Revista Brasileira de Física, Volume 13, n? 1, 1983

Concentration of E2 Strength Near the Fission Barrier of $^{234,236,238}U$

J. D. T. ARRUDA - NETO, S. B. HERDADE, I. C. NASCIMENTO
and B. L. BERMAN*
Instituto de Física, Universidade de São Paulo, Caixa Postal 20.516, São Paulo, 01000, SP, Brasil

Recebido em 26 de outubro de 1982

Abstract The electrofission angular distribution for ^{234}U in the energy range 5.5 to 13 MeV were measured and are analyzed together with those obtained previously for ^{236}U and ^{238}U. The competition between the K=O and $K=1$ fission channels following *E2* excitation is established, showing adominance of the K=O channel for near-barrier fission. A substantial concentration of *E2* strength near the fission barrier is found, in good agreement with earlier photofission angular-distribution studies.

Recent electron- and hadron- induced fission measurements for ^{238}U, in the region of the isoscalar giant quadrupole resonance (GQR), have yielcled contradictory results[1,2]. In addition to the controversy concerning the total amount of *E2* strength concentrated in the fission decay channel for actinide nuclei, another point of conflict concerns the distribution of *E2* strength over the excitation-energy region in which the GQR is found. In this regard, we note here that from the hadron-induced results the GQR peaks systematically at -11 MeV and *vanishes* below -8.5 MeV [3]. Therefore, it is necessary to study carefully the *E2* strength distribution close to the fission barrier ($\lesssim$ 8 MeV) by means of an anambiguous experimental technique, such as the measurement of the electrofission-fragment angular distributions, which can help to delineate the low-lying fission levels populated by *E2* photo-absorption[4]. In so doing, we hope to show that the picture drawn from the hadron-induced results, namely, *zero E2* fission strength at excitation energies $\lesssim$ 8 MeV for actinide nuclei, is physically unreasonable.

A formalism for the analysis of electrofission-fragment angular distributions, utilizing the virtual-photon spectrum technique, was developed recently[4]. The application of this formalism to ^{238}U led to

Supported by Fundação de Amparo à Pesquisa do Estado de São Paulo
* Permanent address: Lawrence Livermore National Laboratory, University of California, Livermore, California 94550, USA.

the identification of the low-lying levels of the transition nucleus; also, the competition between the K=0 and K=1 channels of the fission decay following E2 excitation in ^{238}U was delineated. In this paper we extend the application of this formalism to the study of ^{234}U and ^{236}U. Also, we extract the E2 strength functions for $^{234,236,238}U$ at low excitation energies (near the fission barrier); by comparing them to the angular-distribution data we establish limits for the E2 strength for the $K=0$ and $K=1$ fission channels.

In the present work we have measured electrofission angular distributions for ^{234}U and analyzed them jointly with those for ^{236}U and ^{238}U. The experimental technique and procedures were the same as for our previous work and are described at length in Refs. 4 and 5. The electrofission differential cross sections $d\sigma_e/d\Omega_f$ for ^{234}U, in the energy range from 5.5 to 13 MeV, were obtained by irradiating 255 $\mu g/cm^2$ targets of ^{234}U enriched to 99.1% with an electron beam from 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^o and 100^o (eleven, usually, are plotted in Fig. 1; the twelfth, at 100^o, is redundant, and serves as an experimental check). The uncertainties in $d\sigma_e/d\Omega_f$, arising both from statistical fluctuations and from systematic uncertainties associated with geometry and target thickness determination, are typically ~5%.

The electrofission differential cross section for a particular fission channel (J^π,K) is defined as[4]

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

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 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; and $W^J_{MK}(\theta_f)$ is the angular-distribution function. The coefficients of the angular distributions ϕ_e constitute the link between the electro- and photoexcitation processes and are given by[4] (in what follows we consider only electric transitions)

$$\phi_e(J^\pi,K,M;E_e) = C(L) \int_0^{E_e} \frac{dB}{d\omega}(EL;\omega) . \frac{\Gamma_f}{\Gamma}(J^\pi,K;\omega) . \omega^{2L-1} . N^{(EL,M)}(\omega,E_e)\frac{d\omega}{\omega} \tag{2}$$

