A study of photofission on $^{181}$Ta nucleus induced by Bremsstrahlung with endpoint energies of 50 and 3500 MeV has been performed. The fission yields have been measured by using induced-activity method in off-line analysis. The absolute photofission cross sections for the tantalum target at 50 and 3500 MeV are found, respectively, to be $5.4 \pm 1.1 \mu b$ and $0.77 \pm 0.11 \mu b$, and the corresponding deduced fissilities are $(2.3 \pm 0.5) \times 10^{-4}$ and $(2.9 \pm 0.9) \times 10^{-3}$. Mass- and charge-yield distributions were derived from the data. Results of this work and also of the reaction $^{238}$Pb+$^{7}$Li at 245 MeV and of the system $^{197}$Au+$^{2}$H at 4.4 GeV, and were compared with the simulation of CRISP code for multi-modal fission by assuming the symmetrical mode of fission. It have been concluded that at intermediate energies of incident particle symmetric fission makes the highest contribution to the observed fission cross section of pre-actinide nuclei.

PACS numbers: 24.75.+i, 25.85.Jg

1 Introduction

Fission is a slow process on a nuclear timescale, involving deformation of the whole nucleus, and is always a compound process. It has been studied over a wide energy range and the information obtained from experimental fission data encompassed different characteristics of the fissioning system.

Photofission is one of the most powerful tools for studying the fission process because of the well known spin selectivity of the excitation and the absence of the Coulomb barrier. The main experimental problem in photofission studies is the lack of intense sources of monochromatic photon beams. Therefore, big amount of photofission mass distributions have been measured in Bremsstrahlung spectra with a continuous energy distribution in the energy region 300-1800 MeV, and hence the excitation energy is not well defined [1–4].

In some papers the photofission studies in the intermediate and high-energy region by monochromatic photons was intensively investigated using different experimental techniques [5–9]. In all these experiments the photofission cross section and related fissility were determined for pre-actinide targets with fissility parameter $Z^2/A < 31.6$. As
it was mentioned in [2, 7] at low incident energies pre-actinide nuclei do not exhibit (≤ 30 MeV) the resonance pattern characteristic of the fission cross section. For nuclei of mass number $A < 210$ the trends of the photofission cross section and of the fissility (the ratio of fission cross section to total nuclear photoabsorption cross section), show conversely an increase of several orders of magnitude from fission threshold (≈ 20-30 MeV) up to about 200 MeV.

In spite of the large amount of the data, experimental values for intermediate photon energies are unexpectedly scattered. This is due to the use of bremsstrahlung beams as photon sources, which gives large contributions to fission from giant-resonance energy photons. However, for lighter elements, $Z < 83$, the giant-resonance fission contribution is unimportant because of higher fission thresholds (22-27 MeV [6]) and smaller values of the parameter $Z^2/A$. It is well known that fission is predominantly symmetric for pre-actinides with $A ≤ 227$ due to the nature of the experimental setup.

Mass distributions from actinide fission induced by different projectiles at intermediate energies are possess both symmetric and asymmetric fission modes. These mass distributions can successfully be represented by five Gaussians, and less than five Gaussians were adequate for the pre-actinides and higher actinides where increased symmetric fission is observed [10]. Symmetric fission components have been observed in all photofission experiments with pre-actinides but analysed in different ways so that the results are difficult to compare.

The essential goal of this paper is the measurement of the formation cross sections of fission fragments of $^{181}$Ta nucleus induced by Bremsstrahlung with endpoint energies of 50 and 3500 MeV as well as represent the additional cross section measured for $^7$Li+$^{nat}$Pb system at projectile energy 245 MeV. In this experiment the total fission cross section of $^{181}$Ta, $^{nat}$Pb and $^{197}$Au targets from [1] were derived from the experimental yields/cross sections of fission fragments and from the off-line measured photon spectra using induced-activity method.

Comparison with the results of calculations by CRISP code based on the symmetric and asymmetric fission approach (multi-modal fission) [11] made it possible to determine the contribution of each mode to the total mass-yield of fragments resulting the binary decay of compound nuclei.

