Fission Fragment Angular Distribution measurements of [235]U and [238]U at CERN n_TOF facility

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Abstract. Neutron-induced fission cross sections of ^{238}U and ^{235}U are used as standards in the fast neutron region up to 200 MeV. A high accuracy of the standards is relevant to experimentally determine other neutron reaction cross sections. Therefore, the detection efficiency should be corrected by using the angular distribution of the fission fragments (FFAD), which are barely known above 20 MeV. In addition, the angular distribution of the fragments produced in the fission of highly excited and deformed nuclei is an important observable to investigate the nuclear fission process.

In order to measure the FFAD of neutron-induced reactions, a fission detection setup based on parallel-plate avalanche counters (PPACs) has been developed and successfully used at the CERN-n_TOF facility. In this work, we present the preliminary results on the analysis of new ^{235}U(n,f) and ^{238}U(n,f) data in the extended energy range up to 200 MeV compared to the existing experimental data.

1 Introduction

The angular distribution of the fragments produced in the fission of an excited nucleus (FFAD) provides relevant information of the fission barrier structure and the transition levels. A good knowledge on the FFAD is also required in the calculation of the detection efficiency for fission fragments (FF) to provide accurate measurements of fission cross sections. The fission cross sections of ^{235}U and ^{238}U are used as standards, the first in the neutron energy from 150 keV to 200 MeV and the second from 2 MeV up to 200 MeV. The recently published n_TOF data of the ^{238}U/^{235}U fission cross section ratio [1] were obtained fitting the anisotropy parameter of the FFAD data available in the EXFOR database. The FFAD experimental data for the (n,f) reactions of ^{235}U and ^{238}U published in the EXFOR [2] database reach 20 MeV, the only ^{238}U data exceeding this energy up to 100 MeV are those of Ryzhov et al. [3]. The recently published data of ^{238}U and ^{235}U by Vorobyev et al. [4] and the data of Leong [5] reach 200 MeV. Measurements at intermediate neutron energies would be of interest in the next calculations of the ^{235}U(n,f) and ^{238}U(n,f) cross sections. In this work we present the preliminary results of the FFAD of ^{235}U and ^{238}U up to 200 MeV measured at the n_TOF facility (CERN).

2 Experimental setup

The experiment was accomplished in the CERN Neutron Time-of-Flight (n_TOF) facility [6]. The white neutron beam is produced through spallation induced by a 20 GeV/c bunched proton beam on a lead target and it is moderated in a 4 cm thick layer of borated water. The neutron beam covers the energy range from thermal up to 1 GeV travelling along approximately 185 m from the spallation target to the chamber containing the detectors and targets, which is located in the experimental area EAR 1. A sweeping magnet is located in the neutron path to remove charged particles from the beam and two collimators are used to give shape to the beam, where the second determines the beam diameter of 8 cm for fission measurements.

Nine targets, produced at IPN-Orsay, were used in this experiment: three of ^{234}U, one of ^{237}Np, two of ^{235}U and three of ^{238}U. They consisted of a thin radioactive layer 8 cm in diameter deposited on an Aluminium foil of different thickness: 2.5 μm for the first six targets in the beam direction and 0.7 μm for the last three targets (two of them of ^{238}U and one of ^{235}U).

Ten Parallel Plate Avalanche Counters (PPACs), with the targets alternated, were used to measure the (n,f) reactions. Those are gas detectors constituted by one central anode and two cathodes. The gaps between the electrodes are filled with C_3F_8, which is a non-flammable gas, at 4 mbar pressure. The anode signal has a very fast response, with a time resolution of about 500 ps and the cathodes are segmented with parallel strips in the X and Y directions in order to provide the impact position of each fission fragment in the PPAC plane.

Detectors and targets were located inside a stainless steel chamber filled with the gas, tilted 45° with respect the neutron beam in order to enlarge the angular range from 0° to 90° relative to the non-tilted setup in which the angular acceptance was limited between 0° and 60°; a discussion on the angular acceptance can be found in Ref. [8].

3 Data analysis and preliminary results

The principle of the fission identification is based on the simultaneous detection of the signals produced by the back-to-back emitted FFs in the two PPACs flanking the target. For this purpose the anode signals are used due to their fast response. The coincidence method allows us to discard most of the α background and of the products of spallation reactions. The cathode signals are used to reconstruct the detection position in both PPACs. Assuming that both FFs are back-to-back emitted in the laboratory reference system, their trajectory can be reconstructed and the emission angle determined. This assumption is valid because the error introduced in the angle measurement by the linear momentum transfer even at large neutron energies is negligible, as explained in Ref. [7].

