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Determining neutron-induced reaction cross sections through surrogate reactions at storage rings

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Abstract. Determining the cross sections of neutron-induced reactions on short-lived nuclei is imperative to rate calculations in stellar nucleosynthesis and applications of nuclear physics. It is also an immense experimental challenge due to the radioactivity of the targets involved. Our goal is to circumvent this obstacle by using surrogate reactions in inverse kinematics at the heavy-ion storage rings of GSI/FAIR. We present here preliminary results from the first proof of principle experiment, where a beam of ^{208}Pb impinged on a H_2 gas jet target in the Experimental Storage Ring (ESR).

1. Introduction

Knowledge of neutron-induced reaction cross sections of short-lived nuclei is pivotal to our understanding of processes in nuclear astrophysics such as slow (*s*) and rapid (*r*) neutron capture, about which there are still many uncertainties and open questions [1]. Furthermore, it is also of interest for applications such as nuclear waste management and innovative fuel cycles [2]. A neutron-induced reaction occurs at energies below a few MeV through a two-step process, as illustrated in Fig. 1. In the first step, the nucleus with mass A captures a neutron, forming a compound nucleus with mass *A+1* in an excited state. This compound nucleus then decays by γ-ray emission, neutron emission or fission. Each of these modes of decay has a given probability (P_γ, P_n, P_f) and the sums of these probabilities must add up to 1 at any excitation energy of the compound nucleus.

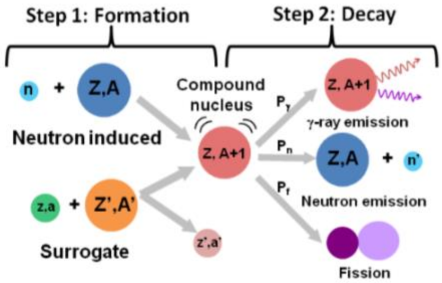

Fig. 1: Illustration of the two-step process, where the compound nucleus is formed in Step 1 (the formation stage) and decays in Step 2 (the decay stage) by γ-ray emission, neutron emission or fission. In Step 1, the same compound nucleus can be formed by either a neutron-induced reaction or through an alternative surrogate reaction which may be more experimentally feasible.

The investigation of neutron-induced reaction cross sections on short-lived nuclei suffers from severe experimental limitations when attempted in direct kinematics, namely significant background related to the radioactive target, scattering of the neutrons in the beam off the target, the setup and the surroundings, as well as detector damage and hazards associated with handling a radioactive target. Performing exactly the same reaction in inverse kinematics, with the heavy, radioactive nucleus impinging upon a target of neutrons, is not possible either, since free neutron targets are not available. In the surrogate reaction method, the same compound nucleus is created during the formation stage as would be the case with the neutron-induced reaction of interest, through an alternative and experimentally feasibly reaction. The compound nucleus then decays and the probabilities of these different modes of decay provide the information which is required to fix the key parameters, which are needed to determine fundamental properties such as the level densities, γ-ray strength functions, fission barriers, etc., that are not well known due to lack of data [3]. This will significantly improve the predictions of the cross sections of the neutron-induced reactions of interest. This method has been benchmarked successfully in direct kinematics [4, 5, 6]. With the surrogate reaction method in direct kinematics, one would still, however, need to cope with significant target radioactivity and background, as well as low efficiencies of γ-ray and neutron measurements.

These problems can be overcome by using the surrogate reaction method in inverse kinematics, using the heavy, radioactive nucleus as beam and colliding it with light target nuclei. This provides access to short-lived nuclei which would otherwise not be experimentally feasible. The heavy compound nucleus in the beam decays by neutron emission, γ-ray emission and fission, and one can measure the heavy reaction products associated with these different modes of decay with efficiencies far beyond what is possible in direct kinematics. The decay probabilities are known to evolve very rapidly as a function of excitation energy around the neutron-emission and fission thresholds of heavy nuclei, thus necessitating excitation energy resolutions of the order of a few hundred keV to scan this rapid evolution. With heavy ions in inverse kinematics, straggling and energy loss in the target would, however, cause a significant loss of excitation energy resolution. The required excitation energy resolutions can be obtained at a heavy-ion storage ring such as the ESR at GSI, where an ultra-thin gas jet target is used in conjunction with an electron cooler [7]. Here a high-quality beam of bare heavy ions circulates in the ring at high frequency, and the electron cooler serves to continually restore the beam quality with each passage through the ring, thus providing the required excitation energy resolution. The high rate of passages through the target (0.69 MHz in our first experiment, described in Section 2) serves to compensate for the low statistics which would otherwise be obtained with the ultra-thin gas jet target.

