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Parity-Transfer (^{16}O, ^{16}F(0^-, g.s.)) Reaction as a Selective Probe of Isovector 0^- States in Nuclei

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We demonstrate that the parity-transfer (^{16}O, ^{16}F(0^-, g.s.)) reaction provides a selective probe of isovector 0^- excitations in nuclei. This reaction selectively populates unnatural-parity states through a $0^+ \rightarrow 0^-$ transition in the projectile. The excitation-energy spectrum of ^{12}B was reconstructed via the ^{12}C(^{16}O, ^{16}F(0^-, g.s.)) reaction at 247 MeV/u from the coincident detection of the ^{15}O + p decay products of ^{16}F. The known 0^- state at $E_x = 9.3$ MeV was clearly observed with an enhanced forward cross section, confirming the selectivity of the reaction. The structures observed at $E_x = 6.6 \pm 0.4$ and 14.8 ± 0.3 MeV exhibit forward-peaked angular distributions and are suggested to contain significant 0^- strength. These results demonstrate that the parity-transfer reaction provides a powerful probe of 0^- excitations and highlight its potential for systematic studies of spin–isospin modes, including pion-related dynamics, in nuclei.

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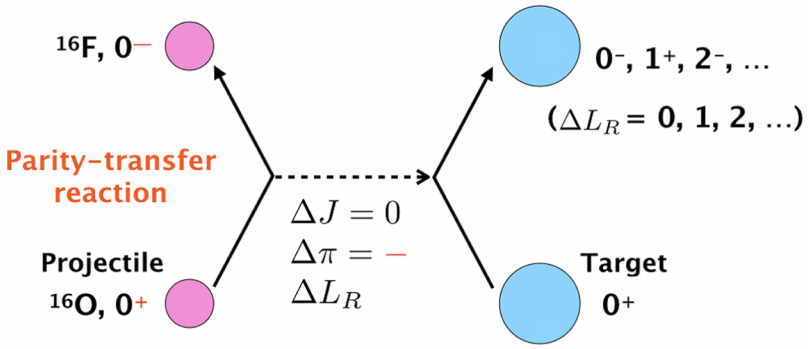


Fig. 1. Schematic illustration of the parity-transfer reaction on an even–even target nucleus. The reaction exploits the $0^+ \to 0^-$ transition in the projectile, effectively transferring internal parity to the target nucleus. Because parity is conserved, unnatural-parity states are selectively populated in the residual nucleus. In this reaction, the projectile spin is unchanged, and the transferred orbital angular momentum ΔL_R of the relative motion between the projectile and target uniquely determines the spin–parity of the populated states, resulting in a one-to-one correspondence between $\Delta L_R = 0, 1, 2, \ldots$ and $J^\pi = 0^-, 1^+, 2^-, \ldots$, respectively. This property enables a clear identification of the J^π components from the angular distributions and underlies the strong selectivity for the 0^- component at forward angles, as discussed in the text.

1. Introduction

The spin–isospin response of nuclei provides essential information on the spin–isospin-dependent interaction in the nuclear medium [1,2]. In particular, this sector of the nuclear interaction is strongly influenced by the pion-exchange interaction, reflecting the isovector ($T = 1$) and pseudoscalar nature ($J^\pi = 0^-$) of the pion. Consequently, studies of spin–isospin excitations offer a sensitive probe of pion-related dynamics in nuclei.

Among such excitations, the isovector 0^- states are of particular interest because they share the same quantum numbers as the pion. Their properties have long been discussed in connection with the possible softening of the pion mode in nuclei, which has been suggested as a precursor phenomenon of pion condensation in nuclear matter [3–5]. Experimental investigations of 0^- states, therefore, provide valuable insight into the behavior of the pion degree of freedom in finite nuclei.

Despite their importance, experimental information on 0^- states remains limited because their identification in reaction spectra is difficult. The spin–dipole (SD) excitation, described by the operator $\sigma\tau rY_1$, consists of three components with $J^\pi = 0^-$, 1^-, and 2^-. Since these excitations share the same orbital angular momentum transfer ($L = 1$), the 0^- component is often obscured by stronger neighboring excitations, particularly the 1^- and 2^- states [1]. Although polarization observables in reactions such as (p, n) [6,7] and $(d, {}^2\mathrm{He})$ [8–10] are known to be sensitive to the spin–parity of excited states and have been used to disentangle these components, the extraction of the 0^- strength remains experimentally challenging.

A promising approach to overcome this difficulty is to utilize nuclear reactions that provide strong selectivity for unnatural-parity states. In this study, we focus on target nuclei with 0^+ ground states and investigate the parity-transfer (^{16}O, ^{16}F(0^-, g.s.)) reaction as such a probe. As illustrated in Fig. 1, this reaction exploits the $0^+ \to 0^-$ transition in the projectile and effectively transfers internal parity to the target nucleus. Because parity is conserved in the reaction, unnatural-parity states are selectively populated in the residual nucleus.

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Moreover, the angular distributions depend sensitively on the spin–parity of the final states. In the present reaction, the spin of the projectile is not changed, and therefore the transferred orbital angular momentum ΔL_R of the relative motion between the projectile and the target uniquely determines the spin–parity of the populated states. This one-to-one correspondence enables a clear identification of the J^π components from the angular distributions. Among these, the present reaction exhibits a particularly strong selectivity for the 0^- component at forward angles, as demonstrated in this work. These features make the parity-transfer reaction a promising probe for identifying and isolating 0^- excitations in nuclei.

The parity-transfer ^{12}C(^{16}O, ^{16}F(0^-, g.s.)) reaction at 247 MeV/u was used to investigate the excitation-energy spectrum of ^{12}B. The ^{12}C nucleus provides an ideal benchmark system because a 0^- state at $E_x = 9.3$ MeV in ^{12}B has been identified in previous polarization measurements [9,10]. By comparing the observed spectrum with theoretical calculations and with results from previous experiments, we investigate the effectiveness of the parity-transfer reaction as a probe for 0^- states in nuclei.

