GELINA, a neutron time-of-flight facility for high-resolution neutron data measurements

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Abstract
Accurate neutron data are required for the assessment of safety aspects of nuclear power installations or for the design of new innovative concepts like nuclear waste transmutation or accelerator driven systems. For the measurement of such data in the resonance region an extremely good energy resolution is required, only achievable using a pulsed white-spectrum neutron source in combination with time-of-flight measurements. The Geel Electron LINear Accelerator Facility (GELINA) at the Institute for Reference Materials and Measurements (IRMM) of the European Commission’s Directorate-General Joint Research Centre (JRC) is especially designed for such purposes. Within the framework of the EURATOM ‘Transnational Access to Large Infrastructure’ programme, JRC-IRMM is able to offer, via the NUDAME project, beam time to external users from EU member countries and associated states.

Introduction
The development and improvement of a comprehensive cross section database is essential for many areas of research and technology. For nuclear power production, neutron-induced reactions are definitely the most important interactions. Many interaction types may occur in numerous isotopes. A precise knowledge of neutron cross sections, over a broad energy range, is of great importance for a proper account of reaction rates and the detailed neutron flux distributions in many nuclear applications. They are vital when evaluating the safety and risks related to the operation of nuclear power plants and to nuclear waste management. Also the development of innovative systems like accelerator-driven transmutation systems or new concepts of nuclear power production must rely on complete, accurate and consistent neutron data libraries. Reducing uncertainties in the neutron cross section data can result in an enhanced safety and efficiency of present and future nuclear power systems [1]. Accurate neutron cross sections play a crucial role not only for nuclear power, but also in many other disciplines such as astrophysics, medicine, and security [2, 3, 4].

In the energy interval from thermal neutron energies to a few MeV the neutron cross sections have a resonance-type energy dependence and large differences exist between the neighbouring isotopes. In the resonance region, two energy domains need to be distinguished:
• the resolved resonance region where the neutron cross sections reveal a complicated resonance structure,
• the unresolved resonance region, where the measured width of the resonances is larger than the resonance spacing, and the resonances appear to be overlapping.

The resonance structure, which largely differs from isotope to isotope, cannot be predicted or reproduced by models. Therefore, experiments with high energy resolution over the whole spectrum are required. These measurements allow extraction of the resonance parameters that describe the cross sections in detail. Accurate resonance parameters are calculated by using the technique of resonance shape analysis [5]. The required measurement accuracy can only be obtained at neutron Time-Of-Flight (TOF) facilities especially designed for very high-energy resolution measurements [6].

In a TOF facility, the neutrons used for the neutron cross section measurements are produced by the impact of a short pulse of high-energy particles on a neutron-pro-
Producing target. The impinging particles can be:

- electrons that create neutrons via the production of bremsstrahlung and consecutive photonuclear reactions, or
- protons that generate neutrons via the spallation reaction.

The TOF-facility GELINA

The TOF-facility GELINA has been especially designed and built for high-resolution cross section measurements. It is a multi-user facility, serving up to 12 different experiments simultaneously, and providing a pulsed white neutron source, with a neutron energy range between 1 meV and 20 MeV. The installation is operated in shift work on a 24 hours/day basis, for about 100 h per week. Figure 1 shows an aerial view of the GELINA facility. Neutrons are produced in bunches of less than 1 ns duration, at repetition rates up to 800 Hz. The total neutron flux of the target is $3.4 \times 10^{13}$ neutrons/s. This flux is rather low compared to the neutron facilities where scattering and diffraction are used as a tool for structure and dynamics analysis, applied in many scientific and technological domains. Such investigations require high fluxes of neutrons at very long wavelengths. For the study of the basic interaction mechanism of neutrons with nuclei (total, capture, fission, inelastic scattering, and charged-particle production cross section measurements) energy resolution in the resonance region is the most important design criterion.

Improvement of the energy resolution, while maintaining good neutron source strength has been a continuing effort at GELINA [7, 8, 9]. Among the pulsed white spectrum neutron sources available in the world, GELINA is the one with the best energy resolution. The resulting excellent neutron energy resolution is made possible by a combination of four specially designed and distinct units:

- a linear electron accelerator delivering a pulsed electron beam,
- a post-acceleration relativistic-energy compression magnet system,
- a rotary mercury-cooled uranium target,
- 12 different flight paths, ranging from 10 m up to 400 m.

