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Shelf effect in the subthreshold photofission of ^{232}Th

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(Received 18 September 1981)

Angular distributions of photofission of ^{232}Th have been measured using bremsstrahlung γ beams in the (5.4–6.4) MeV range. With decreasing energy below 6 MeV the angular anisotropy decreases strongly and, moreover, a shelf appears in the isotropic component of the yield. These effects are interpreted in terms of a competition between prompt and delayed fission. Vibrational resonances in the $1^{-}0$ and $2^{+}0$ channels are detected.

[NUCLEAR REACTIONS, FISSION Angular distributions and yields of subthreshold photofission of ^{232}Th in the (5.4–6.4) MeV range.]

The subthreshold fission of actinides nuclei, which have a double-humped fission barrier,[1] can occur in two ways: (a) prompt fission proceeding via penetration of both maxima of the barrier; (b) delayed fission following the γ decay of excited states in the second well towards the isomeric state, the delay being determined by the isomeric half-life. The above mechanisms have been checked experimentally.[2]

Bowman[3] suggested, a few years ago, that the identification of delayed fission can also be made in experiments which do not discriminate either electronically or geometrically between prompt and delayed events. In fact, while the prompt fission yield is proportional to the product $P_A(E)P_B(E)$ of the transmission coefficients of the two maxima, the delayed fission yield is proportional only to $P_A(E)$, as the outer barrier B is penetrated always at the isomeric level. Consequently, in the energy range where delayed fission predominates, the logarithmic slope of the fission yield (which has an almost exponential energy dependence) strongly decreases and a shelf appears. This effect is clearly observed in the total photofission yields of actinides nuclei[4–7] at energy lower than 4.5 MeV. Furthermore, owing to the fact that the original angular momentum alignment is lost during the γ-decay path in the second well, the delayed fission fragments angular distribution is isotropic. Measurements of photofission angular distributions of ^{236,238}U indicate[8,9] that the angular anisotropy $W(90°)/W(0°)$ is actually influenced by the delayed fission contribution at energy below 6 MeV.

For thorium isotopes there is no irrefutable experimental evidence of delayed fission in literature. The only indication is probably the shelf at low energy in the total photofission yield of ^{232}Th detected by Bowman *et al.*[4] The existence of this shelf in other photofission measurements was at first confirmed also in Ref. 5 but then refuted by the same authors.[10]

One of the findings presented in this paper is the detection of an effect, probably isomeric, in subthreshold photofission of ^{232}Th. The effect, shown in Fig. 1(b), consists of a sharp decrease of the angular anisotropy with decreasing energy below 6 MeV. Further findings are vibrational resonances in the dipole and quadrupole photofission components.

The experimental results reported here have been obtained by accurate measurements of photofission angular distributions in the (5.4–6.4) MeV range in steps of 0.1 MeV using the bremsstrahlung beam of the 13.5 MeV microtron of Catania University. The

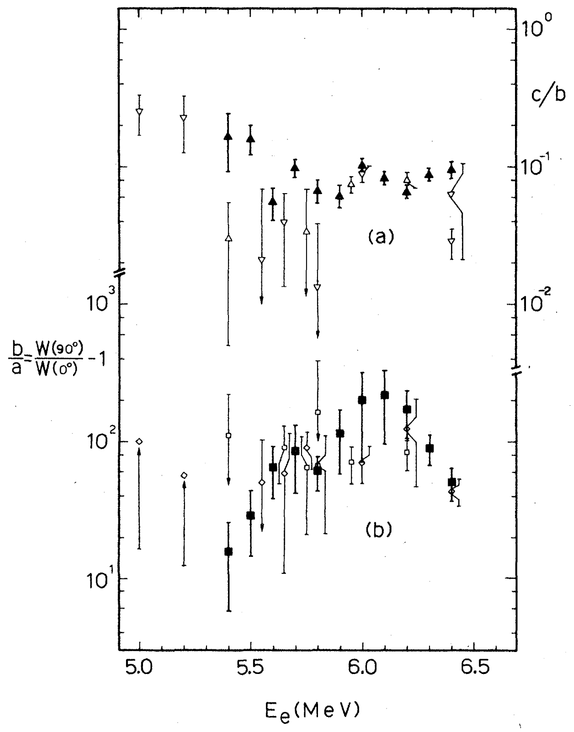

FIG. 1. (a) c/b ratio as a function of electron energy. (▲) present work, (△) from Ref. 13, and (▽) from Ref. 14. (b) b/a ratio as a function of electron energy. (■) present work, (□) from Ref. 13 (target thickness 1.35 mg/cm^2), and (◇) from Ref. 14 (target thickness 200 mg/cm^2).

experimental setup used is the same as that of Ref. 9. Moreover, since we were interested in the study of anisotropy in order to avoid absorption and multiple scattering of the fission fragments, a thin target of 0.84 mg/cm^2 thorium oxide has been used.

