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Gamma-ray spectroscopy of exotic neutron-rich nuclei in the doubly magic ^{132}Sn region

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Abstract. An experiment with the aim to obtain information on the excited states of neutron-rich nuclei with N∼82 was performed at RIBF/RIKEN as part of the HiCARI campaign. The method to identify nuclei on ion-by-ion basis, including charge-state identification, is presented. The Doppler correction technique was validated using the test case of ^{131}In, based on the prompt $\pi p_{3/2} \rightarrow \pi p_{1/2}$ transition at 988 keV. Preliminary analysis of the ^{130}Cd spectrum is also presented.

1. Introduction

Nuclei in the vicinity of doubly magic ^{132}Sn, namely the neutron-rich N=82 nuclei are linked to the astrophysical r-process abundance peak at A∼130. Measuring properties of these neutron-rich nuclei gives information which can be used to improve the nuclear inputs for simulations of the r-process in an attempt to recreate the elemental abundance we observe in the Universe. Difficulties arise when producing such neutron rich nuclei. They can be produced in fission, with relatively low yields. The technique of in-flight fission allows for their separation and identification. The highest yields can be achieved at the RIBF facility at RIKEN, Japan, based on the high primary ^{238}U beam intensity and the large acceptance fragment separator.

In this paper we present preliminary results of a recent experiment, selecting a few cases, focusing on N=82 nuclei.

2. Experiment

To study the structure of neutron-rich N∼82 nuclei an experiment was conducted in November 2020, as part of the HiCARI campaign. Using the high energy, high intensity super conducting ring cyclotron (SRC) at the RIBF a primary beam of ^{238}U was produced with an energy of E/A=345 MeV and an intensity of approximately 60 pnA. It was directed into a 5 mm thick primary target of ^{9}Be in front of the BigRIPS-ZDS spectrometers. BigRIPS was tuned for the optimal transmission of fully-stripped ^{130}Cd fission products. The fission products impinged on a 6 mm secondary target of ^{9}Be positioned at the entrance to the ZeroDegree Spectrometer (ZDS) also known as focal plane 8 (F8). ZDS, used for the identification of the reaction products, was tuned for maximum transmission of fully-stripped ^{129}Ag. Incoming nuclei in BigRIPS and reaction products in ZDS were identified on an ion by ion basis via the $B\rho$-ΔE-TOF method [1].

The HiCARI germanium array [2] was located at the forward angles of 20°-85° at the secondary target. The array consisted of 41 high-purity germanium crystals of differing types. HiCARI included 6 MINIBALL triple clusters, 4 Super Clover four-crystal detectors and two tracking detectors (one triple crystal, and one quad). The array was used to detect prompt gamma rays produced at the secondary target.

The detection rate of ^{130}Cd on the secondary target was measured to be 51 particles per second over a total beam time of 56.4 hours. In the one-proton removal channel from ^{130}Cd a total of ∼9400 ^{129}Ag ions were identified at the final focal plane of the ZDS. More information on the experiment can be found in [3].

3. Analysis

The ion identification is complicated by the presence of different charge states. This was the case for the nuclei after the secondary target which had an energy of E/A∼150 MeV when entering the ZDS. Charge state separation is based on magnetic rigidity measurements in the two parts of the ZDS, between focal planes F8-F9 and F9-F11. The quantity δ is calculated as $\delta = (B\rho - B\rho_0)/B\rho_0$, where $B\rho$ denotes the measured magnetic rigidity for individual particles and $B\rho_0$ is the magnetic rigidity for the central path. Figure 1 shows the charge state separation where the structures correspond to different changes of the charge state (ΔQ) in the middle of ZDS (F9). The structure labelled with $\Delta Q = 0$ contains ions which do not change charge state at F9 (fully stripped or hydrogen like throughout ZDS). Similarly $\Delta Q = +1$ indicates ions which pick up an electron, while $\Delta Q = -1$ includes those which loose one at F9. The ZDS ion identification plot, after selecting the $\Delta Q = 0$ and $\Delta Q = +1$ structures are shown in figure 2. Note that the same species appear multiple times in the ID plot. In the upper $\Delta Q = 0$ panel in black are denoted those which are fully stripped, while in red are those which are H-like throughout ZDS. In the lower $\Delta Q = +1$ panel the black label indicates fully-stripped to H-like, and red H-like to He-like nuclei.