### 2 Experimental Procedure

The irradiation in our experiments was performed in beams of bremsstrahlung photons obtained by using electrons of the Yerevan electron synchrotron at an energy of 3500 MeV and a linear accelerator of the injector type at an energy of 50 MeV. The electrons were converted into a bremsstrahlung-photon beam by means of tungsten converter about 300 μm (about 0.1 radiation-length units) in thickness. The photon-beam intensity was determined in units of equivalent photons per second. The reaction chamber at the injector was arranged immediately after the converter. The beam intensity was measured by means of a Faraday cylinder. A target from $^{181}$Ta 0.164 g and 0.0487 mm thick had a natural isotopic composition. An additional monitoring of the beam was performed by irradiating $^{27}$Al and $^{65}$Cu foils about 50 μm thick. The yields in the reactions $^{27}$Al(γ, 2pn)$^{24}$Na and $^{65}$Cu(γ, n)$^{64}$Cu are known from data published in the literature [12]. The irradiation time was 43 min at an average photon-beam intensity of about $≈ 10^{11}$ eq. q. s$^{-1}$.

A beam-cleaning and beam-formation system was used in the irradiation with a beam of high energy photons. The product photon beam passed through the first collimator $3 × 3$ mm$^2$ in dimensions and a cleaning magnet, which removed the charged component, and the second collimator $10 × 10$ mm$^2$ in dimensions removed the beam halo. Tantalum targets of size indicated above were irradiated for 196 min. The photon-beam intensity was measured by a Wilson-type quantometer and was on average about $≈ 10^{11}$ eq. q. s$^{-1}$. equivalent photons per second. The yield in the reaction $^{27}$Al(γ, 2pn)$^{24}$Na was measured additionally; experimental data in this region were published at $E_{\gamma_{\text{max}}}$ = 3000 MeV [13].

The yields of radioactive fission fragments were measured in the off-line mode with a semiconductor high-purity germanium (HpGe) detector (80 cm$^3$) of resolution about 0.2% at the $^{60}$Co γ-transition energy of 1332 keV. The γ-spectrometer detection efficiency for four values of the target-detector distance (0, 2, 7, and 25 cm) was determined by using the standard radiation sources $^{22}$Na, $^{54}$Mn, $^{57,60}$Co, and $^{137}$Cs. In order to obtain a more comprehensive pattern of the energy dependence of the detector efficiency in the region of energies above 1500 keV, we employed data on the yield in the reaction $^{27}$Al(γ, 2pn)$^{24}$Na (Eγ = 2754 keV). On the basis of the data that we obtained, we determined the energy dependence of the HpGe-detector efficiency to a precision of 10%. Measurements of the γ spectra started about 120 minutes after the completion of the irradiation and lasted for a year.

The identification of the reaction products, and the determination of their production cross section, were performed using data from [14] by means of half-lives, energies and intensities of γ-transition of radioactive fragments.

In the absence of a parent isotope, the cross section of fragment production for each fragment is determined using the following equation:
where $Y$ denotes the cross section of the reaction fragment production (mb); $\Delta N$ is the area under the photopeak; $N_p$ is the projectile beam intensity (min$^{-1}$); $N_n$ is the number of target nuclei (in 1/cm$^2$ units); $t_1$ is the irradiation time; $t_2$ is the time of exposure between the end of the irradiation and the beginning of the measurement; $t_3$ is the time measurement; $\lambda$ is the decay constant (min$^{-1}$); $\eta$ is the intensity of $\gamma$-transitions; $k$ is the total coefficient of $\gamma$-ray absorption in target and detector materials, and $\epsilon$ is the $\gamma$-ray-detection efficiency.

Usually, the cross section of an isotope production in the reaction under investigation is direct and independent (I) of the parent nuclei decay, and the cross section is determined by the eq. \([\text{1}]\). If the yield of a given isotope receives a contribution from the $\beta^\pm$-decay of neighboring unstable isobars, the cross section calculation becomes more complicated \([\text{15}]\).

If the formation probability for the parent isotope is known from experimental data or if it can be estimated on the basis of other sources, then the independent cross sections of daughter nuclei can be calculated by the relation:

$$Y_B = \frac{\lambda_B}{(1 - \exp(-\lambda_B t_1)) \exp(-\lambda_B t_2)(1 - \exp(-\lambda_B t_3)) \times \left[ \frac{\Delta N}{N_p N_n k \epsilon \eta} - Y_A f_{AB} \frac{\lambda_A \lambda_B}{\lambda_B - \lambda_A} \left( \frac{(1 - \exp(-\lambda_A t_1)) \exp(-\lambda_A t_2)(1 - \exp(-\lambda_A t_3))}{\lambda_A^2} \right. \right.}$$

$$\left. \left. - \frac{(1 - \exp(-\lambda_B t_1)) \exp(-\lambda_B t_2)(1 - \exp(-\lambda_B t_3))}{\lambda_B^2} \right] \right],$$

where the subscripts $A$ and $B$ label variables referring to, respectively, the parent and the daughter nucleus; the coefficient $f_{AB}$ specifies the fraction of $A$ nuclei decaying to a $B$ nucleus (this coefficient provides the idea of how much the $\beta$-decay affects our data; and $f_{AB} = 1$, when the contribution from the $\beta$-decay corresponds 100%); and $\Delta N$ is the total photo peak area associated with the decays of the daughter and parent isotopes. The effect of the forerunner can be negligible in some limit cases – for example, in the case where the half-life of the parent nucleus is very long, or in the case where the fraction of its contribution is very small. In the case when parent and daughter isotopes could not be separated experimentally, the calculated cross sections are classified as cumulative ones (C).

