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preprint

IFUSP/P-282

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AUG/1981

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ABSTRACT

The electrofission angular distribution of ^{232}Th, in the energy interval 5.5-7 MeV, was measured. The analysis of the E2 coefficient of the angular distribution revealed that a substantial amount of E2 fission strength is concentrated near the fission barrier, corresponding to (8 ± 2)% of one energy weighted sum rule unity.

* Supported in part by the Fundação de Amparo à Pesquisa do Estado de São Paulo, Conselho Nacional de Pesquisas, and FINEP.

KEYWORD ABSTRACT :

NUCLEAR REACTION $^{232}Th(e,f)$, E = 5.5-7 MeV, with electrons; measured fission -fragment angular distributions; deduced E2 fission strength. Natural target.

The fission decay of the isoscalar giant quadrupole resonance (GQR) for actinide nuclei has been investigated intensively in the last few years by means of both electrofission[1-6] and hadron-induced fission experiments[7-9], since its first determination for ^{238}U [1]. The present status of all the informations so far obtained from these studies is controversial and somewhat confusing (see e.g. ref. 2, and references therein). The excitation energy of the GQR at $60-65\,xA^{-1/3}$ MeV established by the experimental systematics places the resonance in actinide nuclei well above the fission barrier; therefore, it is expected that the GQR would deexcite by fission, as is the case for the giant dipole resonance (GDR). However, the picture drawn from an electrofission[5] and an $(\alpha,\alpha'f)$[7] experiment for ^{238}U and ^{232}Th is that the fission decay channel of the GQR is inhibited. On the other hand, electrofission measurements for ^{234}U, ^{236}U, and ^{238}U performed at this Laboratory[1-3], $^{238}U(^{6}Li,^{6}Li'f)$[8] and $^{238}U(\alpha,\alpha'f)$[9] coincidence measurements, deduced a substantial fission probability of the GQR in agreement with preliminary $^{238}U(e,e'f)$ coincidence measurements performed at Stanford[6]. Also, there is a serious controversy with regard to the E2 strength distribution in the fission decay channel as a function of the excitation energy, namely: a) from the electron-induced fission results for ^{238}U [1-3,6] a large concentration of E2 fission strength near the fission barrier (~6 MeV) and at the peak of the GQR has been detected, whereas from b) hadron-scattering results for ^{238}U and ^{232}Th the GQR peaks sistematically at 11 MeV and vanishes below ~8.5 MeV[7-10]. In order to show that the latter results are physically unreasonable, we performed careful electrofission-fragment angular distributions of ^{232}Th at energies near the fission barrier ($\lesssim$ 7 MeV), which constitute a sensitive means for the study of low-energy E2 fission strength as has been demonstrated recently for ^{238}U [11].

The electrofission differential cross section, for a particular fission channel (J^π,K), is defined as[11]

$$\frac{d\sigma_e}{d\Omega_f}(J^\pi,K;E_e,\theta_f) = \sum_M \frac{\phi_e(J^\pi,K,M;E_e)}{2\pi} W^J_{MK}(\theta_f) \qquad (1)$$

where E_e is the incident electron energy, θ_f is the fission fragment angle with respect to the recoil axis, and $W^J_{MK}(\theta_f)$ is the angular-distribution function. For even-even nuclei (ground state $J^\pi=0^+$) $J^\pi=L^\pi$, where L is the multipolarity of the absorbed photon; K and M $(=0,\pm1,\pm2,\dots,\pm L)$ are the projections of the nuclear angular momentum J on the symmetry axis of the nucleus and on the direction of the incident electron, respectively.

The coefficients of the angular distributions ϕ_e are given by[11]

$$\phi_e(J^\pi,K,M;E_e) = \int_0^{E_e} \sigma_{\gamma,f}(J^\pi,K;\omega)\, N^{(\lambda L,M)}(\omega,E_e)\,\frac{d\omega}{\omega} \qquad (2)$$

where $\sigma_{\gamma,f}(J^\pi,K;\omega)$ is the photofission cross section for the fission channel (J^π,K), $N^{(\lambda L,M)}(\omega,E_e)$ is the virtual-photon spectrum for a λL-transition with magnetic substate M, and ω is the virtual (or real) photon energy.

