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Characterization of the Medley setup for measurements of neutron-induced fission cross sections at the GANIL-NFS facility

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Abstract. Neutron-induced fission cross sections of ^{235}U and ^{238}U are widely used as standards for monitoring of neutron beams and fields. An absolute measurement of these cross sections at an absolute scale, i.e., versus the H(n,p) scattering cross section, is planned with the white neutron beam under construction at the Neutrons For Science (NFS) facility in GANIL. The experimental setup, based on PPACs and ΔE-ΔE-E telescopes containing Silicon and CsI(Tl) detectors, is described. The expected uncertainties are discussed.

1. Introduction

Neutron-induced fission cross sections of ^{235}U and ^{238}U are widely used as standards for monitoring of neutron beams and fields. However, the necessity of improving the quality of the standards has been highlighted [1] because of inconsistencies between experimental information and various evaluations (e.g. ENDF-B/VII, JEFF-3.2, TENDL-2015), as it can be seen in Fig. 1 for the case of ^{238}U. In the particular case of the ratio of fission cross sections $^{238}U/^{235}U$, recent results from Refs. [2–4] are in quite good agreement up to 200 MeV with ENDF/B-VII, whereas results from [5] differ from them up to nearly 10%. Even more remarkable is that only a few experimental measurements have been done versus the H(n,p) scattering cross section (see Ref. [6] and references therein), considered as a primary standard; in particular, the results from Ref. [7] on ^{238}U(n,f) exceed the evaluated values by ∼7% in certain energy ranges. Thus, new accurate measurements of (n,f) cross sections relative to H(n,p) are required [1].

Fission fragment angular distribution (FFAD) is also an important observable for understanding the fission mechanism, as it provides information on the state of the nucleus at the saddle point (spin, parity). Coordinated description of fission cross-section and FFAD is required for the determination of the best set of fission barrier parameters [8]. It is well known that the variations in the anisotropy follow the step-like structure of the fission cross section as a function of the incident neutron energy. The strong anisotropies observed at the opening of the multiple-chance fission channels (n,xn'f) help to determine their thresholds. Moreover, these anisotropies affect the precision of the cross section measurements when using detectors with a limited angular acceptance, requiring a good knowledge on the angular distribution to correct for this effect [9].

Therefore, we propose a quasi-absolute measurement of cross sections and angular distributions for ^{235}U(n,f) and ^{238}U(n,f) using recoil protons from the H(n,p) reaction for normalization, thus linking together three standard cross sections for neutron measurements with good accuracy.

2. Experimental setup

2.1. The NFS facility at GANIL

The NFS (Neutrons For Science) facility is currently being built at GANIL (France). It will provide neutron beams with energies between 1 and 40 MeV, with the possibility of having a quasi-monoenergetic spectrum from the ^{7}Li(p,n) reaction as well as a white spectrum from the ^{9}Be(d,n) reaction [10]. The latter one will allow us to measure cross-sections in a continuous range of incident neutron energies.

2.2. The Medley setup

We plan to use an upgraded version of the Medley setup, which in its original form (see Ref. [11]) has been used repeatedly at the quasi-monoenergetic neutron beam of the The Svedberg Lab (TSL) in Uppsala (Sweden).

The original Medley is equipped with eight three-element telescopes mounted inside a cylindrical vacuum chamber with an inner diameter of 800 mm. Each telescope consists of two fully depleted ΔE silicon surface barrier detectors (SSBD) of 50 µm and 500 µm in thickness and one CsI(Tl) scintillator crystal of 50 mm length, to fully stop protons. The telescopes are mounted at 20° intervals in two sets, covering the forward and backward hemispheres. They are mounted on a rotatable plate so that measurements can be done at any angle.

The described setup is suitable to be used in a quasi-monoenergetic neutron beam. However, to be able to benefit from the high flux of neutrons at various energies in a white neutron beam, the incident neutron energy must be determined by measuring the neutron time of

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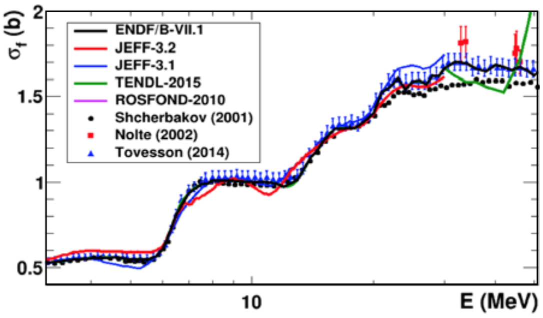


Figure 1. Comparison of some recent measurements and evaluations of ^{238}U(n,f) cross section.