### 3 Results and Discussion

For Ta target, the mass distribution is extracted from the measured cumulative and independent isotope yields by fitting the mass and charge distribution. The fission process is assumed to be symmetric for the sub-actinide targets. Therefore, the mass and the charge distribution for a given mass are each described by a single Gaussian in the fit. Moreover, the assumption is made that the most probable charge, as well as the width of the charge distribution, vary very long, or in the case where the fraction of its contribution is very small. In the case when parent and daughter isotopes could not be separated experimentally, the calculated cross sections are classified as cumulative ones (C).

$$Y_{A,Z} = \frac{Y_A}{\Gamma_z \pi^{1/2}} \exp \left( \frac{-(Z - Z_p)^2}{\Gamma_z^2} \right),$$

where $Y_{A,Z}$ is the independent yield of the nuclide $(Z, A)$. The values $Y_A$ (the total chain yield for given mass number $A$), $Z_p$ (the most probable charge for $Z$ distribution isobars with mass number $A$) and $\Gamma_z$ (the width parameter). The values $Z_p$ and $\Gamma_z$ can be represented as slowly varying linear functions of the mass numbers of fission fragments:

$$Z_p = \mu_1 + \mu_2 A,$$

$$\Gamma_z = \gamma_1 + \gamma_2 A,$$

where $\mu_1$, $\mu_2$, $\gamma_1$ and $\gamma_2$ are adjustable parameters.

The mass distribution of fission fragments, constructed by using of obtained values of $Y_A$, is obtained by the fitting procedure in the form \([\text{10}]\).
\[ Y_f = \lambda_A \exp \left( -\frac{(A - M_A)^2}{\Gamma^2_A} \right) \]  
\[ (6) \]

The curve in eq. (6), representing the mass distribution, is defined by a height \( \lambda_A \), a mean mass \( M_A \), and a width \( \Gamma_A \). The result of the summation over all mass numbers of the fission fragments allows the estimation of the total fission yield. We multiply it by a factor 0.5, due to the two fission fragments in each event.

In the case of sub-actinide targets it is not possible to calculate the competition between symmetric and asymmetric fission modes. Results of the fission channel search in \(^{181}\)Ta exhibit broad mass-yield distribution.

The yields of fragment production of Ta induced by photon beams with Bremsstrahlung energy \( E_{\gamma_{\text{max}}} = 50 \) and 3500 MeV are presented in Table I. In total, for two energies 61 yield are calculated in the fragment mass region \( 7 < A < 70 \) amu. The quoted errors in determining yields received contributions from those associated with the statistical significance of experimental results (\( \leq 2-3\% \)), those in measuring the target thickness (\( \leq 3\% \)), and those in determining the detector efficiency (\( \leq 10\% \)).

The total fission mass yields at two end-point energy of photons are plotted in Fig. 1 and 2, together with the mass distribution obtained in the fit for \(^{181}\)Ta target. The results agree with the assumption of a symmetric mass and charge distribution.

Integrating over the Gaussian and multiplying by a factor 1/2, because of the two fission fragments in each fission event, gives an estimate for the fission yield. The values for the fission yields \( Y_f \) determined in this way for \( E_{\gamma_{\text{max}}} = 50 \) and 3500 MeV have consisted \( 5.4 \pm 1.1 \, \mu\text{b} \) and \( 0.77 \pm 0.11 \, \mu\text{b} \), respectively. The obtained measured total fission cross section at 50 MeV is in good agreement with the experimental value \( 4.8 \pm 1.0 \, \mu\text{b} \) of \([6]\) for photofission on \(^{nat}\)Ta at 69 MeV monochromatic photons. At higher energies 3500 MeV \( Y_f \) of the present work fits well with data \( 0.64 \pm 0.60 \, \mu\text{b} \) for reaction of Bremsstrahlung at endpoint energy 3770 MeV on \(^{181}\)Ta \([17]\).

