeV) corresponding to the photopeak, and the coincident $^{14}\text{B}+1n$ spectrum is reconstructed. The energy gate in the γ -ray spectrum, however, also includes background contributions in addition to the photopeak. This background contribution has to be estimated and subtracted from the reconstructed $^{14}\text{B}+1n$ distribution. In order to do this, the γ -ray spectrum is first fitted to estimate the integral of the counts within the photopeak. The next step is to identify the shape of the "background" $^{14}\text{B}+1n$ distribution. This is done by gating on the deposited energy in CALIFA that exceeds the maximum energy of the photopeak. In the current case, events with deposited energies $E_\gamma > 3$ MeV in CALIFA were chosen. This is reasonable since no structures other than a continuous background was observed beyond this energy. Following this, the "background" gated $^{14}\text{B}+1n$ distribution is scaled and subtracted from the photopeak gated distribution, until the integral of the subtracted spectrum is equal to the integral of the photopeak estimated earlier. The subtracted spectrum and the corresponding fit is shown in Fig. 4.3 (right). It can be clearly observed that the centroid in the subtracted spectrum is shifted as compared to the total $^{14}\text{B}+1n$ distribution (see Fig. 4.2). The subtracted spectrum is fitted with a single simulated resonance following a Breit-Wigner distribution with parameters $E_r = 1.10(7)$ MeV and $\Gamma_r = 0.38(15)$ MeV. The excitation energy of this resonance according to Eq. 4.2 is now $E_x(^{15}\text{B}) = 2.78 + 1.10 + 0.65 = 4.53$ MeV.

The γ -ray coincident resonance is finally included in the fit of the total distribution, while allowing for the inclusion of additional resonances with free parameters. A dominant resonant contribution, with parameters $E_r = 1.63(5)$ MeV and $\Gamma_r = 0.55(15)$ MeV is required to fit the distribution up to $E_r \approx 3$ MeV. A third resonance is further needed at higher energy to finally fit the full distribution. This third resonance

4. Spectroscopy of Boron isotopes

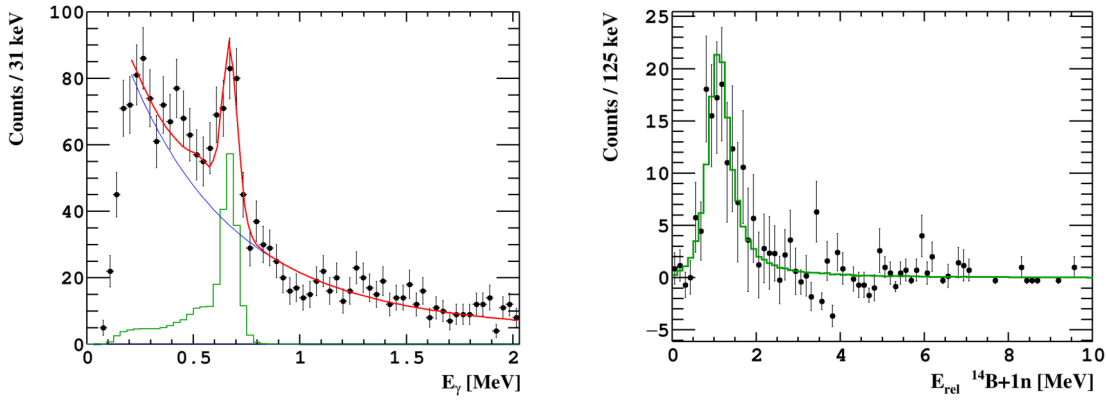


Figure 4.3.: *Left:* γ -ray spectrum of ^{14}B in coincidence with the $^{14}\text{B}+1\text{n}$ system. Known γ -ray photopeak from the 1^- state of ^{14}B at $E_\gamma = 0.653(7)$ MeV can be clearly observed. The γ -ray response function is shown in green, the fitted background in blue and the total fit is shown in red. *Right:* $^{14}\text{B}+1\text{n}$ relative energy distribution in coincidence with the 0.653 MeV γ -ray photopeak. The spectrum shown is obtained after background subtraction (see text for details). The distribution is fitted with a single resonance.

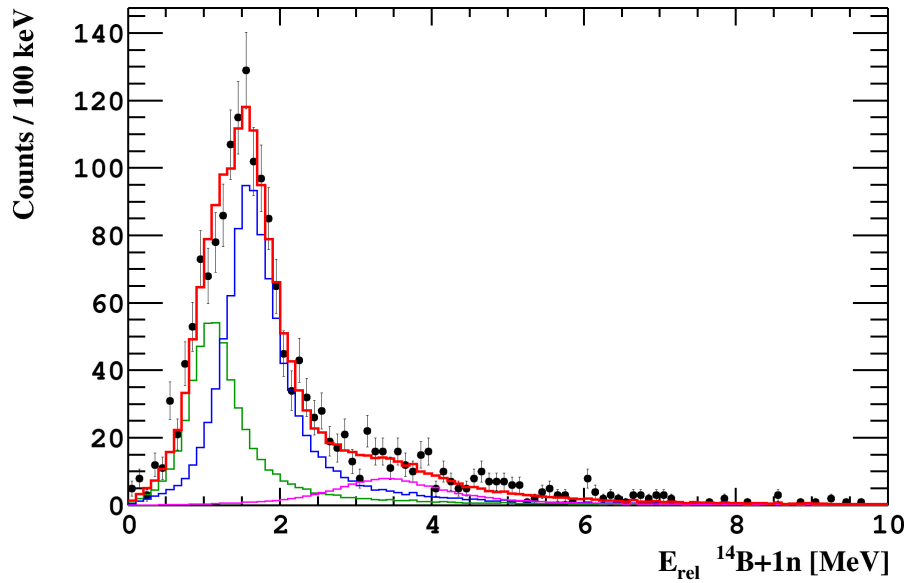


Figure 4.4.: Relative energy spectrum for $^{16}\text{C}(p,2p)^{15}\text{B} \rightarrow ^{14}\text{B}+1\text{n}$ channel, fitted with three identified resonances.

No.	E_x (MeV)	E_r (MeV)	Γ_r (MeV)
1	4.53(7)	1.10(7)	0.38(15)
2	4.41(5)	1.63(5)	0.55(15)
3	6.28(40)	3.50(40)	1.50(70)

Table 4.1.: Obtained resonances from the fit of $^{16}\text{C}(p,2p)^{15}\text{B} \rightarrow ^{14}\text{B}+1n$ relative energy spectrum.

is also identified in the $^{13}\text{B}+2n$ channel, which will be discussed in the following subsection on $^{13}\text{B}+2n$ analysis. The parameters of the resonance are optimized based on the fit information obtained from both systems. This implies the existence of some resonances that decay via both 1-neutron and 2-neutron emission. The final identified resonances from the $^{14}\text{B}+1n$ channel are listed in Table. 4.1 and the relative energy distribution with the full fit is shown in Fig. 4.4.

It is to be noted here, that the state corresponding to the γ -gated component and the component at $E_r = 1.63(5)$ MeV are very close in excitation energy and their centroids could match within 2σ of the uncertainty. Additionally, their widths are also compatible within uncertainty. This suggests that these two resonances could correspond to the same state. However, there are some structure considerations when comparing shell-model calculations which will be discussed later.

4.1.2. $^{15}\text{B}(p,pn)^{14}\text{B}$

In this subsection, the analysis of $^{15}\text{B}(p,pn)^{14}\text{B}$ reaction is presented prior to the discussion of the $^{13}\text{B}+2n$ channel. This serves a dual purpose in that it firstly helps identify the intermediate unbound ^{14}B states, through which the $^{13}\text{B}+2n$ channel could decay, thereby allowing to constraint the decay mechanism. Secondly, it provides insight into the ground-state configuration of ^{15}B , contributing to a more comprehensive understanding of the nucleus.

^{14}B is a weakly bound, odd-odd nucleus with one-neutron separation energy of $S_n = 0.97(2)$ MeV [8]. Its structure has been previously studied using various reaction mechanisms. Several states were reported in [49], where the ^{14}B was populated via the $^{14}\text{C}(^7\text{Li},^7\text{Be})^{14}\text{B}$ reaction. The spin-parity of the states were assigned by comparing the excitation energy spectrum to that of ^{12}B , which has a known level scheme. The bound system of ^{14}B consists of a 2^- ground state (g.s.) and a 1^- excited state at 0.654(9) MeV [62]. In addition to the bound states, several unbound states were also identified at 1.38(3) MeV, 1.86(7) MeV and 2.08(5) MeV, with assigned spin parities of 3^- , 2^- and 4^- respectively. Bound and unbound states for ^{14}B were also reported by [48], where ^{14}B was populated via the $^{13}\text{B}(d,p)^{14}\text{B}$ reaction. In addition to the two bound states, the authors report the identification of the unbound 3^- and 4^- states at 1.38(3) MeV and 2.08(5) MeV. They further estimated the relative spectroscopic factors for the valence neutron $0d_{5/2}$ and $1s_{1/2}$ orbitals by comparing the measured angular distributions corresponding to each state to those obtained from DWBA (Distorted Wave Born Approximation) calculations. The 2^- and 1^- bound states were found to have a dominant $L = 0$ component with a small $L = 2$ ($\sim 20\%$) component in the ground state. The identified 3^- and 4^- unbound states on the other hand were characterized by an almost pure $L = 2$ component. Finally, a positive parity 1^+ unbound state at 1.27(2) MeV has been identified via β -decay and charge exchange reactions on ^{14}Be as reported in [95] and [50], respectively.

In the current work, the quasi-free neutron removal reaction from ^{15}B has been studied. The objective is to confirm the existence of previously identified states and possibly identify additional unbound states which could be observed in the $^{13}\text{B}+2n$ system. Furthermore, the relative occupancy of the neutron orbitals of the knocked out valence neutrons in the ^{15}B g.s. can be estimated by comparing the recoil

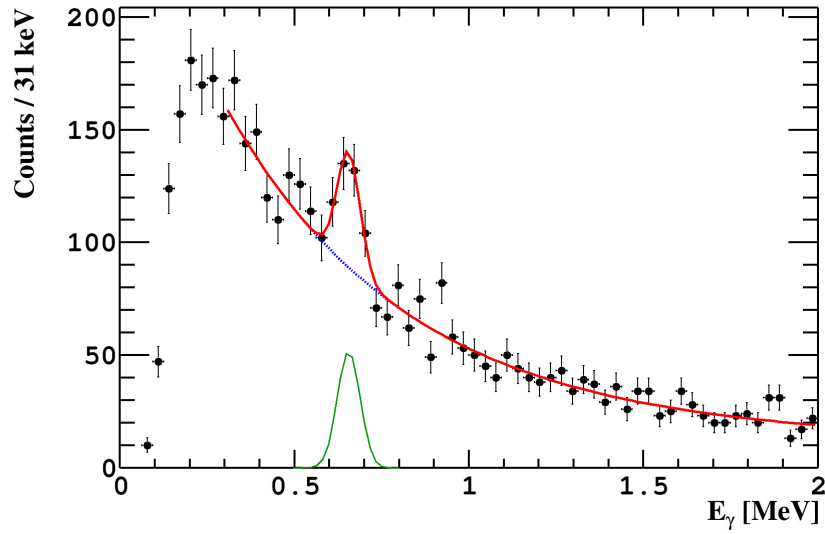


Figure 4.5.: Doppler corrected γ -ray spectrum in coincidence with ^{14}B fragment following a QFS $^{15}\text{B}(p,pn)^{14}\text{B}$ reaction. A peak at $E_\gamma = 0.655(7)$ MeV is identified corresponding to the known 1^- state. The fitted photopeak is shown in green, the double exponential background in blue and the total fit in red.

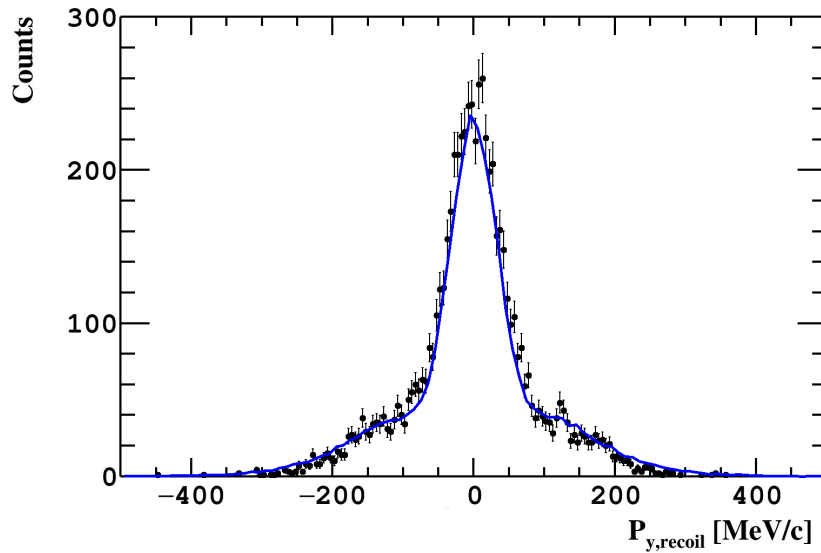


Figure 4.6.: Inclusive transverse recoil momentum distribution $P_{y,\text{recoil}}$ for the bound states populated via $^{15}\text{B}(p,pn)^{14}\text{B}$ reaction. A single $L=0$ component obtained from the DWIA calculations is observed to reproduce the full distribution.

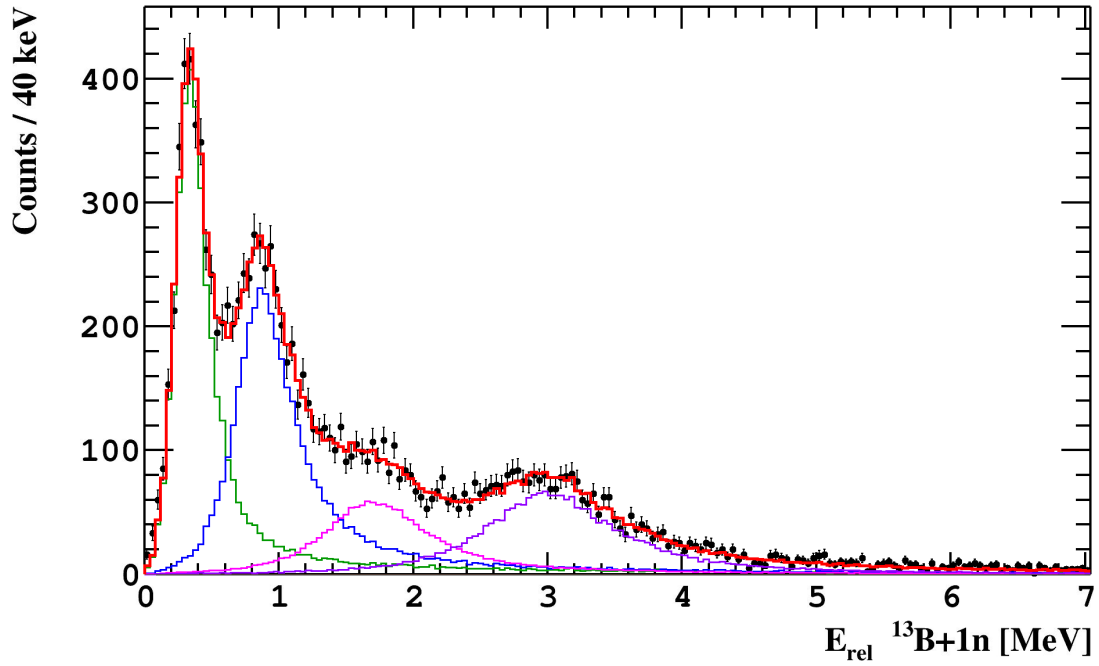


Figure 4.7.: Relative energy spectrum for $^{15}\text{B}(p,pn)^{14}\text{B} \rightarrow ^{13}\text{B}+1n$ channel fitted with four identified resonances. The resonance parameters are tabulated in Table 4.2.

No.	E_x (MeV)	E_r (MeV)	Γ_r (MeV)
1	1.29(3)	0.32(1)	0.124(25)
2	1.84(4)	0.87(2)	0.26(7)
3	2.66(9)	1.69(7)	0.54(20)
4	7.45(8)	2.98(6)	0.64(12)

Table 4.2.: Obtained resonances from the fit of the $^{13}\text{B} + 1n$ relative energy spectrum.

momentum distributions of the identified states to those obtained from DWIA calculations. ^{15}B has two valence neutrons above the $N = 8$ core. Since this region of the nuclear chart is characterized by the degeneracy of the $1s_{1/2}$ and $0d_{5/2}$ orbitals, the two valence neutrons could occupy either of the two orbitals. As the ^{15}B g.s. has a spin parity of $3/2^-$, a neutron knockout from $1s_{1/2}$ orbital will populate 1^- and 2^- states. On the other hand, knockout from the $0d_{5/2}$ orbital will populate 1^- , 2^- , 3^- and 4^- states. Beyond the valence neutrons, a deeper neutron knockout from $0p_{1/2}$ orbital will populate positive parity 1^+ and 2^+ states. Therefore, the relative neutron occupancies of the states appearing prior to those with a dominant $0p_{1/2}$ component (i.e., the 1^+ and 2^+ states) should correspond to the configuration of the valence neutrons.

We would like mention here that the analysis for this channel was carried out in collaboration with A. Barriere [82] and M. Nusir [96] and was completed in the present work to provide a comprehensive picture of the boron isotopes. In the current analysis, the bound states, including the 2^- ground state and the 1^- excited state, are observed to be populated. The Doppler corrected γ -ray spectrum corresponding to the bound outgoing ^{14}B isotope from the $^{15}\text{B}(p,pn)$ reaction is shown in Fig. 4.5. The previously identified, $E_\gamma = 0.654(9)$ MeV, 1^- [62] state is observed in the spectrum at $E_\gamma = 0.655(7)$ MeV. The recoil transverse momentum distribution corresponding to the inclusive bound states, i.e., for both the 2^- and 1^- states, in the $^{15}\text{B}(p,pn)^{14}\text{B}$ system is shown in Fig. 4.6. The distribution is shown in

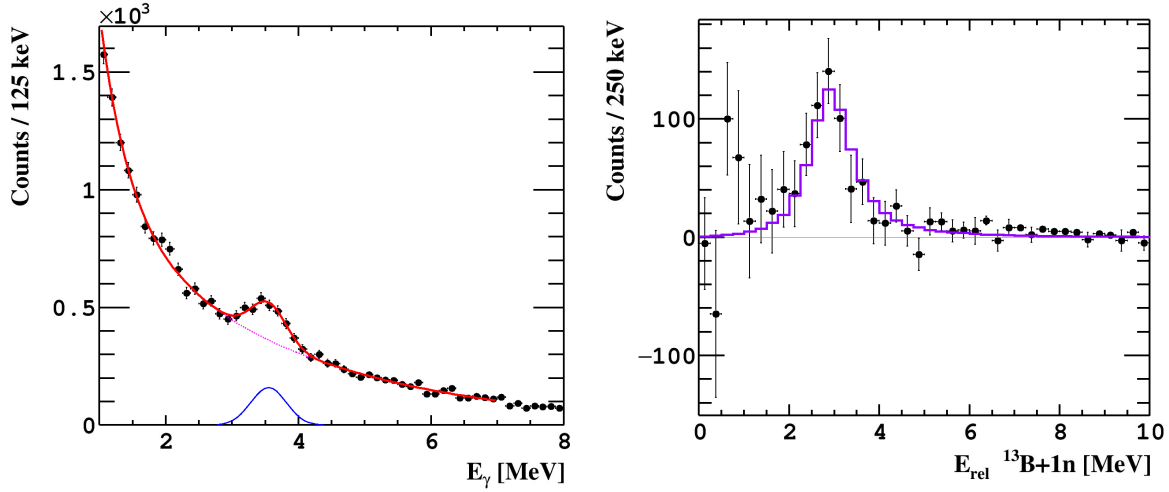


Figure 4.8.: *Left:* ^{13}B γ -ray spectrum in coincidence with the $^{13}\text{B}+1\text{n}$ system. *Right:* $^{13}\text{B}+1\text{n}$ relative energy distribution with a gate on ^{13}B photopeak (shown in left panel) with the background contribution subtracted, fit with resonance at $E_r = 2.98$ MeV.

comparison to the calculated momentum distribution for a knockout from $1s_{1/2}$ orbital obtained from DWIA calculations (see section 1.1) after folding with the experimental resolution. As can be observed, a single $L = 0$ component corresponding to a $1s_{1/2}$ orbital knockout is sufficient to reproduce the full distribution. Therefore, the bound states of ^{14}B are dominated by a significant ($>90\%$) $1s_{1/2}$ component. This is consistent with the dominant $1s_{1/2}$ configuration for the bound states of ^{14}B observed in [48].

Beyond the neutron separation energy of $S_n = 0.97$ MeV, one-neutron unbound states can be populated. In order to identify such states, the $^{13}\text{B}+1\text{n}$ relative energy spectrum is reconstructed as shown in Fig. 4.7. Four clear resonances are identified in the spectrum and found to well reproduce the full distribution. The identified resonances and their widths are reported in Table. 4.2. The narrow resonance at $E_r = 0.32(1)$ MeV most likely corresponds to the 1^+ state identified in [50, 95]. There is another previously reported narrow resonance very close to this energy at $E_r = 0.41(3)$ MeV, identified as 3^- in [48] and [49]. However, the combination of the excellent resolution of the present setup and the intrinsically narrow width of the resonance results in a small uncertainty in the centroid, which unambiguously rules out the 0.41 MeV state.

The next step is to estimate the excitation energy of the identified resonances. The procedure followed here is similar to the $^{14}\text{B}+1\text{n}$ case described in the previous section. The $^{13}\text{B}+1\text{n}$ resonances could decay to the ground state or the excited states of ^{13}B . Several bound excited states of ^{13}B have been reported in previous experiments using various reactions mechanisms [47, 51, 97, 98, 99, 100]. The γ -ray spectrum in coincidence with the $^{13}\text{B}+1\text{n}$ system is shown in Fig. 4.8 (Left). A peak is clearly observed at $E_\gamma \approx 3.5$ MeV. However, ^{13}B has a large density of states around 3.5 MeV, emitting γ -rays with similar energies, which cannot be resolved with the current resolution of CALIFA. Moreover, the width of the peak is found to be much broader than the expected width from the response function (see Fig. 3.8). This suggests the population of multiple excited states of ^{13}B . The $^{13}\text{B}+1\text{n}$ relative energy spectrum in coincidence with the γ -ray photopeak is shown in Fig. 4.8 (right). This spectrum is obtained after estimating and subtracting the "background" contribution (see previous section) present within the applied gate in the region of the γ -ray photopeak. The resonance identified at $E_r = 2.98$ MeV in the non-gated spectrum (Fig. 4.7) is distinctly observed in the γ -gated spectrum. The ratio of the integral of the counts in the resonance in the γ -gated and the total spectrum is consistent with the expected γ -ray photopeak efficiency at $E_\gamma \approx 3.5$ MeV. Finally, there is an indication of some structure below $E_{rel} < 1$ MeV

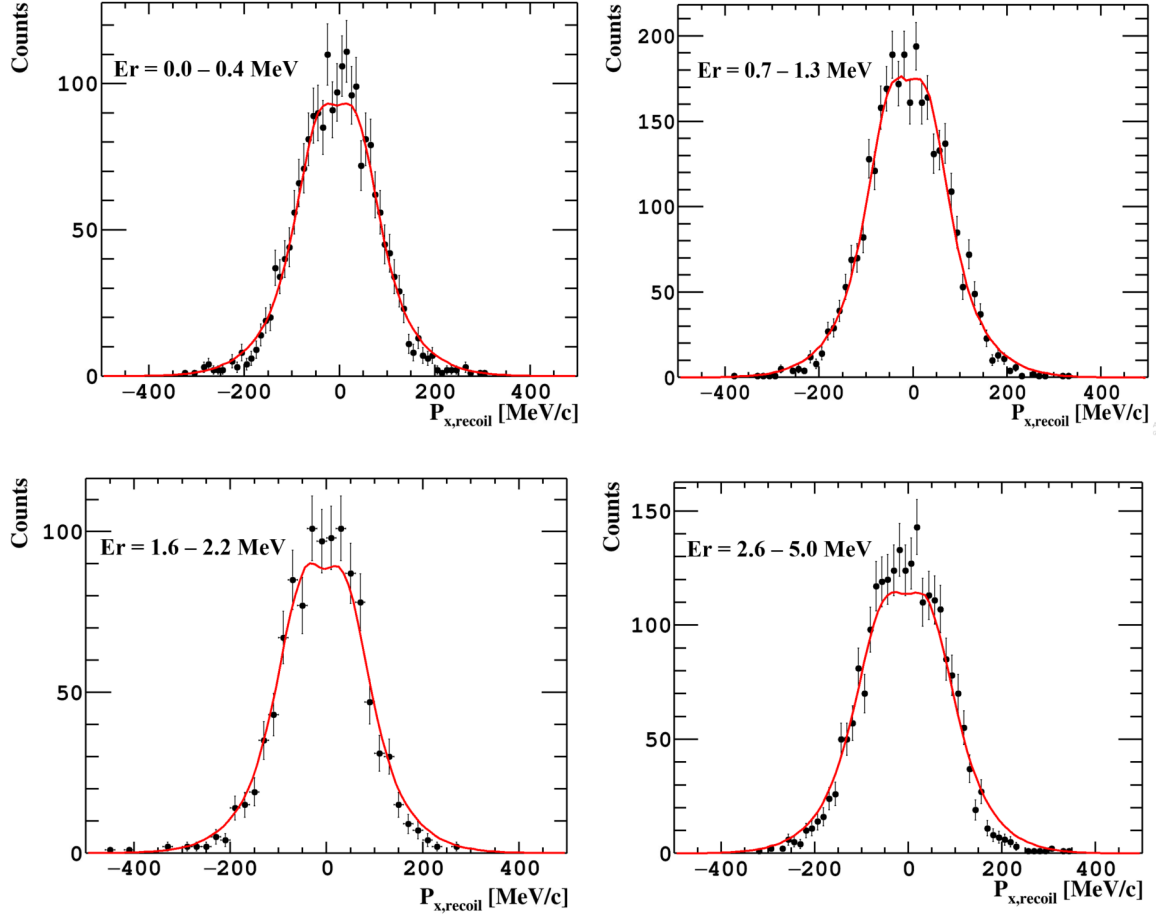


Figure 4.9.: Recoil transverse momentum distributions $P_{x,recoil}$ obtained from the energy gates in the $^{13}\text{B}+1n$ system corresponding to each identified resonance. The applied energy gates are highlighted in each plot. For all energy gates a single $L=1$ component obtained from the DWIA calculations can reproduce almost the full distribution.

in the γ -gated spectrum. However, the data points have very large uncertainties, with some bins having negative values, which likely indicates an artifact from the subtraction procedure.

As a final step, the results on the recoil momentum distributions corresponding to individual resonances are presented. This study is highlighted in Fig. 4.9. The transverse momentum distributions are fitted with the curves obtained from the DWIA calculations at the corresponding excitation energies. As can be observed, for all resonances, the $L = 1$ component corresponding to $0p_{1/2}$ knockout is sufficient to reproduce the full experimental distribution. Within acceptable χ^2 variations, the $1s_{1/2}$ contributions to the momentum distributions of the resonant states can vary between (0 – 5)%. The $L = 2$ distributions were found to be too broad, indicating little to no contribution from the $0d_{5/2}$ component in the resonant states. This is consistent with the fact that the previously identified 3^- and 4^- states have not been observed in the current analysis.

Since all resonant states have a dominant $L = 1$ component, this implies knockout from the lower lying p -orbital(s). The lower energy resonances populated in the $^{13}\text{B}+1n$ relative system should correspond to knockout from the $0p_{1/2}$ orbital. Consequently, these states should have spin parities of 1^+ or 2^+ . As discussed previously, the low lying resonance at $E_r = 0.32(1)$ MeV, based on its energy centroid most likely corresponds to the 1^+ state reported in [50, 95]. The dominant $L = 1$ component associated

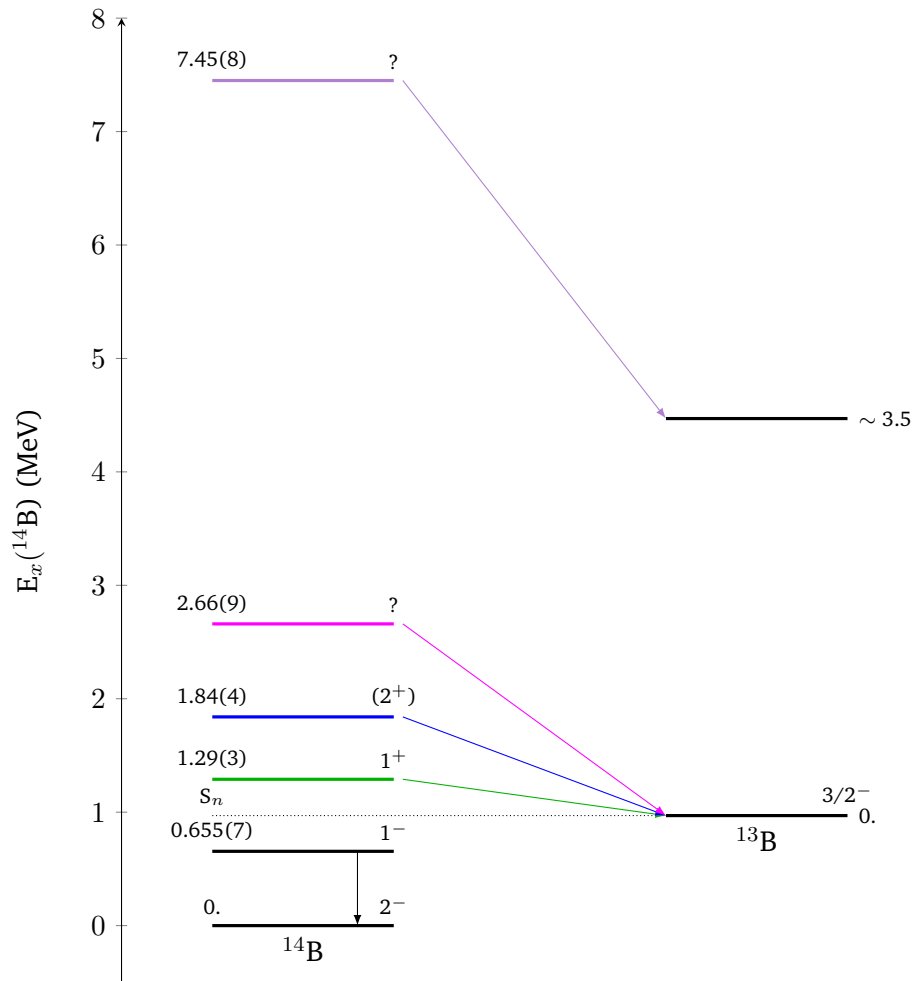


Figure 4.10.: Obtained level scheme for $^{15}\text{B}(p,pn)^{14}\text{B}$ reaction. The multiplet of excited states of ^{13}B is shown as a single state.