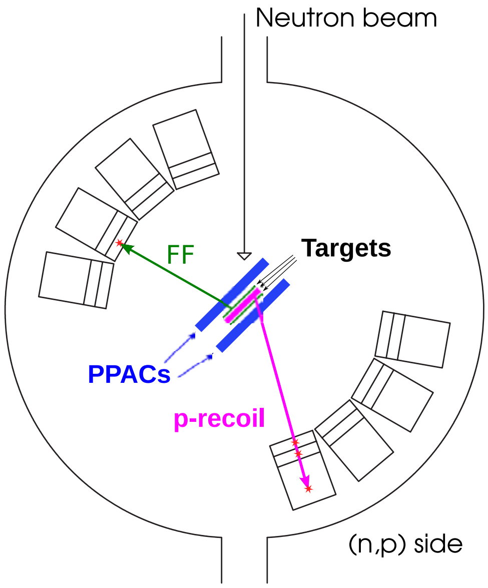


Figure 2. Setup for (n,f) cross section measurements with respect to n-p elastic scattering. The fission fragments will be detected in one PPAC and stopped in the first Si detector in one of the eight telescopes. The proton recoil from H(n,p) will be stopped in the CsI(Tl) scintillator of one of the front telescopes, because of the kinematics of the reaction. The full set of telescopes can be rotated as a whole to measure at different angles.

flight (TOF).The start signal of the TOF will be given by the accelerator, while the stop will be provided by the detection of a fission fragment (FF) in a PPAC (Parallel Plate Avalanche Counter) located close to the fission target. A layout of the setup is presented in Fig. 2.

2.3. Targets

Three circular targets, 25 mm in diameter, will be placed simultaneously in the neutron beam: Two uranium targets (one of ^{235}U and the other of ^{238}U) containing 0.4 mg/cm^2 of the respective isotope; and one 100 µm-thick polyethylene ($(C_2H_4)_n$) target placed between the uranium ones. With this configuration, it is possible to measure, at the same time, the fission cross sections of both uranium isotopes and the elastic neutron scattering on hydrogen, ensuring that all the samples are receiving the same neutron flux and, therefore, canceling out systematic effects due to variations in the beam characteristics.

2.4. Principle of operation

As indicated in Fig. 2, two kinds of events will be detected:

- Fission event: The incoming neutron can induce fission in one of the two uranium samples. Because of the presence of the polyethylene target, only one of the FF will be detected in one PPAC, and it may reach one of the telescopes, where it will be stopped in the first Si detector. Detecting FF at different angles (determined by the positions of the telescopes) will give us the FFAD.
- Elastic event: The other possibility is that the neutron undergoes an elastic collision H(n,p) in the polyethylene target. Due to the kinematics of the H(n,p) reaction, the recoil proton will only be emitted in the forward hemisphere, and it may be detected and identified using the ΔE-ΔE-E technique, thanks to the energy deposited in the Si detectors and in the CsI(Tl). Weakly ionizing particles, like protons, will deposit very little energy in the PPAC and will only be detected in the telescopes.

3. PPAC development

A Parallel Plate Avalanche Counter (PPAC) is a type of gas detector widely used to detect heavy ions [9,12]. It consists of two thin parallel electrodes separated by a gap filled with gas at a pressure of a few mbar. The width of the gap between the electrodes should not exceed a few mm in order to maintain a high electric field and to reduce the time spread, thus ensuring a good time resolution that is typically of the order of 1 ns. Under these low-pressure conditions, a bias voltage of a few hundred V is sufficient for reaching the proportional regime. The electrons released from the gas molecules during the passage of a heavy ion (a fission fragment) gain sufficient energy to cause secondary ionization in the homogeneous electric field, and a Townsend avalanche is triggered [12].

PPACs are insensitive to weakly ionizing particles so that they can be used to detect heavy ions in the presence of neutron or γ-background, making them suitable for studying neutron-induced fission reactions.

The PPACs that are being produced in our group for this project have an active area of $6 \times 10\,\mathrm{cm}^2$ and are composed by two aluminized Mylar foils of 2.5 µm in thickness (although production of 0.9 µm-thick foils is currently being tested), separated by a gap of 3.2 mm containing C_3F_8 gas at a pressure of 3 mbar. To reduce the energy losses, the PPACs are not encapsulated so that the gas fills the whole chamber. No breakdowns were observed in the Silicon detectors during the tests.

