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A new measurement on $^{56}\text{Fe}(n,\text{inel})$ using GAINS@GELINA

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Abstract. The extended dataset of $^{56}\text{Fe}(n,\gamma)$ cross sections measured by our group more than a decade ago at GELINA (Geel Linear Accelerator) was used in many recent evaluations like ENDF, JEFF and CIELO. Despite the special measures we took to ensure reliability and accuracy, concerns were raised by various groups with regard to several features of this dataset (absolute normalization and/or shape) and therefore the $^{56}\text{Fe}(n,\text{inel})$ cross section is still under the evaluation by the International Nuclear Data Evaluation Network (INDEN). Consequently, a new experiment is now under preparation aiming to take advantage of the numerous experimental improvements of the GAINS (Gamma Array for Inelastic Neutron Scattering) setup implemented over the years. While γ spectroscopy combined with the time-of-flight method will remain the main technique involved, several other experimental details will differ substantially.

1 Introduction

Iron represents, arguably, the most important material used in the structure of any nuclear facility. Therefore, a precise knowledge of all cross sections of neutron-induced reactions on iron isotopes is essential for the design of nuclear installations. Iron has four stable isotopes: ^{54}Fe [natural abundancy 5.85(11)%], ^{56}Fe [91.75(11)%], ^{57}Fe [2.12(3)%], and ^{58}Fe [0.28(1)%] [1].

Over the last decade our group published the neutron inelastic cross sections of ^{54}Fe [2], ^{56}Fe [3] and ^{57}Fe [4] for incident energies from ≈ 70 keV to ≈ 18 MeV. The measurement on the major isotope ^{56}Fe was performed in 2007 using the GAINS (Gamma Array for Inelastic Neutron Scattering) spectrometer at the GELINA (Geel Linear Accelerator) neutron source and published a few years later in Ref. [3]. Out of these three experiments it was the only one using a natural target. It allowed the direct measurement of 20 γ -production cross sections and, using the evaluated level scheme [5], the computation of 10 level cross sections and of the total inelastic cross section.

Two major evaluation projects were implemented after the publications of our results on the inelastic cross sections of ^{56}Fe : CIELO (Collaborative International Evaluated Library Organisation) [6] followed by INDEN (International Nuclear Data Evaluation Network) [7]. In both cases the neutron inelastic cross section of ^{56}Fe were considered essential quantities for the development of a new generation of nuclear facilities and were re-evaluated.

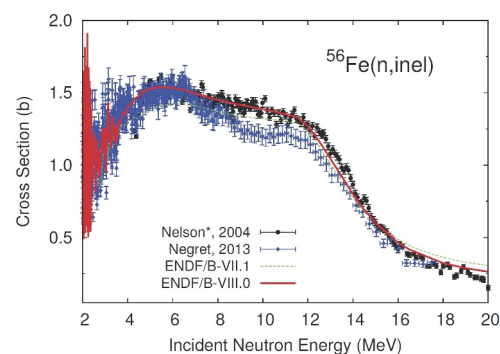


Figure 1. Result of the CIELO evaluation compared with the result of our previous measurement and the result of an experiment performed by R. Nelson et al. [8] at Los Alamos National Laboratory that was rescaled. Figure taken from Ref. [9].

The results of the CIELO evaluation on iron isotopes, also adopted by ENDF/B-VIII.0, were published in Ref. [9]. It overlaps well with our experimental result for a large energy range. Fig. 1, taken from Ref. [9], displays this result.

Nevertheless, within the next important evaluation project, INDEN, it was noted that the ^{56}Fe evaluation from ENDF/B-VIII.0 does not perform well when it is benchmarked against certain integral measurements [10]. In particular, the discrepancies observed in an iron sphere leakage spectrum shown in Fig. 2 were traced back to the in-

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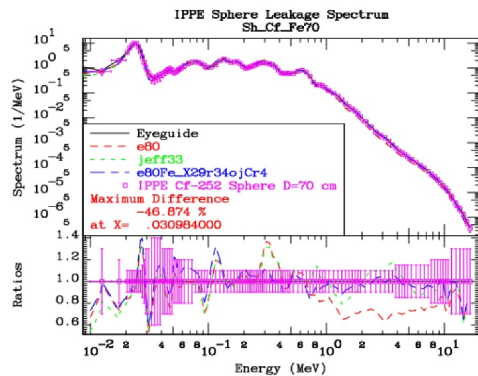


Figure 2. Neutron leakage in a 70-cm diameter sphere with a Cf source. Discrepancies were linked to the inelastic cross section of ^{56}Fe . Figure taken from Ref. [11], page 11.

elastic data for $E_n=1-8$ MeV. Consequently, the new evaluation of $^{56}\text{Fe}(n,\text{inl})$ cross sections performed within the INDEN project rejects, at least partially, our data [11].

