ANISOTROPY OF THE FISSION FRAGMENTS FROM NEUTRON-INDUCED FISSION OF ^{235}U, ^{238}U AND ^{232}Th IN INTERMEDIATE ENERGY RANGE 1- 200 MEV

A.M. Gagarski, A.S. Vorobyev, O.A. Shcherbakov, L.A. Vaishnene

NRC "Kurchatov Institute", B.P. Konstantinov Petersburg Nuclear Physics Institute, 188300, Gatchina, Russia

Abstract

Angular distributions of fission fragments from the neutron-induced fission of ^{232}Th, ^{235}U and ^{238}U have been measured in the energy range 1-200 MeV at the neutron TOF spectrometer GNEIS using position sensitive multiwire proportional counters as fission fragment detector. A description of the experimental setup and measurement procedure are presented. The anisotropy of fission fragments deduced from the data on measured angular distributions is presented in comparison with experimental data of other authors.

1. Introduction

The experimental data on angular distributions of fission fragments and cross-sections of neutron-induced nuclear fission are the principal source of information about fission barrier structure and the properties of transition states of fissioning nucleus passing through the fission barrier. After the decades of experimental research of the neutron-induced fission a vast amount of the relevant experimental data have been accumulated, but mostly for E_n < 20 MeV (E_n is the energy of incident neutrons). These data are not only of high scientific value, but of great significance for nuclear technologies as well. However, nowadays discussion on accelerator-driven systems (for nuclear power generation and nuclear transmutation) has created considerable interest to nuclear fission at intermediate (E_n < 200 MeV) and higher neutron energies.

In this paper new experimental data on angular distributions of fragments from fission of target nuclei ^{232}Th, ^{235}U and ^{238}U by neutrons with energies 1-200 MeV are presented. Measurements were carried out at 36 m flight path of a neutron time-of-flight (TOF) spectrometer GNEIS [1] utilizing the PNPI 1 GeV proton synchrocyclotron as a pulsed high-intensity spallation neutron source. Previously, the neutron-induced fission cross sections have been measured at the GNEIS facility for ^{233}U, ^{235}U, ^{238}U, ^{232}Th, ^{239}Pu, ^{240}Pu, ^{237}Np, ^{243}Am, ^{209}Bi, Pb and W nuclei in the same energy range 1-200 MeV [2,3] using the parallel plate fission ionization chamber (FIC) as a fission fragment detector. Analysis of the experimental data has shown the necessity of considering a correction for fragment anisotropy in the calculation of the fission fragments registration efficiency (the corrections on fragment anisotropy were also used in the determination of the ^{238}U/^{235}U fission cross section ratio for E_n < 1 GeV at the n_TOF facility at CERN [4]).

2. Experiment overview

Schematic view of experimental set-up is shown on Fig.1. In the present measurements we used fissile targets 120×120 mm^2 of size made by vacuum deposition of Th and U tetrafluorides on 2 μm Mylar foil. Their thicknesses were 100-150 μg/cm^2. Two position sensitive multiwire proportional counters (MWPC) 140×140 mm^2 of size [5] were used for fission fragment registration. The detectors were placed close to the target in the beam one after the other inside a stainless steel reaction chamber filled with isobutane working gas at a pressure of ~8 mbar The neutron beam diameter at the target position was equal to 75 mm. The neutron beam axis came through the geometrical centers of the target and MWPC's electrodes being perpendicular to them. An angle, θ, between neutron beam axis and fission fragment momentum has been obtained as $cos(\theta)$ from the coordinates of the fission fragment measured with two detectors (see Fig. 2).

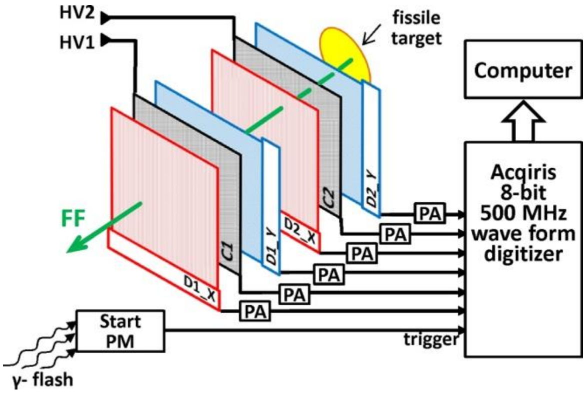
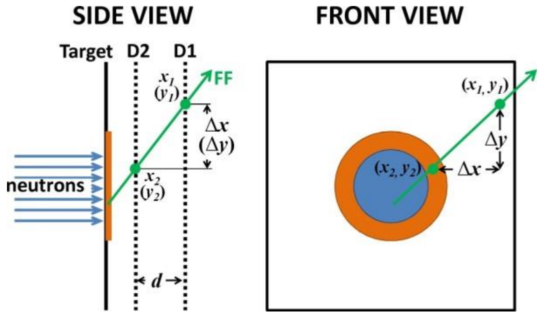


