FISSION OF HEAVY NUCLEI BY LINEARLY POLARIZED PHOTONS

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Analysing power Σ data from photofission of ^{232}Th, ^{233}U, ^{235}U, ^{236}U, ^{238}U at the region of giant resonance have been measured using linearly polarized photons. The polarized photons were obtained by plane channelling of electrons in a silicon single crystal. The analysing power Σ dependence of the mass number of even-even nucleus has been discovered. Comparison of the analysing power Σ values with the data from other experiments with both polarized and unpolarized photon beams was made. It is shown that the analysing power Σ values agree with the modern knowledge of E1 transitions but cannot be explain by domination any one of them. It is supposed that analysing power Σ is very sensitive to different relative inner and outer fission barrier heights and this affects on Σ values for even-even nuclei with the same Z.
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1. INTRODUCTION

The investigation of fission of heavy nuclei by real photons is a convenient method for determining the spin and parity of collective nuclear states. Measurement of the angular distributions of fission fragments reveals the multipole structure of the process. In the vicinity of the fission barrier, the multipole structure is determined mainly by dipole (electric E1 and magnetic M1) transitions and, to a considerably lesser extent, by quadrupole (E2 and M2) transitions [1]. Such a small set of total moments of photons interacting with nuclei yields a restricted number of excited collective states, particularly for even-even nuclei This makes it possible to determine spin and parity of these states.

A new trend in the research of the fission process is the application of polarized photon beams. This opens new possibilities for investigation of the mechanism of fission process and for studying the structure of excited states. It permits one to understand the fission cross section dependence of the direction of the photon polarization vector and to measure the analysing power Σ of photofission. The Σ, a new observable that is possible to measure in experiments using polarized photon beam, is the second (following the cross section at unpolarized photons) independent characteristic of fission. It also contains information about the spin structure of excited collective states.

The application of polarized photon beams in studies of nuclear fission is at its very beginning. First such investigations were carried out in Giessen [2,3] and Kharkov [4,5]. In these works the analysing power of ^{232}Th and ^{236}U fission was measured.

In this paper, we represent the results of measurements of Σ in the fission of ^{232}Th, ^{233}U, ^{235}U, ^{236}U, ^{238}U nuclei by polarised photons in the energy range E_γ~5-20 MeV. Using modern theoretical concepts as a basis, we compare our experimental results with data from [2,3] and with the results of investigations of fission induced by unpolarized photons.

2. EXPERIMENTAL CONDITIONS

The experiment was carried out at the LINAC-2000 Kharkov Institute of Physics and Technology. Linearly polarized photons were obtained by transmitting electrons with the energy E_e=1200 MeV through the silicon single crystal under the conditions approaching channeling in the (110) plane. The intensity and the polarization degree (P_γ) of the photon beam was determined with a deuterium gas polarimeter, by measuring the proton yield from the reaction γ+d=p+n at an angle Θ=90° with respect to the photon beam. An experimental targets of thickness 500 μg/cm^2(^{232}Th), 115 μg/cm^2(^{233}U), 225 μg/cm^2(^{235}U), 186 μg/cm^2(^{236}U), 233 μg/cm^2(^{238}U) were deposited onto a nickel or an aluminum substrates of thickness 10 μm. The thickness nonhomogeneity of the targets is not more than 3%. Isotope enrichments were natural for ^{232}Th and ^{238}U and 98% for ^{233}U, ^{235}U and ^{236}U.

Fission fragments were detected at an angle Θ=90° with respect to the photon beam by 100 μm-thick

Semiconductor Surfacebarrier Detector (SSD). Amplitude spectra of the yield of protons emitted in the reaction γ+d=p+n and fragments formed in the fission were measured simultaneously for each of the three positions of the silicon single crystal: for the photon polarization vector parallel ($N_{\parallel}$) and perpendicular ($N_{\perp}$) to the reaction plane and for disoriented crystal (N_o). Protons detected in our experiment assumed to be produced by the direct photodisintegration of the deuteron, and the photon energy E_{γ} was determined in accordance with this hypothesis. The experimental data for the ratio

$$\beta = \frac{N_{II} + N_{\perp}}{2N_o} \quad (1)$$

show the radiation intensity from the oriented crystal comparing the radiation intensity from the disoriented crystal. The relative photon yield increases sharply with energy decreasing (from about 1.5 at E_{γ}=20 MeV to 5.6 at 5 MeV)[5].