The values of the fit parameters obtained for Ta target at two energies are tabulated in Table II. The width as well as the height of the mass distribution clearly increases with increasing photon energy. From the mean value of the mass distributions it can be concluded that, on average, three and six mass units are emitted before and after fission at low and intermediate energies, respectively.

Our investigation made it possible to estimate the fissility parameter in the region of intermediate energies (at endpoint energies of 50 and 3500 MeV) on absorption in a nucleus (D = \( Y_f / Y_{abs} \)). In determining \( Y_{abs} \), it is necessary to take into account all possible channels of decay of the excited nucleus being considered. The photofission yield, \( Y_f \) is related to the absolute photofission cross section, which was taken from the experimental data of \([6]\) for the photodisintegration cross section. For the endpoint energy 3500 MeV we used also calculated data above the quasi-deuteron region of photonuclear absorption from \([3, 4, 8]\). The results of the calculations confirmed the growth of the fissility in the region of intermediate energies from being \( \leq (2.3 \pm 0.5) \times 10^{-4} \) and \( (2.9 \pm 0.9) \times 10^{-3} \), respectively. The fissility data obtained in the present work for Bremsstrahlung energy \( E_{\gamma_{\text{max}}} = 50 \) is in consistent with the trends calculated for photofission on \(^{nat}\)Ta induced by monochromatic photons of 69 MeV \([6]\) and for photofission of \(^{181}\)Ta at an incident photon energy of 100 MeV using monochromatic photons produced by Compton backscattering \([7]\). Fissility for higher energy \( (E_{\gamma_{\text{max}}} = 3500) \) is in agreement with the systematics of fissilities as a function of \( Z^2/A \) of the target nucleus obtained in photofission reactions with Ta targets at intermediate energies up to 6.0 GeV from different laboratories \([3]\). A general trend of increasing fissility with increasing photon energy for pre-actinide nuclei is consistent with that inferred from early photofission data taken with Bremsstrahlung radiation as a source of real photons incident on Bi, Pb, Ti, Au, Pt, Os, Re, Ta and Hf target nuclei \([18]\).

In this work we also presented the additional cross section measured for \(^{nat}\)Pb + \(^7\)Li system by bombarding a natural lead target with an accelerated \(^7\)Li-ion beam of energy 35 MeV/u from the U-400M Cyclotron in the Joint Institute for Nuclear Research (JINR), Dubna, Russia \([19]\). Although symmetric distributions are typical for the pre-actinide fragment mass distribution, in our measurement there are also exist of fragment cross sections, which attribute to the asymmetric fission. The fission cross section using multimodal fission approach was found to be \( 634.6 \pm 95.0 \, \mu\text{b} \), where the observed cross section of the symmetric mode for the equal-mass division was \( 605.0 \pm 9.0 \, \mu\text{b} \) and the cross section corresponding to the asymmetric component was obtained to be \( 29.6 \pm 4.4 \, \mu\text{b} \). The details of the calculations is presented in the next section this work.

