IN-BEAM γ-RAY SPECTROSCOPY WITH FAST NEUTRON PROBES AT NFS*

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Received 19 November 2024, accepted 17 December 2024,
published online 10 April 2025

Using the high flux of fast neutron beam provided at the Neutrons For Science (NFS) facility of GANIL-SPIRAL2, high-resolution γ-ray spectroscopy of nuclei produced in the (n, xn) reactions is performed with the EXOGAM HPGe array. The nuclei produced by the $(n, 2n)$ and $(n, 3n)$ channels of ^{58}Ni are re-examined through prompt γ-ray spectroscopy in coincidence with fast neutrons to provide a comprehensive and possibly new description of its level schemes and excitation functions.

DOI:10.5506/APhysPolBSupp.18.2-A19

* Presented at the 57$^{\text{th}}$ Zakopane Conference on Nuclear Physics, *Extremes of the Nuclear Landscape*, Zakopane, Poland, 25 August–1 September, 2024.

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1. Introduction

Understanding and predicting the evolution of nuclear structure has long been a central focus of nuclear physics. Established experimental techniques such as charged particle induced reactions and fusion–evaporation reactions have been used extensively for this purpose. However, the possibilities expand by fast neutrons probes as they provide a complementary path. With this goal in mind, an experiment was performed at the NFS facility [1, 2] to probe nuclear structures using fast neutrons for the first time. Fast neutrons can penetrate deep into the nucleus without being deflected or slowed down by the electromagnetic field, allowing for the direct interaction through the strong nuclear force.

The (n, xn) reactions, while studied for cross-sectional data evaluation, have rarely been employed in nuclear structure studies. Consequently, the understanding of the associated reaction mechanism remains limited. The high-energy thresholds and relatively low cross sections of these reactions make them challenging to study. However, the unprecedented neutron flux up to 40 MeV at the NFS facility gives the possibility of a high statistics measurement to perform γ-ray spectroscopy on nuclei produced through these exotic channels in the perspective of nuclear structure physics. As an initial test case, we chose to look at the well-studied Ni-shell. With $^{\rm nat}$Ni target, via the $(n, 3n)$ channel, the doubly magic ^{56}Ni was investigated for the first time using a pure neutron probe. Alongside, Co and Fe isotopes that are produced from $(n, p/d/t/\alpha)$ reactions will also be studied. The nuclei near ^{56}Ni are of particular interest because they are well-suited for various microscopic theoretical approaches, allowing us to explore the interplay between single-particle and collective excitations. For all the isotopes produced, the primary objective is to investigate what yrast surface is populated by these reactions and to understand how they differ from particle transfer and heavy-ion reactions. New spectroscopic information to be collected will also be relevant for nuclear reaction tools (such as TALYS [3]) and nuclear data evaluation libraries.

2. Experimental setup

The neutron beam at NFS was produced by $d+$Be reaction, with significantly higher average flux up to 40 MeV, compared to n_TOF, GELINA or WNR. In the Time of Flight (TOF) hall, at ~ 8 metres from the converter, a 1 mm thick $^{\rm nat}$Ni target is placed, around which 12 EXOGAM detectors [4] were arranged. Using the Co calibration source, the absolute efficiency is determined to be $(5.70 \pm 0.28)\%$ at 1332 keV. To avoid being overwhelmed by inelastic scattering events, for data taking across the full neutron energy range provided by NFS, we implemented strict neutron TOF validations

(175 and 200 ns) to collect data coincident with fast neutrons. Despite the limited timing resolution of HPGe detectors, we were still able to observe a clear distinction between the fast-neutron region and the γ flash (photons produced due to reactions on the Be converter).

During an effective beam time of 8 days with the Ni target, about 10^{10} $\gamma\gamma$ coincidences have been sorted after the addback procedure. Additional 3 days of data were taken with the Pb target. This is the first time EXOGAM experienced such high doses of fast neutrons, hence the corresponding resolution damage was studied extensively. The average beam flux reaching the target was 4.5×10^6 neutrons/cm^2/s, which resulted in a 13.7% deterioration of the detector resolution at 1332 keV within an effective run time of 4 days. Based on earlier neutron damage studies [5], we expected this to correspond to a total neutron dose of $\mathcal{O}(10^8)$ neutrons/cm^2 on EXOGAM. Our estimation for the experiment, shown in Fig. 1, matches well with it. After a total of $\sim$ 50% degradation over 11 days of effective beam time, the detectors were successfully recovered through annealing. All clovers were warmed, re-cooled, annealed at 100°C for a week, and remeasured before the 2024 beam time. The Gaussian shape and the resolution of the peaks were successfully recovered.