2. Experiment and data analysis

The experiment was carried out at the RIKEN Radioactive Isotope Beam Factory (RIBF) [11] using the SHARAQ spectrometer and a high-resolution beamline [12]. A primary ^{16}O beam was accelerated to 247 MeV/nucleon and transported to the target position. The dispersion of the beamline was matched to that of the spectrometer to obtain an optimized excitation-energy resolution [13,14]. The active ^{12}C target was a 1 mm-thick plastic scintillation detector (equivalent ^{12}C target thickness = 103 mg/cm^2). This detector was horizontally segmented into 16 plastic scintillators of area 5 mm$^{\mathrm{H}}$ $\times$ 30 mm$^{\mathrm{V}}$. From the hit pattern of the segments, we determined the horizontal position of the beam on the target. The beam intensity was indirectly monitored by a plastic counter installed after the target outside the acceptance region of the SHARAQ spectrometer. The beam intensity was typically maintained at approximately 8×10^6 particles per second (pps), below the maximum intensity of 1×10^7 pps allowed by the radiation-safety regulations at the RIBF.

To measure the outgoing proton-unbound ^{16}F, the SHARAQ spectrometer was operated in "separated flow" mode [14]. The experimental setup and analysis procedure are detailed in Ref. [14]. In this mode, the outgoing $^{15}\mathrm{O} + p$ pair produced in the ^{16}F decay was separated by the first dipole magnet and detected at two focal planes of the SHARAQ. The ^{15}O particle was detected with two low-pressure multiwire drift chambers (LP-MWDCs) [15] and plastic scintillation counters at the final focal plane S2; meanwhile, the proton was detected with two MWDCs and plastic scintillation counters at focal plane S1, which is located on the low-rigidity side downstream of the first dipole magnet. The spectrometer was fixed at 0°, covering reaction angles up to $\theta_{\mathrm{lab}} \simeq 1^\circ$.

The momentum vectors of the outgoing proton and ^{15}O at the target were reconstructed from the positions and angles measured at the S1 and S2 focal planes using a ray-tracing method. From the reconstructed momentum vectors, the relative energy E_{rel} of the $^{15}\mathrm{O} + p$ system was determined using the invariant-mass method, whereas the excitation energy E_x of ^{12}B was obtained from the missing-mass method. The reaction angle θ_{cm} was also determined event by event.

To isolate the ^{16}F(0^-, g.s.) channel, the following analysis was performed for each angular bin. As a representative example, the results for the forward-angle region ($\theta_{\mathrm{cm}} = 0.0^\circ$–$0.65^\circ$)

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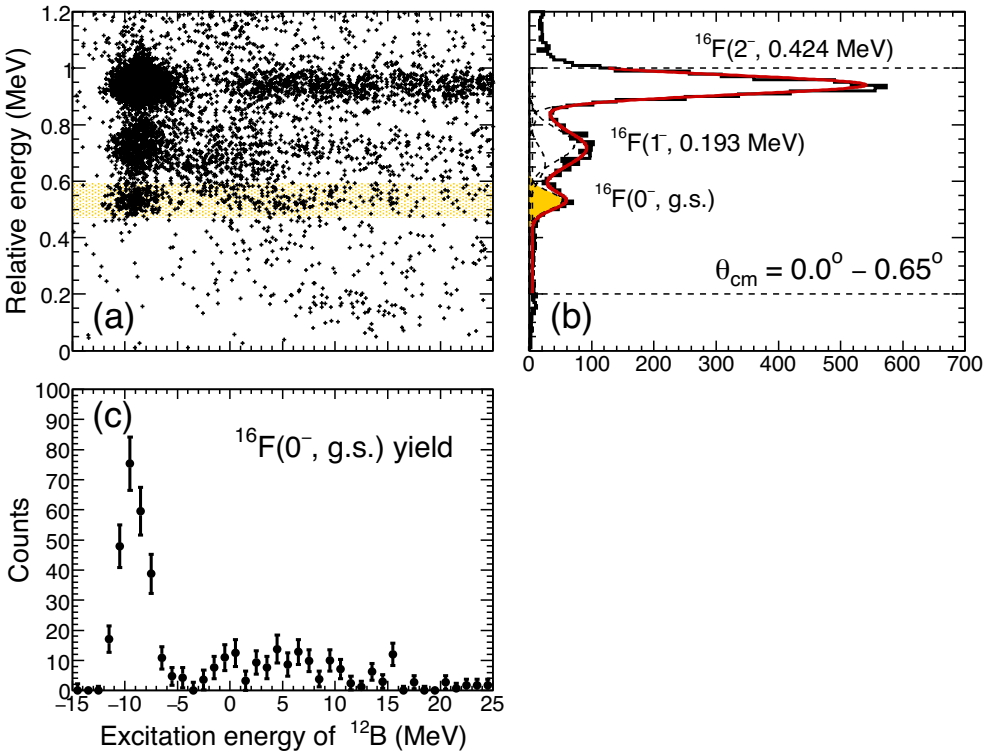


Fig. 2. (a) Correlation between the relative energy $E_{\rm rel}$ of the ^{15}O + p system and the excitation energy E_x of ^{12}B for $\theta_{\rm cm} = 0.0^\circ$–$0.65^\circ$, shown as a representative example. (b) Projection of (a) onto $E_{\rm rel}$. The spectrum is fitted with contributions from the 0^- g.s. of ^{16}F, the 1^- state at 0.193 MeV, and the 2^- state at 0.424 MeV. A Gaussian component at $E_{\rm rel} = 0.664$ MeV and a constant background are also included to account for additional contributions, possibly associated with decays from higher-lying states in ^{16}F. (c) Excitation-energy spectrum of ^{12}B for the ^{16}F(0^-, g.s.) channel, obtained by fitting the $E_{\rm rel}$ distribution in each E_x bin.

are shown in Fig. 2. Figure 2(a) shows the correlation between $E_{\rm rel}$ of the ^{15}O + p system and the excitation energy E_x of ^{12}B. Different loci corresponding to the decay of ^{16}F are observed, indicating a clear kinematic separation of the ^{16}F states.

The $E_{\rm rel}$ spectrum for this angular range is shown in Fig. 2(b). Owing to the energy resolution of 80 keV in full width at half maximum (FWHM), the spectrum exhibits well-separated peaks corresponding to the known low-lying states in ^{16}F, namely the 0^- ground state ($E_{\rm rel} =$ 0.535 MeV), the 1^- state at 0.193 MeV ($E_{\rm rel} = 0.728$ MeV), and the 2^- state at 0.424 MeV ($E_{\rm rel} = 0.959$ MeV). The spectrum was fitted with these three components, where the intrinsic widths were taken from Ref. [16], and folded with the experimental energy resolution. In addition to these components, a Gaussian peak at $E_{\rm rel} = 0.664$ MeV and a constant background term were included to account for residual contributions. These components may originate from the decay of higher-lying states in ^{16}F, leading to ^{15}O* + p final states.

