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Angular distribution measurement of gamma rays from inelastic neutron scattering on ^{56}Fe at the *n*ELBE time-of-flight facility

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Abstract. Inelastic neutron scattering from ^{56}Fe was studied at the *n*ELBE time-of-flight facility. The incoming neutron energy ranges from 100 keV to 10 MeV in the fast neutron spectrum, where high precision nuclear data are needed. A detector setup has been installed to investigate the γ-ray angular distributions. It contains five HPGe and five $LaBr_3$ detectors positioned at 30, 55, 90, 125 and 150 degrees relative to the beam axis. The intrinsic and the neutron induced background from the setup was subtracted by cyclical measurements with and without the natural Fe-target. Corrections for extended source efficiency and gamma-self-absorption, inside the target, were done using GEANT4 simulations.

The angular distributions measured with the HPGe detectors are compared with earlier data. High neutron energy resolution up to a few keV was obtained with the $LaBr_3$ detectors due to their much better time resolution.

1. Introduction

Nuclear data of ^{56}Fe are of great interest, because iron is used as structure material in nuclear applications. Although ^{56}Fe was studied over several decades, the isotope is still on the focus of nuclear measurements as indicated by the Nuclear Data "High Priority Request List" of OECD/NEA from 2008 [1]. Small uncertainties (3–6%) for integral benchmark studies especially for the neutron inelastic scattering cross section are requested. Recently the CIELO-project [2] pointed out the need of cross section data of ^{56}Fe and furthermore a better knowledge of the angular distribution. In inelastic scattering, one can study the angular distribution of both reaction products – the scattered neutron and the emitted γ ray. The γ-ray production cross section of the first transition of ^{56}Fe at $E_\gamma = 847\,\text{keV}$ is a very good indicator of the total inelastic scattering cross section as the first excited 2^+ state is fed from almost every higher lying level. Nevertheless there are only a few data points of the γ-ray angular distribution of $E_\gamma = 847\,\text{keV}$ measured in the 1970s [3]. D.L. Smith et al. measured eleven increasing neutron incident energies up to the second level energy at $E_x = 2085\,\text{keV}$ and determined angular distribution parameters for even Legendre polynomials. The fast neutron generator at Argonne National Laboratory provided quasi-monoenergetic neutrons from $^7\text{Li}(p,n)$ with an energy resolution of about 50 keV. Non-zero a_4-terms were found. This anisotropy can influence the γ-ray production cross section, if not taken into account as a correction in a partial cross section measurement, e.g., taken at an angle of 125°. Moreover the inelastic scattering cross section on ^{56}Fe shows resonant structures below the second excited state. Therefore high-resolution measurements of the γ-ray angular distribution are required to match the resolution of the inelastic scattering cross section measurements e.g., [4] and [5].

2. Experiment at *n*ELBE

The experiment was performed at ELBE, the superconducting **E**lectron **L**inac for beams with high **B**rilliance and low **E**mittance at Helmholtz-Zentrum Dresden – Rossendorf (HZDR).

2.1. Time-of-flight facility *n*ELBE

Part of the user-facility ELBE is the neutron time-of-flight facility *n*ELBE (see Fig. 1), which is the first photo-neutron source worldwide using an electron beam of a superconducting linear accelerator. Main beam parameters for ELBE and the present experiment are shown in Table 1. Due to its time structure and high repetition rate *n*ELBE enables the study of relevant reactions with fast neutrons in the range of some tens keV up to 10 MeV at a flight path between 5 and 11 m. The facility provides a neutron flux up to $3 \cdot 10^4 \frac{n}{\text{s cm}^2\,\text{MeV}}$. Further details describing the

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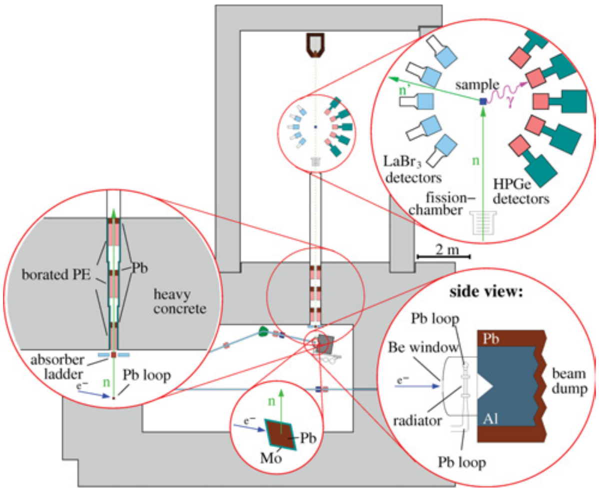

Figure 1. Schematic setup of the angular distribution experiment at *n*ELBE.

