Nuclear data activities at GELINA

Andreea Oprea1,*, Jan Heyse1, Stefan Kopecký1, Carlos Paradela1, Arjan Plompen1, Peter Schillebeeckx1 and Ivan Sirakov2

1European Commission, Joint Research Centre (JRC), Geel, Belgium
2Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria

Abstract. Over the last decade, efforts were made to improve the performance of the experimental set-ups at the Geel Electron Linear Accelerator (GELINA) neutron time-of-flight facility of the European Commission Joint Research Centre (EC-JRC). These efforts, which result in an improved quality of neutron-induced cross section data for many reaction channels like elastic, inelastic, capture, fission, etc., relate to the accelerator, the measurement setups and the data reduction and analysis procedures. This paper presents a summary of the data produced in the last years at GELINA for nuclear energy applications. Most of the work has been performed as part of the EUFRAT open-access program.

1 Introduction

GELINA is a neutron Time-Of-Flight (TOF) facility designed for high-resolution neutron cross section measurements. The neutron beam is produced by photoneutron reactions after the impingement of a 70-140 MeV pulsed electron beam on a depleted uranium target. GELINA is capable of providing both fast (30 keV < E_n < 20 MeV) and moderated (1 meV < E_n < 500 keV) pulsed neutron beams. It is a multi-user facility with measurement stations at 12 flight paths, ranging from 10 m to 400 m. A detailed description of the accelerator and its neutron-producing target can be found in Ref. [1].

The present measurement programme at GELINA contributes to each step of the production of evaluated nuclear data libraries. The experimental programme accounts for data needs in the nuclear fuel cycle with increasing focus on requirements for the development of innovative reactor systems, including small modular reactors, for the back end of the fuel cycle, for decommissioning and support to the neutron standards.

The focus is on the production of experimental data for neutron-induced interactions and the nuclear fission process. The experiments are performed either based on demands of the high priority request list [2], a global coordination effort on nuclear data, or on direct requests of Member States organisation. The results of these experiments are processed using dedicated data reduction and analysis codes to deliver validated nuclear data including full covariance information to the ENDF database.

The methods developed for high-resolution neutron cross section measurements in the resonance region generated spin-off techniques, such as Neutron Resonance Transmission Analysis (NRTA) and Neutron Resonance Capture Analysis (NRCA) [21]. These techniques can be applied for a non-destructive determination of the elemental and isotopic composition of many types of materials. In addition, NRTA is a valuable tool for the validation of cross section data in the Resolved Resonance Region (RRR).

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>(n,xnγ)</td>
<td>64Fe, 56Fe, 59Fe, 52Cr, 209Bi, 208Pb, 40Na, 28Si, 76Ge, 24Mg, 206Pb, Li, Ti, 16O, 80Ni[3]</td>
</tr>
<tr>
<td></td>
<td>235U[4], 235U[5], 235Th[6], 235W[7]</td>
</tr>
<tr>
<td>(n,n)</td>
<td>54Fe[8], 54Fe, 23Na, 20C</td>
</tr>
<tr>
<td>(n,tot)</td>
<td>109Rh[9], 154,155,157Gd[10], 142Ce[11], 164Mo[12], 115Ca, 136Ce, 136V, 134Cu, 89Y, 135La, 209Bi, 90Zr</td>
</tr>
<tr>
<td>(n,γ)</td>
<td>109,109Ag[13], 197Au[14], 241Am[15], 155,156,157,158,160Gd[16], 235U[17], 103Rh, 89Y, 159La, 142Ce, 209Bi, 90Zr, 136Ca, 136Ce, 136V</td>
</tr>
<tr>
<td>(n,γ)</td>
<td>26Al[18], 9Li[19], 16O</td>
</tr>
<tr>
<td>(n,f)</td>
<td>235U[20], 239Pu</td>
</tr>
</tbody>
</table>

* Corresponding author: andreea.oprea@ec.europa.eu
2 Experimental Setups

This section describes the experimental set-ups installed at GELINA. We refer the reader to the publications given in Table 1 for more details.

2.1 GAINS

The GAINS (Gamma Array for Inelastic Neutron Scattering) spectrometer is designed for high-resolution neutron inelastic cross section measurements. It employs γ-ray spectroscopic measurements and the neutron TOF technique to extract information on the γ-ray and neutron energies, respectively. It is currently installed in the 100-m measurement cabin. Due to the relatively long neutron flight path, the neutron energy resolution is 3 keV at 1 MeV and 80-90 keV at 10 MeV.

