ANISOTROPY IN THE FRAGMENTS EMISSION FROM FISSION INDUCED BY INTERMEDIATE ENERGY NEUTRONS (1- 200 MEV) IN ^{nat}Pb AND ^{239}Pu

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Abstract

New results of the neutron-induced fission experiments carried out at the neutron time-of-flight spectrometer GNEIS of the PNPI are given. Angular distributions of fission fragments from the neutron-induced fission of ^{239}Pu and ^{nat}Pb nuclei have been measured in the energy range 1-200 MeV using position sensitive multiwire proportional counters as fission fragment detector. The preliminary data on anisotropy of fission fragments deduced from the measured angular distributions are presented in comparison with the experimental data of other authors.

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).

We present here the results of recent measurements which continue the neutron-induced fission experiments at the neutron time-of-flight (TOF) spectrometer GNEIS [1] of the PNPI. In the previous papers [2-4] we have reported the data on angular anisotropy of fragments from neutron-induced fission of the target nuclei ^{233}U, ^{235}U, ^{238}U, ^{232}Th and ^{209}Bi in the intermediate energy range 1-200 MeV. The similar measurements recently were made at the n_TOF [5-7] for ^{235}U, ^{238}U and ^{232}Th nuclei, and at the LANSCE [8, 9] for ^{235}U nucleus.

The data for ^{239}Pu are of special interest due to its significance as fuel element. Up to now there were no experimental data for ^{239}Pu on the fragment's angular anisotropy for incident neutrons above 16 MeV (this is the upper limit of the rather old measurements [10-16]). In this paper the results of our study of the angular distribution of fragments from fission of ^{239}Pu nuclei by neutrons with the energies 1-200 MeV are presented.

Lead and ^{209}Bi are of interest due to their role in current and future nuclear power technologies. Lead-bismuth eutectic (alloy) is one of the primary coolant candidates for advanced nuclear reactors and Accelerator-Driven System. In addition to, this alloy is proposed as a target material for high power spallation neutron sources of new generation. Bismuth is also considered as a possible candidate to be used as a secondary standard for the cross section of neutron-induced fission because it is a mono-isotope with a high fission threshold about 40 MeV. Up to now, only one measurement of fragment angular anisotropy for ^{209}Bi has been performed with the use of quasi-monoenergetic neutrons of 75 MeV at The Svedberg Laboratory (TSL, Uppsala, Sweden) by Eismont et al. [17]. Our recent measurement was the first successful attempt to study the energy dependence of the fragment's angular anisotropy for ^{209}Bi in the neutron energy range from threshold up to 200 MeV [3, 4].

In a case of neutron-induced fission of lead there are no experimental data on fission fragment angular distributions and anisotropy at all. That is why the results of our measurements carried out for ^{nat}Pb in the neutron energy range up to 200 MeV are the data obtained for the first time.

2. General description of the experimental set-up

The measurements were carried out at the 36 m flight path of the neutron TOF-spectrometer GNEIS. A schematic view of the experimental set-up is shown in Fig. 1, 2. Detailed description of the set-up and delay line readout system created on the basis of waveform digitizers can be found in our previous publications [2, 3].

The ^{239}Pu (99.76 % enrichment) target 80 mm of diameter was made by conventional painting technique with a PuO_2 deposit on a 100 µm thick Ø100 mm Al-metal foil. The target thickness was 325µg/cm^2. The metal ^{nat}Pb target 120x120 mm^2 of size and 150 µg/cm^2 was made by vacuum deposition of high purity ^{nat}Pb on a 2 µm thick Mylar foil.

The fission fragment registration was performed by two coordinates sensitive multiwire proportional counters D1 and D2 (MWPC) 140x140 mm^2 of size [18]. The fragment counters D1 and D2 were placed close to the target in the beam one after the other. The neutron beam axis came through the geometrical centers of the target and the MWPC's electrodes being perpendicular to them. In order to have a possibility to take into account for the linear momentum contribution into the measured angular distribution, the measurements with two set-up orientations relative to the beam direction (downstream and upstream) were performed.

A value of cos(θ), 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.

