Neutron Physics Unit
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The mission of the IRMM is to promote a common and reliable European measurement system in support of EU policies.
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Preface

As in former years, the work programme of the Neutron Physics Unit at IRMM was largely driven by requests formulated at the WPEC and JEFF meetings at the NEA. We appreciated the efforts of the WPEC in restructuring the High-Priority Request List (HPRL) maintained at the NEA databank, and Arjan Plompen volunteered as chairman of the subgroup in charge of these activities. We also continued supporting the activities of the IAEA-INDC by participation in Coordinated Research Projects.

The Transnational Access programme NUDAME started in 2005 at our facilities turned out to be a success story. The second meeting of the Programme Advisory Committee took place on 3 February at IRMM and 8 proposals were accepted for 2006. We appreciated especially the large number of first-time users. The experiments covered a wide range of topics: capture and transmission measurements at GELINA on \( ^{197}\text{Hf} \) and \( ^{114}\text{Cd} \), calibration of Bonner spheres at the Van de Graaff accelerator, tests of data acquisition systems using fast signal digitisers, \( ^{243}\text{Am}(n, f) \) cross section measurements, the fission decay of a shape isomer in \( ^{235}\text{U} \), and short-lived activation measurements on \( ^{206,207}\text{Pb} \) isotopes. The NUDAME programme continues until March 2008 and the Unit plans to apply for a new Transnational Access project thereafter.

Another project where our Unit got involved was the EFNUDAT project (European Facilities for Nuclear Data Measurements). This project is an Integrated Infrastructure Initiative of the EURATOM 6\textsuperscript{th} Framework Programme. The project is coordinated by CENBG Bordeaux, includes 10 European partners, and started on 1st November 2006. The aim of EFNUDAT is to integrate all infrastructure-related aspects of nuclear data measurements by organising Network Activities, Transnational Access Activities, and Joint Research Activities. F.-J. Hambsch is responsible for the scientific coordination, W. Mondelaers for coordinating the Transnational Access Activities, and A. Plompen for one of the three Joint Research Activities.

In a collaborative effort with ORNL on measurements on fission products capture and transmission experiments have been carried out at GELINA on \( ^{103}\text{Rh} \) and \( ^{133}\text{Cs} \). For inelastic scattering, a new acquisition system based on fast signal digitizers was implemented in combination with large-volume HPGe detectors. This allowed improving the quality of the \( ^{206}\text{Pb}(n, n'\gamma) \) measurements and identification of more level-inelastic transitions as compared to the previous results.

Following a recommendation of the NEA-WPEC a new project was started to detect the prompt fission neutron spectrum of \( ^{235}\text{U} \) using liquid scintillation detectors. An unexpected angular anisotropy in the prompt neutron emission was found which needs further investigations.

A priority request in the HPRL addresses the \( ^{16}\text{O}(n, \alpha)^{13}\text{C} \) cross section. This reaction was investigated in detail at the Van de Graaff accelerator of IRMM using a time projection chamber. The results show good agreement with the newest evaluated library, ENDF/B-VII at low neutron energies near 5 MeV but reveal large discrepancies above 6 MeV.

Major efforts were taken to improve the detector setups for neutron inelastic scattering and for neutron capture measurements. Two arrays were designed and ordered, of large-volume HPGe detectors and \( \text{C}_6\text{D}_6 \) detectors, respectively. For the fission fragment spectrometer VERDI the performance of Chemical Vapour Deposition (CVD) diamond detectors for
ultra-fast timing applications was investigated.

The refurbishment efforts at GELINA continued on schedule, and during the first quarter of 2006 the last of the three modulators and the high voltage network were completely rebuilt. The modernisation of the whole interlock and accelerator control systems was finalised. At the Van de Graaff accelerator the gas transfer system was refurbished. It is worth mentioning that large part of these developments was carried out in-house and many tasks in this specialised work were executed by our own staff.

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Neutron data for innovative nuclear applications
Neutron cross-section measurements on $^{103}$Rh and $^{133}$Cs from 20 eV up to 150 keV

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Improved capture and total cross sections for several fission products (i. e. $^{103}$Rh, $^{133}$Cs, $^{144}$Nd, $^{148}$Sm, $^{151}$Sm, $^{155}$Gd and $^{131}$Xe) are on the NEA High Priority Nuclear Data Request List [1]. They are motivated by the objective to extend and optimize the operation of present nuclear power plants and for criticality safety studies of spent fuel storages. A collaboration has been started between the IRMM Geel (B) and the ORNL (USA), with initial measurements at GELINA for $^{103}$Rh and $^{133}$Cs. To improve the above-mentioned data, the capture and the total cross-section were measured at GELINA (Geel Linear Accelerator) pulsed white neutron source from 20 eV up to 150 keV.

The capture experiments were performed at two different flight path lengths: 28.8 m and 58.58 m. The repetition rate of GELINA was 800 Hz. The shape of the neutron spectrum was measured in both cases with ionization chambers loaded with $^{10}$B. C$_6$D$_6$-based liquid scintillators (NE 230) were used to detect the neutron capture gamma rays. A pulse height weighting function was used to make the detection efficiency for a neutron capture event proportional to the total energy released in the capture event. The weighting function was determined using a Monte Carlo simulation [2]. The capture yields were measured for two metallic samples of $^{103}$Rh with thicknesses of $3.36 \times 10^{-3}$ at/b and $1.86 \times 10^{-3}$ at/b. Three powder samples of Cs$_2$CO$_3$ were used with the effective $^{133}$Cs thicknesses of $2.34 \times 10^{-4}$ at/b, $5.16 \times 10^{-3}$ at/b and $1.0 \times 10^{-2}$ at/b. The background for the C$_6$D$_6$ detectors was determined by additional measurements without the sample in position or with a dummy sample in the case of $^{133}$Cs. The dead time of the detection chain was monitored by registering the time-interval distribution between different events. The time dependence of the background for the flux measurements was derived using "black" resonances.

The transmission experiments were carried out at a 50 m flight path station with the accelerator operating at 400 Hz frequency. The $^{103}$Rh sample was placed in an automatic sample changer at a distance of 25 m from the neutron producing target. The neutrons were detected by a 6 mm thick NE912 Li-glass scintillator. The sample was a disc of metallic rhodium, with a thickness of $4.58 \times 10^{-2}$ at/b. A Cd filter was used to eliminate the slow neutrons of previous bursts. The background was measured at the "black" resonances of filters of Cd, Au, Co and Na.

The data reduction for both capture and transmission measurements was done with the AGS (Analysis of Generic tof-pectra) code [3]. The code manipulates time of flight spectra and propagates the uncertainties from different spectra operation. The AGS code creates the
Fig. 1: Experimental capture yield. **Left:** $^{133}\text{Cs}$ sample with thickness of $2.34 \times 10^{-4}$ at/b. **Right:** $^{103}\text{Rh}$-I samples had a thickness of $3.36 \times 10^{-3}$ at/b and $^{103}\text{Rh}$-II had a thickness of $1.86 \times 10^{-3}$ at/b.

covariance matrix for the output spectrum. An example of the experimental capture yield is shown in Fig. 1 for $^{103}\text{Rh}$ and $^{133}\text{Cs}$. The transmission factor was determined from the dead time corrected response of the Li-glass detector in the configurations sample-in and sample-out. In the Resolved Resonance Region (RRR) the capture and the transmission data will be analyzed simultaneously using the code REFIT [4]. In the Unresolved Resonance Region (URR) the data was interpreted in terms of average resonance parameters. Dispersive Coupled-Channel Optical Model Potential (DCCOMP) [5] has been fitted to all available nucleon scattering data on $^{103}\text{Rh}$, including the present measurements, following a well established methodology. The DCCOMP was used to get information about the energy dependence of the potential scattering radius and neutron strength functions, allowing for a smooth transition of the cross section from the URR to the fast neutron region. The same procedure will be followed for the capture data, with the detailed treatment of the self-shielding factors.

New experimental data were obtained at GELINA for the capture and total cross-sections for two stable fission products ($^{103}\text{Rh}$ and $^{133}\text{Cs}$). All the experimental data will be interpreted in terms of resonance parameters, both in the RRR and URR. The new measurements will improve the evaluated databases due to a better statistics, better neutron energy resolution and larger number of samples with different thickness that are analyzed simultaneously. As a consequence of better neutron energy resolution the RRR will be extended to higher energies.

Neutron inelastic scattering on $^{206}$Pb at GELINA with a new setup

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The lead isotopes play an essential role in shielding but also, more generally, in reactor physics: as a coolant (eutectic mixture with Bi) or as a target in some ADS options. Therefore a set of three experiments was dedicated to the study of neutron scattering on $^{206}$Pb, $^{207}$Pb and $^{208}$Pb during the year 2005. Ref. [1] describes all these experiments in detail.

The migration of the acquisition system towards digitisation [2] and the necessity to assure the reliability of the new setup was the first goal of a new experiment dedicated to re-measuring the $^{206}$Pb($n$, $n'$\gamma) reaction in 2006. Moreover, with the upgraded system, the new measurement aimed for better statistics using a thicker target allowing the investigation of more transitions. The measurement took place at the 200 m cabin of flight path 3 of GELINA. The sample was enriched in $^{206}$Pb to 88.5 % and had a thickness of 5.6 mm. The acquisition time was about 700 hours. Four HPGe detectors were placed at 110° and 150° for optimal integration of the differential cross section.

Data analysis is currently ongoing. Due to the impurities in the sample ($^{207}$Pb 8.4 %, $^{208}$Pb 2.9 %), special corrections are necessary for the $^{207}$Pb($n$, 2n\gamma) and $^{208}$Pb($n$, 3n\gamma) contributions to the strongest transitions from $^{206}$Pb($n$, n'\gamma). The higher statistics allowed for an expanded energy range of the HPGe detectors and as a consequence, a few more gamma transitions are visible compared to the 2005 measurement.

Fig. 1 shows the gamma production cross section for the strongest transition in $^{206}$Pb, compared to the one obtained in the previous measurement. It is visible that the energy resolution obtained with the digitisers compares very well with the one of the conventional system.

The comparison of the cross section obtained in 2005 and 2006 is remarkable. As can be seen also in Fig. 2, the total cross section overlaps at the level of 1-2 % with the previous values, although in the two experiments the sample, the acquisition system and the efficiency calibration of the detectors were different. This result validates both experiments and gives us confidence in digitized acquisition.

In conclusion, a new measurement of the neutron scattering on $^{206}$Pb was performed. The results compares very well with a previous experiment although a new acquisition setup and a different sample were used. A few new gamma production cross sections and level cross sections could be determined. Further efforts are necessary to combine the results of the two independent but perfectly compatible measurements in order to extract final cross section values with minimal uncertainties.

Fig. 1: Gamma production cross section of the strongest transition in $^{206}$Pb (803.06 keV) - comparison of the two measurement campaigns; preliminary result.

Fig. 2: Comparison of total neutron inelastic cross section of $^{206}$Pb obtained in the two measurements; preliminary result.

Measurement of the $^{235}\text{U}(n, n'\gamma)$ and $^{235}\text{U}(n, 2n\gamma)$ reaction cross sections

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The elaboration of the next generation nuclear reactors requires the measurement of (n, xn) reactions. One of the possible experimental methods is the prompt $\gamma$-spectroscopy which allows identifying nuclei produced by these reactions in very short-lived excited states. The success of our measurement on lead isotopes ($A = 206\, 208$) at the 200 m detection station of Gelina has encouraged us to investigate the $^{235}\text{U}(n, 2n)$ reaction, having in mind to pursue the study of the $^{233}\text{U}(n, 2n)$ reaction which is of crucial importance in the fast Thorium cycle.

Due to the available quantity of material and the gamma absorption at low energy the $^{235}\text{U}$ sample has to be much thinner than the Pb ones and the measurement has to be performed with a shorter time of flight (30 m). This has implied to adapt our technique. Therefore, several tests have been performed during a few weeks of beam time in 2006. A very important effort has been devoted to obtain a well collimated neutron beam, and the smallest possible rate of $\gamma$-rays from the flash. The shielding against high frequency radiation from the accelerator has also been the source of a delicate and long work. We have appreciated the help of the Gelina staff during this phase. The 8 g $^{235}\text{U}$ sample 93 % enriched in $^{235}\text{U}$ has been provided by IRMM. The $\gamma$-rays emitted by the sample were detected by two HPGe planar detectors separated not more than 12 cm from the target. A fission chamber and two plastic scintillators were placed in the beam to monitor it. Different thicknesses of the scintillators have been tested, in order to determine the best compromise between efficiency to high energy neutrons and sensitivity to the $\gamma$-rays from the flash. The data have been registered with a digital acquisition system developed at IPHC which has already been successfully used for the determination of the (n, n' $\gamma$) and (n, xn$\gamma$) cross sections on $^{207,208}\text{Pb}$ at the 200 m flight path. This system, based on 100 Msamples/s digitisers and equipped with a Field Proggrammable Gate Array (FPGA), had to be adapted to be able to handle the signals from the scintillators and the fission chamber as well as those from the HPGe crystals.

The $\gamma$-energy spectrum shown in Fig. 1 has been obtained with one HPGe planar counter in 280 hours of statistics with a 800 Hz beam. The background, due to the radioactivity of the sample mainly due to the decay of $^{235}\text{U}$, $^{234}\text{U}$ and their daughters, has been subtracted. Fig. 1 shows events registered in the time window 0.6 $\mu$s, corresponding to the neutron energy range from 6 to 20 MeV. On the part of the spectrum presented in Fig. 1 we see $\gamma$-lines at 152 and 201 keV, corresponding to the $6^+ \rightarrow 4^+$ and $8^+ \rightarrow 6^+$ transitions in $^{234}\text{U}$, respectively. From these results we can extrapolate that with four detectors and two months of statistics, we will be able to collect about 15000 events for the 152 keV line, which should be sufficient for the determination of the (n, 2n$\gamma$) cross section in the neutron energy range from threshold to 20 MeV.
Fig. 1: Part of the $\gamma$-energy spectrum obtained with an 8 g $^{235}\text{U}$ sample after 280 hours accumulation, subtraction of the sample radioactivity and selection of neutron energy (6 to 20 MeV).

Fig. 2: Part of the $\gamma$-energy spectrum obtained after 100 hours accumulation, substraction of the sample radioactivity and selection in neutron energy (1 to 6 MeV).

With the same experimental conditions and 100 hours of beam time only, Fig. 2 shows a part of the $\gamma$-energy spectrum for the neutron energy range 1 - 6 MeV. Several lines corresponding to the $^{235}\text{U}(n, n')$ reaction are identified.

The two components of the fission fragment mass distribution are clearly observed in the fission chamber spectrum, and well separated from the $\beta$ particles (see Fig. 3). This demonstrates that the digital acquisition system and the implemented energy determination, originally adapted for HPGe pulses, is able to record correctly fission chamber pulses.

This is true even for fast scintillator pulses. An example of time versus energy distribution measured in one plastic scintillator is given in Fig. 4. We can see a dead zone corresponding to the $\gamma$-flash events. This dead zone reflects the fact that, because of the high intensity of the gamma flash (even with a small sensitivity of the plastic scintillator to $\gamma$-rays), each flash creates a signal with an amplitude out the selected energy range. Only the tail of the $\gamma$-flash events is observed in Fig. 4. It is well separated from the second component coming from the neutrons. However for these events we see clearly a strong dependence of the time on the amplitude. This is due to the fact that the CFD implemented in the FPGA does not completely compensate the variation of the time with amplitude for small signals, and means that the time determination is not correct. The role of the plastic scintillator is to improve the
Fig. 3: Bi-dimensionnal distribution (time in 10 ns/ch vs energy) obtained for the fission chamber. The thin vertical line corresponds to the events due to the $\gamma$-flash. The horizontal line comes from the $\alpha$-radioactivity of the $^{235}\text{U}$ sample placed in the chamber. The two bumps are the fission fragment events.

Fig. 4: Bidimensionnal distribution (time in 10ns/ch vs energy) obtained for the 2 mm thick plastic scintillator.

fluence determination at high neutron energies. With a 2 mm thick plastic scintillator used here, the total number of observed neutron events is a factor 600 larger than those registered with the fission chamber.

The experiment is planned during 2007 with the use of four HPGe detectors equipped with an autofill liquid nitrogen system.
Evaluation of the total and capture cross section on the resolved resonance region for $^{nat}Cd$

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Although cadmium is commonly used as neutron absorber in integral benchmark experiments, only a small number of measurements contributes to the evaluation of the cross section of natural cadmium. The last significant measurement studying Cd for non-fundamental application has been performed by Liou et al in 1974 [1]. Up to now not a single experiment covering the whole resolved resonance range from a few meV up to a few keV has been performed. Therefore a series of capture and transmission measurements at was performed GELINA as part of the NUDAME program.

Transmission measurements were carried out at flight paths 2 and 4 of GELINA. These flight paths form an angle of 279 and 261 degrees, respectively, with the direction of the electron beam. Air conditioning is installed at all the measurement and sample stations, to reduce the drift in the electronics and to allow for a reliable calculation of the Doppler broadening. Two BF$_3$ proportional counters were used to monitor the neutron output of the accelerator and to normalise the spectra.

At flight path 2 the detector is located at a distance of 26.45 m from the source at flight path 4 at 49.33 m. For both setups the sample station is located approximately half way between target and detector. For both measurements $^{10}$B anti-overlap filters are used to eliminate the influence of slow neutrons from a previous neutron burst and Pb filters are used to reduce the intensity of the gamma flash. The background is determined using black resonances. The shape of the background is described by:

$$BKG = a_0 + a_1 T_{OF} + a_2 \exp^{-T_{OF}/\tau}$$

The parameters $a_0,a_1,a_2$ and $a_3$ are determined by fits to the dips of black resonances of Na, S, Rh, Co and Au. The decay parameter $\tau$ can be derived from fits to black resonances, but it also can be deduced from MCNP simulations of the target configuration.

In both setups Li-glass scintillators are used, but different configurations for the light collection systems and the electronic signal processing are employed. In both cases the DAQ2000 data-acquisition system is used, which allows for a precise determination of the effective dead-time.

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To allow for a resonance analysis over the desired energy range, transmission measurements for four different sample thicknesses were performed.

The capture measurements were performed at a 30 m flight path with an angle of 90 degrees between the flight path and electron beam. To reduce the contribution of overlap neutrons a $^{10}$B anti-overlap filter was used. Measurements were performed on three different natural Cd samples. Gamma radiation originating from the capture reaction in the sample was detected in two C$_6$D$_6$-based cylindrical liquid scintillators (NE230), which were positioned at angles of 125 degrees with respect to the neutron direction. The 125 degrees geometry was used to
minimize anisotropy of the radiation emitted from resonances with a spin $J > \frac{1}{2}$. The pulse-height weighting technique [2] making the detection efficiency proportional to the total emitted energy was applied to the detector output pulses. The weighting function was calculated with Monte Carlo techniques [3].

The shape of the neutron spectrum was measured with a double Frisch-gridded ionization chamber placed 80 cm before the sample. For the background correction a similar function as for the transmission measurements was applied. The parameters were determined from a least square fit through the saturated resonance dips of Ag, W, Co, Na and S. The normalisation factor of the capture yields is obtained from a simultaneous analysis of the transmission and capture data using REFIT [4].