2. The first Proof-of-Principle experiment at the ESR storage ring

The first proof-of-principle experiment was performed at the ESR storage ring of GSI/FAIR near the end of June 2022 to investigate the ^{208}Pb(p,p') reaction. In this experiment, an average of $5\cdot10^7$ ions of $^{208}Pb^{82+}$ at 30.77 A MeV were stored per injection and impinged upon a H_2 gas-jet target of thickness 6×10^{13} atoms/cm^2. The target-like residues, in this case inelastically scattered protons represented by the pink arrow in Fig. 2, were measured with a telescope detector positioned at 101.3 mm from the center of the gas jet and at an angle of 60°. This telescope consisted of a DSSSD array of 16×16 Si strips over an area of 2×2 cm^2 and with a thickness of 0.529 mm, followed by six 1.5-mm-thick Si detectors, enabling for full energy measurements on protons up to E_p = 43 MeV. The telescope was kept at atmospheric pressure inside of a stainless-steel pocket which sealed it from the ultra-high vacuum (UHV) of the ring. This pocket featured a 25-µm stainless-steel front window which allowed for protons to travel to the Si detectors. Measurement of proton energies and angular information provided the excitation energy information on the ^{208}Pb nucleus. After the first dipole bending magnet of the ring, downstream from the target, heavy beam-like reaction products related to neutron emission (^{207}Pb) and γ-ray emission (^{208}Pb) were separated by their different magnetic rigidities, before being measured as separate loci in a 0.5-mm-thick DSSSD detector. This detector contained 122×40 strips over an area of 12.2×4.0 cm^2, and was also separated from the UHV by a stainless-steel pocket with a 25-µm-thick stainless-steel window with an area matched to the detector sensitive area.

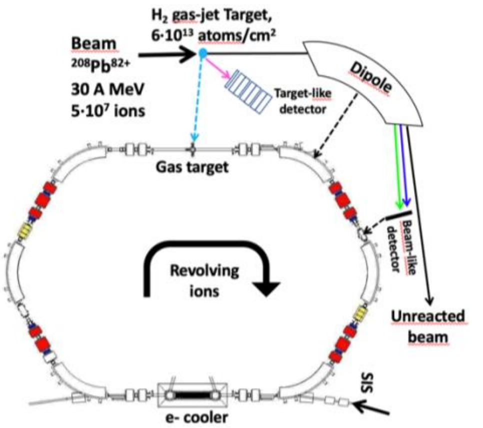

Fig. 2: The ESR storage ring facility, used for our first experiment, is shown in the bottom diagram, with beams entering from the SIS accelerator represented by the black arrow in the bottom-right. The top diagram zooms in on the gas-jet target, the target-like telescope detector and the heavy residue detector situated after the first dipole magnet. The pink arrow represents the trajectory of the target-like residues (protons), while the blue and green arrows represent, respectively, the ^{208}Pb and ^{207}Pb residues measured in the heavy residue detector.

Preliminary data from the telescope DSSSDs and thick Si stack are shown in Fig. 3 Left, where the red contour depicts a gate set around the elastically scattered data that are plotted in excitation energy in Fig. 3 Right. Here the excitation energy resolution was found to be around ΔE = 600 keV for the ^{208}Pb g.s. This is mainly related to the width of the gas jet target, which had a radius of r = 2.5 mm. Simulations indicate that, with the setup used in this experiment, this should improve to 200 – 300 keV at r = 0.5 – 1 mm, which will be available in our future experiments. When one selects scattered proton events in the telescope data, then heavy residue spectra such as Fig. 4 Right are obtained where data resulting from ^{208}Pb (γ-ray emission) and ^{207}Pb (neutron emission) are clearly separated. This result is crucial, since it means that it will be possible to extract separate emission probabilities as a function of excitation energy for γ-ray and neutron emission. The probability for γ-ray emission will be obtained by taking the total number of γ-related events measured in the heavy residue detector in coincidence with protons in the telescope. The same will be done for the neutron emission probability and the sum of these two probabilities should at all times add up to 1, since this experiment was performed well below the fission threshold of ^{208}Pb. Testing this will provide a powerful validation of the experimental method. The detection efficiencies were found to be nearly 100% for neutron emission residues, and above 70% for γ-related residues. This is significantly better than what is possible in direct kinematics.