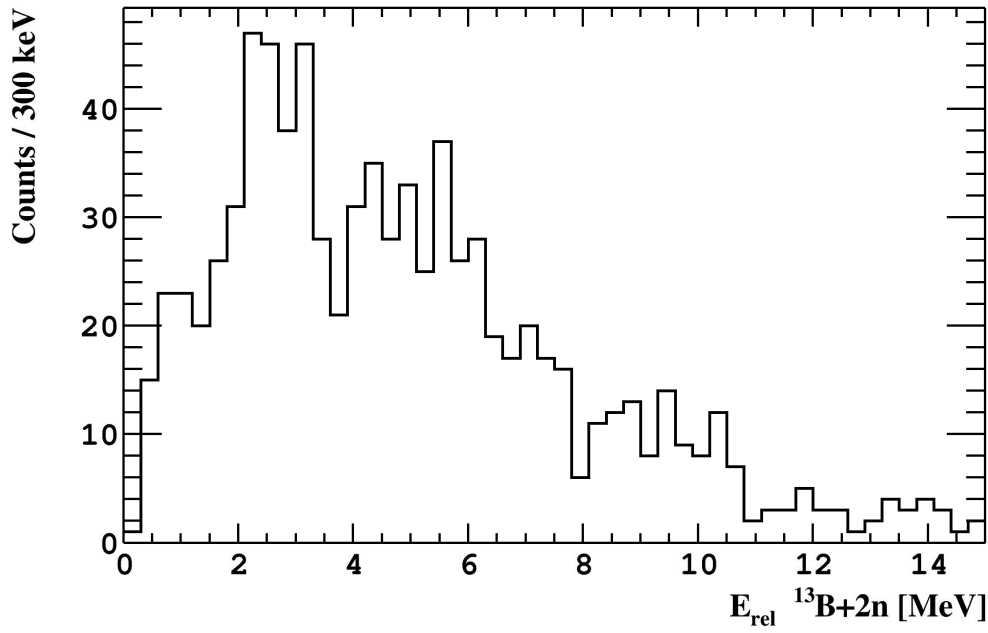


Figure 4.11.: Relative energy spectrum for $^{16}\text{C}(p,2p)^{15}\text{B} \rightarrow ^{13}\text{B}+2n$ reconstructed with the "Causality method".

with this state is therefore consistent with the previous 1^+ assignment. The state at $E_r = 0.87(2)$ MeV is similar in energy to the previously reported 2^- state in [49, 94]. However, its width ($\Gamma_r = 0.26$ MeV), is significantly narrower than the 2^- state in [49, 94], which is reported to have a width of $\Gamma_r \approx 1.0$ MeV. Furthermore, if the state was a 2^- , the recoil momentum distribution should have a strong $1s_{1/2}$ component, which is not seen in the current case as it is almost fully dominated by the $L = 1$ component. Therefore, this state could correspond to the 2^+ of the $0p_{1/2}$ doublet, which had not been observed so far. The higher lying states, especially the one at $E_x = 7.45$ MeV could be populated via a neutron knockout from the deeper $0p_{3/2}$ orbital.

As mentioned previously, the relative occupancy of the states identified prior to those with a dominant $L = 1$ component should correspond to the configuration of the valence neutrons. This is reflected in the recoil momentum distribution of the bound states which has already been shown to have a dominant $1s_{1/2}$ (see Fig 4.6) component. Therefore, this study implies that the two valence neutrons in the ^{15}B ground state almost only occupy the $1s_{1/2}$ orbital. These results, however, need to be further confirmed through calculation of the spectroscopic factors for the identified states, which is currently in progress and thus not reported in the present work.

The decay scheme for the states obtained from the $^{15}\text{B}(p,pn)^{14}\text{B}$ reaction is shown in Fig. 4.10.

4.1.3. $^{16}\text{C}(p,2p)^{15}\text{B} \rightarrow ^{13}\text{B}+2n$

The two neutron separation threshold of ^{15}B is at $S_{2n} = 2.78 + 0.97 = 3.75(2)$ MeV [8]. Beyond this excitation energy, 2-neutron unbound states can be populated, manifesting as resonances in the $^{13}\text{B}+2n$ system. The reconstructed $^{13}\text{B}+2n$ relative energy spectrum with the "Causality method" (see section 3.4.1) is shown in Fig. 4.11. A single resonance was found to be insufficient to reproduce the full distribution. In order to fit the distribution, a straightforward approach was adopted using the minimum number of resonances required to reproduce the overall structure. With this strategy, four

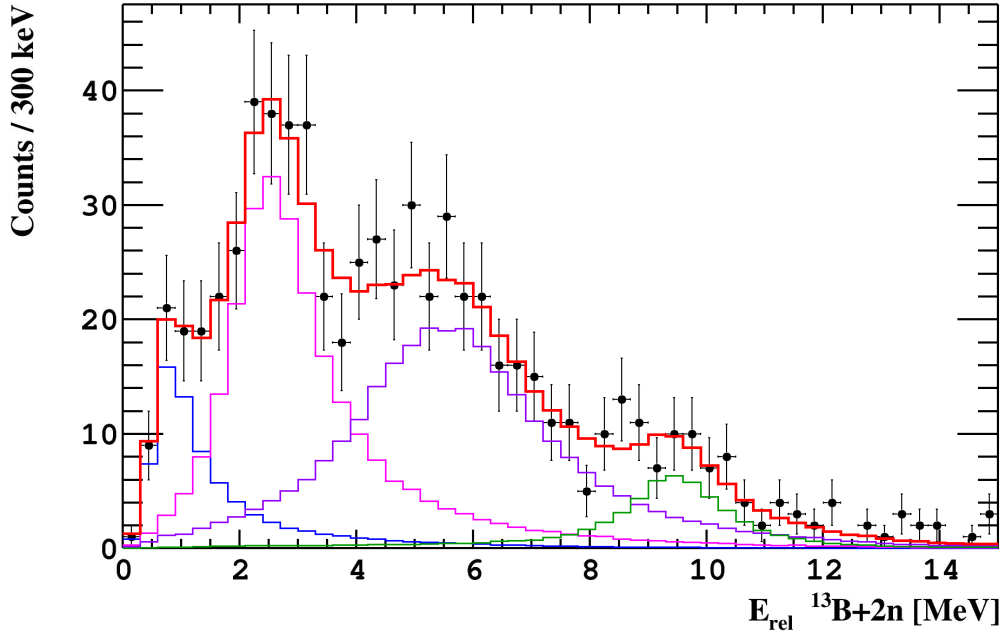


Figure 4.12.: Relative energy spectrum for $^{16}\text{C}(p,2p)^{15}\text{B} \rightarrow ^{13}\text{B}+2n$ channel fit with 4 resonances.

No.	E_x (MeV)	E_r (MeV)	Γ_r (MeV)
1	4.45(30)	0.70(25)	0.50(40)
2	6.18(30)	2.43(25)	1.50(70)
3	$9.38(50)_{\text{stat}}(65)_{\text{sys}}$	$5.63(50)_{\text{stat}}(60)_{\text{sys}}$	>2.50
4	13.25(75)	9.50(70)	0.80(40)

Table 4.3.: Obtained resonances from fit of $^{13}\text{B}+2n$ relative energy spectrum.

resonances were identified which have been outlined in Table. 4.3. The full fit of the $^{13}\text{B}+2n$ distribution with the corresponding resonances is shown in Fig. 4.12. Some of these 'resonances' may represent combinations of multiple unresolved states, however, within the limits of the current resolution, only four can be identified.

The next step is to estimate the excitation energy of the identified resonances. Following the approach from the previous cases, the γ -ray spectrum of ^{13}B in coincidence with the $^{13}\text{B}+2n$ system is analyzed to identify the resonances decaying to the excited states of ^{13}B . The ^{13}B γ -ray spectrum in coincidence with the reconstructed $^{13}\text{B}+2n$ relative energy spectrum is shown in Fig. 4.13. A peak is observed at $E_\gamma = 3.50(4)$ MeV; however as discussed in the previous section, ^{13}B has a high density of states in this region, which cannot be resolved with CALIFA's resolution at this energy. Thus the peak could correspond to the overlap of multiple states. Nevertheless, the fitted peak width is consistent with that of a single γ -ray photopeak, expected from the response function shown in Fig. 3.8. This suggests that only a single state may be populated. However, within the uncertainty of the current fit, both previously reported states at $E_\gamma = 3.48$ MeV ($1/2^+$) and $E_\gamma = 3.54$ MeV ($3/2^-$) are compatible. In any case, some of the resonances appear to decay to the excited states of ^{13}B . As in the $^{14}\text{B}+1n$ case, the ideal approach to identify the resonances decaying to the excited states would be to gate on the photopeaks and examine the corresponding $^{13}\text{B}+2n$ spectrum. However, this is not possible due to the limited statistics of the $^{13}\text{B}+2n$ channel. Therefore, an alternative approach is adopted to gate on the resonances in the $^{13}\text{B}+2n$ relative energy distribution and examine the ^{13}B γ -ray spectrum. The energy gates are chosen in the

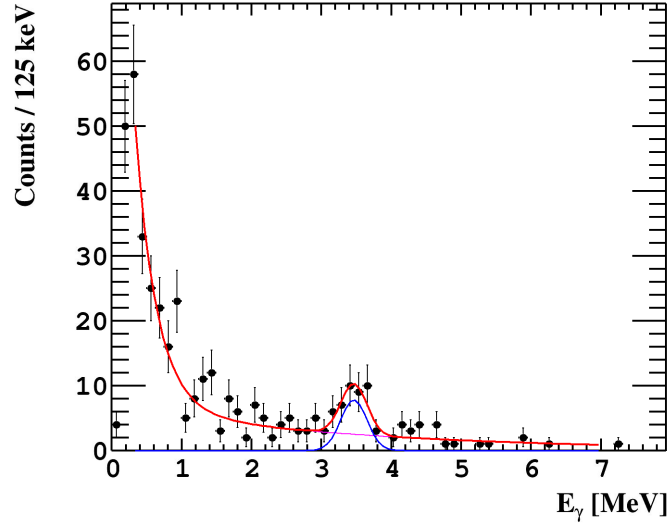


Figure 4.13.: γ -ray spectrum in coincidence with the $^{13}\text{B}+2n$ events. A clear peak can be observed around ~ 3.5 MeV.

relative energy spectrum such that there is minimum overlap between the resonances. However since the resonances are broad, some overlaps still exist within the cuts. If the photopeaks are observed with significant intensity in coincidence with the energy gate, then the corresponding resonance very likely decays through the excited state of ^{13}B . The gates on the $^{13}\text{B}+2n$ relative energy spectrum and the corresponding γ -ray spectra are shown in Fig. 4.14. A strong photopeak intensity is observed for the gate corresponding to $E_{rel} \in [4.2, 7.8]$ MeV, which indicates that a resonance at this E_{rel} range very likely decays to the excited states of ^{13}B . However, it should be noted that the region of the 5.4 MeV resonance might have some components decaying to the ground state of ^{13}B while others decay to the excited state. This is backed by the fact that the integral of the photopeak in the gated spectrum, after correction by the γ -ray efficiency, is lower than the integral of the resonance within the gate. It is also noted that the excitation energy corresponding to the gate is $E_x \approx 13$ MeV which is close to the excitation energy of the fourth identified resonance at $E_r = 9.50(70)$ MeV with an excitation energy of 13.25(75) MeV. Therefore, it is proposed that the same state at $E_x = 13.25$ MeV decays to both the excited state and ground state of ^{13}B . This indicates that within the resonance identified at $E_r = 5.63$ MeV there are two components. However, due to the current statistics and limited resolution, these two components cannot be resolved, and Therefore, the presence of separate states cannot be confirmed. To account for this, a systematic uncertainty is added to the energy and width of the resonance at $E_r = 5.63$ MeV, based on the inclusion of this second component. Finally, the resonances at $E_r = 0.7$ MeV, 2.43 MeV and 9.5 MeV appear to decay to the ground state of ^{13}B since no clear photopeak is seen in coincidence. The excitation energies corresponding to the identified resonances are also outlined in Table. 4.3.

The decay scheme of the identified resonances can also be estimated. This is done by analyzing the two-body Fragment + 1n distributions corresponding to the three-body decay. The ideology behind the analysis is as follows — if a resonant state in the $^{13}\text{B}+2n$ system decays directly with simultaneous neutron emission to a state in ^{13}B , the two $^{13}\text{B}+1n$ subsystems will carry the same energy over a phase-space defined by the available energy and the width of the resonance. In this case, the $^{13}\text{B}+1n$ distribution corresponding to the $^{13}\text{B}+2n$ resonant system should be a smooth distribution, with the kinematic boundary defined by the total $^{13}\text{B}+2n$ relative energy. However, if the system decays sequentially, i.e., through intermediate states of ^{14}B , the width and energy of the $^{13}\text{B}+1n$ subsystem decaying through the intermediate states is constrained to the those of the intermediate state. This also constraints the width

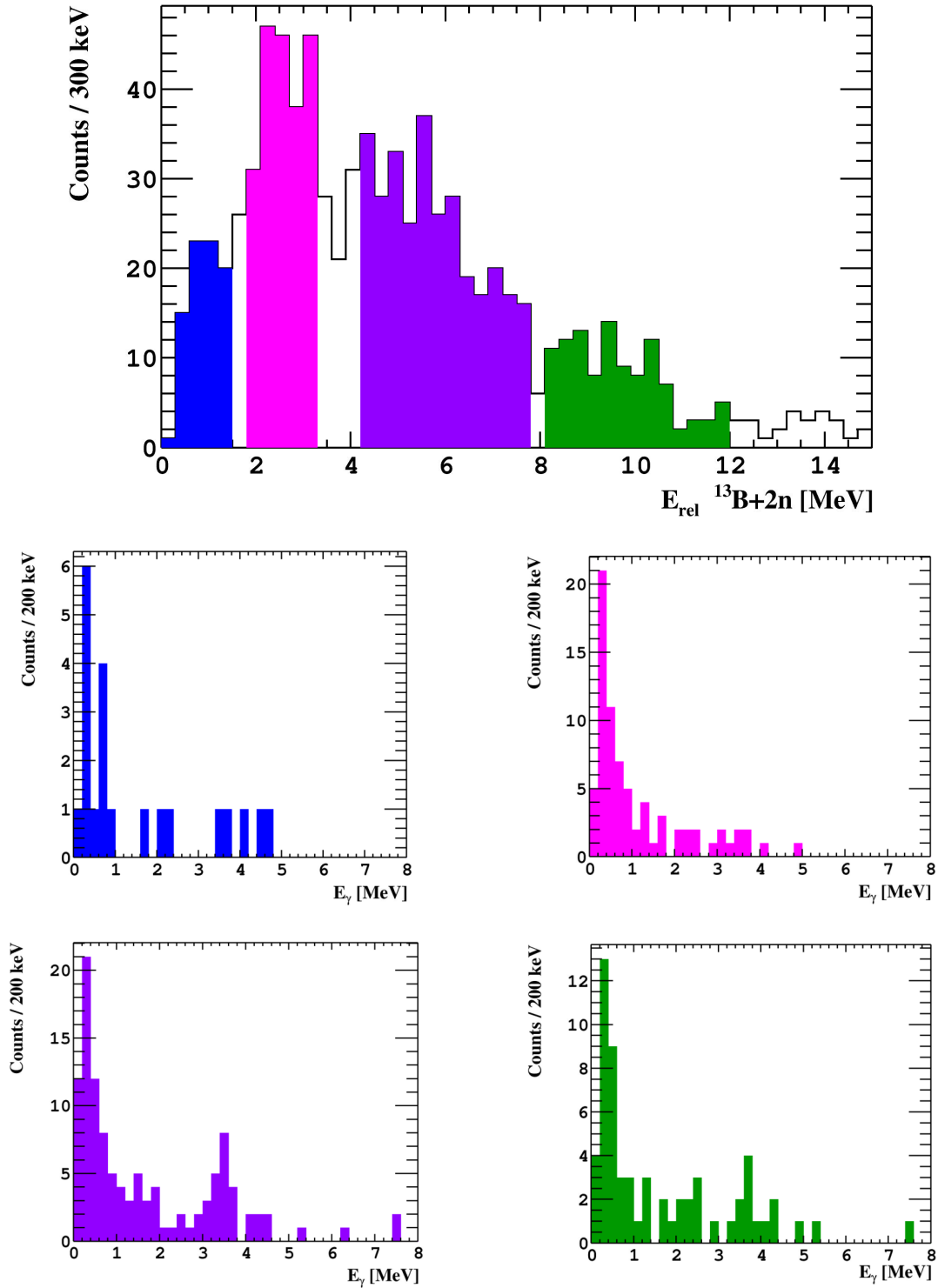


Figure 4.14.: *Top Panel:* $^{13}\text{B}+2\text{n}$ relative energy distribution showing the different cuts corresponding to the identified resonances. *Bottom Panel:* ^{13}B γ -ray spectra corresponding to the different gates in the relative energy distribution. The cuts have been color matched with the corresponding spectrum.

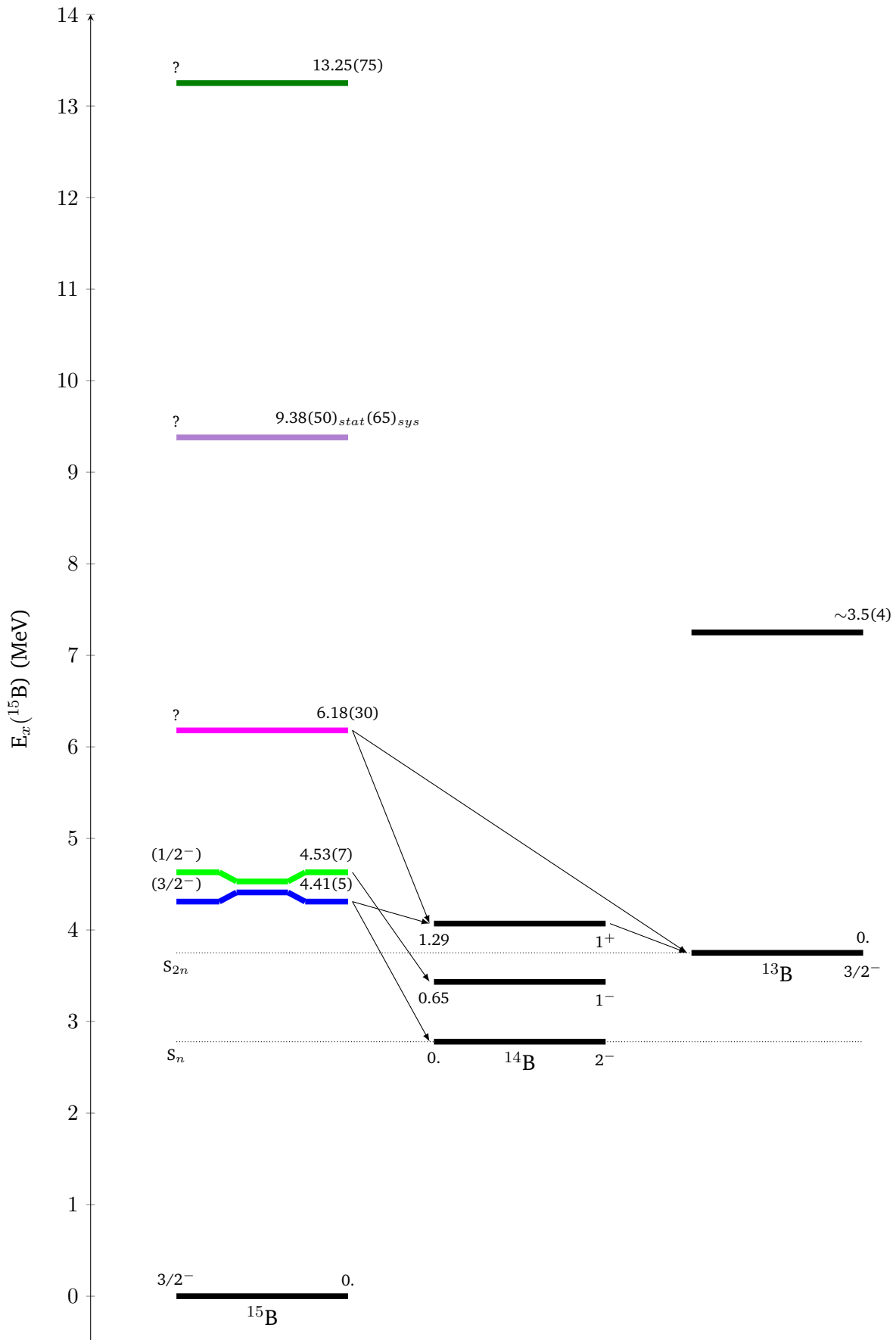


Figure 4.15.: Level diagram for state obtained from $^{16}\text{C}(p,2p)^{15}\text{B}$ QFS reaction.

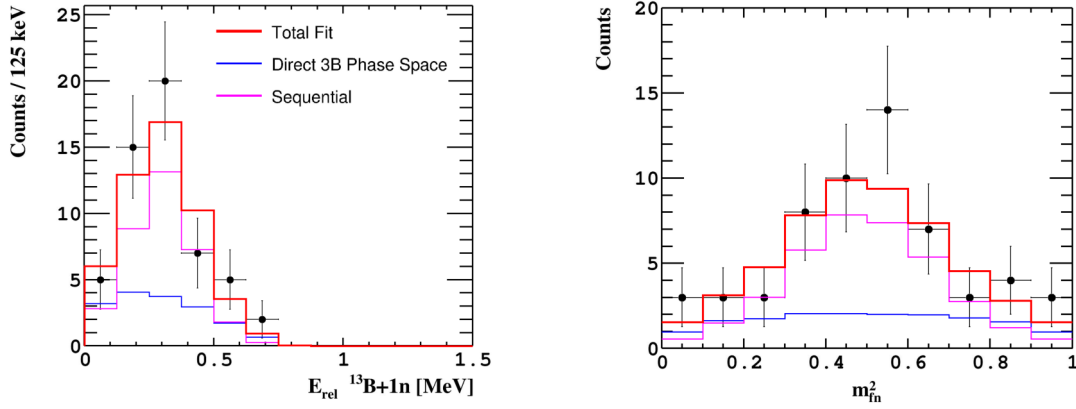


Figure 4.16.: *Left:* Two-body $^{13}\text{B}+1\text{n}$ relative energy distribution corresponding to the energy gate $E_{\text{rel}} \in [0, 0.8]$ MeV for the resonance at $E_r = 0.7(25)$ MeV in the three body $^{13}\text{B}+2\text{n}$ spectrum. The distribution is fitted with the identified sequential (in pink) and direct decay (in blue) components. *Right:* m_{fn}^2 distribution corresponding to same cut fitted with components following the same decay mechanism.

and energy of the other $^{13}\text{B}+1\text{n}$ subsystem which can only take the energy of the $^{13}\text{B}+2\text{n}$ resonance minus the energy of the intermediate ^{14}B state, and the width is similarly constrained by the available phase-space. Therefore, in case of such sequential decay, distinct structures should be observed in the $^{13}\text{B}+1\text{n}$ spectrum. To proceed with the analysis, a thorough understanding of the intermediate resonant states of ^{14}B is required. The information obtained from the previous section on the $^{15}\text{B}(p,pn)^{14}\text{B}$ analysis and from previously published results [48, 49, 50] is used towards this end.

The two-body distributions are obtained by gating on the $^{13}\text{B}+2\text{n}$ relative energy in the ranges corresponding to the identified resonances. The analysis of the two-body $^{13}\text{B}+1\text{n}$ system is then carried out by fitting the $^{13}\text{B}+1\text{n}$ relative energy spectrum and the corresponding reduced invariant mass, i.e., the m_{fn}^2 ($\sim E_{\text{rel}}(\text{Frag}+1\text{n})/E_{\text{rel}}(\text{Frag}+2\text{n})$) distribution. Due to limited statistics, a reasonable decay scheme of only the first two resonances could be extracted in the current work. To fit the distributions, the $^{13}\text{B}+2\text{n}$ resonances are simulated within the same energy ranges as the experimental gates, following either direct or sequential decay mechanisms. The simulations take the energy and width of the $^{13}\text{B}+2\text{n}$ resonances as input (Table. 4.3), and if sequential decay is simulated, it additionally also takes the energy and width of the intermediate ^{14}B resonances. A combination of several $^{13}\text{B}+1\text{n}$ (and m_{fn}^2) spectra obtained from these simulations, each corresponding to different decay mechanism, are then used to fit the experimental distributions.

The two-body experimental distributions and their fits obtained from the $^{13}\text{B}+2\text{n}$ relative energy gate of $E_{\text{rel}} \in [0., 0.8]$ MeV, corresponding to the first resonance, is shown in Fig. 4.16. The sequential decay through the 1^+ state of ^{14}B at $E_r = 0.32$ MeV (see Fig. 4.10) is observed to be the dominant contribution in the decay pattern. Some direct decay component is also observed to be present in the distribution, but its integral is consistent with that of the tails of the higher lying resonances within the applied gate. Similarly, the fitted two-body distributions corresponding to the second resonance within the $^{13}\text{B}+2\text{n}$ relative energy window of $E_{\text{rel}} \in [2., 3.2]$ MeV is shown in Fig 4.17. In this case, a significant direct decay component is observed. In addition, there is a small fraction of the system that appears to decays sequentially, again through the 1^+ state of ^{14}B . Within the energy window applied, there are overlaps with other resonances, but the major contribution $\sim 80\%$ is estimated to be from the resonance at $E_r = 2.43$ MeV.

It is noted that, since the S_{2n} of ^{15}B is only $S_n + 0.97$ MeV, the resonances identified in the $^{14}\text{B}+1\text{n}$

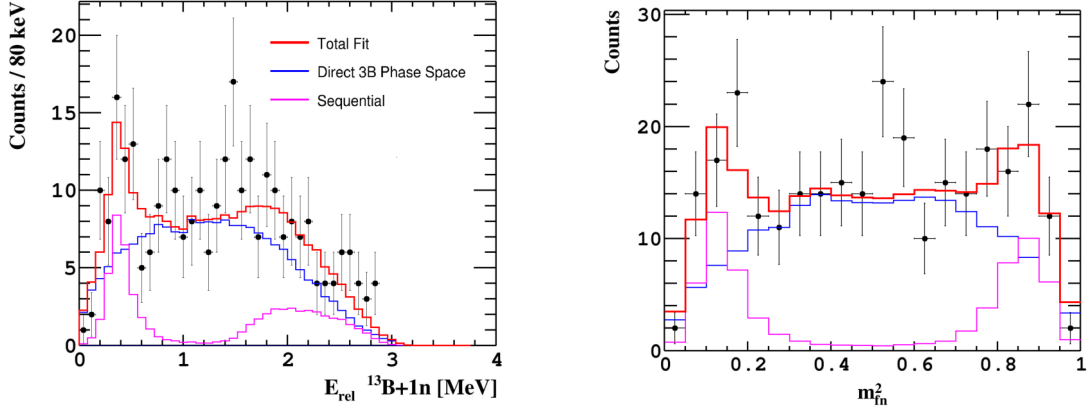


Figure 4.17.: *Left:* Two-body $^{13}\text{B}+1n$ relative energy distribution corresponding to the energy gate $E_{rel} \in [2, 3.2]$ MeV for the resonance at $E_r = 2.43(25)$ MeV in the three body $^{13}\text{B}+2n$ spectrum. The distribution is fitted with the identified sequential (in pink) and direct decay (in blue) components. *Right:* m_{fn}^2 distribution corresponding to same cut fitted with components following the same decay mechanism.

spectrum lie above this threshold. This implies that these resonances also have a probability to decay via two-neutron emission. Upon examination of the excitation energies of the resonances obtained from the one-neutron and two-neutron decay channel, it is observed that some of the identified states overlap. The resonances identified at $E_r(^{14}\text{B}+1n) = 1.63(5)$ MeV and $E_r(^{13}\text{B}+2n) = 0.7(25)$ MeV seem to overlap in their excitation energies. A similar overlap is also observed for the resonances at $E_r(^{14}\text{B}+1n) = 3.50(40)$ MeV and $E_r(^{13}\text{B}+2n) = 2.43(10)$ MeV. These resonances decaying via one-neutron and two-neutron emission at nearly the same excitation energy are very likely the same states. Using this information, the final level scheme of ^{15}B obtained from $^{16}\text{C}(p,2p)$ QFS reaction is shown in Fig. 4.15.

Figure. 4.18 shows the comparison of the experimentally identified states to shell-model (SM) calculation based on the YSOX interaction [33]. Additionally, the states are also compared to those identified in [51]. It can be observed that some of the states are compatible to those observed by the authors of [51]. The states at $E_x \sim 4.5$ MeV from the current work could be compatible with the state at $E_x = 4.9$ MeV from [51]. However, given the relatively small uncertainties in the centroids in both studies and the large ~ 0.5 MeV separation, they may represent different states. On the other hand, the states at $E_x = 6.18$ MeV and 9.38 MeV have clear agreement from both studies. Further discussions, including comparing to the SM calculations is presented in the next section.

