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Angular distributions and anisotropy of fission fragments from neutron-induced fission in intermediate energy range 1–200 MeV

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Abstract. Angular distributions of fission fragments from the neutron-induced fission of ^{232}Th, ^{233}U, ^{235}U, ^{238}U and ^{209}Bi have been measured in the energy range 1–200 MeV at the neutron TOF spectrometer GNEIS based on the spallation neutron source at 1 GeV proton synchrocyclotron of the PNPI (Gatchina, Russia). The multiwire proportional counters have been used as a position sensitive fission fragment detector. A description of the experimental equipment and measurement procedure is given. The anisotropy of fission fragments deduced from the data on measured angular distributions is presented in comparison with experimental data of other authors, first of all, the recent data from WNR at LANSCE (Los Alamos, USA) and n_TOF(CERN).

1. Introduction

Angular distributions of fission fragments arise due to two factors. First, an ensemble of spins of fissioning nuclei is to be aligned and, second, distribution of transitional states over the projection K of nuclear spin on the fission axis should be nonuniform. The first factor is determined by the processes which precede to fission, while the latter one is given by the mechanism of fission. At the energies much exceeding the fission barrier, the fission is preceded by the multi-step particle emission. A relative contribution of equilibrium and nonequilibrium processes into the dynamics of highly excited nuclei is not clear up to now. The angular distribution of fragments from neutron-induced fission at the energies up to 200 MeV may shed some light on these questions. Besides, the data on nuclear fission in this intermediate energy range are of prime importance for the advanced nuclear technologies such as Accelerator-Driven Systems (for nuclear power generation and nuclear transmutation).

In this article preliminary experimental data on angular distribution of fragments from fission of target nuclei ^{232}Th, ^{233}U, ^{235}U, ^{238}U and ^{209}Bi by neutrons with energies 1–200 MeV are presented.

2. Experimental setup

A schematic view of the experimental setup is shown in Fig. 1. Detailed description of the setup and readout system created on the basis of waveform digitizers can be found in our previous publications [1,2]. It was located at the flight path 5 of the TOF-facility GNEIS [3] at a distance of 36 m from the pulsed neutron source.

The short pulse width 10 ns of the neutron source enable to carry out TOF-measurements with the energy resolution from 0.8% (at 1 MeV) to 13% (at 200 MeV).

The thickness of the ^{209}Bi and actinide targets was $1000\,\mu g/cm^2$ and $100 \div 150\,\mu g/cm^2$, respectively. To estimate the possible contribution of the neutron-induced spallation reactions into the measured quantities both $100\,\mu m$ Al foil and $2\,\mu m$ Mylar film were used as the target backing. The fission fragment registration was performed by two coordinates sensitive multiwire proportional counters (MWPC) $140 \times 140\,mm^2$ of size. The fragment counters were placed close to the target, one after the other. The neutron beam axis came through the geometrical centers of the target and MWPC's electrodes being perpendicular to them. The measurements with two setup orientations relative to the beam direction (downstream and upstream) were performed.

A value of $cos(\theta)$, where θ is an angle between neutron beam axis and fission fragment momentum, can be derived easily from the coordinates of the fission fragment measured by two counters. Time and pulse-height analysis of the signal waveforms allowed to derive the neutron energy and the fission fragment coordinates on the MWPCs, and, hence, the angle information.

3. Data processing

Because only one of two complementary fission fragments was registered, the exact method of separation of fission fragments from neutron-induced spallation and other reactions products had to be used. The effective separation of the fission events was achieved using the "dynamic" registration threshold. This threshold was dependent on $cos(\theta)$ and chosen to exclude the events with lower specific energy losses and include the events with larger specific energy losses (fission fragments) in further data processing. For example, in Fig. 2 the fission events

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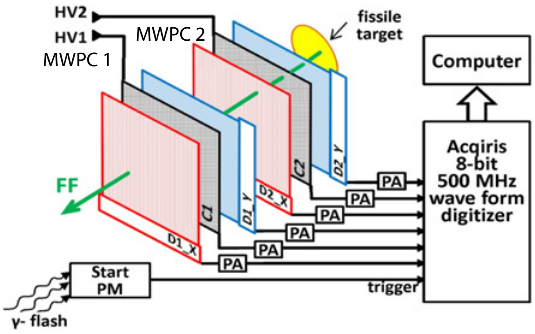

Figure 1. Schematic view of experimental setup: PA – preamplifier; PM – photomultiplier; HV – high voltage; FF – fission fragment; D1_X, D2_X – detector 1, 2 (X - axis); D1_Y, D2_Y – detector 1, 2 (Y - axis); C1, C2 – cathode 1, 2.

