

In-beam γ -ray spectroscopy with fast neutron probes at NFS

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Abstract. 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.

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 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 allows 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 ^{nat}Ni target, via the (n,3n) channel, the doubly magic ^{56}Ni was

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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 $d + \text{Be}$ 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 ^{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 was taken with 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/cm²/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 $O(10^8)$ neutrons/cm² on EXOGAM. Our estimation for the experiment, shown in Figure. 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.

3 Results and Discussion

Evidence of the $^{58}\text{Ni}(n,3n)^{56}\text{Ni}$ 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 $\gamma\gamma$ analysis, reinforcing the presence of this isotope.

Statistical model calculations show that the $(n,2n)$ channel has 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. Fig. 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 and orange represent previously identified but unobserved and unconfirmed transitions, respectively. An initial analysis reveals that states exclusively populated through particle transfer reactions are absent from our dataset, as evidenced on the right side of Fig. 3, at energies of 1113, 3007, 3840, 4234, 5238, 5561, and 5980 keV. Based on this, we observe that the $(n,2n)$ channel

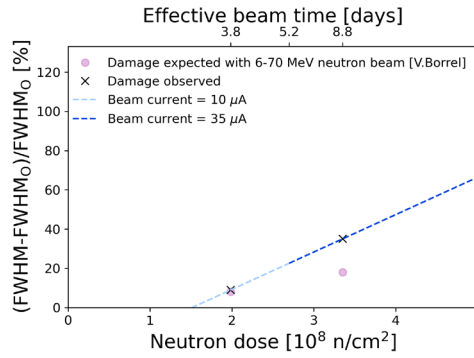


Figure 1. The evolution of degradation with neutron dose, as observed for the 1332 keV line of ^{60}Co , is shown. The fits performed are linear, based on only two data points, which describe the behavior of the relative FWHM.

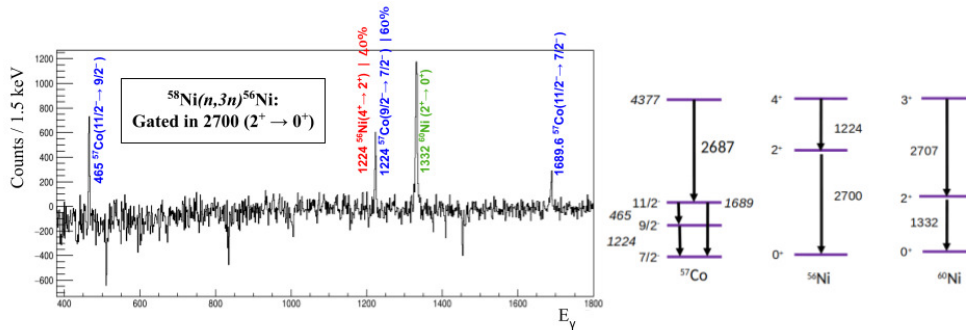


Figure 2. Prompt γ spectrum, gated on 2700 keV, showing the evidence of ^{56}Ni along with other contributions.

behaves similarly to heavy-ion fusion evaporation reactions, but is limited to low angular momentum. Despite this, new transitions, highlighted in green, are observed in the (n,2n) channel. These transitions were not previously identified in heavy-ion fusion-evaporation experiments.

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}) calculations, 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 used to validate the positive parity of the 3701 keV state (see Fig. 5) based on $g_{3/2}$ orbital as measured by Rudolph *et al.* [8, 9], which were different from the earlier spin and parity assignments from pick-up reactions [10].

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 signif-

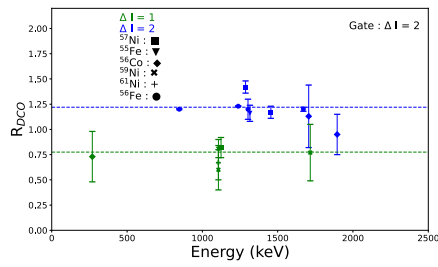


Figure 4. Measured DCO ratios for known dipole and quadrupole transitions using gates on stretched quadrupoles.

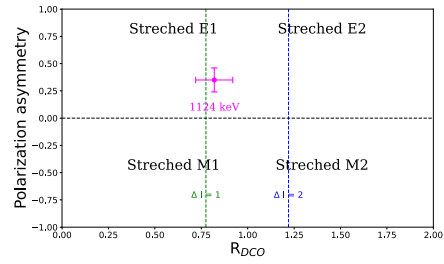


Figure 5. Asymmetry ratio as a function of the DCO ratio for the transition from the 3701 keV state in ^{57}Ni .

icantly 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 in the ^{nat}Ni target. Additionally, data have been collected using a ^{nat}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.

5 Acknowledgements

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