The excitation-energy spectrum of ^{12}B corresponding to the ^{16}F(0^-, g.s.) channel was extracted by fitting the $E_{\rm rel}$ spectrum in each E_x bin. The resulting spectrum is shown in Fig. 2(c). The excitation-energy resolution was 2.6 MeV in FWHM. A peak is also observed at $E_x \sim -10$ MeV. This structure originates from reactions with hydrogen contained in the target material and does not correspond to states in ^{12}B.

The same fitting procedure was applied to all angular bins. After correcting for the detection efficiency of the ^{15}O + p coincidence events, which was estimated by Monte Carlo simulations,

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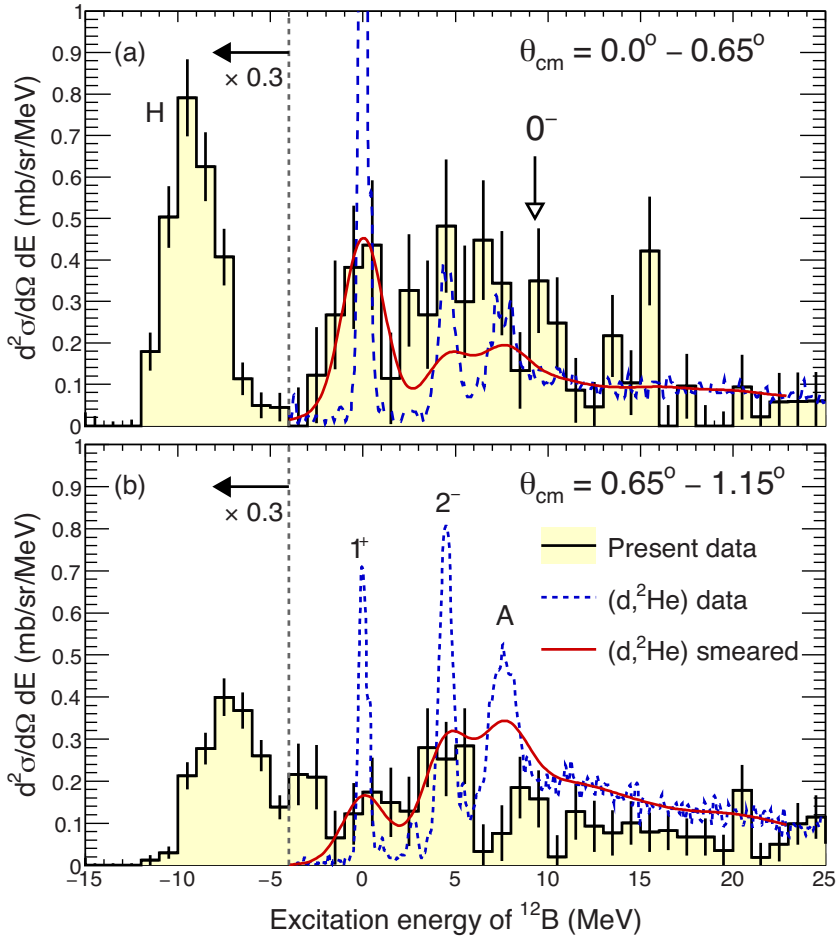


Fig. 3. Double-differential cross sections of the ^{12}C(^{16}O, ^{16}F(0^-, g.s.)) reaction at (a) $\theta_{cm} = 0^\circ$–0.65° and (b) $\theta_{cm} = 0.65^\circ$–1.15°. Dashed curves are the experimental data of the ^{12}C(d, ^{2}He) reaction at 270 MeV [8]. The (d, ^{2}He) spectra (solid curves) are smeared out to match the energy resolution of our data. See text for details.

the double-differential cross sections for the (^{16}O, ^{16}F(0^-, g.s.)) reaction were extracted. The detection efficiency (19%) was mainly limited by the angular acceptance range of the protons.

3. Results

Figure 3(a) and (b) show the double-differential cross sections of the ^{12}C(^{16}O, ^{16}F(0^-, g.s.)) reaction at $\theta_{cm} = 0^\circ$–0.65° and 0.65°–1.15°, respectively. The hydrogen-induced peak at $E_x \sim -10$ MeV is clearly separated from the ^{12}B excitation region at forward angles. Owing to the kinematic shift with increasing scattering angle, the hydrogen-related events move toward higher excitation energies and gradually approach the ^{12}B excitation region.

To demonstrate the selectivity of the parity-transfer reaction, the present results were overlaid on previous data of the ^{12}C(d, ^{2}He) reaction at an incident energy of 270 MeV [8]. The spectra at $\theta_{cm} = 0^\circ$–1° and 6°–8° are presented as the dashed curves in Fig. 3(a) and (b), respectively. In both cases, the momentum transfers were comparable [$q \sim 0.3$ and 0.5 fm^{-1} for Fig. 3(a) and (b), respectively]. The (d, ^{2}He) cross sections, plotted as solid curves, were smeared to match our energy resolution. The (d, ^{2}He) spectra were scaled to match the (^{16}O, ^{16}F(0^-, g.s.)) cross sections of 1^+ g.s.

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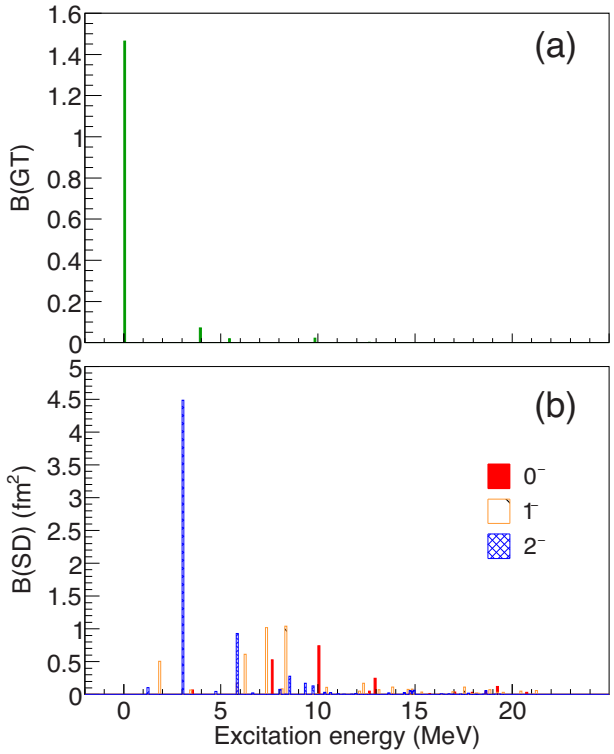


Fig. 4. SM transition strengths calculated with the WBT interaction [17]. (a) Gamow–Teller (1^+) strength distribution B(GT). (b) SD strength distribution B(SD) for the 0^- (solid), 1^- (hatched), and 2^- (cross-hatched) components as a function of excitation energy in ^{12}B.