GAINS consists of 12 large volume High Purity Germanium (HPGe) detectors centred around the sample at backward angles (110°, 125° and 150°) with regard to the incident neutron beam. The 110° and 150° angles allow an accurate angular integration of the differential cross sections. The neutron fluence rate is measured with a fission chamber loaded with 235U deposits. The detector signals are read out by 420-MHz 12-bit ACQIRIS digitizers. There is an ongoing effort to upgrade the DAQ. More details can be found in Ref. [3].

2.2 GRAPhEME

GRAPhEME (GeRmanium array for Actinides PrEcise Measurements) is a spectrometer optimized for measurement of relatively low energy γ-rays in a large sample-radioactivity background (typical of actinides). The setup allows for the extraction of angle-integrated γ-ray production neutron inelastic scattering cross sections normalized to the 238U(n,f) standard cross section [22].

It is composed of 6 HPGe planar detectors, including one segmented detector, and includes a fission chamber for determining the neutron fluence rate. In the past, the detector signals were recorded by a digital acquisition system based on TNT2 cards [23] (14 bits for amplitude resolution and a 100 MHz sampling frequency). This digitizer is replaced by a FASTER digitizer [24]. More details can be found in Refs. [4-7].

2.3 ELISA

ELISA (ELastic and Inelastic Scattering Array) is designed to measure angular differential neutron elastic scattering cross sections. Special analysis procedures are applied to decouple the elastic and inelastic channels. This decoupling requires that the level scheme of the nucleus under study is known [13].

ELISA consists of 32 liquid organic scintillators, placed at eight scattering angles, with a time resolution of about 2 ns. The detection angles together with the Gauss (numerical) quadrature allow the extraction of integral cross sections with a good accuracy. The determination of the neutron scattering yields through neutron spectrometry depends on a good knowledge of the response function of the neutron detector. For neutron fluence rate monitoring, a 235U fission chamber is used.

A digitizer-based acquisition system was developed to collect the signals of the scintillators. It consists of eight cards with four input channels each, 14-bit amplitude resolution, and 500 MS/s sampling rate (SP Devices, model ADQ14DC- 4A-VG-PXle). To synchronize all digitizer channels, an external 10 MHz reference is provided by a clock generator. The waveforms produced by the scintillators and their respective timestamps are saved for offline processing. The processing includes the determination of the total integrated charge, the correction of the timestamp, and a pulse shape analysis. The DAQ system of the fission chamber consists of conventional front-end electronics. The extracted time and amplitude information is stored in list mode.

2.4 Neutron transmission setup

At present neutron transmission, measurement stations to determine the total cross section are installed at 10 m, 25 m and 50 m. Neutrons are detected using liquid glass scintillators. The experimental transmission is obtained from the ratio of TOF-spectra measured with and without the sample in beam, after subtracting the background contributions, which are estimated by applying the black resonance technique [25]. More details on the transmission setups are given in Refs. [9, 11].

2.5 Neutron capture setup

Capture cross section measurements are carried out at 12.5 m, 30 m and 60 m using setups based on C6D6 liquid scintillators. The total energy detection principle, in combination with the pulse height weighting technique is applied [25,26]. The neutron fluence rate is measured by 10B ionisation chamber. The capture yield is derived from the background subtracted response of the C6D6 detectors and ionisation chamber. More details are given in Refs. [13-17]

2.6 Charged particle and fission setup

Charged particle and fission cross section measurements are carried out at a 10 m and 60 m station using Frisch grided ionization chambers and surface barrier detectors. The 10 m station is also used for fission-fragment yield, prompt neutron and γ-ray characteristics measurements in the resonance region using the SCINTIA spectrometer [20].

3 Reporting to EXFOR

A substantial effort is made to improve the procedures for the analysis and reporting of time-of-flight cross section data [25], including the production of full covariance information, using the AGS (Analysis of Geel Spectra) code developed at JRC Geel [27]. The AGS formalism results in a substantial reduction of data.
storage volume and provides a convenient structure to verify the sources of uncertainties through each step of the data reduction process. The concept is recommended by the Nuclear Data Section of the IAEA to prepare the experimental data for storage into the EXFOR data library [28].