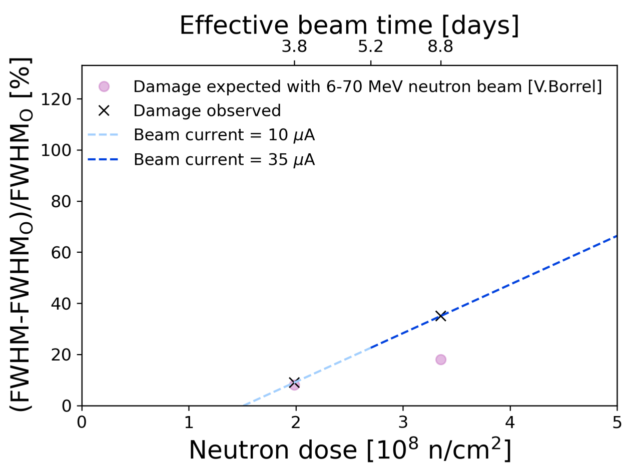

Fig. 1. The evolution of degradation with neutron dose, as observed for the 1332 keV line of ^{60}Co, is shown. The fits performed are linear, based on only two data points, which describe the behavior of the relative FWHM.

3. Results and discussion

Evidence of the $^{58}\mathrm{Ni}(n, 3n)^{56}\mathrm{Ni}$ reaction channel was observed as shown in Fig. 2, with additional contributions leaking into the gate. Notably, ^{57}Co accounts for $\sim 60\%$ of the 1224 keV yield, and the remaining 40% must come from ^{56}Ni. Furthermore, ^{56}Ni was also seen in the $\gamma\gamma\gamma$ analysis, reinforcing the presence of this isotope.

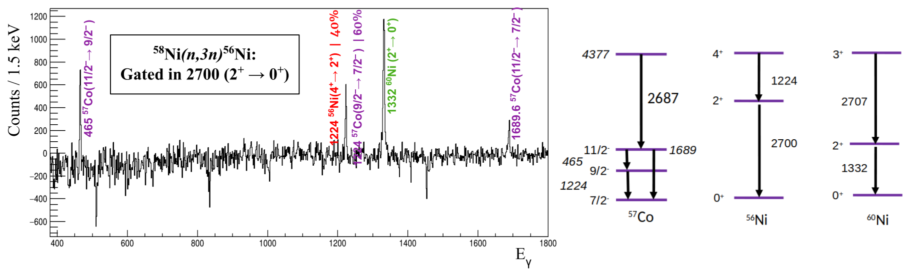

Fig. 2. (Color online) Prompt γ spectrum, gated on 2700 keV, showing the evidence of ^{56}Ni along with other contributions.

Statistical model calculations show that the $(n, 2n)$ channel is two orders of magnitude higher cross section compared to the $(n, 3n)$ channel [6], hence we focused our studies on ^{57}Ni. The observed transitions for this isotope were compared with previous studies. Figure 3 illustrates the observed gamma transitions in our dataset. Transitions displayed in black correspond to previously identified and observed in our data set, while those in red/gray and orange/light gray represent previously identified but unobserved and unconfirmed transitions, respectively. An initial analysis indicates that states populated solely through particle transfer reactions are absent in our data set, as can be seen on the right-most side of Fig. 3. Based on this, we observe that the $(n, 2n)$ channel behaves similarly to heavy-ion fusion evaporation reactions, but is limited to low angular momentum. Despite these similarities, new transitions — some highlighted in green (1808, 2533 keV) — are observed in the $(n, 2n)$ channel. These transitions, not previously identified in heavy-ion fusion–evaporation experiments, are to be integrated into the level scheme.

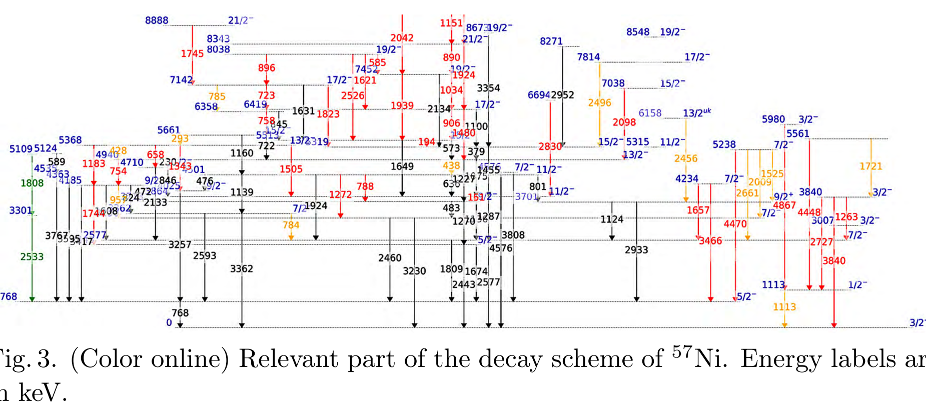

Fig. 3. (Color online) Relevant part of the decay scheme of ^{57}Ni. Energy labels are in keV.