4.1.4. Cross Section

As a final step, the cross section of the states populated from the $^{16}\text{C}(p,2p)^{15}\text{B}$ reaction has been estimated. The integrated experimental cross section σ_{exp} is generally defined as,

$$\sigma_{exp} = \frac{1}{\tau_t \varepsilon} \frac{N_r}{N_i}, \quad (4.3)$$

where N_r and N_i corresponds to the number of measured reacted outgoing fragments and the number of unreacted nuclei respectively. τ_t corresponds to the number of scattering centers per unit area of the target given by,

4. Spectroscopy of Boron isotopes

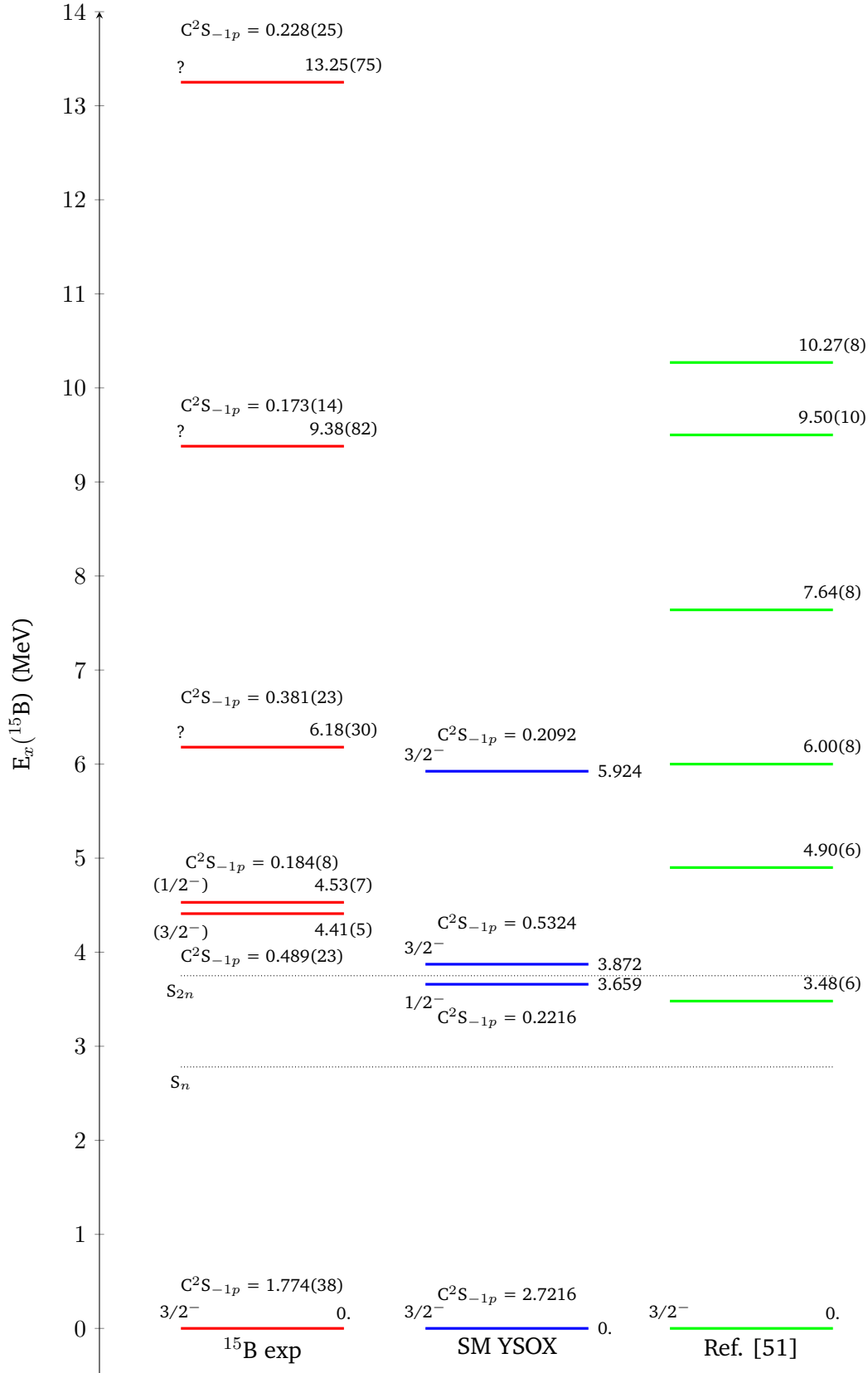


Figure 4.18.: Comparison of experimentally obtained states for $^{16}\text{C}(p,2p)^{15}\text{B}$ (in red) to the states predicted by YSOX SM [33] with significant spectroscopic factors for proton removal reaction from ^{16}C (in blue). The corresponding proton removal spectroscopic factors are also shown. The states identified via multi-nucleon transfer reaction in [51] are also included for comparison (in green).

E_x (MeV)	J^π	σ_{exp} (mb)	$\sigma_{s.p.,th}$ (mb)	C^2S_{exp}	$C^2S_{exp,norm}$
0.00	$3/2^-$	7.63(16)	7.168	1.065(23)	1.774(38)
4.41(5)	$(3/2^-)$	2.02(10)	6.889	0.293(14)	0.489(23)
4.53(7)	$(1/2^-)$	0.76(3)	6.896	0.110(5)	0.184(8)
6.18(30)	?	1.55(10)	6.801	0.229(14)	0.381(23)
9.38(79)	?	0.69(6)	6.659	0.103(8)	0.173(14)
13.25(75)	?	0.90(10)	6.546	0.137(15)	0.228(25)

Table 4.4.: Experimental cross section σ_{exp} and spectroscopic factors (C^2S_{exp}) corresponding to the identified states from the $^{16}\text{C}(p,2p)^{15}\text{B}$ reaction. The spectroscopic factors are calculated by taking the ratio of the experimental cross section to the single particle theoretical cross section obtained from the DWIA calculation, i.e, $C^2S_{exp} = \sigma_{exp} / \sigma_{s.p.,th}$. The $C^2S_{exp,norm}$ is obtained by scaling the C^2S_{exp} by the reduction factor of 0.6.

E_x (MeV)	J^π	C^2S_{sm}
0.000	$3/2^-$	2.7216
3.659	$1/2^-$	0.2216
3.872	$3/2^-$	0.5324
5.924	$3/2^-$	0.2092

Table 4.5.: Excitation energies and spectroscopic factors (C^2S_{sm}) of states predicted by YSOX SM calculations for proton knockout from ^{16}C . Only the states predicted with significant spectroscopic factors are shown.

$$\tau_t = \rho_t d_t \frac{N_A}{M_t}, \quad (4.4)$$

where ρ_t is the volume density of the target, d_t the thickness of the target, M_t the molar mass of the target material and N_A the Avogadro constant. As discussed in section 2.2, in the current experiment a 5 cm LH_2 target was used, with a volume density of $\rho_t = 0.0711 \text{ g/cm}^3$.

The ε term in Eq. 4.3 accounts for the detection efficiencies of all the outgoing particles in the corresponding detectors. In general, since the presented data is obtained with the selection on the QFS protons (see section 3.2.1), the QFS efficiency $\varepsilon_{QFS} = 0.5$ is always included. In addition, if an excited state is populated, which corresponds to the detection of γ -rays and/or neutrons, then the corresponding efficiency is also included. Details on the γ -ray and neutron efficiencies have been discussed in Chapter. 2.

Here, a detail concerning the counting of the number of unreacted nuclei N_i is pointed out. A more general form of Eq. 4.3 defines the cross section as the ratio of number the reacted nuclei to the number incoming nuclei. However, since the cross section for QFS reaction is generally very small ($< 50 \text{ mb}$), it is reasonable to assume that the number of incoming is almost equal to the number of unreacted, which is then counted in the fragment arm. This has the added advantage that the detection and reconstruction (with MDF) efficiency of the unreacted beam and the reacted outgoing fragments in the fragment arm are very similar, and therefore cancel out in the ratio.

When measuring the exclusive cross sections of the individual states, the counts used for N_r in Eq. 4.3 corresponds to the number of counts attributed to the respective state. For the ground state (g.s.), however, the exclusive cross section cannot be directly calculated if the system consists of multiple bound states. In this case, first the inclusive cross section σ_{inc} for the bound system is calculated. This is followed

4. Spectroscopy of Boron isotopes

Isotope	E_x (MeV)	J^π	Proton Config.					Neutron Config.				
			$0p_{1/2}$	$0p_{3/2}$	$0d_{3/2}$	$0d_{5/2}$	$1s_{1/2}$	$0p_{1/2}$	$0p_{3/2}$	$0d_{3/2}$	$0d_{5/2}$	$1s_{1/2}$
^{16}C	0.000	0^+	0.30	3.59	0.05	0.05	0.01	1.81	3.89	0.21	1.33	0.76
^{15}B	0.000	$3/2^-$	0.17	2.75	0.04	0.03	0.01	1.76	3.88	0.20	1.29	0.88
	3.659	$1/2^-$	0.49	2.44	0.03	0.03	0.01	1.66	3.81	0.20	2.03	0.30
	3.872	$3/2^-$	0.19	2.74	0.04	0.03	0.01	1.83	3.90	0.20	1.15	0.92
	5.924	$3/2^-$	0.69	2.22	0.04	0.04	0.01	1.52	3.72	0.27	2.05	0.45

Table 4.6.: Orbital occupation numbers for the ^{16}C g.s. and predicted ^{15}B states for proton knockout from ^{16}C , obtained from YSOX shell-model calculations. Only the states predicted with significant spectroscopic strength are shown.

by the calculation of the exclusive cross section $\sigma_{exc,i}$ of each bound i th excited state. The ground state cross section is then give by,

$$\sigma_{g.s.} = \sigma_{inc} - \sum_i \sigma_{exc,i}. \quad (4.5)$$

In the present case, no bound excited states are observed. Therefore, the ground state cross section is equal to the inclusive cross section of the bound ^{15}B system, i.e., $\sigma_{g.s.} = \sigma_{inc}$. The extracted cross sections for all measured states, along with their corresponding spectroscopic factors (C^2S_{exp}) are summarized in Table. 4.4. The spectroscopic factors are obtained by taking the ratio of the experimental cross section (σ_{exp}) to the single-particle cross sections from DWIA calculations ($\sigma_{s.p.,th}$) [31], i.e.,

$$C^2S_{exp} = \frac{\sigma_{exp}}{\sigma_{s.p.,th}}. \quad (4.6)$$

The calculated experimental spectroscopic factors are scaled by the reduction factor $R_s = 0.6$ taken from [101] to obtain $C^2S_{exp,norm}$. This reduction factor accounts for the systematic differences between experimental data and theoretical predictions, arising from the presence of nuclear correlations which are not included in the theoretical models [102, 103]. The errors shown represent only the statistical uncertainties, as a detailed estimation of the systematic uncertainties related to the applied efficiencies and target thickness was still ongoing at the time of writing this thesis.

Predicted states along with their spectroscopic factor from shell-model (SM) calculations are shown for comparison in Table. 4.5. The shell-model calculations were performed using the YSOX interaction [33] in the psd valence space over an inert helium core. The calculations were carried out and provided by C. Yuan (Priv. Comm.) for comparison with the present work. Only the states with have significant spectroscopic strenght are shown. Comparison of the experimental and SM ground state spectroscopic factors shows a clear discrepancy. It is observed that, even after the correction with R_s , the experimental spectroscopic factor accounts for only 65% of the g.s. spectroscopic strength predicted by the SM calculation. This discrepancy could arise from the differences in the orbital occupation numbers between the SM calculations and the actual nuclear structure. The calculated orbital occupation numbers for the ^{16}C g.s. and the populated ^{15}B states following proton knockout from ^{16}C are shown in Table. 4.6. The configurations of the ^{16}C g.s. and the ^{15}B g.s. appear to be very similar in the SM calculations with the difference of 1 proton in the proton $0p_{3/2}$ orbital. The relative spectroscopic strengths of the neutron $0d_{5/2}$ and $1s_{1/2}$ orbitals in ^{16}C predicted by the SM calculations appear consistent with the experimental values reported in [104], with the $0d_{5/2}$ and $1s_{1/2}$ strengths measured to be 1.35(32) and 0.65(16) respectively. On the other hand, in the current work, reported in section 4.1.2, it has been established

that the valence neutron configuration in the ^{15}B g.s. is almost purely $1s_{1/2}$. In the SM calculations, however, the $0d_{5/2}$ orbital carries more than half of the valence neutron strength, suggesting that the calculations may overestimate the overlap between the two ground states, which could explain the larger spectroscopic factor.

Finally, the identified low lying excited states at $E_x = 4.41$ and 4.53 MeV are compared to those predicted from the SM calculations. As discussed above, the excitation energy centroids and widths of the states are consistent within $\sim 2\sigma$ of their uncertainties. This suggests that these two resonances may correspond to the same state. However from the SM calculations, a doublet of $J^\pi = 1/2^-$ and $3/2^-$ states is expected at $E_x = 3.659$ MeV and 3.872 MeV respectively. Though systematically shifted in energy, the two identified resonances could correspond this doublet. For this purpose, the $^{14}\text{B}+1\text{n}$ decay channel is revisited (see section 4.1.1). A part of the resonant system decays directly to the 2^- ground state of ^{14}B , while the rest decays to the 1^- excited state. A $3/2^-$ state can decay to both the 2^- ground state and the 1^- excited state via an $L = 0$ neutron decay. $L = 2$ and higher orders are also possible but heavily inhibited by the centrifugal barrier. On the other hand, a $1/2^-$ state can decay only to the 1^- excited state via an $L = 0$ neutron emission, while it would need a minimum $L = 2$ neutron emission to decay to the 2^- ground state, which would be inhibited. Therefore, the state decaying to the excited state of ^{14}B can be tentatively assigned a $J^\pi = 1/2^-$, while the state decaying to the ground state of ^{14}B can be assigned a $J^\pi = 3/2^-$. Decay to the ground state is expected to dominate for the $3/2^-$ state due to its higher Q -value. A fraction of the $3/2^-$ strength may also decay to the 1^- excited state, but estimating this branching is beyond the scope of the present analysis.

4.2. $^{18}\text{C}(\text{p},2\text{p})^{17}\text{B}$

^{17}B is a weakly bound Borromean nucleus, since ^{16}B is unbound by $\sim 0.046(3)$ MeV [56], and the 2-neutron separation energy of ^{17}B is $S_{2n} = 1.38(21)$ MeV [8]. Experimental studies propose a two-neutron halo structure for ^{17}B based on measurements of a large rms radius extracted from the total reaction and interaction cross section [57, 58], and a narrow 2-neutron removal momentum distribution [59]. However, recent results using the $^{17}\text{B}(\text{p},\text{pn})^{16}\text{B}$ reaction indicate a very small s-wave component of around $\sim 9(2)\%$ [56] for the four valence neutrons, with the majority of the strength concentrated in the $0d_{5/2}$ orbital. This implies a more [core+4n]-like structure. The detailed structure of ^{17}B has been previously investigated via inelastic scattering reactions of ^{17}B on carbon and LH_2 targets as reported in [53] and [62], respectively. A bound excited state at 1.08 MeV has been reported in both studies, where they assign the spin-parity of the state as $5/2^-$, in agreement with theoretical shell model (SM) and antisymmetrized molecular dynamics (AMD) calculations. The authors of [53] also present a study of the angular distribution of the 1.08 MeV state, which suggests a $\Delta L^\pi = 2^+$ transition. In the current work, ^{17}B is populated via $^{18}\text{C}(\text{p},2\text{p})^{17}\text{B}$ QFS reaction. Since the valence protons in ^{18}C occupy $0p_{3/2}$ or $0p_{1/2}$ orbital, similar to the ^{15}B case (section 4.1), only $3/2^-$ and $1/2^-$ states should be observed. If the state observed in the previous experiments is a $5/2^-$, it should not be populated in the current work—at least not directly. In the following sections, results on the populated bound states of ^{17}B are presented first, followed by the two-neutron spectroscopy of the unbound $^{15}\text{B}+2\text{n}$ system.

4.2.1. Bound states

The Doppler corrected γ -ray spectra of ^{17}B , populated via the $^{18}\text{C}(-1\text{p})$ reaction, are shown in Fig. 4.19. The top panel shows the spectrum without the QFS condition, while the bottom panel corresponds to

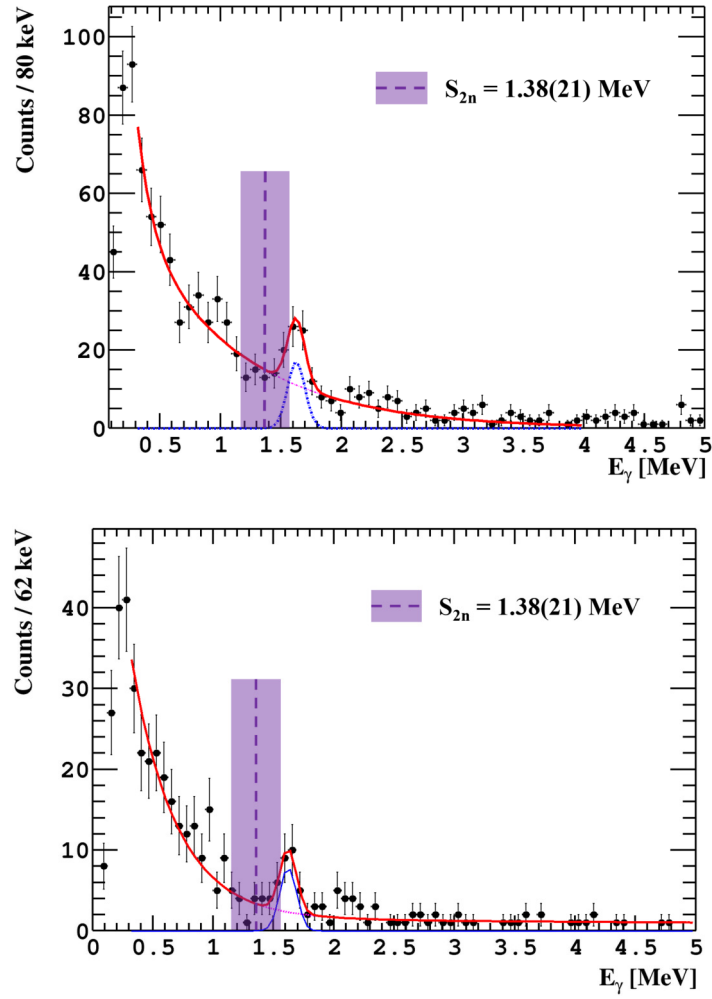


Figure 4.19.: *Top:* γ -ray spectrum of $^{18}\text{C}(-1p)^{17}\text{B}$ without QFS conditions with a fitted Gaussian peak over a double exponential background. *Bottom:* Same plot but with a strict QFS condition and fitted with the same conditions. Both spectra are obtained for events with gamma multiplicity $N_\gamma = 1$.

events in coincidence with the two QFS protons. Both spectra are plotted for γ -multiplicity $N_\gamma = 1$ in CALIFA, since the peak-to-background ratio deteriorates significantly at higher multiplicities. The spectra are fitted according to the response defined in section 3.2.2. The background is fitted with a double exponential decay function, while the photopeak is fitted with a standard Gaussian function, wherein the widths are constrained according to the expected response (see Fig. 3.8). A photopeak with low intensity is observed at 1.64(3) MeV in both spectra. The plot without the QFS condition is included only to show the photopeak with more statistics, and is reasonable to compare as no additional peaks are observed. The peak in the QFS gated spectrum has a significance of 5.6σ as compared to the fitted background. This peak has not been observed in the studies reported by [53] and [62], where the excited states of ^{17}B were populated via inelastic excitation. However, a $E_\gamma = 1.62$ MeV peak has been previously observed in the work of [7], where ^{17}B was populated from ^{19}C via a multi-nucleon knockout reaction. A very low cross section may explain why this state was not observed in [53] and [62]. Additionally, the 1.08 MeV state, reported in the inelastic scattering experiments is not observed in the current γ -ray spectrum. As noted, this state was assigned a J^π of $5/2^-$ by the authors of [53] and [62] based on comparisons with SM and AMD calculations. In the present case, the reaction is more selective, where only $3/2^-$ and $1/2^-$ states should be directly populated, making the assignment of $5/2^-$ to the 1.08 MeV state is very likely.

A discussion on the possible J^π of the identified state is presented here. If the state at $E_\gamma = 1.64$ MeV has a J^π of $3/2^-$, it could decay sequentially via two M1 γ -ray transitions through the $5/2^-$ state, or it could decay directly to the ground state. However, in the latter case, it is noted that the transition probabilities between states with the same J^π is generally low. Therefore, if the observed 1.64 MeV transition corresponds to a $3/2^-$ state, the transition through the $5/2^-$ is more likely and one should also observe a peak at 1.08 MeV. On the other hand, if the 1.64 MeV state has a J^π of $1/2^-$, it could decay via an M1 γ -ray transition directly to the ground state, while it would need an E2 transition to decay sequentially through the $5/2^-$ state. This would imply a higher probability to decay directly to the ground state and the 1.08 MeV state would not be observed or have very little intensity. Since the 1.08 MeV state is not observed in the current spectrum, the 1.64 MeV state could therefore tentatively be assigned $J^\pi = 1/2^-$.

The currently reported 1-neutron and 2-neutron separation thresholds of ^{17}B are $S_n = 1.47(21)$ MeV and $S_{2n} = 1.38(21)$ MeV, respectively. This implies that the newly observed γ -ray transition at 1.64 MeV is ~ 260 keV above the 2-neutron separation threshold. Such a γ -ray transition above the S_{2n} has not been previously reported in any isotope. Although, γ -ray transitions above the 1-neutron separation energy has been previously reported [105]. However, it should be noted that the uncertainty in the S_{2n} of ^{17}B is very large owing to the significant uncertainty in its mass. Consequently, the state at 1.64 MeV could be below the S_{2n} within 2σ of this uncertainty. If such a state above the S_{2n} does indeed exist, it may indicate the presence of so called "cluster-states" analogous to the $3-\alpha$ Hoyle state in ^{12}C [10, 106, 1, 2]. Such a state could then decay competitively via γ -ray or 2-neutron emission. A natural next step would be to study the $^{15}\text{B}+2\text{n}$ system populated at excitation energies above the 2-neutron separation energy, which will be discussed in the upcoming sections.

4.2.2. $^{17}\text{C}(\text{p},2\text{p})^{16}\text{B}$

A thorough understanding of the ^{16}B structure is essential to interpret the $^{15}\text{B}+2\text{n}$ relative energy spectrum. This is important because the 2-neutron unbound states of ^{17}B could decay sequentially through the intermediate 1-neutron unbound states of ^{16}B . ^{16}B is known to be 1-neutron unbound, and its structure has been studied using several reaction mechanisms [51, 54, 55, 56]. The authors of [54] and [55] populated ^{16}B states via the $^{17}\text{C}(-1\text{p})^{16}\text{B}$ reaction, where a near threshold narrow resonance

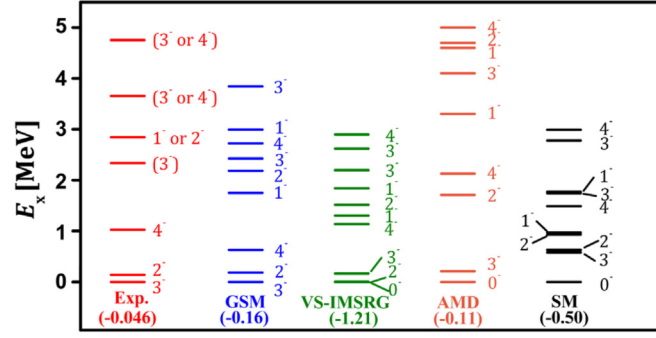


Figure 4.20.: ^{16}B level scheme for the $^{17}\text{B}(p,pn)^{16}\text{B}$ reaction reported in [56]. The obtained results (in red) are shown in comparison to GSM, VS-IMSRG, AMD and SM calculations. The corresponding separation energies are highlighted in parentheses. Figure taken from [56].

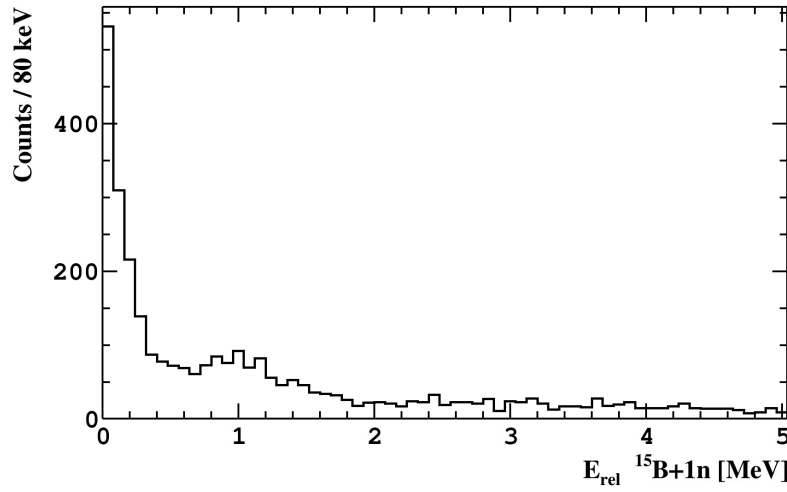


Figure 4.21.: Relative energy distribution for $^{17}\text{C}(p,2p)^{16}\text{B} \rightarrow ^{15}\text{B}+1n$ channel.

corresponding to the ground state (g.s.) was observed, with a resonant energy of $E_r \sim 60$ keV in the $^{15}\text{B}+1n$ relative energy distribution.

More recently, the quasi-free neutron knockout reaction $^{17}\text{B}(p,pn)^{16}\text{B}$ has been employed [56], where, in addition to the ground state, several higher lying states have also been identified. Four primary states were identified in the $^{15}\text{B}+1n$ relative energy spectrum, below $E_{rel} < 3$ MeV at $E_r = 0.046, 0.183, 1.08$ and 2.8 MeV. For each resonance, the relative $0d_{5/2}$ and $1s_{1/2}$ spectroscopic factors were extracted by comparing the experimental recoil transverse momentum distributions following neutron knockout with those obtained from DWIA calculations. The momentum distribution of the states at $E_r = 0.046$ and 1.08 MeV were shown to have pure $0d_{5/2}$ configuration. While the states at $E_r = 0.183$ and 2.8 MeV have a partial $1s_{1/2}$ contribution in addition to a $0d_{5/2}$ component. Since the spin-parity of the ^{17}B g.s. is $3/2^-$, the possible spin-parities of the states populated from $1s_{1/2}$ neutron removal should be $J^\pi = 1^-, 2^-$, while for the $0d_{5/2}$ neutron removal it should be $J^\pi = 1^-, 2^-, 3^-, 4^-$. Thus, the states with $1s_{1/2}$ components were assigned $J^\pi = 1^-, 2^-$, while the states with pure $0d_{5/2}$ components were assigned $J^\pi = 3^-, 4^-$. The assigned states and their respective spins are shown in Fig. 4.20. Finally, the authors propose a dominant $0d_{5/2}$ component (~ 91 (7)%) and a very small (~ 9 (2)%) $1s_{1/2}$ component for the ^{17}B g.s. valence neutron configuration.

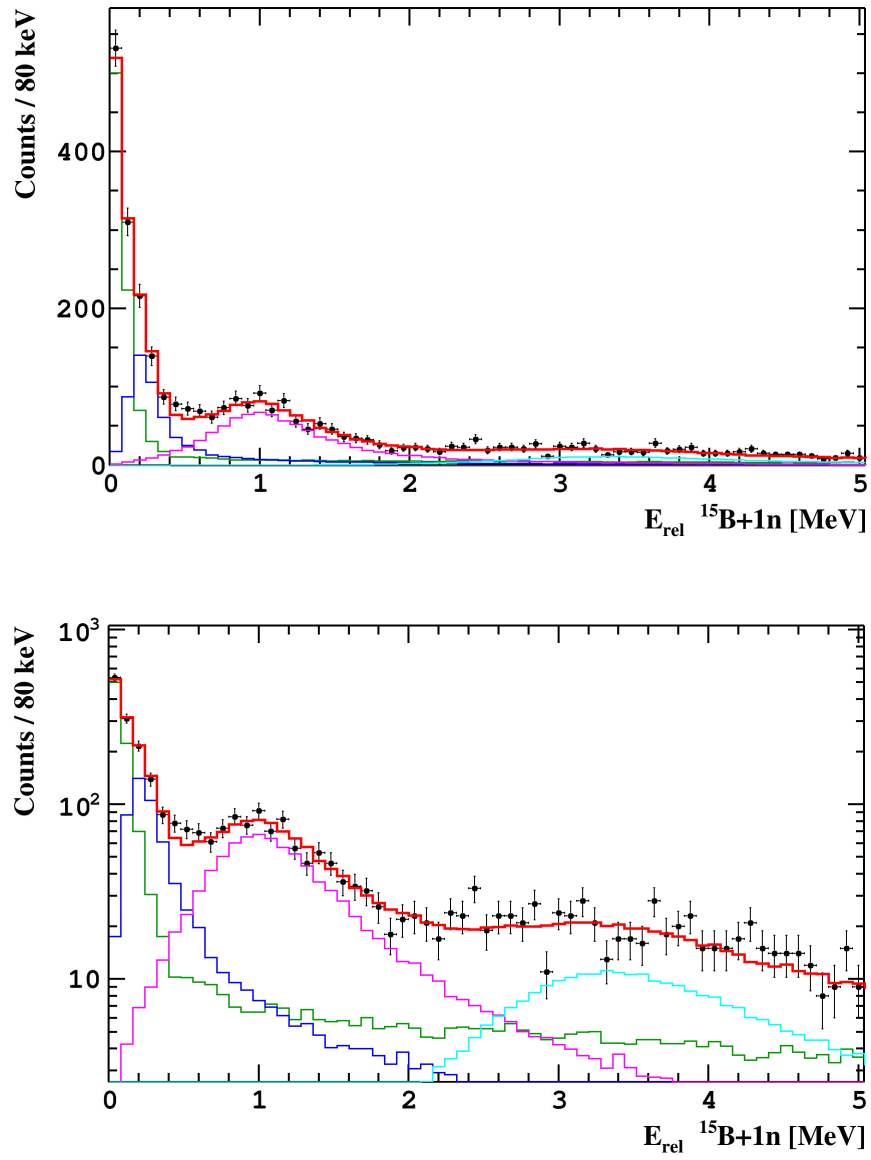


Figure 4.22.: Fit of relative energy spectrum for $^{17}\text{C}(p,2p)^{16}\text{B} \rightarrow ^{15}\text{B}+1n$. **Top:** Plot in linear scale. **Bottom:** same plot but in logarithmic scale. The resonances and their corresponding parameters are listed in Table. 4.7.