Excitation of the 1^+ g.s. and the 2^- state at $E_x = 4.5$ MeV is observed in both reactions, but the structures at $E_x \gtrsim 6$ MeV are markedly different between the two reactions. The peak at $E_x = 7.5$ MeV (labeled "A" in Fig. 3(b)) is prominent in the $(d, {}^2\mathrm{He})$ data, but is barely observable in the $({}^{16}\mathrm{O}, {}^{16}\mathrm{F}(0^-, \text{g.s.}))$ data. This difference is discussed in detail in Section 4.3.

Another striking difference is seen at $E_x \sim 9$ MeV in Fig. 3(a): the clear enhancement in the $({}^{16}\mathrm{O}, {}^{16}\mathrm{F}(0^-, \text{g.s.}))$ data vanishes in the $(d, {}^2\mathrm{He})$ data. This enhancement is attributed to the known 0^- state at $E_x = 9.3$ MeV, which was found only with the help of tensor analyzing powers of the $(d, {}^2\mathrm{He})$ reaction [9], indicating the selectivity of the present reaction for 0^- states. A similar enhancement at $E_x \sim 15$ MeV is a potential candidate for a new 0^- state.

4. Discussions

In this section, we discuss the observed features of the excitation-energy spectrum and angular distributions in terms of the reaction selectivity and the underlying spin–parity structure.

4.1. *Reaction selectivity and distorted-wave Born approximation + shell model interpretation*

Figure 4 shows the Gamow–Teller (1^+) and SD (0^-, 1^-, and 2^-) strength distributions calculated with the shell model (SM) using the WBT interaction [17]. The Gamow–Teller strength is predominantly concentrated in the g.s. transition, whereas the SD strength is distributed over a wide excitation-energy region, particularly above $E_x \sim 4$ MeV. The overall features of these distributions are consistent with those observed in previous charge-exchange reactions such as (n, p) and $(d, {}^2\mathrm{He})$ [8–10,18,19].

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To examine whether the observed excitation-energy spectrum reflects the expected selectivity of the parity-transfer reaction, we compared the data with distorted-wave Born approximation (DWBA) calculations using the SM transition strengths shown in Fig. 4 as input. In the following, this combined framework is referred to as DWBA+SM. The DWBA calculations were performed for the 0^-, 1^+, and 2^- components using the reaction code FOLD/DWHI [20,21], with the Franey–Love nucleon–nucleon interaction at 270 MeV [22]. The one-body transition densities for both the projectile and target systems were taken from the SM calculations. The optical-model potentials used to generate the distorted waves were taken from the global optical potential of Ref. [23], which was constructed within a double-folding model using the CEG07b G-matrix interaction.

The calculated double-differential cross sections were folded with the experimental angular resolution (3 mrad in FWHM) and integrated over the corresponding angular ranges to obtain the spectra. The resulting spectra were then folded with the experimental energy resolution (2.6 MeV in FWHM).

Since the absolute cross sections are subject to uncertainties in the DWBA+SM framework, including both the reaction mechanism and the structure input, normalization factors were introduced separately for each spin–parity component by reproducing the known states at $E_x =$ 0.0 MeV(1^+), 4.5 MeV(2^-), and 9.3 MeV(0^-). The same normalization factors were applied to all angular bins. The resulting normalization factors were 1.1, 1.0, and 3.8 for the 1^+, 2^-, and 0^- components, respectively. In addition, small energy shifts were introduced to align the reference states used for the normalization. The required shifts were $+1.35$ MeV for the 2^- component and -0.8 MeV for the 0^- component relative to the shift applied to the 1^+ component.

The large normalization required for the 0^- component may reflect limitations of the present DWBA description of the reaction mechanism. In particular, the exchange term is treated approximately in the present framework, and the tensor-force exchange contribution is neglected [21], which may affect the calculated cross sections. Uncertainties in the structure description of the transitions may also affect the normalization factors. A quantitative understanding of the normalization factors, especially for the 0^-component, is beyond the scope of the present work and remains as a subject for future study. The present comparison should therefore be regarded as qualitative.

Figure 5 compares the experimental spectra with those predicted by the DWBA+SM calculation. The overall spectral features are reasonably well reproduced by the calculations for both angular ranges. This agreement suggests that the observed excitation-energy spectrum follows the pattern expected for the parity-transfer reaction, which selectively populates unnatural-parity states. In the experimental spectrum, the cross section at forward angles increases above $E_x \sim 6$ MeV. The DWBA+SM calculation predicts that this excitation-energy region is dominated by the 0^- component, suggesting that the observed enhancement is largely associated with 0^- contributions.

To clarify further the spin–parity nature of individual structures suggested by the DWBA+SM interpretation, a quantitative decomposition of the spectrum is presented in the following subsection.