The quantities in Fig. 1 are the ratios of the coefficients of the photofission angular distribution

$$W(\theta)=a+b\sin^2\theta+c\sin^2 2\theta \tag{1}$$

of even-even nuclei as a result of the absorption of γ rays with $E1$ and $E2$ multipolarity.[11] The absorption of the $E1$ multipolarity produces compound states with $I^\pi=1^-$ and projection on the symmetry axis $K=0,1$. States with $I^\pi=2^+$ and $K=0,1,2$ are produced when the $E2$ multipolarity is absorbed. At energy near and below the fission threshold the angular distribution is expected to show contributions from the three lower lying channels[12] $I^\pi K=1^-0$, 2^+0, and 1^-1 to which dipole ($\alpha\sin^2\theta$), quadrupole ($\alpha\sin^2 2\theta$), and isotropic terms correspond, respectively. So, the coefficients of Eq. (1) can be related to the photofission yields $Y^{I^\pi K}$ of the transition states, such as[9]

$$a=\frac{1}{4\pi}\left(\tfrac{3}{2}Y^{1^-1}+Y_{\rm del}\right)\ , \tag{2a}$$

$$b=\frac{3}{8\pi}Y^{1^-0}\ , \tag{2b}$$

$$c=\frac{15}{32\pi}Y^{2^+0}\ , \tag{2c}$$

with

$$Y(E_e)=N\int_0^{E_e}\phi(E_\gamma,E_e)\,\sigma_{\gamma,f}(E_\gamma)\,dE_\gamma\ , \tag{3}$$

where N is the thickness of the target in atoms/cm^2, $\phi(E_\gamma,E_e)$ is the bremsstrahlung spectrum and $\sigma_{\gamma,f}$ is the photofission cross section. In Eq. (2a) the isotropic delayed contribution $Y_{\rm del}$ is also included.

As the subbarrier photofission cross section $\sigma_{\gamma,f}(E_\gamma)$ is, on average, an exponentially increasing function, while the bremsstrahlung spectrum, near the electron energy E_e, is approximately described by a function decreasing linearly with E_γ, the integral yield $Y(E_e)$ fits to a good approximation the average energy dependence of the photofission cross section, with a shift of about 0.1–0.2 MeV to the right along the energy axis. Moreover, possible resonances in the $\sigma_{\gamma,f}$ appear as shelves in the photofission yield.

The measured values of b/a (which are proportional to the angular anisotropy) are compared with the experimental results of Refs. 13 and 14 in Fig. 1(b). Although the various sets of data agree upon the order of magnitude, the energy dependence of our values is better outlined. In fact, we find the slope of $\ln b/a$, which is negative for $E_e>6$ MeV, to be positive in the (5.4–6.0) MeV range. This effect, already known for U isotopes[8,9] is revealed in this work thanks to the use of a thin target and to the higher precision of the angular distributions. The improved quality of the present data is also pointed out in Fig. 1(a) where the measured values of c/b, which is proportional to the ratio of the dominant yields Y^{2^+0}/Y^{1^-0}, are reported.

The current interpretation of such an energy dependence of b/a has already been perceived by Huizenga[15] in 1969 and is the same as the Bowman's interpretation of the shelf effect at lower energy in the total yields[3]: with decreasing energy, at first the prompt fission dominates in Eq. (2a), so b/a is proportional to Y^{1^-0}/Y^{1^-1}, and as the threshold 1^-1 is higher, a decreases more rapidly than b and b/a increases; but, as soon as the delayed fission dominates in Eq. (2a), the coefficient a decreases less rapidly than b and b/a decreases. By examining Fig. 2, where the three components