No.	E_x	E_r (MeV)	Γ_r (MeV)
1	0.00	0.06(2)	<0.05
2	1.48(4)	0.21(4)	0.16(8)
3	0.94(10)	1.00(10)	0.60(15)
4	3.34(30)	3.40(30)	2.2(6)

Table 4.7.: Resonances obtained from the best fit of the $^{15}\text{B} + 1n$ relative energy spectrum. Assigned excitation energy of the $E_r = 0.21$ MeV state is tentative, since feeding to the ^{15}B excited states is not constrained.

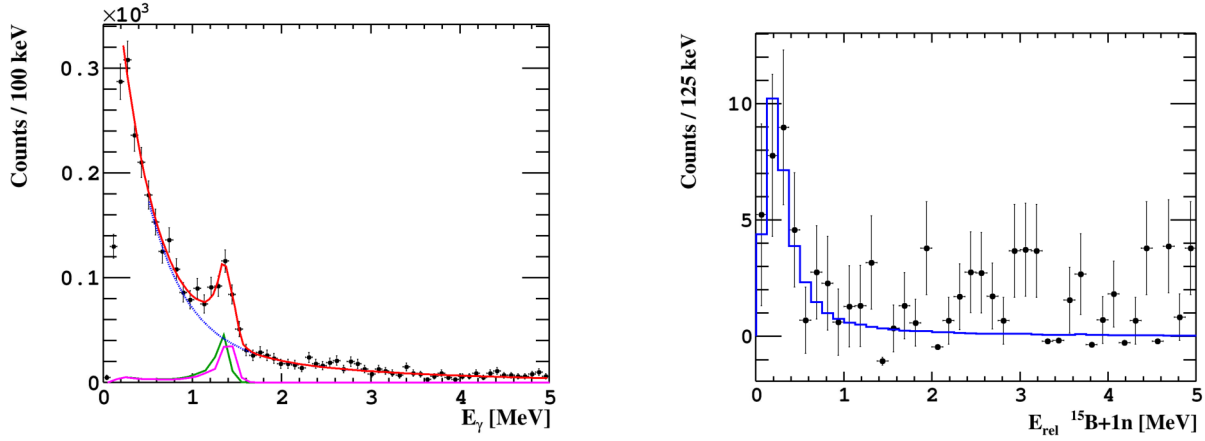


Figure 4.23.: *Left:* ^{15}B γ -ray spectrum in coincidence with the $^{15}\text{B}+1\text{n}$ relative system. The distribution is fitted with two γ -ray components with fixed energies taken from [52] ($E_\gamma = 1.327$ (green) and 1.407 (pink) MeV) and the double exponential background. *Right:* $^{15}\text{B}+1\text{n}$ relative energy distribution obtained with a gate on the ^{15}B photopeak region after background subtraction, fitted with the resonance at $E_r = 0.21$ MeV.

In the current work, ^{16}B states are populated using the quasi-free proton knockout reaction, $^{17}\text{C}(p,2p)^{16}\text{B}$. The objective is to confirm previously identified states and to identify additional states beyond those already observed via the neutron knockout reaction. The ^{17}C g.s. has a J^π of $3/2^+$ with a dominant neutron configuration of $\nu(d_{5/2}^3)_{J=3/2^+} + \nu(d_{5/2}^2, s_{1/2})_{J=3/2^+}$. Therefore, for the case of a proton removal from the $0p_{3/2}$ orbital in ^{17}C , states with spin-parities of $J^\pi = 0^-, 1^-, 2^-, 3^-$ should be populated. Since a 0^- state is expected from shell-model calculations (see Fig. 4.20), at least one additional state beyond those identified in the neutron knockout measurement should be observed in the current case. Conversely, proton knockout should not populate any 4^- states; therefore, the assigned 4^- states observed in [56] should not be populated.

The 1-neutron relative energy spectrum obtained from $^{17}\text{C}(p,2p)^{16}\text{B} \rightarrow ^{15}\text{B}+1\text{n}$ reaction is shown in Fig. 4.21. The extremely narrow ground state of ^{16}B is clearly observed near the threshold at $E_r \sim 50$ keV. But in addition to this, as is apparent from the shape, a few other resonances are needed to fit the complete distribution. The approach taken is to fit the spectrum with the minimum number of resonances that can reproduce the full distribution. The final fit of the distribution is shown in Fig. 4.22. A minimum of four resonances is needed to reproduce the complete distribution up to a relative energy $E_r = 5$ MeV. The identified resonances and their corresponding widths are tabulated in Table. 4.7.

The next step is to determine the excitation energy E_x corresponding to each resonance. As before, this is achieved by identifying whether the resonant states decay to the ground state or a bound excited state of ^{15}B . Following the approach used for the ^{15}B analysis in the previous section, the ^{15}B γ -rays emitted in coincidence with the $^{15}\text{B}+1\text{n}$ resonances are examined. As discussed in section 4.1, the detailed γ spectroscopy of the ^{15}B states has been previously performed in [52, 53, 62]. The γ -ray spectrum in coincidence with the $^{15}\text{B}+1\text{n}$ events is shown in Fig. 4.23 (left). There are two known bound excited states of ^{15}B decaying sequentially via the emission of γ -rays. The two γ -rays are very close in energy ($E_\gamma = 1.327(12)$ and $1.407(20)$ MeV [52]), and are therefore difficult to resolve within the detector resolution. However, it is observed that the peak is slightly broader than the expected width for a single photopeak, indicating the possible presence of both γ -ray transitions in the distribution. This suggests that the ^{16}B unbound states very likely feed to both bound states of ^{15}B . This is illustrated in the γ -ray spectrum shown in Fig. 4.23 (left), which is fitted with the two γ -ray components in addition

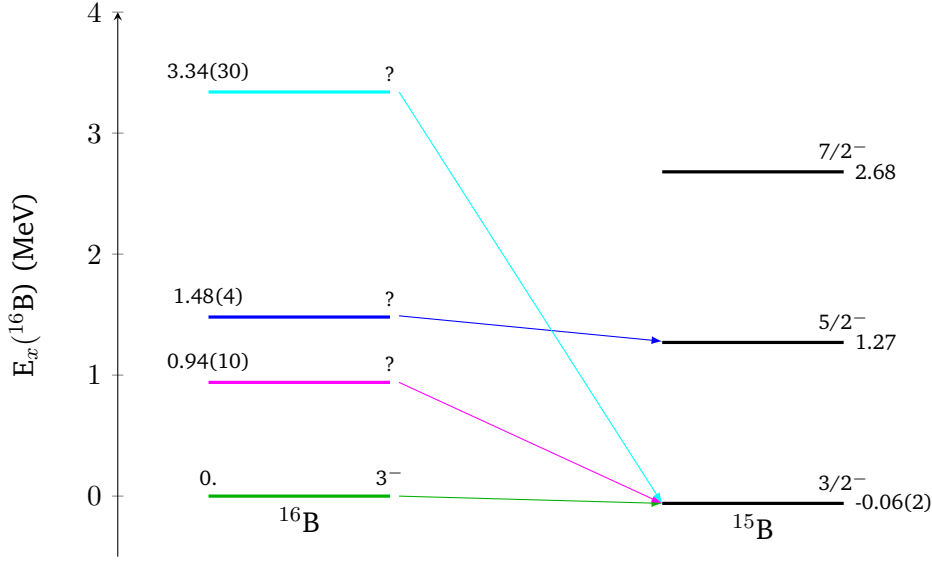


Figure 4.24.: Tentative level scheme for $^{17}\text{C}(p,2p)^{16}\text{B} \rightarrow ^{15}\text{B}+1n$ reaction. Assigned excitation energy of the $E_r = 0.21$ MeV state is tentative, since the decay to ^{15}B excited states is not constrained.

to the double exponential background. In this case, rather than fitting the photopeak with a Gaussian distribution, it is fitted with the full simulated γ -ray response functions in CALIFA corresponding to the two known transitions in ^{15}B . This is done to highlight the full effect of the response on the observed peak. As can be observed, the two γ -rays have a very strong overlap and thus it is impossible to separate the relative contributions.

To identify the resonances decaying through the excited states of ^{15}B , the same approach discussed in the analysis of the $^{14}\text{B}+1n$ states (see section 4.1.1) is adopted. To reiterate the procedure; the objective is to select a gate on the γ -ray energy corresponding to the photopeak, and obtain the $^{15}\text{B}+1n$ relative energy spectrum in coincidence with the gate. The γ -gated $^{15}\text{B}+1n$ relative energy distribution is shown in Fig. 4.23 (right). The background contribution within the γ -ray energy gate has been estimated and subtracted with the procedure discussed in section 4.1.1. The resulting $^{15}\text{B}+1n$ distribution is found to be dominated by the low-energy resonance at $E_r = 0.21(2)$ MeV. Therefore, this resonance very likely decays to the excited states of ^{15}B . As discussed previously, this resonance could decay through either of the two bound excited states of ^{15}B , which cannot be resolved in the current work. For the purpose of assigning a decay scheme, the state is tentatively assumed to decay to the $5/2^-$ of ^{15}B . A more detailed analysis, including the calculation of the cross sections and related C^2S with comparison to theoretical calculations could resolve this ambiguity.

It was also observed that a significant part of the $^{15}\text{B}+1n$ relative system above $E_{rel} > 3$ MeV, decays through the excited states of ^{15}B . However, a high density of states is expected at the higher excitation energies of ^{16}B . Although the high-energy region is fitted with a single broad distribution, it could in fact represent a collection of several states, some decaying through the excited states of ^{15}B , and others decaying directly to the ground state. Given the resolution limits of the experimental setup and the available statistics, it is not possible to distinguish the individual contributions. Therefore, for the present analysis, the decay of this "resonance" is assigned to the ^{15}B g.s.

To summarize, the resonance at $E_r = 0.21(4)$ MeV and a portion of the resonance at $E_r = 3.4(3)$ MeV decay through the excited states of ^{15}B , while the resonances at $E_r = 0.06(2)$ MeV and $E_r = 1.0(1)$ MeV decay directly to the ground state of ^{15}B . The final level scheme is shown in Fig. 4.24.

4. Spectroscopy of Boron isotopes

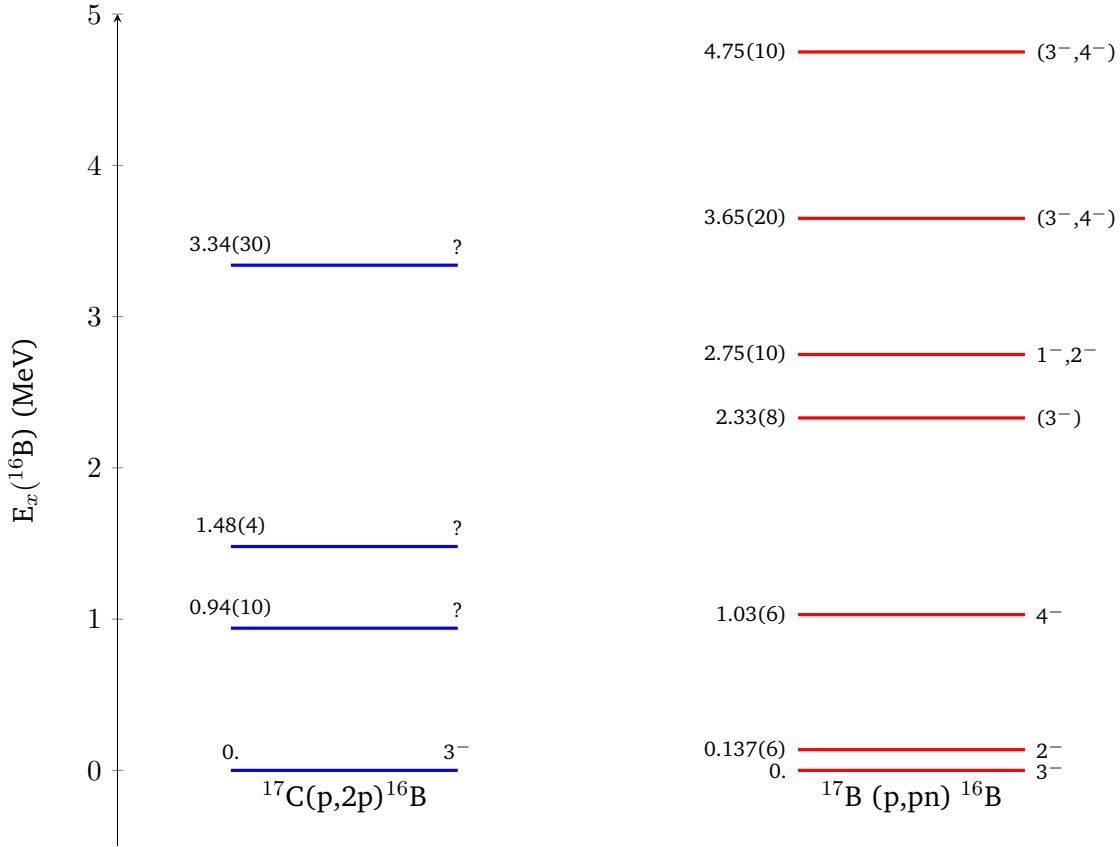


Figure 4.25.: Comparison of level schemes of ^{16}B obtained from proton/neutron removal. **Left:** Level scheme obtained from quasi-free $(p,2p)$ reaction in the current work. Assigned excitation energy of the $E_r = 0.21$ MeV state is tentative, since the decay to ^{15}B excited states is not constrained. **Right:** Level scheme from [56] for quasi-free (p,pn) reaction. According to [56], the states at $E_x = 2.33$ MeV, 3.65 MeV and 4.75 MeV decay to the excited states of ^{15}B with negligible spectroscopic factors.

Finally, the current results are compared with those from the neutron knockout $^{17}\text{B}(p,pn)^{16}\text{B}$ reaction [56] (see Fig. 4.25). A strong component of ground state resonance is observed in the current work, which was assigned as a 3^- by the authors of [56]. Since 3^- states are also expected to be populated via the proton removal reaction, this assignment remains consistent. In the neutron removal study, a state at $E_r = 0.18$ MeV, assigned as 2^- , decays to the ground state of ^{15}B . In the current proton removal case, a resonance close to this relative energy at $E_r = 0.21(2)$ MeV is observed. However, as discussed above, this resonance decays through the excited states of ^{15}B and is therefore likely not the same state observed in the neutron removal study. Consequently, the 2^- state at $E_r = 0.18$ MeV is not observed in the proton removal case. The next dominant contribution in the neutron removal study is a resonance at $E_r = 1.08(6)$ MeV, which the authors propose to be a 4^- state. In the current proton removal analysis, a state at almost the same energy, $E_r = 1.0(1)$ MeV, is also observed with a compatible width. However, 4^- states should not be populated in the proton removal reaction. Thus, either the spin assignment in [56] is incorrect, or this is a different state than the one observed in that case. The other states observed in the (p,pn) study are not compatible with the relative energy distribution measured in the present work. Finally, the broad resonance at $E_r = 3.4(3)$ MeV included in the current analysis does not match the neutron removal results.

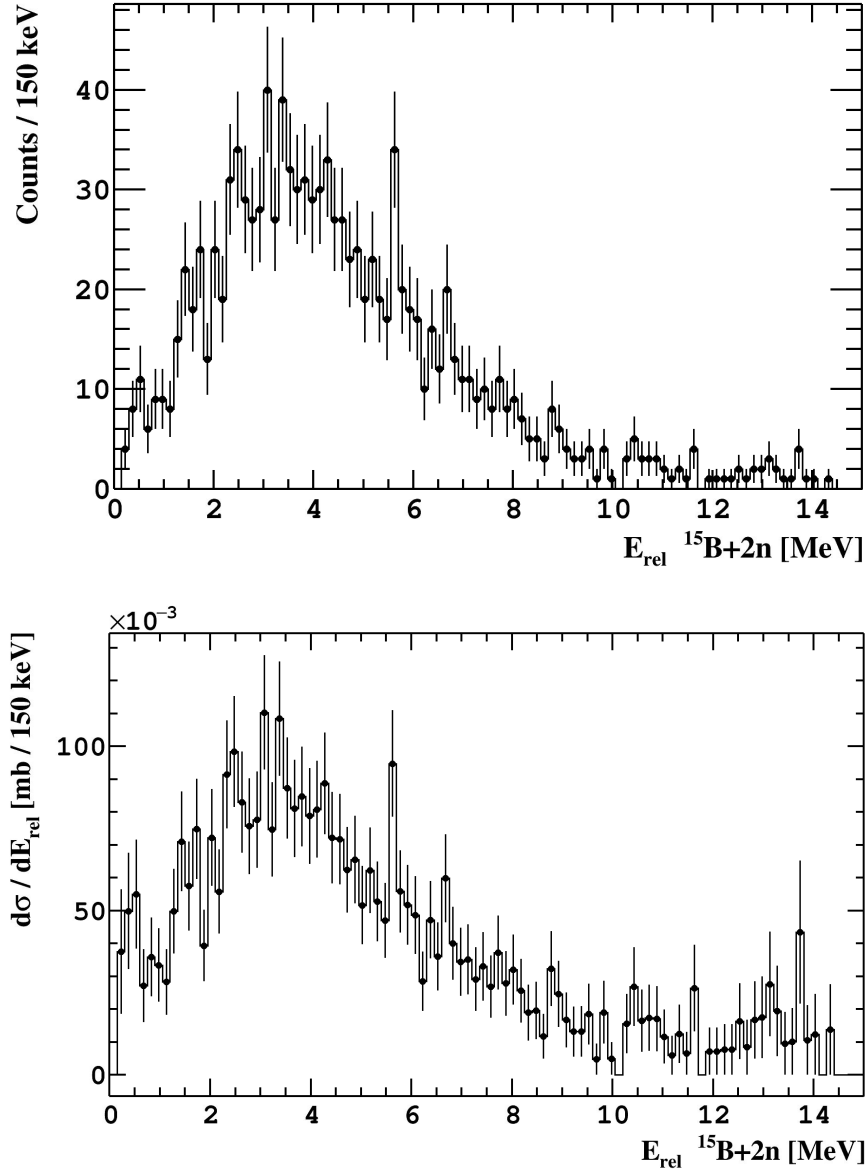


Figure 4.26.: **Top:** Relative energy spectrum for $^{18}\text{C}(p,2p)^{17}\text{B} \rightarrow ^{15}\text{B}+2\text{n}$ reaction reconstructed using "Causality method". **Bottom:** Same spectrum but corrected for with the neutron efficiency distribution along with other detection efficiencies.

4.2.3. $^{18}\text{C}(\text{p},2\text{p})^{17}\text{B} \rightarrow ^{15}\text{B}+2\text{n}$

As mentioned, the 2-neutron separation energy of ^{17}B is at $S_{2n} = 1.38(21)$ MeV. States populated above this excitation energy would decay via the emission of two neutrons in the $^{15}\text{B}+2\text{n}$ system. The relative energy distribution corresponding to the $^{18}\text{C}(\text{p},2\text{p})^{17}\text{B} \rightarrow ^{15}\text{B}+2\text{n}$ reaction, with the selection on the QFS protons, is shown in Fig. 4.26 (Top). This spectrum has been reconstructed using the "Causality method" (see section 3.4.1), in order to obtain sufficient statistic. One can observe that no distinct structures stand out in the distribution and indeed it can be correspond to a single broad distribution. The lack of structure is accentuated by the overall low statistics, due to which the spectrum presented here is overbinned compared to the resolution of the 2-neutron reconstruction. However, after correction of the spectrum with the neutron efficiency distribution (see Fig. 3.23), as shown in Fig. 4.26 (bottom), an indication of a near threshold state can be observed around $\sim 0.4 - 0.5$ MeV. Though the low statistics and large error bars prevent a conclusive determination of its significance. Further discussion with respect to this "state" is presented in Chapter. 5.

An alternative approach to analyze the $^{15}\text{B}+2\text{n}$ spectrum is to study the two-body components corresponding to the three-body relative energy, more specifically the $^{15}\text{B}+1\text{n}$ system. This information can indicate presence of structures beyond what is observed in the total three-body spectrum. The approach taken here is similar to the one described for the $^{13}\text{B}+2\text{n}$ system in section 4.1.3 and extended based on the methodology adopted in [107]. To reiterate the procedure, the method is based on fitting the two-body $^{15}\text{B}+1\text{n}$ distributions corresponding to gates applied on the three-body $^{15}\text{B}+2\text{n}$ relative energy. In case of direct decay, the two $^{15}\text{B}+1\text{n}$ subsystems will democratically share the total available energy of the resonance. On the other hand, if the system decays via a sequential decay, the energy and width of one of the $^{15}\text{B}+1\text{n}$ subsystems are fixed to the values of the intermediate ^{16}B resonance, while the other carries the remaining energy. Therefore, distinct structures are generally observed in the two-body $^{15}\text{B}+1\text{n}$ distributions in case of sequential decays. As in the $^{13}\text{B}+2\text{n}$ case, a good knowledge of the ^{16}B resonances is essential for this analysis. Towards this end, the information summarized in Fig. 4.25, obtained from [56] and the current work, is utilized. The procedure then involves gating on particular energy ranges of the total $^{15}\text{B}+2\text{n}$ relative energy and fitting the corresponding $^{15}\text{B}+1\text{n}$ relative energy and m_{fn}^2 ($\sim E_{rel}(\text{Frag}+1\text{n})/E_{rel}(\text{Frag}+2\text{n})$) distributions. If the $^{15}\text{B}+1\text{n}$ spectrum changes for different ranges of the $^{15}\text{B}+2\text{n}$ relative energy, i.e., if the decay proceeds through different sequential/direct components, this indicates the presence of two separate states. Care must be taken, however, to ensure that the differences in the sequential components are not merely due to the intermediate state being energetically inaccessible. To explain this, a hypothetical situation is assumed — if there are no intermediate states in ^{16}B in the range of $E_r = 0 - 2$ MeV of the $^{15}\text{B}+2\text{n}$ system, a broad resonant state in this range would only decay directly. Above this range, if an intermediate state in ^{16}B opens up, the *same* broad resonant state can now decay not only directly but also via the intermediate state. Thus, there can be a change in the decay scheme for the same state if such a decay becomes energetically viable.

In order to study the change in the decay mechanism along the total $^{15}\text{B}+2\text{n}$ relative energy distribution, gates were applied on different energy ranges of the total relative energy, and the corresponding $^{15}\text{B}+1\text{n}$ and m_{fn}^2 spectra were fitted. Due to the lack of structure in the $^{15}\text{B}+2\text{n}$ distribution, as one can deduce, it can be a long and arduous process to obtain the correct energy gates corresponding to changes in the decay mechanisms. Here, the energy gates where significant changes in the decay mechanisms were observed are presented directly. The first four energy gates along with their fits are shown in Fig. 4.27 – 4.30.

The first energy gate is applied in the range of $E_{rel} \in [0, 0.6]$ MeV in the three-body $^{15}\text{B}+2\text{n}$ relative energy (Fig. 4.27), in order to cover the possible near-threshold resonance. As can be observed, this region has

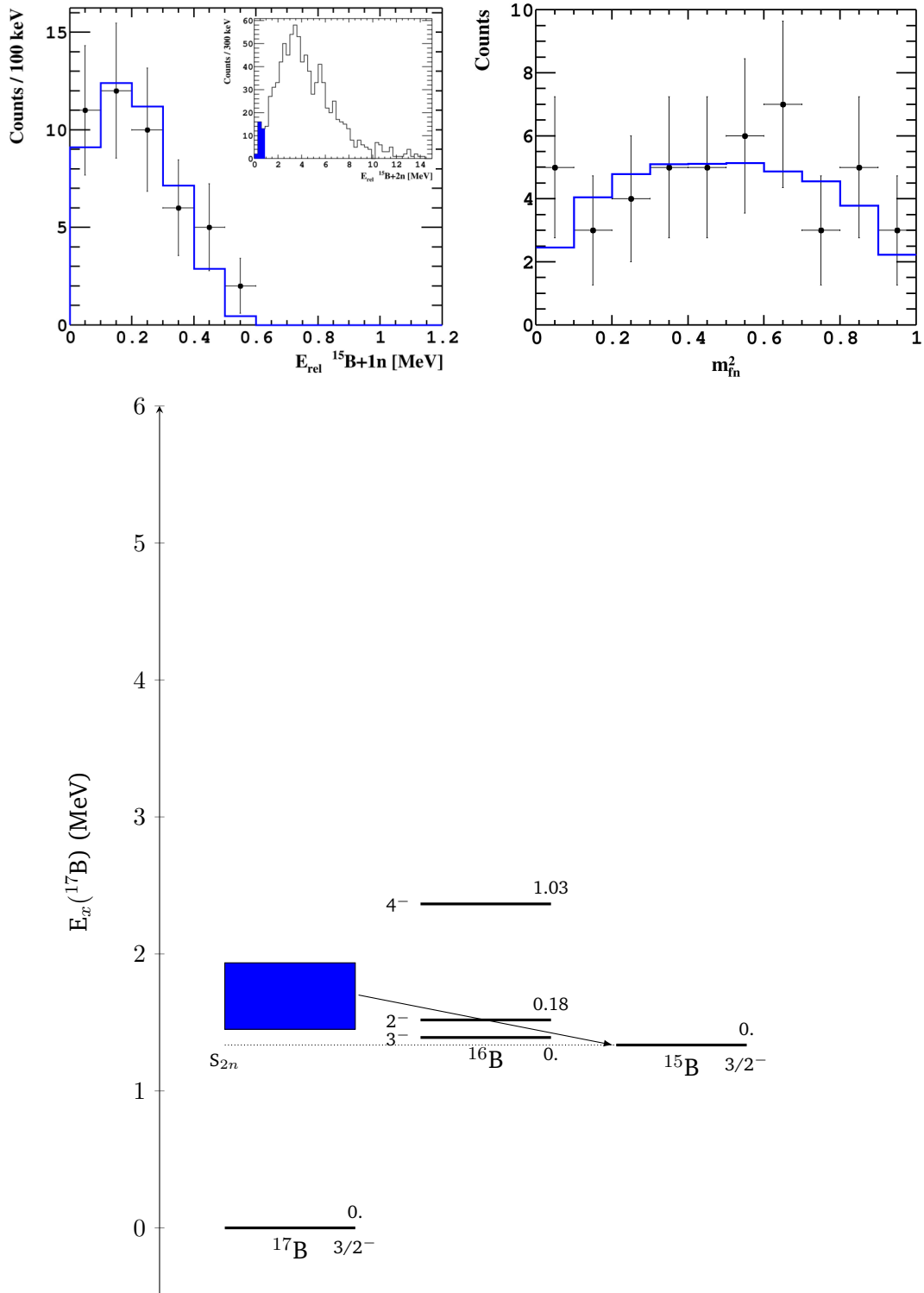


Figure 4.27.: **Top Left:** Direct decay fit of two-body $^{15}\text{B}+1\text{n}$ relative energy distribution corresponding to an energy gate on the $^{15}\text{B}+2\text{n}$ system in the range $E_{\text{rel}} \in [0, 0.6]$ MeV (shown in inset). **Top right:** m_{fn}^2 distribution corresponding to the same energy gate shown with a fit using the same direct decay component. **Bottom:** Level diagram of ^{17}B corresponding to the energy gate with the proposed decay mechanism.

4. Spectroscopy of Boron isotopes

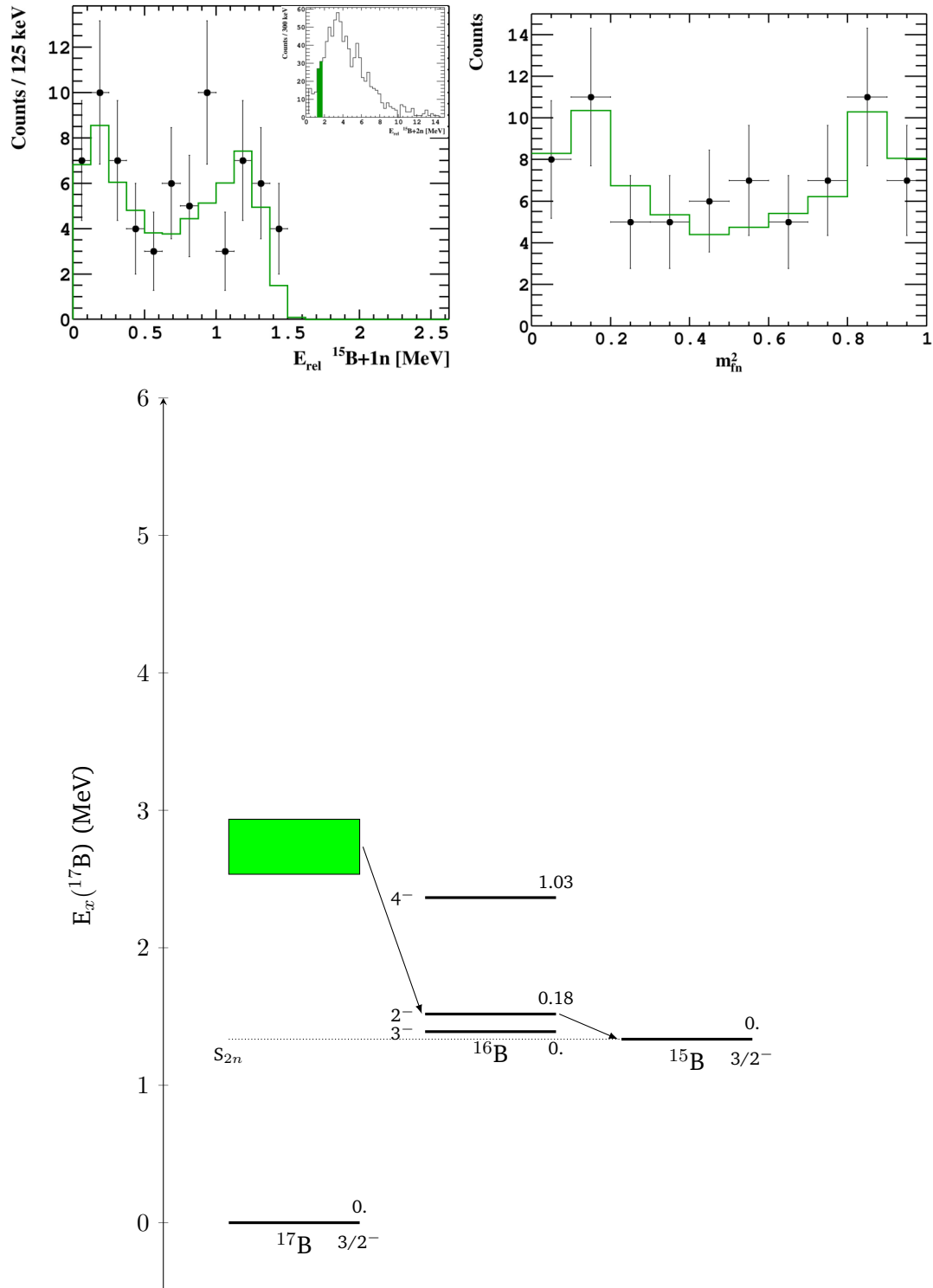


Figure 4.28.: *Top Left:* Fit of two-body $^{15}B+1n$ relative energy distribution using a single sequential component, corresponding to an energy gate on the $^{15}B+2n$ system in the range $E_{rel} \in [1.2, 1.6]$ MeV (shown in inset). *Top Right:* m_{fn}^2 distribution corresponding to the same energy gate, shown with a fit using the same sequential decay component. *Bottom:* Level diagram of ^{17}B corresponding to the energy gate with the proposed decay mechanism.