Fig. 1. Schematic view of the experimental setup: PA – preamplifier; PM – photomultiplier; HV – high voltage; FF – fission fragment; D1_X, D2_X – detector 1, 2 (X - axis); D1_Y, D2_Y – detector 1, 2 (Y - axis); C1, C2 – cathode 1, 2.



$$\cos(\theta) = \frac{d}{\sqrt{(\Delta x)^2 + (\Delta y)^2 + d^2}}$$

Fig. 2. Determination of the angle θ between normal to the plane of two MWPC electrodes and the fission fragment direction: D1, D2 – the MWPC 1 and MWPC 2 respectively; Δx (Δy) – the difference between x (y) coordinates of two MWPC.

Each one of the MWPCs consists of X and Y anodes wire planes made of 25 μm gilded tungsten wires and common cathode located between them. The cathode is made as a square mesh from the same wires. The wire spacing is 1 mm and anode-cathode gaps are about 3 millimeters. Every two (of 140) neighboring anode wires are connected to the 70 taps of delay line with a specific delay of 2 ns/step for coordinate information readout. The timing signals from corresponding ends of the delays carry position information. The coordinates are proportional to the time differences between cathode and anode signals. The two MWPC cathodes were installed at distance of 9 mm from each other, and the cathode of the first MWPC was 6 mm apart from the target. The assembly of two MWPCs inside the reaction chamber is shown in Fig.3. In Fig.4, a photo of the reaction chamber on the neutron beam is presented. The detectors arrangement used in the present measurements enables to cover the interval $0.16 < cos(\theta) < 1.0$. The data with $cos(\theta) < 0.3$ are much less accurate due to sharp decrease of the registration efficiency. To determine the energy of neutron, the TOF-technique was used with a flight path length ~ 37 m. The cathode signals of MWPC were used as STOP signals, whereas a "bare" PMT FEU-30, being installed at the neutron beam 1 m downstream the MWPC, produced START signal due to registration of a "gamma-flash".

A readout system (Fig.1) used three outputs from each MPWC, which were fed through the fast preamplifiers into 2 waveform digitizers (Acqiris DC-270, 8 bit resolution, 500 Ms/s sampling rate). The digitizers were triggered by signals from START photomultiplier for each accelerator pulse. The waveforms were stored on computer hard disk for offline reduction. Time and pulse-height analyses of the waveforms allowed to derive the neutron energy and the fission fragment coordinates on the MWPCs, and, hence, the angle information.

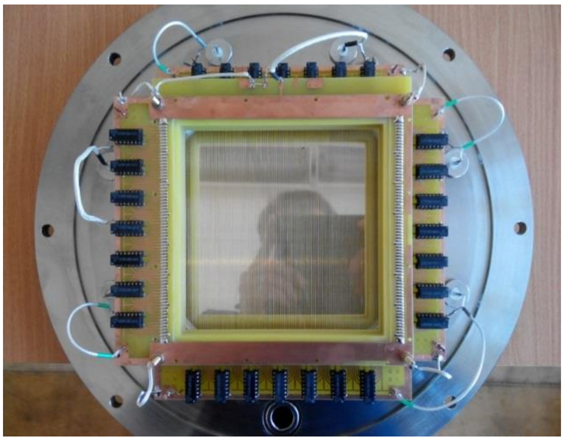


Fig. 3. Assembly of two MWPCs. Target to be installed from the top.

Fig. 4. View of the reaction chamber on the neutron beam.