In the tilted PPACs setup used in this work, the emission angle is calculated as the scalar product of two vectors, one for the FF trajectory ($\vec{V}_{FF}$), and another for the beam direction ($\vec{V}_{beam}$). As shown in Fig. 1, the cosine of the emission angle is given by (1).

$$\cos\theta = \frac{\vec{V}_{FF} \cdot \vec{V}_{beam}}{|\vec{V}_{FF}| \cdot |\vec{V}_{beam}|} \tag{1}$$

Making the assumption that the angular dependence of the FFs detection efficiency is constant along the whole energy range, we can deduce it from the actual FFAD obtained for the ^{235}U targets below 1 keV, where it is known to be isotropic [8]. The thickness of the respective targets backings must be taken into account.

The experimental FFAD ($W(\theta)$) can be fitted by the sum of Legendre polynomials:
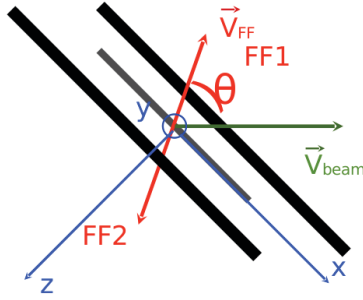
Figure 1. Scheme of the reference frame used to reconstruct the trajectories of the FFs, as is explained in [7, 8].

$$W(\theta) = A_0 \cdot \left[1 + \sum_{L_2}^{L_{max}} A_L \cdot P_L(\cos\theta) \right] \tag{2}$$

where A_L are the coefficients and L is the order of the polynomial. Only even terms must be included due to the symmetry of the fission fragments. In this work we have fitted $(W(\theta))$ by the sum of Legendre polynomials up to 4th order because the 2nd order polynomial alone is not sufficient to accurately reproduce the angular distribution behaviour, see Fig. 2.
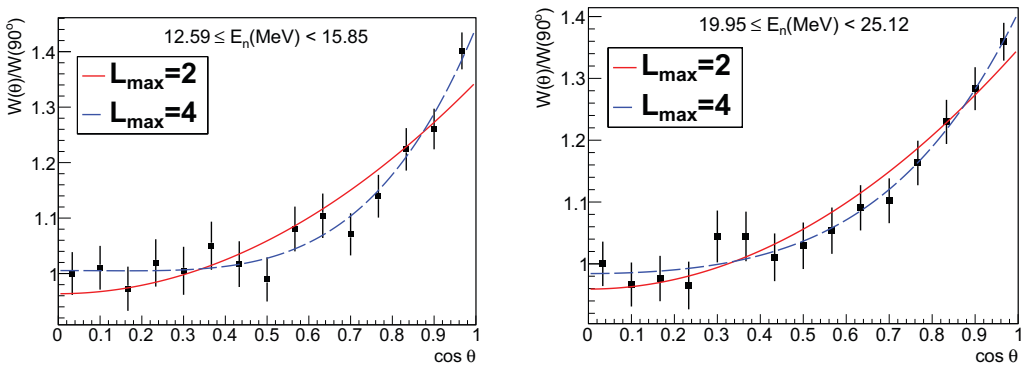

Figure 2. Angular distribution measured with one of the ^{235}U targets from 12.59 MeV to 15.85 MeV (left panel) and with one of the ^{238}U targets from 19.95 MeV to 25.12 MeV(right panel) fitted up to the 2nd and 4th order Legendre polynomials.

The FFAD dependence on the neutron energy is commonly described in a simple way using the anisotropy parameter, defined as $(W(0°)/W(90°))$. It can be expressed as:

$$W(0°)/W(90°) = \frac{1 + A_2 + A_4}{1 - \frac{1}{2} \cdot A_2 + \frac{3}{8} \cdot A_4} \tag{3}$$

where the coefficients are obtained from the fit to the experimental FFAD data.