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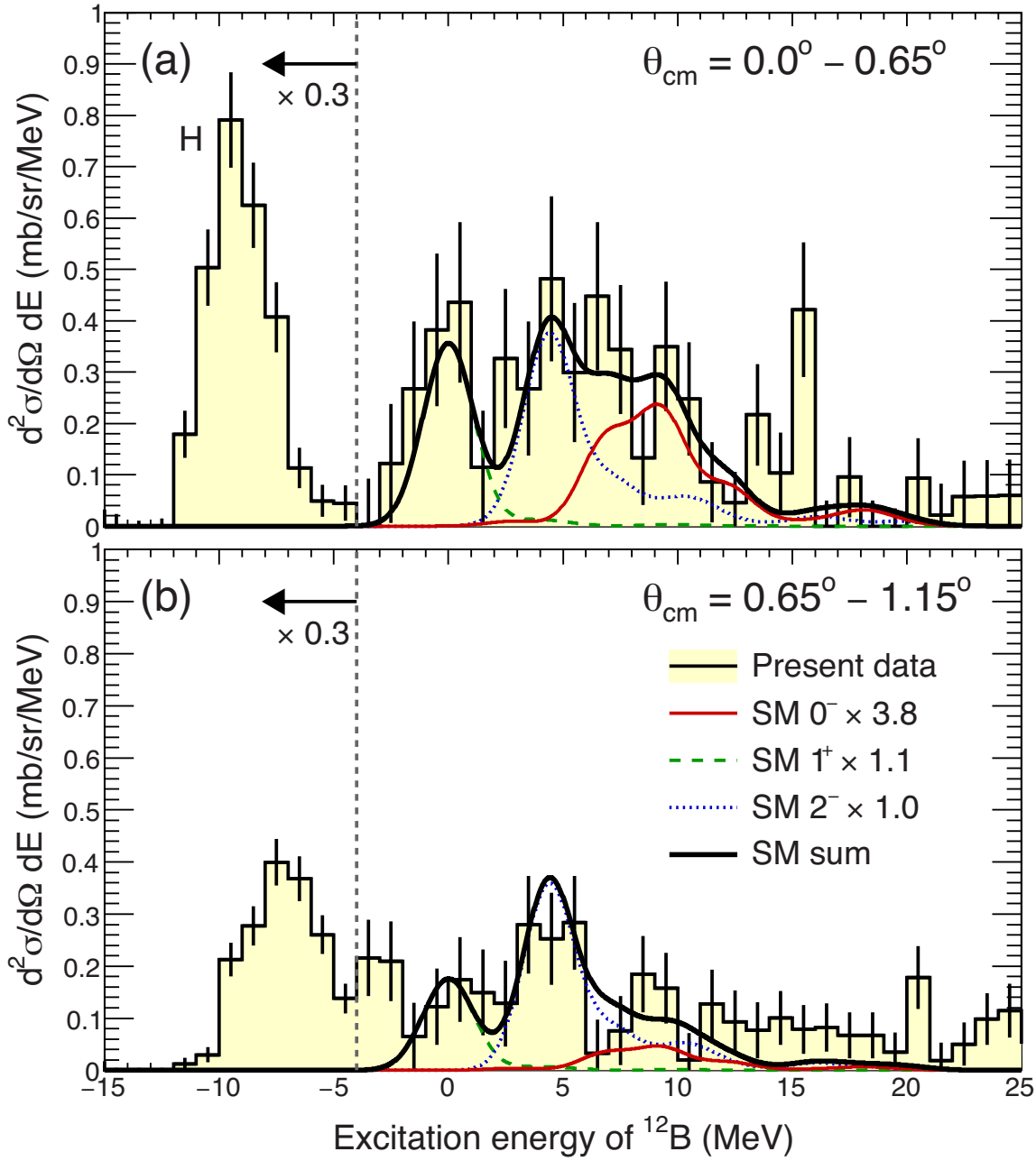


Fig. 5. Double-differential cross sections of the ^{12}C(^{16}O, ^{16}F(0^-, g.s.)) reaction (histograms) compared with DWBA+SM calculations (thick solid lines) at (a) $\theta_{cm} = 0^\circ$–0.65° and (b) $\theta_{cm} = 0.65^\circ$–1.15°. Contributions from different spin–parity components are also shown: 0^- (solid), 1^+ (dashed), and 2^- (dotted). See text for details of the normalization procedure.

4.2. *Spin–parity analysis of the observed structures*

To investigate the spin–parity of individual structures in more detail, the cross sections of individual components were extracted by fitting the excitation-energy spectra with a set of Gaussian peaks. The continuum background arising from quasi-free scattering events was estimated by the formula in Ref. [24], and the parameters were taken from Ref. [9]. The ^{1}H(^{16}O, ^{16}F(0^-, g.s.)) background at $E_x < 0$ MeV was described as a Gaussian peak with an exponential tail. Three known states with unnatural parity, namely the 1^+ g.s., the 2^- state at $E_x = 4.5$ MeV, and the

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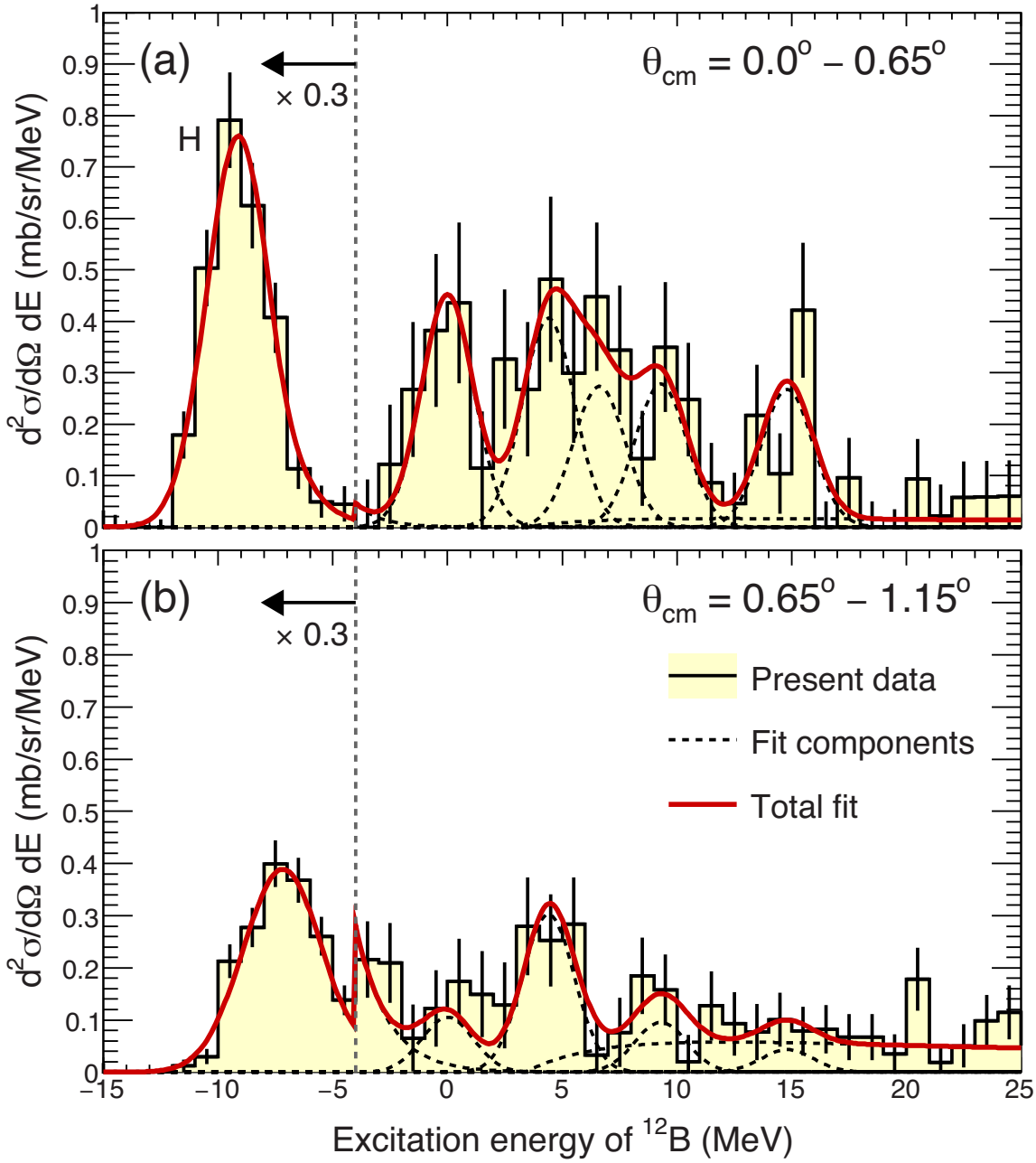