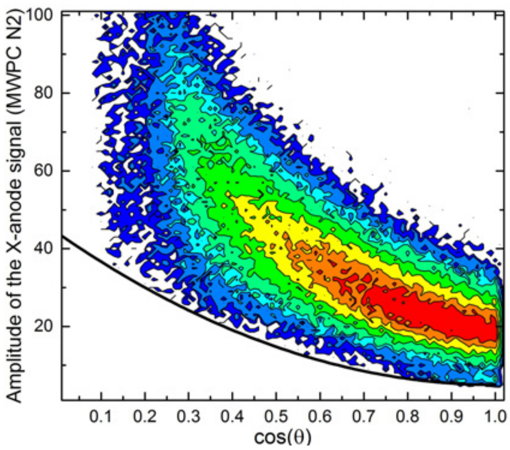

Figure 2. Dependence of the amplitude of the X-anode signal of MWPC 2 (D2_X) on the angle between fission fragment momentum and normal to the anode plane (^{209}Bi measurement). The fission events are located above the threshold (solid curve).

collected using the “dynamic” registration threshold are presented [2].

The calculations of fragment energy losses in thick ^{209}Bi target carried out by means of SRIM code [4] showed that in the angular range of $cos(\theta) > 0.24$ a residual energy of the heaviest fragments will be above 10 MeV. The specific ionization caused by these slowed fragments will be substantially higher than the registration threshold. This is confirmed by the experiment (Fig. 2). As a result, deficit of the fission events due to absorption of the fragments in the target does not exceed a few percents for $cos(\theta) \geq 0.24$.

The measured angular distributions of the fission fragments were corrected for the efficiency of fission fragment registration. This efficiency was calculated by means of the Monte-Carlo method taking into account following parameters: the electrode wire structure, distances between MWPCs and target, sizes of electrodes and distances between them, sizes of the target and neutron beam, the position (angular) resolution. The results of this simulation for ^{238}U measurement are plotted in Fig. 3: the dashed line is a result of exact geometry simulation with perfect position resolution, triangles show the simulation with real experimental position resolution (~2 mm), open circles are a final result where small existing misalignment of the neutron beam and the detectors axis was taken into

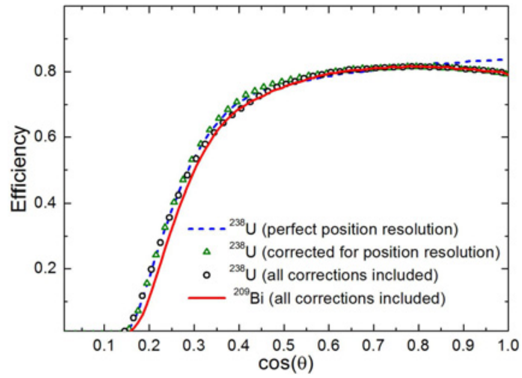

Figure 3. Geometrical efficiency of the setup calculated by means of Monte-Carlo simulation (comments in the text).

account. For comparison a final result of simulation for ^{209}Bi measurement, where the target was slightly more distant from the detectors compared to ^{238}U measurement, is also shown by solid line in Fig. 3.

The correction for the differential nonlinearity of coordinate scales was also taken into account. This correction was obtained by means of additional measurement of ^{252}Cf spontaneous fission source placed at the same position as the targets of nuclei [2].

An anisotropy W(0°)/W(90°) of angular distributions of fission fragments in the center-of-mass system were deduced from obtained angular distributions of fission fragments in the laboratory system by fitting them in the range $0.24 < cos(\theta) < 1.0$ by the sum of even Legendre polynomials up to the 4-th order. To account for the linear transfer momentum contribution into the measured angular distribution, the measured anisotropies were averaged over two setup orientations relative to the beam direction (downstream and upstream).

4. Results

The angular distributions of fission fragments in the centre of mass system for ^{233}U are presented in Fig. 4 for two neutron energy intervals, 1.49 ± 0.16 MeV and 15.7 ± 1.4 MeV in comparison with experimental data of the other authors [5–7]. The results of the data fitting are also shown in Fig. 4. It is seen that in these examples our results are in a good agreement with the other data. It is worthwhile to note that experimental techniques used by referred authors differ both in fragment detectors and in neutron sources. It may be treated as a convincing proof of accuracy and reliability of our measurement technique and data handling procedure, at least in the neutron energy range below 20 MeV.