Presently the combined analysis of the transmission and capture data is ongoing. Further experiments are planned for the beginning of 2007, when GELINA will operate with a repetition rate of 40 Hz. This will allow for transmission and capture measurements to determine the 0.178 eV resonance of $^{113}$Cd. Furthermore, important information on the shape of the cross section down to thermal neutron energies will be obtained. Therefore data over the whole resolved resonance range will be available and a new evaluation of the cadmium cross section will be possible.


The impact of the resolution function on the determination of resonance parameters

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To test the influence of the resolution function on the determination of the resonance parameters two different resolution functions, describing the same target with a comparable accuracy, were used in the R-matrix analysis code REFIT. The code had to be modified to use a resolution function given by a numerical table, which was provided by MNCP simulations. The simulation used in this work has a finer grid, both for neutron energy and the delay distance for a given neutron energy, compared to an earlier work by Coceva and coworkers [2]. Furthermore is the statistical uncertainty for all the bins reduced.

To use the numerical tables of the resolution function in REFIT[1] the following procedure was applied. The MCNP code provided the resolution function for neutron energy intervals. For a given neutron energy a lethargy weight was determined and a weighted mean of the resolution function for two neighbouring energy intervals was calculated. For the numerical integration of the delay distance the step width was adjusted to the required accuracy and to the FWHM of the resolution function. This procedure can only reduce the dependence of the output to the neutron energy step width, it cannot completely eliminate it. As a compromise between speed and accuracy the step width was chosen as large as possible, under the condition that a reduction of the step width did not show any significant differences in the calculated yields.

The simulated resolution function was compared to the analytical description used in the R-matrix code REFIT. This analytical resolution function has three major components. The most important contribution at low energies stems from the moderation of the neutron in the moderator. Its form can be described as a function of the ratio between delay distance and the mean free path of the neutron in moderator. Experimental data at thermal neutron energies can be ideally used for determining the mean free path.

A second contribution to the resolution function can be described by an exponential decay. This contribution can be ascribed to neutrons having to transverse the source material and undergoing multiple scattering. The time constant for this decay is typical for a given neutron target and can be fitted to experimental data. At neutron energies above approximately 20 keV, this part of the resolution function becomes dominant.

The third component can be described by an exponential decay with varying decay time and amplitude. An explanation for this contribution can be found in neutrons that are emitted from the neutron target and reflected back to the moderator, before they are sent towards the detector. The parameters for this component can be extracted from fits to experimental data and the obtained results compared to the resolution function obtained in the MCNP calculation. It is observed that this additional exponential decay has an amplitude proportional and an amplitude which indirectly proportional square-root of the energy. For the energy range between 100 eV and 30 keV functional expressions for the amplitude and the decay time can be given as:
\[ T(E) = \frac{60.6}{\sqrt{E}} \quad A(E) = 5.15 + 1.95\sqrt{E} \]

with \( E \) in keV, the time \( T(E) \) in ns and the amplitude \( A(E) \) in per cent. The parameters were determined from capture experiments on \(^{103}\text{Rh}\) and natural iron.

Finally, the resolution function as derived by MCNP and the analytical function were used to determine the neutron widths of resonances in a neutron capture experiment. For this test the capture yield of \(^{103}\text{Rh}\), as determined at the 50 m flight station at GELINA was used, details on the experimental procedures can be found elsewhere [3]. In the energy region between 80 eV and 3500 eV the experimental capture yield was fitted and the neutron width of the resonances was determined. The R-matrix code REFIT was used, and only the two resolution functions were interchanged. For the comparison only 45 well separated resonances were used. Examining the values for the individual resonances one would be tempted to conclude that the results derived with the two resolution functions are identical, as the values for most of the resonances are in agreement well within the uncertainties given by the fitting routine. But looking at the overall distribution and the average values, it becomes obvious that the MCNP resolution function gives systematically lower values compared to the REFIT intrinsic function. Taking the average of the selected resonances, a value of order 2 \% for this difference can be given. The reason for the difference can be found in the differences of the FWHM of the two resolution functions. The fits using the MCNP resolution function tend to underestimate the capture yield peaks, whereas using the analytical function results in a slight overestimation of the same peaks. Presently it is not possible to experimentally favour either description of the resolution function. Therefore an additional systematic uncertainty of order 2\% should be added to all the results of resonance analysis using either of these two descriptions of the resolution function.


Fig. 1: Amplitude and decay time as derived from fits to experimental data
Measurement of the $^{236}\text{U}(n, f)$ cross section as a function of the neutron energy

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The experimental data base for the $^{236}\text{U}(n, f)$ cross section is very poor: with thermal neutrons, only one direct measurement is available [1], whilst with resonance neutrons only two conflicting measurements have been published [2, 3]. To improve this situation, a new measurement in the neutron resonance region was performed at the GELINA facility, using a highly enriched $^{236}\text{U}$ sample. This sample was mounted back-to-back with a $^{10}\text{B}$ sample, in the centre of a Frisch-gridded ionisation chamber. From this measurement the $^{236}\text{U}(n, f)$ cross section was obtained in the neutron energy region from 1 eV to 20 keV. Besides a dominant resonance at 5.45 eV, the next resonance only occurs at about 1.3 keV, hence confirming the results of Parker et al. [3] and of preliminary data from nTOF [4]. So the series of resonances observed in between these two energies by Theobald et al. [2] are not due to fission but correspond to (n,$\gamma$) resonances erroneously identified as (n,f) resonances.

This will have a strong impact on the evaluated data files for the $^{236}\text{U}(n, f)$ cross section, which all appear to be too high by two orders of magnitude. In all cases, a value $I_f \approx 4.4 \text{ b}$ is reported for the fission resonance integral, which is also too large by two orders of magnitude. The same is true for the thermal fission cross section.

The present data in the resonance region and the thermal fission cross section previously reported by Wagemans et al. [1] constitute a coherent set of data.

Prompt fission neutron multiplicity and spectrum calculations for thermal and fast neutron induced reactions on $^{233,231}$Pa nuclei

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The Th-U fuel cycle is subject of a Coordinated Research Project (CRP) of the IAEA [1] in view of a consistent and improved evaluation for the relevant nuclei of this fuel cycle. The isotope $^{233}$Pa plays an important role, as the intermediate between the $^{232}$Th source material and the $^{233}$U fissile nucleus. $^{231}$Pa is important too, as being the homologue to $^{239}$Pu in the U-Pu cycle having a similar half life and toxicity. Recently, much effort has been invested to measure the fission cross-section of $^{233}$Pa [2, 3] and also to obtain improved experimental fission cross-section data for $^{231}$Pa [4]. Based on these experimental data, new neutron cross-section calculations of $^{233,231}$Pa nuclei were performed using refined models [1, 5].

Beside the neutron cross-sections, other neutron data of interest in nuclear applications are the prompt fission neutron multiplicity (PFNM) and the prompt fission neutron spectrum (PFNS). For the nuclei of the Th-U fuel cycle relevant experimental PFNM and PFNS data are scarce or totally missing. In the present work the PFNM and PFNS are calculated up to 50 MeV incident neutron energy in the case of $^{233}$Pa and up to 30 MeV incident neutron energy for $^{231}$Pa. Refined nuclear models have been used which were already successfully applied to the PFNM and PFNS evaluation for many neutron induced reactions on actinides like $^{238}$U [6], $^{235}$U [7], $^{233}$U [6, 6], and others.

In the frame of the Point by Point (PbP) model the experimental fission fragment (FF) mass and TKE distributions play the most important role. At a given $E_n$ the total PFNM and total PFNS are calculated as superposition of the multiplicity and of the spectrum of the FF pairs weighted with the charge and mass distributions, according to the following equations:

\[
\langle \nu_p \rangle_{\text{tot}} = \frac{\sum_{i=1}^{NP} p_{zi} Y_i \nu_{\text{pair}}^i}{\sum_{i=1}^{NP} p_{zi} Y_i}
\]

\[
N_{\text{tot}}(E) = \frac{\sum_{i=1}^{NP} p_{zi} Y_i N_{\text{pair}}^i(E)}{\sum_{i=1}^{NP} p_{zi} Y_i}
\]

where the index $i$ is running over the FF pair range (NP being the number of FF pairs). $Y_i$ and $p_{zi}$ are, respectively, the mass and charge distributions of the $i$-th FF pair. The quantities $\nu_{\text{pair}}^i$ and $N_{\text{pair}}^i$ are respectively the prompt fission neutron multiplicity and spectrum of each FF pair. A description of this model is given in detail in Refs. [7, 8]. The neutron multiplicity as a function of mass and FF pair as calculated by the PbP model for the $^{233,232,231}$Pa($n_{th}, f$) reactions are given in Fig. 1.

$^\dagger$deceased
At higher $E_n$, when more than one fission chance is involved, the PbP approach can not be used because of the impossibility to distinguish the FF mass and charge distributions corresponding to each CN undergoing fission. Hence, in this case the 'most probable fragmentation' approach with average values for the input model parameters has to be used, instead. The average values of the model parameters as well as their most appropriate dependence on the excitation energy of each CN are determined using available experimental FF data of those reactions where the fissioning nuclei under consideration are the main compounds (first fission chance) by taking into account the entire FF range with the PbP treatment according to the description given in Refs. [6, 7].

Above 30 MeV also fission of nuclei formed by charged particle emission becomes important and the PFNM and PFNS resulting from the fission of those compound nuclei must be taken into account. The full description of the extended model is given in Ref. [6] where the model was applied for the $n + {^{238}}U$ reaction up to 80 MeV incident neutron energy. The calculations were performed with the PbP version of the computer code SPECTRUM [7, 8] developed to take into account a large number of fragmentations (more than 200 FF pairs). The input model parameters of the FF pairs involved in the PbP treatment are calculated by our computer code PAIRPAR according to the procedures described in Refs. [7, 8].

The experimental data from Ref. [9] allow also the use of the PbP treatment to determine the most probable fragmentation and the average values of the model parameters. These model parameters for Pa nuclei heavier than in the present case were calculated in the frame of the $n + {^{238}}U$ reaction where the $^{238-231}Pa$ nuclei acted as secondary chain [6]. At incident neutron energies higher than thermal, where one or more fission chances are involved, the dependence of the average model parameters on $E_n$ (or on the excitation energy $E^*$ of the fissioning nucleus) must be taken into account. The FF experimental data of Petit [9] measured in a wide range of excitation energies as well as the PbP treatment can again be exploited, giving

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**Fig. 1**: Neutron multiplicity as a function of mass (closed symbols) and for FF pairs (open symbols) of $^{233,232,231}Pa(n, f)$ at thermal incident neutron energy.
us the possibility to find appropriate dependences on $E_n$ for the average model parameters of the $^{234-232}$Pa fissioning nuclei. In the case of the $n + ^{233}$Pa reaction up to $E_n = 50$ MeV the total and partial fission cross-section ratios used for the PFNM and PFNS calculations have been taken from Ref. [10]. In the case of the $n + ^{231}$Pa reaction up to $E_n = 30$ MeV, the contributions of the secondary nuclei chains obtained by charged particle emission are very low and were neglected, only the fission of the main chain nuclei was considered and the corresponding RF taken from Ref. [10]. The present calculation of the $^{233}$Pa total PFNM up to 50 MeV incident energy is given in Fig. 2 with a solid line in comparison with the most important evaluated nuclear data libraries (ENDF/B-VI, JENDL3.3). Our calculation is very close to the JENDL3.3 evaluation (thin solid line) up to about 15 MeV as it can be seen in the figure. The present calculation is lower than the ENDF/B-VI evaluation (dotted line) in the energy range of the first chance (up to about 6 MeV) and higher above 14 MeV. In Fig. 2 the contribution of the Pa main nucleus
chain (dashed line) as well as of the Th secondary nucleus chain (proton way with double dot-dashed line and neutron via proton way with dash-dotted line) are given, too. The calculated total PFNM of the \( n + ^{231}\text{Pa} \) reaction up to 30 MeV is plotted in Fig. 3 with a solid line in comparison with the most important evaluations (ENDF/B-VI, JEF3.1, JENDL3.3). As it can be seen our calculation is rather close to the JENDL3.3 evaluation (dash-dotted line, obtained from the semi-empirical formula of Blois and Fréhaut) and higher than the ENDF/B-VI evaluation (dashed line).


[9] M. Petit, Mesure de la section efficace de fission du \( ^{233}\text{Pa} \), thesis, University of Bordeaux I (2002), and private communication 2003

[10] G. Vladuca, A. Tudora, F.-J. Hambsch, S. Oberstedt, D. Filipescu, Evaluation of the neutron induced cross-sections of \( ^{233}\text{Pa} \) up to 50 MeV and of \( ^{231}\text{Pa} \) up to 30 MeV incident neutron energy, to be published.
The nuclear fission process
Properties from the reaction $^{238}\text{U}(n, f)$ from $E_n = 0.9$ to 2.0 MeV

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One of the oldest problems in nuclear physics is to describe the fission fragment mass and kinetic energy distributions. With the Multi-Modal Random Neck-Rupture (MM-RNR) model [1], fission-fragment distributions can be described over the whole actinide range from $^{213}\text{At}$ to $^{258}\text{Fm}$. However, the relative yield of each fission mode, in the MM-RNR model, is found by fitting a two-dimensional function to the experimental yield $Y(A, \text{TKE})$ and the model can not be used to predict fission-fragment distributions.

Recent calculations of neutron-induced fission, inelastic and elastic neutron scattering as well as capture cross-sections in the framework of an extended statistical model, performed for several isotopes triggered the idea to incorporate the modal picture of the fission process into these calculations. The parameters of the common first and the mode-dependent second barrier, as the height, penetrability and transition states, can be determined based on the neutron-induced fission cross-section and fission-mode weights obtained from experimental data in a given neutron energy range. When the structure of the complete double-humped fission barrier is known for all fission modes, calculation of the neutron-induced modal fission cross-section may be used to predict fission fragment distributions, since each mode has a characteristic mean mass and TKE. A description of such calculations for $^{235,238}\text{U}(n, f)$ and $^{237}\text{Np}(n, f)$ can be found in Refs. [2, 3, 4, 5]. In order to further confirm the predicting power of the multi-modality unfolding of the cross-sections, measurements on $^{238}\text{U}$ were performed at IRMM around the vibrational resonances at 0.9 and 1.2 MeV, where the calculations predict an inversion of the S1 and S2 fission mode weights. This would mean that the mean heavy fission fragment mass would be at least 1.5 amu lower at $E_n = 0.9$ MeV compared to $E_n = 1.8$ MeV.

The experiments were performed using a highly enriched UF$_4$ sample, which consisted of 99.9997% $^{238}\text{U}$, which had a total uranium mass of $(921 \pm 46) \mu$g. The reactions $^7\text{Li}(p, n)^7\text{Be}$ (445 and 832 $\mu$g/cm$^2$ LiF) and $^3\text{H}(p, n)^3\text{He}$ (2060 $\mu$g/cm$^2$ TiTi) were used to create the neutrons.

The fission fragments were detected using a double Frisch grid ionization chamber, from which the anode and the sum of grid and anode signals were collected. The sum signal carries information about the emission angle, which is needed to determine the energy loss in the target and the target backing. An iterative procedure is made to obtain the pre-neutron kinetic energy from the detected anode pulse heights. Prompt neutron evaporation was determined using the $\nu(A)$ from Ref. [6]. These $\nu(A)$-values were adjusted with a TKE dependence according to Ref. [7]. The pulse height defect (PHD) was determined using the function described in Ref. [8] with parameters adjusted together with the energy calibration factor to obtain a mean heavy mass ($A=139.6$) and TKE (170.15 MeV) corresponding to the data from Vivès et al. [6] taken at $E_n = 1.8$ MeV. This particular choice of PHD parameterization was based on the
study of cold fission from this experiment. The average total kinetic energy and the widths of the TKE distributions as a function of incident neutron energy is shown in Fig. 1 (upper part). The TKE is approximately 0.5 MeV higher at the two vibrational resonances in the fission cross-section at $E_n = 0.9$ MeV and $E_n = 1.25$ MeV than at $E_n = 1.8$ MeV. The widths are significantly lower compared to the widths reported in Ref. [6], because of the correct energy dependence used when the number of prompt neutrons were determined. The mean heavy mass shows some fluctuation (see Fig. 1, middle left part), but at $E_n = 0.9$ MeV no significant decrease is observed.

Two even Legendre polynomials were fitted to the angular distribution ($0.20 \leq \cos \theta \leq 0.85$) and the value of the function at 0° and 90° are compared and plotted in the middle right part of Fig. 1 as a function of incident neutron energy together with the values of Refs. [6, 9, 10]. The full line is just a guide to the eyes. All measurements are in quite good agreement with each other. The present results confirm the resonance-like structure at $E_n = 1.6$ MeV.

In order to reveal changes in the $Y(A, \text{TKE})$ distribution as a function of incident neutron energy in a model-free approach, two regions $[\Delta A, \Delta \text{TKE}]$ have been defined. Any change in fission characteristics should cause a change in the relative number of counts in the defined regions. The two regions correspond to the S1 and S2 fission modes. There is an apparent trend visible towards higher yields of the S1-region, when the incident neutron energy decreases. This increase, however, does not exceed about 2% (see bottom left part of Fig.1). Two fission modes were assumed (S1 and S2) and the data were fitted using the program Origin 7.5 [11]. Only small fluctuations in the mode weights are seen in the bottom right part of Fig. 1. At $E_n = 0.9$ MeV the calculations predict a mode weight inversion between S1 and S2 fission mode. This is definitely not supported by the experimental results.

The prediction of fission fragment properties was based on the calculation of the modal fission cross-sections, taking information on fission mode weights from previous measurements [6, 12], which could not be reproduced in this work. Although the observation of fission-mode weight inversion could have been taken as a first experimental proof for the existence of fission modes, the non-observation certainly does not allow to rule that out. Possibly, taking the present results into consideration, the calculation of the modal fission cross-sections could be redone with appropriately refined barrier parameters. If the total fission cross-section is still well described, the modal fission cross-sections could well be used to predict mass and kinetic energy distributions.

Fig. 1: As a function of incident neutron energy is shown the total kinetic energy (upper left), the widths of the total kinetic energy distributions (upper right), the mean heavy mass (middle left) and the anisotropy values from this work compared to those from Refs. [6, 9, 10]. The full line to the anisotropy (middle right part) is a guide to the eyes. In the bottom left part the relative yield in the elliptic region 1, corresponding to the peak of the standard 1 fission mode is shown, and the S1 fission mode weight (bottom right) is shown together with mode weights from Refs. [6, 12].
Studying photo-induced fission on $^{238}$U with bremsstrahlung at the S-DALINAC

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Parity nonconservation can be observed in nuclei due to the influence of the weak interaction. The probably best studied example for such an effect is the helicity-dependent transmission of polarized neutrons from a variety of targets from $^{81}$Br to $^{238}$U. Very large asymmetries of the order of a percent are detected, and the magnitude of this effect is interpreted to arise from parity-violating mixing of the $s$- and $p$-wave capture states in the compound nucleus near threshold [1]. As the experimental effects are several orders of magnitude larger than expected from the relative strengths of the weak and the strong interaction, kinematic and dynamic enhancement factors are believed to play an important role [2]. In order to resolve open questions [1, 3] in describing the enhancement factors, further experiments with different probes are helpful.