Fig. 6. Peak-fitting results of the excitation-energy spectra for the ^{12}C(^{16}O, ^{16}F(0^-, g.s.)) reaction. (a) $\theta_{cm} = 0^\circ$–0.65° and (b) $\theta_{cm} = 0.65^\circ$–1.15°. The solid curves show the total fit, whereas the dashed curves indicate individual fit components.

0^- state at $E_x = 9.3$ MeV, were included as discrete components in the fit. In addition, two structures were observed around $E_x \sim 7$ and 15 MeV, and corresponding Gaussian components were introduced to describe these features. The fitted peak positions were determined to be $E_x = 6.6(4)$ MeV and 14.8(3) MeV. For the peak widths, only the experimental energy resolution of 2.6 MeV was considered, assuming that the intrinsic widths of the states are small compared to the resolution. The peak positions and widths were fixed in the fitting procedure. Figure 6 shows the peak-fitting results of the spectra at $\theta_{cm} = 0^\circ$–0.65° (a) and $\theta_{cm} = 0.65^\circ$–1.15° (b).

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The angular distributions of the extracted cross sections are shown in Fig. 7. The 0^- state at $E_x = 9.3$ MeV shows a forward-peaking angular distribution, which enhances the signal-to-noise ratio of this state at the most forward reaction angle. The cross-section ratio of the 0^- state to the 1^+ g.s. reaches about 0.6 in the present reaction, whereas in the $(d, {}^2\mathrm{He})$ reaction it is much smaller than 0.1 (e.g. see Fig. 1 in Ref. [9]). This comparison indicates the high efficiency of the parity-transfer reaction for investigating 0^- states.

The DWBA results for the 0^-, 1^+, and 2^- states are also shown in Fig. 7. The same normalization factors as those determined in the DWBA+SM spectral comparison were used. The calculations predict characteristic spin–parity-dependent oscillatory patterns in the angular distributions. In particular, the 0^- state exhibits a strong forward peak, whereas the 1^+ and 2^- states show their first maxima at finite angles. These patterns reproduce well the experimental data of the known states: the 0^- state at $E_x = 9.3$ MeV, the 1^+ g.s., and the 2^- state at $E_x = 4.5$ MeV. Thus, the characteristic oscillatory pattern of the angular distributions provides information on the spin–parity of the excited states.

Using these characteristic features, we investigate the spin–parity structures at 6.6 MeV. According to the SM calculations shown in Fig. 4, this energy region is expected to contain both 0^- and 2^- transition strengths, with comparable contributions from the 0^-_2 and 2^-_4 states. The observed angular distribution exhibits forward-peaked behavior, which cannot be reproduced by a pure 2^- component, particularly at forward angles. A better agreement is obtained when a 0^- contribution is included. An illustrative comparison based on such a mixture is shown in Fig. 7.

Additional fits were performed to examine the stability of this structure. The significance of the 6.6-MeV component was found to depend on the fitting conditions, reflecting the influence of nearby states such as the 2^- state at $E_x = 4.5$ MeV and the 0^- state at $E_x = 9.3$ MeV. Therefore, although the present data suggest that the 6.6-MeV structure may contain a nonnegligible 0^- component, its existence and detailed composition remain tentative.

A similar analysis was performed for the structure observed at $E_x = 14.8$ MeV. The angular distribution also shows a forward-peaked behavior, although the statistical uncertainty is relatively large. To examine the possible contribution of 0^- excitations in this energy region, the experimental angular distribution was compared with DWBA calculations obtained by summing the contributions of higher-lying 0^- states.

An illustrative comparison based on such a summed 0^- contribution is shown in Fig. 7, where the forward-peaked tendency of the data is reasonably reproduced. Although the present statistics do not allow a unique spin–parity assignment, the observed angular distribution suggests that the enhancement around $E_x = 14.8$ MeV is consistent with the presence of significant 0^- strength.

The angular distributions of the structures at $E_x = 6.6$ and 14.8 MeV can also be reproduced, within the experimental uncertainties, by DWBA curves for the 1^+ component. However, this assignment appears unlikely. SM calculations predict that the 1^+ strength is predominantly concentrated in the g.s. transition and show negligible strength in this excitation-energy region, as clearly shown in Fig. 4. In addition, previous charge-exchange experiments do not exhibit pronounced structures in this region characteristic of strong 1^+ transitions. Taken together, these considerations suggest that the forward-peaked structures observed at $E_x = 6.6$ and 14.8