The electrofission reaction is dominated by nuclear transitions having L=1 and 2 because of the low q transferred to the nucleus, as discussed at length in Ref. 3. Assuming only E1 and E2 transitions contributing to the fission process we obtain

$$\frac{d\sigma_e}{d\Omega_f}(E_e,\theta_f) = \sum_{J^\pi=1^-,2^+} \sum_{K=0}^{\pm J} \frac{d\sigma_e}{d\Omega_f}(J^\pi,K;E_e,\theta_f) =$$

$$A(E_e) + B(E_e)\sin^2\theta_f + C(E_e)\sin^2(2\theta_f) \tag{3}$$

where the C coefficient contains contributions from the 2^+ fission levels only which are populated by E2 photoabsorption. Therefore, the electrofission angular distribution constitutes an unambiguous experimental technique which allows the isolation of the E2 component of the photofission process. From Ref. 11) we know that

$$C(E_e) = \frac{5}{32\pi}\int_0^{E_e}\left[3\sigma_{\gamma,f}(2^+,0;\omega) - 4\sigma_{\gamma,f}(2^+,1;\omega) + \sigma_{\gamma,f}(2^+,2;\omega)\right] N^{(E2,*)}(\omega,E_e)\,\frac{d\omega}{\omega} \tag{4}$$

and

$$N^{(E2,*)}(\omega,E_e) = -\frac{3}{2}N^{(E2,0)}(\omega,E_e) + N^{(E2,1)}(\omega,E_e) - \frac{1}{4}N^{(E2,2)}(\omega,E_e) \tag{5}$$

is obtained from DWBA calculations[12].

The electrofission differential cross section for ^{232}Th , in the energy range from 5.5 to 7 MeV, were obtained by irradiating thin targets of ^{232}Th (~80 μg/cm^2) with the electron beam of the University of São Paulo Linear Accelerator. The fission fragments were detected with mica-foil track detectors located at up to twelve different angles between 10° and 100° . The details of the experimental apparatus and procedures and of the data reduction are presented in detail in Refs. 3 and 11.

Figure 1 shows the electrofission differential cross section , divided by the isotropic coefficient A (see eqn. 3), for a few values of E_e ; the solid curves were obtained as least-squares fits of $A + B\sin^2\theta_f + C\sin^2(2\theta_f)$ to the experimental points. The error flags arise both from statistical fluctuations and systematic errors. The systematic enhancement found in $d\sigma_e/d\Omega_f$ near 50° reveals the presence of a major E2 component in the electrofission cross section at least at energies ≲ 7 MeV. The C coefficient (in mb/sr) obtained from the above mentioned fitting procedure is shown in Fig. 2.

For actinide nuclei like the ^{232}Th it is reasonable to assume that the K=0 channel is the only one open to fission at energies near the fission barrier[11,13,14]; then, from eqn.(4) one has

$$C(E_e) = \frac{15}{32\pi}\int_0^{E_e}\sigma_{\gamma,f}(2^+,0;\omega)\,N^{(E2,*)}(\omega,E_e)\,\frac{d\omega}{\omega} \tag{6}$$

where $N^{(E2,*)}$ is calculated in DWBA[12]; the photofission cross section $\sigma_{\gamma,f}(2^+,0;\omega)$ is related to the E2 fission strength function $\frac{dB}{d\omega}(E2,\omega)\cdot\frac{\Gamma_f}{\Gamma}(2^+,0;\omega)$ by[2]

$$\sigma_{\gamma,f}(2^+,0;\omega) = \frac{4}{3}\pi^3\alpha\omega^3\frac{dB}{d\omega}(E2,\omega)\cdot\frac{\Gamma_f}{\Gamma}(2^+,0;\omega) \quad . \tag{7}$$

We obtained $\sigma_{\gamma,f}(2^+,0;\omega)$ by solving the integral equation (6) using the least-structure unfolding method of Cook[15]. The result was converted into the E2 fission strength function using the definition given by eqn. 7 and it is shown in Fig. 3. The solid line in Fig. 2 represents the fold-back of the result for $\sigma_{\gamma,f}(2^+,0;\omega)$. It should be stressed that the result presented in Fig. 3 does not contain any kind of normalization.