An enrichment of the spectrum of the photons emitted from the oriented crystal takes place at energies up to 20 MeV, which falls within the region of the giant resonance. To eliminate the effect of photons with energies above 20 MeV, we subtracted the yield of reaction products measured for disoriented single crystal from the yield obtained for the oriented crystal. That is, the result was obtained only for the coherent part $(\beta-1)N_{\gamma}^{br}$ of the photon spectrum (N_{γ}^{br} is the spectrum of photons emitted from the disoriented crystal, i.e. bremsstrahlung spectrum).

The degree of polarization of the photon beam in the coherent part of the spectrum was defined as

$$P_{\gamma}^{c} = \frac{1}{\Sigma_{\gamma d \to pn}} \frac{N_{II}^{c} - N_{\perp}^{c}}{N_{II}^{c} + N_{\perp}^{c}} \quad (2)$$

where $N^c_{\parallel,\perp}=N_{\parallel,\perp}-N_o$ The value of $\Sigma_{\gamma d \to pn}$ was taken from [6].

The photon polarization for coherent part of the spectrum is nearly constant in the energy range E_{γ}=5.4-20 MeV, with an averaged value P_{γ}^{c}=0.77+0.17.

The coherent part $(\beta-1)N_{\gamma}^{br}$ of the photon spectrum was used to form a convolution with the photofission cross section (σ) from [7]. This convolution shows that we have measured the yield of fragments produced at the energies of the giant dipole resonance.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 AMPLITUDE SPECTRA AND MEASURED AZIMUTHAL ASYMMETRY OF FISSION FRAGMENTS YIELD

Under above experimental conditions, yields of fragments produced in the photofission of ^{232}Th, ^{233}U, ^{235}U, ^{236}U and ^{238}U were measured for three orientations of the silicon single crystal. Fig. 1 illustrates the amplitude spectra of fragments yield in ^{232}Th and ^{236}U fission. For clarity, curves are drawn through the experimental points. Fig. 1 shows that the yield of fission fragments for the oriented single crystal ($N_{\parallel}$ and $N_{\perp}$) is considerably larger than that for the disoriented one (N_o) and that the spectrum of $N_{\parallel}$ and $N_{\perp}$ differ one from another as a result of change in orientation of the photon polarization vector.

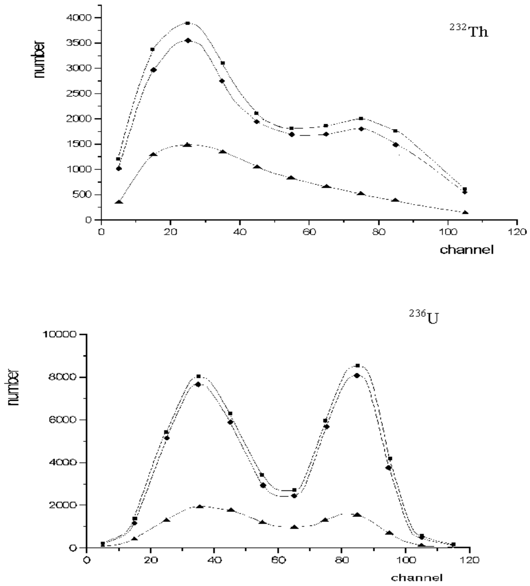

***Fig. 1**. Amplitude spectra of photofission fragments yields: (■) and (•) are the yields for photon polarization vector parallel ($N_{\parallel}$) and perpendicular ($N_{\perp}$) to the reaction plane and (▲) - for disoriented silicon crystal (N_o)*

The experimentally measured azymuthal asymmetry ε in the yield of fission fragments at Θ=90° for the coherent part of the photon spectrum was determined using the formula:

$$\varepsilon = P_{\gamma}^{c}\Sigma = \frac{N_{II}^{c} - N_{\perp}^{c}}{N_{II}^{c} + N_{\perp}^{c}} \quad (3)$$

3.2 THEORETIC FORMULAS

The theoretic formalism developed in [2,8] shows that the analysing power in fission induced by polarized photons may be compared with the coefficients of the angular distribution of fission fragments for unpolarized photons. Previous investigations of the fission of the nuclei being discussed showed the dominant role of E1 transitions in the energy region of giant dipole resonance. The contribution of the E2 and M1 components is significantly smaller then the E1 contribution.