Until now we did not discover any experimental reason to question the result published in Ref. [3]. However, following the same arguments as the INDEN evaluators, we consider that a new measurement of the $^{56}\text{Fe}(n,\text{inl})$ cross sections using the GAINS setup at GELINA is required. In the present paper we emphasize the differences and similarities between the current setup and the one previously used arguing that the upgrades already implemented or that are now under consideration are significant and will probably allow us to identify any possible hidden issue of our previous measurement.

2 Experimental setup and technique

The experimental setup consists of the neutron source and time-of-flight facility GELINA and the HPGe array GAINS operated by the European Commission's Joint Research Centre in Geel, Belgium. These experimental facilities were used together for more than 15 years generating a significant quantity of high precision neutron inelastic data [12].

GELINA consists of a high intensity electron accelerator (140 MeV) operated in a pulsed mode at 400 Hz, a depleted uranium target and several flight paths. GAINS is an array of 12 high volume HPGe detectors currently installed at the end of a 100-m flight path of GELINA. The detectors are placed at backward angles of 110° , 125° and 150° with respect to the incoming neutron beam. They point to a sample that usually has a thickness of 1-3 mm and a diameter larger than the neutron beam that is collimated to 61 mm. The total efficiency of GAINS is around 2% for 1.3-MeV γ rays. A more detailed description of GAINS, including a picture of the current setup can be found in Ref. [12].

The experimental method makes use of the very good time resolution of GELINA (≈ 2 ns) and the long flight path to determine very accurately the neutron energy. The γ rays emitted following inelastic scattering of neutrons are detected by the HPGe detectors. The special choice

of emission angles allows a precise integration of the γ -ray angular distribution as explained in Section 4.1.1 from Ref. [13].

The neutron beam is monitored by a fission chamber with multiple layers of ^{235}U .

The primary experimental results consist of the γ -production cross sections for the most important transitions from the nucleus of interest. In most cases the exceptional γ -energy resolution specific of the HPGe detectors allows very good separation of the main transitions. The γ -production cross sections are reported as absolute values, but one should keep in mind that the beam is monitored using a fission chamber and, therefore, they are calculated relative to the standard ^{235}U cross section [14]. The neutron energy resolution of the setup is influenced by the time resolution of the HPGe detectors (≈ 10 ns) and the length of the flight path (≈ 100 m), resulting in ≈ 3 keV at $E_n=1$ MeV. Consequently, the resonant structures of the strongest γ -production cross section are visible in many cases (see fig. 3). Whenever statistics is insufficient and the statistical uncertainties are too high (i.e. larger than 2-3% for the strong transitions), one can combine several time-of-flight channels and sacrifice neutron energy resolution in order to increase the statistics per channel. This procedure is generally avoided at small neutron energies where the resonant structures of the cross section are visible (see Fig. 3) but can be safely applied at higher energies.

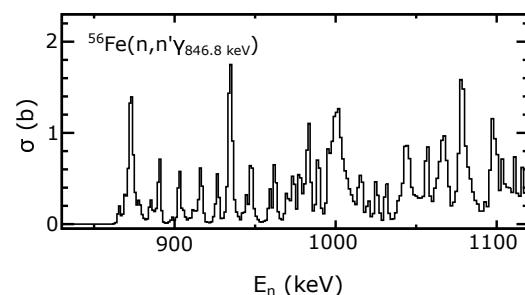


Figure 3. 846.8-keV γ -production cross section from ^{56}Fe obtained in our previous measurement. A limited energy range is displayed to show the resonant structures visible due to the good resolution.

Several corrections are applied using Monte Carlo simulations, including the multiple-scattering correction and the correction for the detection efficiency from the extended sample.

The final step in data analysis employs an external nuclear structure database - namely the ENSDF (Evaluated Nuclear structure Data File) [15] - to generate transition probabilities from the γ -production cross section (i.e. correcting for the internal conversion when necessary) and further, using the branching ratios, to generate the total inelastic and the level cross sections. These are accurate only over a limited energy range depending on which γ rays from the reaction were observed. In this context it should be noted that the neutron inelastic scattering is a rather non-selective process, populating most of the accessible levels of the target nucleus.

