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by

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ABSTRACT

The electrofission cross section for ^{235}U has been measured from 5.8 to 22 MeV. From a combined analysis of it and the previously measured photofission cross section, using the virtual-photon formalism, the photofission cross section for excitations other than E1 has been determined.

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Keyword abstract:

NUCLEAR REACTIONS: $^{235}U(e,f)$. Measured $\sigma(e,f)$; deduced multipolar components other than E1 in the photofission channel. Enriched target.

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I. INTRODUCTION

The study of the fission decay of the giant multipole resonances for the actinide nuclei is a rapidly developing field. Fission-fragment angular-distribution data, using electromagnetic probes, have demonstrated unambiguously the existence of a substantial E2 component in the photofission of even-even actinides, at least at excitation energies just above the fission barrier (Arruda Neto et al 1982a, 1982b, Arruda-Neto 1984), where one might expect to find the low-energy tail of the isoscalar giant quadrupole resonance (GQR). At somewhat higher energies, the fission decay of the giant monopole (E0) resonance (GMR) for ^{238}U has been observed (Morsch et al 1982). The fission of 1^+ states (populated by M1 photo-absorption) has been observed in the even-even uranium isotopes (Arruda-Neto et al 1982a, 1980, 1980a, 1981). The fission decay of the GQR in actinide nuclei has been investigated by means of both electromagnetic and hadronic probes, particularly for ^{238}U. The results of Arruda-Neto et al (1982a, 1980a, 1981), Shotter et al (1979), and Bertrand et al (1981) are in qualitative agreement with respect to the fact that the GQR does fission, but the parameters so far deduced (peak energy, width, and strength) are contradictory (Arruda-Neto et al 1982a, Arruda-Neto and Berman 1980, Arruda-Neto 1984b). Other electron- and hadron-induced fission experiments, on ^{232}Th and ^{238}U (Aschenbach et al 1979; Ströher et al 1981, van der Plicht et al 1979), yielded results compatible with a GQR fission branching ratio equal to the apparently unphysical value of zero. The necessity for additional data, especially those obtained from relatively unambiguous electromagnetic interactions, is clear (see, for example, Hanna (1981) and Arruda-Neto (1984a)).

Kinematically complete (e,e'f) coincidence measurements certainly would help to elucidate the characteristics of the fission decay of the giant multipole resonances, but (e,e'f) experiments alone are not decisive; we also need the strength function evaluated at the photon point, which can be obtained most easily from inclusive (e,f) measurements like the one described in this paper. (We refer the reader to Arruda-Neto (1984a), where this matter is discussed extensively.)

The statistical nature of the decay of the giant dipole (E1) resonance (GDR) in heavy nuclei is well established, from both the theoretical and experimental points of view (Wagner 1980). Notwithstanding, the E2 fission strength, deduced from electrofission studies for the even-even uranium isotopes, is considerably larger than that for E1 excitation (Arruda-Neto et al 1982a); otherwise, the E1 fission channel increases in strength more rapidly with fissility than does the E2 channel (Arruda-Neto et al 1981). This very interesting, and somewhat unexpected, peculiarity of the actinide nuclei calls for both confirmation and explanation. This has motivated us to pursue another electrofission investigation on a highly fissionable actinide nucleus.

II. EXPERIMENT

In this paper we report, for the first time, the results of an electrofission measurement on ^{235}U performed at the University of São Paulo Electron Linear Accelerator. The data were taken at electron energies E_e ranging from 5.8 to 22 MeV in steps of ~ 0.25 MeV up to 12.7 MeV, and in steps of ~ 0.5 MeV from 12.7 to 22 MeV. A Faraday cup was used for the beam monitoring. The fission fragments were detected with mica foils, arranged in a way that produced angular-distribution measurements as well. The target samples were UO_2, enriched to 99.7% in ^{235}U, vapor-plated onto 5-μm thick titanium backing foils. The target thickness are 211 $\mu g/cm^2$, which were measured to ±2% by a conventional alpha-counting method. The experimental apparatus and procedures for this experiment were the same as for previous ones (Arruda-Neto et al 1982a). Details of the accelerator, reactor chamber, monitoring devices, and detection techniques and procedures can be found in Arruda-Neto et al (1982a, 1980, 1980a).