Linear electron accelerator

A schematic overview of the electron accelerator is given in figure 2. The pulsed electron beam is generated in an injector with a Pierce-type triode gun. The injected electron pulses have a duration of 10 ns and a very high peak current of 12 A. The linear accelerator consists of three S-band accelerator sections operating at a frequency of 2999 MHz. The electrons are accelerated along the axis of the sections by the longitudinal electric field of an electromagnetic wave travelling synchronously with the highly charged electron pulses. The accelerating waves in the sections are produced with three pulsed high-power klystrons. The klystrons are powered with line-type pulse power modulators. They deliver to each section 25 MW peak power wave trains of 2 µs at a maximum repetition rate of 800 Hz. The duration of a wave train is longer than the so-called filling time of an accel-

Figure 2. Scheme of the GELINA linear electron accelerator
erator section (the filling time is the time required to fill a section completely with electromagnetic power – for GELINA the filling time is typically 1.2 µs). In this way all cavities from an accelerator section can be filled with electromagnetic power before an electron pulse is injected. The energy of the electrons in a pulse leaving the accelerator varies linearly from 140 MeV at the start of the pulse to 70 MeV at the end of the pulse. This is because the first electrons of a pulse ‘see’ the full accelerating field during their travel along the accelerator, all cavities being filled with the maximum power. Each electron extracts power from the wave. The electron pulse is so short that there is not enough time to replenish the consumed power in the cavities during the duration of the electron pulse. The following electrons in a pulse experience a lower accelerating field than their forerunners. As a result of this so-called transient beam loading, the energy of the electrons is decreasing monotonically, from the beginning to the end of the pulse. This intrinsic feature of time-energy relationship during the electron pulse is now fully exploited to compress further the electron pulse lengths in the compression magnet installed at the end of the accelerator [8].

**Compression magnet**

Before hitting the neutron-producing rotary target, the electrons make a ‘looping’ in a specially designed 360° compression magnet. This magnet has a diameter of 3 m and a weight of 50 tons. It consists of five magnetic sectors with zero gradient fields and is designed to accept...
the 50% electron energy spread in the beam of the accelerator. The operational principle of the relativistic post-acceleration compression magnet is shown in figure 3. The bending radius of an electron in a magnet is proportional with its energy. Therefore, the first highest-energy electrons in a pulse will follow a longer trajectory than the later ones. Since all electrons have a speed close to the velocity of light, this results in a delayed arrival of the leading edge of the pulse at the exit of the magnet as compared with the arrival of the trailing edge. The magnet is designed such that all electrons of a 10 ns pulse, entering the magnet, will leave the compression magnet within a time bin of 1 ns. The peak current rises by this charge conserving compression from originally 12 A to about 120 A at the exit of the magnet. Figure 4 shows a photo of the target hall, in which the position of the compression magnet is shown, with respect to the neutron-producing target.

**Neutron-producing target**

After the compression magnet the high-energy electrons impinge on a rotating neutron-producing target [10]. The rotary target consists of a U-Mo alloy with 10 wt% of Mo, cooled with liquid mercury and sealed in stainless steel. The neutron target, designed for optimum neutron production, has to withstand the full electron beam power (10 kW) almost completely dissipated in the target. A lay-out of the target is shown in figure 5. The electrons are decelerated and produce high-energy photons via the Bremsstrahlung process. These photons may interact with target nuclei and produce neutrons via $(\gamma, n)$ and to a much lesser extent by $(\gamma, f)$ reactions. Uranium is chosen as target material because it favours the production of photons in the Bremsstrahlung process and neutrons by photon-induced nuclear reactions. Above ~30 MeV electron energy, the neutron production rate is nearly proportional to the electron beam power. The use of uranium increases the total neutron yield by a factor ~2 compared with another high-Z target, such as tantalum. From a thick uranium target roughly 6 neutrons are emitted per 100 electrons of 100 MeV. The power density in the body, deposited by the electron beam may reach 10 kW/cm³. Therefore the target is rotating in the beam. Mercury is chosen as a coolant, mainly to avoid neutron moderation.

The target delivers an average neutron intensity of $3.4 \times 10^{13}$ neutrons/s. In order to have a significant number of neutrons in the energy range below 100 keV, two light-water moderators are placed above and below the existing target. The partially moderated neutrons have an approximate $1/E$ energy dependence plus a Maxwellian peak at thermal energy. Two flux set-ups are available: one optimised for energies below 500 keV by using neutrons coming from the moderators and one with fast neutrons emerging directly from the uranium. Based on the required energy range in a particular measurement station, shadow bars are properly placed between the source and the flight path to shield unwanted neutrons. Further tailoring of the spectral shape is done with movable filters. Figure 6 shows a photo of the rotating target, collimators and shadow bars and the neutron shutters, leading to the flight paths. The present rotary

![Figure 5. Scheme of neutron-producing target](image-url)
target has been designed taking into account the need to limit the target-related contribution to the neutron energy resolution. A project has been launched in order to improve the accuracy of the high-resolution neutron cross-section measurements by designing a new target configuration. A compact stationary target has been designed, which can reduce further the target-related inaccuracy, while preserving, and even enhancing the time-averaged neutron flux in all relevant neutron energy ranges [9, 11].