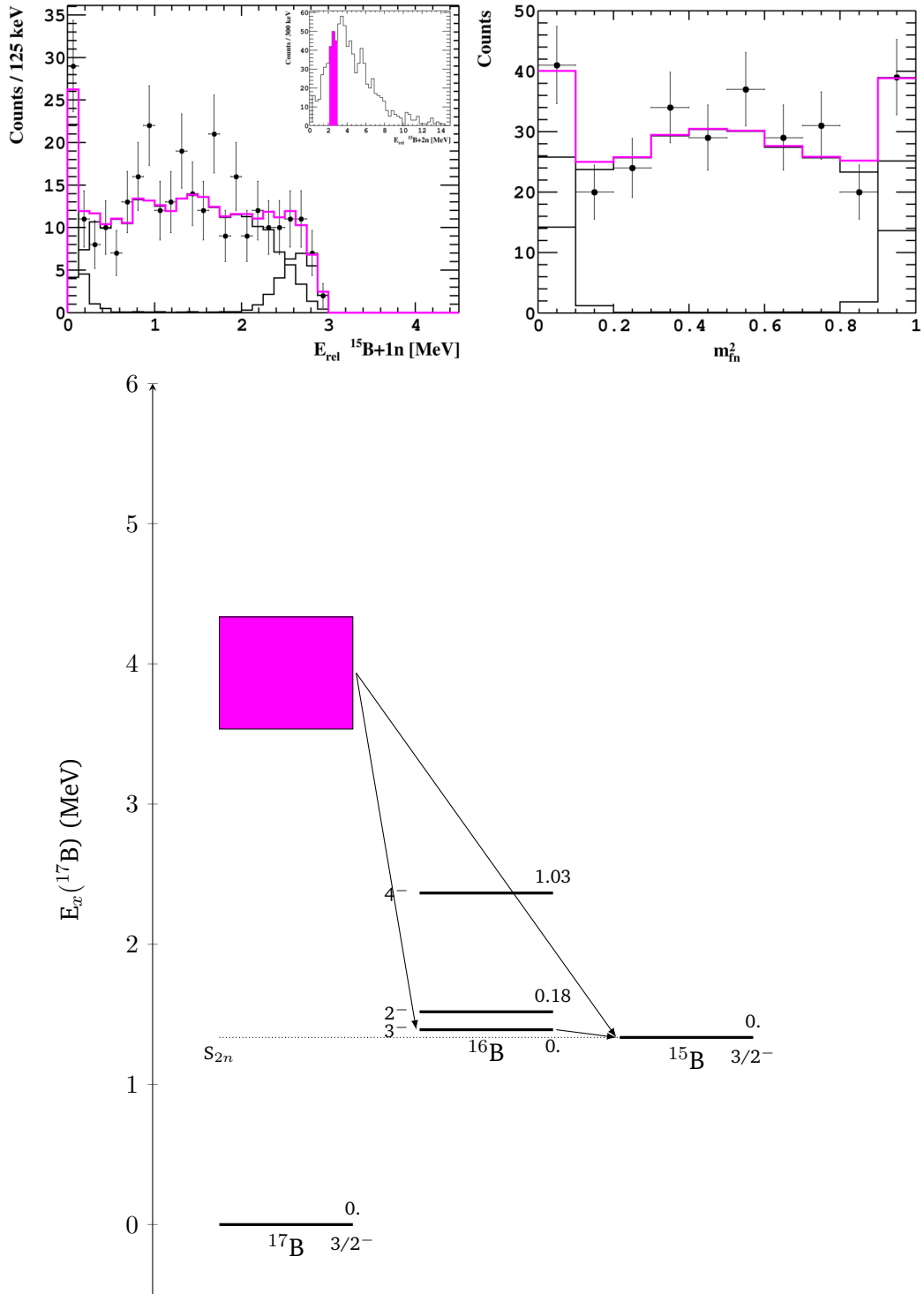


Figure 4.29.: **Top Left:** Fit of two-body $^{15}\text{B}+1n$ relative energy distribution with direct and sequential components, corresponding to an energy gate on the $^{15}\text{B}+2n$ system in the range $E_{\text{rel}} \in [2.2, 3]$ MeV (shown in inset). **Top Right:** m_{fn}^2 distribution corresponding to the same energy gate, shown with a fit using the same decay components. **Bottom:** Level diagram of ^{17}B corresponding to the energy gate with the proposed decay mechanism.

4. Spectroscopy of Boron isotopes

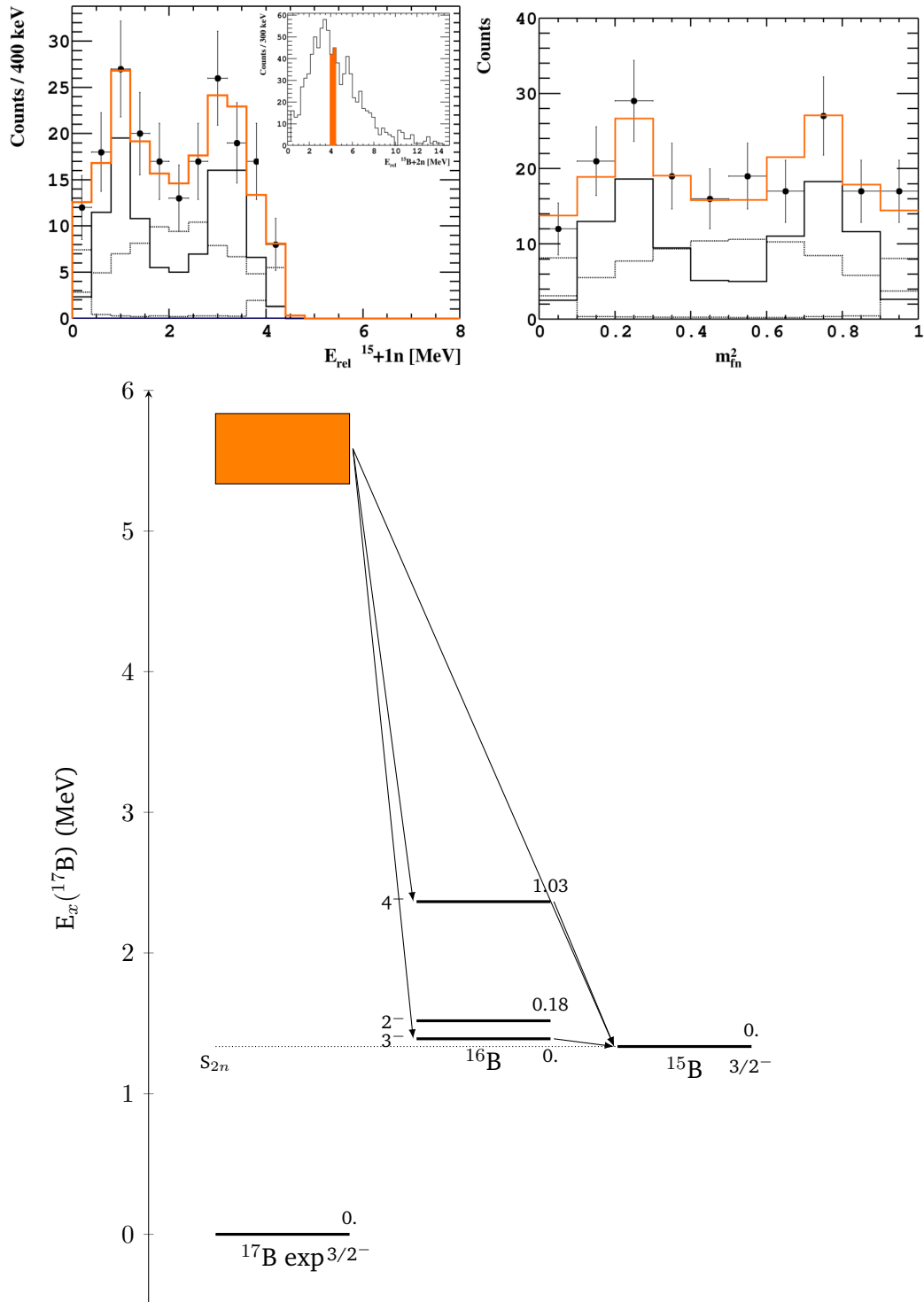


Figure 4.30.: **Top Left:** Fit of two-body $^{15}\text{B}+n$ relative energy distribution with several direct and sequential components, corresponding to an energy gate on the $^{15}\text{B}+2n$ system in the range of $E_{\text{rel}} \in [4, 4.5]$ MeV (shown in inset). **Top Right:** m_{fn}^2 distribution corresponding to the same energy gate, shown with a fit using the same decay components. **Bottom:** Level diagram of ^{17}B corresponding to the energy gate with the proposed decay mechanism.

very limited statistics, however, the distributions indicate mostly equal energy sharing between the two neutrons, suggesting that direct decay can adequately reproduce the two-body $^{15}\text{B}+1\text{n}$ distributions. However, due to the extremely limited statistics, other forms of decay through the intermediate states or the contribution from the tails of higher lying resonances cannot be excluded. Further discussions regarding this "state" and the corresponding distributions, including the nn distribution, will be presented in the next chapter. The next cut is applied in the region of $E_{\text{rel}} \in [1.2, 1.6]$ MeV (Fig. 4.28). In this case, the $^{15}\text{B}+1\text{n}$ distribution show a clear sequential decay contribution, with two peaks appearing at different energies. A compatible fit was found for the sequential decay through the 180 keV state of ^{16}B (see Fig. 4.25). This state was assigned a 2^- by the authors of [56]. Since, in the current case, only $3/2^-$ and $1/2^-$ states should be populated, assuming an $L = 0$ decay is compatible with a $3/2^-$ assignment. Here again, the relative contribution of the sequential component as compared to other decay mechanisms is hard to estimate because of the apparent strong overlap with other resonant states. The next cut shown in Fig. 4.29, corresponds to the range of $E_{\text{rel}} \in [2.2, 3]$ MeV. Here, the distribution is dominated by equal sharing of the relative energy between the two neutrons, which indicates a strong direct decay component. However, a clear peak can be observed at ~ 60 keV in the $^{15}\text{B}+1\text{n}$ relative energy spectrum. Therefore, there appears to be a component feeding sequentially through the g.s. of ^{16}B . The ^{16}B g.s. was assigned a 3^- spin by the authors of [56]. Additionally, the authors of [54] proposes a d-wave decay for this resonance to the ^{15}B g.s., whose spin is $3/2^-$. Since $3/2^-$ and $1/2^-$ states are populated in the current case, this implies that this sequential component decays via at least an $L = 2$ neutron emission to the intermediate g.s. of ^{16}B . It should be noted that such a clear peak at ~ 60 keV was not observed in the previous gates, even though the phase space imposes no energetic constraint on this transition. This strongly indicates the presence of a separate state compared to the previous gates. It should be emphasized, however, that the direct and sequential components might not originate from the same resonance. The plots corresponding to the next gate in the range of $E_{\text{rel}} \in [4, 4.5]$ MeV are shown in Fig. 4.30. The fit suggest a possible sequential decay component through a 1 MeV state in ^{16}B , which is compatible with the 4^- assigned in Fig. 4.25, in addition to a direct decay component. If the spin assignment is correct, the sequential decay in this case again proceeds via at least an $L = 2$ neutron emission to the intermediate ^{16}B state. Furthermore, the multiple components included in the fit could also again come from multiple overlapping resonances. It is further noted that there is a relative decrease in the sequential decay through the 60 keV ^{16}B g.s. as compared to the previous gate, indicating a significant change in the decay mechanism.

While this procedure is very powerful in indicating the presence of multiple resonances based on changes in the decay mechanisms, it is still difficult to estimate the exact number and properties of the resonances in the current $^{15}\text{B}+2\text{n}$ system. This is due to the clear lack of structure in the total distribution, indicating that the resonances, if present, have a very strong overlap. This makes it difficult to precisely estimate the relative contributions of the overlapping resonances to the total distribution, and consequently, it is not trivial to obtain their energy, width and amplitude. In principle, a relatively precise estimation could still be performed with the current resolution if sufficient statistics was available, which is not the case here. Therefore, the presence of structural components in the $^{15}\text{B}+2\text{n}$ system is reported in the current work, which cannot be explained with just a single resonance approximation for the full distribution. Based on the study of decay mechanisms using different energy gates in the $^{15}\text{B}+2\text{n}$ spectrum, the existence of 3 — 5 resonances is proposed. It is expected that future work with higher resolution and statistics can evidence the existence of the said resonances.

The change in the excitation energy along the $^{15}\text{B}+2\text{n}$ spectrum can also be estimated by identifying the parts of the continuum that decay to the excited states of ^{15}B . As in the previous sections, this can be achieved by fitting the γ -gated $^{15}\text{B}+2\text{n}$ spectrum. However, it was observed that only $\sim 10\%$ of the $^{15}\text{B}+2\text{n}$ events decay to the excited states of ^{15}B . Due to the very limited statistics in the γ -gated $^{15}\text{B}+2\text{n}$

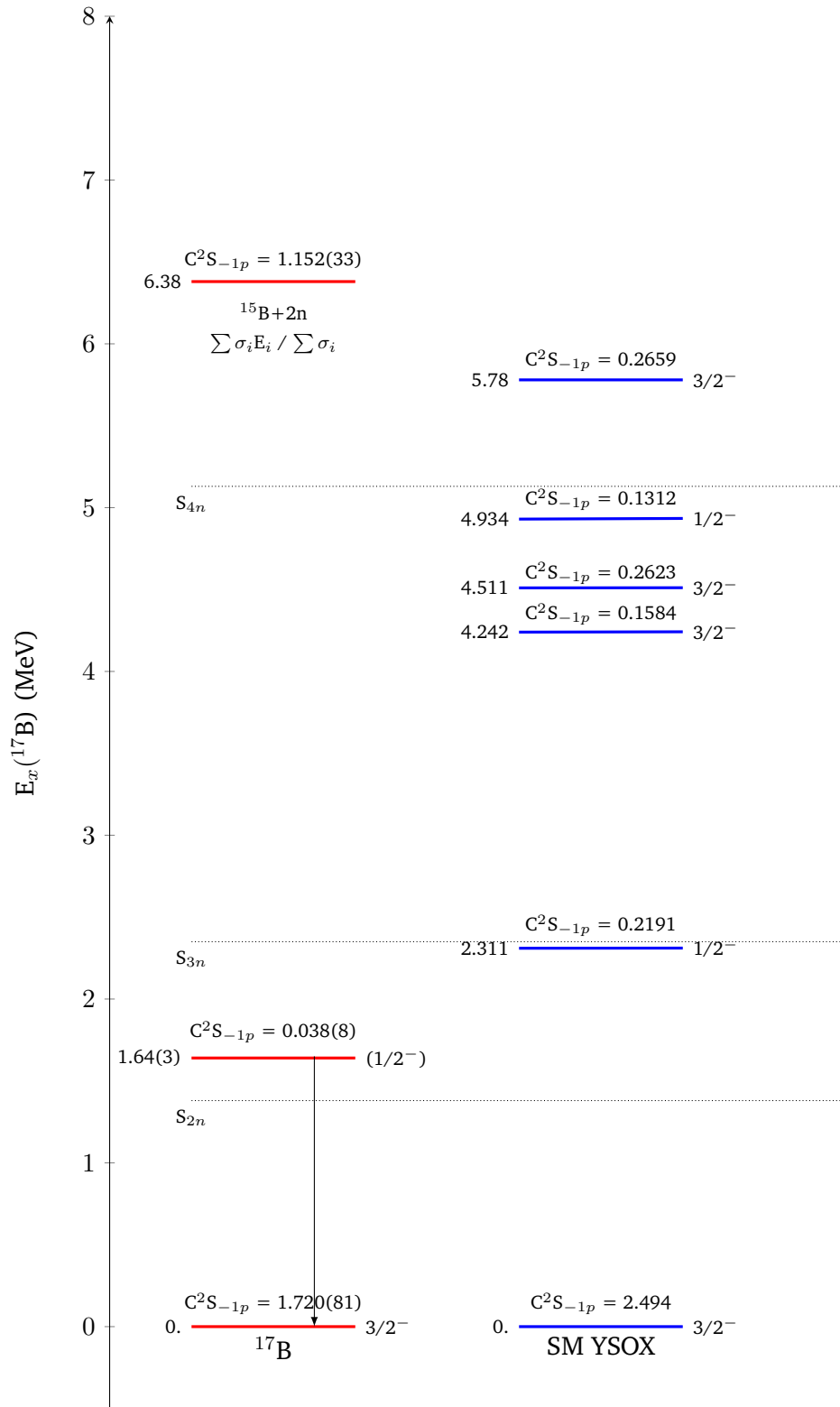


Figure 4.31.: Obtained experimental level scheme for $^{18}\text{C}(p,2p)^{17}\text{B}$ (in red) compared to SM YSOX calculations [33] (in blue). The experimental $^{15}\text{B}+2n$ contribution and corresponding parameters shown are obtained assuming single state placed at the cross section weighted centroid. For the SM calculations only states with significant spectroscopic factors are shown.

spectrum, a detailed analysis is not realistic, preventing any conclusive interpretation.

It was found that a large component of the $^{15}\text{B}+2n$ system decays sequentially. This is contrary to results on the other core+4n systems, where the direct decay component was reported to be the dominant contribution, as discussed in [20]. This may be due to the phase space for the decay being strongly influenced by the high density of available ^{16}B intermediate states through which the $^{15}\text{B}+2n$ system could decay.

The final obtained level scheme for the $^{18}\text{C}(p,2p)^{17}\text{B}$ reaction is shown in Fig 4.31, and compared to predicted states from shell-model calculations obtained using the YSOX interaction[33]. Only the states with significant spectroscopic factors from the SM calculations are included in the comparison. For the $^{15}\text{B}+2n$ contribution, a single state is shown, placed at the cross-section weighted centroid, i.e., the mean of the spectrum shown in Fig. 4.26 (bottom). However, as discussed above, this single state does not represent the full picture of the $^{15}\text{B}+2n$ structure.

4.2.4. Cross Section

In this section, the cross sections associated with the $^{18}\text{C}(p,2p)^{17}\text{B}$ reaction are presented. As discussed in section 4.1.4, the integrated cross sections are calculated by implementing Eq. 4.3. In the current case, as discussed in the previous sections, the bound ^{17}B system has an additional excited state at 1.64 MeV. Thus, the ground state cross section in this case using Eq. 4.5 is,

$$\sigma_{gs} = \sigma_{inc} - \sigma_{exc,1.64 \text{ MeV}} \quad (4.7)$$

The final calculated cross sections and their corresponding spectroscopic factors are tabulated in Table. 4.8. For the $^{15}\text{B}+2n$ system, since individual states could not be resolved in the distribution, a single cross-section value corresponding to the integral of the spectrum shown in Fig. 4.26 (bottom) was assigned. The spectroscopic strength for the $^{15}\text{B}+2n$ system is then centered at the cross section weighted mean energy value of the distribution (i.e., $\sum \sigma_i E_i / \sum \sigma_i$). The uncertainties shown include only the statistical uncertainties, as the evaluation of the systematic uncertainties are still under progress. However, a part of the systematic uncertainty, has been included for the bound states, originating from a significant acceptance correction ($\sim 50\%$) for the outgoing ^{17}B fragment.

The shell-model predicted states along with their spectroscopic factors are shown in Table. 4.9. The shell-model calculations were performed using the YSOX interaction [33] in the *psd* valence space over an inert helium core. Comparison of the g.s. spectroscopic strengths shows a discrepancy between the experimental normalized (scaled by $R_s = 0.6$ [101]) and SM calculated values. Strikingly, the ratio of $C^2S_{g.s.,exp,norm} / C^2S_{g.s.,SM} \approx 0.7$ is similar to the ratio of the ground states in the $^{16}\text{C}(p,2p)^{15}\text{B}$ case. However, unlike the ^{15}B case, there is a smaller discrepancy in the neutron orbital configurations (see Table. 4.10) between the SM predicted structure and the measured data. The ^{18}C g.s. configuration of the $1s_{1/2}$ and $0d_{5/2}$ occupations in the SM calculation agrees almost exactly with the results of [108]. For the ^{17}B g.s., as reported in the work of [56], the valence neutron occupation is 91(7)% $0d_{5/2}$ and 9(2)% $1s_{1/2}$. The SM calculation is not significantly different, as they it predicts majority of the occupation in the $0d_{5/2}$ orbital and a smaller $1s_{1/2}$ component, although it does overestimate the relative contribution of the $1s_{1/2}$ orbital ($\sim 22\%$). However, as mentioned, the outgoing ^{17}B nucleus has a significant acceptance cut in the current setup. If the acceptance correction has not been implemented accurately, result in an over- or underestimation of the final cross section.

4. Spectroscopy of Boron isotopes

E_x (MeV)	J^π	σ_{exp} (mb)	$\sigma_{s.p.,th}$ (mb)	C^2S_{exp}	$C^2S_{exp,norm}$
0.00	$3/2^-$	$6.25(15)_{stat}(25)_{sys}$	6.055	$1.032(25)_{stat}(32)_{sys}$	$1.720(42)_{stat}(70)_{sys}$
1.64(3)	$(1/2^-)$	$0.13(3)_{stat}(1)_{sys}$	5.829	$0.023(5)_{stat}(1)_{sys}$	$0.038(8)_{stat}(1)_{sys}$
6.38	?	3.99(12)	5.772	0.691(20)	1.152(33)

Table 4.8.: Experimental cross section σ_{exp} and spectroscopic factors (C^2S_{exp}) corresponding to the identified states from the $^{18}\text{C}(p,2p)^{17}\text{B}$ reaction. The spectroscopic factors are calculated by taking the ratio of the experimental cross section to the single particle theoretical cross section obtained from the DWIA calculation, i.e, $C^2S_{exp} = \sigma_{exp} / \sigma_{s.p.,th}$. The $C^2S_{exp,norm}$ is obtained by scaling the C^2S_{exp} by the reduction factor of 0.6.

E_x (MeV)	J^π	C^2S_{sm}
0.000	$3/2^-$	2.494
2.311	$1/2^-$	0.2191
4.242	$3/2^-$	0.1584
4.511	$3/2^-$	0.2623
4.934	$1/2^-$	0.1312
5.780	$3/2^-$	0.2659

Table 4.9.: Excitation energies and spectroscopic factors (C^2S_{sm}) of states predicted by YSOX SM [33] calculations for proton knockout from ^{18}C . Only the states predicted with significant spectroscopic factors are shown.

^{18}C has 4 valence protons in its p -orbital, which implies that the sum of the spectroscopic factors for states populated by valence-proton removal should be close to ~ 4 . In the current case, the total experimental spectroscopic factor, after correction with R_s , is found to be $\sum C^2S_{exp,norm} = 2.91(8)$ up to an excitation energy of $E_x \approx 13$ MeV. In ^{17}B , however, the 3-neutron and 4-neutron separation thresholds open up at very low energies, i.e., at $S_{3n} = 2.35$ MeV and $S_{4n} = 5.13$ MeV. Thus, a significant portion of the missing spectroscopic strength may be carried by the $3n$ and $4n$ decay channels, which are difficult to access in the present analysis. Nevertheless, development of the multi-neutron reconstruction is currently under progress to infer at least some partial information from these channels.

In principle, no bound excited states below the $S_{2n} = 1.38(21)$ MeV are predicted in the SM calculations. The first excited state predicted with a significant spectroscopic factor for the proton removal reaction is at 2.311 MeV with a J^π of $1/2^-$. As discussed previously, based on the decay path of the observed γ -ray transition, the state at 1.64 MeV could likely be a $1/2^-$ (see discussion in section 4.2.1). If this assignment is correct, the observed $1/2^-$ state is shifted by ~ 0.7 MeV relative to the SM calculations, which represents a relatively large deviation. The experimental cross section of this proposed $1/2^-$ state, calculated from the γ -ray transition, is found to be very low, with a spectroscopic strength of only $\sim 2\%$ relative to the ground state. Comparing to the SM calculated $1/2^-$ state, the experimental C^2S value accounts for only $\sim 17\%$ of the total expected strength. If the observed state, as discussed previously, lies above the two-neutron separation threshold ($S_{2n} = 1.38(21)$ MeV), then part of the decay strength could be carried by the two-neutron emission channel. But as noted earlier, the current S_{2n} has a very large uncertainty, making it difficult to place the observed 1.64 MeV state, decaying via γ -ray emission, relative to the $^{15}\text{B}+2n$ distribution. Referring to the efficiency corrected $^{15}\text{B}+2n$ spectrum in Fig. 4.26 (bottom), a possible resonance is observed at $E_{rel} = (0.4 - 0.5)$ MeV. An indication of this resonant state is also apparent in the shape of the uncorrected distribution (Fig.4.26 (top)), where a sudden drop is observed at $E_{rel} \leq 1$ MeV. If such a resonance exists, it could be compatible to a state with competing decay pathways via γ -ray and 2-neutron emission. However, preliminary calculations based

Isotope	E_x (MeV)	J^π	Proton Config.					Neutron Config.				
			$0p_{1/2}$	$0p_{3/2}$	$0d_{3/2}$	$0d_{5/2}$	$1s_{1/2}$	$0p_{1/2}$	$0p_{3/2}$	$0d_{3/2}$	$0d_{5/2}$	$1s_{1/2}$
^{18}C	0.000	0^+	0.42	3.50	0.04	0.03	0.01	1.86	3.92	0.39	2.96	0.86
^{17}B	0.000	$3/2^-$	0.21	2.73	0.03	0.02	0.01	1.87	3.93	0.37	2.96	0.87
	2.311	$1/2^-$	0.36	2.59	0.03	0.02	0.01	1.86	3.92	0.27	2.58	1.36
	4.242	$3/2^-$	0.23	2.71	0.02	0.02	0.01	1.93	3.96	0.32	3.02	0.77
	4.511	$3/2^-$	0.38	2.57	0.03	0.02	0.01	1.89	3.94	0.40	2.68	1.10
	4.934	$1/2^-$	0.57	2.37	0.02	0.03	0.01	1.82	3.90	0.37	3.22	0.70
	5.780	$3/2^-$	0.27	2.67	0.03	0.03	0.01	1.82	3.89	0.33	2.88	1.08

Table 4.10.: *Orbital occupation numbers for the ^{18}C g.s. and predicted ^{17}B states for proton knockout from ^{18}C , obtained from YSOX shell-model calculations. Only the states predicted with significant spectroscopic factors are shown.*

on shell-model including continuum effects (S. Wang, Priv. Comm.) indicate that if the 1.64 MeV state has a competing decay modes via neutron and γ -ray emission, it must lie very close to the threshold, as its decay probability decreases rapidly with increasing energy. A relative energy of $E_{rel} \sim 0.4$ MeV is already quite high for such a decay; therefore, this *resonance* might not correspond to the $1/2^-$ state but could instead correspond to a separate $3/2^-$ state. Depending on how close the $1/2^-$ state lies to the threshold, the corresponding resonance might not be reconstructed in the current setup. This is because, as shown in the two-neutron reconstruction efficiency plot (c.f Fig. 3.23), the efficiency drops to extremely low values at very low relative energies. Therefore, if the corresponding state lies around $E_r \approx 50$ keV above the threshold, it is unlikely to be observed.

4.3. Summary

In this chapter, results on the structure of several neutron-rich Boron isotopes have been presented. First, ^{14}B states were populated via the $^{15}\text{B}(p,pn)$ reaction. Several new positive-parity unbound states are reported to be populated via the neutron knockout from the $0p_{1/2}$ and $0p_{3/2}$ orbitals. Furthermore, the ground-state valence neutron configuration of ^{15}B was found to be dominated by an almost pure $1s_{1/2}$ occupation. In contrast, the authors of [56] report a dominant $0d_{5/2}$ configuration for the g.s. of ^{17}B . Thus, the addition of just two more neutrons to the ^{15}B system, where the valence neutrons occupy the $1s_{1/2}$ orbital, appears to scatter all four valence neutrons to the $0d_{5/2}$ orbital.

Results on the $^{16}\text{C}(p,2p)^{15}\text{B}$ reaction have also been presented. This includes the identification of several new unbound states and their corresponding decay mechanisms. The cross sections and the corresponding spectroscopic factors (C^2S) for each identified state were extracted and compared with shell-model calculations. A reduction in the experimental ground-state C^2S was observed in comparison to the SM predictions. As discussed, this discrepancy arises from the mismatch between the g.s. configuration obtained from the shell-model calculations and the true configuration of ^{15}B inferred from the $^{15}\text{B}(p,pn)$ reaction.