III. RESULTS

Figure 1 shows the electrofission cross section $\sigma_{e,F}(E_e)$ for ^{235}U; the curve was obtained by numerical integration of the photofission cross section $\sigma_{\gamma,F}(\omega)$ measured at Livermore (Caldwell et al 1980), with the E1 virtual-photon spectrum $N^{E1}(E_e,\omega)$ calculated in DWBA (Soto Vargas et al 1977), that is, $\int_0^{E_e} \sigma_{\gamma,F}(\omega) N^{E1}(E_e,\omega) \frac{d\omega}{\omega}$, where ω is the real (or virtual) photon energy. The difference $\Delta\sigma_{e,F}(E_e)$, between $\sigma_{e,F}(E_e)$ and the calculated curve, is shown in Fig. 1 as well. The ratio

$$R(E_e) = \frac{\sigma_{e,F}(E_e)}{\int_0^{E_e} \sigma_{\gamma,F}(\omega) N^{E1}(E_e,\omega) \frac{d\omega}{\omega}} \qquad (1)$$

is shown in figure 2. It is important to note that for a pure E1 process the electrofission cross section is given by $\int_0^{E_e} \sigma_{\gamma,F}(\omega) N^{E1}(E_e,\omega) \frac{d\omega}{\omega}$, where now

$$\sigma_{\gamma,F}(\omega) = \sum_{\lambda L} \sigma^{\lambda L}_{\gamma,F}(\omega) = \sigma^{E1}_{\gamma,F}(\omega) \quad . \qquad (2)$$

If this assumption were true, $R(E_e)$ should be a constant, and the difference $\Delta\sigma_{e,F}(E_e)$ might be the consequence of normalization problems between the São Paulo ($\sigma_{e,f}$) data and the Livermore ($\sigma_{\gamma,f}$) data. However, a simple visual inspection of figure 2 shows that this is not the case. It should be noted that the virtual-photon-spectrum calculations has been tested again recently (Dodge et al 1983), and that in the energy region of the present experiment the nuclear-size effects are small. Therefore, one is led to the conclusion that sizable multipolar components other than E1 must be contributing to the photofission process, in all likelihood E2 and M1. In an inclusive (e,f) cross section, at low energies, the contributions from E0 and from multipoles higher than E2 probably are negligible (Arruda-Neto et al 1980a).

A quantitative analysis of the non-electric-dipole components contributing to the photofission process can be performed by means of a technique developed at this Laboratory. According to this technique, based on virtual-photon theory, we have that (Arruda-Neto et al 1980a, 1978).

$$\Delta\sigma_{e,F}(E_e) \equiv \sigma_{e,F}(E_e) - \int_0^{E_e} \sigma_{\gamma,F}(\omega) N^{E1}(E_e,\omega) \frac{d\omega}{\omega} =$$

$$\int_0^{E_e} (\sigma^{E2}_{\gamma,F}(\omega) + G\sigma^{M1}_{\gamma,F}(\omega)) (N^{E2}(E_e,\omega) - N^{E1}(E_e,\omega)) \frac{d\omega}{\omega} \qquad (3)$$

where $G = \left\langle \frac{N^{M1}}{N^{E2}} \right\rangle = 3$. (We refer the reader to Arruda-Neto et al (1978) for further details.) Thus, the unfolding of $\Delta\sigma_{e,F}(E_e) \times E_e$ makes possible the evaluation of the non--electric-dipole photofission cross section $\sigma^{ND}_{\gamma,F}(\omega)$. For the actinides, it is highly probable that

$$\sigma^{ND}_{\gamma,F}(\omega) \cong \sigma^{E2}_{\gamma,F}(\omega) + G\sigma^{M1}_{\gamma,F}(\omega) \quad . \qquad (4)$$

Figure 3 shows $\sigma^{ND}_{\gamma,F}(\omega)$ for ^{235}U, obtained from $\Delta\sigma_{e,F}$ (figure 1), using the least-structure unfolding method (Cook 1963). From the systematic study carried out at this Laboratory for the even-even uranium isotopes (Arruda-Neto et al 1982a), we know that a detectable M1 photofission component manifests itself around 6 MeV, and the disentangling of the M1 from the E2 component was accomplished with the aid of the electrofission angular distribution. However, for ^{235}U the measurements yielded nearly isotropic angular distributions; small anisotropies were found only at very low energies ($\lesssim$ 7 MeV). Therefore, a realiable evaluation of the M1 component cannot be made from these data. Also, as discussed in previous publications (Arruda-Neto et al 1980a, 1981, Arruda-Neto and Berman 1980), the present technique does not differentiate between first chance fission $\sigma^{\lambda L}_{\gamma,f}$ and second-chance fission $\sigma^{\lambda L}_{\gamma,nf}$. In order to subtract $\sigma^{E2}_{\gamma,nf}$ from the total E2 photofission cross section $\sigma^{E2}_{\gamma,F}$, it is necessary to assume that the ratio $\sigma^{E2}_{\gamma,f}/\sigma^{E2}_{\gamma,nf}$ is the same as that obtained experimentally for E1 transitions. Since that ratio is not available for ^{235}U we used the one obtained for ^{236}U (Caldwell et al 1980). The result of this tentative subtraction is shown in figure 3. Thus, the resulting parameters for the non-electric-dipole