In the dipole approximation, the analysing power in fission has the form

$$\Sigma(90^o)=\omega b/(a + b) \quad (4)$$

and the cross section

$$d\sigma/d\Omega(\Theta)=a+b\cdot sin^2(\Theta) \quad (5)$$

where ω=1 for electric and ω=-1 for magnetic transitions.

The coefficients a and b may be expressed through σ (J^π,K) – the cross section of the excitation of the collective state with fixed quantum numbers: J, the spin of a compound nucleus; π, its parity; and K, the projection of J onto the symmetry axis of the nucleus. For electric excitation:

$$a=3/2\cdot\sigma(1^-,\pm1) \quad (6)$$

$$b=3/4\cdot\sigma(1^-,0)-3/4\cdot\sigma(1^-,\pm1) \quad (7)$$

In the case of any one state excitation only the analysing power have the value not dependent of the excitation energy

$$\Sigma(1^-,0)=1, \quad (8)$$

$$\Sigma(1^-,\pm1)=-1. \quad (9)$$

3.3 ANALYSING POWER Σ OF ^{232}Th

Fig. 2 presents the existing experimental data for the Σ of fission together with Σ values obtained from known values of a and b under the assumption that fission is governed by the dipole transition alone.

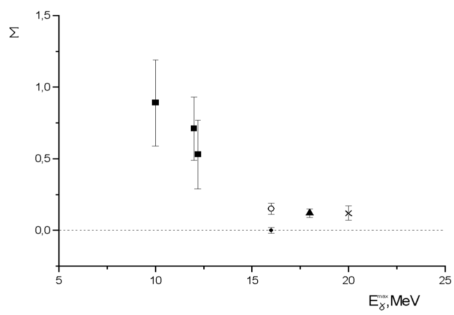

Fig. 2. *The analysing power Σ of ^{232}Th photofission as a function of the maximum energy E_γ^{max} of the photon spectrum: (×) - bremsstrahlung photons [10]; (•) - electrons, virtual photons [11]; (o) - positrons, virtual photons [11]; (■) - bremsstrahlung polarised photons [2]; (▲) - polarised photons obtained at channelling (our work)*

These measurements were performed with a bremsstrahlung spectrum, and not with monochromatic photons. For this reason, the energy at which measurements were made ranges from photofission barrier (5.8 MeV) to the maximum photon energy used in the experiments, and the experimental values are located at the maximum photon energy. Our Σ value is given in Fig. 2 at E_γ=18 MeV.

Of all the data obtained in experiments with an unpolarized photon beam, only the part that covers our energy range most completely is used for constructing Fig. 2. It also shows the data on electron- and positron induced fission of ^{232}Th nucleus [11] at 16 MeV, along with the data obtained in experiments with a polarized bremsstrahlung photon beam at maximum energies of 10 and 12 MeV [2]. It should be noted that additional data obtained using a polarized bremsstrahlung photon beam in the energy range 10-12 MeV [3] (and not presented in Fig. 2) shows good agreement with the results represented in [2].

It can be seen from Fig.2 that, in spite of the difference in photon spectra (bremsstrahlung photons, virtual photons obtained using electron and positron beams, and the coherent part of the photon spectrum formed during channeling), the analysing power Σ values are in a rather good agreement one with another at the energy E_γ=15-20 MeV. Thus, in the energy range under study, the quadrupole excitation does not manifest itself in the analysing power Σ of fission (which is a new observable of the process) within the experimental error.

Comparison of our results with the data obtained in [2] by direct measurement of the Σ reveals a considerable discrepancy in the values determined by these two methods. This can be attributed to the fact that different ranges of photon energies were used in the two studies. It was shown in [10,12] that the coefficient b decreases from unity to zero (the angular distribution of fragments becomes increasingly isotropic) with increasing E_γ; hence, the Σ also tends to zero with increasing E_γ.