Spontaneous fission in a ^{252}Cf sample provides us with suitable fragments to study the characteristics of the PPACs. Different values of the pressure have been tested. As an example, counting characteristics of a PPAC at a pressure of 3 and 7 mbar are shown in Fig. 3. The curves represent the detection efficiency for the fission fragments as well as for the α particles from the ^{252}Cf decay, as a function of the applied voltage to the anode. For this test, the ^{252}Cf was placed at 1 cm distance from the PPAC. The signals were amplified and a discriminator set a threshold level to distinguish the real events from electronic noise.

As it can be seen in Fig. 3, the detection efficiency for the fission fragments increases with the bias voltage,

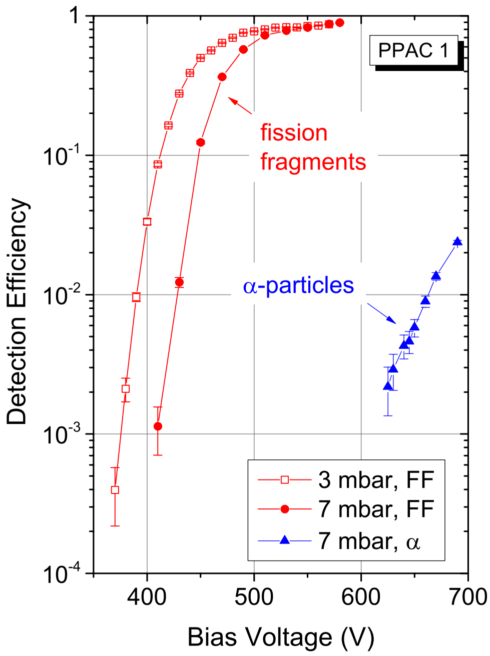


Figure 3. Detection efficiency of fission fragments and α-particles from a ^{252}Cf source using one of the PPACs at different pressures of the gas. The results in the region around 600 V are omitted in the graph (see the text for details).

and eventually reaches a plateau, from ∼550 V, where the efficiency is nearly constant and close to 100%, within the uncertainties of the measurements. The minimum voltage required for the detection of fission fragments increases with the gas pressure. Because of the weaker ionization being produced in the PPAC gas, α-particles are only detected at higher pressures and bias voltages. At the pressure of 7 mbar, detection of α-particles begins at the voltage of ∼630 V, whereas no α-particles are detected at 3 mbar. Increasing the voltage further will increase the detection efficiency for the α-particles up to a maximum of 2.5% at around 700 V in the case of 7 mbar pressure. It is not possible to apply higher voltages since that would produce discharges between the electrodes of the PPAC. In the voltage range around 600 V, the discrimination between α-particles and fission fragments becomes difficult and it will require a deeper analysis that has not been completed yet. Therefore, we omit those results in Fig. 3.

4. Energy losses

A detailed study of the energy losses has been done by using Geant4 simulations, and reported in Ref. [13]. The maximum energy deposited by an α-particle in a 50 μm-thick Si detector is 8 MeV; therefore, any fission fragment depositing more than 8 MeV in a front Silicon can be unambiguously identified. The fission fragments will lose an average of ∼8 MeV per PPAC foil and, despite the energy losses in the target and in the gas (C_3F_8 at 3 mbar), only less than 0.1% of them will reach the telescopes with an energy lower than 8 MeV, so that they will be discriminated from α-particles.

Those simulations have also shown that the secondary protons produced in the mylar foils of the PPAC detectors will only contribute with ∼1% to the number of protons detected in the most forward telescope.

5. Angular distribution and cross section calculation

The total fission cross section will be determined using the integration of the angle-differential cross section, measured thanks to the use of the four telescopes placed at 20° intervals. The angular distribution of the fragments can be described using a series of even Legendre polynomials $P_L(\cos\theta)$ including terms up to the order $L_{max} = 4$, thus leaving 3 free parameters to fit the data [9, 14]:

$$W(\cos\theta) = \sum_{L=0,\,L\,even}^{L_{max}} A_L \cdot P_L(\cos\theta) \qquad (1)$$

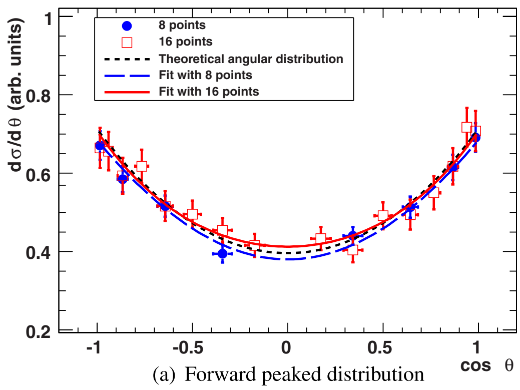
The full set of telescopes is attached to a circular plate that can be rotated as a whole, allowing to place them at any angle. In that way, measurements at 20°, 40°, 60° and 80° can be complemented with a second round of measurements at, for example, 10°, 30°, 50°, and 70°. Given that only one fragment can be detected at the time, the set of targets will also be rotated 180°, corresponding to a total of 8 or 16 measuring angles, in order to subtract any systematic effect caused by differences in the detectors and, at the same time, to study forward and backward emission of fragments from both uranium isotopes.