Our preliminary results on the anisotropy parameter in function of the neutron energy are shown in Fig. 3, where the mean values have been calculated for both ^{235}U targets and for the three ^{238}U targets. The error bars include only the propagation of the statistical uncertainties.
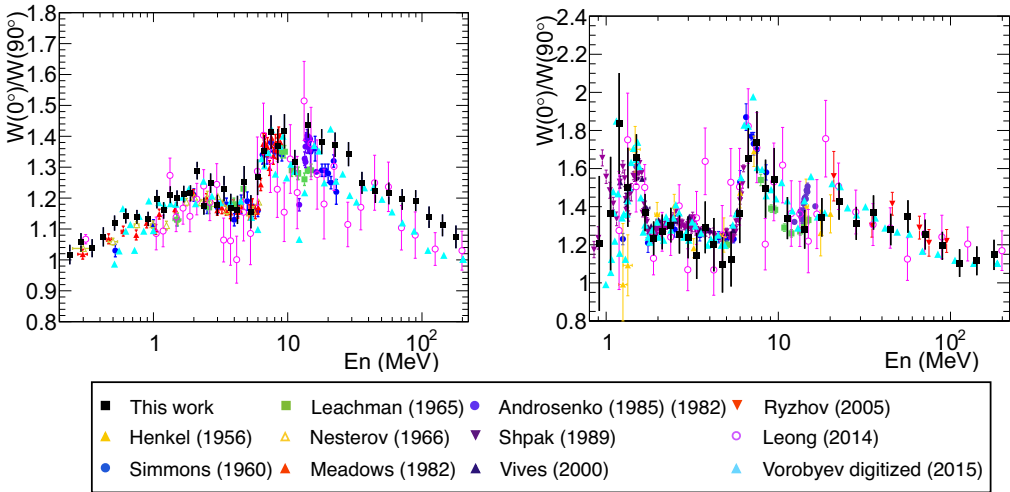

Figure 3. The anisotropy parameter measured in this work with the two ^{235}U targets (left panel) and with the three ^{238}U targets (right panel) compared with the available experimental datasets.

When compared with the available ^{235}U experimental data up to 20 MeV, the anisotropy parameter data here presented agree in general within their uncertainties. Above 20 MeV and up to 200 MeV there are only two datasets, Vorobyev et al. [4] and Leong [5] giving values 8% below the present data at 100 MeV.
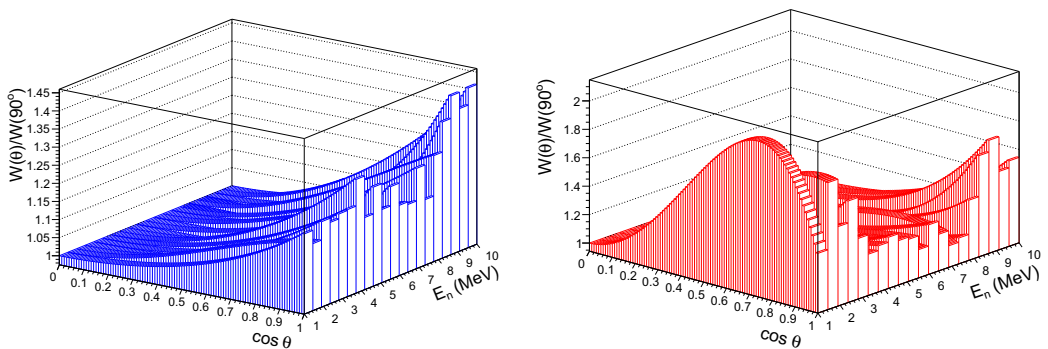

Figure 4. Evolution of the FFAD found in this work for ^{235}U (left panel) and ^{238}U (right panel) in the energy range from 1 MeV to 10 MeV.

Concerning ^{238}U, the anisotropy parameter data presented in this work are in general in good agreement with previous works in the entire energy range up to 200 MeV. It is worth to note that the statistics is not enough to describe with accuracy the behaviour of the ^{238}U angular distributions at the thresholds of the different fission chances where the anisotropy shows large variations for small changes in the neutron energy. This is better seen in Fig. 4, where the evolution of the FFAD is shown in the energy range from 1 to 10 MeV. Conversely to ^{235}U, in the case of ^{238}U the A_4 parameter in the Legendre expansion changes very suddenly from positive to negative giving as a result an angular distribution that can not be described by a simple anisotropy parameter defined as $(W(0°)/W(90°))$.

4 Conclusions

The angular distributions of the ^{235}U(n,f) and ^{238}U(n,f) reactions have been measured at the n_TOF facility (CERN) using parallel-plate avalanche counters (PPACs). In this work the preliminary results of the anisotropy parameter up to 200 MeV are presented and compared with the datasets available in EXFOR and the more recent data reaching 200 MeV [4, 5].

In general, the results for both ^{235}U and ^{238}U are in good agreement with previous measurements up to 20 MeV. From 20 MeV to 200 MeV, the results for ^{235}U are higher than those of the two datasets recently published [4, 5] (around 8% at 100 MeV); and for ^{238}U the present data are within the uncertainties of previous ones [3–5].

The results on ^{238}U show the high complexity of its fission mechanism, already seen for ^{232}Th [7] and ^{234}U [9]. A better understanding of this behaviour around the thresholds for first and third chance fission for even-even isotopes requires much higher statistics in order to resolve the sharp changes of the anisotropy parameter near the fission chance thresholds. Accordingly, new measurements are planned in the forthcoming n_TOF campaigns, taking advantage of the high resolution of the PPACs setup at the n_TOF facility.

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