Finally, results on the structure of ^{17}B , populated via the QFS proton knockout from ^{18}C , are discussed. A γ -ray transition, from a state at 1.64(3) MeV, above the currently established S_{2n} of ^{17}B (1.38(21) MeV), has been observed and tentatively assigned a J^π of $1/2^-$. Above the S_{2n} , the $^{15}\text{B}+2n$ spectroscopy reveals the possible presence of several structures in the relative energy distribution. However, these could not be resolved in the current experiment given the limited statistics and resolution of the setup. The cross

4. Spectroscopy of Boron isotopes

sections and the C^2S corresponding to the identified states were also extracted and compared to SM calculations. In this case too, there appears to be a discrepancy between the experimental g.s. C^2S and the SM prediction. However, unlike in the $^{16}\text{C}(p,2p)^{15}\text{B}$ case, the discrepancy in the g.s. configuration is not as prominent between the calculations and the true configuration. The cross section of the $1/2^-$ state at 1.64 MeV is also found to be very small, comprising only $\sim 20\%$ of the strength predicted by SM for the lowest lying $1/2^-$ state.

A possible near threshold state is also indicated around $E_{rel} = (0.4 - 0.5)$ MeV in the $^{15}\text{B} + 2n$ spectrum. A similar feature was also reported in the work of [7]. However, the authors of that work ruled out the presence of a resonance based on the argument that the peak matches another low-energy structure originating from 1-neutron cross-talk events from the $^{17}\text{C}(-1p)^{15}\text{B} + 1n$ channel (section 1.5). If present, this state could be compatible with the above-threshold state decaying via γ -ray emission. However preliminary calculations indicate that this relative energy is too high for such a competitive decay to occur. Therefore, it is possible that another state exists extremely close to the threshold but was not observed in the current experiment due the limitations of the setup.

5. nn -analysis

Results on the spectroscopy of the neutron-rich Boron isotopes were presented in the previous chapter. In particular, new results on the two-neutron spectroscopy of ^{15}B and ^{17}B were discussed, following proton removal from ^{16}C and ^{18}C , respectively. It is noted that, for both channels a significant portion of the Fragment+2n resonant system decays via direct 2-neutron emission. In this chapter, the study of the nn -distributions associated with the identified resonant systems undergoing direct two-neutron emission is presented. This analysis has been carried out for different total Fragment+2n relative energy ranges. Firstly, a direct decay case corresponding to a resonance at higher total relative energy ($\sim E_{rel} > 2$ MeV) in the $^{15}\text{B} \rightarrow ^{13}\text{B} + 2n$ system is presented. This will then be followed by the study of the nn -correlations in near-threshold resonances identified in the $^{17}\text{B} \rightarrow ^{15}\text{B} + 2n$ and $^{14}\text{Be} \rightarrow ^{12}\text{Be} + 2n$ systems.

As mentioned previously, several examples of the nn -final state interaction (FSI) signature have been observed across a wide range of neutron-rich light nuclei [15, 16, 19, 20, 90]. This signature appears as a systematic enhancement at low nn relative energy and has been proposed to be a universal behavior for weakly bound neutron rich light nuclei. It is considered to be a consequence of the overlap between the weakly bound initial state of the neutrons inside the nucleus and the final state where the neutrons are unbound. The neutron then appear to interact in the final state, which manifests as a correlation with a signature similar to low-energy nn -scattering. An analogous description could be provided for *proton-proton* systems in neutron deficient nuclei, although the interaction is more complex due to the presence of the Coulomb potential. In the nn case, the nn -interaction, characterized by the neutron-neutron scattering length $a_s = -18.63(4)$ fm [21], is the dominant part of the FSI, owing to the absence of the Coulomb barrier.

The low-energy nn -interaction has been shown to be well described with the assumption of a virtual s -wave nn -interaction in accordance with the Watson-Migdal approximation [109, 110]. In this approximation, the two-neutron system in the final state is assumed to be in a virtual s -wave, characterized by the neutron-neutron scattering length a_s . This then manifests as a modification of the cross section distribution expected from a three-body phase-space (PS) decay by a correlation factor which changes as a function of the nn -relative momentum q_{nn} ,

$$\sigma(q_{nn}) = \sigma_{PS}(q_{nn})C_{nn}(q_{nn}), \quad (5.1)$$

where $\sigma(q_{nn})$ is the observed cross section distribution, $\sigma_{PS}(q_{nn})$ the phase-space cross section and $C_{nn}(q_{nn})$ the nn -FSI correlation function introduced to modify the phase-space cross section. The C_{nn} is governed by the nn -scattering length a_s , and the general form at low relative momentum is given by,

$$C_{nn}(q_{nn}) = \frac{a_s^2}{1 + 2\mu E_{nn} a_s^2}, \quad (5.2)$$

where E_{nn} is the nn relative energy and μ , the reduced mass.

The authors of [111], further defines a formalism based on this approximation to parameterize the nn -interaction as a function of the relative distance between the neutrons. Thus, the s -wave scattering amplitude is further modified by assuming a Gaussian source parameterized by the relative space-time parameters of the two neutrons. Therefore in this case, the nn -FSI correlation function C_{nn} depends on both the nn -interaction and the parameterized size of the source emitting the two neutrons, allowing for the modification of the strength of the nn -FSI signal. Although the assumption of a Gaussian source emitting two neutrons appears too simplistic, this model has been successful in accurately describing the low-energy nn -distribution as shown in [18, 20, 90].

Such a parameterized phenomenological approach of describing the nn -interaction has clear disadvantages in providing a full description of the scattering state. This is because, no information on the structure of the system emitting the two neutrons is included, nor is the role that the core- n sub-system plays in the modification of the said nn -interaction. Furthermore, it does not take into account the relative internal momentum distributions between the two neutrons which could modify the FSI signal. The authors of [112] indicate the possible contributions of from p - and d -wave neutron configurations in addition to the s -wave configuration, which could modify the nn -FSI signature. The only information the current formalism gives is whether the signature of an s -wave nn -FSI is present or not. Modern microscopic calculations employing a proper three-body modeling, such as those reported in the work of [15], provide deeper insight into the correlations arising out of the three-body decay, as well as a stronger theoretical argument.

5.1. $^{15}\text{B} \rightarrow ^{13}\text{B}+2n$

The spectroscopy of the $^{13}\text{B}+2n$ system, populated via $^{16}\text{C}(p,2p)^{15}\text{B} \rightarrow ^{13}\text{B}+2n$, has been discussed in section 4.1.3. Here, the analysis of the nn -distributions corresponding to the $^{13}\text{B}+2n$ resonance, identified at $E_r = 2.43(25)$ MeV ($E_x(^{15}\text{B}) = 6.18(30)$ MeV), is presented. The analysis of the two-body $^{13}\text{B}+1n$ distributions, corresponding to this resonance has been presented in section 4.1.3. It was observed that part of the system decays sequentially through the previously identified 0.32 MeV resonant state in ^{14}B (section 4.1.2), while most of it decays via simultaneous neutron emission to the g.s. state of ^{13}B (see Fig. 4.17).

The fitted nn E_{rel} and m_{nn}^2 distributions along with the corresponding sequential and direct decay contributions are shown in Fig. 5.1. For direct decay, the distributions used in the fits are obtained from simulations taking into account three-body phase-space decay shown in Fig. 5.1 (top) and nn -FSI in Fig. 5.1 (bottom). It is evident that the phase-space direct decay alone cannot fully describe the experimental nn -distributions, where a strong enhancement at low nn -relative energies is observed. This enhancement towards lower nn -relative energies is the characteristic signature of s -wave nn -FSI. In contrast, an excellent agreement with the experimental data is OBSERVED for the fit with the simulated distribution including the nn -FSI. This is consistent with all previous results on nn -distributions corresponding to two-neutron decay in neutron-rich light nuclei. Therefore, a clear and strong nn -FSI signal for the resonance at $E_r = 2.43$ MeV in the $^{13}\text{B}+2n$ system is confirmed.

Of interest would be to study the nn -distributions for the lower energy resonance at $E_r = 0.70(25)$ MeV (see Fig. 4.12). However, the decay pattern for this state was found to be predominantly sequential through the 0.32 MeV state in ^{14}B (c.f. Fig. 4.16). Neutrons undergoing sequential decay generally lose the signature of the nn -FSI and the nn relative energy simply spreads out over the available phase-space.

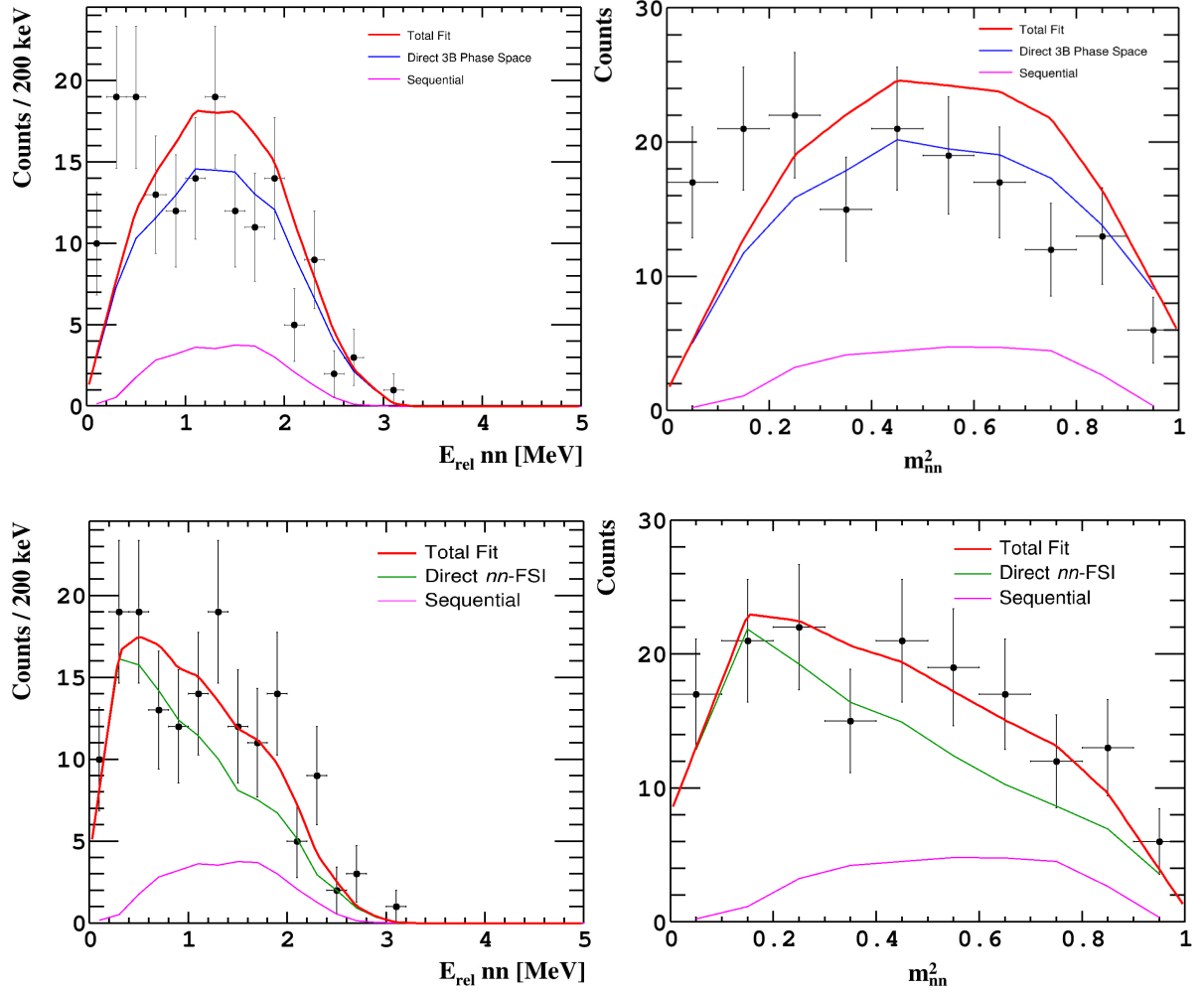


Figure 5.1.: *Top:* Fit of $E_{\text{rel}}(nn)$ (left) and m_{nn}^2 (right) distributions corresponding to the resonance at $E_r = 2.43$ MeV in the $^{13}\text{B} + 2n$ channel. The fits include the sequential (in pink) and three-body phase-space direct decay (in blue) components. **Bottom:** $E_{\text{rel}}(nn)$ (left) and m_{nn}^2 (right) distributions for the same channel, fitted with sequential decay (in pink) and direct decay with nn -FSI (in green). The bottom plots clearly show a better agreement with the experimental data.

5.2. $^{17}\text{B} \rightarrow ^{15}\text{B}+2n$

Details on the spectroscopy of ^{17}B from the $^{18}\text{C}(\text{p},2\text{p})$ QFS reaction have been presented in section 4.2. A γ -ray transition at $E_\gamma = 1.64(3)$ MeV, above the current S_{2n} (1.38(21) MeV) of ^{17}B , has been observed. However, as previously noted, given the large uncertainty in the S_{2n} , the identified state could still lie below the S_{2n} within 2σ of the uncertainty. An indication of a compatible resonant state around $E_r \approx 0.45$ MeV ($E_x \approx 1.8(2)$ MeV) was also observed in the $^{15}\text{B}+2n$ relative energy distribution obtained in coincidence with the QFS protons (see Fig. 4.26). However, the statistics in the $^{15}\text{B}+2n$ channel are too low to confirm the presence of the resonance. One way to increase the statistics is to relax the strict (p,2p) QFS condition (see section 3.2.1). This approximation remains valid provided that the neutron multiplicity and the four-momenta of the two neutrons are reconstructed accurately. This is because the selection of the incoming and outgoing ions, together with the correct neutron multiplicity, ensures the selection on a proton knockout reaction. Consequently, this imposes a strong constraint on the reconstruction procedure, requiring the neutron multiplicity to be determined with high accuracy. In particular, when a single neutron interacts in the detector, it must be reconstructed as a 1-neutron event. Without the selection on the reaction mechanism (in this case, (p,2p)) increases the likelihood of having more 1-neutron events overall, some of which could be wrongly reconstructed as 2-neutron events. This concern of having significant 1-neutron cross-talk contribution was also highlighted in [7], where states of ^{17}B were populated via a multi-nucleon knockout reaction from ^{19}C without any selection on the reaction mechanism. A pronounced peak at $E_{rel} \sim 400$ keV was also observed in their reconstructed $^{15}\text{B}+2n$ relative energy spectrum. However, the authors also reconstructed a "fake" 2-neutron relative energy spectrum from 1-neutron events corresponding to $^{15}\text{B}+1n$ channel, obtained assuming proton knockout from incoming ^{17}C beam. These events should therefore correspond purely to cross-talk events, assuming charge exchange contribution on the ^{17}C beam is low. This cross-talk 2-neutron spectrum also exhibited a peak at around 400 keV, leading the authors to conclude that the peak observed in the true $^{15}\text{B}+2n$ spectrum was not real, but rather a result of cross talk (see Fig. 1.6).

With the current causality reconstruction method, approximately $\sim 3\%$ of the incoming 1-neutron events will be reconstructed as 2-neutrons. Although this fraction is already quite low, the objective is to reduce it further in order to increase confidence in the presented results. Therefore, a modification to the causality reconstruction method is proposed to further suppress one-neutron cross-talk events. This is feasible because the removal of the QFS condition provides significantly higher statistics. The changes to the reconstruction method are discussed below:

- To cleanly separate out 1-neutron and 2-neutron events in NeuLAND, its calorimetric properties, as described in [75], is exploited. For this purpose, after the clustering step in the causality method reconstruction procedure (see section 3.4.1), the total number of clusters and the total deposited energy per event in NeuLAND are determined and plotted in a two-dimensional (2-D) histogram. To distinguish between the distributions obtained from the 1-neutron and 2-neutron events, this plot must be reconstructed using clean 1-neutron and 2-neutron events. For the clean 1-neutron events, the $^{16}\text{C}(\text{p},2\text{p})^{15}\text{B} \rightarrow ^{14}\text{B}+1n$ channel was chosen. A 2-D plot of the total cluster multiplicity versus total deposited energy was reconstructed for all events with total $^{14}\text{B}+1n$ relative energy ≤ 2 MeV (see Fig. 4.4). This relative-energy cut ensures that the final distribution is free from acceptance effects. The obtained 2-D distribution is shown in Fig. 5.2 (left) with the green points. For clean 2-neutron events, the $^{15}\text{B}(\text{p},2\text{p})^{14}\text{Be} \rightarrow ^{12}\text{Be}+2n$ channel was chosen. As will be discussed in the following section, in this channel, a 250 keV resonance right above the S_{2n} is populated. Since no other 1-neutron states of ^{13}Be exist below 400 keV (the ^{13}Be ground state lies at 450 keV above S_{2n}), all events with the two-body relative energy below $E_{rel}(^{12}\text{Be}+1n) \leq 200$ keV should

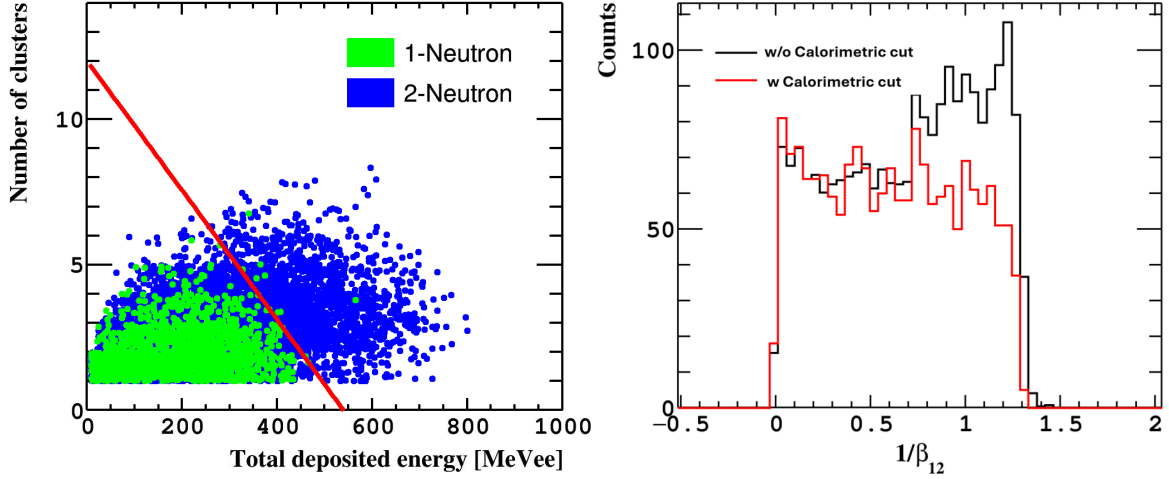


Figure 5.2.: *Left:* Total cluster multiplicity *vs* Total deposited energy distributions for 1- neutron (in green) and 2-neutron (in blue) events. The cut separating the 1-neutron events from the clean 2-neutron events, used in the current analysis, is shown in red (see text). *Right:* The $1/\beta_{12}$ (virtual velocity between two clusters) velocity distribution for the causality method with and without the calorimetric cut.

correspond to this resonance in the three-body $^{12}\text{Be} + 2n$ system. This cut on the relative energy ensures the selection of the resonance, thereby avoiding acceptance effects in the final distribution. The 2-D plot of total cluster multiplicity versus total deposited energy was then constructed for all events with $E_{\text{rel}}(^{12}\text{Be} + 1n) \leq 200$ keV. The choice of obtaining the 2-D plot using a cut on the two-body $^{12}\text{Be} + 1n$ relative energy rather than the reconstructed three-body $^{12}\text{Be} + 2n$ relative energy is to avoid biases in the distribution induced by the 2-neutron reconstruction procedure. The final distribution obtained for the 2-neutrons events is shown in Fig. 5.2 (left) with the blue points. While the distribution of the $1n$ events completely overlaps with a part of the $2n$ distribution, a clear difference is observed between the two distributions, where the $2n$ events extend to larger cluster multiplicities and total deposited energies as compared to the $1n$ events. Based on this, a cut is defined to remove most of the $1n$ events while still retaining a portion of the $2n$ events. The cut is indicated by the red line in Fig. 5.2 (left). The advantage of such a *calorimetric* cut is that it does not affect the relative energy distribution. However, as expected, it further reduces the reconstruction efficiency.

- After the *calorimetric* cut, the remaining events are likely to be predominantly two-neutron interactions in NeuLAND. To recover statistics, the other selection cuts can therefore be relaxed. The causality condition is therefore applied by excluding clusters with $\beta_{01}/\beta_{12} > 1$. The choice of this cut is further discussed in the following point.
- It was found that the cut for the γ -crosstalk can now be completely removed. This is illustrated in Fig. 5.2 (right), where the comparison of the $1/\beta_{12}$ distributions (see section 3.4.1) are shown for the standard causality method and that obtained with the additional calorimetric cut, after applying the causality condition from the previous point and requiring exactly two reconstructed neutrons for the $^{15}\text{B} + 2n$ channel. The histograms are scaled to match the integral in the region of $1/\beta_{12} = 0 - 0.5$. As can be observed, there is an enhancement for $1/\beta_{12} \geq 0.8$ in the standard method, which is absent in the distribution with the calorimetric cut. This enhancement, in the standard method, arises partly from the γ -crosstalk centered at $1/\beta_{12} = 1$, and partly from the incomplete removal of the causality hits, which were removed with the strict cuts defined in section 3.4.1. Since, this enhancement disappears after the calorimetric cut, it justifies the removal of the

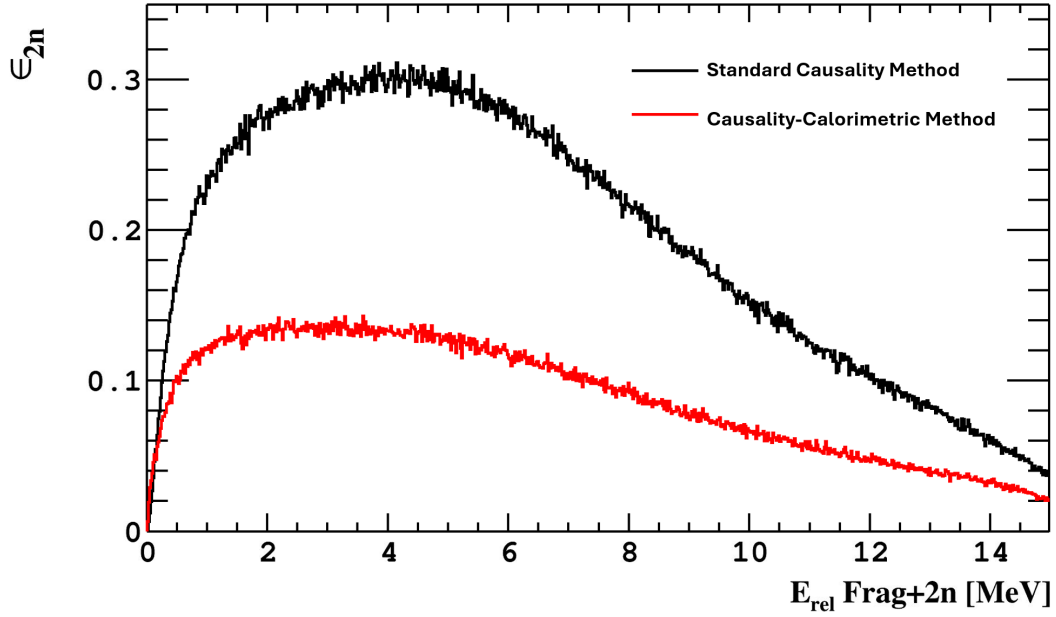


Figure 5.3.: Efficiency distribution as a function of the reconstructed relative energy for the "causality-calorimetric method" (in red) compared to the standard "causality method" (in black).

γ -crosstalk cut and relaxation of the causality condition.

After applying the above conditions, only 0.4% of 1-neutron events are reconstructed as 2-neutron events, reducing the 1-neutron cross-talk contribution by an order of magnitude. The Fragment+2n efficiency distribution obtained after applying these conditions is shown in Fig. 5.3, and compared to the distribution from the standard causality method. As can be observed, the overall efficiency is nearly $\sim 55\%$ of the original distribution. However, it is important to note that despite this reduction, the analysis can now be performed without the QFS proton selection, resulting in an overall gain in statistics. Additionally, this modification offers several advantages over the standard "causality method" due to the relaxed velocity cuts. Firstly, the efficiency distribution is less biased at low total relative energies. Secondly, similar to the "two-wall" method, the nn -distributions are more sensitive at lower relative energies compared to the standard "causality method". It is also important to point out that, even though this method decreases the probability of reconstructing 1-neutron events as 2-neutrons, it does not significantly suppress the cross-talk arising from bad reconstructions within the 2-neutron events.

The reconstructed $^{15}\text{B}+2n$ relative energy spectrum corresponding to the $^{18}\text{C}(-1p)^{17}\text{B} \rightarrow ^{15}\text{B}+2n$ reaction, obtained with the standard "Causality" method and without the selection on the QFS protons, is shown in Fig. 5.4. In this case, a clear peak at $E_{rel} \sim 0.4$ MeV is observed with high statistical significance. In comparison, the relative energy distribution for the same reaction, obtained without the QFS cuts using the "Causality-calorimetric" method described above, is shown in Fig. 5.5. In this case too, a peak is observed at $E_{rel} \sim 0.4$ MeV. Thus, a near-threshold peak around ~ 0.4 MeV is observed in the reconstructed relative energy distributions obtained from both methods. However, the causality-calorimetric method offers clear advantages over the standard causality method, including a lower probability of reconstructing 1-neutron cross-talk events and improved sensitivity to the shape of the nn distributions at low relative energies, which is the focus of the current analysis. Accordingly, the remainder of the analysis is carried out using the causality-calorimetric method, although the results will also be compared with the "Two-wall" method introduced in section 3.4.2, which is similarly sensitive to low-energy nn -distributions.

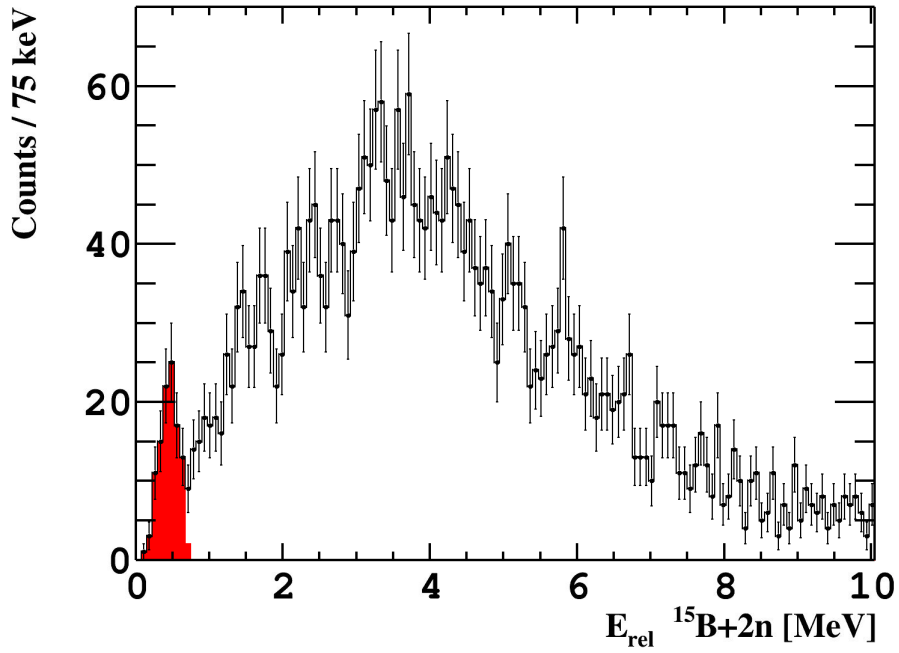


Figure 5.4.: Relative energy spectrum for $^{18}\text{C}(-1\text{p})^{17}\text{B} \rightarrow ^{15}\text{B} + 2\text{n}$ reconstructed using the "Causality method" **without** selection on the QFS protons. The region of the near-threshold peak around $E_r \sim 0.4$ MeV is highlighted.

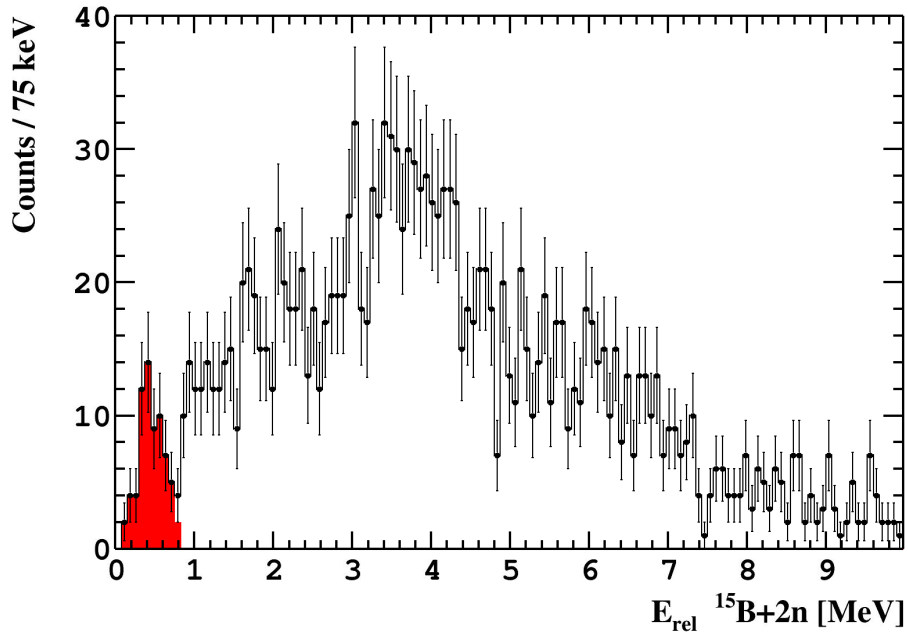


Figure 5.5.: Relative energy spectrum for $^{18}\text{C}(-1\text{p})^{17}\text{B} \rightarrow ^{15}\text{B} + 2\text{n}$ reconstructed using "causality-calorimetric method" (see text) **without** selection on the QFS protons. The region of the near-threshold peak around $E_r \sim 0.4$ MeV is highlighted.