3. Data processing

Assuming that the fragment angular distribution can be described by the function $W(\theta)\sim 1+b\cos^2(\theta)$, where $b = W(0^o)/W(90^o)-1$, the anisotropy parameters of angular distributions of fission fragments in the center-of-mass system, $W(0^o)/W(90^o) = b+1$, were deduced from the data on measured angular distributions in the laboratory system by fitting them in the range $0.4<\cos(\theta)<0.99$. To take into account the linear momentum contribution into the measured angular distribution, the anisotropy parameters obtained from the data accumulated with two set-up orientations relative to the beam direction (downstream and upstream) have been averaged. As it follows from Monte-Carlo simulation, in the fitting range the fission fragment efficiency registration is slightly varied about constant due to angular resolution of set-up, but on the average the result is not dependent on design features of the MWPC. Therefore, in the first approximation, it is not necessary to take into account any additional corrections to the measured angular distribution. Fig. 5 shows angular distributions for ^{232}Th, averaged over two set-up orientation relative to the neutron beam, obtained in different neutron energy intervals and the results of their fit.

4. Results and discussion

The anisotropy parameters are shown in Figs. 6-8 in comparison with the experimental data of other authors. The error bars shown include both statistical and systematic errors. The statistical errors were obtained directly from the fitting procedure. The systematical errors were estimated as a difference between anisotropy parameters obtained using two angular ranges for fitting: $0.4 < \cos(\theta) < 0.99$, and $0.48 < \cos(\theta) < 0.99$. A solid line connecting present data points is used solely for convenience of presentation. It must be admitted that near the fission threshold, as well as for lower energies, a contribution of the 4-th Legendre polynomial (or, more simply, of the term $\sim\cos^4(\theta)$) into the fragment angular distribution can be sizable (see, for example, Fig. 3 in Ref. [6]). However, at higher neutron energies only the 2-nd polynomial is of significance (see Fig. 5). Since this work is mainly dedicated to the high neutron energies, we used only the term $\sim\cos^2(\theta)$ for fitting the data. Thus, in principle, there exists some additional uncertainty for anisotropy parameter in the narrow energy range near the fission threshold and below. Nevertheless, even in this range, E_n =1÷2 MeV, as it follows from Fig. 6, there is an agreement (within the experimental uncertainties) of our data for ^{232}Th and the data other authors [6] obtained with an account for the 4-th Legendre polynomial.

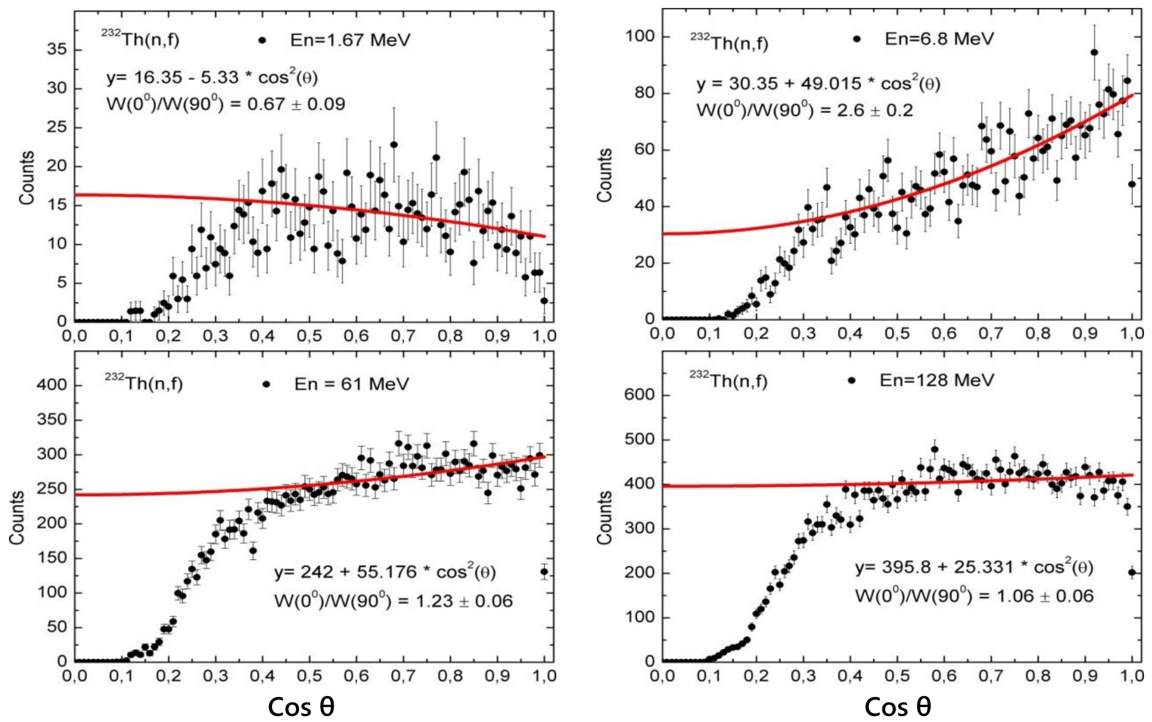


Fig. 5. Measured angular distributions and the results of their fit.