Table I. Yields of fission fragments measured for the reaction with photons at \( E_{\gamma_{\text{max}}} = 50 \) and 3500 MeV on \(^{181}\)Ta target.
| Element | Type | Yield, µb/eq.q | \( E_{\gamma_{\text{max}}} = 50 \) MeV | \( E_{\gamma_{\text{max}}} = 3500 \) MeV |
|---------|------|----------------|---------------------------------|---------------------------------|
| \(^{59}\text{Fe}\) | C | - | \( \leq 10.0 \) | \( \leq 10.0 \) |
| \(^{64}\text{Cu}\) | I | - | \( 12.0 \pm 2.0 \) | \( 12.0 \pm 2.0 \) |
| \(^{65}\text{Zn}\) | C | - | \( 18.0 \pm 5.0 \) | \( 18.0 \pm 5.0 \) |
| \(^{69m}\text{Zn}\) | I | - | \( 21.0 \pm 3.0 \) | \( 21.0 \pm 3.0 \) |
| \(^{71m}\text{Zn}\) | C | - | \( 22.0 \pm 2.0 \) | \( 22.0 \pm 2.0 \) |
| \(^{72}\text{Zn}\) | C | 0.13±0.02 | 23.0±3.0 | 23.0±3.0 |
| \(^{72}\text{Ga}\) | I | - | \( \leq 7.2 \) | \( \leq 7.2 \) |
| \(^{73}\text{Ga}\) | C | 0.14±0.02 | 25.0±3.7 | 25.0±3.7 |
| \(^{74}\text{As}\) | I | 0.20±0.03 | 20.0±4.0 | 20.0±4.0 |
| \(^{75}\text{Se}\) | C | - | 29.0±4.0 | 29.0±4.0 |
| \(^{76}\text{As}\) | I | 0.20±0.03 | 22.0±3.0 | 22.0±3.0 |
| \(^{77}\text{Ge}\) | C | 0.20±0.03 | 29.0±4.0 | 29.0±4.0 |
| \(^{77}\text{Br}\) | I | - | \( \leq 5.0 \) | \( \leq 5.0 \) |
| \(^{78}\text{Ge}\) | C | 0.25±0.04 | 22.0±2.2 | 22.0±2.2 |
| \(^{78}\text{As}\) | I | - | 15.0±2.3 | 15.0±2.3 |
| \(^{82}\text{Br}\) | I | - | 23.0±4.0 | 23.0±4.0 |
| \(^{84}\text{Br}\) | C | 0.40±0.06 | 31.0±6.0 | 31.0±6.0 |
| \(^{84}\text{Rb}\) | I | - | 4.0±0.7 | 4.0±0.7 |
| \(^{85m}\text{Rb}\) | C | - | 27.0±5.0 | 27.0±5.0 |
| \(^{86}\text{Rb}\) | I | 0.36±0.05 | 15.0±3.0 | 15.0±3.0 |
| \(^{87}\text{Kr}\) | C | 0.45±0.07 | 33.0±3.3 | 33.0±3.3 |
| \(^{87}\text{Y}\) | C | - | \( \leq 8.8 \) | \( \leq 8.8 \) |
| \(^{88}\text{Kr}\) | C | 0.40±0.06 | 30.0±6.0 | 30.0±6.0 |
| \(^{88}\text{Y}\) | I | - | \( \leq 7.0 \) | \( \leq 7.0 \) |
| \(^{88}\text{Zr}\) | C | - | \( \leq 10.0 \) | \( \leq 10.0 \) |
| \(^{90m}\text{Y}\) | C | - | 41.0±6.0 | 41.0±6.0 |
| \(^{91}\text{Sr}\) | C | 0.38±0.06 | 35.0±7.0 | 35.0±7.0 |
| \(^{91m}\text{Y}\) | C | - | \( \leq 9.0 \) | \( \leq 9.0 \) |
| \(^{92}\text{Sr}\) | C | 0.36±0.05 | 33.0±7.0 | 33.0±7.0 |
| \(^{92}\text{Y}\) | I | - | \( \leq 7.0 \) | \( \leq 7.0 \) |
| \(^{93}\text{Y}\) | C | 0.29±0.04 | 36.0±6.0 | 36.0±6.0 |
| \(^{95}\text{Zr}\) | C | 0.40±0.06 | 34.0±5.0 | 34.0±5.0 |
| \(^{95m}\text{Nb}\) | I | - | 9.0±1.4 | 9.0±1.4 |
| \(^{96}\text{Nb}\) | I | - | 32.0±5.0 | 32.0±5.0 |
| \(^{96}\text{Tc}\) | I | - | \( \leq 4.0 \) | \( \leq 4.0 \) |
| \(^{97}\text{Zr}\) | C | 0.28±0.04 | 27.0±5.4 | 27.0±5.4 |
| \(^{99}\text{Mo}\) | C | 0.27±0.04 | 29.0±6.0 | 29.0±6.0 |
| \(^{100}\text{Pd}\) | C | - | 13.0±2.6 | 13.0±2.6 |
| \(^{102}\text{Rh}\) | C | - | 22.0±5.0 | 22.0±5.0 |
| \(^{103}\text{Ru}\) | C | 0.15±0.03 | 25.0±5.0 | 25.0±5.0 |
| \(^{105}\text{Ru}\) | C | 0.15±0.03 | 13.0±2.6 | 13.0±2.6 |
| \(^{105}\text{Rh}\) | I | - | \( \leq 4.0 \) | \( \leq 4.0 \) |
Table II. Values for parameters of mass and charge distributions for $^{181}$Ta target at $E_{\gamma_{\text{max}}}=50$ and 3500 MeV on.

| Parameter | 50 MeV     | 3500 MeV  |
|-----------|------------|-----------|
| $\lambda_A$ | $0.011\pm0.0001$ | $1.68\pm0.02$ |
| $M_A$      | $89.02\pm0.21$    | $87.29\pm0.17$ |
| $\Gamma_A$ | $14.39\pm0.20$    | $23.03\pm0.32$ |
| $\mu_1$    | $1.690\pm0.113$   | $0.779\pm0.046$ |
| $\mu_2$    | $0.397\pm0.002$   | $0.420\pm0.001$ |
| $\gamma_1$ | $0.59\pm0.007$    | $0.59\pm0.003$ |
| $\gamma_2$ | $0.0050\pm0.0009$ | $0.0050\pm0.0004$ |