A compromise must be reached between the number of measured angles and the collected statistics (i.e., required beam time). For a fixed total number of counts $N = 3000$ (with an overall statistical uncertainty $1/\sqrt{N} = 1.82\%$) an increment by a factor R in the number of measured angles (i.e., in the number of rotations to cover intermediate values of the angles) will result in an increase of the statistical uncertainty of each point by a factor $\sqrt{R}$. In order to investigate whether a larger number of angles will improve the uncertainty in the integrated cross section, a Monte Carlo analysis of pseudodata has been done.

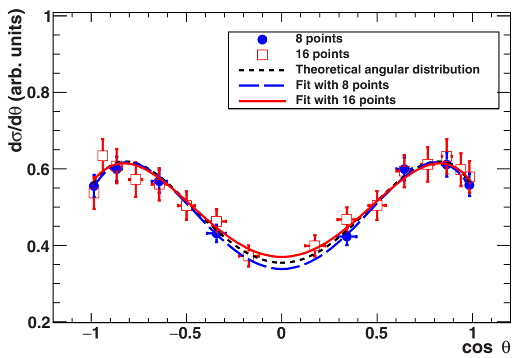
Figure 4 shows two examples where typical values of the Legendre coefficients have been chosen (the black dotted line) to produce initial pseudodata at different angles. Figure 4(a) represents a forward peaked distribution, what is the predominant situation in neutron-induced fission of actinides at intermediate energies, whereas Fig. 4(b) shows an example of a side peaked distribution, typical case from threshold and subthreshold fission of some even-even actinides [9, 14]. In these conceptual simulations we have neglected the (minor) effect of linear momentum transfer from the incident particle to the fissioning nucleus.

The pseudodata are randomly shifted from that distribution according to their statistical uncertainty, that in the case of the 16-angles set (hollow red squares) will be $\sqrt{2}$ times larger than in the 8-angles set (full blue circles). Each dataset is fitted to the angular distribution given by Eq. (1) (continuous red line for the 16-angles case, and dashed blue line for the 8-angles case), whose integral in the whole angular range $\cos\theta = [-1, 1]$ will give the final value of the total fission cross section. Therefore, to compare both simulations, the previous cases have been calculated 10^6 times, by randomly shifting the values within the statistical uncertainties.

The final results for both cases are shown in Table 1. The integral value corresponds to 1 in all the cases (the



(a) Forward peaked distribution



(b) Side peaked distribution

Figure 4. Example of pseudodata representing two typical values of the anisotropy: one case where most of the fragments are emitted in the beam direction (a) and the other where the emission is side-peaked (b). The lines represent fits to series of Legendre polynomials up to 4th order, using 8 or 16 angles.

Table 1. Total fission cross sections (in arbitrary units) and uncertainties associated to the fitting of the angular distributions.

Distribution	8 values	16 values
Forward peaked	1.000 ± 0.021	1.000 ± 0.011
Side peaked	1.000 ± 0.022	1.000 ± 0.011

same as the integral of the initial distribution) but the uncertainty in the fit is significantly smaller when using 16 points than when using only 8, despite the increase in the statistical uncertainty of each value.

6. Summary and outlook

The existing reaction chamber (Medley) containing 8 telescopes with Silicon and CsI detectors, has been equipped with PPACs to study neutron-induced fission cross sections using neutron-proton elastic scattering as a reference. The time signal given by the PPACs will allow us to use it with both quasi-monoenergetic and white neutron beams. The PPACs are being developed and tested at our laboratory and the present status has been described.

The experimental setup will provide us with the angle-differential cross sections and the total fission cross section will be obtained from the angle-integration of a fit to the experimental points. It has been shown that increasing the amount of measured angles will reduce the statistical uncertainty in the integrated cross section, even though the individual statistical uncertainty of each point will be larger. Therefore, measurements at intermediate angles should also be done, taking advantage of the rotating support of the telescopes.

Of particular interest will be the simultaneous measurement of ^{235}U(n,f) and ^{238}U(n,f) with respect to H(n,p), that will relate three neutron standard cross sections, providing with results of good accuracy that will hopefully allow to improve the quality of the evaluations. Measurements of other actinides, such as ^{232}Th, are also envisaged.

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