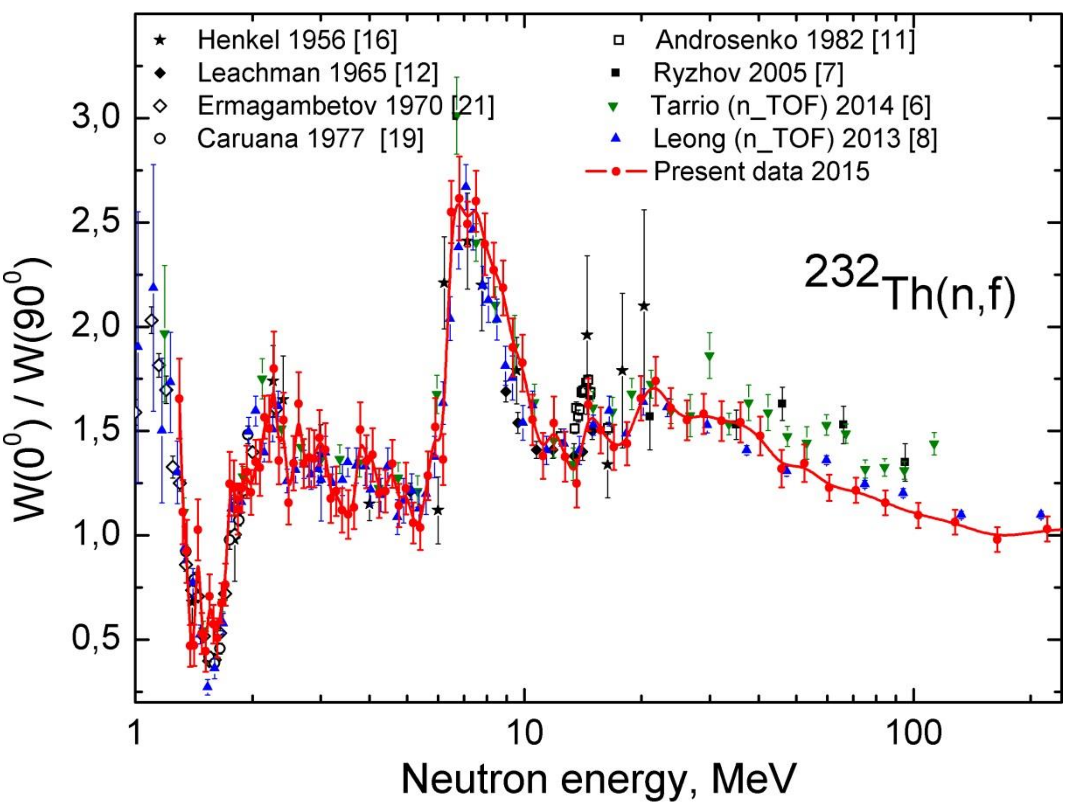


Fig. 6. Anisotropy of fission fragments of ^{232}Th

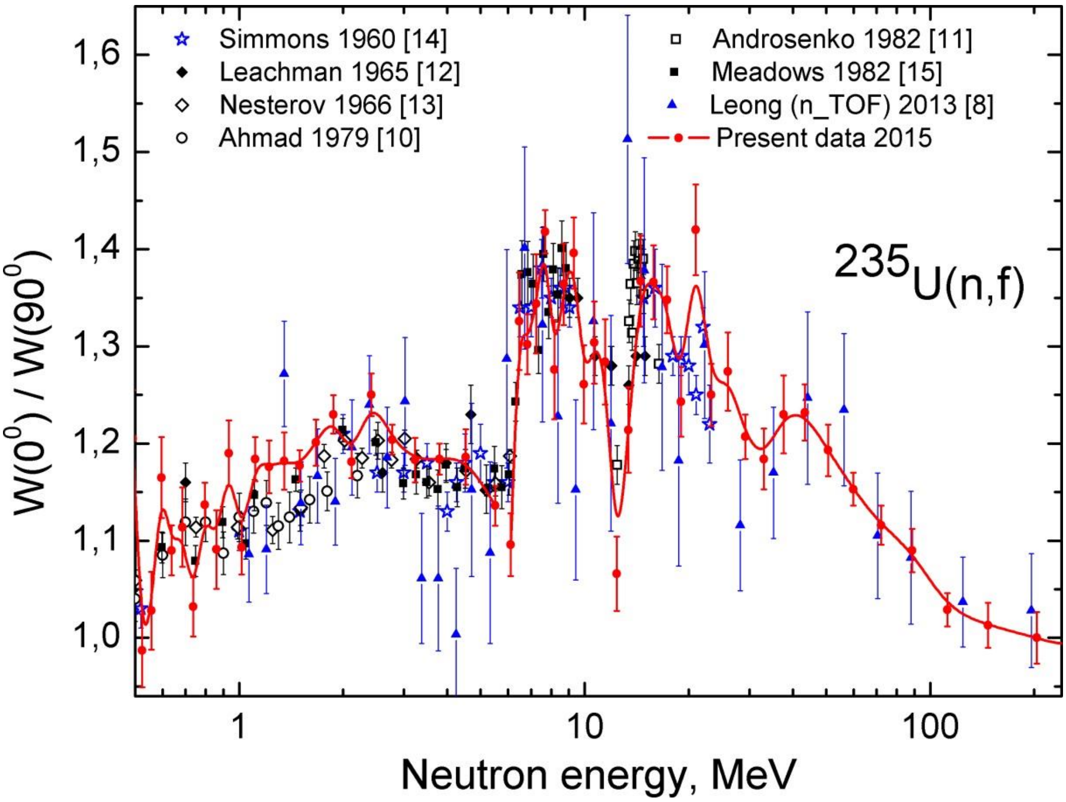


Fig. 7. Anisotropy of fission fragments of ^{235}U

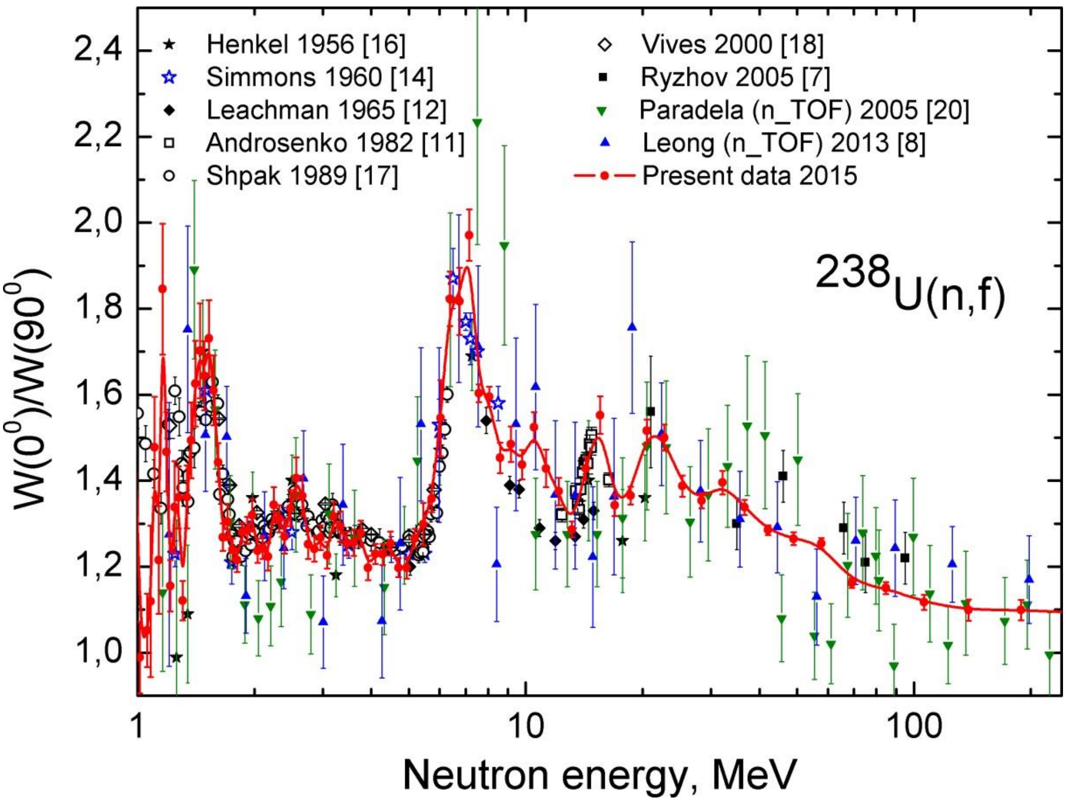


Fig. 8. Anisotropy of fission fragments of ^{238}U

Until recently in the energy range 20-100 MeV only the data by Ryzhov et al. [7] on the angular anisotropy of fission fragments for ^{232}Th and ^{238}U isotopes existed, while there were no data for neutron-induced fission of ^{235}U. It is also of interest that a significant difference in fission fragment angular anisotropy was observed for ^{232}Th and ^{238}U isotopes with the use of quasi-monochromatic neutron source [7]. The TOF spectrometers seem more appropriate, but currently only two neutron TOF facilities, namely, the GNEIS at PNPI and n_TOF at CERN, which enable to cover a whole energy range 1-200 MeV in a single measurement, are used for the measurements of fission fragment anisotropy.

At n_TOF, 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. For ^{232}Th isotope, the results by Leong [8] and Tarrio et al. [6] have small experimental errors, but differ significantly from each other (data from the work [6] are shown in Fig. 6). At the same time, for the nuclei of ^{235}U and ^{238}U there are only the data from n_TOF collaboration [8, 20], but they have high experimental errors (these data are shown in Figs. 7 and 8). Notice that in the paper by Paradela et al. [4], the n_TOF collaboration uses old data by Ryzhov [7] to correct registration efficiency for the fission fragment angular anisotropy (i.e. only for ^{238}U isotope in the energy range up to 100 MeV).