Table III. Measured fragment fission cross sections for the reaction of 245 MeV $^7$Li on $^{208}$Pb.

| Element | Type | Cross section, mb |
|---------|------|-------------------|
| $^{28}$Mg | C | $0.15\pm0.02$ |
| $^{34m}$Cl | I | $\leq0.16$ |
| $^{38}$S  | I  | $\leq0.03$ |
| $^{38}$Cl | I  | $\leq0.02$ |
| $^{39}$Cl | C  | $0.07\pm0.01$ |
| $^{41}$Ar | C  | $0.20\pm0.04$ |
| $^{42}$K  | C  | $0.31\pm0.06$ |
| $^{43}$K  | C  | $0.22\pm0.03$ |
| $^{43}$Sc | C  | $0.13\pm0.02$ |
| $^{44}$K  | I  | $\leq0.09$ |
| $^{44m}$Sc | I | $\leq0.18$ |
| $^{44m}$Sc | I | $0.12\pm0.01$ |
| $^{45}$K  | C  | $0.15\pm0.02$ |
| $^{46(m+g)}$Sc | I | $0.56\pm0.07$ |
| $^{47}$Ca | I  | $\leq0.06$ |
| $^{47}$Sc | I2 | $0.52\pm0.05$ |
| $^{48}$Sc | I  | $0.31\pm0.03$ |
| $^{48}$V  | I  | $\leq0.21$ |
| $^{48}$Cr | I  | $0.01\pm0.001$ |
| $^{49}$Cr | C  | $\leq0.02$ |
| $^{51}$Cr | C  | $0.34\pm0.03$ |
| $^{52g}$Mn | C | $\leq0.10$ |
| $^{52m}$Mn | I | $\leq0.06$ |
| $^{54}$Mn | I  | $0.32\pm0.03$ |
| $^{55}$Co | C  | $0.03\pm0.006$ |
| $^{56}$Mn | C  | $\leq0.25$ |
| $^{56}$Co | I  | $0.07\pm0.01$ |
| $^{57}$Co | I  | $0.25\pm0.03$ |
| $^{57}$Ni | I  | $0.03\pm0.006$ |
| $^{58(m+g)}$Co | I | $0.27\pm0.03$ |
| $^{59}$Fe | C  | $0.45\pm0.05$ |
| $^{60(m+g)}$Co | I | $0.56\pm0.06$ |
| $^{60}$Cu | C  | $\leq0.05$ |
| $^{61}$Cu | C  | $\leq0.11$ |
Table 1. (Continued.)

| Element | Charge | Uncertainty |
|---------|--------|-------------|
| $^{62}$Zn | C | $\leq 0.04$ |
| $^{63}$Ni | I | $\leq 0.20$ |
| $^{65}$Zn | I | $0.40 \pm 0.08$ |
| $^{65}$Ga | C | $\leq 0.02$ |
| $^{66}$Ni | I | $0.11 \pm 0.02$ |
| $^{66}$Ga | I | $\leq 0.04$ |
| $^{67}$Cu | C | $0.72 \pm 0.07$ |
| $^{67}$Ga | C | $0.03 \pm 0.003$ |
| $^{69}$Ge | C | $\leq 0.045$ |
| $^{149}$Nd | C | $\leq 0.07$ |
| $^{151}$Pm | C | $0.15 \pm 0.03$ |
| $^{153}$Sm | C | $0.30 \pm 0.06$ |
| $^{155}$Tb | C | $0.22 \pm 0.05$ |
| $^{160}$Tb | I | $0.35 \pm 0.07$ |
| $^{167}$Tm | C | $0.22 \pm 0.05$ |
| $^{168}$Tm | I | $0.25 \pm 0.04$ |
| $^{172}$Lu | C | $0.10 \pm 0.03$ |
| $^{173}$Lu | C | $0.12 \pm 0.02$ |
| $^{176}$Ta | C | $\leq 0.05$ |