fission decay of ^{235}U, as shown by its fission strength function (Arruda-Neto and Berman 1980) in figure 4, are (a) peak energy: 10.4 ± 0.8 MeV; (b) full width at half maximum (FWHM): ~ 4 MeV; and (c) strength: $140 \pm 35\%$ of the isoscalar-E2 energy-weighted sum rule (EWSR). It is worth remembering that the E2-EWSR unit is proportional to the second moment of the ground-state charge distribution of the nucleus $\langle R^2 \rangle$. Since there are no available data for the charge distribution of ^{235}U, we used the value for $\langle R^2 \rangle^{1/2}$ of 5.730 fm calculated by Pitthan et al (1980) for ^{238}U. Also, it was found in Pitthan et al (1980) that the assumed ground-state radius of ^{238}U had to be increased by about 10% for all multipolarities in order to bring the strength found into agreement with systematics and with other experiments on ^{238}U. Therefore, taking into account all the uncertainties (including an estimated uncertainty of ~ 20% in N^{E2}, from Arruda-Neto et al (1980b) we establish here a lower limit of $120 \pm 27\%$ of an E2-EWSR unit for the non-electric-dipole fission strength for ^{235}U.

IV. DISCUSSION

In spite of the large uncertainties associated with the determination of the properties of the non-electric-dipole fission process, it is nevertheless possible to obtain the following:

1) The shape of the non-electric-dipole strength distribution is similar to that of the GQR fission decay observed in the even-even actinides (Arruda-Neto et al 1982a); this could be an indication that the non-electric-dipole strength in the

fission of ^{235}U is dominated by E2 transitions.

2) Below the E1 photofission barrier $B_f(E1)$ at 5.8 MeV and even below the photoneutron threshold B_n at 5.3 MeV the non-electric-dipole fission strength is substantial; this fact constitutes evidence for $B_f(E2) \leq B_n$.

3) Above the structure in the fission strength function at ~5.5 MeV (see figure 4), which probably results from the competition between neutron emission and fission, we observe a shoulder around 6.5 MeV. A peak at this energy region also was observed systematically for ^{234}U, ^{236}U, and ^{238}U, and was attributed mainly to M1 photoexcitation (Arruda-Neto et al 1982a, 1980, 1980a).

4) The non-electric-dipole fission strength (figure 4) amounts to ~60% of an E2-EWSR unit in the energy region $5 < \omega < 8$ MeV, and ~80% above 8 MeV. This is quite illuminating, especially in light of the fact that below ~8 MeV no E2 strength was detected for actinide nuclei in hadron-scattering experiments (see, for example, the discussion in Arruda-Neto (1984b).

As noted above, this experiment alone does not permit one to disentangle the multipolar components which are present in the non-electric-dipole fission strength function for ^{235}U (figure 4). However, it is easy to show that the strength concentrated between 5 and 7.5 MeV cannot be attributed to E2 excitation alone; or, at least, that it is physically unreasonable. Assuming a Breit-Wigner shape for the GQR peaking at ~10 MeV, having a width of ~4 MeV and an area which encompasses the strength under the shoulder around 6.5 MeV (see figure 4), we find that its total strength equals

~6 E2-EWSR units. On the other hand, the resonant curve under the peak around 10 MeV (the dashed curve in figure 4) has an area which exhausts ~90% of an E2-EWSR unit; this is very similar to the E2 fission strength found for ^{234}U (Arruda-Neto et al 1981). From a statistical calculation (Arruda-Neto and Berman 1980) we know that large fission branching ratios are expected when $B_f \leq B_n$, as is the case for the E2 fission barrier of ^{235}U (see the discussion above). If we assign an M1 character to the strength in the energy region from 5 to 7.5 MeV which stands above the low-energy tail of the (dashed) E2 curve in figure 4, we find that this strength corresponds to $16^{+4}_{-3}\,\mu_N^2$, where μ_N is the nuclear magneton. Since we are investigating only the fission decay channel, this M1 strength represents a lower limit, and is compatible with theoretical predictions for heavy nuclei (Richter 1983).