Parity violation effects of the order of a few times $10^{-4}$ have also been observed in nuclear fission induced by thermal polarized neutrons [4, 5]. In this process, kinematical effects are not expected to play a role. The search for parity-violation effects in photo-induced fission might help clarify this surmise. While photo-induced fission has been studied with unpolarized and linearly polarized photon beams (see [6] and Refs. therein for an overview), to our knowledge no data are available for fission following irradiation with circularly polarized photons. There are further open questions, such as studying mass and angular distributions of the fragments [7, 8] for different polarizations or determining the spectrum and angular distribution for the prompt fission neutrons [9]. Data on the latter subject might help clarifying at what point of time in the fission process the neutron is emitted. Also the population and decay of isomeric states in heavy fissile nuclei is of interest, and neither sub-threshold fission experiments [10] nor nuclear resonance fluorescence studies have been performed with polarized bremsstrahlung in these nuclei. From the measured isomeric yields one could, e.g., learn something about fission barriers.

At the superconducting Darmstadt electron linear accelerator S-DALINAC [11] there is a long standing research program using bremsstrahlung with endpoint energies of about 3 up to 10 MeV [12]. Due to the compact setup and the continuous-wave (cw) time structure of the accelerator, high intensities of unmarked bremsstrahlung are available. In order to elucidate the feasibility of experiments on photo-induced fission, we have performed a test experiment using a double ionization chamber [13] which was operated with P-10 gas. At the cathode, a 130 $\mu$g/cm$^2$ $^{238}$U target was mounted. The nucleus $^{238}$U was chosen to assure minimal background from $\alpha$ decay in the target for this test experiment. The bremsstrahlung produced by a 10 $\mu$A cw electron beam in an air-cooled copper target was collimated, and the double ionization chamber was placed in the beam with the target orientation being perpendicular
to the incident beam. The signals of the cathode, the two anodes, and the two Frisch grids installed in the ion chamber were amplified and digitized.

Fission fragments were identified by a software coincidence of the anode signals. Figure 1 shows the distribution of fission fragments depending on the pulse height in anode 1 versus the pulse height in anode 2 measured at an endpoint energy of the bremsstrahlung of 7.0 MeV. The well-known asymmetric distribution of the fission fragment masses is visible. No background problems due to α decay in the target were encountered.

Fission yields were measured for endpoint energies of the bremsstrahlung between 6.0 MeV and 8.5 MeV, in steps of 500 keV. The number of detected events was normalized to the data acquisition time and the electron beam current on the bremstarget. The dependence of the fission yield on the endpoint energy is displayed in Fig. 2 where the data points have statistical uncertainties smaller than the symbol size. Data acquisition times varied from about 80 minutes to several hours, depending on the number of registered fission events.

A rough estimate based on simulations of the bremsstrahlung spectrum using the code GEANT4 [14] indicates that the cross section from the present data are in agreement with the literature [15]. However, determining absolute energy-integrated fission cross section from our measurement has at present still non-negligible systematic uncertainties.

The main source of uncertainty is the alignment of electron beam and the copper collimator selecting a narrow region of the bremsstrahlung cone. In the GEANT simulations, good align-
Fig. 2: Fission yield obtained with the 130 $\mu$g/cm$^2$ $^{238}$U target at the 10 MeV bremsstrahlung set-up of the S-DALINAC as a function of the endpoint energy. The number of detected events was normalized to the beam current (about 10 $\mu$A) and the data acquisition time.

Assuming a correct alignment of the electron beam with respect to the collimator and a vanishing instrumental asymmetry, the data of our test experiment show that parity violation in photo-induced fission can be probed at a level of $\sim 10^{-2}$ even at endpoint energies of 6 MeV, very close to the threshold. This precision can be achieved within about one week of beam time. At higher endpoint energies, the sensitivity limit will be even smaller, but a large number of resonance states will contribute to the fission yield. Such data might aid our understanding of enhancement effects for parity violation in highly excited complex nuclei. Further tests for optimizing the set-up and minimizing systematic and apparative uncertainties are foreseen.

We are indebted to M. Chernykh, Y. Poltoratska, and I. Pysmenetska for assistance with the data taking and to J. Hasper for the simulations of the bremsstrahlung spectrum using the code GEANT. The Darmstadt group acknowledges funding by the Deutsche Forschungsgemeinschaft through SFB 634.
New experimental results for the $^{235}\text{U}$ fission neutron emission

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Following a recommendation of the NEA Working Party on Evaluation Cooperation (WPEC) [1] the prompt fission neutron spectrum (PFNS) was measured at 0.5 MeV incident neutron energy. An angular anisotropy in the prompt neutron emission was found in this experiment. The neutron yield is $\approx 10\%$ higher and the average energy 80 keV smaller at 90° than at 120° neutron emission angle. The spectral difference diminishes with increasing prompt neutron energy.

The time-of-flight method was applied in the measurement. A neutron beam with a time resolution of $\approx 1.5$ ns was produced via the $^7\text{Li}(p, n)^7\text{Be}$ reaction. A cylindrical metallic $^{235}\text{U}$-sample of 161.3 g was used in the experiment. Two liquid-scintillation neutron detectors shielded against direct neutrons were placed at 90° and at 120°. For gamma-background reduction traditional pulse-shape analysis was applied. Detector efficiencies were measured relative to the $^{252}\text{Cf}(\text{SF})$ prompt neutron spectrum. As much as $\approx 3 \times 10^6$ fission-neutron events were collected during several independent runs for each detector. The data were corrected for multiple scattering and attenuation by means of MCNP Monte-Carlo simulations. Additional Monte Carlo simulations were carried out to calculate the zero-time including the real time resolution, sample size and to estimate the time resolution correction. The experimental procedure has been described in detail in Ref. [2]. Additional measurements with a Pb-sample (see Fig. 1) allowed us to conclude that no time dependent background events are observed in the range of interest.

The PFNS was normalized to unity and the average neutron energy was calculated. A Maxwellian spectrum was fitted in the energy range of 0.7 - 1.5 MeV and 9 - 11 MeV to the measured spectrum and the calculated values were used for the extrapolation to zero and to 20 MeV. The average energies for both detectors and for each independent run are given in Tab. 1. An obvious difference in the average neutron energy at the different angles exists. Possible sources of uncertainty on the average energy are the calculation of the zero-time, the detector efficiency (standard neutron spectrum), and any of the other corrections mentioned above. For example, a 1 ns time shift, changes the average energy by 60 keV for our experimental conditions. The analysis of the prompt gamma-ray position allows us to estimate an uncertainty of the zero-time determination to less than 0.4 ns. Having in mind this value and the spread of the data in Tab. 1 we concluded that for our conditions the average energy was estimated with an accuracy of $\pm 0.020$ MeV. Finally, for the total data set $\langle E \rangle = 2.018 \pm 0.020$ MeV for the 90° detector and $2.094 \pm 0.020$ MeV for the 120° detector. In general, the spectrum at 120° is closer to a Watt distribution whereas the spectrum at 90° resembles a Maxwellian shape.

The ratio $R(E) = N(90°, E)/N(120°, E)$ for each measured run is shown in Fig. 2. Small absolute differences (as given in the inset of Fig. 2) between runs may be explained with the
Fig. 1: U- and Pb-samples runs after subtraction of the time independent background

Tab. 1: Total amount of fission neutrons collected in each run, run duration, and average neutron energies.

<table>
<thead>
<tr>
<th>name</th>
<th>neutrons</th>
<th>$t_{mess}$</th>
<th>$\langle E \rangle_{90^o}$</th>
<th>$\langle E \rangle_{120^o}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>run 1</td>
<td>$8.0 \times 10^5$</td>
<td>37.0</td>
<td>2.018</td>
<td>2.087</td>
</tr>
<tr>
<td>run 2</td>
<td>$1.1 \times 10^6$</td>
<td>42.1</td>
<td>2.022</td>
<td>2.103</td>
</tr>
<tr>
<td>run 3</td>
<td>$8.5 \times 10^5$</td>
<td>39.2</td>
<td>2.014</td>
<td>2.092</td>
</tr>
</tbody>
</table>

uncertainty of the sample position and proton beam position of $\pm 2$ mm. This conclusion was confirmed by MCNP simulations. Below 5 MeV a definite difference between the spectrum taken at $90^o$ and at $120^o$ is visible. The average ratio for the energy interval 6 - 10 MeV is $\langle R \rangle = 1.022 \pm 0.015$.

An angular dependence of the PFNS shape and neutron yield was already discussed in Refs. [3, 4, 5, 6, 7]. Knitter et al. [3, 4] measured the energy-angular distribution at different incident neutron energies in the range 0.4 - 5 MeV. They concluded that the angular distribution of the fission neutrons show an isotropic dependence within the error, though the evidence for anisotropy cannot be completely ruled out.

In Refs. [3, 4] the PFNS was measured at 0.4 MeV for $^{235}$U at angles of $45^o$, $90^o$ and $135^o$. However, the data were not analysed separately. All three spectra were summed and the spectrum shape fitted with a Maxwellian distribution. The parameter $T = (2.06 \pm 0.05)$ MeV based on the fit in the energy range 0.55 - 7 MeV leads to an average energy $\langle E \rangle = 1.5$ MeV. We can assume that the present $120^o$ spectrum corresponds to the $45^o$ and $135^o$ runs of Refs. [3, 4], and can construct the spectrum $N(E) = 0.33 N_{90^o}(E) + 0.67 N_{120^o}(E)$. The
resulting Maxwellian T-parameter from this constructed spectrum, fitted in the energy range between 0.7 and 7 MeV, gives as average energy $\langle E \rangle = 1.5$, $T = 2.055$ MeV, in perfect agreement with the data of Refs. [3, 4].

The angular distribution for $^{235}$U fission neutrons integrated in the energy range 3 - 6 MeV was shown in Ref. [4] for neutron input energies of 1.5 - 2.3 MeV. Indeed, from the data a practically isotropic emission can be concluded. However, it seems that the $\approx 7\%$ effect expected for this energy interval according to the present results cannot be identified by the experiment of Ref. [4] due to the large error bars (minimal error is about 15 % and the data scatter exceeds 20-30 %).

In Ref. [5] the energy-angular distribution was measured for $^{238}$U at an input energy of 2.47 MeV from 30° to 150°. The neutron spectra were investigated in the energy range $> 2.5$ MeV. The authors did not find any deviation from isotropy in the absolute yield and spectral shape. However, the deviation may have again been masked by the statistical uncertainty.

The fission neutron spectra for $^{233},^{235}$U, $^{240,241}$Pu were measured relative to $^{252}$Cf with the Argonne National Laboratory (ANL) time-of-flight spectrometer [6]. An angular range of about 140° was covered in this investigation. The input energy was about 0.5 MeV. Due to a long flight path of 5 m and a distance of 13 cm from the target to the sample the count rate in this experiment was about $\approx 15$ times lower than in the present case. It seems, that the poor statistics did not allow an analysis of the data at separate angles. The conclusion was that ancillary measurements did not show any significant angular-dependent effects and for each isotope all spectra were summed up.

The results of a similar investigation for $^{235,238}$U at $E_n = 2.07$ MeV were presented in Ref. [7]. Angular distributions were presented for different energy intervals of the emitted neutrons. For the energy interval 2.5 - 3 MeV an isotropic distribution for $^{235}$U with an accuracy better than 5 % and for $^{238}$U $\approx 10\%$ anisotropy was found. However, in the latter case the anisotropy has an opposite sign compared to our result. Neither the spectrum shape nor an average energy dependence was discussed.

No direct evidence of an anisotropic effect was found in the investigation of the inelastic neu-
tron scattering of $^{235,238}\text{U}$ for incident neutron energies of 1 - 2.2 MeV [8]. The measurement was made at an angle of 120°. Extrapolation to zero neutron energy using a Watt spectrum resulted in a much better value for the neutron multiplicity than with a Maxwellian distribution, which was proclaimed in many experimental papers.

In conclusion, most of the previous experiments were not able to reveal an anisotropic effect in the prompt neutron spectrum mainly due to their low statistical accuracy. The difference between our result and those of Ref. [7] is unclear.

The PFNS at 90° agrees with all previous measurements [9, 10, 11, 12, 13, 14], available in numerical form within an accuracy of smaller than 10 % in the prompt neutron energy range from 1-7 MeV (see Fig. 3). Even more, our data agree inside the error bars with the data of Refs. [9, 10] in the energy interval 0.7 - 5 MeV, with the data of Johansson et al. [11] in the energy interval 3 - 12 MeV, and with the data of Staples et al. [12] in the energy interval 1 - 8 MeV inside our error bars.

The fission neutron spectra for $^{235}\text{U}$ in Refs. [11, 12, 13, 14] were measured at 90° relative to the incident neutron beam. The measurement angle used in Refs. [9, 10] is unknown. Both thermal [9, 10, 14] and about 0.5 MeV [11, 12, 13] incident neutron energies were investigated. Hence, one may conclude that our result at 90° agrees with all previous measurements.

The present PFNS is systematically higher by $\approx 10 - 20 \%$ in the high energy range above 6 MeV compared to some of the literature data and the smooth curve predicted by the theoretical model. The following peculiarities should be taken into account when we are discussing this problem:

a. The total energy release is $\approx 25$ MeV, so each fragment gets on average $\approx 12$ MeV only. The high energy part of the fission neutron spectrum can not be described by
an evaporation process of neutrons from excited fragments only, but will be modulated by the fission fragment yield at low kinetic energy and by the energy release (Q-value) available for a given mass split. Therefore, a smooth function can not be applied for the description of the high energy part of the spectrum and for the extrapolation to infinitely high energy some 'structure' may exist in this energy range.

b. A larger difference is visible for the data measured with ionisation chambers (Refs. [9, 10]). It may be connected with the experimental method itself. Rather thick fissile layers were applied in the ionisation chamber to provide reasonable count rates. As a result, the counting efficiency of fission fragments is smaller than 1. Hence, some fission fragments with low kinetic energy (high excitation) may be lost, leading to a systematic difference which increases with neutron energy. A special effort was made in Ref. [13] to minimize this effect, which may explain the much better agreement with the present result in the high energy part of the spectrum (see Fig. 3).

In general one may conclude, that the present experiment at 90° together with other available numerical data does not confirm the Madland-Nix model or its latest modifications [15]. At presence no model can explain the experimental finding of an anisotropic PFNS. We have to assume that an additional mechanism of neutron emission, like an emission at the scission point, has to be incorporated.

The measurement will be continued covering more angles to verify the effect and estimate the full angular dependence. It would be very interesting to look also as a function of incident neutron energy, for different fissile targets and investigate the relation between neutron and fission fragment anisotropy.

[2] N. V. Kornilov et al., Internal report GE/NP/01/2007/02/14
Measurement of the prompt neutron emission in resonance neutron induced fission of $^{235}\text{U}$, $^{239}\text{Pu}$ and spontaneous fission of $^{252}\text{Cf}$

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The development of the experimental apparatus for simultaneous measurements of prompt neutron emission in resonance neutron induced fission of $^{235}\text{U}$ and $^{239}\text{Pu}$ was finished and calibration measurements were done with 8 NE213 liquid-scintillator based neutron detectors (ND) from the DEMON collaboration [1]. The experimental setup was assembled at a flight path of about 9 m at the GELINA facility. Besides the ND it includes a double back-to-back Frisch-grid ionization chamber (IC), the electronic setup based on the CAMAC standard and a dedicated data acquisition and analysis software. The $^{235}\text{U}$ target deposited on a thin (35 $\mu\text{g/cm}^2$) polyimide foil was mounted on the common cathode of the IC. A spontaneously fissioning $^{252}\text{Cf}$ target mounted in the same IC was used for calibration measurement and adjustments.

The kinetic energies of both correlated fission fragments (FF) along with their angles in respect to the cathode plane were determined using waveforms of FF induced pulses from both anodes of the IC sampled with a 80 MHz waveform digitizer. The incident resonance neutron time-of-flight (TOF) value was measured as the time difference between the "T-Zero" pulse from the GELINA accelerator and the pulse from the cathode of the IC. Pulse shape analysis electronic was used to separate prompt fission neutrons from the gamma radiation. Measurements were started at the end of 2006 with an uranium target and will be continued during 2007. The resonance neutron induced fission event distribution measured with the described apparatus is presented in Fig. 1. In parallel a development of a completely waveform digitizer (WFD) based acquisition system was started.

A schematic diagram of the four double channel 100 MHz WFD is presented in Fig. 2. The development of the data acquisition software for the digital measurement system is planned in 2007.