The anisotropy W(0°)/W(90°) obtained in present work for ^{209}Bi and actinide nuclei, in the neutron energy range 1–200 MeV, are shown in Figs. 5, 6, respectively.

Until recently, in the neutron energy range 20–100 MeV only one dataset [12] on angular anisotropy of fission fragments existed. It is of interest that a significant difference in fission fragment angular anisotropy was observed for ^{232}Th and ^{238}U isotopes. This work was performed with the use of quasi-monochromatic neutron source. Therefore, it seems appropriate to compare their results with data obtained recently at TOF spectrometers

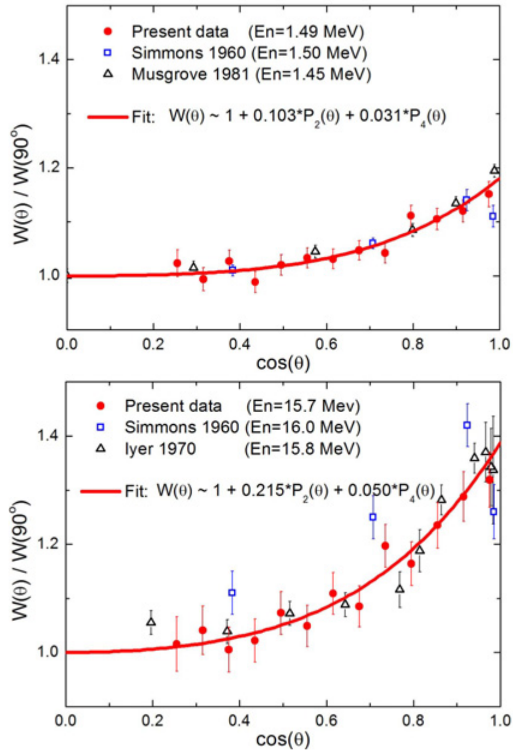

Figure 4. Angular distributions for ^{233}U compared with the other EXFOR data [5–7]. The error bars represent statistical uncertainties. Solid line is a result of the fitting by the sum of even Legendre polynomials up to the 4th order.

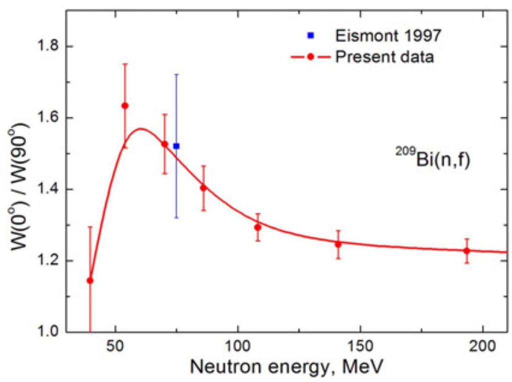

Figure 5. Anisotropy of fission fragment of ^{209}Bi (left) compared with the Eismont's data [8]. The solid curve is only the eye guide to the experimental data.