To improve the resolving power of particle identification corrective factors were applied to the A/Q values. These were determined iteratively by removing any position dependence (as measured by parallel plate avalanche counters, PPACs) of A/Q. This improved the A/Q resolution in ZDS from $\sigma(A/Q)/(A/Q) = 0.133\%$ to 0.08%. Background removal techniques were also applied. These included removing events in which position and energy loss are not correlated in the plastic scintillator detectors located at F3, 5, 7, 9 and 11. Minimum and maximum criteria were also set on the summed signal produced from the various PPACs. The combined background removal techniques remove approximately 2% of the total data. Pile up events in the ionisation chambers in BigRIPS and ZeroDegree were also removed as they lead to contamination in the particle identification plot.

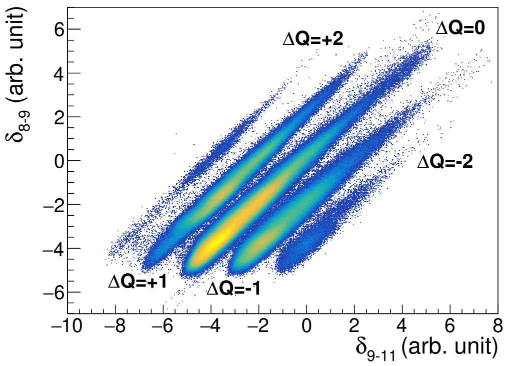

Figure 1. Charge state separation in ZDS. The ΔQ labels indicate the amount of change in the charge state at the F9 focal plane in units of e.

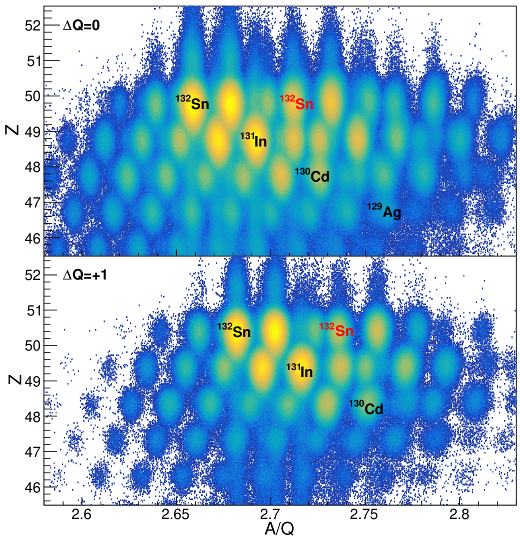

Figure 2. Identification plots of nuclei passing through ZDS. See the text for details.

Due to the high beam energy of the ions at the mid target (E/A$\sim$185 MeV, corresponding to β=v/c=0.55), accurate Doppler correction is critical. This requires precise knowledge of both β and θ (the angle of emission of the gamma ray with respect to its axis of motion) on an event by event basis. β before and after the target can be determined experimentally using the time of flight of the particles measured by the plastic scintillator detectors. To determine the velocity in the middle of the target, energy loss calculations in LISE++ [4] were used to propagate the average β before the target forward and after the target backwards. The values obtained via each direction are in agreement. The θ angle was determined via two components. Positions of each Ge detector crystal were determined via photogrammetry. A PPAC placed after the secondary target was used to determine the outgoing direction of the reaction product. The outgoing beam direction was combined with the detector positions to calculate the angle of detection of the gamma ray with respect to the particle's axis of motion.

4. The γ spectrum of ^{131}In

To ensure all experimental parameters were correct, with special emphasis on Doppler correction, the ^{132}Sn $\rightarrow$ ^{131}In channel was chosen as the test case. This is the optimal one in this experiment, as removing one proton from the double-magic ^{132}Sn nucleus populates single-particle states directly. The $\pi p_{3/2}$ to $\pi p_{1/2}$ transition of 988 keV [5] is of M1 character, and is expected to have a sub-picosecond lifetime. Therefore, it is valid to assume that on average the decay happens in the middle of the secondary target. This mid-target velocity is used for the Doppler correction.