Fig. 1: Resonance neutron induced fission distribution

Fig. 2: Simplified schematic diagram of the WFD based experimental setup
Nuclear reaction mechanisms and standards
Measurement of the $^{16}$O(n, $\alpha$)$^{13}$C cross section

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A project was started in 2006 at IRMM aiming at the measurement of the cross section of the $^{16}$O(n, $\alpha$)$^{13}$C reaction for neutron energies between threshold (2.35 MeV) and 10 MeV. This activity was triggered by a data request created in the High Priority Nuclear Data Request List (HPRL) of the Nuclear Energy Agency. A comparison of evaluations shows that cross section values of ENDF/B-VI.8 are 10% to 50% higher than those of JENDL3.3 in the energy range between 3 and 8 MeV. Due to the spread of experimental data it is assumed that the $^{16}$O(n, $\alpha$)$^{13}$C cross section is known with an accuracy of 30% from threshold (2.35 MeV) to 8 MeV. According to the data request, an accuracy of 5% is required in order to achieve improvement in applications such as reactivity predictions of thermal and fast reactors, calculation of helium production in fuel pins and claddings, and calibration of neutron source strengths. A cross section measurement of the inverse reaction $^{13}$C($\alpha$, n)$^{16}$O with an overall accuracy of 4% for $\alpha$-particle energies from 0.8 to 8.0 MeV was published in December 2005 by Harissopulos et al. [1]. Their cross sections are lower than those of Bair and Haas [2], which were the basis of the ENDF/B-VI.8 evaluation. Explicitly, $\sigma_1/\sigma_2 \approx 0.63, 0.68, 0.64$, and 0.72 at $E_\alpha = 2.3, 3.3, 4.4, \text{ and } 5.0 \text{ MeV}$, respectively, with a mean ratio value $< \sigma_1/\sigma_2 > = 0.67$. These cross section ratios, not the cross section values, were used at LANL in order to produce ENDF/B-VII.0 by performing a renormalisation of ENDF/B-VI.8 in the neutron energy range from 2.4 to 8.9 MeV. The ENDF/B-VII.0 cross sections for $^{16}$O(n, $\alpha_0$)$^{13}$C were obtained from ENDF/B-VI.8 by performing a 32% reduction of its cross section values. It has to be taken into account that measurements of the inverse $^{13}$C($\alpha$, n)$^{16}$O reaction of the Harissopulos et al. [1] type, e.g. those where the total number of produced neutrons but not the different neutron groups, such as $n_0$, $n_1$, $n_2$, are measured, can provide $^{16}$O(n, $\alpha_0$)$^{13}$C cross sections only up to an $\alpha$-particle energy $E_\alpha = 5.0 \text{ MeV}$ (threshold of the $^{13}$C($\alpha$, $n_1$)$^{16}$O reaction), which corresponds to a neutron energy $E_n = 6.4 \text{ MeV}$ for $^{16}$O(n, $\alpha_0$)$^{13}$C. Therefore the LANL renormalisation can be applied only up to this energy. New accurate data are required in order to test its validity between 6.4 and 8.9 MeV. For this purpose a oxygen gas target, a 1D-TPC (one-dimensional time projection chamber) spectrometer, and a novel FNBP (fast neutron beam profiling) technique were used at IRMM. The oxygen component of the detector gas, a Kr(97 %)CO$_2$(3 %) mixture, was used as target for $^{16}$O(n, $\alpha$)$^{13}$C. The basic elements of the 1D-TPC are an ionisation chamber, signal digitisation, and off-line analysis [3]. Those of the FNBP are a collimated neutron beam, neutron activation, and a threshold reaction [4]. A simple equation was produced for the relation between reaction yield, cross section, and neutron-beam profile [5]. The D(d,n)$^3$He reaction and a deuterium gas target were used to produce monoenergetic neutrons. A set of $^{16}$O(n, $\alpha_0$)$^{13}$C cross sections with an accuracy of better than 5% were obtained between 6.2 and 7.4 MeV and at a few points in the region of the 5 MeV resonance. Due to the low energy resolution of the neutron beam the measured resonances are broadened and partly shifted. Although very preliminary, our results provide important information on the magnitude of the cross section. Above 6.2 MeV the
IRMM data are close to the values of the ENDF/B-VI.8 evaluation, but there is disagreement with ENDF/B-VII.0. The 5 MeV data are in reasonable agreement with ENDF/B-VII.0. The IRMM cross sections are shown in Fig. 1 together with predictions of different evaluations and other experimental data. Cross section values for $^{16}$O($n, \alpha_0$)$^{13}$C between 2.4 and 6.4 MeV were obtained at IRMM by detailed balance calculations [6] from the inverse reaction data of Harissopulos et al. [1] and are also shown in Fig. 1. The measurements at IRMM are presently being continued in the energy intervals 3.9-5.2 MeV and 7.4-8.9 MeV in order to investigate the most relevant structures of the $^{16}$O($n, \alpha_0$)$^{13}$C excitation function in the requested energy range between 2.4 and 8.9 MeV.


[3] G. Giorginis, V. Khryachkov, V. Corcalciuc, M. Kievets, A 1D-TPC (one-dimensional time projection chamber) technique for the study of $^{16}$O($n, \alpha$)$^{13}$C reaction by using gas targets, internal report in preparation
[4] G. Giorginis, V. Khryachkov, V. Corcalciuc, M. Kievets, A FNBP (fast neutron beam profiling) technique for the determination of the profile of a collimated neutron beam, internal report in preparation

[5] G. Giorginis, V. Khryachkov, V. Corcalciuc, M. Kievets, Relation between reaction yield, cross section, and beam profile for cross-section measurements with gas targets and collimated neutron beams, internal report in preparation

[6] G. Giorginis, V. Khryachkov, V. Corcalciuc, M. Kievets, Detailed balance calculations for the determination of the $^{16}\text{O}(n, \alpha)_{0}^{13}\text{C}$ cross section from published measurements of the inverse reaction $^{13}\text{C}(\alpha, n)^{16}\text{O}$, internal report in preparation
Neutron induced reactions related to the abundance of $^{36}\text{S}$ and $^{26}\text{Al}$ in our Galaxy

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It is well known that stars are the cooking pots of the elements, but a few questions about how and where some of the elements in nature are generated still remain. To perform reliable nucleosynthesis calculations, accurate cross section data for the underlying reactions are necessary. Our work focuses on the origin of $^{36}\text{S}$ and the destruction of $^{26}\text{Al}$.

![Graph](image)

**Fig. 1:** The $^{26}\text{Al}(n, \alpha)^{23}\text{Na}$ reaction cross section up to approximately 100 keV.

For this purpose, $(n, p)$ and $(n, \alpha)$ measurements on $^{26}\text{Al}$, $^{36}\text{Cl}$ and $^{41}\text{Ca}$ were performed at the time-of-flight facility GELINA of the IRMM. Partial results on the $^{41}\text{Ca}(n, \alpha)^{38}\text{Ar}$ reaction cross section have been presented at a conference [1]. Final results on the $^{36}\text{Cl}(n, p)$ and $^{36}\text{Cl}(n, \alpha)$ reaction cross sections have been accepted for publication in Phys. Rev. C [2]. Final results on the $^{26}\text{Al}(n, \alpha)^{23}\text{Na}$ reaction cross section up to approximately 100 keV are shown in Fig. 1.


Studies of neutron-induced activation cross sections

V. Semkova, R. Jaime Tornin, A. Moens, A. J. M. Plompen

Neutron-induced cross section data for Ta and W are of importance both for nuclear technologies research and development and for basic studies. Precise experimental cross section data for fast neutron-induced reactions are of considerable interest for testing nuclear model calculations. Several reaction channels are energetically allowed in the investigated energy range and different reaction mechanisms play roll. A precise and complete experimental data base for a given mass region allows systematic development of nuclear model parameterization.

Measured cross sections were determined by the activation technique in combination with high-resolution $\gamma$-spectrometry. A detailed description of the measurement procedure has been given earlier [1]. The emphasis here will be on the specifics for the present study.

Tab. 1: Decay constants of the reaction products, samples weight and dimensions

<table>
<thead>
<tr>
<th>reaction</th>
<th>decay constant</th>
<th>size</th>
<th>nominal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$T_{1/2}$</td>
<td>$E_\gamma$ (keV)</td>
<td>$I_\gamma$ (%)</td>
</tr>
<tr>
<td></td>
<td>NuDat 2.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{50}$Cr (n, x) $^{48}$V</td>
<td>15.9735d</td>
<td>983.35</td>
<td>100</td>
</tr>
<tr>
<td>$^{58}$Ni (n, $\alpha$) $^{54}$Mn</td>
<td>312.05(4)d</td>
<td>843.848(3)</td>
<td>99.976</td>
</tr>
<tr>
<td>$^{58}$Ni (n, x) $^{56}$Co</td>
<td>77.233(27)d</td>
<td>846.771</td>
<td>99.94(3)</td>
</tr>
<tr>
<td>$^{63}$Cu(n, $\alpha$) $^{59}$Fe</td>
<td>44.495(9)d</td>
<td>1099.245(3)</td>
<td>56.5(18)</td>
</tr>
<tr>
<td>$^{181}$Ta(n, 2n) $^{180}$gTa</td>
<td>8.154(6)h</td>
<td>93.4(2)</td>
<td>4.51</td>
</tr>
<tr>
<td>$^{181}$Ta(n, p) $^{181}$Hf</td>
<td>42.39(6)d</td>
<td>482.18(9)</td>
<td>80.5(4)</td>
</tr>
<tr>
<td>$^{181}$Ta(n, x) $^{180}$Hf</td>
<td>5.47(4)h</td>
<td>332.275(11)</td>
<td>94.1(12)</td>
</tr>
<tr>
<td>$^{181}$Ta(n, $\alpha$) $^{178m}$Lu</td>
<td>23.1(2)min</td>
<td>426.36(5)</td>
<td>97.0(18)</td>
</tr>
<tr>
<td>$^{181}$Ta(n, $\alpha$) $^{178g}$Lu</td>
<td>28.4(2)min</td>
<td>1340.8(2)</td>
<td>3.42(16)</td>
</tr>
<tr>
<td>$^{184}$W(n, $\alpha$) $^{181}$Hf</td>
<td>42.39(6)d</td>
<td>482.18(9)</td>
<td>80.5(4)</td>
</tr>
<tr>
<td>$^{186}$W(n, $\alpha$) $^{183}$Hf</td>
<td>8.7(1)h</td>
<td>252.85(4)</td>
<td>43(3)</td>
</tr>
<tr>
<td>$^{184}$W(n, p) $^{184}$Ta</td>
<td>1.067(17)h</td>
<td>783.753(21)</td>
<td>66(9)</td>
</tr>
<tr>
<td>$^{186}$W(n, x) $^{185}$Ta</td>
<td>49.4(15)min</td>
<td>177.59(10)</td>
<td>25.7(10)</td>
</tr>
</tbody>
</table>

High purity metallic chromium, nickel, copper, tantalum and tungsten samples with natural abundances supplied by Goodfellow Metals, Cambridge, UK were employed in these measurements. Information about the sample masses and dimensions is given in Table 1. The irradiations were carried out at the 7 MV Van de Graaff accelerator at IRMM, Geel. Quasi mono-energetic neutrons with energies between 14.8 and 20.5 MeV were produced via the $^3$H(d, n)$^4$He reaction ($Q = 17.59$ MeV) employing a solid-state Ti:T target (2 mg/cm$^2$ thick)
on a silver backing (0.4 mm thick) at incident deuteron energies of 1, 2, 3 and 4 MeV. The samples, each sandwiched between monitor foils, were placed at angles between 0° and 75° relative to the incident deuteron beam and at a distance between 4 and 7 cm from the centre of the target depending on the size of the sample. A long-counter operated in multichannel-scaling acquisition mode was used to record the time profile of the neutron flux during the irradiation in order to correct for fluctuation of the flux.

The neutron energy and yield distributions as a function of deuteron energy and emission angle were determined by the program code EnergySet that is based on the cross sections of DROSG-2000 of IAEA, version 2.1 and the stopping powers of Ziegler.

The neutron fluence rate was determined by the \( ^{27}\text{Al}(n, \alpha)^{24}\text{Na} \) ENDF/B-VI.6 standard cross section. To account for the contribution of the low energy neutrons the neutron flux density distributions were determined by the spectral index method that involves the \( ^{115}\text{In}(n, \gamma)^{115}\text{mIn}, ^{58}\text{Ni}(n, p)^{58}\text{Co}, ^{27}\text{Al}(n, p)^{27}\text{Mg}, ^{27}\text{Al}(n, \alpha)^{24}\text{Na}, ^{56}\text{Fe}(n, p)^{56}\text{Mn} \) and \( ^{93}\text{Nb}(n, 2n)^{92}\text{mNb} \) dosimetry reactions with distinct energy thresholds combined with results from time-of-flight spectrum measurements.

The radioactivity of the samples was measured by \( \gamma \)-ray spectrometry. A HPGe detector with 100 % relative efficiency was used. The data acquisition was controlled by the Maestro software, and the \( \gamma \)-ray spectra were analysed by the Genie-2000 spectrometry software. Standard point sources were used for detector efficiency calibration. A fitting of experimental values with empirical functions provides accuracy of 2.5 to 5 % for conventionally used sample geometry. To achieve higher geometry flexibility and better accuracy for extended samples, Monte Carlo simulations of the full-energy peak and total efficiencies of the detector in the energy range 60-1500 keV were performed with the MCNP code.

The cross sections were determined by the well known activation formula. The measured \( \gamma \)-ray count rates were corrected for \( \gamma \)-ray abundance, \( \gamma \)-ray self-absorption, efficiency of the detector, coincidence summing effects, irradiation and measurement geometry, neutron flux fluctuation during the irradiations and secondary neutrons.

The experimental results of this work are shown graphically in Figs. 1 and 2.

The \( ^{50}\text{Cr}(n, x)^{48}\text{V}, ^{58}\text{Ni}(n, p\alpha)^{54}\text{Mn}, ^{58}\text{Ni}(n, x)^{56}\text{Co} \) and \( ^{63}\text{Cu}(n, p\alpha)^{59}\text{Fe} \) reaction cross sections (Fig. 1):

Due to the generally low cross sections for \((n, t)\) or multiple charge particle emission cross sections in the investigated energy range, care was taken for possible interference with reactions that occur on impurities in the sample provided by the supplier. The threshold of the reactions which contribute to the \( ^{48}\text{V} \) production from \( ^{50}\text{Cr} \) are 12.9 MeV for \((n, t)\), 19.3 MeV for \((n, nd)\) and 21.6 MeV for \((n, 2np)\) reactions respectively. So we can consider the \( ^{50}\text{Cr}(n, x)^{48}\text{V} \) reaction as a pure \((n, t)\) reaction in the investigated energy range. Our results for the \( ^{50}\text{Cr}(n, x)^{48}\text{V} \) reaction are in a very good agreement with EAF-2005 and TALYS calculations. The new results for the \( ^{58}\text{Ni}(n, p\alpha)^{54}\text{Mn} \) reaction agree with the data of Fessler et al. [2] and the EAF-2005 evaluation [3]. Regarding the \( ^{58}\text{Ni}(n, x)^{56}\text{Co} \) reaction the potential interference comes from the \( ^{58}\text{Ni}(n, 3n)^{56}\text{Ni} \) and \( ^{58}\text{Ni}(n, 3p)^{56}\text{Mn} \) reactions. Both reactions were discarded.
because the threshold of the first one is 22.9 MeV and the contribution from the second reaction will be low due to Coulomb barriers. The experimental data for the $^{58}\text{Ni}(n, x)^{56}\text{Co}$ reaction around 14 MeV split into two groups. Our results are in agreement with the data of Sudar et al. [2] and Katoh et al. [2]

Impurities of Fe, Co and Ni in the Cu sample can contribute to the production of $^{59}\text{Fe}$ by the $^{58}\text{Fe}(n, \gamma)^{59}\text{Fe}$, $^{59}\text{Co}(n, p)^{59}\text{Fe}$, and $^{62}\text{Ni}(n, \alpha)^{59}\text{Fe}$ reactions respectively. However there were no traces found from the activities produced by other high cross section reactions on the above mentioned elements in the measured spectra.

The neutron-induced reaction cross sections on W and Ta isotopes (Fig. 2):

Unique data above 14 MeV were produced for the $^{181}\text{Ta}(n, x)^{180}\text{Hf}$, $^{181}\text{Ta}(n, \alpha)^{178m}\text{Lu}$, $^{181}\text{Ta}(n, \alpha)^{178}\text{Lu}$, $^{184}\text{W}(n, \alpha)^{181}\text{Hf}$, $^{186}\text{W}(n, \alpha)^{183}\text{Hf}$, and $^{184}\text{W}(n, p)^{184}\text{Ta}$ reactions. Our results are in agreement with most of the data from other authors at 14 MeV for the $^{184}\text{W}(n, \alpha)^{181}\text{Hf}$, $^{186}\text{W}(n, \alpha)^{183}\text{Hf}$, $^{184}\text{W}(n, p)^{184}\text{Ta}$, $^{181}\text{Ta}(n, x)^{180m}\text{Hf}$ and $^{181}\text{Ta}(n, \alpha)^{178m}\text{Lu}$ reactions. Measurements using both enriched and natural W are on-going at the IRMM Van de Graaf laboratory. Concerning the $^{181}\text{Ta}(n, \alpha)^{178}\text{Lu}$ reaction cross sections the results from this work agree with the EAF-2005 evaluation and the shape of the excitation curve agree with the data around 14 MeV. The new data tend to agree better with the data of Lu Hanlin et al. [2] both for the $^{181}\text{Ta}(n, 2n)^{180}\text{Ta}$ and $^{181}\text{Ta}(n, p)^{181}\text{Hf}$ reaction cross sections.
Fig. 2: Comparison of experimental cross sections for the indicated reactions with evaluated data and TALYS-0.57 calculations


NUDAME - NUclear DAta MEasurements
NUDAME Euratom Transnational Access programme

W. Mondelaers

The combination of the two accelerator facilities at IRMM offers unique neutron data research capabilities over a wide energy range from a few meV to about 24 MeV. The IRMM is one of the few laboratories in the world which is capable of producing neutron data with the required accuracy for studies of waste transmutation and innovative nuclear energy systems. Therefore, the IRMM facilities provide an excellent opportunity for trans-national collaborations.

To facilitate for outside users the access to the facilities, a project ‘NUclear DAta MEasurements at IRMM’ (NUDAME) has been launched within the framework of the Euratom Trans-national Access programme. Experiments in the areas of radioactive waste management, radiation protection and other activities in the field of nuclear technologies and safety at the IRMM facilities can be supported. The proposals for experiments are peer-reviewed by a Programme Advisory Committee (PAC), composed of international experts in the fields of interest. Approved experiments get the necessary beam time and the same scientific, logistical and technical support provided to all researchers of the Institute. The user groups are also (partly) supported for their travel and the subsistence costs during the time required conducting the experiment. More information can be found on the NUDAME website (http://www.irmm.jrc.be/html/homepage.htm).

The NUDAME project is running from April 1, 2005 until March 31, 2008. For each year of the project a Call for Proposals has been launched. Recently, the PAC decided on the experiments for the third and last year, so that the overall interest generated by the project can already be assessed. The majority of the proposed measurements are of high importance and have a high priority in the research fields of interest. Within the NUDAME budget, it was possible to offer for the whole duration of the project a maximum of 3000 supplementary data-taking hours to new external users. The requested beam time largely exceeded the time that could be made available. Despite the fact that the scientific quality of the proposed experiments was in general very high, the PAC could endorse only 43 % of the beam time requested by the external users. Out of 22 proposals 18 experiments have been approved, but with a drastically reduced beam time. 7 experiments have been performed up to now and the data are analysed.

Until the end of 2006, the following experiments have already been performed in the framework of NUDAME:

- High-resolution capture and transmission measurements of $^{\text{nat}}$Hf (G. Noguère, CEA Cadarache) - two weeks of beam time at the GELINA facility

- $^{243}$Am(n, f) in the 0.7 - 10 MeV energy range (B. Jurado, CENBG) - two weeks of beam time at the Van de Graaff facility
• Experimental validation of a multi-sphere spectrometric system used for radiation protection applications around high-energy electron accelerators and medical linacs (R. Bedogni, INFN) - one week of beam time at the Van de Graaff facility.

• Capture and Transmission on $^{nat}$Cd (A. Trkov, IAEA) - two weeks of beam time at the GELINA facility.

• Test of data acquisition with C$_6$D$_6$ detectors using fast signal digitisers (G. Tagliente, INFN Bari) - one week of beam time at the GELINA facility.

• Fission decay of shape isomer in $^{235}$U (A. Oberstedt, Örebro) - two weeks of beam time at the Van de Graaff facility.

• Sort-lived activation cross-sections on $^{206,207}$Pb (A. Pavlik, Vienna) - one week of beam time at the Van de Graaff facility.

The following experiments have been approved by the NUDAME-PAC and will be performed before the end of 2007:

• $^{233}$U capture-to-fission ratio (B. Jurado, CENBG Bordeaux) - two weeks of beam time at GELINA.

• $^{235}$U(n, 2n) (Ph. Dessagne, IReS Strasbourg) - one week of beam time at GELINA.

• Validation of $^3$He counter and Bonner spheres (C. Domingo, Barcelona) - one week of beam time at the Van de Graaff accelerator.

• $^{241}$Am(n, 2n) measurements (O. Bouland, CEA Cadarache) - two weeks of beam time at the Van de Graaff facility.