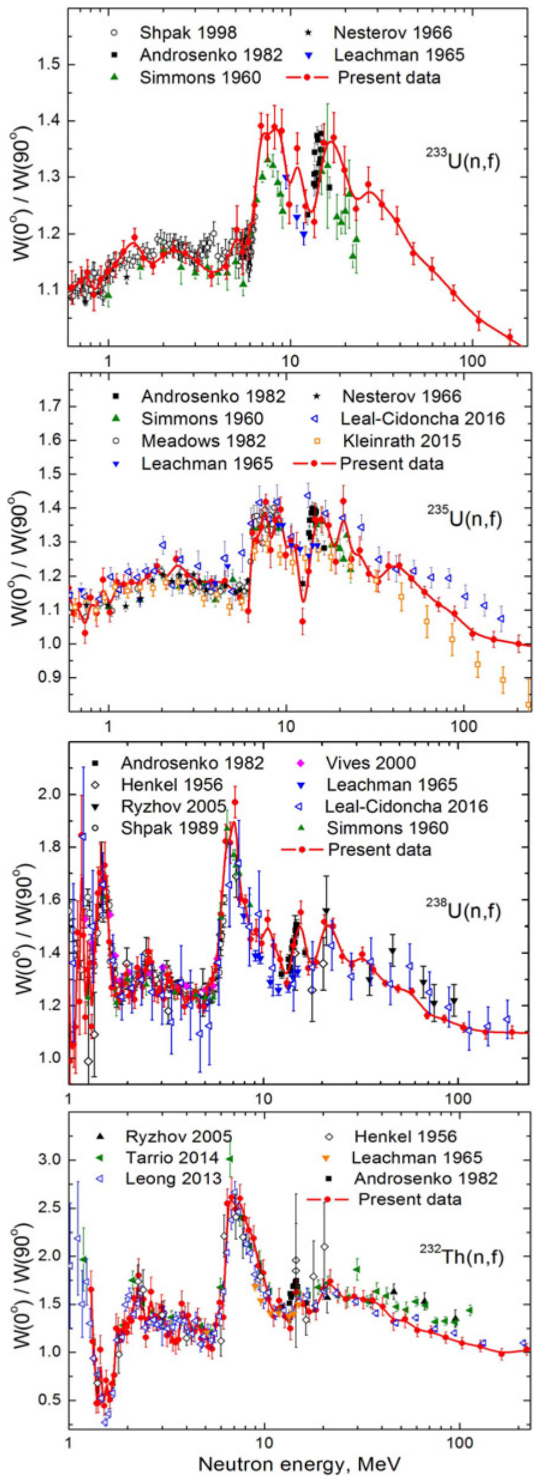

Figure 6. Anisotropy of fission fragment of investigated actinide nuclei compared with the experimental data of other authors [9–20]. The solid curve on each graph is only the eye guide to the experimental data.

such as GNEIS (PNPI) [1,2], n_TOF (CERN) [13–15] and WNR (LANSCE) [16]. This analysis gives the possibility to determine anisotropy of angular distribution of fission fragments and estimate systematical errors of used methods and experimental setups.

At the n_TOF facility (CERN), the studies of angular anisotropy of fission fragments were performed for a number of nuclei in the energy range up to 200 MeV. However, the situation with the data is ambiguous. These data are not available in EXFOR database except data of Tarrio et al [13]. For ^{232}Th isotope, the results of Tarrio et al. [13] and Leong [14] have small experimental errors, but differ significantly from each other (see Fig. 6). At the same time, the data for the ^{238}U nucleus [13–15] are the same within big experimental errors. The ^{235}U anisotropy data by Leal-Cidoncha [15] are located systematically above (∼2–3%) the data available in EXFOR. In neutron energy range above 50 MeV these data are higher than our data [1] (∼8% at 100 MeV).

At the WNR facility (LANSCE), the measurements of angular distributions of fission fragments were performed for ^{235}U and ^{239}Pu nuclei. Only the results of ^{235}U measurements are available and presented in PhD thesis [16]. There is a general agreement between these data and previous data in low neutron energy range 1–20 MeV. In neutron energy range above 50 MeV these data are lower than our data [1] (∼10% at 100 MeV). Also it is seen that the anisotropy is less than 1.0 at neutron energy about 100 MeV.

Our results may be summarized as follows:

- The angular distributions of fragments from fission of the ^{233}U, ^{235}U, ^{238}U, ^{232}Th and ^{209}Bi nuclei by neutrons in the energy range 1–200 MeV have been measured.
- For all actinide the anisotropy increases with the opening of each fission chance (n,f), (n,nf), (n,2nf), etc.
- In the neutron energy range below 20 MeV our data agree well with the numerous previously obtained results [9–20]. This confirms the reliability of the used method of measurement of angular distributions of fission fragments.
- In the energy region 20–200 MeV our data for ^{232}Th differ substantially from the n_TOF data given by Tarrio et al. [13] and Ryzhov et al. [12], but show an agreement within the experimental errors with the n_TOF data given by Leong[14]. As for ^{238}U isotope, the fission fragment anisotropies obtained by different experimental setup are approximately the same within the experimental errors. Herewith, uncertainties of our data are much smaller than those presented by Leal-Cidoncha et al. [15] and Ryzhov et al. [12]. Up to now, there were no experimental data on the fragment's angular anisotropy of ^{233}U for incident neutrons above 24 MeV. As mentioned above, for ^{235}U isotope there is disagreement between results obtained by us and at different TOF spectrometers. For example, the anisotropy measured by LANSCE and CERN groups differs by ∼20% at 100 MeV. Additional investigation should be performed.
- For ^{209}Bi, at the achieved accuracy level, it can be stated that at the energy of $\sim 50 \div 60$ MeV there is a maximum of the anisotropy equal to 1.6 ± 0.1 followed by a smooth descend with an increase of the neutron energy which resulted in a plateau about 1.2 ± 0.05 of height at ∼200 MeV. In literature there is the only one data point measured by Eismont et al. [8], where anisotropy is equal to 1.5 ± 0.2 at the neutron energy of ∼75 MeV. This result agrees with our data.

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