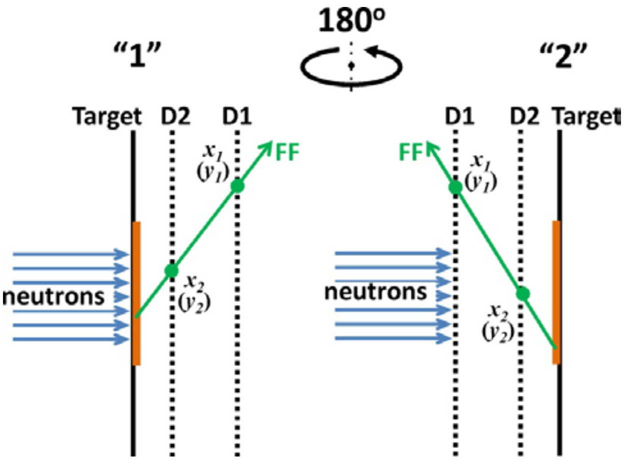

Fig. 1. Schematic view of the experimental set-up at two orientation relative to the neutron beam direction (downstream and upstream)

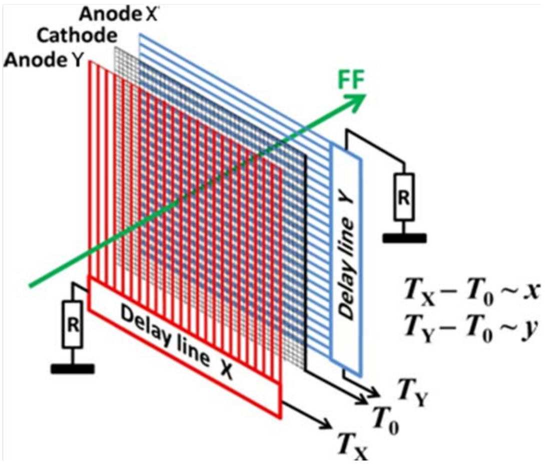

Fig. 2. Construction of the MWPC and principle of the coordinate determination

3. Data processing

The measured angular distributions for selected fission fragment events 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 (~2 mm). Also, the additional corrections due to the differential nonlinearity of the delay line chips and the mutual influence (signal crosstalk) of the anodes of two adjacent MWPCs were taken into account [3].

An anisotropy $W(0^o)/W(90^o)$ of angular distributions of fission fragments in the center-of-mass system were deduced from the corrected $\cos(\theta)$ angular distributions in the laboratory system for two set-up orientations relative to the neutron beam direction ($\cos(\theta)$ bins were equal to 0.01) 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 momentum contribution into the measured angular distributions, the measured anisotropies were averaged over two set-up orientations (downstream and upstream).

4. Results

The angular distributions of fission fragments in the centre of mass system for ^{239}Pu are presented in Fig. 3 for four neutron energy intervals, in comparison with experimental data of the other authors [10-13]. The results of the data fitting by the sum of even Legendre polynomials up to the 4-th order are also shown in Fig. 3.