• Leakage spectrum measurements on Pb and Bi (J. Csikai, Debrecen) - two weeks of beam time at the Van de Graaff facility.

• Capture cross section measurements of isotopic enriched Hf samples (C. Dean, Serco Winfrith) - two weeks of beam time at GELINA.

• Measurement of the $^{235}$U(n, n$'$γ) and $^{235}$U(n, 2nγ) reaction cross sections (Ph. Dessagne, IReS Strasbourg) - two weeks of beam time at GELINA.

• Accurate measurement of neutron cross sections of the tungsten stable isotopes (S. Marrone) - two weeks of beam time at GELINA.

• Population of super-deformed ground state in $^{235}$U - a feasibility study (A. Oberstedt, Örebro) - two weeks of beam time at GELINA.

• Very short-lived activation cross sections from inelastic scattering in $^{206,207}$Pb (A. Pavlik, Vienna) - two weeks of beam time at the Van de Graaff facility.

• Testing and calibration of neutron dosemeters for radiation protection in the nuclear industry and space applications (F. Vanhavere, SCK•CEN) - one week of beam time at the Van de Graaff facility.
Inspired by the success of NUDAME a proposal for an Integrated Infrastructure Initiative has been launched by the experimental nuclear data community. The I3 Project proposal entitled: ‘European Facilities for Nuclear Data Measurements’ (acronym: EFNUDAT) aims at creating a consortium of European experimental facilities for nuclear data measurements. The proposal has been evaluated positively and the project started on November 1, 2006. The EFNUDAT consortium groups 10 partner institutes equipped with nuclear data research infrastructures. The aim of EFNUDAT is to integrate all infrastructure-related aspects of nuclear data measurements by organising Networking Activities, Trans-national Access Activities and Joint Research Activities to raise the performance of the facilities and the efficiency of their use. External scientists can get support to perform experiments at one of the EFNUDAT facilities, or they can be supported for short-term visits at one of the EFNUDAT institutes. For more information consult the EFNUDAT website (http://www.efnudat.eu).
Very short-lived activation cross sections from inelastic scattering on $^{206}$Pb


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Neutron inelastic scattering and $(n, xn)$ cross sections are of importance to lead cooled reactors and subcritical accelerator driven systems. Such reactions have been investigated with the $(n, xn\gamma )$ technique at the GELINA facility for several target isotopes [1, 2, 3] amongst them $^{206}$Pb [3, 4]. For inelastic neutron scattering on $^{206}$Pb an isomer (11$^{th}$ excited state of $^{206}$Pb, $E_x = 2200$ keV, $J^\pi = 7^-$, $T_{1/2} = 125$ $\mu$s, see Fig. 1) plays an important role. The production cross section of this isomer cannot be measured by the technique of detecting promptly emitted gamma rays. But this isomer carries a significant part of the inelastic cross section and it is therefore of importance to verify the model predictions for the $^{206}$Pb$(n, n')$ reaction. To complement the prompt gamma ray emission measurements performed at the GELINA facility we intend to measure the $^{206}$Pb$^{206m}$Pb cross section at the IRMM’s Van-de-Graaff facility by observing the decay of the 7$^-$ isomer. Due to the short half-life of

![Figure 1: Partial level scheme of $^{206}$Pb](image-url)
only 125 \( \mu s \) it is not possible to transport the activated sample from the irradiation position to the detector. Leaving the sample in place and using the beam chopper at the Van-de-Graaff facility [5], measurement cycles consisting of short activation periods followed by short periods for activity measurement are possible. The activity measurement is performed when the accelerated particle beam is deflected off the neutron production target. The method was tested during one week beam time and data were taken for three different neutron energies (5.07 MeV, 6.15 MeV, and 7.18 MeV). A 40 \% relative efficiency HPGe detector was placed at 47 cm distance from the sample, which itself was positioned at a distance of 44 cm from the neutron production target at an irradiation angle of 0 degrees. The detector was placed at 90 degrees with respect to the deuteron beam axis and shielded by a shadow bar. Below the threshold of the \( ^{207}\text{Pb}(n, 2n) ^{206}\text{Pb} \) reactions there are no interfering reactions from other lead isotopes and samples of natural isotopic composition may be used. The sample was a stack of 5 to 10 disks of 10 cm diameter and 1 mm thickness each. Neutrons were produced via the \( \text{D(d, n)}^3\text{He} \) source reaction using a deuterium gas-cell as neutron production target. The beam chopper was set in such a way that cycles of 250 \( \mu s \) irradiation time were followed by 500 \( \mu s \) time to observe the decay of the isomer. To determine the neutron fluence we used the IRMM proton-recoil telescope [6]. In addition activation foils were mounted on the sample and the neutron fluence was monitored by a BC-501 liquid scintillator and a long counter. Conventional electronics was employed for these measurements (ADC for recording of the pulse height and time coder for measuring the time from the start of the irradiation, defined by the chopper control signal). We could clearly identify the 803-keV transition both during the irradiation (mainly prompt emission) and after the irradiation (decay of the isomer). Figure 2 shows the gamma-ray spectra obtained during the activation and during the decay of the isomer for \( E_n = 6.15 \) MeV.
Fig. 3: Decay curve for the 803-keV gamma line intensity following neutron-capture with an incident energy $E_n = 6.15$ MeV

The intensity distribution of the net peak contents of the 803-keV line as a function of the time during the beam-off cycles is shown in Fig. 3. The exponential decay can be fitted assuming a half-life of 125 µs (red curve in Fig. 3); a fit with the decay constant as a free parameter results in a half life of 136 µs. Gas-out measurements were done under identical conditions for the same deuteron energies. They did not show any lines at or near 803-keV, but are an important check for possible background contributions.

A detailed analysis of the measurement is in progress, but the already available results demonstrate the feasibility of such short-time activation experiments using the beam chopper at the Van-de-Graaff facility of IRMM.


[3] L. C. Mihailescu, *Neutron (n, xn\gamma) cross-section measurements for \textsuperscript{52}Cr, \textsuperscript{209}Bi and \textsuperscript{206,207,208}Pb from threshold up to 20 MeV*, Doctoral Thesis, University of Bucharest 2006.


Quasi-absolute neutron-induced fission cross section of $^{243}$Am

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$^{243}$Am is present in a rather important amount in the waste generated by current pressurized water nuclear reactors (PWR). Nowadays, $^{241}$Am and $^{243}$Am are the only isotopes that can be fully separated and extracted from spent fuel rods. Therefore, they represent the only nuclei for which fast neutron incineration could be seriously considered in a relatively near future. A reliable design of incineration reactors requires the precise knowledge (around 5 % of accuracy) of the neutron-induced fission cross section of $^{243}$Am in a fast neutron spectrum. However, in the 1 to 6 MeV neutron-energy range, the existing data indicate significant discrepancies and could be segregated into two distinct groups. The most recent data from Laptev et al. [1] lie in the higher-cross section group which is more than 15 % above evaluations and older values by Knitter et al. [2]. Actually, this discrepancy seems to be related to a normalisation problem [3] due to the difficulty in determining precisely the neutron flux. In order to solve this controversy, we have performed for the first time a quasi-absolute measurement of the $^{243}$Am neutron-induced fission cross section. Most of the fission data on $^{243}$Am have been measured in reference to the $^{235}$U neutron-induced fission cross section. In our case we have used the neutron-proton scattering cross section as a reference reaction to determine the incident neutron flux. While for the $^{235}$U fission cross section the dispersion between available data is 5 %, the neutron-proton scattering cross section is known with a precision better than 1 % for a wide range of neutron energies (1 meV to 20 MeV [4]). This high precision explains why we can call our measurement 'quasi-absolute'.

The experiment was performed at the VdG-driven neutron source of the IRMM. The T(p, n)$^3$He reaction was used to produce neutrons with energies ranging from 1 to 4 MeV and the D(d, n)$^3$He reaction to produce neutrons in the 4 to 8 MeV energy range. Two $^{243}$Am targets each of about 550 $\mu$g/cm$^2$ thickness where placed back-to-back in between two sets of photovoltaic cells. The cells allowed detection of fission fragments with an efficiency of approximately 70 %. A 50 $\mu$m thick polypropylene foil was placed at 45 mm from the $^{243}$Am targets. This foil served as a radiator to convert neutrons into protons. Protons recoiling from the polypropylene foil were detected by means of a Si telescope located at 75 mm from the foil. The ensemble polypropylene-telescope formed our neutron detector.

Preliminary results for the fission cross section determined in this experiment are displayed in Fig. 1. Our results are in agreement with the international evaluations and the data of Knitter et al. [2]. Consequently, our data indicate that the latest results of Laptev et al. [1] overpredict this cross section. The overall precision of our data is 4 %. These results will be completed...
Fig. 1: Preliminary fission cross section of $^{243}$Am as a function of neutron energy in comparison with other data and with the JENDL and ENDF evaluations

at the CENBG where we will perform measurements at the fission threshold and between 3.5 and 5 MeV. In addition, we will use the statistical code of the CENBG to perform our own evaluation of this cross section. In that way, fundamental fission parameters such as fission barrier heights and curvatures will be determined. These parameters can then be used to infer other neutron-induced cross sections that are much more difficult to measure like capture, inelastic and (n, 2n) cross sections.

Acknowledgements
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Search for the fission decay-mode of the super-deformed ground state in $^{235}\text{U}^*$

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Since the early 1960s many fission isomers have been discovered in nuclei ranging from $^{236}\text{U}$ to $^{245}\text{Bk}$ [1]. Their existence is a consequence of the appearance of a second minimum in the potential energy surface of actinide nuclei, as firstly described by Strutinsky [2] as the superposition of microscopic shell corrections in a nuclear potential to the nuclear binding energy, varying periodically with deformation, and the unstructured macroscopic part of the deformation energy usually described by the liquid-drop model. One of the persisting problems still today is the lack of any shape-isomer half-life data for odd-N uranium and neptunium isotopes. Only for $^{239}\text{U}$ the population of the super-deformed (SD) ground state in a neutron-induced capture experiment was observed [3, 4]. Since for these isotopes fission half-lives are expected to be in the order of several hundreds of $\mu$s or even longer, the detection with commonly used pulsed particle beams is very difficult. It is even more difficult in neutron-induced reactions, where the environmental background created from sub-sequent pulses is extremely disadvantageous. Together with the extremely low production cross-section for shape isomers, typically of the order of a few $\mu$b, as well as half-life predictions ranging in some cases over five orders of magnitude leaves the measurement of shape-isomer decay data to a challenging venture for the experimentalist.

However, a recent theoretical work [5], giving reliable predictions for half-lives for isomeric fission in the reaction $^{234}\text{U} + n$, motivated an experiment, which was applied for and which was granted within the NUDAME programme at IRMM. The first results are presented in this report.

The experiment was performed with the NEw Pulsed and TUneable NEutron source NEPTUNE, which was designed as isomer spectrometer and installed recently at IRMM [6]. The 7 MV Van de Graaff accelerator created neutron beams with $E_n = 0.95$ and 1.27 MeV, that were used at repetition frequencies of 100 Hz and 50, 100 as well as 150 Hz, respectively. In all cases the duty cycle was chosen to be 0.30. The working principle is based on the deflection of the charged-particle beam prior to hitting the neutron production target. The neutrons impinged on the targets, placed in the center of a twin Frisch-grid ionization chamber with common anode (cf. Fig. 1). On the side closest to the beam a 1.364 mg $^{234}\text{U}$ sample was mounted, whose contamination with $^{235}\text{U}$ was less than $9 \times 10^{-4}$. On the backside a $^{235}\text{U}$ sample with mass 2.38 mg was placed in order to serve as monitor for room-scattered and thermalized neutron induced fission. For the monitoring of direct and scattered neutrons a NE213 scintillator was placed in beam direction, allowing for neutron-gamma separation by employing the pulse-shape discrimination technique. The timing information for both fission events and neutron detector signals was obtained by the interval between the start of a neutron
Fig. 1: Sketch of the experimental set-up: a twin Frisch-grid ionization chamber with common anode was loaded with a 1.364 mg $^{234}$U sample (close to the beam) and a 2.38 mg $^{235}$U sample.

pulse and the registration of the corresponding particle. The fission fragment pulse-heights were corrected for angular dependent energy loss. Fig. 2 shows the distribution of the timing signals of delayed fission events from $^{234}$U(n, f) versus pulse height. The projection onto the pulse height axis is shown on the left hand side of Fig. 3. To our knowledge, it is the first time an energy spectrum from the isomeric fission of $^{235}$U* was measured. It is compared to the prompt fission fragment pulse height spectrum from the same system. During two weeks of beam time, the observed number of fission events for the system $^{234}$U+n was 55, when the neutron beam was deflected, and $8.865 \times 10^6$ with beam on target. For the system $^{235}$U+n the corresponding numbers were 8789 and $1.588 \times 10^6$, respectively. The first number denotes obviously those fission events that were caused by scattered neutrons as well as spontaneous fission. Taking the amount of $^{235}$U atoms in the $^{234}$U sample into account, one may correct the numbers above for the system $^{234}$U+n to those attributed to $^{234}$U only. This results in about 50 observed isomeric fission events, compared to about $8.864 \times 10^6$ prompt fission events. From the ratio of both numbers, one may deduce a lower limit for the population probability for the super-deformed ground state in $^{235}$U, $P_{iso} \approx 6 \times 10^{-6}$. A more detailed data treatment, also in order to determine the half-life for isomeric fission is in progress. Two of the authors (A. O. and M. G.) would like to gratefully acknowledge both the financial and scientific support within the NUDAME programme at IRMM.


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Fig. 2: Time versus pulse height of delayed fission events from the reaction $^{234}\text{U}(n, f)$.

Fig. 3: Pulse height spectra for isomeric (left hand side) and prompt (right hand side) fission of $^{235}\text{U}^*$. 

Experimental validation of a multi-sphere spectrometric system used for radiation protection applications around high energy electron accelerators

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The variability of the response of neutron sensitive instruments with the neutron energy constitutes one of the main concerns in neutron dosimetry for radiation protection. This arises from several factors, related to either the definition of the radiation protection operational quantities or practical problems in the instruments design or calibration [1]. As a consequence, two necessary conditions for accurate neutron dosimetry evaluations are

1) the knowledge of the energy dependence of the response the instruments/dosemeters and
2) the knowledge of the energy spectrum of the workplace neutron fields, achievable with a neutron spectrometer.

The availability of mono-energetic neutron fields at the Van de Graaff facility of the EC-JRC-IRMM constitutes a rare opportunity for testing radiation protection neutron sensitive instruments.

With this aim, the INFN-LNF Radiation Protection Group proposed the experiment "Experimental validation of a multi-sphere spectrometric system used for radiation protection applications around high energy electron accelerators".

The instruments tested were a Bonner Sphere Spectrometer (BSS) constituted by a \textsuperscript{6}LiI(Eu) scintillator in seven polyethylene moderating configurations (2”, 3”, 5”, 8”, 10”, 12” and 12” + 1 cm Pb) and a batch of CR-39 nuclear track dosemeters. All devices are routinely used for the ambient monitoring of the neutron fields around the INFN-LNF accelerators [2, 3].

The 0.3 MeV, 2 MeV, 5 MeV, 6.5 MeV and 16 MeV mono-energetic beams from the IRMM Van de Graaff facility were used.

This experiment allowed confirming, even if in few discrete points, the mono-energetic response functions of the BSS previously derived by Monte Carlo calculation. An agreement of ±3 % between the calculated and measured mono-energetic response was obtained. In addition, a performance test was carried out on the unfolding code, FRUIT (FRascati Unfolding Interactive Tool) [4], developed by the INFN-LNF group to derive the neutron spectra from the readings of the Bonner Spheres. FRUIT is a Bayesian unfolding code that models a generic neutron spectrum as the superposition of different elementary spectra described by a limited set (less than 10) of parameters. The code was run using as only input parameters the counts of the Bonner Spheres and a qualitative suggestion on the shape of the peak, supposed to be Gaussian. The code outputs were then compared with the spectra simulated by the IRMM team taking into account the kinetic of the nuclear reactions and the real materials and geometry of the irradiation room. For all mono-energetic tests, the unfolding code determined the peak
energy and the fraction of neutron fluence under the peak with a maximum difference of ±5 %
with respect to the simulated spectra. This confirms the results of previous measurements
performed with the 2.5 MeV and 14 MeV beams from a fusion based neutron generator [5].
As far as the CR-39® nuclear track detectors are concerned, the measured dependence of
the response in terms of Ambient Dose Equivalent in the energy interval 0.3 - 16 MeV was
±60 % with a maximum at 2 MeV [6], fully in agreement with literature data taken with
similar dosemeters [7].

[1] International Commission on Radiation Units and Measurement, Determination of opera-
tional dose equivalent quantities for neutrons, Publication 66, (Bethesda, Maryland: ICRU)
energy electron-positron collider using a multi-sphere system with passive detectors, Radiat.
Prot. Dosim., accepted for publication
Meas.
high energy electron/positron collider, PhD Thesis. Universidad Autonoma de Barcelona,
Barcelona, Spain (2006); http://www.tesisenxarxa.net/TDX-1220106-103144
[5] R. Bedogni, A. Esposito, C. Domingo, F. Fernandez, M. J. Garca, M. Angelone, Per-
formance of the UAB and the INFN-LNF Bonner sphere spectrometers in quasi mono-
energetic neutron field, Radiat. Prot. Dosim., accepted for publication
New instruments and methods
Neutron spectrometry of MOX fuel rods using the DONA detector

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The DONA detector is a novel approach for measurement of environmental neutron spectra. It is based on measuring the neutron activity induced in a series of small metal disks followed by spectrum unfolding to obtain a neutron energy spectrum from the measurement site. A similar technique, usually referred to as the foil activation technique, is widely used for the characterisation of high neutron fluence rates, for example inside nuclear reactors and at neutron research institutes, see for example [1]. The DONA detector, however, is aimed for the measurement of much lower fluxes which is facilitated by using thicker disks and low-background gamma-ray detectors for measuring the activation products. The overall uncertainty is larger compared to conventional foil activation but for environmental neutron monitoring there is no reason to aim for very low uncertainties.

In this study the DONA detector, see Fig. 1, was used to measure the neutron spectrum from MOX fuel rods at the storage location of Belgonuclaire in Mol, Belgium. Two detectors were positioned on the fuel container, one on the centre of the container (position 1) and the second about 30 cm from the edge of the container (position 2). The detectors were irradiated for about 60 h followed by gamma spectrometry of the activated metal disks in the IRMM low background gamma measurement stations, and in the IRMM underground ultra-low background stations HADES.

The measured gamma data were corrected for neutron self-shielding in the disks and for neutron scattering between disks, and used as input data for spectrum unfolding using the iterative technique Gravel [2]. The “MOX fuel at storage place” spectrum, from the IAEA library of operational neutron spectra for radiation protection purposes [3] was used as default spectrum.
The unfolded spectra, see Fig. 2, agree well with the spectra obtained from the IAEA database. Particularly the spectrum measured in position 2 has a very similar structure as the "MOX fuel at storage place" spectrum. A higher lower energy component is measured which may be explained by a more shielded container used at Belgonucléaire than what is assumed by IAEA. In position 1, a spectrum is measured which do not have any spectral component above 1.2 MeV at all. The reason for this is not yet known but could, again, be a result of shielding.