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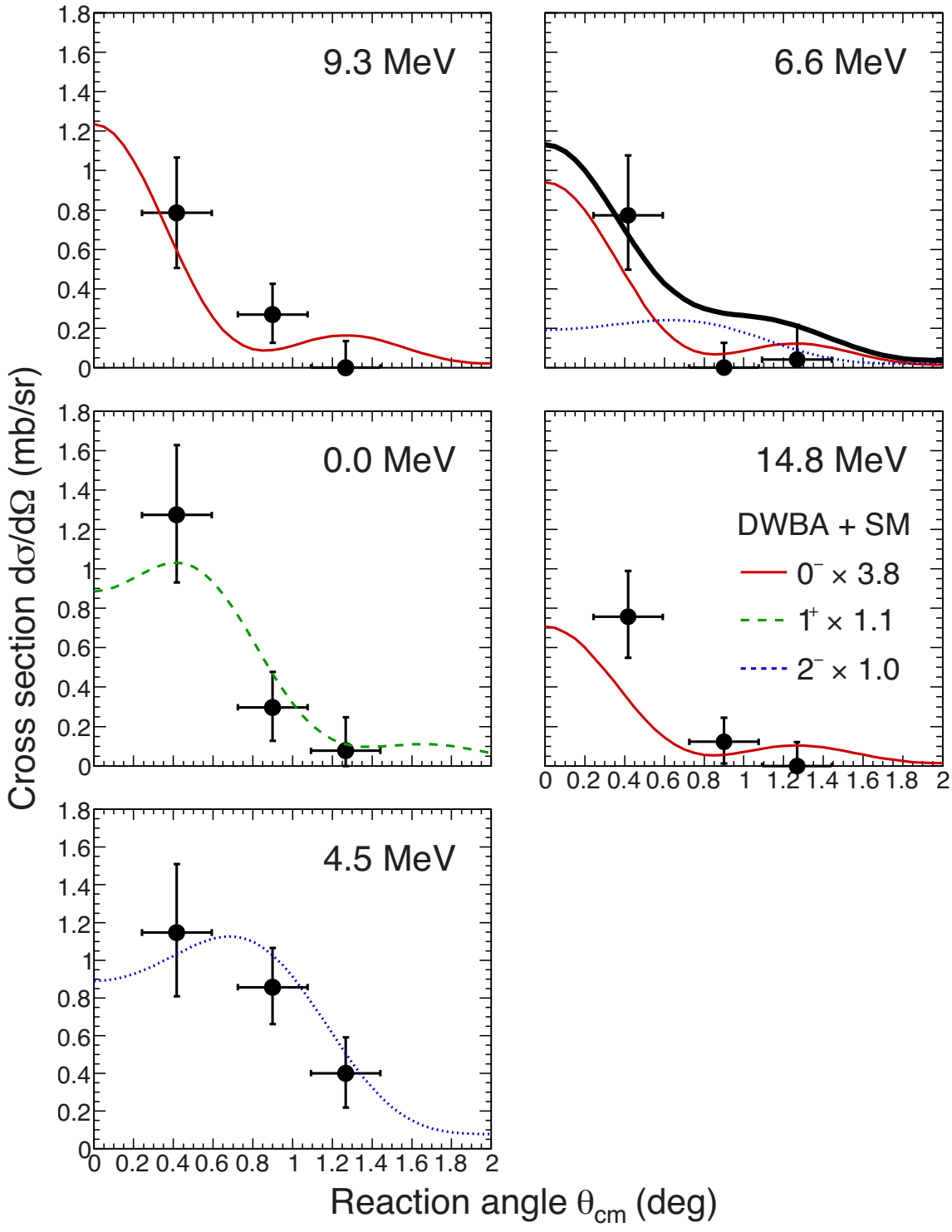


Fig. 7. Measured angular distributions of the differential cross sections for the indicated excitation energies in ^{12}B. The solid, dashed, and dotted curves represent the DWBA calculations for the 0^-, 1^+, and 2^- components, respectively, whereas the thick solid curve shows their sum. The normalization factors of the DWBA cross sections are the same as those used in the DWBA+SM spectral comparison. The SM states used in the DWBA calculations are: 0^-_4 (9.3 MeV), 1^+_1 (g.s.), 2^-_2 (4.5 MeV), a mixture of 0^-_2 and 2^-_4 (6.6 MeV), and the summed 0^-_{5-20} states (14.8 MeV).

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MeV are more naturally interpreted as arising from 0^- strength, although a unique assignment cannot be established with the present statistics.

4.3. *Nature of the 7.5-MeV structure*

While the structures discussed above can be understood in terms of the spin–parity selectivity of the parity-transfer reaction, the present data also offer new insight into the long-standing controversy on the spin–parity of the bump structure at $E_x = 7.5$ MeV [labeled "A" in Fig. 3(b)]. The Uppsala and Los Alamos groups, who studied the cross section of the ^{12}C(n, p) reaction, attributed this bump mainly to $J^\pi = 1^-$ [18,19]. This interpretation was based on the SM prediction that the transition strength around $E_x \sim 7$ MeV is dominated by the 1^- component (see Fig. 4), together with the good agreement between the measured angular distributions and theoretical calculations based on these strengths. The result was supported by angular-distribution measurements of the decay neutrons from residual ^{12}B produced by the ^{12}C$(d, ^2$He) reaction, performed at Research Center for Nuclear Physics [25]. However, tensor analyzing powers of the ^{12}C$(\vec{d}, ^2$He) reaction measured at RIKEN [8,9] suggested a main component of $J^\pi = 2^-$. New polarization data from the high-resolution ^{12}C$(\vec{d}, ^2$He) reaction experiment at Kernfysisch Versneller Instituut [10] have refined the picture. The bump appears to comprise two components: a low-energy part with $J^\pi = 2^-$ and a high-energy part with $J^\pi = 1^-$. The inconsistency among the spin–parity assignments remains unsolved.

Our data showed no apparent structure at $E_x = 7.5$ MeV, indicating that the structures seen in the (n, p) and $(d, ^2$He) reactions are dominated by 1^- states. This is expected because the parity-transfer reaction does not excite the natural parity state. Furthermore, the possible presence of 0^- strength in the vicinity of $E_x \sim$ 6-7 MeV suggests that a small 0^- admixture may be present in the 7.5-MeV structure. In the $(d, ^2$He) reaction, the tensor analyzing powers of the 0^- and 1^- transitions have opposite signs. Therefore, a mixture of these components can lead to a strong cancellation, resulting in tensor analyzing powers close to zero. Such a cancellation may lead to an ambiguous spin–parity assignment when tensor analyzing powers are used as the primary observables.

To examine this effect quantitatively, reaction calculations were performed using the adiabatic coupled-channel Born approximation (ACCBA) code [26]. The parameters were taken from Ref. [26], except for the transition strengths, which were obtained from SM calculations using the WBT interaction. The calculations were compared with the experimental data for the ^{12}C$(d, ^2$He) reaction at 270 MeV measured at RIKEN [8,9].