$$Y_a=4\pi a=\tfrac{3}{2}Y^{1^-1}+Y_{\rm del}\ , \tag{4a}$$

$$Y_b=\tfrac{8}{3}\pi b=Y^{1^-0}\ , \tag{4b}$$

$$Y_c=\tfrac{32}{15}c=Y^{2^+0}\ , \tag{4c}$$

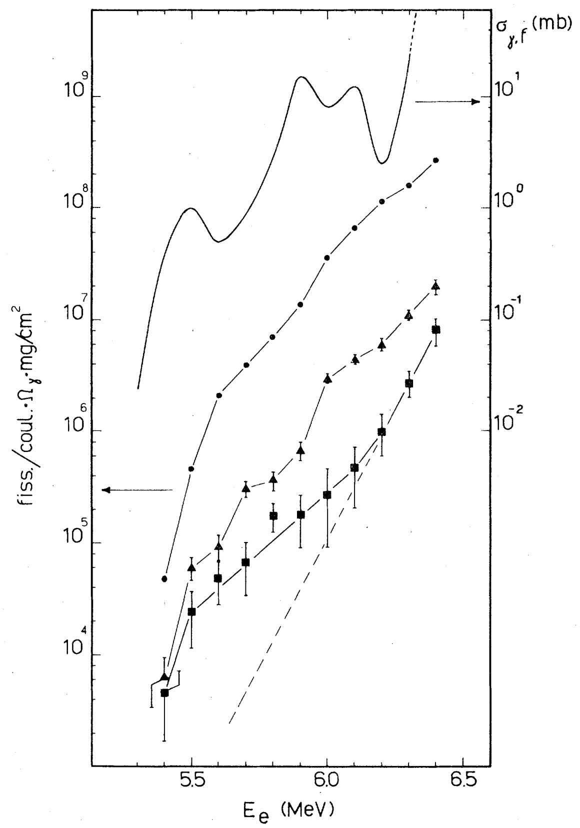

FIG. 2. The figure shows the experimental yields (■) Y_a, (♦) Y_b, and (▲) Y_c as functions of electron energy. The upper solid curve is our unfolded total photofission cross-section. Yields are normalized to the solid angle Ω_γ subtended from the target to the bremsstrahlung converter.

are reported, it can be seen that below 6 MeV the slope of $\ln Y_a$ actually decreases; namely, there is a shelf effect in the isotropic component which, as stated above, originates from the same phenomenon as the shelf effect in the total yields at lower energy.[4–7] The difference is that while the shelf in Y_a is caused by the competition between the delayed photofission and the small isotropic component of prompt photofission via the 1^-1 channel, the shelf in the total yields is caused by the competition between delayed and total prompt photofission.

According to this interpretation it seems that an isomer of ^{232}Th has revealed itself through a shelf in the energy dependence of the isotropic component of photofission.

The total photofission cross-section, such as obtained solving Eq. (3) by the Tarasko method[16] and using the total yield $Y = Y_a + Y_b + Y_c$, is drawn in Fig. 2. This cross-section presents some vibrational resonances and is in good agreement with that measured by Dickey and Axel[17] with monochromatic γ beams. Furthermore, it results that the total $\sigma_{\gamma,f}$ is coincident with the unfolded $\sigma^{1^-0}_{\gamma,f}$ (not reported in figure) obtained by using Y_b in Eq. (3). Accordingly, all resonances in Fig. 2 are due to the 1^-0 channel. The analysis of the quadrupole component Y_c is still in progress, however present data show evidence of resonances also in the lowest channel 2^+0. In fact, it can be seen in Fig. 2 that Y_c has some small shelves which indicate the existence of low damped vibrational states acting as doorway states towards fission.

Since the case of thorium isotopes is not yet clear, we do not propose at this stage the assignment of these vibrational states to the second minimum of the usual double-humped barrier. For these nuclei there are also theoretical predictions,[18] supported by experimental indications,[19] of a triple-humped barrier with a third asymmetrical shallow minimum caused by a split of the normal second maximum of the double-humped barrier. If this is true, the assignment of a vibrational state to the second or third minimum would be somewhat difficult. Naturally a similar problem would arise when one asks which minimum gives rise to the observed isomeric fission. However, despite the small size of the prompt isotropic component, it is very unlikely that, in a shallow minimum delimited by thin barriers, delayed fission may dominate in Y_a.

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