5. Summary and further plans

Measurements of the fission fragment angular distributions have been done for ^{235}U, ^{238}U and ^{232}Th in intermediate neutron energy range 1-200 MeV using TOF-technique. Low pressure position sensitive multiwire proportional counters (MWPC) were used for fission fragment registration. Anisotropy of fission fragments ($W(0^o)/W(90^o)$) has been obtained from the measured angular distributions. For all three nuclei the energy-dependent structure of the anisotropy demonstrates a strong correlation with the well-known step-like structure of fission cross-section [9]. Namely, the anisotropy coefficient increases with the opening of each fission chance (n,f), (n,nf), (n,2nf), etc.

In the low energy range up to 20 MeV an accuracy obtained in our experiments is comparable with that of previous experiments, and our data agree well with the numerous previously obtained results [6-8, 10-21]. This confirms the reliability of the used method of measurement of angular distributions of fission fragments.

Our present data obtained at GNEIS facility in the energy range 20-100 MeV for ^{235}U and ^{238}U are the most accurate ones. In the energy range 20-100 MeV, we do not endorse the result shown by Ryzhov et al. [7] about a significant difference in the anisotropy for ^{232}Th and ^{238}U. To the contrary, according to our data, the fission fragment anisotropies are approximately the same within the errors for these isotopes.