The total E2 fission strength concentrated between 5 and 7 MeV is given by the area under the curve in Fig. 3, and represents (8 ± 2)% of one energy weighted sum rule unity (EWSR). For ^{238}U the fraction of E2 fission strength, approximately in the same energy interval, is (6 ± 1)% of the EWSR as obtained from electrofission[1,2] and (7 ± 1)% as deduced from recent photofission angular distributions results[13]. The E2 photoabsorption process near the fission barrier corresponds to the low energy tail of the GQR, and the probability $P_f(E2)$ for its fission decay was estimated for the uranium even isotopes[2,3], and in particular for ^{238}U (table I). The dominance of the fission decay of the GQR for ^{238}U near the barrier was well explained as a consequence that the fission barrier of the 2^+ fission level $B_f(2^+)$ is located below the neutron emission threshold B_n[2]. For ^{232}Th we found that the E2 fission strength is nearly the same as for ^{238}U (for $\omega \lesssim 7$ MeV); therefore, the E2 fission probabilities should be approximately the same too if these nuclei have comparable E2 photoabsorption cross section (as is the case for E1[16]). Another peculiar behavior of ^{232}Th fission decay was verified for the GDR, namely[16]: $P_f(E1;^{232}Th) \approx 1.6x\ P_f(E1;^{238}U) \approx 40\%$ at $\omega \cong 6.3$ MeV, while near the peak of the GDR $P_f(E1;^{232}Th) \approx \frac{1}{2}x\ P_f(E1;^{238}U) \approx 10\%$. The picture drawn from all these results is that both the GQR and GDR of ^{232}Th have a substantial fission branching ratio at energies near the barrier, reflecting the characteristics of the competition of fission decay and neutron emission. On the other hand, it is hard to see how a zero E2 fission strength could be true, as is implied by the results of the $(\alpha,\alpha'f)$ and (e,f) works of Refs. 7 and 5, respectively.

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TABLE I

E1 and E2 fission probabilities, and %EWSR, for ^{232}Th and ^{238}U , between 5 and 7 MeV

Nucleus	% EWSR (E2)	$P_f(E2)$ %	$P_f(E1)$ %
^{232}Th	8 ± 2 [a)]	-	~40 [a)]
^{238}U	6 ± 1 [b)]	80 ± 10 [c)]	~25 [d)]

a) Present work.

b) Ref. 2, and (7 ± 1) as deduced from Ref. 13 .

c) Ref. 2 .

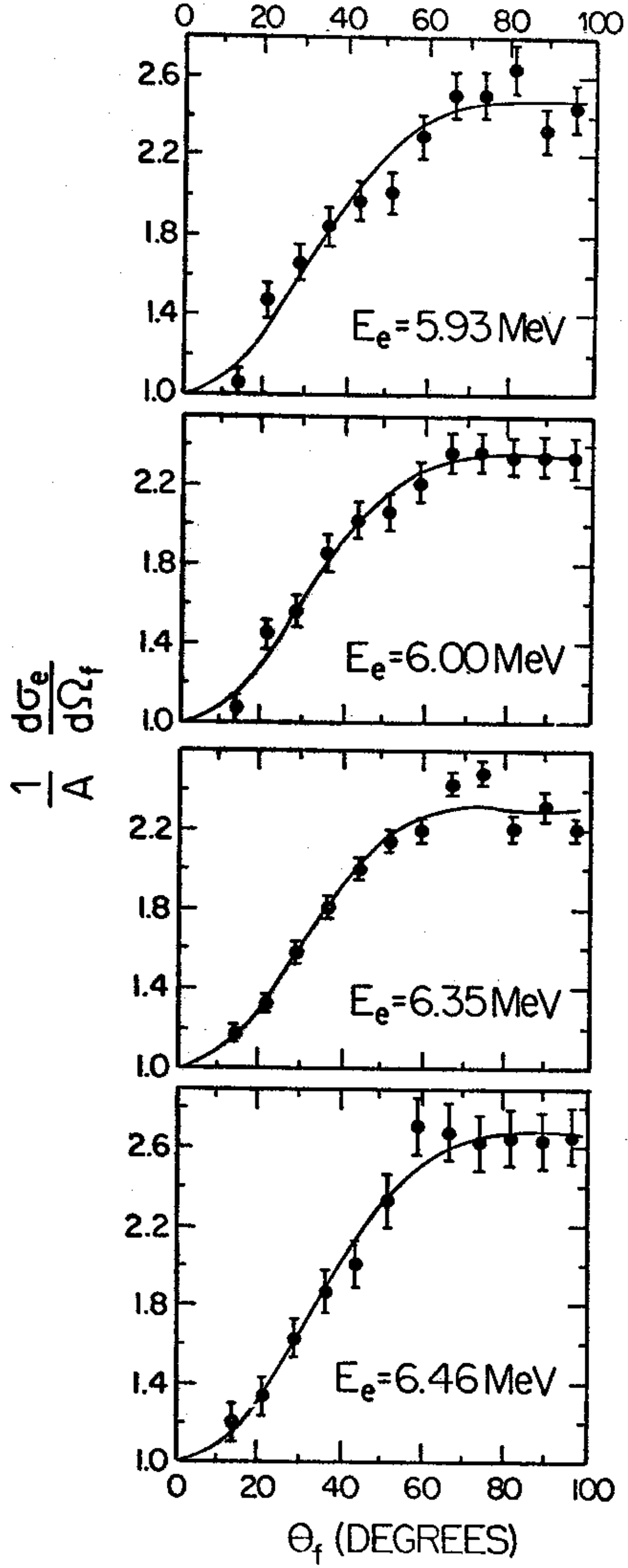
d) Ref. 16 at $\omega \cong 6.3$.