4 Model Calculations

Numerous experimental investigations of the mass and energy distributions of fragments in the fission of nuclei from Pb to No [20] have confirmed the validity of a hypothesis concerning the existence of independent fission modes, as first stated by Turkevich and Niday [21]. This hypothesis has received physical substantiation in theoretical works by Pashkevich [22] and Brosa et al. [23]. These studies have shown that multimodality of the mass and energy distributions of fission fragments is caused by the valley structure of the deformation potential energy surface of a fissioning nucleus. The experimental mass and energy distributions from the fission of actinide nuclei are usually assumed to consist of different mass and energy distributions for two independent fission modes: symmetric (S) and asymmetric (AS). Mode S is mainly conditioned by the liquid drop properties of nuclear matter, and therefore the most probable values of fragment masses $A$ are close to $A_f/2$, where $A_f$ is the mass of the fissioning nucleus. The asymmetric mode AS with average masses of the heavy and light fragments $A_H$, $A_L$ with $Z_H$, $N_H$ and $Z_L$, $N_L$ (proton and neutron numbers of a heavy and light fragments) close to one of the shell numbers.

The calculation of fission cross section within different models provides an opportunity to estimate the validity of the various reaction mechanisms and to investigate characteristics of the processes taking place in reactions induced by different probes. CRISP is a Monte Carlo code for simulating nuclear reactions [24] that uses a two step process. First, an intranuclear cascade is simulated, following a time-ordered sequence of collisions in a many-body system [25, 26]. Besides, when the intranuclear cascade finishes, the evaporation of nucleons and alpha-particles starts to compete with fission [27].

The possibility of the fission asymmetry of the pre-actinides has been predicted by Pashkevich [22] and Mustafa [28]. Pashkevich has shown that for the lead region, there are two valleys in the potential deformation energy higher valley corresponds to the process of asymmetric fission, which is less probable and the lower one corresponds to symmetric fission. The former is entirely due to the shell effects, the latter corresponds to the shape of the liquid-drop fission barrier. This explains the well-known properties of the two fission modes and the distinctions between them.

In the study of fission of pre-actinide nuclei based on the fission-fragment mass and energy distributions, [29] the asymmetric component has been observed in the mass distribution of the fission fragments in the reactions with $\alpha$-particles and protons at low excitation energies. The boundaries of validity of the hypothesis of two distinct fission modes have been estimated at $200 \leq A_f \leq 232$ and $82 \leq Z_f \leq 92$, where $Z_f$ is number of the fissioning nucleus.

The experimental data used in the calculations of this paper included photon, deuteron and $^7$Li induced fission between 50 MeV and 4400 MeV are given in Fig. – and taken from the works on sub-actinide fission of Ta (present...
work), $^{197}$Au [1] and nat$^{208}$Pb [19]. In calculations for Ta and Au targets only symmetric fission were considered, the asymmetric fission modes are discarded.

As it was obtained in [?], the contribution of the asymmetric component for pre-actinides to the total yield is small and slightly depends on energy. It is well known that the asymmetric mode predominates in fission of the heavy actinide nuclei. With increasing projectile energy, the contribution of asymmetric fission decreases. The values of the fit parameters, tabulated in Table VI, show a maximum around mass $A = 103$ for reaction of nat$^{208}$Pb at 245 MeV of incident particles (and excitation energy $E^* = 90\pm 18$ MeV [19]). Therefore a mass $A = 206$ is expected for the fissioning nucleus. Estimated part of the fission cross section originating from asymmetric fission mode was found to be 4.7 %.

For comparison, the value of the asymmetric fission component obtained for the fissioning nucleus with $A=206$ of proton-induced fission $^{205}$Bi at 28.3 MeV, corresponding to an excitation energy $E^* = 10.6$ [?], is 5.7 %. Therefore, the mass distribution from a given fissioning nuclide at a given excitation energy is expected to be independent of the original target and projectile.

It can be concluded that at intermediate energies of incident particle symmetric fission makes the highest contribution to the observed fission cross section of pre-actinide nuclei. As it was investigated in the study of [?], the contribution of the asymmetric component to the total yield decreases steadily with decreasing $A$ and breaks off at $^{204}$Pb because no events of asymmetric mode was observed for $^{201}$Tl.

In the multimodal model, the fission cross section as a function of mass number is obtained by the sum of three Gaussian functions, corresponding to the three modes mentioned above [30]:

$$
\sigma = \frac{1}{\sqrt{2\pi}} \left[ \frac{K_{AS}}{\sigma_{AS}} \exp \left( -\frac{(A - A_S - D_{AS})^2}{2\sigma_{AS}^2} \right) + \frac{K'_{AS}}{\sigma'_{AS}} \exp \left( -\frac{(A - A_S + D_{AS})^2}{2\sigma'_{AS}^2} \right) + \frac{K_S}{\sigma_S} \exp \left( -\frac{(A - A_S)^2}{2\sigma_S^2} \right) \right],
$$

where $A_S$ is the mean mass number determining the center of Gaussian functions; and $K_i$, $\sigma_i$, and $D_i$ are the contribution, dispersion and position parameters of the $i^{th}$ Gaussian functions. The indexes AS, S designate the asymmetric and symmetric components.