Table 1. Parameters of the ELBE beam.

Parameter	ELBE	this exp.
Electron beam energy [MeV]	8–40	30
Max. bunch charge [pC]	77	77
Max. average beam current [μA]	1000	7.7
Micropulse duration [ps]	1–10	1–10
Micropulse repetition rate [kHz]	13000	101.5625

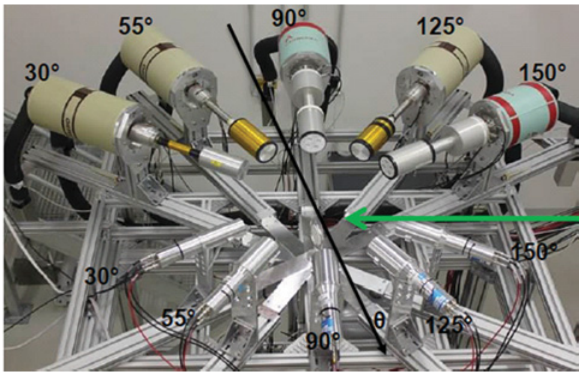

Figure 2. The experimental setup with five HPGe-detectors and five LaBr$_3$ scintillators. The target can be moved vertically out of the beam. The neutron beam (green) enters from the right.

liquid-lead-loop as photo-neutron source and characterizing the facility *n*ELBE can be found in [6].

2.2. Setup for angular distribution measurement

To study the γ-ray angular distributions of ^{56}Fe(n, n$'\gamma$) a new setup has been constructed. A sample of natural iron is positioned, at a flight path of $s = 8.3$ m. It has a cyclindric shape with a diameter of 79 mm, a thickness of 4.5 mm and a mass of $m = 172.103$ g. Ten detectors are set up around the target at a distance of 300 mm in the horizontal plane (see Fig. 2). Five lanthanum bromide scintillation (LaBr$_3$) and five high-purity germanium (HPGe) detectors are mounted at angles of 30°, 55°, 90°, 125° and 150°, relative to the beam axis.

The scintillation detectors have a very good time resolution ($\Delta t \approx 300$ ps). The HPGe semiconductor detectors are used for high resolution γ-spectroscopy, but with their time resolution of about 10 ns at the flight path available at *n*ELBE they will achieve neutron energy resolutions comparable to that of [3]. The LaBr$_3$ detectors will be used to determine γ-ray angular distribution data with high neutron energy resolution.

Table 2. Correction factor $c_{\mathrm{abs},\theta}(E_\gamma)$ due to γ-ray self-absorption inside the ^{nat}Fe-target for each detector and a γ-ray energy of $E_\gamma = 847$ keV. The statistical uncertainty of the simulation is about 0.001.

HPGe	30°	55°	90°	125°	150°
$c_{\mathrm{abs},\theta}(E_\gamma)$	1.186	1.460	1.365	1.150	1.125
LaBr$_3$	30°	55°	90°	125°	150°
$c_{\mathrm{abs},\theta}(E_\gamma)$	1.125	1.151	1.366	1.458	1.186