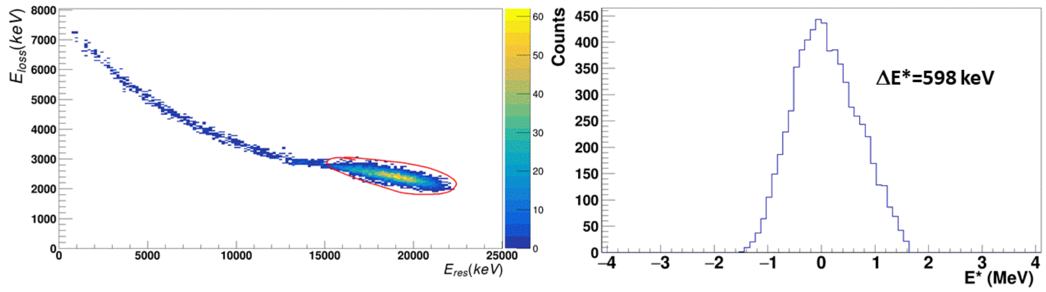

Fig. 3: The telescope data are shown on the left, where E_{loss} vs E_{res} represents the energy loss in the DSSSD vs total energy deposited in the thick Si layers. The red contour selects the region of elastically scattered protons, which are projected on the spectrum right to provide an indication of the excitation energy resolution. The standard deviation is indicated on the spectrum to the right.

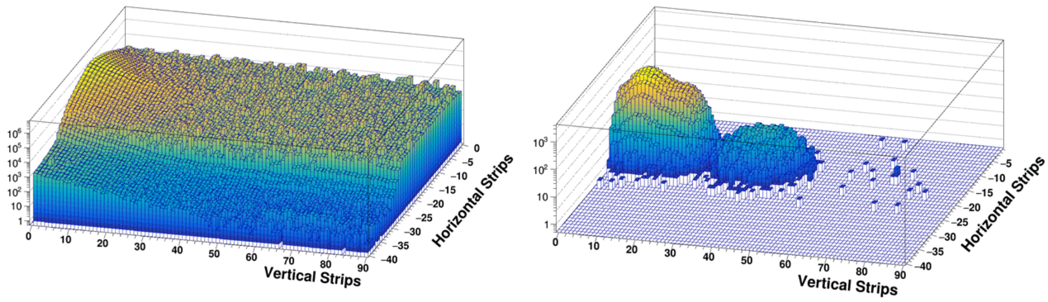

Fig. 4: Heavy residue position data shown without (left) and with (right) selection of scattered protons measured in the telescope detector. In the figure to the right, events related to γ-ray emission (^{208}Pb residues) are associated with the peak to the left, while events related to neutron emission (^{207}Pb residues) are in the peak to the right.

3. Conclusion and Outlook

A first proof of principle experiment was successfully conducted at the ESR storage ring on the ^{208}Pb(p,p') surrogate reaction. We were able to separate heavy residues related to neutron and γ-ray emission in high-efficiency measurements and to evaluate the excitation energy resolution. The measured probabilities for γ-ray and neutron emission will be used to improve the predictions for the ^{207}Pb(n,γ) and ^{208}Pb(n,n') cross sections. In the near future, our setup is to be supplemented with fission fragment detectors for the investigation of various U isotopes. Thereafter, these investigations are to be expanded to a range of nuclei in this heavy mass region. In the longer term we aim to explore the neutron-deficient actinides and pre-actinides towards the N = 126 shell closure.

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