Development of an energy degrader technique for light particle spectroscopy

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The unambiguous identification of light-charged particles (LCP), produced in e.g. ternary nuclear fission, is a necessary prerequisite for the full understanding of the nature of their formation. Solid state detectors, assembled as $\Delta E$-$E$ telescope, may provide a separation of atomic numbers, while time-of-flight measurements may give information of the particles’ mass. A severe disadvantage, however, is the fact that particles with low kinetic energies are stopped in the $\Delta E$-detector and, thus, remain unidentified. In addition, since the solid state detectors have to be protected from the intense flux of binary fission fragments, thin absorber foils are usually installed in front of the detectors. This makes it obviously difficult to assess the entire energy distribution, which is depicted in Ref. [1]. As an alternative, a mass-separator like LOHENGRIN at Institute Laue-Langevin (ILL) in Grenoble [2] in combination with an ionization chamber with split anode, the latter serving as $\Delta E$-$E$ telescope, may be employed. Although originally designed for binary fission fragments, also LCPs from ternary fission have been detected in the past with LOHENGRIN and mean kinetic energies and widths of their energy distributions as well as emission yields were extracted. However, in some cases the complete energy distribution was not measurable because of the kinematic limits due to maximum electric field settings of LOHENGRIN. In order to make practically the entire energy spectrum of some of the lightest ternary particles accessible, we suggest applying an energy degrader foil (e.g. nickel) of appropriate thickness into the particle beam between target and spectrometer entrance to reduce the initially high kinetic energies. Below we discuss the influence of the energy degrader on the measured particle spectra and present results from a Monte-Carlo simulation that shows how the original energy distributions are reconstructed. Finally, we apply this procedure to experimental data.

From the choice of energy, corresponding to the spectrometer’s field settings for a given ionic charge state and the properties of the degrader material, the kinetic energy, with which the particles were emitted in the fission process, can be calculated according to their energy loss in the degrader foil. The use of an energy degrader affects the particle beam in two ways: for one, the particles will have a reduced kinetic energy before they enter the spectrometer; secondly, due to the constant energy acceptance of the mass separator $\delta E/E$, less particles pass the separator because of their lower kinetic energy. As a consequence, we expect to observe a reduced yield at a reduced energy in the spectrum. Fig. 1 shows the result of a Monte-Carlo simulation starting from a typical distribution. We have chosen a Gaussian with the following characteristics: a mean energy of 15 MeV, a width of about 11 MeV (FWHM), and 1000 particles. The full drawn line shows the energy distribution and the full black circles the randomly obtained yield, i.e. number of particles per energy unit, for selected energies. For the energy loss we assume that events with $E < 12$ MeV are stopped, while those with $E = 30$ MeV leave the degrader foil with $E_{\text{res}} = 24$ MeV. According to results of energy
loss calculations performed with the computer code SRIM [3], the residual energy for incident energies between 12 and 30 MeV may be obtained by linear extrapolation. If one calculates now the residual energies behind the degrader for each event and determines their number per MeV, one obtains the distribution shown as open diamonds in Fig. 1. Moving these points to their correct, i.e. initial, energies results in the open circles. Obviously, the yields are underestimated, which is due to the fact that the spectrometer lets through fewer particles with reduced energy than it would be the case without energy degrader. This effect can be corrected for by multiplying these yields with the energy ratio $E/E_{\text{res}}$ at a given energy $E$. However, the transformation from $E_{\text{res}}$ to $E$ in the Fig. 1 leads to an effective bin size that is less than 1 MeV. Hence, the yields have to be multiplied as well by the derivative $dE/dE_{\text{res}}$. Due to the fact that particle lose more energy the less energy they have, this derivative is less than 1. Applying both corrections and binning around the same energies as indicated by the black dots leads finally to the original energy distribution, now shown as grey dots. We observe a very nice agreement, of course only for events with energies large enough to pass the degrader foil. In the following section we apply the method described above to the measured energy spectrum of $^7$Li produced in the reaction $^{235}$U$(n_{th}, f)$.

High-resolution measurements of ternary particles produced in the thermal neutron-induced fission of $^{236}$U* were performed at the high-flux reactor at ILL ($\Phi_n = 5.4 \times 10^{14}$ cm$^{-2}$ s$^{-1}$). The target consisted of $^{235}$UO$_2$ of 500 $\mu$g/cm$^2$ thickness and a size of 7.0 $\times$ 0.5 cm$^2$. In order to extend the kinetic energy of the LCPs measurable with the mass-separator LOHENGRIN, we introduced a 10 $\mu$m thick Ni-foil as energy degrader. The details about this experiment as well as the presentation of all results will be found elsewhere [4], here our intention is to demonstrate the value of the degrader technique. Fig. 2 shows the measured energy
distribution of $^7$Li. The experimental data were corrected for target burn-up, energy loss and ionic charge state distribution according to the procedures described e.g. in Ref. [5]. The Li-ions were measured for charge states $q=3^+$ and $2^+$, depicted in Fig. 2 as open circles and open squares, respectively. The full circles show the total yield, integrated over all ionic charge states.

All data obtained without energy degrader are shown in black, the ones taken with energy degrader are depicted in grey. The thick, full drawn line corresponds to a Gaussian fitted to all experimentally obtained yields. The full drawn and dotted lines indicate the calculated contributions of $^7$Li$^{3+}$ and $^7$Li$^{2+}$, respectively, whereas the $^7$Li$^{1+}$ contribution is hardly visible (dashed lines). The error bars contain statistical errors and, in case the energy degrader was used, systematic uncertainties from the different corrections applied. In the latter case an uncertainty in energy was estimated from the linear fit to the $E-E_{res}$ dependence calculated with SRIM [3]. In comparison, the energy uncertainty due to energy straggling is of the order of less than 1 % of the particle’s incident energy in the Gaussian limit and may be neglected. Again we refer to the detailed description in Ref. [4]. The degrader data shown as open symbols are already shifted to the correct energies and correspond, thus, to the open circles in Fig. 1. The yields were then corrected as described in the previous chapter. The excellent agreement between data taken with and without energy degrader is obvious, particularly in the region from 13 to 15 MeV, where an overlap exists between both sets of data. Furthermore, even the symmetric shape of the Gaussian for both the low and the high-energy tail of the spectrum makes us confident in the presented energy degrader technique.

We have presented an experimental technique to increase the kinematical limits of mass sep-
arators in general by using an energy degrader that reduces the kinetic energies of an entering particle beam. By means of Monte Carlo simulations the effect of the energy degrader on a measured energy distribution was demonstrated and explained. We have also shown how the original energy distribution easily is constructed from the observed, distorted one. The only information that is required is the dependence between initial and residual energy, which may be determined by energy loss calculations. Hence, the energy degrader technique offers the possibility for new, precise measurements of the essentially complete energy distributions of LCPs. Further details may be found in Ref. [6].


Commissioning of a new setup for neutron inelastic scattering measurements at GELINA

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The inelastic neutron-nucleus interaction produces gamma radiation and reduces the energy of the incident particle. Its cross section accounts for a significant part of the total interaction cross section and therefore, its knowledge is important for numerous applications. We refer to the total inelastic cross section but also to the gamma and level production cross sections which are of importance e.g. for radioprotection shielding calculations. Additionally, the \((n, 2n\gamma)\) and occasionally the \((n, 3n\gamma)\) channels are investigated.

During the last years a neutron inelastic scattering measurement program running at the GELINA time-of-flight facility of IRMM produced very precise high resolution nuclear data on \(^{52}\text{Cr}, ^{58}\text{Ni}, ^{206,207,208}\text{Pb}\) and \(^{209}\text{Bi}\). The typical uncertainty of the main cross sections was of the order of 5\%. However, the duration of a data-taking campaign was of about two months. Taking into account the success of the previous measurements and the need for new improved data, we decided to increase the detection efficiency by upgrading the setup. Two major possibilities exist: the increase of the number of detectors and the upgrade of the acquisition system. We addressed both these approaches. The measurement takes place in the cabin situated on Flight path 3 of GELINA at a distance of 200 m from the neutron source. The neutron bursts have a frequency of 800 Hz and an energy range from 134 eV to about 25 MeV. HPGe detectors are used to detect the gamma radiation emitted by the investigated sample. The energy and the timing of the detected gammas are both recorded and time-of-flight - \(\gamma\) energy matrices are built and analysed in order to extract the differential gamma production cross section for each energy of the neutrons. Setting the angular position of the detectors to 110\(^\circ\) and 150\(^\circ\) allows for an optimal accounting of the angular distribution of the emitted gammas and therefore a simple angular integration procedure. Further, the level cross sections and the total inelastic cross section are deduced, based on the known level structure of the sample.

An essential limitation of the conventional acquisition system is related to the gamma flash that is produced by the incident electron beam in the neutron source via bremsstrahlung. This
very intense gamma radiation precedes the neutron burst and, if detected, it induces a dead
time in the detection system equal to almost the entire time spread of the neutron burst. The
solution applied in the past was to block all signals whose timing corresponds to the arrival of
the gamma flash at 200 m. If a detector senses a gamma flash, the corresponding beam burst
is completely disregarded by that detector. The timing of the conventional detection system
is shown in Fig. 1. However, this procedure induces a decrease of the detection efficiency
of the order of 15 %. As already mentioned, two approaches were taken into account in
order to increase the detection efficiency: the increase of the number of detectors and the
migration towards a digitised system that would allow us to overcome to a certain extent the
gamma-flash limitation.

During the last years, the experiments used two, three or four HPGe detectors, placed in
a horizontal plane at 110° and 150° scattering angle with respect to the incoming beam.
Backward angles are preferred in order to reduce the gamma flash detection probability. In
order to further increase the number of detectors, an aluminium frame that can hold up to 12
detectors was designed. It is shown in Fig. 2.

Out of the 12 positions, 8 cover the 110° and 150° angles in the horizontal and vertical planes.
The 4 remaining positions correspond to scattering angles of 125° and are of interest only for
studies of the angular distribution of the gamma rays. Presently, the number of detectors was
extended from four to six and a further upgrade is foreseen to eight detectors. The acquisition
electronics can now accommodate eight detectors. An effort was made during the last years
for the migration towards a digitised acquisition system. We currently use four digitiser cards Acquiris DC440, capable to record $420 \times 10^6$ samples of 4 Mbytes per second. Each digitiser card has two data inputs. The timing scheme of the digitised acquisition is shown in Fig. 3. We typically record a trace of $10^5$ samples of 2.38 ns each directly from the preamplifier of the detector. Each card is triggered only when a signal is present in the time region of interest. Then the trace is transferred to a PC where dedicated software performs the analysis.

Choosing the trigger and the digitiser intervals as shown in Fig. 3, the digitiser is triggered only when a signal is present in the region of interest and avoids triggering on the (very intense) gamma flash. Following this procedure we do not have to eliminate from the analysis the traces containing a coincidence between a neutron-induced event and a gamma flash. This increases the efficiency of the digitised acquisition by about 15 %, while the electronics used for the trigger signal remain very simple compared to those used for the conventional acquisition. An increased reliability is expected as a consequence of reduced number of electronic modules.

The commissioning of the new setup is now finalised and a data taking campaign started for a $^{nat}$Fe sample. For the moment, the conventional and the digitised systems work in parallel. However, as soon as the reliability and compatibility tests of the digitised acquisition will be concluded, we will eliminate completely the conventional one. Fig. 4 displays an online amplitude spectrum acquired by one of the digitizers for the $^{nat}$Fe(n, n'$\gamma$) reaction.

In conclusion, the setup for neutron inelastic scattering measurement at GELINA underwent major upgrades. The number of detectors is extended from four to eight, six being already in
place. The acquisition system migrates towards digitisation, providing a better handling of the
gamma flash together with much simplified electronics. The higher efficiency will have impact
on the duration of the experiments and consequently on the stability of the system during one
experiment. This setup will provide highly reliable results and will become a "data factory"
for the present and future applications and could also be used as a powerful spectroscopic tool
for improving the knowledge of the structure of the studied nuclei. Once the commissioning
period finished, the setup will become available also as a user facility for external collaborators.
Monte Carlo simulations for the new array of C$_6$D$_6$ detectors for capture cross section measurements at GELINA

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$^3$ CEA Sclay, DAPNIA/SPhN F-91911 Gif-sur-Yvette
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Capture cross section measurements at the Geel linear accelerator GELINA rely on the so-called total energy method. This principle implies the use of a low $\gamma$-ray detection efficiency that is proportional to the $\gamma$-ray energy. Thus, an efficiency for a capture event is obtained that is independent of the decay cascade and hence of the resonance.

At GELINA, so far, a set of maximum four C$_6$D$_6$ detectors is used. The required proportionality is obtained by applying the pulse height weighting technique and C$_6$D$_6$ has the great advantage of very low neutron sensitivity. In view of the proven suitability for the determination of high accuracy capture results this will remain the system of choice at GELINA.

For the study of enriched, possibly radioactive, isotopes it was, however, found that we need to maximise detection efficiency in order to cover a wider range of cases of interest to various applications and users. Therefore an array of ten new C$_6$D$_6$ detectors in a close-packed dodecahedron geometry is being constructed, combining a low sensitivity to neutrons with a substantial increase of the detection efficiency. This will allow carrying out measurements on nuclides for which only small quantities of sample material are available, such as Am and exotic isotopes.

Effective use of the array requires precise characterisations of its detectors and of the array as a whole, for both gamma-ray and neutron sensitivity. Here, results of Monte Carlo simulations using MCNP will be shown concerning responses to monoenergetic photons point sources and neutron sensitivity. In a later stage the impact of gamma-coincidences will be studied and the array will be commissioned by studies on well known materials and on $^{241}$Am. Indeed the capture measurements planned on $^{241}$Am are included in a large project of differential measurements in progress through an IRMM Geel - FZK Karlsruhe - BNC Budapest - CEA France collaboration. The final objective is a very high precision in the measurements which can be reached by such a new efficient apparatus in capture [1].

The first step for the modelling of the detector geometry is the transcription of the detectors geometry in the language of the simulation code. A detector is composed of two parts: a C$_6$D$_6$ Aluminium container and a photomultiplier connected to it through a boron free quartz window. The geometry of the new C$_6$D$_6$ containers has been re-designed in comparison to the previous ones, so as to set them in a packed dodecahedron. The container itself is thus a truncated 5-sides 12.5 cm high pyramid. The connected PM is an EMI9823KQ photomultiplier.
Figure 1 shows the modelled geometry as designed in the MCNP input file. A mu-metal shield covers the PM to prevent from the influence of any magnetic field.

![Detector geometry](image)

Fig. 1: C₆D₆ detector geometry as modelled in the MCNP input file: the orange part is the C₆D₆ and the blue one the quartz window, the white parts are the vacuum inside the PM.

For the simulation of the γ-ray efficiency we first used the F8 pulse height tally to track photons and electron interactions along the path of the photon emitted by a monoenergetic point source [2]. Figure 2 shows the plotted output from this tally considering different gamma energies which correspond to available calibration sources. For γ-ray energies above 1.022 MeV, the electron-positron pairs creation is made possible and observed here as a peak before the end of the Compton edge. The second curve shows the total gamma efficiency, calculated as the integral of the previous spectra for other photons energies from 200 keV up to 15 MeV.

For the simulation of the neutron sensitivity we used the same tally than for the γ-ray efficiency simulation: tracking the photon and electron interactions along the path of the neutron emitted from a point source. We simulated bunches of energies from 0.1 eV to 1 MeV. Each output was integrated and normalized to the 4 MeV gamma total efficiency. Figure 3 shows the final result for one C₆D₆, along with the contribution in percents from each detector material to this neutron sensitivity. These different contributions are depending on each respective neutron capture cross section, as we can see for the 5.9 keV and 35 keV aluminium resonances for instance.

First MCNP simulations of the new C₆D₆ detectors array have thus been performed concerning gamma efficiency and neutron sensitivity. Specific cases referring to experiments to be performed have also been simulated. The comparison between simulations and experiments will then enable us to get to the next step, which is the calculation of the weighting function of these new C₆D₆ detectors.
Fig. 2: Simulated responses of a C\textsubscript{6}D\textsubscript{6} to different monoenergetic gamma point sources. The second curve shows the total gamma efficiency defined as the integral of the first curves, which is the total of deposited energy in the detector normalized to the incident energy.

Fig. 3: Simulated neutron sensitivity for one C\textsubscript{6}D\textsubscript{6} detector. The second curve shows the relative contribution of each material.


In the Neutron Physics group, there are at the moment a variety of heterogeneous data acquisition and some data analysis programs in use, the most complete being LISA [1], a program based on the analysis program PV-WAVE [2] from Visual Numerics Inc. At the moment, LISA is used in several analogue-electronics experiments for the acquisition and analysis of data taken from different type of ADCs or Multiplexers connected to a Multi-Parameter-Acquisition-Interface (MPI 8100) from Send GmbH [3] via a parallel SCSI data bus and a RS232 control interface.

LISA is a data analysis/acquisition program which uses the PV-WAVE CL language, as well as compiled C code modules, a so-called processor, whose output is piped into the PV-WAVE main program for online monitoring and offline data display. The data analysed is manipulated only within this processor. The advantage of LISA is that with this construction it is possible for a user to write his or her analysis in a relatively easy way by writing plain C-code into this processor, and compile it using the GNU C compiler. Many of those processors for standardized experiments are available and ready to be copied. For more than a decade, a lot of analysis code had been developed by many users doing nuclear fission experiments at the IRMM. This yielded a certain amount of tested analysis code in the language C for analogue data. LISA is running on a Sun Solaris UNIX platform. However, its built-in tools and functionality to analyse huge amounts of data are to some extent limited and a modern Graphical User Interface (GUI) is missing. Since PV-Wave is a commercial program, expensive licences have to be bought for the use on every data acquisition or analysis computer, thus an expansion to other DAQ devices is cost intensive.

The next step: GENDARC using ROOT

In order to improve the NP Unit’s DAQ and DAA capabilities, it has been decided in a modernisation initiative to phase out the PV-WAVE program and to develop a software based on the object oriented program package ROOT [4, 5] as a new basis. ROOT has been developed at CERN with high energy physics experiments like the planned Large Hadron Collider (LHC) in mind, where literally thousands of detectors are used, and is continuously being updated by the CERN development team. The program is nowadays widely used in the medium and high energy physics community with the number of users steadily increasing.

State-of-the-art features:
GENDARC is able to acquire, display and analyse list-mode data and store it either in list-mode or in spectral mode to a data file in native ROOT format. This data format, containing at the same time spectral data (histograms) as well as Ntuple data, provides the functionality to make sophisticated n-dimensional analytical cuts within the data from the command line interpreter. In the program, the definition of regions of interest in the Ntuple data using 2-
Fig. 1: Screenshot of GENDARC, the new ROOT-based data acquisition and analysis program. Shown are (from left to right) the pull-down menu on the top left side, 3 data display windows for 1-dim and 2-dim histograms, the file browser, fit panel and input parameter file, and the editor showing the user analysis source code written in C that filled the histograms shown. All windows can be generated by using the mouse only (e. g. double-clicking etc.). The data displayed were taken from a $^{252}$Cf-run.

dimensional graphical cuts is implemented. An additional benefit is that the Ntuple data need less disc space than binary data due to the built-in compression algorithm. Included in the current version are various tools for histogramming in 1, 2 and 3 dimensions, as well as curve fitting. The development of the program is taking place within our experiments (e. g. [6]), see Fig. 1 for a screen shot.