REFERENCES

Arruda-Neto J D T, Herdade S B, Bhandari B S, and Nascimento I C 1978 Phys. Rev. C18 863.

Arruda-Neto J D T, Herdade S B, and Nascimento I C 1980 Nucl. Phys. A334 297.

Arruda-Neto J D T, Berman B L, Herdade S B, and Nascimento I C 1980 Phys. Rev. C22 1996.

Arruda-Neto J D T and Berman B L 1980 Nucl. Phys. A349 483.

Arruda Neto J D T, Berman B L, Herdade S B, and Nascimento I C 1980 Phys. Rev. C22 1794.

Arruda-Neto J D T, Berman B L, Herdade S B, and Nascimento I C 1981 Phys. Rev. C23 2595.

Arruda-Neto J D T, Herdade S B, Nascimento I C, and Berman B L 1982 Nucl. Phys. A389 378.

Arruda-Neto J D T, Vannucci M F B M, Herdade S B, Vannucci A, and Nascimento I C 1982 Phys Rev. C25 1689.

Arruda-Neto J D T 1984 Z. Phys. A315 247.

Arruda-Neto J D T 1984a J. Phys. G: Nucl. Phys. 10 101.

Arruda Neto J D T 1984b Phys. Rev. C29 1905.

Aschenbach J, Haag R, and Krieger H 1979 Z. Phys. A292 285.

Bertrand F E, Beene J R, Bemis Jr C E, Gross E E, Horen D J, Wu J R, and Jones W P 1981 Phys. Lett. 99B 213.

Caldwell J T, Dowdy E J, Berman B L, Alvarez R A, and Meyer P 1980 Phys. Rev. C21 1215.

Cook B C 1963 Nucl. Instrum. Methods 24 256.

Dodge W R, Hayward E, and Wolynec E 1983 Phys. Rev. C28 150.

Hanna S S 1981 Nucl. Phys. A358 229c.

Morsch H P, Rogge M, Decowski P, Machner H, Sükösd C, David P, Debrus J, Hartfiel J, Janszen H, and Schulze J 1982 Phys. Lett. 119B 315.

Pitthan R, Buskirk F R, Houk W A, and Moore R W 1980 Phys. Rev. C21 28.

van der Plicht J, Harakeh M N, van der Woude A, David P, and Debrus J 1979 Phys. Rev. Lett. 42 1121

Richter A 1983 Physica Scripta T5 63.

Shotter A C, Gellike C K, Awes T C, Back B B, Mahoney J, Symons T J M, and Scott D K 1979 Phys. Rev. Lett. 43 569

Soto Vargas C W, Onley D S, and Wright L E 1977 Nucl. Phys. A288 45

Ströher H, Fischer R D, Drexler J, Huber K, Kneissl U, Ratzek R, Ries H, Wilke W, and Maier H J 1981 Phys. Rev. Lett. 47 318.

Wagner J G 1979 Proc. Giant Multipole Topical Conference ed F E Bertrand (New York: Harwood) vol. 1 .

FIGURE CAPTIONS

Fig. 1 - The measured electrofission cross section $\sigma_{e,F}$ for ^{235}U as a function of incident electron energy (full circles); electrofission cross-section differences between $\sigma_{e,F}$ and the curve (open circles). The curve was obtained by integrating the photofission cross section with the E1 virtual-photon spectrum (details in the text).

Fig. 2 - The ratio of the E1 electrofission cross section and the total electrofission cross section for ^{235}U, as a function of the incident electron energy.

Fig. 3 - The non-electric-dipole photofission cross section $\sigma^{ND}_{\gamma,F}$ for ^{235}U obtained by solving the integral equation (3) using the least-structure unfolding method (Cook 1963). The curve was obtained from $\sigma^{ND}_{\gamma,F}$ after subtraction of the assumed second-chance fission cross section, as described in the text.