Figure 3 shows a Doppler corrected γ-ray spectrum of ^{131}In populated in the one-proton removal channel. The fit, shown in blue, identifies the peak at the correct energy. This validates the Doppler correction parameters such as angle, velocity and target position. It is important to note however that despite these optimal conditions of a very short-lived transition, the peak is still quite broad with a FWHM of 54 keV. This peak broadening is a consequence of the thick target, as it is impossible to determine where in the target the decay occurred and thus what velocity the particle would be travelling at.

The response of the HiCARI array was simulated using a GEANT4 package (UCHiCARI), containing the HiCARI geometry [6]. The known 988 keV γ-ray energy, zero lifetime, and mid-target β were assumed. The resulting spectrum is shown in green on figure 3. The position, and the shape, including the width of the γ-ray are well reproduced.

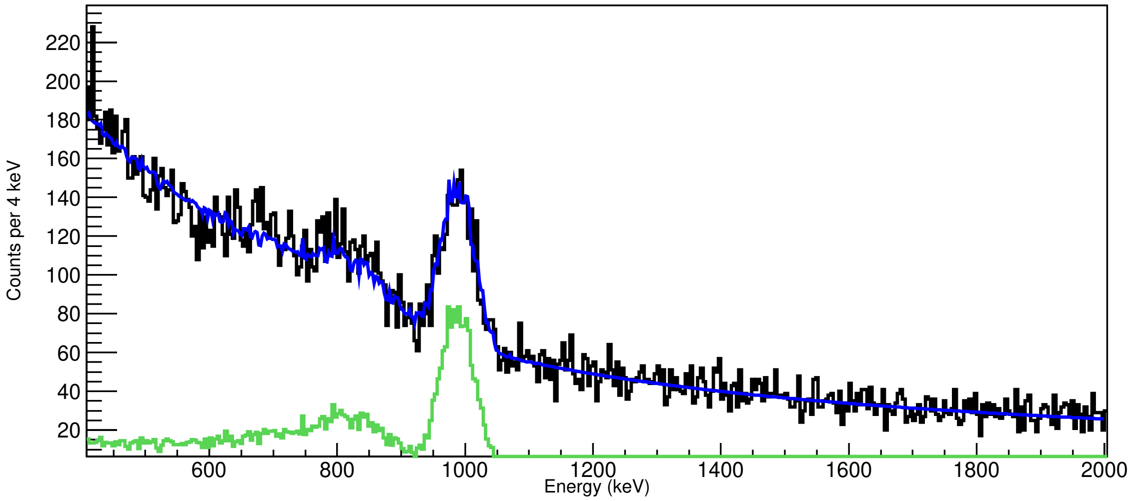

Figure 3. Gamma spectrum associated to the ^{132}Sn $\rightarrow$ ^{131}In proton knockout reaction. Shown in green, is the GEANT4 simulated response of HiCARI of the $\pi p_{3/2} \rightarrow \pi p_{1/2}$ single particle transition with a known energy of 988 keV. The blue line is a combined fit of the simulated response and a double exponential background estimate.

5. The γ spectrum of ^{130}Cd

The method used for and tested on ^{131}In was applied to other nuclei. One of the main points of interest in the region is the r-process waiting point nucleus ^{130}Cd. It was studied in the one-proton removal ^{131}In $\rightarrow$ ^{130}Cd reaction. The ^{131}In nuclei impinging on the target can be in their $9/2^-$ $\pi g_{9/2}$ ground-state, or in the $1/2^+$ $\pi s_{1/2}$ or even the high-spin $17/2^+$ and $21/2^+$ isomeric states [7]. Consequently, predominantly two-particle states will be populated in ^{130}Cd, with at least one proton (hole) being in the $g_{9/2}$ or $p_{1/2}$ orbitals.