3. Data analysis

The angular distribution W_n can be determined in a relative measurement, because all detectors measure at the same time and in that way W_n is independent from the neutron flux in contrast to the single detector measurement of Smith [3]. The photo production cross section

$$\sigma_\theta(E_\gamma, \Delta E_\mathrm{n}) = \frac{\mathrm{d}\sigma}{\mathrm{d}\theta}(E_\gamma, \Delta E_\mathrm{n}) \sim \frac{N_\theta(E_\gamma, \Delta E_\mathrm{n})}{\Phi_\mathrm{n}(E_\mathrm{n}) \cdot n_\mathrm{at}} \quad (1)$$

is normalized to the one of 90°:

$$W_\mathrm{n}(\theta, E_\gamma, \Delta E_\mathrm{n}) := \frac{\sigma_\theta(E_\gamma, \Delta E_\mathrm{n})}{\sigma_{90^\circ}(E_\gamma, \Delta E_\mathrm{n})} = \frac{N_\theta^{\aleph}(E_\gamma, \Delta E_\mathrm{n})}{N_{90^\circ}^{\aleph}(E_\gamma, \Delta E_\mathrm{n})}. \quad (2)$$

Consequently W_n is also independent of the uncertainties of the neutron flux $\Phi_\mathrm{n}(E_\mathrm{n})$ and the areal density n_at. For the photon intensity $N_\theta(E_\gamma, \Delta E_\mathrm{n})$ the following corrections have to be made:

$$N_\theta^{\aleph}(E_\gamma, \Delta E_\mathrm{n}) = \frac{c_{\mathrm{abs},\theta}(E_\gamma) \cdot N_\theta(E_\gamma, \Delta E_\mathrm{n})}{c_{\mathrm{ext},\theta} \cdot \varepsilon_{\mathrm{point},\theta}(E_\gamma)}. \quad (3)$$

The efficiency calibration is done with pointlike calibration sources such as ^{137}Cs, ^{60}Co and ^{88}Y. Since an extended target of $^{\mathrm{nat}}$Fe is used, a correction factor $c_{\mathrm{ext},\theta}$ is calculated with a simulation in Geant4, which takes into account the solid angle of the detectors and the position of possible emitting centres.

Another correction, which has to be applied, is the self-absorption of γ-rays inside the target. This effect is lowered by tilting the sample normal to beam axis by an angle of 19.5°. Nevertheless the self-absorption correction factor c_abs, calculated with Geant4, is significant for the 55° HPGe and the 125° LaBr$_3$ detector, see Table 2.

$N_\theta(E_\gamma, \Delta E_\mathrm{n})$ is the main measure of the correlated time and energy information of the detected events. The time of flight t_n, calibrated with the γ-flash, can be transformed to the incident neutron energy via:

$$E_{\mathrm{kin,n}} = m_\mathrm{n} c^2 \left(\frac{1}{\sqrt{1 - \left(\frac{s}{t_\mathrm{n} \cdot c}\right)^2}} - 1 \right). \quad (4)$$

For the accumulated E_γ-t_n-histograms (see Fig. 3) a channel-dependent dead-time correction factor α [6] was applied (approximately 71% if target is inside the beam). Furthermore the intrinsic and the neutron induced background of the setup has been subtracted by cyclical

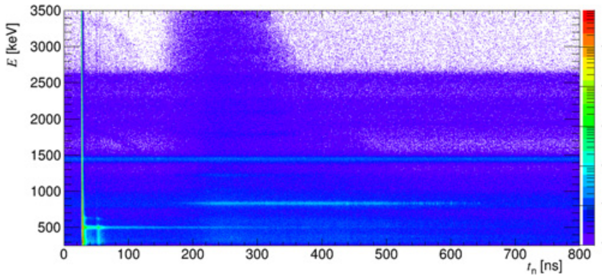

Figure 3. Relation between detected γ-ray energy and neutron time of flight measured with a $LaBr_3$ detector under an angle of 55°.

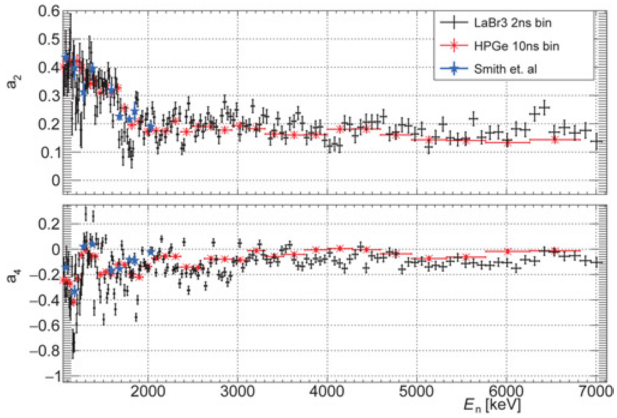

Figure 4. Comparison of fit parameters a_2 and a_4 for neutron energy from threshold up to 7 MeV. The angular anisotropy of the γ-ray distribution shows decreases with increasing neutron energy.