More details on the experimental setup and the data analysis technique are available in Ref. [16].

3 Main differences between the previous and the newly-proposed measurement

In the previous section we gave a short overview of the experimental technique and the main facilities used to measure neutron inelastic cross sections. Most of these features remain unchanged as they represent the basis of our method: a combination of the γ spectroscopy using HPGe detectors with the time-of-flight technique.

However, the newly-proposed measurement of the neutron inelastic cross section of ^{56}Fe will benefit from a number of upgrades that make it significantly different from the one reported in Ref. [3]. The most important changes are the following:

- A new flight path is used,
- A different sample is irradiated,
- GAINS was upgraded,
- A new data acquisition system will be implemented,
- A double-normalization method is proposed.

Compared to the measurement performed in 2007 when a flight path of 200 m was used, the newly proposed experiment will use a new **flight path**, GAINS being now installed at 100 m from the neutron source. The accelerator is now operated at 400 Hz instead of 800 Hz and the whole flight path area was refurbished. Consequently the instantaneous flux on the sample is now higher and its shape may be slightly different. In general these differences are not essential, but they result in a somewhat different neutron flux which constitutes an advantage for the new proposal.

The **sample** used in the previous measurement was composed of three ^{nat}Fe disks, each of them with a thickness of 1 mm, a diameter of 80 mm and a purity of 99.5%. For the future measurement an enriched sample (99.77(1)% of ^{56}Fe), procured from the Oak Ridge national Laboratory, will be used. It has a thickness of 1 mm and a diameter of 70 mm.

Over the years **GAINS was continuously upgraded**. An overview of these upgrades (and of the experimental program conducted there) is given in Ref. [12]. Practically all HPGe detectors used in 2007 were replaced or at least reconditioned. Moreover, four extra detectors were added to the system at the scattering angle of 125° allowing a double calculation (though less precise in terms of angular integration) of the γ -production cross sections. A new supporting frame and a new nitrogen filling system are now in place.

The **data acquisition system** processing the signals from the HPGe detectors of GAINS was based for the last 15 years on Acqiris digitizers running at a sampling rate of 420 MHz and having 12 bits. They can accommodate 2 input channels per card with a common trigger (so, for the 8 detectors used in the previous measurement, 4 cards were used in two dedicated crates). The trigger signal was

built using conventional electronics and was delivered to the card only when at least one of the two input channels showed an event in the time range of interest. The system resulted in a counting rate of only 10-15 events/second in each detector. However, recently it became unstable most probably because of the ageing of the electronics.

Therefore, an upgrade of the data acquisition is currently being implemented in collaboration with University of Groningen. The new system developed there is based on Struck SIS3316-250-14 SADC cards with 16 channels, 250 MHz sampling rate and 14 bits. They benefit from a GBE readout and will be operated using internal triggering with an external gate. The fact that all GAINS detectors will be connected to the same module will open the possibility for coincidence measurements eliminating the issue of time synchronization among different modules. Although the counting rate in our experiments is rather low and, therefore, the number of coincident events is also small, this may at least allow various checks for cases when overlapping γ transitions are present in the spectra.

Finally, an additional **normalization method** was proposed. As already discussed, the current setup uses a fission chamber and, therefore, the cross sections are scaled to the $^{235}\text{U}(n,f)$ standard [14]. As this is a powerful and reliable technique, it will be kept during the proposed experiment. However, we propose to perform a double check simply by measuring a second sample together with the ^{56}Fe target. As this implies additional corrections and complicates some of the corrections already used, it will probably not be used for the entire duration of data taking. But performing such a check for several runs using for example a ^7Li [17] and/or ^{48}Ti [18] sample is an interesting option.

4 Conclusions

The main conclusion of this report is that a new measurement of the neutron inelastic cross section of ^{56}Fe is being proposed using the GAINS spectrometer at GELINA, 15 years after a similar experiment was performed. The main effort is to decouple as much as possible the two measurements: although the same general method will be used, many other experimental details will be changed including the target, the data acquisition and possibly the normalization method.

As a more general remark, we note an important specificity of the nuclear data field: if in general in the scientific environment, and particularly in case of basic research the emphasis is always on world premieres, in case of nuclear data experiments the redundancy and the repetition of certain measurements is an essential tool in our quest for reliability and precision.

Acknowledgements

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