Prior to this work, only the $\pi g^2_{9/2}$ configuration yrast states were observed in ^{130}Cd [8, 9]. Due to the nature of the setups used in this earlier literature, only decays following the isomeric $T_{1/2}$ ~230 ns 8^+ [8, 9] state were detected. In contrast, HiCARI is sensitive to prompt and near-prompt transitions. The resulting γ-ray spectrum can be seen in Figure 4. Two previously identified yrast transitions, $4^+ \rightarrow 2^+$ and $2^+ \rightarrow 0^+$ can be seen. These have energies of 539 keV and 1325 keV respectively. Due to the E2 nature of the 539 keV transition, a significant lifetime is expected. Using shell model considerations [10] the expected lifetime is in the order of hundreds of picoseconds. This lifetime causes a shift in the energy returned after Doppler correction which assumes that the γ ray is emitted mid-target. Consequently, the transition appears at a lower energy, at 509 keV in the spectrum, illustrating that such experiments have the potential to determine both energies and lifetimes simultaneously. The $2^+ \rightarrow 0^+$ transition, as it is populated from above, is also delayed by the same amount, causing a shift in the measured energy to a lower energy. The detector response of these two transitions is simulated, and shown in red in figure 4. Comparing it with the measured spectrum, it is clear that there must be a prompt component of the 1325 keV transition, simulated and shown in green. It is anticipated that this is due to the 2^+ state (which is expected to have very short lifetime) being populated directly and/or by its population of high energy (>1 MeV) transitions from above. The combination of these two components reproduces very well the step-like structure seen on the measured spectrum. Other, previously unknown transitions can also be seen in the spectrum. The interpretation of these transitions is yet to be determined, guided by shell model calculations [10] and particle knockout reaction theory [11].

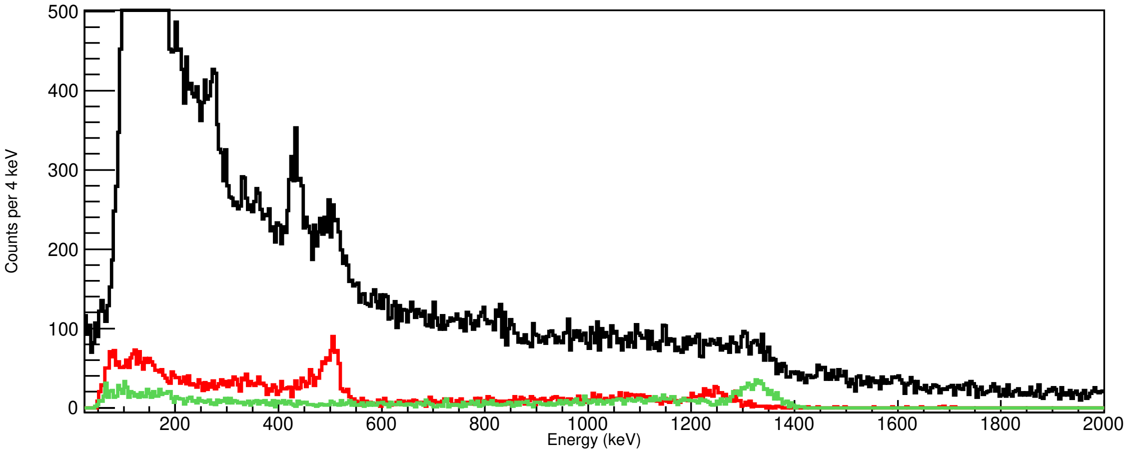

Figure 4. Measured Doppler corrected γ-ray spectrum of the ^{131}In $\rightarrow$ ^{130}Cd proton knockout reaction (black). The simulated response of HiCARI for the 539 keV and 1325 keV transitions assuming $T_{1/2}$=350 ps, and that of the 1325 keV $T_{1/2}$=0 ps transition are shown in red and green, respectively.

6. Conclusion

An experiment to study neutron-rich nuclei in the vicinity of ^{132}Sn has been carried out at RIBF, RIKEN, in November 2020. Nuclei were populated in particle removal reactions, and the associated γ rays detected. The test case nucleus of ^{131}In was used to validate the analysis method used in the experiment. In the spectrum of ^{130}Cd two previously identified transitions are observed. The analysis is ongoing, aiming to incorporate new transitions in the level scheme. Analysis of other nuclei, such as ^{130,132}In, will provide insight on the neutron-proton interaction below and above the N=82 closed neutron shell.

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