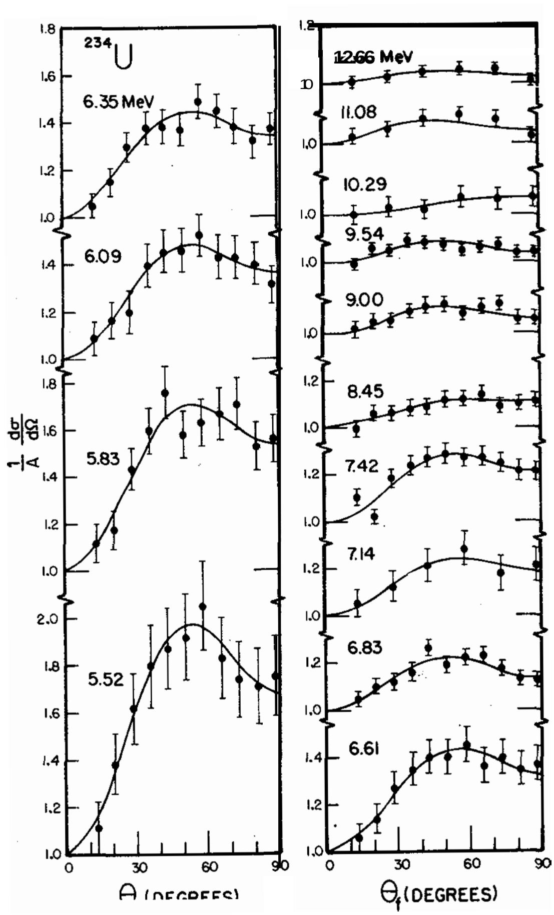

Fig. 1 - Electrofission-fragment angular distributions $\frac{1}{A_e(E_e)} \frac{d\sigma}{d\Omega_f}(E_e,\theta_f)$ for ^{234}U, for incident electrons having energies from 5.5 to 12.7 MeV. The curves are least-squares fits of the function defined in eqn. (3) to the experimental points. Both systematic and statistical uncertainties are included in the error flags (and were used in the fitting procedure). Similar figures for ^{236}U and ^{238}U appear in Refs. 5 and 8, respectively.

where $\frac{dB}{d\omega}$ is the nuclear strength function, $N^{(EL,M)}$ is the virtual-photon spectrum (calculated in DWBA[6]) for an EL-transition with magnetic substate M, and $C(L) = (2\pi)^3\, a \frac{(L+1)}{L\left[(2L+1)!!\right]^2}$. The nuclear photoabsorption near the fission barrier takes place in the energy region corresponding to the low-energy tails of the GDR and GQR; thus the product $\frac{dB}{d\omega} \cdot \frac{\Gamma_f}{\Gamma}$ reflects mainly the properties of the low-lying fission levels.

The (e,f) inclusive reactions for actinide nuclei are dominated by nuclear transitions having L=l and 2. Therefore, from eq. (1) one has

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

$$= A_e(E_e) + B_e(E_e)\sin^2\theta_f + C_e(E_e)\sin^2(2\theta_f) \qquad (3)$$

where the coefficient C_e, which contains contributions from the 2^+ levels only, is given by[4] (for K=O and 1)

$$C_e(E_e) = \frac{5C(L=2)}{32\pi} \int_0^{E_e} \left[3\,\frac{dB}{d\omega}(E2;\omega)\,.\,\frac{\Gamma_f}{\Gamma}(2^+,0;\omega) - 4\,\frac{dB}{d\omega}(E2;\omega)\,.\,\frac{\Gamma_f}{\Gamma}(2^+,1;\omega)\right] \times$$

$$\times\, N^{(E2,\mathrm{tot})}_{(\omega,E_e)}\, \omega^2 d\omega \qquad (4)$$

and

$$N^{(E2,\mathrm{tot})}_{(\omega,E_e)} = -\frac{3}{2}\, N^{(E2,0)}_{(\omega,E_e)} + N^{(E2,1)}_{(\omega,E_e)} - \frac{1}{4}\, N^{(E2,2)}_{(\omega,E_e)} \qquad (5)$$

An angular distribution having the form given by Eqn. (3) has been assumed (solid curves in Fig.1), and the coefficients A_e, B_e, C_e were obtained by least-squares fitting to the experimental $d\sigma_e/d\Omega_f$ data. A simple visual inspection of Fig.1 reveals the presence of a major $E2$ component in the electrofission cross section, at least at low energies, as indicated by the systematic enhancement found in $d\sigma_e/d\Omega_f$

near 50°. Fig. 2 displays the C coefficient (representing contributions from $E2$ transitions alone) obtained here for ^{234}U and from previous work[4,5] for ^{236}U and ^{238}U. The fission strength functions $\sum_K \frac{dB}{d\omega}(E2) \cdot \frac{\Gamma_f}{\Gamma}(2^+,K)$ which were obtained from the $E2$- photofission cross sections are also plotted in Fig.2. If the photon energy $\omega \lesssim [B_f(2^+) + \Delta]$, where $B_f(2^+)$ is the 2^+ fission barrier and Δ is the pairing gap, then the K-values appearing in the above summation are representative only of the corresponding rotational bands (and are dominated by the K=0 and K=1 bands). The solid curves in Fig. 2 were obtained by numerical integration of