The CRISP code works on an event-by-event basis, and therefore the parameter $A_S$ in Eq.3 is completely determined by the mass of the fissioning nucleus $A_f$, that is, $A_S = A_f/2$. The quantities $A_S + D_{iAS} = A_H$ and $A_S - D_{AS} = A_L$, where $A_H$ and $A_L$ are the masses of the heavy and light fragment, respectively, determine the positions of the heavy and light peaks of the asymmetric components on the mass scale. The values of $A_H + A_L = 2A_S$ is treated as the masses of nuclei that undergo fission in the respective channel.

The total fission cross sections for the three targets studying in this paper was determined by summing all fission modes, symmetric and asymmetric. Thus, the results obtained in this work concerning Pb target are not only a theoretical diction of pre-asymmetric fission of the pre-actinides, but they are a physical substantiation of the hypothesis of two distinct fission modes.
Table IV. Calculated values for parameters of 245 MeV \textsuperscript{7}Li on \textsuperscript{nat}Pb fission.

| Parameter | \textsuperscript{nat}Pb |
|-----------|---------------------|
| $K_{AS}$  | 0.048               |
| $K'_{AS}$ | 0.048               |
| $\sigma_{AS}$ | 10.0       |
| $\sigma'_{AS}$ | 10.0     |
| $D_{AS}$  | 52.5                |
| $K_{S}$   | 1220.0              |
| $\sigma_{S}$ | 12.74            |
| $\mu_1$  | 2.53                |
| $\mu_2$  | 0.395               |
| $\gamma_1$ | 0.92           |
| $\gamma_2$ | 0.003           |

In general the agreement with the calculations is very good, both for the position of the most probable mass and for the width of the distribution. The assumption that for these nuclides asymmetric fission can be neglected seems valid for these energies.
FIG. 1: Fission-product mass yields from $E_{\gamma \text{max}} = 50$ MeV photon-induced fission on $^{181}$Ta: the total fission cross-section (thick black continuous curve), experimental data (■).
FIG. 2: Fission-product mass yields from $E_{\gamma\text{max}} = 3500$ MeV photon-induced fission on $^{181}\text{Ta}$: the total fission cross-section (thick black continuous curve), experimental data (■).
FIG. 3: Fission-product mass yields from $^7$Li-induced fission on $^{nat}$Pb: the total fission cross-section (thick black continuous curve), experimental data (■).
FIG. 4: Fission-product mass yields from deuteron-induced fission on $^{197}\text{Au}$: the total fission cross-section (thick black continuous curve), experimental data (□).
4 Conclusion

In the course of the present work, the fission of $^{181}$Ta nucleus has been investigated by using Bremsstrahlung photon beams with endpoint energies of 50 and 3500 MeV. Photofission yields have been measured taking advantage of an induced-activity method in off-line analysis. The absolute photofission yields have been determined at two very different energy regimes taking into account the photon spectrum and measured. Photofissility values were subsequently deduced for each endpoint energy of photons. The resulting total fission yields and fissility values have been found to compare quite well with the measured ones from other laboratories at 69 and 3770 MeV of incident photon energies.

An analysis of the charge- and mass-distribution of fission fragments from $^{181}$Ta targets and from the reactions $^{nat}$Pb+$^7$Li at 245 MeV and $^{197}$Au+$^2$H at 4.4 GeV using the simulation code CRISP was done. The comparison between calculated parameters and data has shown that the calculations describe correctly the main characteristics of charge, such as the most-probable charge for a given fission product mass chain and the width parameter. The mass distribution of photofission fragments has been analyzed via the multimodal fission approach. The analysis has shown the two main fission modes (symmetric and asymmetric) to be determined by two distinct valleys in the deformation potential energy, which had been theoretically predicted by Pashkevich. The contribution of the asymmetric component to the total fission cross section for $^{nat}$Pb is small, while it is totally absent for such pre-actinide targets as $^{197}$Au and $^{181}$Ta and independent on the projectiles.

Acknowledgment

G. Karapetyan is grateful to Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) 2011/00314-0, and to International Centre for Theoretical Physics (ICTP) under the Associate Grant Scheme.

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