FIGURE CAPTIONS

FIG. 1 - Electrofission-fragments angular distributions for ^{232}Th, $\frac{1}{A(E_e)} \frac{d\sigma_e}{d\Omega_f}(E_e, \theta_f)$. The curves are least-square fits of the function defined in eqn. 3 to the experimental points.

FIG. 2 - Absolute values for the coefficient of the $\sin^2 2\theta_f$ term in the electrofission differential cross section $C(E_e)$ (eqn.3), obtained from the measured angular distributions for ^{232}Th . The dashed curve is the fold-back of $\sigma_{\gamma,f}(2^+,0)$ in eqn. 6 .

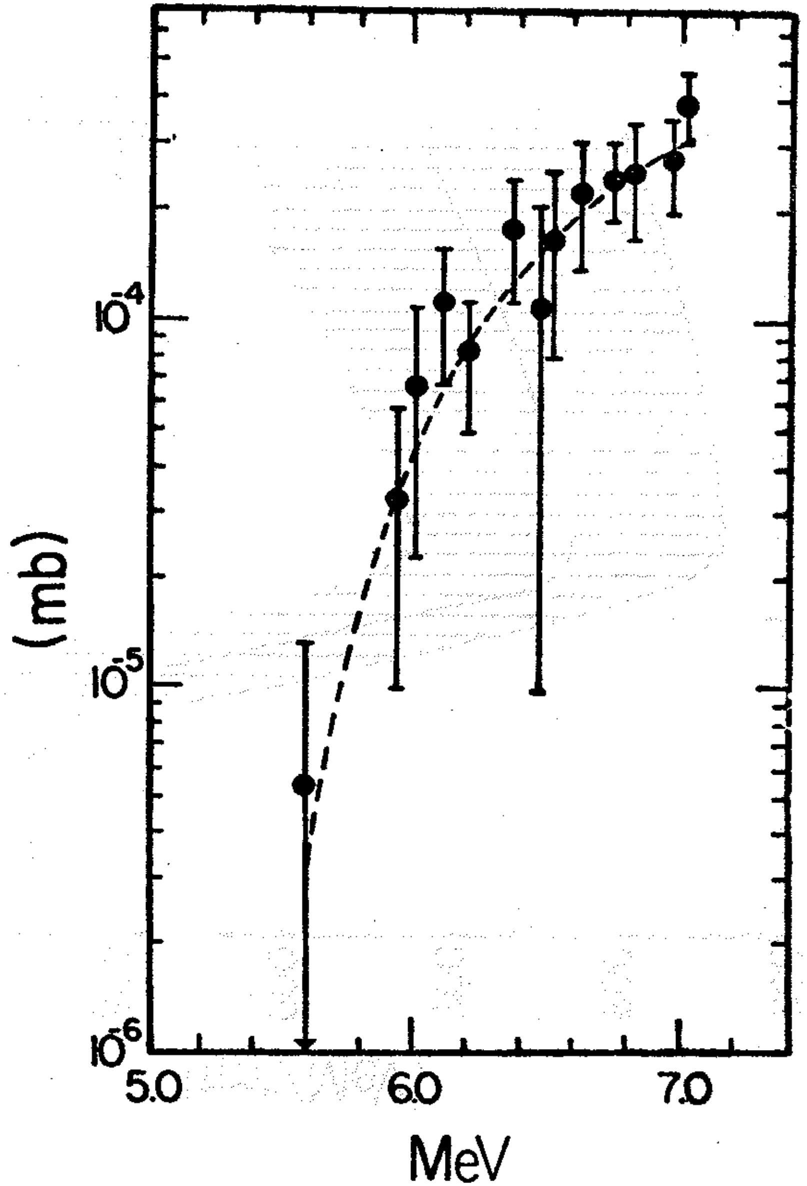
FIG. 3 - E2 fission strength function deduced from the experimentally determined photofission cross section $\sigma_{\gamma,f}(2^+,0)$ (obtained by solving the integral equation 6, as explained in the text). Both systematic and statistical uncertainties are included in the error band.