$$\frac{15}{32\pi}\int_0^{E_e} \sigma^{E2}_{\gamma,f}(\omega)\; N^{(E2,\mathrm{tot})}_{(\omega,E_e)} \frac{d\omega}{\omega} \equiv C'_e(E_e) \qquad (6)$$

using the experimentally determined E2 photofission cross sections $\sigma^{E2}_{\gamma,f}(\omega)$, from Refs. 5, 7 and 8, defined as

$$\sigma^{E2}_{\gamma,f}(\omega) = C(L=2)\,.\,\omega^3.\ \frac{dB}{d\omega}(E2;\omega)\ .\sum_K \frac{\Gamma_f}{\Gamma}(2^+,K;\omega) =$$

$$= \sum_K \sigma_{\gamma,f}(2^+,K;\omega) \qquad (7)$$

Comparing eq. (4) and (6) we see that $C_e = C'_e$ if $\sigma_{\gamma,f}(2^+,0) = \sigma^{E2}_{\gamma,f}$, that is, in a situation where the K=0 channel is the only one open to fission. The opening of the K=1 channel causes a diminution of the cross-section kernel of the integral C_e [eqn.(4)] and as a consequence results in a change of its slope, as shown in Fig. 2 by the dashed curves. Therefore, the comparison of C_e and C'_e clearly establishes the energy $B_f(2^+,1)$ corresponding to the location of the fission barrier for the $(2^+,1)$ level. The structure observed in $\frac{dB}{d\omega}(E2)\cdot\frac{\Gamma_f}{\Gamma}(2^+)$ near 6 MeV resultspartly from the locations of the $(2^+,0)$ levels and partly from the neutron-emission competition. The total amount of E2 fission strength concentrated in the K=O channel near the barrier is substantial, and is in good agreement with earlier photofission angular-distribution data[9]; these results are listed in Table 1, and the E2 fission strength is expressed as a percentage of the isoscalar $E2$ energy

-weighted sum-rule (EWSR), namely

$$\frac{1}{B(E2)} \int_{0}^{\geq B_f(2^+,1)} \frac{dB}{d\omega}(E2;\omega) \cdot \frac{\Gamma_f}{\Gamma}(2^+,0;\omega)\, d\omega \times 100 ,$$

where $B(E2)$ is equal to one $E2$ EWSR unit.

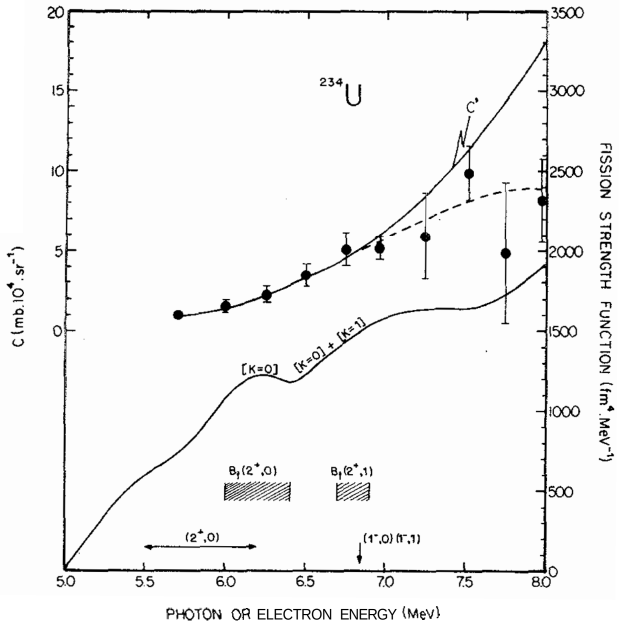

Fig.2 - Absolute values for the coefficients of the $\sin^2(2\theta_f)$ term in the electrofission differential cross section $C(E_e)$ [eqn. (3)], obtained from the measured angular distributions for ^{234}U (data points, scale on left), along with $\sum_K \frac{dB}{d\omega}(E2) \cdot \frac{\Gamma_f}{\Gamma}(2^+,K)$ over the same energy range (solid curve, scale on right). The solid curve C' is defined in the text. The shaded bands (whose widths represent the uncertainty in their determination) and arrows represent the location of the fission barriers as determined in this work and in Ref. 9, respectively. The locations of $B_f(2^+,0)$ were assigned simply frorn consideration of the concentration of the E2 strength below $B_f(2^+,1)$.