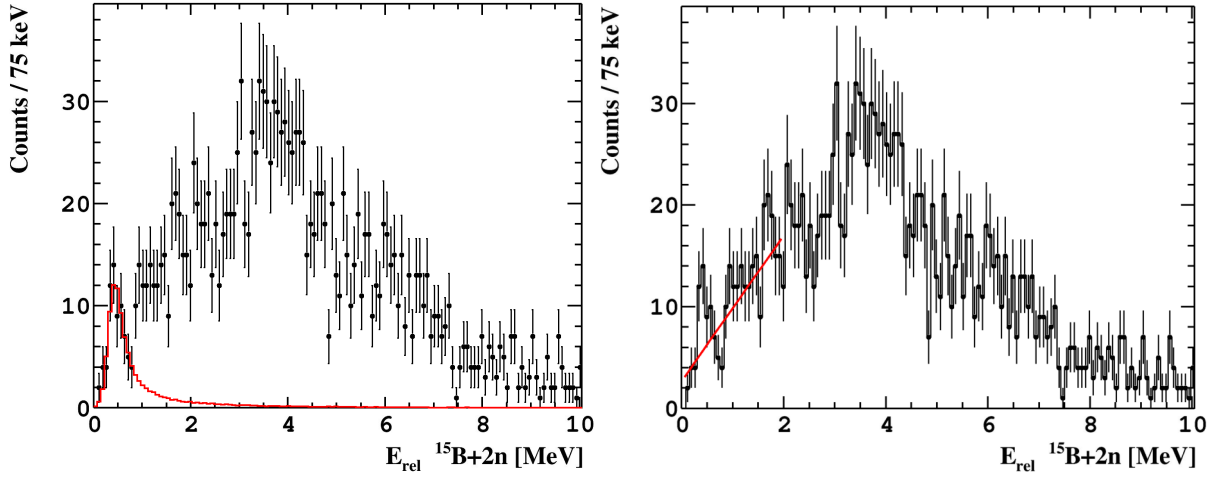


Figure 5.6.: *Left:* $^{15}\text{B}+2\text{n}$ relative energy distribution without the QFS ($p,2p$) cut, with the near-threshold peak fitted with a simulated resonance following a Breit-Wigner distribution. *Right:* The same spectrum fitted with a linear distribution from 0 – 2 MeV to estimate the "background" and the significance of the observed peak.

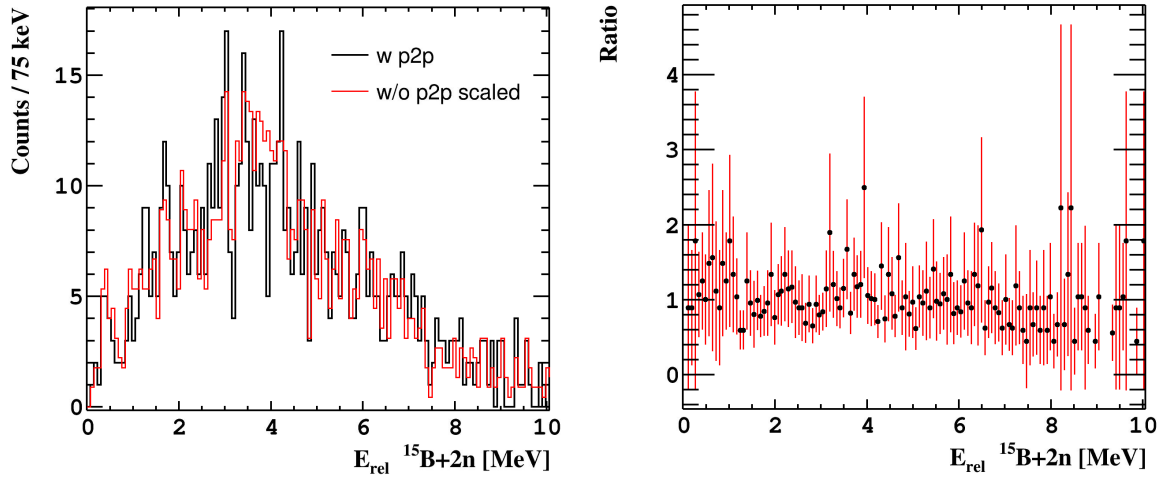


Figure 5.7.: *Left:* $^{15}\text{B}+2\text{n}$ relative energy distribution with QFS ($p,2p$) cut (in black) and without ($p,2p$) cut (in red). The distribution without the QFS condition is scaled to match the one with the QFS condition. *Right:* The ratio of the two relative energy distributions on the left.

The peak identified in Fig. 5.5, is fitted with a simulated resonance following a Breit Wigner distribution, as shown in Fig. 5.6 (left). The parameters of the simulated resonance that best describes the distribution was found to be $E_r = 401(30)$ keV and $\Gamma_r < 150$ keV. Only an upper limit on the width could be estimated, as the fit was not sensitive to it given the available statistics and the resolution of the setup. Finally, the significance of the peak was also estimated by modeling the "background" distribution with a linear fit in the range of $E_{rel} = 0 - 2$ MeV, as shown in Fig. 5.6 (right). Although this process likely overestimates the background, the significance of the peak was still found to be $\sim 4.5 \sigma$.

A study was conducted to evaluate whether removing the (p,2p) QFS condition still reproduces the correct $^{15}\text{B} + 2\text{n}$ spectrum while improving statistics. This comparative study is illustrated in Fig. 5.7. The left panel shows the overlap of the $^{15}\text{B} + 2\text{n}$ spectra with and without the QFS condition. The spectrum obtained without the QFS condition is scaled to match the integral of the distribution with the condition. As can be observed, there is a general agreement between the two distributions. This is further highlighted in the right figure, which shows the ratio of the non-QFS histogram to the QFS one. The distribution is essentially flat, with no significant structures, indicating good agreement between the two. It was therefore considered reasonable to perform the nn analysis using $^{15}\text{B} + 2\text{n}$ events without the strict QFS condition. It is noted, however, that despite the increase in total statistics, the number of counts in the peak remains low and the final analysis is limited by this. The low statistics also suggest that the cross section for this resonance is relatively small compared to the rest of the $^{15}\text{B} + 2\text{n}$ distribution, with most of the cross section concentrated at higher relative energies.

Since the 400 keV peak now has more statistics, the two-body $^{15}\text{B} + 1\text{n}$ distributions can be reanalyzed to identify the decay mechanism more accurately. The fits of the $E_{rel}(^{15}\text{B} + 1\text{n})$ and m_{fn}^2 spectra in the range $E_{rel} \in [0, 0.8]$ MeV, are shown in Fig 5.8. The best fit was found for a combination of direct and sequential decay components. The sequential component appears to decay through the ground state of ^{16}B at ~ 50 keV above the S_{2n} (see Fig. 4.24). The contribution from the sequential component was estimated to be around 30 - 45% of the total, while the remaining fraction appears to decay directly to the ground state of ^{15}B . This is inconsistent with the conclusions drawn from the same analysis for this energy range in the previous chapter, when the QFS (p,2p) condition was applied (see section 4.2.3), where only the direct decay component was sufficient to describe the full distribution. However, as already mentioned, the statistics in the 2-body $^{15}\text{B} + 1\text{n}$ distributions obtained with the QFS cut were extremely limited and could still be consistent with the inclusion of multiple components. Even in the present case without the QFS cut, the information that can be extracted is still limited due to the available statistics. This is evident with the large uncertainty associated with the relative contributions of the decay mechanisms. Furthermore, the contributions from the overlapping tails of other possible resonances in the distribution are difficult to account for. Though in this case, the peak appears to be well separated, suggesting that the relative contribution from the tails of higher-lying resonances should be small.

With the decay mechanism now constrained to some extent, the nn -distributions corresponding to the peak at 400 keV in the $^{15}\text{B} + 2\text{n}$ spectrum can be analyzed by studying the $E_{rel}(nn)$ and the m_{nn}^2 ($\approx E_{rel}(nn) / E_{rel}(^{15}\text{B} + 2\text{n})$) distributions. To this end, a comparison is made between the results from the two reconstruction methods, namely the "causality-calorimetric" method and the "two-wall" method described previously (see section 3.4.2).

Causality-calorimetric method – The $E_{rel}(nn)$ and the m_{nn}^2 distributions corresponding to an energy gate of $E_{rel} \in [0, 0.8]$ MeV in the $^{15}\text{B} + 2\text{n}$ spectrum, obtained using this method (Fig. 5.5), are shown in Fig. 5.9. The plots are shown along with the corresponding fits. The contribution from the sequential component is also included and fixed in the fits (pink distributions), while the direct decay components vary depending on the inclusion of nn -FSI. The direct decay components in the fits shown in the top panels correspond to the nn -distributions obtained assuming direct decay following simple three-body phase-space kinematics.

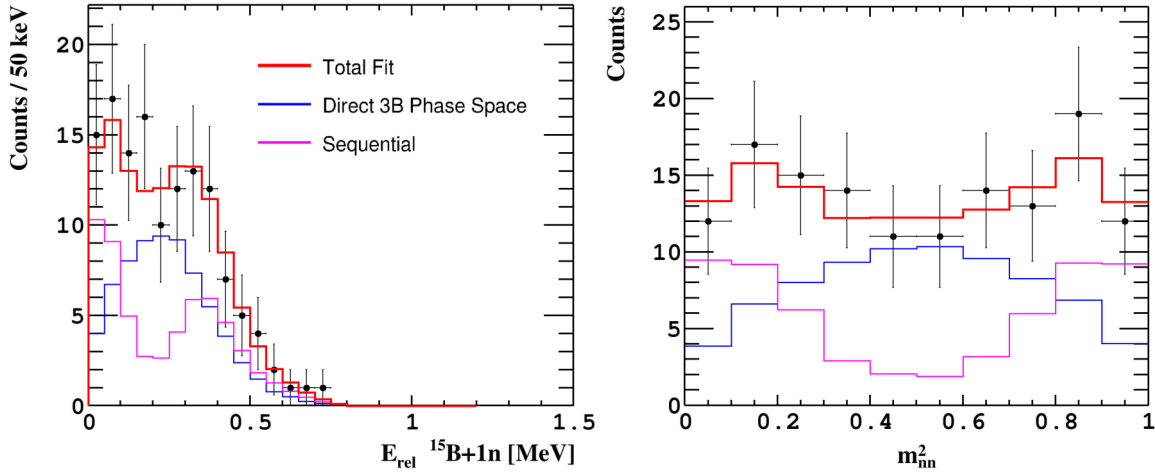


Figure 5.8.: *Left:* Two-body $^{15}\text{B}+1\text{n}$ relative energy distribution corresponding to the energy gate of $E_{\text{rel}} \in [0, 0.8]$ MeV in the three-body $^{13}\text{B}+2\text{n}$ spectrum, reconstructed with causality-calorimetric method, fitted with identified sequential (in pink) and direct decay (in blue) components. *Right:* m_{nn}^2 distribution corresponding to the same energy gate, shown with a fit using the same decay components.

On the other hand, the direct decay components in the fits shown in the bottom panels correspond to the nn -distributions obtained for direct decay including nn -FSI. The fits were carried out by keeping the total integral constant. The χ^2 values appear to slightly favor the fits including direct decay with nn -FSI. However, this difference appears to be minimal, especially considering the degrees of freedom and the fact that the overall shape of the total distributions changes only slightly with or without the inclusion of nn -FSI. This is a consequence of the extremely limited statistics compounded by the fact that the nn -FSI signal is generally very weak at low relative energies [112]. Consequently, given these limitations, no definitive conclusion can be drawn regarding the presence or absence of an nn -FSI signal.

Two-wall method – The $^{15}\text{B}+2\text{n}$ distribution without the QFS condition obtained with the "two-wall" reconstruction method, is shown in Fig. 5.10. For this method, the QFS condition is again removed due to limited statistics, which are lower than in the previous method with the calorimetric cut because of the lower reconstruction efficiency (Fig. 3.26). In this case, the probability of reconstructing a single neutron interaction as a two-neutron event in NeuLAND is $\sim 0.8\%$, and thus the reconstruction remains relatively reliable. A peak around 400 keV is again observed in the $^{15}\text{B}+2\text{n}$ spectrum obtained with this method, although in this case it appears slightly broader over larger background distribution. Following the same procedure as before, the decay mechanism can be estimated by studying the two-body $^{15}\text{B}+1\text{n}$ distributions. The $E_{\text{rel}}(^{15}\text{B}+1\text{n})$ and m_{nn}^2 spectra, along with their corresponding fits are presented in Fig. 5.11. The contributions from sequential and direct decay are observed to be in agreement with the conclusions drawn from the previous method. Similarly, the nn -interaction is studied by analyzing the $E_{\text{rel}}(nn)$ and the m_{nn}^2 distributions. The nn -distributions and their corresponding fits are shown in Fig. 5.12. As before, the sequential decay contributions are kept constant, while the direct decay components change based on the inclusion of nn -FSI. The top plots show fits with direct decay components following three-body phase-space kinematics, while the bottom plots show fits with direct decay components including nn -FSI. The χ^2 values again slightly favor the direct decay including nn -FSI. However, the statistics for this method are even lower, resulting in significantly larger uncertainties compared to the previous method.

In this section, the $^{18}\text{C}(-1\text{p})^{17}\text{B} \rightarrow ^{15}\text{B}+2\text{n}$ channel has been revisited with a focus on the near-threshold state. In order to increase statistics, the $^{15}\text{B}+2\text{n}$ system was reconstructed without the QFS (p,2p)

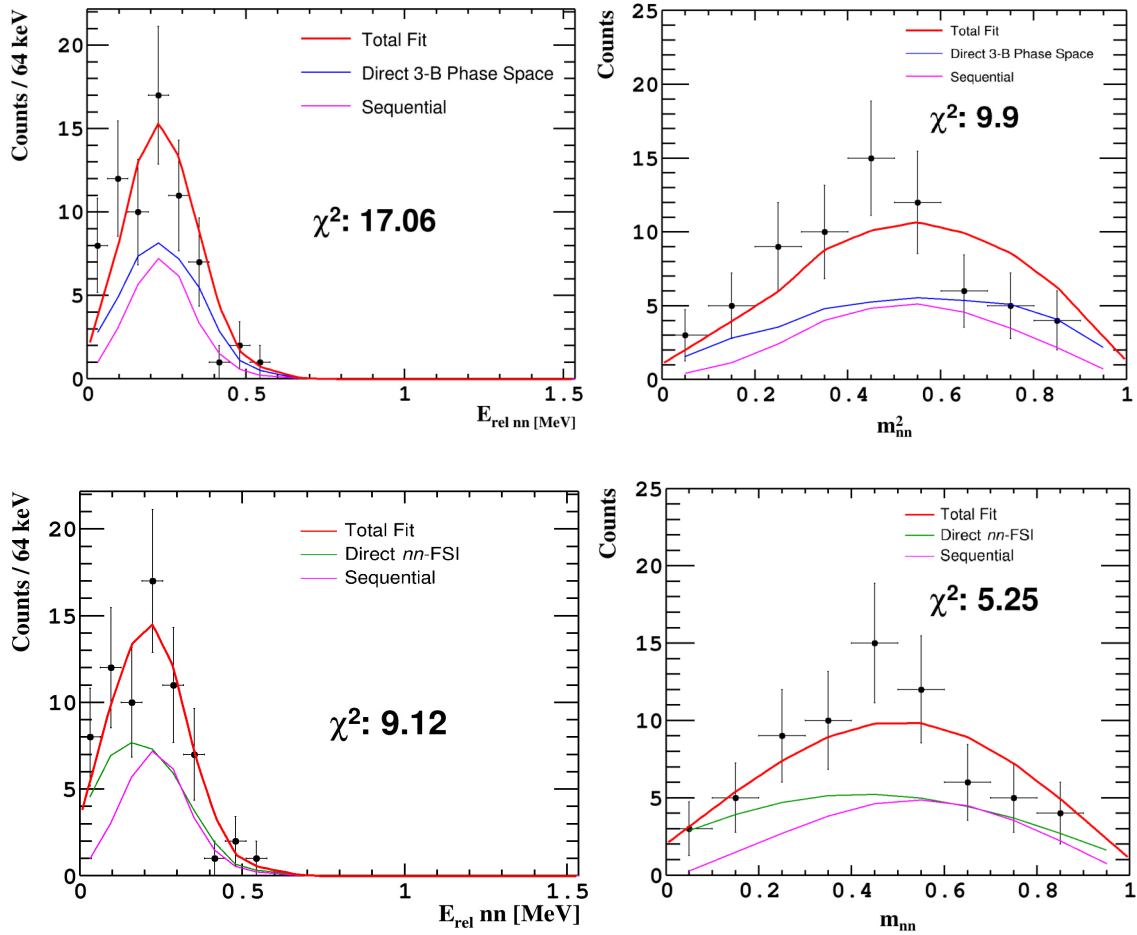


Figure 5.9.: *Top:* Fit of $E_{rel}(nn)$ (left) and m_{nn}^2 (right) distributions corresponding to an energy gate of $E_{rel} \in [0, 0.8]$ MeV in the three-body $^{13}\text{B} + 2n$ spectrum, reconstructed with the causality-calorimetric method. The fits include the sequential (in pink) and three-body phase-space direct decay components (in blue). *Bottom:* Fit of the same $E_{rel}(nn)$ (left) and m_{nn}^2 (right) distributions with components for sequential (in pink) and direct decay including nn -FSI (in green). The χ^2 values indicate a better fit when the direct decay component with nn -FSI is included.

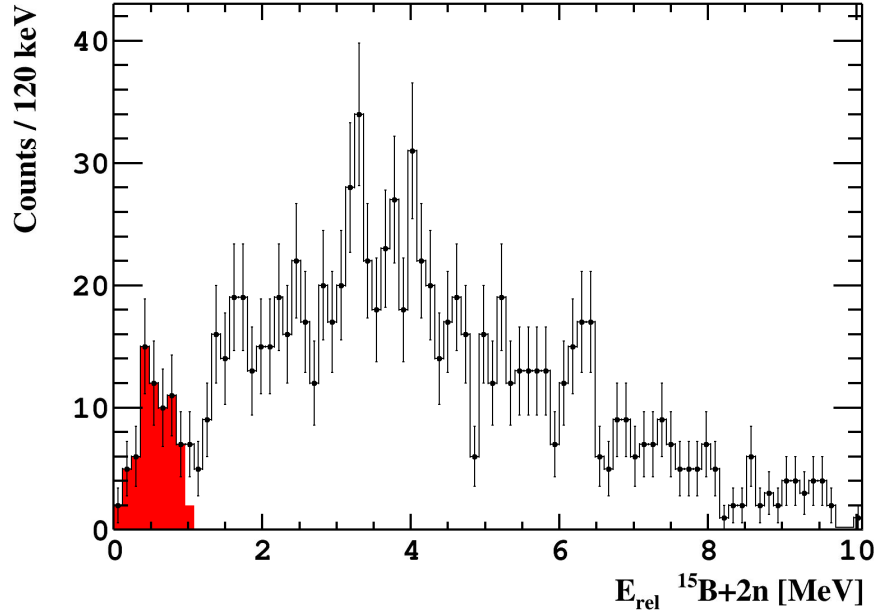


Figure 5.10.: Relative energy spectrum for $^{18}\text{C}(-1p)^{17}\text{B} \rightarrow ^{15}\text{B}+2n$ reconstructed using "two-wall method" **without** selection on the QFS protons. The region of the near-threshold peak around $E_r = 0.4$ MeV is highlighted.

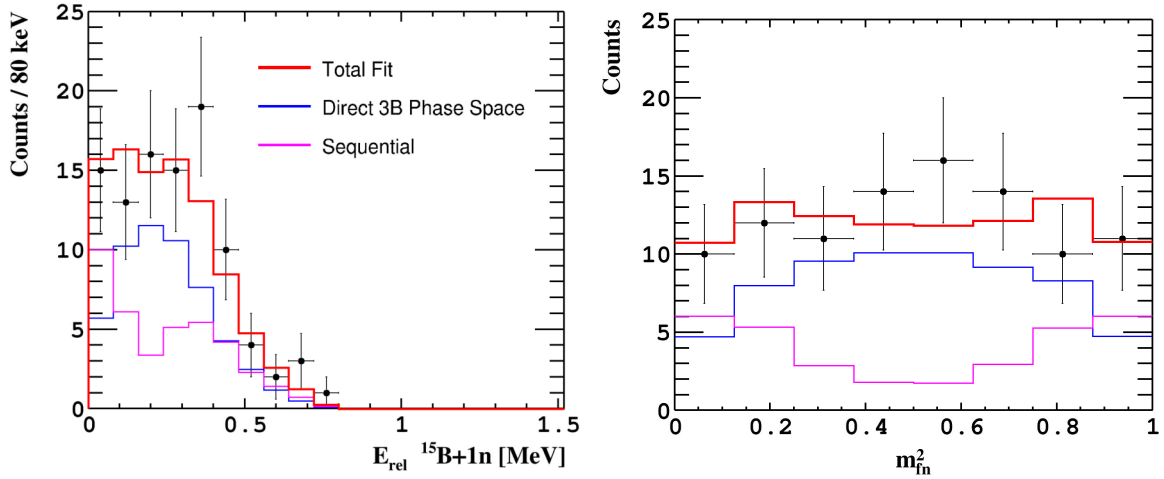


Figure 5.11.: **Left:** Two-body $^{15}\text{B}+1n$ relative energy distribution corresponding to the energy gate $E_{rel} \in [0.2, 0.8]$ MeV in the three-body $^{13}\text{B}+2n$ spectrum, reconstructed with the two-wall method, fitted with identified sequential (in pink) and direct decay components (in blue). **Right:** m_{fn}^2 distribution corresponding to same energy gate, fitted with components following the same decay mechanism.

condition. The reconstruction using three different methods, namely the standard causality, the causality-calorimetric and the two-wall methods, all indicate the presence of a peak at ~ 0.4 MeV. Additionally, the extracted decay scheme corresponding to this resonance also shows an agreement between the methods, exhibiting both direct decay and sequential components. Finally, the analysis of the nn -distributions corresponding to this resonance at ~ 0.4 MeV, indicates a possible nn -FSI contribution in the direct decay component; however, the difference between the fits with and without FSI is minimal. This is due to the limited statistics in both cases, and the strong sequential component, which further obscures the contribution from the direct decay component, making extraction of the FSI contribution difficult. Therefore a definitive conclusion cannot be drawn.

The study of the nn -FSI at higher energies in the $^{17}\text{B} \rightarrow ^{15}\text{B}+2\text{n}$ system is not presented here due to several complication. First, the structure of the $^{15}\text{B}+2\text{n}$ system is not well constrained, since unique resonances could not be identified at the higher relative energies, although there consistently appears to be an enhancement in the range of $E_{\text{rel}} = 3 - 4$ MeV (see Fig. 5.4–5.5). Second, as discussed in section 4.2.3, there is a complex overlap of several sequential decays within each energy gate, which is difficult to disentangle. This makes the analysis of the final nn -distribution particularly challenging. Finally, certain nn -distributions were observed which appear to diverge from the standard expected distributions corresponding to FSI/phase-space. The analysis and interpretation of these distributions are still under progress and hence not presented.

5.3. $^{15}\text{B}(-1\text{p})^{14}\text{Be} \rightarrow ^{12}\text{Be}+2\text{n}$

^{14}Be is a weakly bound ($S_{2n} = 1.27(13)$ MeV [8]) Borromean nucleus, since ^{13}Be is unbound with respect to one-neutron emission. It has been proposed to exhibit a two-neutron halo structure with a ^{12}Be core and two weakly bound neutrons [113]. A narrow near-threshold 2_1^+ resonant state has previously been reported at 280(10) keV [3] above the S_{2n} ($E_x(^{14}\text{Be}) = 1.27+0.28 = 1.56$ MeV). This resonance was observed in the $^{12}\text{Be}+2\text{n}$ relative energy distribution, populated via inelastic scattering of ^{14}Be on a carbon target. This state is known to decay directly to the ground state of ^{12}Be , as there are no intermediate states for the system to decay through due to the higher ground state energy of ^{13}Be (0.44(1) MeV [114]). In the current work, ^{14}Be is populated via proton removal from ^{15}B . Results concerning the structure of ^{14}Be following $^{15}\text{B}(p,2p)^{14}\text{Be}$ QFS reaction are not discussed here. The focus is instead on the nn -distributions associated with the near-threshold 2_1^+ resonant state at 280 keV in the $^{12}\text{Be}+2\text{n}$ system, which is also populated in the current reaction (Fig. 5.13). Previous studies [115, 116] have shown that the nn -relative energy distribution for this state can be well described by a three-body phase-space decay without requiring the inclusion of nn -FSI. A similar analysis is presented here, where the experimental nn -distributions are fitted with simulated direct decay components with and without the inclusion of nn -FSI.

In order to increase statistics, as done previously for ^{17}B , the $^{12}\text{Be}+2\text{n}$ relative energy distribution can be reconstructed without the selection on the QFS protons in CALIFA. As discussed in the previous section, this is a reasonable approximation provided the two neutrons are reconstructed correctly and no additional structures appear in the relative energy spectrum. The test for this is illustrated in Fig. 5.14. The left panel shows the $^{12}\text{Be}+2\text{n}$ relative energy distributions reconstructed with the "causality-calorimetric method" (discussed in the previous section) with and without selection on the QFS protons. The latter is scaled to match the integral of the former for comparison. A good agreement between the two distributions can be observed. This is further highlighted with the figure on the right panel, which shows the ratio of the two

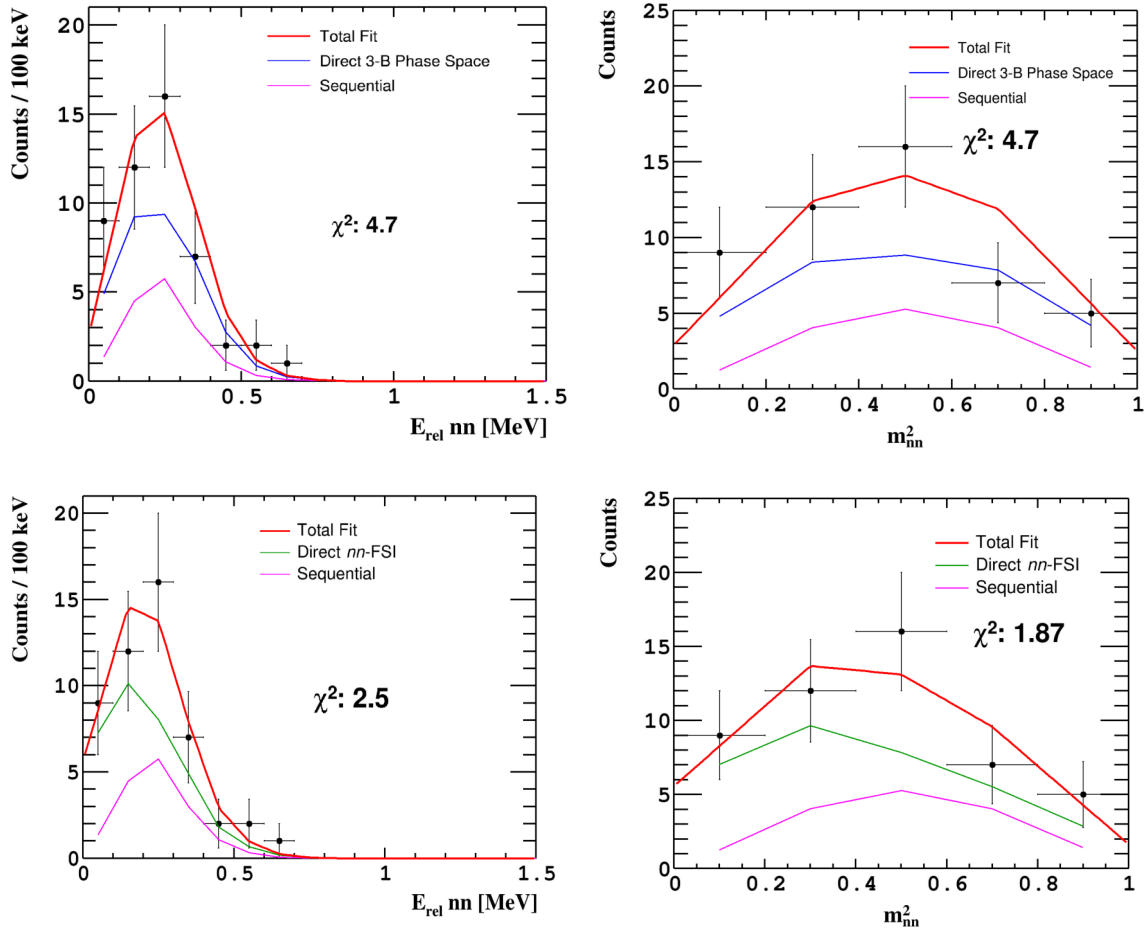


Figure 5.12.: **Top:** Fit of $E_{rel}(nn)$ (left) and m_{nn}^2 (right) distributions corresponding to an energy gate of $E_{rel} \in [0.2, 0.8]$ MeV in the three-body $^{13}\text{B}+2n$ spectrum, reconstructed with the two-wall method. The fits include the sequential (in pink) and three-body phase-space direct decay (in blue) components. **Bottom:** Fit of the same $E_{rel}(nn)$ (left) and m_{nn}^2 (right) distributions with components for sequential (in pink) and direct decay including nn -FSI (in green). The χ^2 values indicate a better fit when the direct decay component with nn -FSI is included.