Figure 7 shows the absolute neutron flux of the moderated spectrum that was measured in the energy range from 25 meV to 200 keV by Borella et al. [12]. The results are compared with MCNP4C3 Monte Carlo calculations performed by Flaska et al. [9]. Figure 8 shows the comparison of similar calculations with the absolute neutron flux of the unmoderated spectrum in the energy range from 200 keV to 20 MeV, as measured by Mihaelescu et al. [13].

Neutron flight paths and measurement stations

In order to apply the TOF technique, 12 flight-paths are installed in a star-like configuration around the neutron production target, schematically shown on the scheme in figure 9. The flight tubes are under vacuum, they have a diameter of 50 cm and their lengths range up to 400 m. Several measurement stations are installed at different distances (with nominal distances of 10, 30, 50, 60, 100, 200, 300 and 400m) along the flight paths. These experimental stations are equipped with a wide variety of sophisticated detectors, and data acquisition and analysis systems, especially designed for neutron-induced total and partial cross-section measurements with an exceptional precision and energy resolving power. Modern detection techniques such as advanced HPGe Compton-suppressed detectors and data acquisition systems based on fast signal digitisers are currently implemented. Many types of neutron cross section measurements are possible. There are neutron measurement set-ups for transmission experiments, capture, fission, elastic and inelastic cross sections, and flux measurements.

Transmission measurements can be performed at a 25m, 50m, 100m, 200m and 400m flight path using Li-glass detectors, plastic scintillators or NE213 scintillators. To study the Doppler broadening one of the transmission measurement stations is equipped with a cryostat, which is able to cool the samples down to 10K. Fission cross section measurements are performed at a 8m and 30 m station using Frisch gridded ionisation chambers and surface barrier detectors. These measurement stations are also used to study (n,p) and (n,α) reactions. Inelastic scattering reactions are studied at a 30m or 200m station using HPGe-detectors. Capture measurement systems, using C12 or scintillators or HPGe detectors, are available at a 15m, 30m and 60m flight path.

Transnational Access via NUDAME

Besides the GELINA facility, the JRC-IRMM is also equipped with a Van de Graaff (VdG) facility. At the VdG quasi mono-energetic beams of neutrons are produced in the energy range up to 24 MeV, using different charged-particle induced reactions. The high-resolution
measurements at GELINA can be complemented by measurements at the VdG, especially in the MeV neutron energy domain where the resonance structure of the cross-sections is averaged out. The VdG is a 7 MV electrostatic accelerator for the production of continuous and pulsed proton-, deuteron- and helium ion beams. Ion beams can be produced with a current of up to 60 µA in DC mode and up to 5 µA in pulsed mode. The pulse repetition rates are 2.5, 1.25 or 0.625 MHz. The energy of the mono-energetic neutrons is defined by using lithium, deuterium or tritium targets and choosing appropriate emission angles. Depending on the neutron energy up to 10⁸ neutrons/s can be obtained.

Due to the combination of the GELINA white neutron TOF-facility and the quasi mono-energetic neutron source at the VdG, the Reference Laboratory for Neutron Measurements at IRMM is one of the few laboratories in the world which is capable of producing the required accuracy of neutron data over a wide energy range from a few meV to about 24 MeV. These unique research capabilities offered at the two accelerators are an excellent opportunity for transnational collaborations in the field of transmutation research and innovative nuclear energy systems. To facilitate the access to the facilities for outside users, a project ‘NUclear DAta MEasurements at IRMM’ (NUDAME) has been launched within the framework of the Euratom Transnational Access programme. Applications for support can be submitted via the NUDAME website which can be found on the main web portal of IRMM [14].

Any type of experiment in the areas of radioactive waste management, radiation protection and other activities in the field of nuclear technologies and safety can be proposed provided our experimental infrastructure can offer a significant added value to the project. Access to the IRMM accelerator installations implies the same scientific, logistical and technical support provided to all researchers of the Institute.