measurements with and without the ^{nat}Fe-target in the beam. From the lifetime- and background-corrected 3D-plots γ-ray spectra are projected for certain neutron time of flight gates. These gates are 2 ns for $LaBr_3$ and 10 ns for HPGe spectra, which allow to reach sufficient counting statistics and take into account the time resolution of the detectors. The γ-ray peak emitted from the inelastic scattering is fitted with a gaussian peak function and N_θ of the deexitation γ-rays is determined for every detector. Finally, the normalized ratios are fitted with

$$W_{\mathrm{n,fit}}(\theta, E_\gamma, \Delta E_\mathrm{n}) = \frac{1 + a_2(\Delta E_\mathrm{n}) P_2(\cos\theta) + a_4(\Delta E_\mathrm{n}) P_4(\cos\theta)}{1 + a_2(\Delta E_\mathrm{n}) \cdot \underbrace{P_2(\cos 90^\circ)}_{=-0.5} + a_4(\Delta E_\mathrm{n}) \cdot \underbrace{P_4(\cos 90^\circ)}_{=0.375}}. \quad (5)$$

4. Results

The γ-ray angular distribution parameters a_2 and a_4 are determined in the energy range from threshold of $E_{\mathrm{thr}} \approx$ 860 keV to about 7 MeV for the first transition, $E_\gamma =$ 847 keV, in the inelastic neutron scattering from ^{56}Fe (see Fig. 4).

The tendency of decreasing parameter values with increasing neutron energy is confirmed and the HPGe data agree with the ones of Smith quite well. The higher resolution of the $LaBr_3$ detectors show strong fluctuations especially near the threshold until to 2 MeV which are correlated to resonant-like structures in the cross section determined e.g., by Negret [4]. This behaviour is illustrated

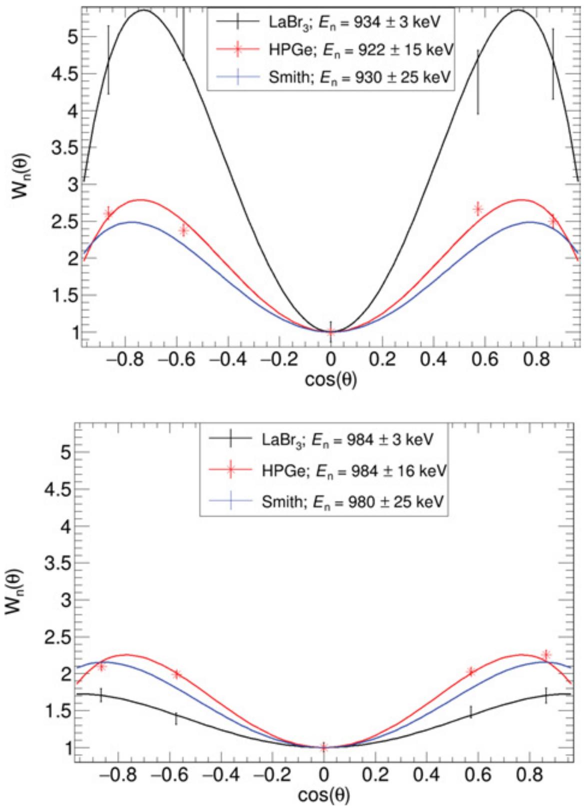

Figure 5. Exemplary γ-ray angular distributions of the 847 keV transition, measured in this work with $LaBr_3$ scintillation detectors and HPGe detectors, are compared with the measurement of D.L. Smith [3].