It can be seen from the formula (4) that the sign of Σ in the case of dipole excitation is opposite for electric and magnetic transitions. The positive Σ value obtained by us shows that the energy range under study is dominated by the electric dipole transition.

3.4 ANALYSING POWER Σ OF ^{236}U

Fig. 3 shows the value of Σ for ^{236}U obtained by us, results of work [3], and values of Σ calculated from coefficients a and b [11] as a function of maximum photon energy (E_γ^{max}). Value of the analysing power Σ from [3] was obtained by using the value of photon beam polarization from work [2]. Our result is shown for E_γ^{max}=18 MeV.

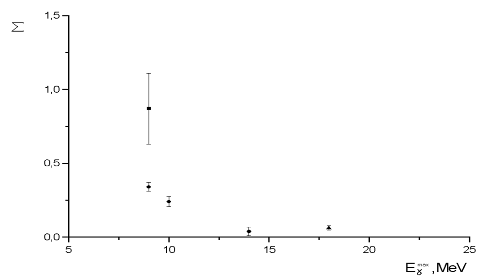

Fig. 3. *The analysing power Σ of ^{236}U photofission as a function of the maximum energy E_γ^{max} of the photon spectrum: (•) - work [13], (■) - work [3], (▲)- our work*

One can see from Fig. 3 that neither the (1^-, 0) state nor the (1^-, ±1) state dominates in the region of the giant resonance. Asymmetry of fission, reported in work [3] agrees with our result only in sign, but is significantly bigger. This may be so, because the (1^-, 0) state dominates at the small energy. The contribution of the (1^-,±1) state become bigger with E_γ^{max} increasing and correspondingly the coefficient *b* decreases (the angular distribution becomes more isotropic) that leads to Σ decreasing. Most close to our energy region are results of work [10], where the value of *b/a* decreases and tends to zero with E_γ^{max} increasing and, therefore, the Σ also will tend to zero according to expression (4). The value of analysing power Σ obtained by us agrees with the Σ behavior from results of work [10]. It is necessary to mention that our result, nevertheless, differs from zero. It means that angular distribution should not be isotropic for the giant resonance region.

3.5 ANALYSING POWER Σ OF ^{238}U

Fig. 4 shows the results for ^{238}U of our measurements and values of Σ obtained from the coefficients *a* and *b* for different E_γ^{max} and E1 transition assumptions. All experimental data for E_γ^{max}>12 MeV existing now are shown here except the results of work [13] for E_γ^{max}=12.01 and 14.02 MeV, which coincide with the data shown in Fig.4 within the limits of experimental error. The value from work [14] for E_γ^{max}=20 MeV is moved to 0.3 MeV for picture clarity. Our result is shown at E_γ^{max}=18 MeV.

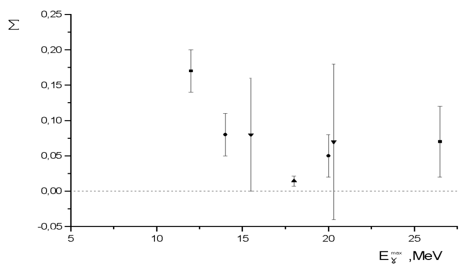

Fig. 4. *The analysing power Σ of ^{238}U photofission as a function of the maximum energy E_γ^{max} of the photon spectrum: (•) - works [10,17], (■) – work [18], (▼) – work [14], (▲) - our work*

As for ^{236}U the measured value of Σ differs significantly from Σ of any of dipole fission channels (1^-, 0) or (1^-,±1).

From comparison between our measurements and the results obtained by calculation from coefficients *a* and *b* it is seen that they coincide very good in spite of the fact that the measurements were made by different research groups with the photon spectrum that differs from ours. It means that the manifestation of E2 transition is not observed in the new observable (analysing power Σ).

3.6 ANALYZING POWER Σ OF ^{233}U AND ^{235}U

The theoretic formulas from [2,8] are not valid for these nuclei. It is not possible to write such simple equation for the angular distribution at unpolarized photons and the analyzing power at polarised photons comparison as for even-even nuclei. The main reason of this is the nonzero spin and therefor a big number of spin projections (K).

But from general reasons the Σ should be close to zero. For these nuclei with spin $5/2^+$ (^{233}U) and $7/2^-$ (^{235}U) even the E1 excitation gives the big number of intermediate states with different (J^π, K). It is improbable that such big number of excited states gives the Σ value, which differs from zero.