E_e=5.93 MeV
E_e=6.00 MeV
E_e=6.35 MeV
E_e=6.46 MeV
$\frac{1}{A}\frac{d\sigma_e}{d\Omega_f}$
Θ_f (DEGREES)

Fig. 1

Fig. 2



(mb)
MeV

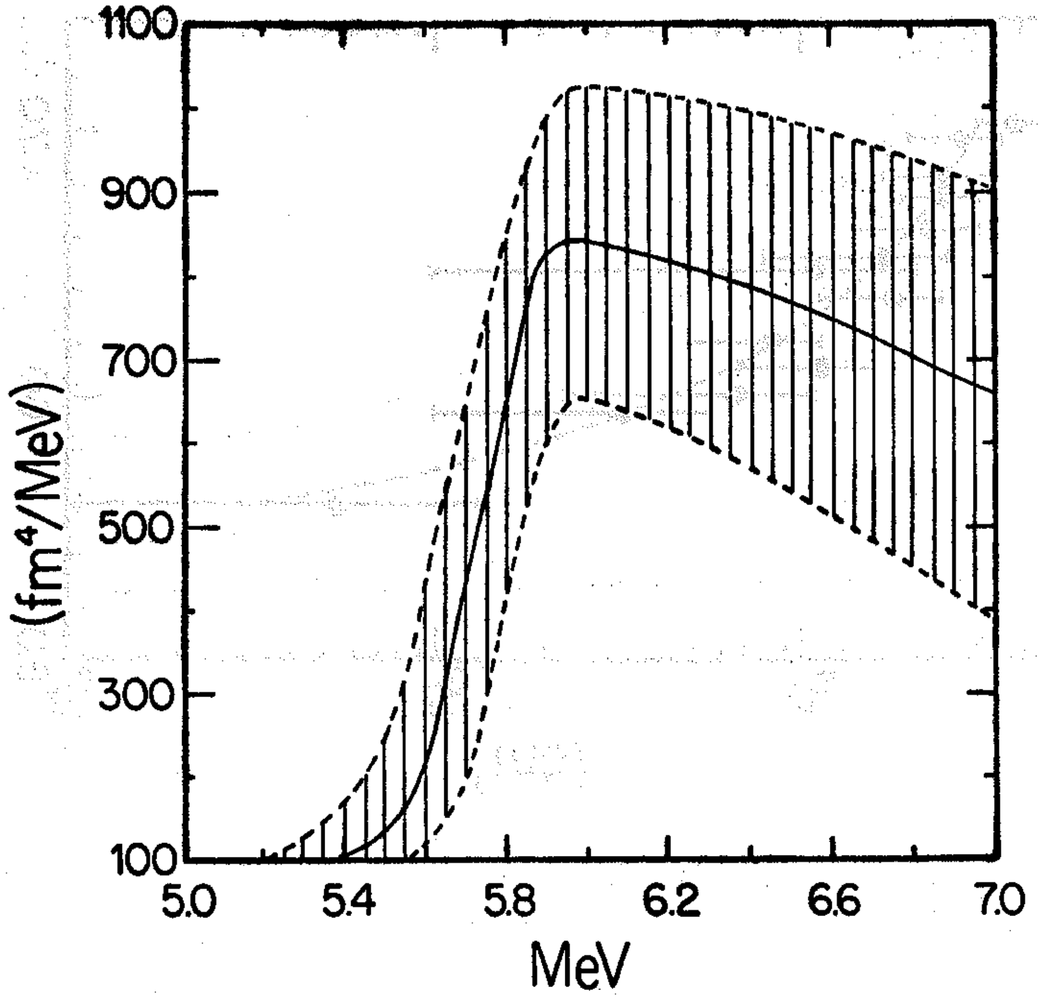


Fig. 3