**Short overview of in-house research areas**

For the safety assessment of presently operating reactors reliable predictions must be made about their behaviour under different operating conditions. For these calculations the accurate knowledge of changes in neutron spectra are highly important. As an example, the neutron multiplicity averaged over the whole mass distribution is of crucial importance for the physics of conventional reactors and needs to be known with accuracy better than 1%. Researchers at IRMM are presently concentrating on neutron multiplicities, fission neutron spectra and delayed neutrons, total-absorption and neutron capture cross-sections, fission fragment yields and kinetic energy distributions. In view of the assessment of the temperature dependence of the reactor criticality Doppler broadening measurements have been carried out on ⁵⁷⁷Eu, ²⁵⁷Np and ³⁴⁴Hf at different temperatures. Improved capture cross sections for various stable fission products are motivated by the objective to extend and optimize the fuel cycle associated with present nuclear power plants. These data are also important for criticality safety of spent fuel storage and transportation of spent fuel in licensed shipping casks. To improve these data, the IRMM started a collaboration with CEA Saclay (F) and ORNL (US) and initiated measurements at GELINA for ¹⁰³Rh and ⁹⁰⁰Mn.

The Generation IV International Forum (GIF) pursues the in-depth investigation of six advanced concepts for nuclear energy systems, with the objective to arrive at energy production with a largely reduced volume of high-level radioactive waste, proliferation resistant fuel cycles and much enhanced safety. Future hydrogen production is envisaged as well. The nuclear data requirements for the development of these systems address the same neutron-induced reactions as those for thermal systems, but extending into the 10-20 MeV range. At the GELINA TOF facility high-resolution cross section measurements will be carried out for the relevant isotopes.

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**Figure 9. Scheme of flight path area**
and reaction types. A key issue for the future of nuclear energy production is a satisfactory solution that must be elaborated for the disposal of nuclear waste. The research in this field concentrates on the chemical separation, called partitioning, of long-lived radioactive isotopes in the nuclear waste and subsequent transmutation into short-lived or stable isotopes. By exposing the materials to high neutron fluxes transmutation occurs via neutron capture or fission reactions. The goal is to burn the so-called long-lived fission products (LLFP) such as $^{99}$Tc, $^{129}$I, and $^{135}$Cs, and minor actinides (MA) such as Np, Am, and Cm isotopes. In all cases the knowledge of the associated set of nuclear data is not complete. In order to improve the nuclear data high-resolution total and capture cross section measurements were performed at GELINA for the long-lived fission products $^{99}$Tc and $^{129}$I and for the minor actinide $^{237}$Np. Measuring $^{244}$Am is under preparation.

Different types of accelerator driven systems (ADS) for transmutation of nuclear waste have been proposed. The most promising one is based on a liquid Pb-Bi spallation target. Although the initial neutron energies resulting from spallation are in general above the energy range of GELINA, the neutron spectrum outside the target area and at larger distances approaches that of a conventional fast (or thermal) reactor. Using the TOF technique neutron capture cross-section measurements have been measured in the resonance region for $^{232}$Th, $^{206,207,208}$Pb, $^{209}$Bi and $^{235,238}$U. For Pb and Bi isotopes capture measurements must be combined with future total cross-section measurements in the resolved resonance region in order to lead to the unambiguous determination of the essential parameters. Elastic and inelastic scattering cross-section measurements have been carried out at GELINA for $^{23}$Na, $^{27}$Al, $^{56}$Fe and $^{235,238}$U via $(n,n')\gamma$ experiments. The majority of basic and applied measurements in neutron physics are performed relative to cross-section standards. It is therefore essential that these standards are continuously improved and their underlying physical mechanisms are understood.

Under the steering of the OECD and the Data Centre of the International Atomic Energy Agency (IAEA) needs for new standards are identified and proposals are made for improvements of established standards. The detailed requirements for neutron data measurements, and in particular for improvements of the standards database, are collected in the high priority list of the NEA. For example, the $^{10}$B(n,$\alpha$)$^7$Li reaction cross section, recently investigated at GELINA, is amongst the most important standards used in neutron measurements.

The techniques developed for high-resolution neutron cross section measurements in the resonance region generate also spin-off techniques, not directly belonging to our core-business. A new fully non-destructive method ‘Neutron Resonance Capture Analysis’ (NRCA) has been developed, in collaboration with the Delft University of Technology. NRCA allows the determination of the elemental composition of samples. The method is based on the use of neutron resonances as fingerprints to identify and quantify elements. Details of the NRCA technique are discussed in another contribution to this issue [15].

References

14. H. Postma and P. Schillebeek, “Neutron-resonance capture as a tool to analyse the internal compositions of objects non-destructively”, in this issue