High performance due to compiled structure:
The GENDARC code has been structured to a compiled program instead of an interpreted script. With this measure, a drastic increase of performance was achieved, since a compiled program is up to 10 times faster than an interpreted one. The program is now using the freely available GNU- compiler which is called from within ROOT itself via ACLiC, the Automatic Compiler of Libraries for CINT (the C++ - interpreter).

User-friendliness due to GUI:
However, the cost of this is often, that within a compiled program running at full speed, the Graphical User Interface (GUI) becomes blocked or unresponsive. Also, the "look and feel" is
determined by this and is important for the user-friendliness of a program, facilitating the data acquisition or analysis process. This problem has been solved in GENDARC as well, using a programming approach which allocates special CPU time for the processing of GUI-events, e.g., zooming in/out of histograms, pressing buttons, etc.

Cost-effectiveness due to open-source nature:
The open-source nature of our development, combined with that of ROOT, allows the use of free copies of it on every PC or Workstation, without the need to obtain expensive software licences, saving a large amount of financial resources that can be used elsewhere. It is now running on the major platforms UNIX, Linux, and Windows using the Cygwin Unix emulation.

Re-use of existing source code due to a new LISA/GENDARC software interface:
Although ROOT is potentially powerful, new users have to spend a lot of time and effort to be able to use ROOT efficiently. Also, a great amount of source code for nuclear fission, data acquisition and data analysis has been developed within LISA in the last decade. This code had also been used in publications and includes many tested algorithms. It would take a lot of effort and time to re-program this code.

In order to solve these problems, our idea is to apply the following approach: Within our program we have developed a special LISA/GENDARC-software interface, which allows using exactly the same programming code within GENDARC than within LISA. It also uses the same syntax and data structure as LISA. With this approach, above mentioned problems are solved and it is possible to:

a. Start with data analysis/data acquisition immediately without the need to know ROOT. New users get immediately familiar with GENDARC and ROOT, because what the user does is actually programming in C instead of C++. The physicist doesn’t have to know anything about ROOT to be able to perform a full data analysis.

b. Use all of the new ROOT-features, including 2-dimensional cuts, online fitting of spectra, mouse-driven GUI, etc. When or if the user decides he wants to learn the ROOT syntax he can use it parallel to the LISA syntax.

c. Re-use all existing tested data analysis code from LISA built over the last decade, for nuclear fission analysis, etc., and also used in numerous publications. The analysis source code - formerly the LISA processor written in C - can be run within GENDARC, thus saving an enormous amount of programming effort, time and also cost.

Hence, in this way the best of two worlds - LISA and ROOT - are combined within GENDARC.

[2] Visual Numerics Incorporation, Boulder CO, USA


CVD diamond detector characteristics in low-energy heavy-ion counting after priming

S. Oberstedt, C. C. Negoita, F.-J. Hambsch, W. Geerts

For the final design of VERDI, a polycrystalline CVD (Chemical Vapour Deposition) diamond detector was chosen to be used as fast timing detector. Diamond is known to be a suitable material for radiation detectors to be used in harsh environments and to have a fast signal collection time (due to high electron and hole mobility and high saturation velocity).

During the previous experimental investigations (the diamond detector performance was studied in the "as-grown" state by irradiation with a 239Pu-241Am-244Cm mixed-α calibration source, instabilities of the count rate due to deterioration of the pulse-height signal in time were observed. In order to increase the pulse height stability, the priming effect is used. It consists of pre-irradiating the CVD diamond film with ionizing radiation (e. g., β-particles) prior to detector operation. Therefore, before using the diamond detector, it was irradiated with a $^{90}$Sr/$^{90}$Y β-source of 3.4 ± 0.2 MBq.

After priming, the diamond detector was installed inside a vacuum chamber and irradiated with α-particles from a $^{241}$Am source to observe the effect of priming. A positive bias voltage of 150 V (1.5V/$\mu$m) was applied. The detector was kept during all procedure protected from ambient light to avoid optical de-priming.

The output of the diamond detector was connected to a pre-amplifier. Two types of MESYTEC pre-amplifiers were used: the single channel charge sensitive pre-amplifier MPR-1 and the eight-channel pre-amplifier/shaper box MSI-8. The α-particle pulse height spectra were recorded using calibrated standard electronics chain composed of a Canberra 2026 amplifier and a Canberra 8715 analog-to-digital converter. The shaped timing output was split before constant-fraction discriminator modules, to obtain the start and the stop signal for an ORTEC TAC/SCA module. Data acquisition and analysis were made using the LISA program package.

The measurements were done a couple of weeks after the priming procedure and took place during a total period of three weeks. The running time of the experiments was between 24 min and 64.5 h. As expected, the priming effect can persist for a long period of time in suitable circumstances (cf. Fig. 1).

The energy stability was analyzed by fitting the pulse height spectra with a Gaussian function. Although, some variations can be observed in the position of the energy peak, the variations are smaller than 1.25 % of the calculated average value as shown in Fig. 2. One can conclude that the position of α-particle peak is stable and reveals the achieved stability of the detector response.

During these experiments, it was found that the shape (which depends on field polarity) was improved by the pumping procedure to (Fig.3). Also, the count rate remained very stable during all experimental period.

The achieved signal stability in time will be crucial for obtaining good results when using CVD diamond detectors as time pick-up in the fission-fragment spectrometer VERDI. The "intrinsic time resolution" of polycrystalline CVD diamond detector with associated electronics was ob-
Fig. 1: The position of the energy peaks as a function of time (the x-error bars represent the experimental time periods in which the stability of the CVD diamond detector was investigated). After priming the signal remains stable for a long period of time.

Fig. 2: The mean value of the pulse height spectra shown in Fig. 1 are distributed within $\pm 1.25\%$ around the calculated average value. The different values obtained were influenced by electronics and not by the detector itself.

Comparing the results with the previous experimental campaign, one can conclude that after priming the characteristics of diamond detectors are considerably improved and remained stable for a long period of time features which are important for the future experiments on VERDI. In the next step CVD detector performance has to be tested when irradiated with fission fragments.
Fig. 3: $\alpha$-particle spectra from a $^{241}$Am source measured with the CVD diamond detector in "as grown" and in "primed" states.
Use of a $^{90}\text{Sr}/^{90}\text{Y}$ $\beta$-source for priming process

S. Oberstedt, C. C. Negoita, T. Altzitzoglou†

During the last year state-of-the-art polycrystalline chemical vapour deposited (CVD) diamond material has been introduced for using it as high-resolution timing detectors for heavy-ionizing particles, e. g. $\alpha$-particles and fission fragments, in the VERDI fission-fragment time-of-flight spectrometer [1]. First irradiation with a $^{239}\text{Pu}-^{241}\text{Am}-^{244}\text{Cm}$ mixed-$\alpha$ calibration source showed a strong degradation of the detector signal as a function of irradiation time. This is explained by polarisation due to the creation of space charges by particles stopped in the deep trapping defects of the as-grown detector material, see e. g. [2].

In order to achieve the highest detection efficiency and stability, the polycrystalline chemical vapour deposited (CVD) diamond detectors must be pre-irradiated with ionizing radiation (so called "priming" or "pumping" process). The priming process is qualitatively explained through passivation of traps by occupation with charge carriers. The achieved saturation can persist for several months in suitable circumstances, as for example in the absence of ambient light.

Before exposure of the CVD diamond detector to heavy ions we plan to irradiate it with a $^{90}\text{Sr}/^{90}\text{Y}$ $\beta$-source (in equilibrium) prepared in the Isotope Measurement Unit of the IRMM. The source has a diameter of approximately 10 mm and is mounted on a stainless steel disc (20 mm diameter and 0.5 mm thick). The activity is $3.4 \pm 0.2$ MBq and, to improve safety during manipulations, the source was covered by a 80 $\mu$m thick plastic foil. By that measure about 10 % of the emitted electrons are absorbed. The distribution of the source activity is shown in Fig. 1.

Fig. 1: Radiograph of the $^{90}\text{Sr}/^{90}\text{Y}$ $\beta$-source used for the priming of CVD poly-crystalline diamond detectors

†Isotope Measurements Unit
First tests confirmed that pulse amplitude and time evolution of the $\alpha$-particle signals were extremely stable after pre-irradiating the CVD-detector (see p. 92 in this report).


Accelerators:
Instrumentation and development
The first IRMM electrostatic accelerator was a 3.7 MV Van de Graaff (VdG) accelerator from High Voltage Engineering (HVE). This machine was constructed on the base of a standard HVE 3.0 MV accelerator and upgraded in voltage prior to installation in 1963. Initially the accelerator was used for production of mono-energetic neutrons but in the early eighties the laboratory was expanded and a project for materials analysis by means of PIXE (Particle Induced X-ray Emission), RBS (Rutherford Back Scattering) and SPM (Scanning Proton Microprobe) was launched. The IRMM neutron research programme continued however by means of the 7 MV VdG that was up operational already in 1977. The 3.7 MV VdG was finally decommissioned in 2001 when the materials research programme was closed. A second materials analysis programme for extreme surface analyses by means of NRA (Nuclear Reaction Analysis) and ERDA (Elastic Recoil Detection Analysis), was launched in the early nineties. This programme was run in a dedicated laboratory using one extended beam line, split into two dedicated target chambers, from the 7.0 MV machine. The programme was closed in 1999 when the IRMM VdG laboratory activities focused on neutron physics research. A series of upgrades related to the 7.0 MV accelerator and the necessary infrastructure have since been performed, including:

1999 General refurbishment of the accelerator including:
- installation of a new accelerator tube,
- installation of an automatic voltage conditioner for automatic increase of the high voltage on the terminal. This is intended for voltages from about 6.0 MV where sparks to the ground may be a serious problem.
- Installation of new charging belt,
- installation of a derippler system including a CPU (Capacitive Pick-Up) which adjusts for high frequency ripple on the high voltage terminal.
2000-2003 Installation of new and rearrangement of present ion beam optics
2000-2005 Installation of a new computer controlled vacuum system with oil-free pumps
2000 Installation of computer controlled sample (rabbit system) changer for activation analysis
2001 Building of a new shielding wall around the neutron target halls
2001 Decommissioning of the 3.5 MV Van de Graaff machine and laboratory
2001 Installation of the level 0 beam line; the ”high intensity” beam line
2002 Installation of a new the safety and security system
2002 Decommissioning of the ion beam analytical laboratory for materials re-
search
2003 Decommissioning of the fixed motor controlled shadow cone goniometer in target hall 4.6
2003 Refurbishment of the hot-lab. Installation of the fire-safe tritium com-
artment room
2003  Installation of a new beam stabilisation system
2004  Upgrade and prolongation of the level 4.6/0 free area beam line; the "time-of-flight beam line"
2005  Rebuilding of office building and installation of a new detector laboratory as well as a new computer room and workshop
2005  Installation of a low frequency beam deflection system (NEPTUNE)
2006  Refurbishment of the VdG gas transfer compressor
2006-2007 - Installation of a new beam charge measurement system;
- Replacement of the radio-frequency ion source for an ECR (Electron Cyclotron Resonance) ion source

Today, the accelerator is operated in either DC or in fast or slow beam pulsing mode. In the fast beam pulsing mode, ion beam pulses down to about 2 ns fwhm can be produced with a pulse frequency of $f = 2.5, 1.25$ or $0.625$ MHz. The slow pulsing system facilitates a minimum pulsing width of $10 \mu$s at an adjustable frequency up to $5$ kHz. In DC mode, a constant beam current up to $50 \mu$A of protons can be maintained for long periods (week).

Neutrons are produced using either of the following nuclear reactions:

$$^7\text{Li}(p, n)^7\text{Be}, \quad E_n = 0 - 5.3 \text{ MeV}$$
$$T(p, n)^3\text{He}, \quad E_n = 0 - 6.2 \text{ MeV}$$
$$D(d, n)^3\text{He}, \quad E_n = 1.8 - 10.1 \text{ MeV}$$
$$T(d, n)^4\text{He}, \quad E_n = 12.1 - 24.1 \text{ MeV}$$

Typical neutron spectra from various energy areas, calculated using the kinematics programme EnergySet [1] and the Monte Carlo code Target [2] are given in Fig. 1. EnergySet does not include scattering in the neutron producing target construction and is a pure kinematics programme while Target also calculates target scattering but not air in/out-scattering or room in-scattered neutrons. These calculated spectra reflects the expected full energy peak characteristics whereas various not included additional target effects and room scattering effects should be expected in the lower energy part, dependent on target quality, ion beam energy, surrounding materials and measurement positioning in the room.

**Accelerator operation**

In 2006 the accelerator was operated for about 4530 hours with a maintenance stop in August, see Fig. 2. Less than 20 % of the time was used for accelerator and beam optics tuning and tests while the rest was available for experimental purposes. The large number of annual hours, which is a machine record, is a result of operating the machine unattended during non-office hours and week-ends.


Fig. 1: Typical calculated neutron spectra using EnergySet [1] for the 0.3, 1.0 and 7.3 MeV neutron spectra and the Monte Carlo code Target [2] for the 3.0, 16.0 and 19.5 MeV neutrons. For the 0.3 and 1.0 MeV neutrons the $^7\text{Li}(p, n)^7\text{Be}$ reaction has been used with a 0.25 mg/cm$^2$ LiF target. For the 3.0 MeV spectrum the $T(p, n)^3\text{He}$ reaction was used with a 2.0 mg/cm$^2$ Ti:T target, and for the 16.0, and 19.5 MeV calculations the $T(d, n)^4\text{He}$ reaction was used, again with a 2.0 mg/cm$^2$ Ti:T target.

Fig. 2: Operation statistics for 2006 for the IRMM 7.0 MeV VdG accelerator
The Geel electron linear accelerator facility GELINA


The Geel Electron Linear Accelerator facility GELINA is a pulsed white-spectrum neutron source in combination with a time-of-flight (TOF) facility designed and built for high-resolution neutron cross section measurements. The excellent neutron energy resolution is made possible by a combination of four specially designed and distinct units: a high-power pulsed linear electron accelerator, a post-accelerating beam compression magnet system, a mercury-cooled uranium target, and very long flight paths.

The neutron source is based on a linear electron accelerator producing electron beams with a typical beam operation mode characterised by 100 MeV average energy, 10 ns pulse length, 800 Hz repetition rate, 10 A peak and 80 μA average current. Using a unique post-acceleration pulse compression system, the electron pulse width can be reduced to approximately 1 ns (FWHM) while preserving the current, resulting in a peak current of 100 A. The accelerated electrons produce Bremsstrahlung in an uranium target which in turn, by photonuclear reactions, produces neutrons. Within a 1 ns pulse a peak neutron production of $4.3 \times 10^{10}$ neutrons is achieved (average flux of $3.4 \times 10^{13}$ neutrons/s).

The neutron energy distribution emitted by the target ranges from subthermal to about 20 MeV, with a peak at 1-2 MeV. In order to have a significant number of neutrons in the energy range below 100 keV, a hydrogen-rich moderator is added. The partially moderated neutrons have an approximate $1/E$ energy dependence plus a Maxwellian peak at thermal energy. By using collimators and shadow bars moderated or unmoderated neutron beams are selected for the twelve neutron flight paths. Further tailoring of the spectral shape is done with movable filters. GELINA covers the neutron energy range 1 meV - 20 MeV. The up to 400 m long flight paths point radially to the uranium target, lead to experimental locations at distances of 10, 30, 50, 60, 100, 200, 300 and 400 m. These experimental stations are equipped with a wide variety of sophisticated detectors, and data acquisition and analysis systems. GELINA is a multi-user facility operating on a continuous 24 h shift basis from Monday morning to Friday evening, and serving simultaneously a maximum of 10 concurrent experiments.

During 2006, GELINA was used exclusively in the framework of the institutional work programme and for the trans-national access programme NUDAME. The facility produced neutron beams for experiments during 2251 hours. For reasons explained below, this is only 80 % of the average number of beam hours during the previous years. The detailed operation statistics are shown in Fig. 1. GELINA was serving up to 10 experiments simultaneously (7.4 on average). The total number of data-taking hours, integrated over all flight paths, was 16558 hours (only 3.5 % less than in 2005). The accelerator is operated in two modes:

- high pulse repetition frequency mode (800 Hz and 400 Hz repetition rate) with electron beams on target of 100 A peak current, 1 ns pulse length (80 μA average current).
- low pulse repetition frequency mode (100 Hz and 40 Hz repetition rate) with electron beams on target of 10 A peak current, 1 ns pulse length.
For reasons dictated by the experimental requirements, only the high pulse repetition frequency mode was used in 2006.

Modulator 1 was completely renewed during the first quarter of 2006. Modulators 2 and 3 were already reconstructed in 2005. The technicians of the GELINA crew rebuilt the mechanical configuration of the modulators. They also redesigned and reconstructed part of the charging units and the cabling. They rebuilt completely the high-voltage network. The discharging units were refurbished. The pulse-forming networks (PFN) were adapted to optimise the negative mismatch condition and the inverse diode circuitry was rebuilt. The technicians installed also the newly developed control and interlock (MCI) system and modernised the interlock hardware. All home-built equipment performed very well.

The high-power high-voltage DC power supply (25 kV, 150 kW) for modulator 1 was ordered from the same company that delivered similar power supplies for modulator 2 and 3. The three DC power supplies have the same power rating, but the power supply of modulator 1 is operating typically at 22 kV, while in modulators 2 and 3 the nominal power supply voltage is 12 kV. The major characteristics of the new high-voltage PFN charging power supply are:

- SCR-controlled primary, dry step-up transformer, rectifying system and filter system.
- High voltage: variable between 7 and 25 kV DC
- Voltage stability and accuracy: better than 0.5 % (combined)
- Maximum power: 150 kW per power supply
- Standard internal and external interlocks

Fig. 1: Neutron beam-time distribution of the GELINA facility
• Fast power supply switch off and filtering capacitor discharge (ms-range) with a solid-state crowbar system in the event of a load, switch tube or power supply fault.

The power supplies are operating in the 6-phase fully-controlled rectifier bridge mode. The power supplies of modulator 2 and 3 are arranged with an additional common phase shifting autotransformer to shift one converter with -15 degrees, the other with +15 degrees. Since the three converters operate under the same nominal load conditions, but each with a phase shift of 15 degrees, line current higher harmonics are reduced substantially, the ripple factor to the 380 V mains being 18-pulse.

The power supplies of modulator 2 and 3 have accumulated up to now more than 6500 high-voltage hours each and performed very well. In contrast, the newly installed power supply for modulator 1, which has similar characteristics, created serious problems already during its start-up phase: instabilities, arcing, failing components. The basic reason is the different voltage level of this HVDC power supply. Remedies by the constructor caused a four weeks delay of the GELINA restart. The subsequent running of GELINA during the period April June was hampered by additional intermittent problems caused now by the voltage-doubling charging inductor from this power supply. These problems were related with overheating and voltage breakdown. In June, the charging inductor failed completely. The inductor had to be redesigned and reconstructed by the constructor. To avoid a long GELINA stop we developed and implemented a temporary solution. Since June, modulator 1 operates very stable and reliable. Recently the newly designed charging inductor is installed and performs very well.