Fig. 4 - The fission strength function $\frac{dB^{ND}}{d\omega} \cdot \frac{\Gamma_f}{\Gamma}$ for ^{235}U, calculated from $\sigma^{ND}_{\gamma,F}$ (figure 3) in the long-wave length approximation (details in Arruda-Neto and Berman (1980)).

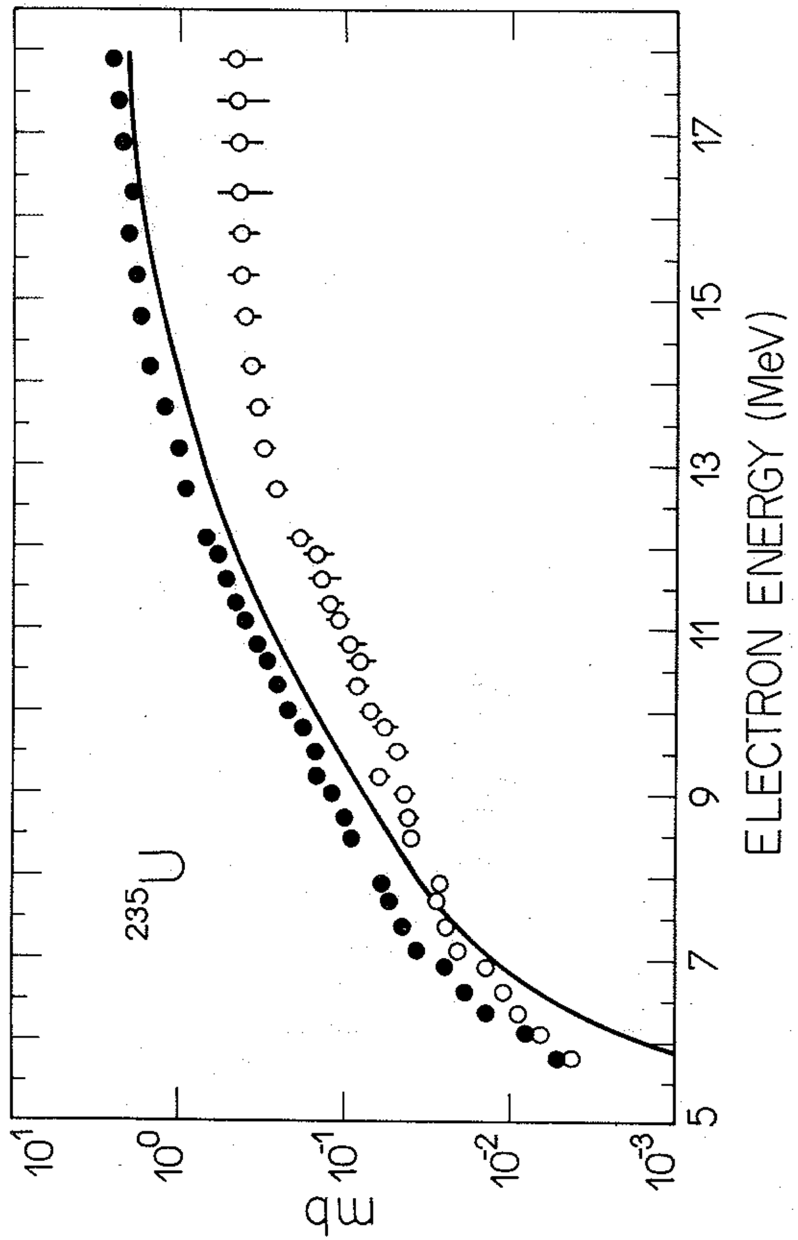
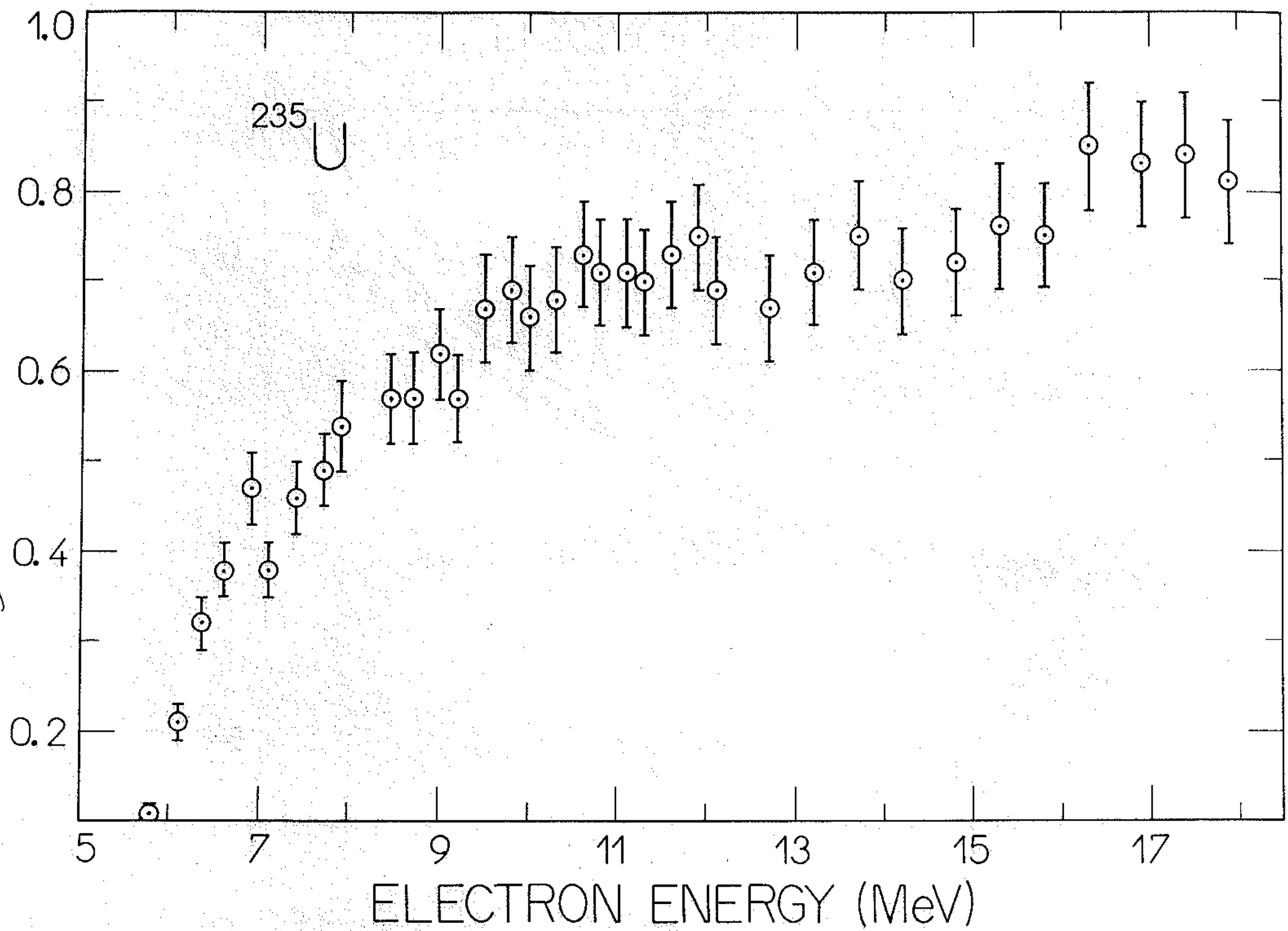
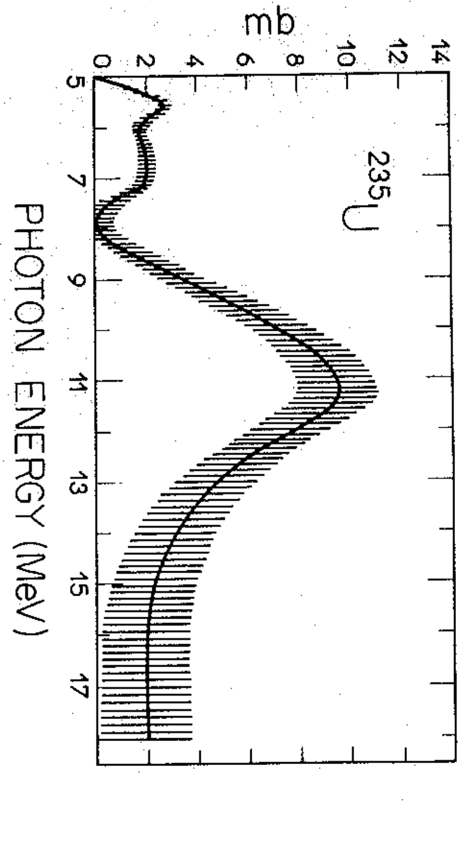