As an illustrative example, the cross sections and tensor analyzing powers were calculated assuming contributions from representative 0^-, 1^-, and 2^- states as predicted by SM calculations in this excitation-energy region. The normalization factors for the 0^- and 2^- components were determined so as to reproduce the known 0^- state at $E_x = 9.3$ MeV and the 2^- state at $E_x = 4.5$ MeV, respectively, whereas the normalization of the 1^- component was adjusted to reproduce the overall magnitude of the bump at 7.5 MeV. The resulting normalization factors were 0.5, 0.3, and 0.3 for the 0^-, 1^-, and 2^- components, respectively.

The resulting calculation, shown in Fig. 8, reproduces both the cross section and the tensor analyzing powers reasonably well. In particular, the tensor analyzing powers can be close to zero when a small 0^- component is mixed with a dominant 1^- contribution, because their tensor analyzing powers have opposite signs and partially cancel each other. This behavior explains why the experimental analyzing powers are similar to those expected for a pure 2^- transition,

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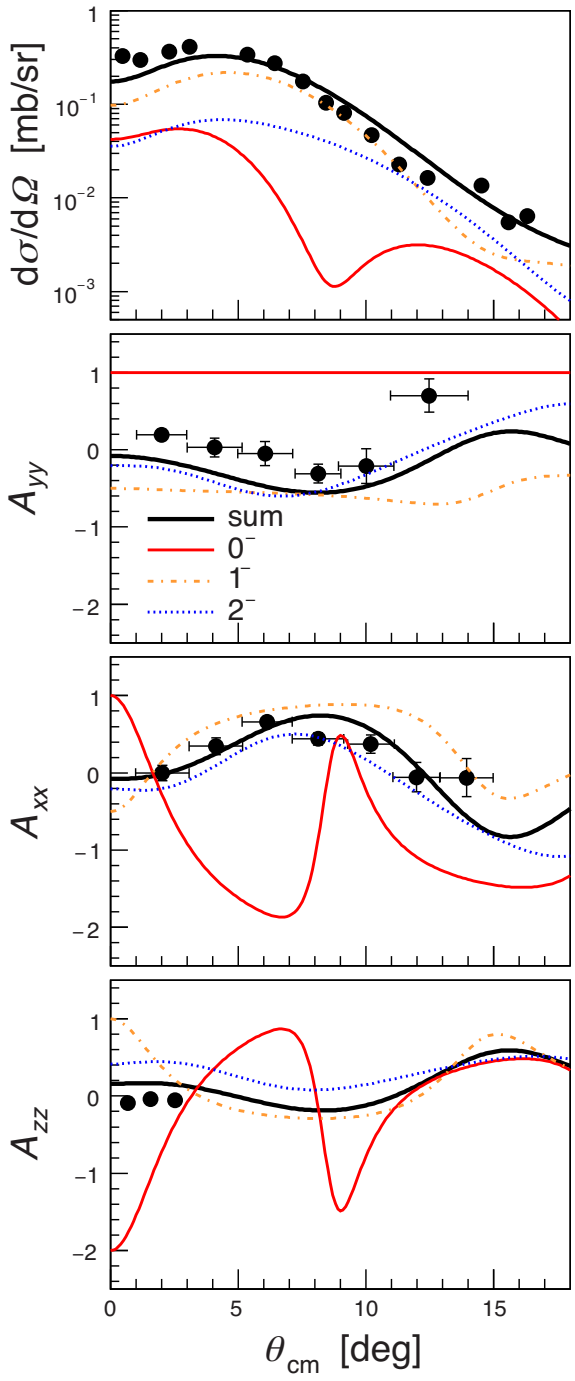


Fig. 8. Cross section and tensor analyzing powers for the ^{12}C(d, ^{2}He) reaction populating the E_x = 7.5 MeV component in ^{12}B. The experimental data are taken from the RIKEN measurement at E_d = 270 MeV [8,9]. The curves are calculated assuming contributions from representative SM states in this energy region (e.g. 0^-_2, 1^-_{4-7}, and 2^-_4), and are shown for the 0^-, 1^-, and 2^- components and their sum. The normalization factors for the 0^- and 2^- components were determined to reproduce the known states at E_x = 9.3 MeV and E_x = 4.5 MeV, respectively, whereas that of the 1^- component was adjusted to reproduce the bump structure around E_x = 7.5 MeV.

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even though the underlying structure is not dominated by 2^-. Together with the absence of a clear peak at $E_x = 7.5$ MeV in the present parity-transfer reaction, the results suggest that the bump structure is mainly associated with a 1^- excitation with a smaller admixture of 0^- strength.

5. Summary

In summary, we have demonstrated that the parity-transfer (^{16}O, ^{16}F(0^-, g.s.)) reaction provides a selective probe of isovector 0^- excitations in nuclei. The excitation spectrum of ^{12}B was studied via the ^{12}C(^{16}O, ^{16}F(0^-, g.s.)) reaction at 247 MeV/u. The known 0^- state at $E_x = 9.3$ MeV was clearly observed with an enhanced signal at forward angles, confirming the selectivity of the parity-transfer reaction.

The observed excitation-energy spectrum and angular distributions are reasonably described by DWBA calculations based on SM transition strengths. In this description, structures observed at $E_x = 6.6 \pm 0.4$ and 14.8 ± 0.3 MeV are suggested to contain significant 0^- strength and may represent candidates for previously unidentified 0^- excitations in ^{12}B.

The present results also shed new light on the bump structure around $E_x = 7.5$ MeV observed in previous charge-exchange reactions. Reaction calculations for the ^{12}C(d, ^{2}He) reaction indicate that a dominant 1^- excitation with a small admixture of 0^- strength can reproduce both the cross sections and tensor analyzing powers. This explains why the structure appears prominently in conventional charge-exchange reactions but is suppressed in the present parity-transfer reaction.

These findings indicate the effectiveness of the parity-transfer reaction as a probe of 0^- excitations and highlight its potential for systematic studies of spin–isospin modes, including pion-related dynamics, in atomic nuclei.

The statistical precision of the present measurement is lower than in previous charge-exchange experiments because of the limited intensity of the ^{16}O beam (8×10^6 pps), which was restricted by radiation-safety regulations at RIBF. Future experiments with higher-intensity beams would allow more definitive identification of the 0^- candidates in ^{12}B, and may reveal additional 0^- states in other nuclei.

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Data availability

The data underlying this article are available from the corresponding author upon reasonable request.

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