In the present experiment, 4 (8) clover detectors are placed at 135° (90°) with respect to the neutron beam axis. Based on the directional co-relation ratio (R_{DCO}) calculated based on Eq. (1), the fast neutrons seem to align the nuclei, as seen in Fig. 4, like in the case of fusion–evaporation of heavy-ions. Thanks to EXOGAM's ability to act as a polarimeter [7], we are also sensitive to asymmetry measurements as given by Eq. (3), where $a(E_\gamma)$ is calculated using unpolarized sources with Eq. (2). This asymmetry is used to validate the positive parity of the 3701 keV state (see Fig. 5) based on $g_{\frac{9}{2}}$ orbital as measured by Rudolph *et al.* [8, 9], which were different from the earlier spin and parity assignments from pick-up reactions [10]

$$R_{\mathrm{DCO}} = \frac{I\,(\gamma_1 \,\mathrm{at}\, 135°;\,\mathrm{gated\,by}\,\gamma_2\,\mathrm{at}\,90°)}{I\,(\gamma_1\,\mathrm{at}\,90°;\,\mathrm{gated\,by}\,\gamma_2\,\mathrm{at}\,135°)}\,, \tag{1}$$

$$a(E_\gamma) = \frac{N_\parallel\,(\mathrm{unpolarized})}{N_\perp\,(\mathrm{unpolarized})}\,, \tag{2}$$

$$A = \frac{[a\,(E_\gamma)\,N_\perp] - N_\parallel}{[a\,(E_\gamma)\,N_\perp] + N_\parallel}\,. \tag{3}$$

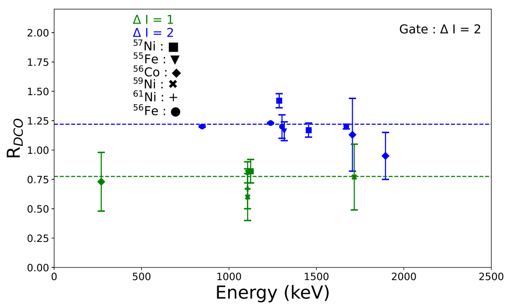

Fig. 4. Measured DCO ratios for known dipole and quadrupole transitions using gates on stretched quadrupoles.

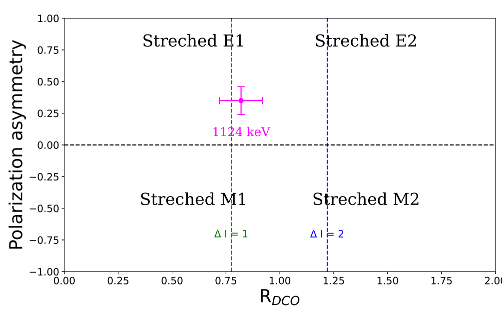

Fig. 5. Asymmetry ratio as a function of the DCO ratio for the transition from the 3701 keV state in ^{57}Ni.

In addition to collecting spectroscopic information, we were also able to measure excitation functions based on the event-by-event measurement of the TOF between the HPGe CFD and RF of the LINAC. Specifically, we compared the excitation function for the $\frac{5}{2}^- \rightarrow \frac{3}{2}^-$ transition in the $(n, 2n)$ reaction with predictions from TENDL data [6] and observed significantly higher values at higher neutron energies. This discrepancy highlights the need for further refinement in theoretical models to accurately represent the experimental data.

4. Conclusions and prospects

The experiment was successfully conducted, demonstrating that high-resolution γ-spectrometry is feasible even for fast neutron-induced reactions. Preliminary results suggest that the $(n, 2n)$ channel resembles heavy-ion fusion–evaporation, though limited to low angular momentum. The present work indicates that the reactions induced by fast neutrons produce aligned nuclei. We also potentially observed new γ transitions that would be integrated into the level scheme, with the possibility of assigning spin and parity. Further studies are planned, including neutron-rich Co isotopes from ^{60}Ni and data collected with a Pb target.

Present work is an initial effort of a bigger goal to investigate the interplay between direct and compound nuclear reaction mechanisms. Methods to approach this complex problem are being explored.

We acknowledge the GANIL facility and the NFS team for providing the neutron beam, and the EXOGAM Collaboration for their support.

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