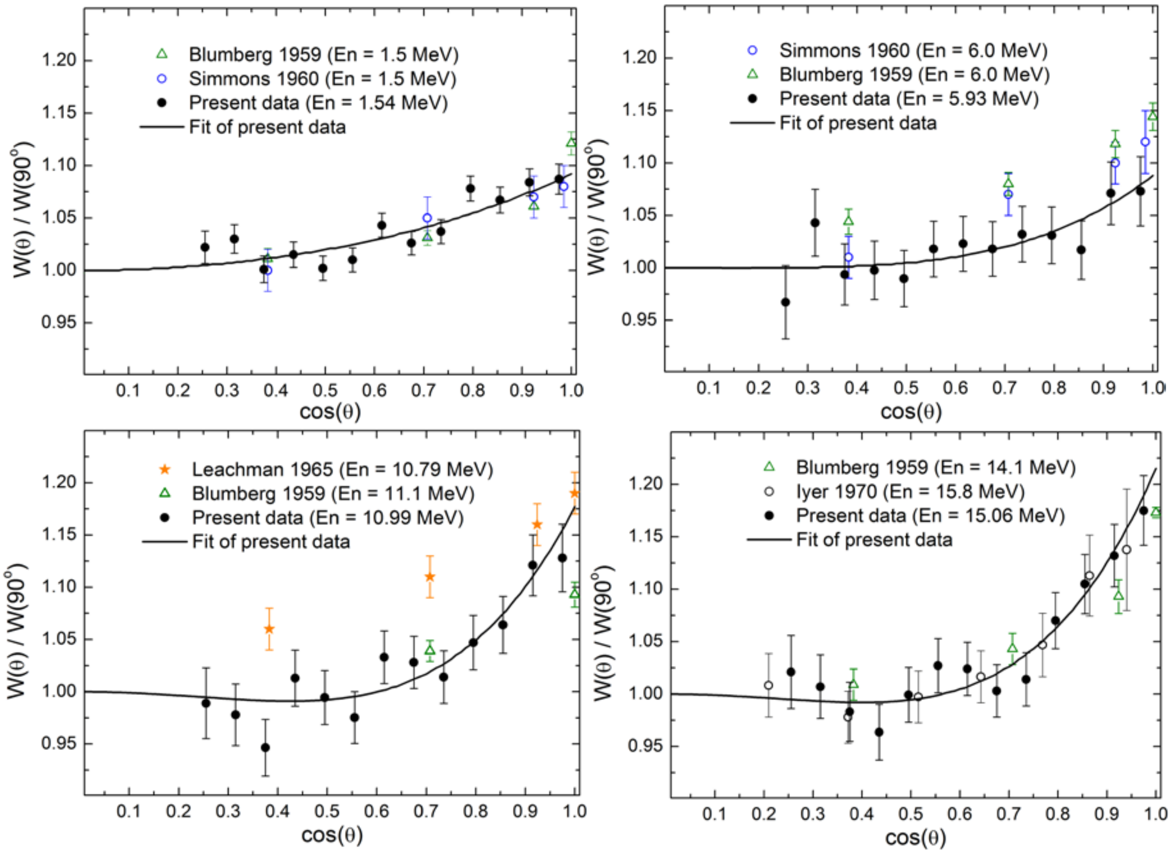

Fig. 3. Example of fission fragment angular distributions for ^{239}Pu. The error bars represent statistical uncertainties. Solid line is a result of the fitting by the sum of even Legendre polynomials up to the 4-th order.

The anisotropy W(0°)/W(90°) obtained from fitting of the fission fragment distributions measured in present work for ^{239}Pu and ^{nat}Pb in the neutron energy range 1-200 MeV are shown in Fig. 4.

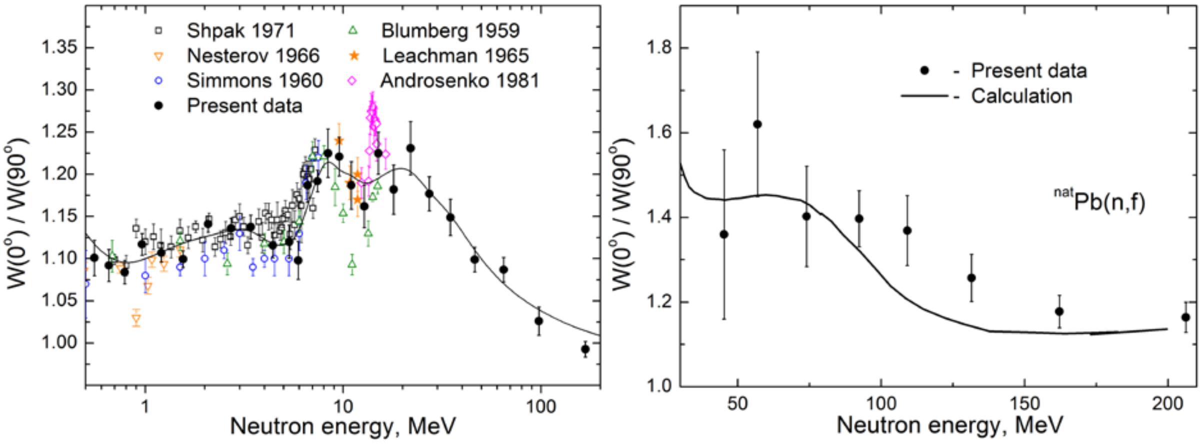

Fig. 4. Anisotropy of fission fragment of ^{239}Pu (left) and ^{nat}Pb (right) compared with the experimental data of other authors ([10-12, 14-16] for ^{239}Pu). The error bars represent statistical uncertainties. The solid curve for ^{239}Pu is only the eye guide to the experimental data while for ^{nat}Pb that is calculation from ref. [17].

As mentioned above, the results from EXFOR data base [19] on the fission fragment anisotropy for ^{239}Pu nuclei induced by neutrons with energies exceeding 1 MeV are not numerous. Apart from our data, the results of six former experiments are shown on Fig. 4. Only three data sets [11, 12, 15] deal with the data in the energy range 10-16 MeV.

At present the measurements with the ^{239}Pu target are continued. Therefore, status of the data presented in this report is PRELIMINARY. Nevertheless, some remarks and conclusions can be done right now. In the energy range below ~8 MeV our results agree within experimental uncertainties with the most complete data sets by Shpak [16] and Simmons [10]. In the energy range 10-16 MeV our data are between the “min” and “max” data points of Blumberg [11] and Androsenko [15], being in agreement with the data of Leachman [12]. Average value of the present uncertainties of our data is equal to 2÷3 % in the energy range 20 - 200 MeV.