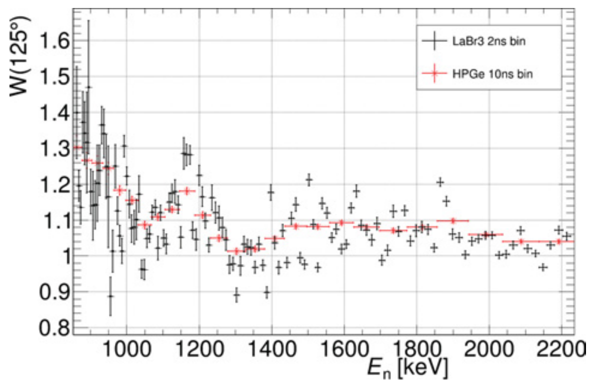

Figure 6. Angular correction factor $W(125^\circ)$ determined with different detectors. The average relative uncertainty is around 2%, increasing near the threshold due to lower counting statistics.

in Fig. 5 near $E_\mathrm{n} \approx 930$ and 980 keV. Our high-resolution data of $LaBr_3$ reveal high anisotropies and the lower resolution data measured with the HPGes and from D.L. Smith [3] show less fluctuations due to averaging over a wider energy spread. For $E_\mathrm{n} > 2$ MeV the angular distribution flattens through the population of the $E_x =$ 847 keV state from higher states.

5. Correction of partial cross sections for γ-Ray angular distribution

In a previous experiment at *n*ELBE [7] the inelastic scattering cross section on ^{56}Fe was determined from a

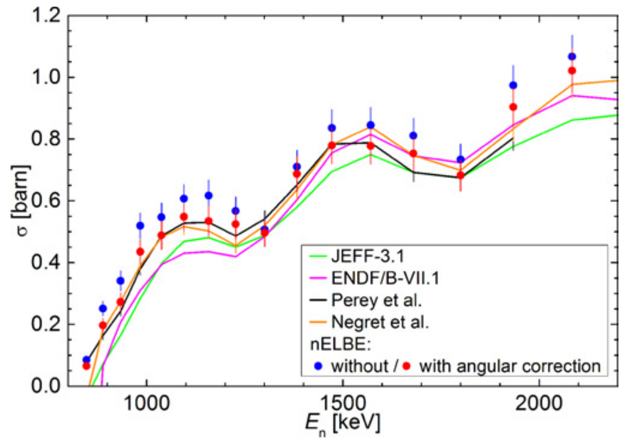

Figure 7. The corrected data of Beyer [7] shows very good agreement with Perey [5] and Negret [4]. Therefore one could further suspect that discrepancies in the evaluated data could also be caused by unconsidered angular distribution influences, because the region around 1.3 MeV matches quite good for this case. (Remark: All referenced data are rebinned to the experimental binning of the *n*ELBE measurement.)

partial cross section measurement at 125°. At that time a correction for the γ-ray angular distribution was not made and isotropy of the γ-ray angular distribution was assumed. Therefore the resulting cross section was found to be slightly higher than reference data. From the results of the present work the angular correction factor $W(125^\circ)$ can be deduced:

$$\sigma_{\text{inel}} = \frac{d\sigma}{d\Omega}(125^\circ) \cdot \frac{4\pi}{W(125^\circ)} \quad \text{with} \qquad (6)$$

$$W(125^\circ) = 1 + a_2(E_n)P_2(125^\circ) + a_4(E_n)P_4(125^\circ). \quad (7)$$

As can be seen in Fig. 6 the assumption of isotropy ($W = 1$) is only applicable for $E_n \approx 1.3$ and >2 MeV. The revised data of Beyer et al. [7] is shown in Fig. 7.

Other corrections can also be derived for a more complex detector setup such as the double time-of-flight experiment [8] at *n*ELBE.

6. Conclusion

With a new detector setup the γ-ray angular distribution of the $E_\gamma = 847$ keV transition in the inelastic neutron scattering on ^{56}Fe was measured at *n*ELBE. Near the threshold up to 2 MeV the experiment from D.L. Smith [3] were confirmed and with the $LaBr_3$ detectors high neutron energy resolution data of a_2 and a_4 parameters were obtained and strong anisotropic fluctuations next to almost isotropic regions were revealed. Finally necessary corrections can be made for different experimental setups e.g., one detector under 125° [7].

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