Our results ((-1.17±1.07) 10^{-2} for ^{233}U and (-6.23± 3.76) 10^{-2} for ^{235}U) confirm these assumptions.

3.7 MASS NUMBER DEPENDENCE OF THE ANALYZING POWER OF EVEN-EVEN NUCLEI

The values of Σ for even-even nuclei ^{232}Th, ^{236}U, ^{238}U measured by us differ significantly one from another. The Σ obtained in our experiments is shown in Fig. 5a as a function of mass number (A). One can see that analyzing power decrease with mass increasing.

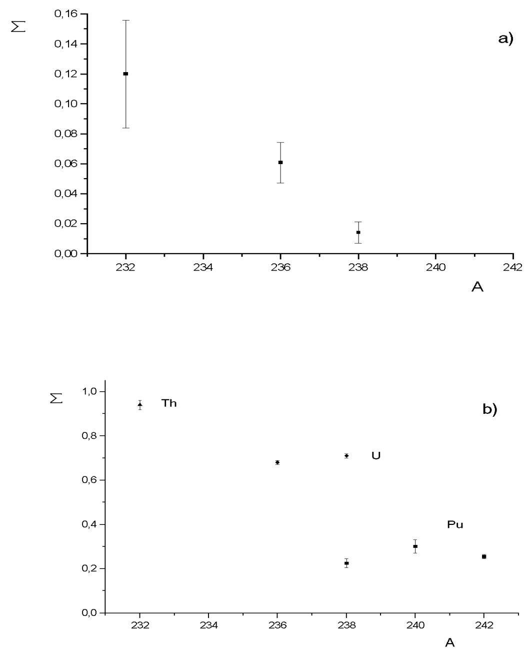

Fig. 5. *Mass number dependence of the analyzing power Σ. a) our work. b) from works [9,15] for E_γ^{max}=7 MeV*

For all three elements Σ values agree well with the Σ calculated from *a* and *b* coefficients on the basis of E1 assumption. Therefore, it is interesting to compare our analyzing power mass number dependence with the analyzing power mass number dependence calculated from these coefficients near the barrier, where the experimental errors are significantly smaller than at E_γ^{max}~20 MeV and there are the experimental results for bigger number of elements. To eliminate the systematic errors of different experiments it is necessary to compare the results of coefficients *a* and *b* measurements obtained by one experimental group. Fig.5b shows Σ mass number dependence calculated from the results of work [10,15] for E_γ^{max}=7 MeV. If for this E_γ^{max} the experimental result was absent, the necessary data were obtained by the linear interpolation of results for nearest E_γ^{max}. It is seen from Fig. 5b that the calculated Σ has clear dependence on the charge of the nucleus (Z) and it is practically constant while the number of neutrons (N) is changed for nuclei with the same Z. Such dependence is the result of the well known effect of the angular distribution of fission products "anomaly", which reflect the arbitrary value of inner and external fission barrier dependence on Z (see for example [16]).

Accuracy of Σ values obtained by us is significantly higher than the accuracy of calculated results in the same region of E_γ^{max}. The difference of Σ values for ^{236}U and ^{238}U is more than three standard deviations and the probability that this difference has an accidental character is small. The existence of analyzing power dependence not only on Z but also on N means that either there is the contribution of another (not E1) multipole, or such kind of measurements is very sensitive to different relative inner and outer fission barrier heights and this effect is observed in our experiments for the nuclei with the same Z.

4. CONCLUSION

The measurements of the cross section analyzing power Σ of ^{232}Th, ^{236}U and ^{238}U in the giant dipole resonance region carried out by us show the sensitivity of the fission cross section to the polarization vector direction. The obtained values of the Σ can not be explain by domination of either channels (1^-, 0) or (1^-,± 1) but agrees with the modern knowledge of E1 domination in this energy region.

The analyzing power Σ dependence on the nucleus mass is observed. Such dependence cannot be explained on the basis of E1 transition and by existing now results of the experiments with unpolarized photons. So, it will be very interesting to carry out the systematic investigation of even-even nuclei analyzing power mass number dependence especially near the barrier.

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