In the energy region 20-200 MeV our data for ^{232}Th differ substantially from the n_TOF data given by Tarrio et al. [6], but show an agreement within the experimental errors with another set of n_TOF data given by Leong [8]. As for ^{235}U and ^{238}U isotopes, uncertainties of our data in this energy region are much smaller than those presented by n_TOF collaboration in [6, 8, 20]

The accuracy of our data can be significantly improved by extension of the θ angular range using for fitting procedure up to $cos(\theta)>0.25$ instead of $cos(\theta)>0.4$ in the presented work. For this more precise study of the angular registration efficiency has to be undertaken. Namely we will perform precise Monte-Carlo simulation of the angular efficiency of the two MWPCs setup, and also we will calibrate the efficiency with isotopically emitting fission fragments from spontaneous fission ^{252}Cf source.

We note in conclusion that our data points for ^{232}Th and ^{238}U isotopes in the intermediate energy range that are presented in Figs. 6, lie not only below the data by Ryzhov et al. [7], but below the theoretical curve obtained in the same paper in the framework of the standard statistical model with account for pre-equilibrium processes. This means that some elements of this model require revision. We plan to perform such an analysis and to describe the results obtained for ^{232}Th and ^{238}U isotopes with zero spins, as well as for ^{235}U nucleus with a relatively high initial spin I=7/2.

Measurements with other isotopes like ^{233}U and ^{239}Pu are in the nearest plans of the fission fragment angular distributions studies at GNEIS facility.

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