4 Data evaluation

Most of the data are used to produce evaluated data files in support to nuclear data projects such as JEFF, ENDF/B (see Ref. [29]) and the neutron standards projects [22]. Recent evaluations largely based on data from GELINA are: $^{107,109}$Ag[13], $^{99}$Tc[30], $^{235}$Am[31], $^{238}$U[32], $^{197}$Au[14, 22], $^{16}$O(n,α) [33], $^{175}$Lu [34] and Mo [12].

For the evaluations in the Resolved Resonance Region (RRR) a shape analysis is performed using the REFIT code. For the Unresolved Resonance Region (URR), a best estimate for the average total and capture cross section is obtained from a fit to experimental data. These average cross sections are used to derive average resonance parameters by a Hauser-Feshbach approach combined with width fluctuations, see e.g. Refs. [14, 32, 35].

5 Data validation

Neutron resonance transmission analysis (NRTA), with the areal density as the derived integral quantity, can be considered as one of the most accurate integral benchmarks to validate cross section data in the RRR. This is illustrated in Fig.1, which shows the transmission through a PuO$_2$ reference sample [36]. The experimental transmission from measurements at a 10 m station of GELINA is compared with the theoretical one. The latter is obtained from a least squares fit with REFIT with the areal density of $^{235,239,240,241,242}$Pu, $^{234}$U and $^{241}$Am as free parameters. The result of the fit is given in Table 2. The fit was performed using the resonance parameters listed in ENDF/B-VIII.1 and JEFF-3.2. Most of the differences between the values determined by NRTA and the declared ones are within the uncertainties due to counting statistics. For the $^{241}$Am the substantial overestimation using the ENDF/B-VIII.0 data suggests underestimation of the capture cross section, supporting the conclusions of Lampoudis et al. [15] based on measurements at GELINA. For even plutonium isotopes, systematic deviations might be due to limitations in the nuclear data used for the analysis.

6 Summary

GELINA is a neutron TOF- facility delivering accurate experimental data in support to the Nuclear Data Community. Dedicated procedures are used to obtain the data for the EXFOR data library. Most of the data are used to improve the cross sections in evaluated data libraries. The nuclear data activities at JRC Geel include the use of these data to produce ENDF/B compatible evaluations utilising dedicated analysis procedures for the resolved and unresolved resonance region. In addition, it was demonstrated that transmission measurements on well-characterised reference materials are a powerful tool to validate evaluated data in the resolved resonance region.

![Transmission through a PuO$_2$ reference sample. The experimental (blue points) and theoretical transmission obtained from a resonance analysis (red curve) are compared.](image)

Fig. 1. Transmission through a PuO$_2$ reference sample. The experimental (blue points) and theoretical transmission obtained from a resonance analysis (red curve) are compared.

Table 2. Atomic abundances relative to total Pu and $^{241}$Am in a PuO$_2$ reference sample. The reference values are compared with those derived by NRTA using the ENDF/B-VIII.0 and JEFF-3.2 libraries. The uncertainties of the NRTA data are only due to propagating uncertainties due to counting statistics.

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>$n_{REF}$</th>
<th>$n_{NRTA}/n_{REF}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{238}$Pu</td>
<td>0.009514 (20)</td>
<td>0.823 (74)</td>
</tr>
<tr>
<td>$^{239}$Pu</td>
<td>0.62603 (28)</td>
<td>0.9928 (14)</td>
</tr>
<tr>
<td>$^{240}$Pu</td>
<td>0.25273 (24)</td>
<td>1.0169 (14)</td>
</tr>
<tr>
<td>$^{241}$Pu</td>
<td>0.015697 (20)</td>
<td>1.0028 (64)</td>
</tr>
<tr>
<td>$^{242}$Pu</td>
<td>0.041489 (60)</td>
<td>1.0447 (25)</td>
</tr>
<tr>
<td>$^{241}$Am</td>
<td>0.06290 (63)</td>
<td>1.1503 (33)</td>
</tr>
<tr>
<td>$^{234}$U</td>
<td>0.002918 (10)</td>
<td>0.989 (34)</td>
</tr>
</tbody>
</table>

Acknowledgement

Part of this work is supported by the EUFRAT open access programme of the JRC-Geel.

References

International Conference on Nuclear Data for Science and Technology (ND2022)


28. F. Gunning, P. Schillebeeckx and V. Semkova, INDC(NDS)-0647 (2013)


33. S. Urlass et al., submitted to Phys. Rev. C