Fig. 1



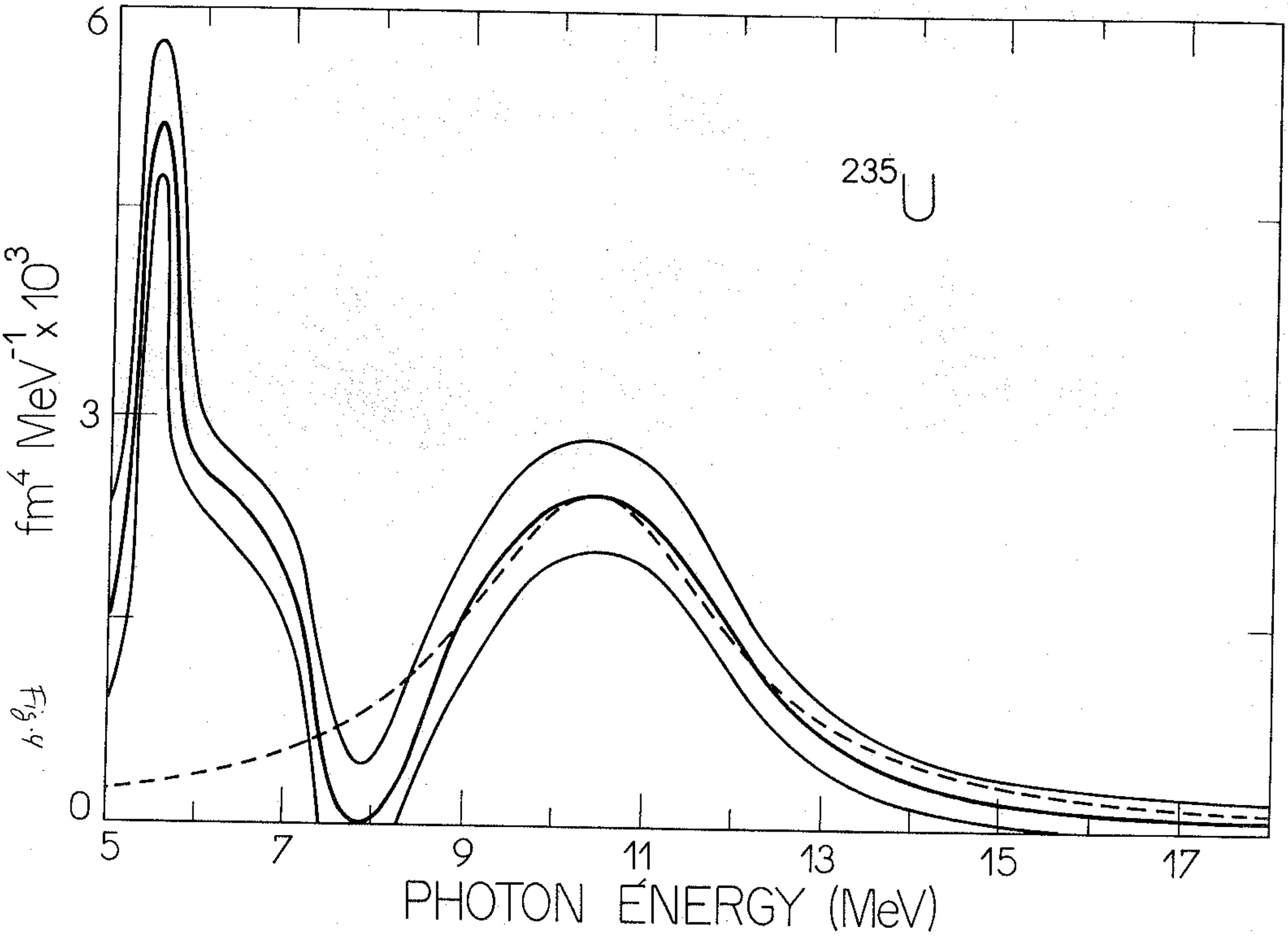
1.0
0.8
0.6
0.4
0.2
235U
5
7
9
11
13
15
17
ELECTRON ENERGY (MeV)

Fig. 2



mb
0
2
4
6
8
10
12
14
235U
5
7
9
11
13
15
17
PHOTON ENERGY (MeV)

Fig. 3



6
3
0
$fm^4\ MeV^{-1} \times 10^3$
^{235}U
5
7
9
11
13
15
17
PHOTON ÉNERGY (MeV)
Fig. 4