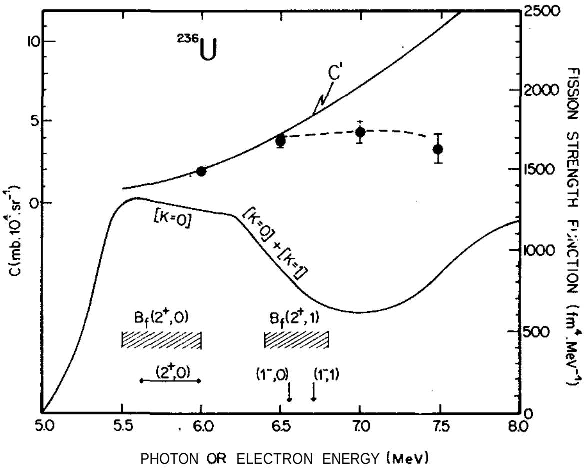

Fig. 2B - Sane as in Fig. 2A, for ^{236}U

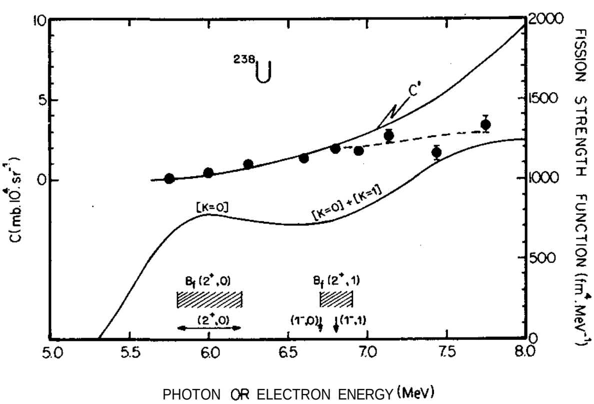

Fig. 2C - Same as in Fig. 2A, for ^{238}U.

Table 1 - E2 strength concentrated in the $(2^+,0)$ físsion channel and the 2^+ fission-barrier heights.

Nucleus	E2 Strength % $(J^\pi,K) = (2^+, 0)$		$B_f(2^+,0)$ (MeV)		$B_f(2^+,1)$ (MeV)
	a)	b)	a)	b)	a)
^{234}U	10 ± 2	16 ± 3	6.0 to 6.4	5.4 to 6.2	≳6.7
^{236}U	13 ± 2	8 ± 2	5.5 to 6.0	5.6 to 6.0	≳6.4
^{238}U	6 ± 1	7 ± 1	5.8 to 6.2	5.8 to 6.2	≳6.7

a) Present work.

b) Derived from the cross sections published in Ref. 9.

In conclusion: our results show that the fission process is strongly favored in the decay of the GQR (for these actinide nuclei) at excitation energies close to the fission barrier, because of the fact that the 2^+ fission-barrier heights are considerably lower than the values for B_n (the neutron evaporation threshold), whereas the 1^- barrier heights are much closer to the B_n values (more details can be found in Ref.1). However, for energies $>B_f+\Delta$, where intrinsic excitations become increasingly important, it would be expected that $\frac{\Gamma_f}{\Gamma}(2^+) \cong \frac{\Gamma_f}{\Gamma}(1^-) \cong$ the fission probability of the compound nucleus. Finally, the present results stand in sharp contrast with those obtained for the hadron-induced fission of ^{238}U in the energy region of the GQR, where no E2 fission strength was detected at energies ≲ 8 MeV.

REFERENCES

1. J.D.T. Arruda-Neto and B.L. Berman; Nucl. Phys. A*349*, 483 (1980) and references therein.
2. H Ströher *et al.*; Phys. Rev. Lett. *47*, 318 (1981), and references therein.
3. Proceedings of the *Giant Multipole Resonance Topical Conference*, edited by F.E. Bertrand (1979); Harwood Academic Publishers, New York.
4. J.D.T. Arruda-Neto et *al.*; Nucl. Phys. A 334, 297 (1980).
5. J.D.T. Arruda-Neto et *al.*; Phys. Rev. C 22, 1996 (1980).
6. W.W. Gargaro and D.S. Onley; Phys. Rev. C 4, 1037 (1971).
7. J.D.T. Arruda-Neto et *al.*; Phys. Rev. C 23, 2595 (1981)
8. J.D.T. Arruda-Neto et *al.*; Phys. Rev. C *18*, 863 (1978).
9. L.J. Lindgren et *al.*; Nucl. Phys. A 298, 43 (1978).

RESUMO

As distribuições angulares de eletrofissão do ^{234}U, na faixa de energias de 5,5 a 13 MeV, foram medidas e a seguir analisadas conjuntamente com as distribuições angulares do ^{236}U e ^{238}U obtidas anteriormente neste Laboratório. Foi estabelecida a competição entre os canais de fissão $K=0$ e $K=1$, mostrando o domínio do canal $K=0$ perto da barreira de fissão. Foi detetada uma concentração apreciável de "strength" E2 perto da barreira de fissão, em excelente acordo com dados anteriores de distribuição angular de fotofissão.