An experimental data set on the energy dependence of ^{nat}Pb anisotropy in the neutron energy range 1-200 MeV has been obtained for the first time. As in a case of our data for ^{209}Bi, at the achieved accuracy level, it can be stated for ^{nat}Pb that at the energy of ~ 50-60 MeV there is a maximum of the anisotropy equal to 1.6±0.2 followed by a smooth descend with an increase of the neutron energy which resulted in a plateau about 1.15±0.05 of height. This behavior of the energy dependence of anisotropy qualitatively coincides with the result of theoretical calculations carried out by Eismont et al. [17].

5. Conclusion

New experimental data on the angular distributions of fragments from neutron-induced fission of the ^{239}Pu and ^{nat}Pb nuclei in the neutron energy range 1-200 MeV are presented. Apart from its significance for applications, these data are of great interest from theoretical point of view. Together with the other experimental results obtained in a course of present investigation, a vast amount of data for three different groups of nuclei, fissile (^{233}U, ^{235}U, ^{239}Pu), non-fissile (^{238}U, ^{232}Th) actinides and non-actinides (^{209}Bi, ^{nat}Pb) could provide valuable information to separate the contributions of equilibrium and pre-equilibrium processes to the evolution of nuclear spin alignment during the evaporation cascade. Thus the new directions to study nuclear dynamics at high excitation energies may be open.

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References

[1] N.K. Abrosimov, G.Z. Borukhovich, A.B. Laptev, V.V. Marchenkov, G.A. Petrov, O.A. Shcherbakov, Yu.V. Tuboltsev, and V.I. Yurchenko, Nucl. Instrum. Methods Phys. Res. A **242**, 121 (1985).

[2] A.S. Vorobyev, A.M. Gagarski, O.A. Shcherbakov, L.A. Vaishnene, and A.L. Barabanov, JETP Letters **102**(**4**), 203 (2015).

[3] A.S. Vorobyev, A.M. Gagarski, O.A. Shcherbakov, L.A. Vaishnene, and A.L. Barabanov, JETP Letters **104**(**6**), 365 (2016).

[4] A.S. Vorobyev, A.M. Gagarski, O.A. Shcherbakov, L.A. Vaishnene, and A.L. Barabanov, Proc. of the Int. Conf. "Nuclear data for Science and Technology ND-2016", September 11-16, 2016, Bruges, Belgium. EPJ Web of Conferences **146**, 04011 (2017).

[5] L.S. Leong, PhD Thesis, Universite Paris Sud, CERN-Thesis-2013-254.

[6] L.S. Leong, L. Tassan-Got, D. Tarrio, *et al*. Proc. of the Int. Conf. "Nuclear data for Science and Technology ND-2013", March 4-8, 2013, New York, USA. EPJ Web of Conferences **62**, 08003 (2013).

[7] E. Leal-Cidoncha, I. Duran, C. Paradela, *et al*. Proc. of the Int. Conf. "Nuclear data for Science and Technology ND-2016", September 11-16, 2016, Bruges, Belgium. EPJ Web of Conferences **111**, 10002 (2016).

[8] V. Kleinrath, PhD Thesis, Technischen Universitat Wien, 2015.

[9] V. Geppert-Kleinrath, F. Tovesson, J. S. Barrett, et al., arXiv preprint: 1710.00973, 2017.

[10] J.E. Simmons and R.L. Henkel, Phys. Rev. **120**, 198 (1960).

[11] L. Blumberg, R.B. Leachman, Phys. Rev. **116**, 102 (1959).

[12] R.B. Leachman and L. Blumberg, Phys. Rev. **137**, B814 (1965).

[13] R. H. Iyer, M. L. Sagu, in Proceedings of the Nuclear Physics and Solid State Physics Symposium, December 27–30, 1970; Madurai, India: Nuclear Physics, Vol. 2, p.57 (1970).

[14] V.G. Nesterov, G.N. Smirenkin, and D.L. Shpak, Yadernaya Fizika **4**(**5**), 993 (1966).

[15] Kh. D. Androsenko, G. G. Korolev, and D. L. Shpak, VANT, Ser.Yadernye Konstanty **46**(**2**), 9 (1982).

[16] D.L. Shpak, Yu.B. Ostapenko, G.N. Smirenkin, Soviet Journal of Nuclear Physics **13**, 547 (1971).

[17] V.P. Eismont, N.P. Filatov, A.N. Smirnov, et al. Proc. Int. Conf. "Nuclear Data for Science and Technology", September 26 – October 1, 2004; Santa Fe, N.M., USA. AIP Conference Proceedings **769**, 633 (2005).

[18] G.F. Knoll, Radiation Detection and Measurements, NY: J. Wiley, 3rd ed., 2000, p. 190.

[19] N. Otuka, E. Dupont, V. Semkova, B. Pritychenko, A.I. Blokhin, et al., Nuclear Data Sheets **120**, 272 (2014).