Since the HVDC problems were solved, the modulators operate at a rate of almost 100 % of the scheduled hours. In general, the modernisation of the modulators proved to be very successful, despite the setbacks with the power supply of modulator 1. In accordance with our expectations, the reliability, stability and reproducibility of the modulators, and consequently also of the whole GELINA facility, improved drastically.

In 2006 we had an additional major intervention which was more of a routine nature. In March we had to replace the vacuum sealing rings of the relativistic compression magnet as a result of radiation damage after two years of operation. The relativistic compression magnet is a magnet of a very special design. It transports an electron beam with an energy spread \( \Delta E/E = 50 \% \) over a maximum distance of 7.5 m. The role of this magnet is to compress the beam pulse with duration of 10 ns by a factor of 10 while preserving the charge in the pulse. The large vacuum chamber of the compression magnet is sealed with two specially-shaped elastomer O-rings \( \approx 8.1 \text{ m} \). Replacement of these seals implies opening of the magnet (weight 50 tons) and cleaning of the magnet chamber flange assemblies. Due to the high level of radioactivity in the magnet and its heavy weight, replacement of these seals is a delicate, highly demanding and time-consuming work. Despite the fact that a few years ago, we installed beam loss monitors, the lifetime of the elastomer rings remains around two years, mainly due to the high neutron background that is present in the neutron target hall. So, it has been decided to plan in the future preventive replacements of the magnet O-rings at the end of the summer stops, when the radiation exposure of the technicians is lowest.
During 2006, progress was made with the implementation of the new GELINA monitor, control and interlock (MCI) system (described in detail in the scientific report 2004). This system allows simultaneous monitoring and control of many discrete and analog (or digital) signals and commands. The modernization of the control and interlock system is an ongoing project spread over many years, because this work must be accomplished with a minimum interference with GELINA operation. In 2006 we implemented the control and interlock system for modulator 1, vacuum system, beam diagnosis and RF system. The renewal of the control desk follows accordingly. The new MCI system is PC-controlled and based on a distributed architecture with decentralised input/output (I/O) controller nodes. At the nodes we are using FieldPoint modular I/O hardware with LabVIEW software support. Communication with the control room and between different I/O controllers is performed via Ethernet.

Because of the great request for annual beam time and the increasing number of experimental users from outside (in the framework of the EURATOM Transnational Access to Infrastructures project NUDAME, see elsewhere), the improvement of the GELINA availability and reliability remains a permanent effort. Therefore the GELINA modernization project is an ongoing task, with the following installation schedule for 2007:

- new injector cathodes: April
- new injector fast pulse amplifier system and peripheral equipment: August
- three new water chillers for the pulse modulators: August
- new monitor, control and interlock system via a step-by-step procedure, with a minimum interference of GELINA operation.
Annex
List of publications

Determination of the $^{232}$Th (n, $\gamma$) Cross Section from 4 to 140 keV at GELINA
A. Borella, K. Volev, A. Brusegan, P. Schillebeeckx, F. Corvi N. Koyumdjeva, N. Ianeva, A. Lukyanov
*Nuclear Science and Engineering* 152 (2006) 1-14

The Cross Section of the $^{10}$B(n, $\alpha$)$^{7}$Li Reaction Measured in the MeV Energy Range
G. Giorginis, V. Khryachkov

Neutron Capture and Total Cross Sections of Iodine-127 and Iodine-129
G. Noguere, O. Bouland, A. Brusegan, P. Schillebeeckx, P. Siegler, A. Leprêtre, N. Herault, and the n_TOF Collaboration

The Total Neutron Cross Section of $^{61}$Ni
S. Kopecky, A. Brusegan

The Recoil Proton Telescope in no-Coincidence Mode for Neutron Fluence Measurements
G. Lövestam

An International Evaluation of the Neutron Cross Section Standards

Measurement of the $^{151}$Sm(n, $\gamma$) Cross Section from 0.6 eV to 1 MeV Via The Neutron Time-of-flight Technique at the CERN n_TOF Facility
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Neutron-Resonance Capture as a Tool to Analyse the Internal Compositions of Objects Non-Destructively
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GELINA, a Neutron Time-of-Flight Facility for High-Resolution Neutron Data Measurements
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Nuclear Needs for Generation IV Nuclear Energy Systems
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Digitisation Techniques Applied in Nuclear Experiments
F.-J. Hambsch, S. Oberstedt, I. Fabry, N. Kornilov, N. Varapai, Sh. Zeynalov

The EC-JRC IRMM Neutron Facilities and Measurement Programme
S. Oberstedt
The American Nuclear Society’s 14th Biennial Topical Meeting of the Radiation Protection and Shielding Division. 3-6 April 2006, NM, USA

Neutron-Induced Dosimetry Reaction Cross Section Measurements from the threshold
V. Semkova, A. Plompen
Tenth Symposium on Neutron Dosimetry. June 12-16 2006, Uppsala (Sweden)

NEPTUNE New Pulsed and TUnable Neutron Source for Isomer Spectroscopy
Spring Meeting of the German Physical Society, Hadrons and Nuclei, 20-24 March, 2006 Muenchen, Germany, HK57.4

Dynamics in the Low Energy Neutron Induced Fission Process
F.-J. Hambsch, E. Birgerson, A. Oberstedt, S. Oberstedt
IX International Conference on Nucleus Collisions (INN2006) Several Brazilians Universities, IAEA and ICP (Trieste, Italy), August 28 - September 1, 2006, Rio de Janeiro, Brazil

Production of Multigroup Data Covariance in the Resonance Range by Monte-Carlo Calculations
G. Noguere, C. De Saint-Jean, B. Iooss, P. Schillebeeckx, P. Siegler
PHYSOR 2006 American Nuclear Society’s Topical Meeting on Reactor Physics, The Canadian Nuclear Society, 10-14 September, 2006, Vancouver, BC, Canada

New Neutron Cross-Section Measurements on $^{19}$F, $^{39,41}$K, $^{55}$Mn and $^{103}$Rh for Improved Nu-
Determination of the Branching Ratio for the $^{209}\text{Bi}(n, \gamma)^{210}\text{Bi}$ Reaction from 500 eV to 20 keV
A. Borella, P. Schillebeeckx, T. Belgya, N. Colonna, C. Domingo Pardo, F. Gunsing, S. Marrone, T. Martinez, C. Massini, P. M. Mastinu, P. Milazzo, G. Tagliente, J. Tain, R. Terlizzi, R. Wynants
PHYSOR 2006, American Nuclear Societys Topical Meeting on Reactor Physics, The Canadian Nuclear Society, 10-14 September, 2006, Vancouver, BC, Canada

Measurement of the Neutron Capture Cross Section of $^{236}\text{U}$
F. Gunsing, E. Bertoumieux, A. Borella, W. Dridi, W. Furman, A. Goverdovski, P. Schillebeeckx, R. Wynants, and the n_TOF collaboration
PHYSOR 2006, American Nuclear Societys Topical Meeting on Reactor Physics, The Canadian Nuclear Society, 10-14 September, 2006, Vancouver, BC, Canada

Determination of the neutron resonance parameters for $^{209}\text{Bi}$ from new capture and transmission measurements at GELINA
A. Borella, F. Gunsing, S. Kopecky, P. Mutti, P. Schillebeeckx, P. Siegler, R. Wynants
PHYSOR 2006, American Nuclear Societys Topical Meeting on Reactor Physics, The Canadian Nuclear Society, 10-14 September, 2006, Vancouver, BC, Canada

P. Schillebeeckx, C. Bastian, A. Borella, F. Gunsing, J. Heyse, G. Noguere
PHYSOR 2006, American Nuclear Societys Topical Meeting on Reactor Physics, The Canadian Nuclear Society, 10-14 September, 2006, Vancouver, BC, Canada

Measurement at n_TOF of the $^{237}\text{Np}(n, \gamma)$ and $^{240}\text{Pu}(n, \gamma)$ Cross Sections for the Transmutation of Nuclear Waste
C. Guerrero, A. Plompen, P. Rullhusen, and the n_TOF Collaboration
PHYSOR 2006, American Nuclear Societys Topical Meeting on Reactor Physics, The Canadian Nuclear Society, 10-14 September, 2006, Vancouver, BC, Canada
n_TOF Fission Data of Interest to GEN-IV and ADS
C. Paradela, A. Plompen, P. Rullhusen, and the n_TOF Collaboration
PHYSOR 2006, American Nuclear Society’s Topical Meeting on Reactor Physics, The Canadian Nuclear Society, 10-14 September, 2006, Vancouver, BC, Canada

Measurement of the Neutron Capture Cross Section of $^{234}\text{U}$ in n_TOF at CERN
W. Dridi, A. Plompen, P. Rullhusen, and the n_TOF Collaboration
PHYSOR 2006, American Nuclear Society’s Topical Meeting on Reactor Physics, The Canadian Nuclear Society, 10-14 September, 2006, Vancouver, BC, Canada

EFNUDAT: European Facilities for Nuclear Data Measurements in the Interest of Nuclear Waste Transmutation and Minimisation
A. Plompen
OECD-NEA Ninth Information Exchange Meeting on Actinide and Fission Product Partitioning and Transmutation

High Precision and High Resolution Measurements of $(n, xn\gamma)$ Cross Sections on the isotopes of Lead and Bismuth
OECD-NEA Ninth Information Exchange Meeting on Actinide and Fission Product Partitioning and Transmutation

Fission Cross-Sections and the Dynamics of the Fission Process
F.-J. Hambsch
Workshop on the Theories of Fission and Related Phenomena, CEA Saclay (F), May 9-12, 2006, http://www-dapnia.cea.fr/Sphn/Espace_Theorie/May2006/talks/Hambsch.ppt

ENERGYSET- A Software Tool for the Calculation of Mono-Energetic Neutron Fields from Ion Beam Nuclear Reactions
G. Lövestam
The 7th International Conference on Electrostatic Accelerators and Beam Technologies (ESACCEL 2006), State Scientific Center of the Russian Federation SSC RF IPPE. June 2-8, 2006, Obninsk, Russia, Proceedings to the ESACCEL 2006 (Ed. V. Romanov)

Experimental Determination of the $^{41}\text{Ca}(n, \alpha)^{38}\text{Ar}$ Reaction Cross Section as a Function of the Neutron Energy
L. De Smet, C. Wagemans, J. Heyse, S. Vermote, J. Van Gils
International Symposium on Nuclear Astrophysics Nuclei in the Cosmos IX, 25-30 June 2006, CERN, Genève (CH)

Report on the Nuclear Data Activities of the Neutron Physics Unit of the Institute for Reference Materials and Measurements of the European Commission’s Joint Research Centre
A. Plompen
International Nuclear Data Committee Meeting, Organiser: A.L. Nichols, Nuclear Data Section, IAEA, 9-12 May 2006, IAEA Headquarters, Vienna (AT)

The Fission Fragment TOF Spectrometer VERDI
S. Oberstedt, C. C. Negoita, F.-J. Hambsch, W. Geerts, Sh. Zeynalov, T. Gamboni

Recent Measurements of Activation Cross Sections at IRMM
V. Semkova, A. Plompen
JEFF Meeting, 22-24 May 2006, Issy-les-Moulineaux (F), OECD-NEA, List of EFFDOCs, EFFDOC-982, OECD-NEA, JEFF Project

Comparative Study of the Ternary Particle Emission in $^{243}\text{Cm}(nth, f)$ and $^{244}\text{Cm}(SF)$
S. Vermote, C. Wagemans, O. Serot, J. Heyse, T. Soldner, P. Geltenbort
International Conference on Dynamical Aspects of Nuclear Fission, 2-6 October 2006, Smolenice, Slovak Republic, Ed. S. Gmuca, University Bratislava

Experimental Subthreshold Fission
O. Bouland, H. Weigmann
Workshop on Nuclear Data Evaluation for Reactor Applications (Wonder 2006), 9-11 October 2006, CEA Cadarache, Saint-Paul-Lez-Durance (F)

The Impact of the Resolution Function on Resonance Parameters
S. Kopecky, D. Ene, P. Schillebeeckx
Workshop on Nuclear Data Evaluation for Reactor Applications (Wonder 2006), 9-11 October 2006, CEA Cadarache, Saint-Paul-Lez-Durance (F)

Evaluation of Neutron Cross Section Data in the Unresolved Resonance Region with a Link to the Optical Model
I. Sirakov, P. Schillebeeckx R. Capote Noy
Workshop on Nuclear Data Evaluation for Reactor Applications (Wonder 2006), 9-11 October 2006, CEA Cadarache, Saint-Paul-Lez-Durance (F)

Neutron Data Measurements at IRMM
A. Plompen
3rd Workshop on Neutron Measurements, Evaluations and Applications (NEMEA-3), 25-28 October 2006, Borovets (BU), Organiser: Arjan Plompen

Upgrade of the Neutron Inelastic Scattering Measurements Setup at GELINA
A. Negret, C. Borcea, A. Plompen
3rd Workshop on Neutron Measurements, Evaluations and Applications (NEMEA-3), 25-28 October 2006, Borovets (BU), Organiser: Arjan Plompen

Neutron Capture Cross-Section Measurements on $^{103}\text{Rh}$ and $^{133}\text{Cs}$ for Improved Nuclear Crit-
Cadmium Transmission Measurements at GELINA
I. Ivanov, P. Siegler, S. Kopecky, A. Trkov, M. Moxon
3rd Workshop on Neutron Measurements, Evaluations and Applications (NEMEA-3), 25-28 October 2006, Borovets (BU), Organiser: Arjan Plompen

NEPTUNE The New Isomer Spectrometer at IRMM
S. Oberstedt, A. Oberstedt, A. Plompen, V. Semkova G. Lövestam
3rd Workshop on Neutron Measurements, Evaluations and Applications (NEMEA-3), 25-28 October 2006, Borovets (BU), Organiser: Arjan Plompen

Neutron-Induced Activation Cross Sections of Different Isotopes of Zr, W and Ta from the Threshold to 20 MeV
V. Semkova, R. Jaime Tornin, A. Moens, A. Plompen
3rd Workshop on Neutron Measurements, Evaluations and Applications (NEMEA-3), 25-28 October 2006, Borovets (BU), Organiser: Arjan Plompen

Fission-Fragment Characteristics in the Reaction $^{238}$U(n, f) in the Vicinity of the Vibrational Resonances at $E_n = 1$ MeV
E. Birgersson, S. Oberstedt, A. Oberstedt, F.-J. Hambsch
Svenskt kärnfysiker möte XXVI, 14-15 November 2006, Lund (S), Svenska fysikersamfundet kärnfysiksektionen

Neutron Cross Section Measurements at n_TOF for ADS Related Studies
P. F. Mastinu, A. Plompen, P. Rullhusen, and the n_TOF Collaboration

Measurement of the $^{90, 91, 92, 94, 96}$Zr neutron Capture Cross Sections at n_TOF
G. Tagliente, A. Plompen, P. Rullhusen, and the n_TOF Collaboration
International Symposium on Nuclear Astrophysics Nuclei in the Cosmos IX, 25-30 June 2006, CERN, Genève (CH)

Experimental Challenges for the Re/Os Clock
M. Mosconi, A. Plompen, P. Rullhusen, and the n_TOF Collaboration
International Symposium on Nuclear Astrophysics Nuclei in the Cosmos IX, 25-30 June 2006, CERN, Genève (CH)

Neutron Capture Measurements on the s-Process Termination Isotopes Lead and Bismuth
C. Domingo Pardo, A. Plompen, P. Rullhusen, and the n_TOF Collaboration
International Symposium on Nuclear Astrophysics Nuclei in the Cosmos IX, 25-30 June 2006, CERN, Genève (CH)

Neutron Capture Cross Section Measurements for Nuclear Astrophysics at n_TOF
M. Heil, A. Plompen, P. Rullhusen, and the n_TOF Collaboration
International Symposium on Nuclear Astrophysics Nuclei in the Cosmos IX, 25-30 June 2006, CERN, Genève (CH)

Measurement of $^{139}$La(n, $\gamma$) Cross Section at n_TOF
R. Terlizzi, A. Plompen, P. Rullhusen, and the n_TOF Collaboration

Implications of $^{151}$Sm(n, $\gamma$) Cross Section at n_TOF
S. Marrone, A. Plompen, P. Rullhusen, and the n_TOF Collaboration

Measurement of the Resonance Capture Cross Section of $^{204,206}$Pb and Termination of the s-Process
C. Domingo Pardo, A. Plompen, P. Rullhusen, and the n_TOF Collaboration

Measurement of $^{139}$La(n, $\gamma$) Cross Section
C. Terlizzi, A. Plompen, P. Rullhusen, and the n_TOF Collaboration

Neutron Capture Cross Section Measurements at n_TOF of $^{237}$Np, $^{240}$Pu and $^{241}$Am for the Transmutation of Nuclear Waste
D. Cano Ott, A. Plompen, P. Rullhusen, and the n_TOF Collaboration
Internal reports

Evaluation of Cross Sections and their Functional in the unresolved resonance region - Evaluation of the $^{232}$Th in the region between 4 - 140 keV
Nina Koyumdjieva
GE/NP/01/2005/02/24

Gas production in ternary fission (Final report)
Jan Heyse
GE/NP/02/2005/03/11

Measurement of neutron inelastic scattering cross-sections for $^{209}$Bi and $^{207}$Pb (Intermediate Report - second year)
L. C. Mihailescu
GE/NP/03/2005/03/29

Verification of the nuclear reaction theory predictions of fission fragment properties for the example $^{238}$U(n, f) (Intermediate Report - first year)
E. Birgesson
GE/NP/04/2005/07/15

IRMM participation in a EUROMET key comparison of neutron fluence measurements in mono-energetic neutron fields at 15.5, 16, 17 and 19 MeV
Göran Lövestam
GE/NP/05/2005/09/30

Measurement of fast neutron induced ($E_n = 25 - 75$ MeV) microscopic reaction cross sections at the Louvain la Neuve Cyclotron
V. Corcalciuc, A. Plompen
GE/NP/06/2005/10/13

EUR Reports and Special publications

Neutron Physics Unit Scientific Report 2005
S. Oberstedt and P. Rullhusen

A. Plompen
Status of Pb and Bi Measurements after 18 Months of EUROTRANS
A. Plompen
TECHNICAL REPORT, EUR N° 22516 EN (2005)

Neutron (n,xnγ) cross section measurements for $^{52}$Cr, $^{209}$Bi and $^{206,207,208}$Pb from threshold up to 20 MeV
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Abstract
This report is a compilation of status reports on all ongoing neutron physics research and development activities at the JRC IRMM.
The mission of the JRC is to provide customer-driven scientific and technical support for the conception, development, implementation and monitoring of EU policies. As a service of the European Commission, the JRC functions as a reference centre of science and technology for the Union. Close to the policy-making process, it serves the common interest of the Member States, while being independent of special interests, whether private or national.