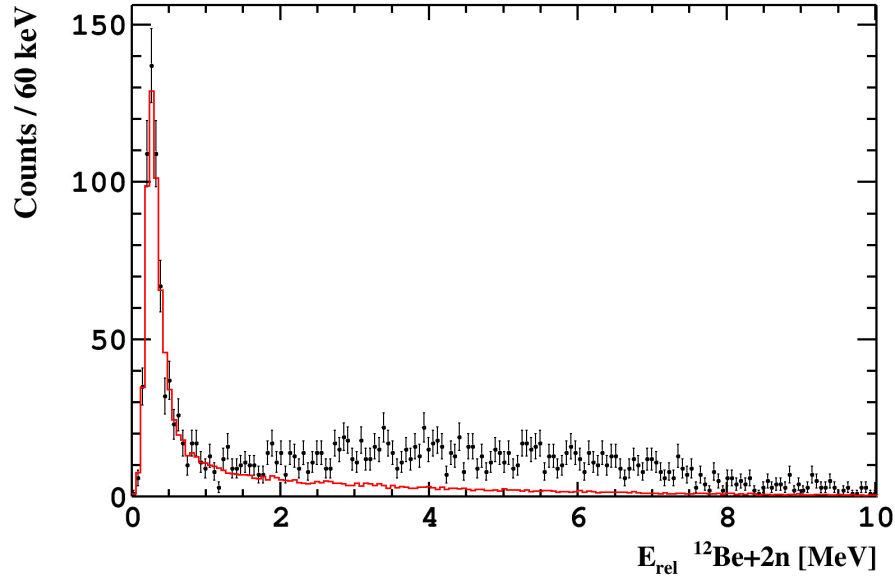


Figure 5.13.: Relative energy spectrum for $^{15}\text{C}(-1p)^{14}\text{Be} \rightarrow ^{12}\text{Be}+2n$ reconstructed using "causality-calorimetric method" **without** selection on the QFS protons. The near-threshold resonance at $E_r = 0.24$ MeV is fitted with a simulated resonance following a Breit-Wigner distribution with an $L = 2$ neutron emission.

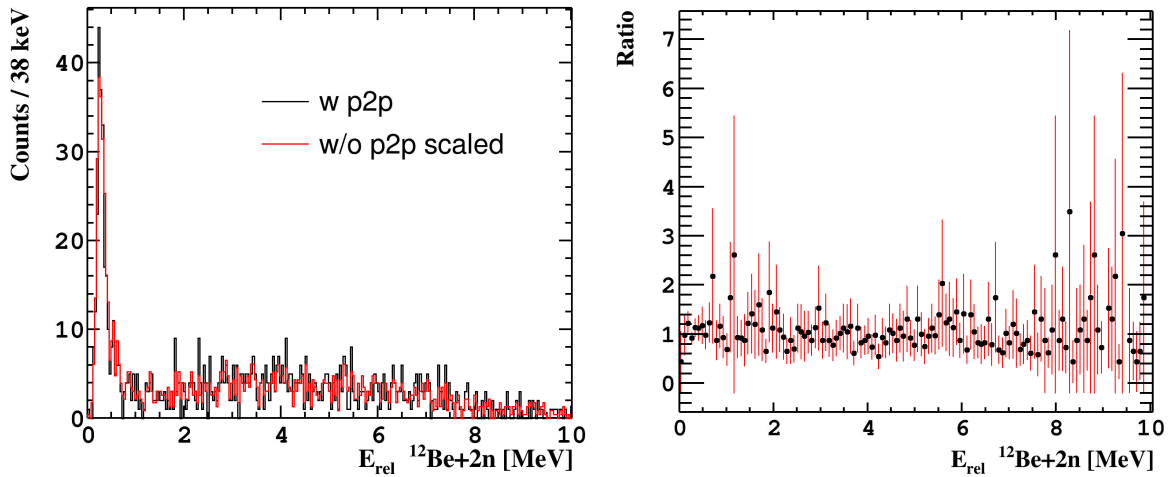


Figure 5.14.: **Left:** $^{12}\text{Be}+2n$ relative energy distribution with QFS ($p,2p$) cut (in black) and without ($p,2p$) cut (in red). The distribution without the QFS cut is scaled to the one with the QFS cut. **Right:** The ratio of the two relative energy distributions on the left.

spectra on the left. The distribution is observed to be essentially flat with no distinct additional structures. Therefore, the $^{12}\text{Be}+2n$ events without the QFS condition are used for the subsequent analysis.

The $^{12}\text{Be}+2n$ relative energy distribution reconstructed with the causality-calorimetric method is shown in Fig. 5.13. The prominent low-energy resonance at $E_r \sim 250$ keV is fitted with a simulated resonance following a Breit-Wigner distribution assuming an $L = 2$ decay. An $L = 2$ neutron emission is chosen, since the state has a spin of 2_1^+ , which decays directly to the 0_1^+ state of ^{12}Be . The parameters of the simulated resonance that best reproduce the peak were found to be $E_r = 240(30)$ keV and $\Gamma_r = 20_{-20}^{+60}$ keV. It is evident that the 240 keV resonance does not reproduce the full experimental distribution, especially at higher relative energies, which indicates the presence of additional structure beyond just the 2_1^+ state.

In order to study the nn -distribution associated with the 240 keV resonance, the corresponding $E_{rel}(nn)$ and the $m_{nn}^2 (\approx E_{rel}(nn) / E_{rel}(^{12}\text{Be}+2n))$ spectra were analyzed. For this analysis, the result obtained from the causality-calorimetric method and the "two-wall" method (see section 3.4.2) were compared. This comparison allows for verification of the results and tests the robustness of the two methods.

Causality-calorimetric method – The obtained nn -distributions corresponding to the 240 keV peak, obtained with the selection on the energy gate of $E_{rel} \in [0, 0.4]$ MeV, are shown in Fig. 5.15. The corresponding fits taking into account direct decay including three-body phase-space kinematics (top) and nn -FSI (bottom) are also shown. The total integral of the fits were constrained to match the integral of the experimental data. In this case, due to the significant statistics within the peak, noticeable differences are already evident in the shapes of the distributions. As observed, the direct decay following phase-space kinematics provides the best description of the experimental distributions. This is further supported by the significantly lower χ^2 values obtained for the phase-space decay fit. Therefore, the two-neutron emission associated with the 240 keV resonance in the $^{12}\text{Be}+2n$ system is consistent with a three-body phase-space decay.

Two-wall method – The nn -distributions for the 240 keV peak (the three-body spectrum is shown in Fig. 3.30), obtained with an energy gate of $E_{rel} \in [0, 0.4]$ MeV using the two-wall method, are shown in Fig. 5.16. The experimental distributions were again fitted with the simulated direct decay components following the two mechanisms. Similar to the previous method, a distinct difference is observed between the shapes of the nn -distributions corresponding to simulations including three-body phase-space and nn -FSI. This difference is even more pronounced in the m_{nn}^2 distributions and the experimental data appear to agree best with the fit corresponding to the phase-space decay. The χ^2 values obtained for the fits confirm this result, with the lower χ^2 corresponding to the phase-space decay. Therefore, it can be concluded that, according to this method, the two neutrons are emitted following three-body phase-space kinematics. This conclusion is consistent with that drawn from the previous method.

In conclusion, that the nn -distributions corresponding to the 240 keV resonance in the $^{14}\text{Be} \rightarrow ^{12}\text{Be}+2n$ system, obtained from two separate methods, are in excellent agreement with the decay following three-body phase-space kinematics. Even though the nn -distributions are distorted with the cross-talk rejection algorithms at these low $\text{Frag}+2n$ energies, it can be clearly observed that the fitting procedure still remains sensitive to the presence of an nn -FSI signal.

5.4. Summary

In this chapter, the results on the analysis of the nn -distributions corresponding to identified resonances has been reported. A clear signature of the low-energy s -wave nn -FSI is observed for the direct decay

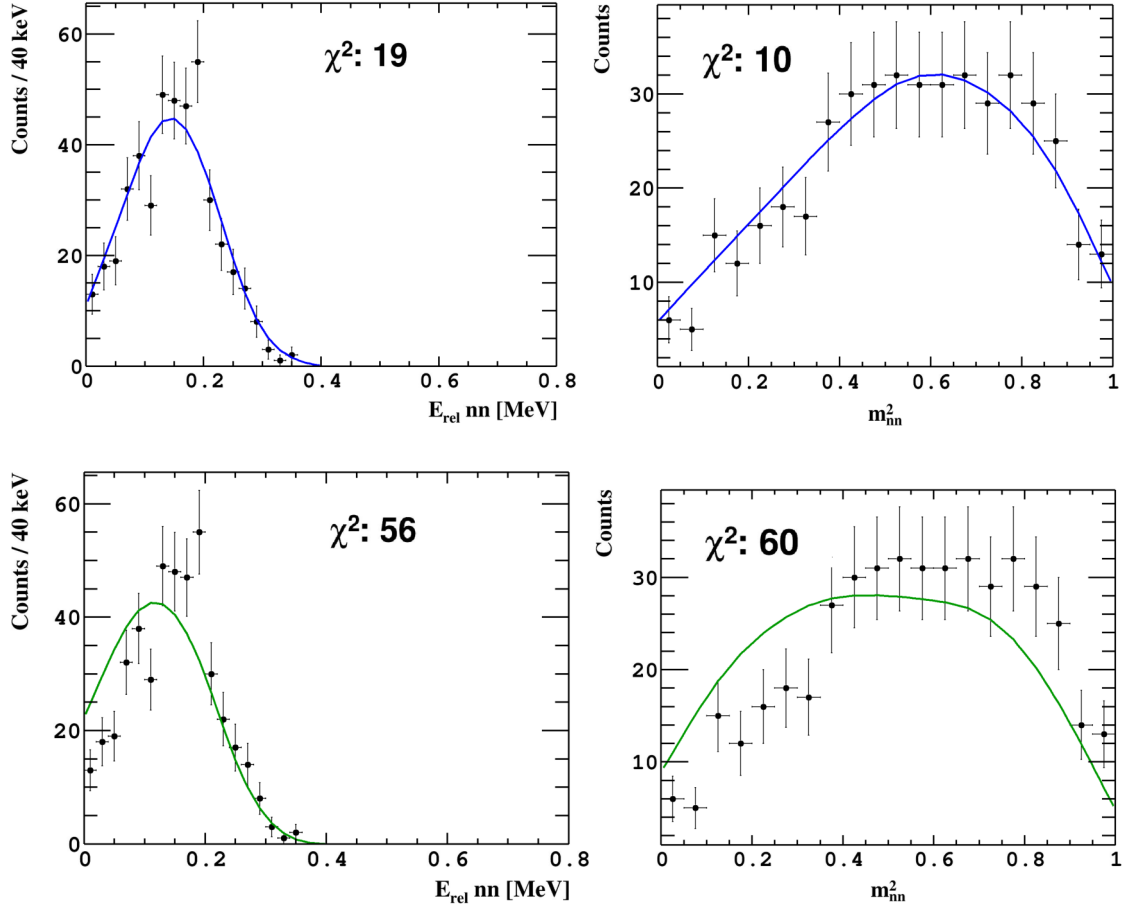


Figure 5.15.: *Top:* Fit of $E_{rel}(nn)$ (left) and m_{nn}^2 (right) distributions corresponding to an energy gate of $E_{rel} \in [0, 0.4]$ MeV in the three-body $^{12}\text{Be}+2n$ spectrum, reconstructed with the causality-calorimetric method. The distribution is fitted with a single direct decay component following phase-space kinematics (in blue). *Bottom:* Fit of the same $E_{rel}(nn)$ (left) and m_{nn}^2 (right) distributions with a direct decay component including nn -FSI (in green). A notable improvement in the χ^2 values is observed for the fits with the three-body phase-space direct decay component.

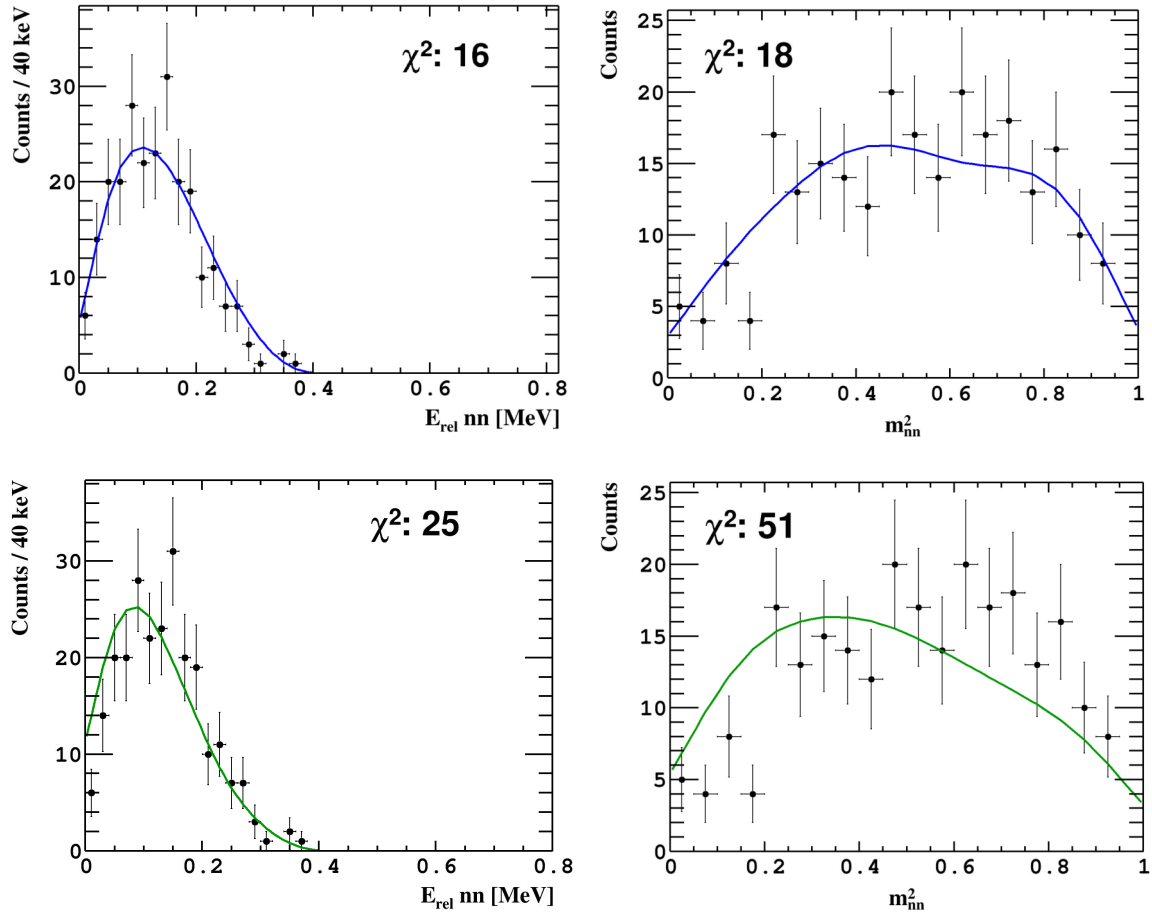


Figure 5.16.: *Top:* Fit of $E_{rel}(nn)$ (left) and m_{nn}^2 (right) distributions corresponding to an energy gate of $E_{rel} \in [0, 0.4]$ MeV in the three-body $^{12}\text{Be}+2n$ spectrum reconstructed with the two-wall method. The distribution is fitted with a single direct decay component following phase-space kinematics (in blue). **Bottom:** Fit of the same $E_{rel}(nn)$ (left) and m_{nn}^2 (right) distributions with a direct decay component including nn -FSI (in green). A notable improvement in the χ^2 values is observed for the fits with the three-body phase-space direct decay component.

part of the resonance at $E_r = 2.43$ MeV populated in the $^{15}\text{B} \rightarrow ^{13}\text{B} + 2n$ system. This is consistent with the general observation of nn -FSI signature in neutron-rich light nuclei.

In the $^{17}\text{B} \rightarrow ^{15}\text{B} + 2n$ channel, the reconstructed $^{15}\text{B} + 2n$ spectrum obtained without the QFS condition show a clear peak at $E_r = 401(30)$ keV across three independent methods. A detailed analysis of the decay mechanism indicates the presence of both direct and sequential decay components, which is also consistent between the methods. The direct decay component shows indications of the presence of an nn -FSI signal; however, caution on the conclusion is advised, since the fitted nn -distributions have very limited statistics, and the difference in the shape between the final fits including the nn -FSI and phase-space decay is minimal. Furthermore, the prominent sequential component suggests a strong core- n interaction, which has been previously shown to hinder the observation of nn -correlations [17, 20].

Finally, the analysis of the nn -distributions corresponding to the $E_r = 240$ keV resonance, identified in the $^{14}\text{Be} \rightarrow ^{12}\text{Be} + 2n$ system, is presented. In this case, a clear agreement with the phase-space distribution is observed, although the system still appears sensitive to the presence of the nn -FSI signal. This result is consistent with the previous reported findings [115] and [116], where phase-space decay was also found to provide the best description of the nn -distributions.

The lack of an s -wave nn -FSI signature in the 2_1^+ 240 keV resonance in the $^{12}\text{Be} + 2n$ system is indeed unique, especially considering that ^{14}Be is a 2-neutron halo nucleus, consisting of two weakly-bound neutrons. In the present work, ^{14}Be is populated via proton knockout from ^{15}B , where both the ground and 2_1^+ states are observed. It has been shown in the previous chapter that the valence neutrons in ^{15}B predominantly occupy the $1s_{1/2}$ orbital. This implies that the states populated in ^{14}Be should also have a similar configuration. This is consistent with the known two-neutron halo structure of the ^{14}Be ground state. Since the 2_1^+ resonance is also populated with large intensity, it is expected to share a similar configuration, suggesting a core+ $2n$ structure. However, it is noted that ^{12}Be is not an ideal core, as its g.s. exhibits a strong intruder configuration with the breakdown of the $N = 8$ shell closure [46, 117, 118]. Additionally, the absence of an observable nn -FSI signature may be partially attributed to the low total relative energy of the system, which limits the available phase-space. Certain calculations suggest that at such lower energies, the nn -FSI signal is too weak to noticeably modify the phase-space distribution [112]. Although, as shown in the current case, the shape of the simulated nn -distributions are still sensitive to the presence of the nn -FSI signal.

As discussed at the beginning of this chapter, the assumption of an s -wave nn -FSI model is highly simplistic. This is because it neglects the structure of the system emitting the neutrons. The inclusion of the core- n interaction is particularly important, since it plays a key role in the formation of the observed Fragment+ $2n$ resonances. Therefore, in order to draw more conclusive insights into the role and significance of the nn -FSI in the three-body system, detailed microscopic calculations explicitly treating the full three-body decay are necessary. Such calculations should account for the complete internal structure of the emitting system and provide information on the correlations of each sub-system. Unfortunately, at the time of writing this thesis, microscopic calculations based on halo-EFT [119, 120] were still ongoing and could not be included in the present work.

6. Conclusions and Outlook

The objective of the current work was to identify and characterize the structure of near-threshold resonances. This falls within a broader goal of understanding the role of the nn -interaction and the continuum in the evolution of the structure of dripline nuclei. In this context, the structure of several neutron-rich boron isotopes has been investigated, with particular emphasis on states populated beyond the 2-neutron emission thresholds. In addition, all possible near-threshold states in the Fragment+ $2n$ systems accessible in the current experiment have been identified. Finally, the nn -distributions corresponding to the identified Fragment+ $2n$ resonances have been systematically investigated and characterized.

The present analysis is based on the s509 experiment conducted at the R³B setup at GSI, as part of the FAIR Phase-0 program. Neutron-rich light nuclei were delivered to the setup via the FFragment Separator and impinged on an LH₂ target. Proton and neutron knockout reactions, proceeding via the QFS mechanism, were employed in inverse kinematics to populate bound and unbound states in the nuclei of interest. The resulting reaction products were detected by employing a combination of detectors, that could provide information of the complete reaction kinematics. This includes the CALIFA calorimeter, used to detect QFS-scattered protons and neutrons in addition to γ -rays from nuclear de-excitations, and the NeuLAND array, used to detect and reconstruct neutrons emitted from unbound resonant states with high resolution and efficiency.

The full capabilities of the setup were exploited to extract comprehensive spectroscopic information on several neutron-rich boron isotopes. Bound and unbound states of ¹⁴B were populated via the ¹⁵B(p,pn)¹⁴B reaction. In addition to the bound states of ¹⁴B, several new unbound resonant states have been identified in the ¹³B+1n system. These resonant states have been attributed to population through neutron knockout from the lower lying $0p$ orbitals. The g.s. configuration of the valence neutrons in ¹⁵B was also extracted and found to have a dominant contribution of the $1s_{1/2}$ orbital. In comparison, the results from [56] show that ¹⁷B exhibits a valence neutron configuration dominated by the $0d_{5/2}$ orbital, suggesting an inversion of orbital occupancy with the addition of two neutrons to the ¹⁵B core. Interestingly, the trend reverses again with the addition of two more neutrons, as ¹⁹B has been shown to form a halo nucleus with a dominant $1s_{1/2}$ component in its g.s. [60]. These observations indicate that the ESPE of the $1s_{1/2}$ and $0d_{5/2}$ orbitals change drastically along the boron isotopic chain. A final confirmation of the current results requires an estimation of the spectroscopic factors associated with the identified states, which is currently under progress.

The structure of ¹⁵B was also investigated via the proton knockout reaction ¹⁶C(p,2p)¹⁵B. Several new unbound states were populated in the ¹⁴B+1n and ¹³B+2n relative energy spectra. The decay scheme and the spin-parities of some of the resonances were also tentatively assigned. The spectroscopic factors, C^2S , of the identified states were extracted and compared to SM YSOX calculations [33]. A discrepancy in the strength of the g.s. C^2S was observed and attributed to the discrepancy in the g.s. orbital configurations. In Chapter. 5, the nn -distributions correspond to the identified ¹³B+2n resonance at 2.43 MeV were also investigated. The analysis revealed a clear nn -FSI signal, consistent with a core+ $2n$ structure.

Bound and unbound states in ¹⁷B were populated via the ¹⁸C(p,2p)¹⁷B reaction. A new γ -ray transition at 1.64(3) MeV has been observed above the current S_{2n} of ¹⁷B (1.38(21) MeV). This transition was

tentatively assigned a spin-parity of $1/2^-$. The unbound continuum corresponding to the $^{15}\text{B}+2\text{n}$ system was also extracted. Though unique resonant structures are difficult to observe in the distribution, analysis of the two-body $^{15}\text{B}+1\text{n}$ system indicates the presence of structures beyond just a single continuum. It is expected that future experiment with higher statistics and resolution can evidence the detailed structure of the $^{15}\text{B}+2\text{n}$ system. Nevertheless, a possible near-threshold state is observed around $E_{\text{rel}} = (0.4-0.5)$ MeV, which could be compatible to the 1.64 MeV state, identified in the γ -ray spectrum. However, theoretical indications that the decay probability decreases with increasing relative energy suggest that it could instead correspond to a separate state. Therefore, if the 1.64 MeV state has a neutron component, a state much closer to the threshold would be expected, which, depending on its energy and cross section, could be difficult to identify in the current experiment. To fully understand the system, a more precise determination of the S_{2n} is required. In addition, future experiments with neutron detector systems having higher granularity would enable a more sensitive search for this competitive decay.

To improve statistics for the near-threshold state, the $^{15}\text{B}+2\text{n}$ spectrum was reconstructed without applying the QFS proton selection. To avoid incorrect reconstruction of the neutron multiplicity, an improvement to the developed neutron reconstruction method was proposed. Three separate reconstruction approaches consistently indicate the presence of a peak at $E_r = 0.4$ MeV. The two-body $^{15}\text{B}+1\text{n}$ analysis suggests a competitive decay via sequential and direct neutron emission. Finally, the nn -analysis shows a slight improvement in the χ^2 of the fit when nn -FSI is included in the direct decay component. However, the deviation from a pure phase-space decay is not significant enough to draw a definitive conclusion.

The nn -distributions corresponding to the 2_1^+ resonance at $E_r = 240(30)$ keV in the $^{14}\text{Be} \rightarrow ^{12}\text{Be}+2\text{n}$ channel were also investigated. The experimental nn -distributions show good agreement with phase-space decay, with no observable nn -FSI signal.

In the current work, the presence of the nn -FSI signal and consequently nn -correlations has been investigated assuming a very simple model corresponding to emission of two independent neutrons interacting in an s -wave. However, the resonance is a consequence of a three-body interaction, and to understand the formation of said resonances and the role that the nn -interaction plays in it, the explicit treatment of the three-body decay is essential. Therefore, to have a comprehensive understanding of the nn -distributions associated with the identified resonances, microscopic calculations involving such three-body decay should be performed. At the time of the thesis, such calculations, based on halo-EFT [119, 120], were still ongoing. Consequently, definitive conclusions are postponed until those results become available.

A key achievement of the current work is the development and implementation of two-neutron reconstruction algorithms for the first time within the R^3B setup with NeuLAND. A major challenge was the reconstruction of near-threshold resonances, as the efficiency is significantly reduced in the low relative energy region due to cross-talk rejection. Despite NeuLAND not being optimally configured for two-neutron spectroscopy of near-threshold states, the results obtained for various Fragment+ 2n systems demonstrate the promising multi-neutron detection capabilities of the setup. The detector with its full geometry of 30 double planes, configured properly, should be able to extend its detection and reconstruction performance, allowing access to neutron spectroscopy with even higher multiplicities.

Appendices

A. Experimental Runs and Downscaling factors

Run Number	Setting	TBits					
		MinBias	Fragment	p2p	p2p+veto	CALIFA OR	Neutron
152-155	$^{19}\text{N-}^{22}\text{O}$	1	1	1	1	1	1
156-164	$^{19}\text{N-}^{22}\text{O}$	8	8	1	1	1	1
190-191	$^{18}\text{C-}^{21}\text{N}$	8	8	1	1	1	1
192-194	$^{18}\text{C-}^{21}\text{N}$	1	1	1	1	1	1
195-203	$^{18}\text{C-}^{21}\text{N}$	4	4	1	1	1	1
204	$^{19}\text{N-}^{22}\text{O}$	8	8	1	1	1	1
205	$^{19}\text{N-}^{22}\text{O}$	8	8	1	1	1	2

Table A.1.: Downscaling factor values for each TBit of the "ON-Spill" triggers corresponding to different runs along with the incoming beam setting.

The runs used in the current analysis along with the incoming beam setting are listed in Table. A.1. Additionally, the change in the downscaling factors for different TBits corresponding to the different runs is also listed in Table. A.1.

B. Fragment-n velocity alignment

After reconstructing the 4-momentum of the neutrons and the fragments, a further fine-tuning procedure is required to obtain the correct relative energy. This procedure corresponds to the alignment of the fragment and neutron momenta. Ideally, if the calibrations were perfect, the obtained neutron and fragment momenta should correspond to the correct values and no further alignment is needed. In practice, however, there is always some uncertainty in the reconstructed momenta, arising from the imprecise detector position measurements, beam angles, etc. In order to account for this, an alignment procedure is performed to obtain the correct longitudinal momentum component.

In this process, the neutron momentum is considered to be the reference, since the reconstruction of its momentum is straightforward compared to the fragment momentum, which is obtained from the MDF. To align the two momenta, three variables are defined,

- The mean of the reconstructed Fragment+1n relative energy E_{rel}
- The difference in the velocity of the Fragment and neutron, i.e., $\beta_n - \beta_f$, where β_n and β_f are the neutron and fragment velocities, respectively
- The parallel momentum of the neutron in the fragment rest frame, $P_Z^f(n)$

These quantities are plotted as a function of the shift in the fragment velocity, $\delta\beta$, as illustrated in Fig. B.1. The optimal velocity shift corresponds to the minimum of the mean E_{rel} , which follows a distribution resembling a second-order polynomial, while for the $\beta_n - \beta_f$ and $P_Z^f(n)$, the optimal shift occurs when their magnitudes are zero. As shown in Fig. B.1, there is a clear value of the velocity shift for which all three variables give an agreeable result.

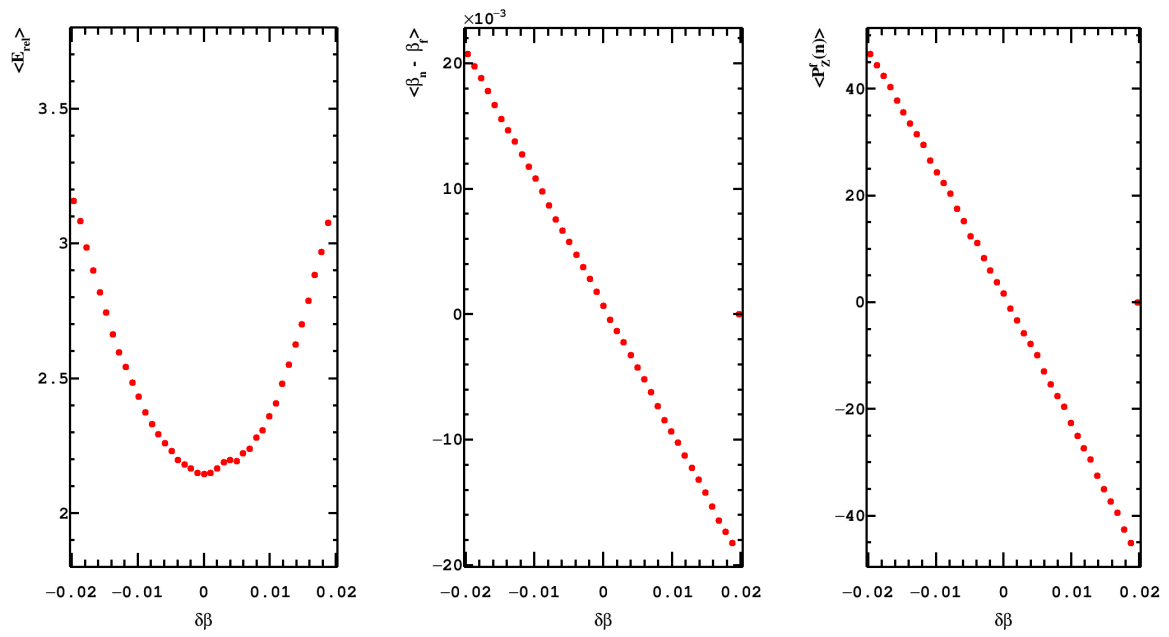


Figure B.1.: Evolution of the alignment variables as a function of the velocity shift $\delta\beta$ applied to the fragment.

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