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preprint

IFUSP/P-252

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ABSTRACT

The electrofission cross section for ^{234}U from 5.5 to 25.4 MeV has been measured. From a combined analysis of it and the previously measured photofission cross section, using virtual-photon spectra calculated in the distorted-wave Born approximation, the E2 photofission cross section has been determined. Parameters of the fission-decay branch of the GQR for this nucleus have been obtained. A comparison of the E2 and E1 integrated photofission cross sections for the even uranium isotopes shows that the E1 fission channel increases in strength more rapidly with fissility than does the E2 channel.

KEYWORD ABSTRACT

NUCLEAR REACTIONS: Measured $\sigma(e,f)$ for ^{234}U; deduced $\sigma^{E2}(\gamma,f)$.

PACS Numbers:

The fission decay of the isoscalar Giant Quadrupole Resonance (GQR) for the actinide nuclei has been studied recently through the utilization of both electromagnetic [1-4] and hadronic [5-7] probes, since its first determination[1] for ^{238}U. However, the hadron-induced fission experiments have yielded contradictory results and have not yet helped to establish the characteristics of the fission channel of the GQR with confidence; in this regard we refer the reader to Ref. 3. On the other hand, electrofission studies performed at this Laboratory have shown that for both ^{238}U and ^{236}U sizable E2 strength is concentrated in the fission channel. An E2 fission probability P_f of $40 \pm 10\%$ near 10 MeV was estimated for ^{238}U, in accord both with statistical calculations[3] and with preliminary (e, e'f) coincidence measurements.[4]

The present work was motivated by the necessity to study the GQR fission decay for the actinide nuclei systematically, and in particular to try to understand the role played by the nuclear fissility in the concentration of E2 strength in the fission channel. The experimental technique and the method for data analysis that we used for this work were the same as for the study [1,2] of ^{238}U and ^{236}U. The electrofission and bremsstrahlung-induced fission cross sections for ^{234}U, in the energy range 5.5 to 25.4 MeV, were obtained by irradiating thin (255 $\mu g/cm^2$) targets of ^{234}U enriched to 99.1% with the electron beam of the University of São Paulo Linear Accelerator. Mica foils served as the fission-fragment detectors. The details of the experimental apparatus and procedures and of the data reduction are described at length in Ref. 2.

The electrofission cross section σ_e, as a function of incident electron energy E_o, is given by

$$\sigma_e(E_o) = \sum_{\lambda L} \int_o^{E_o} \sigma_\gamma^{\lambda L}(E) N^{\lambda L}(E,E_o) E^{-1} dE \tag{1}$$

where λ identifies the electric or magnetic character of the transition and L its multipolarity, $N^{\lambda L}$ is the virtual-photon spectrum calculated in DWBA (Ref. 8), E is the real or virtual photon energy, and the photofission cross section σ_γ is given by

$$\sigma_\gamma(E) = \sum_{\lambda L} \sigma_\gamma^{\lambda L}(E). \tag{2}$$

Combining Eqs. (1) and (2), for λL = E1, E2, and M1, we obtain the cross-section difference

$$\Delta\sigma_e(E_o) = \sigma_e(E_o) - \int_o^{Eo} \sigma_\gamma(E) N^{E1}(E,E_o) E^{-1} dE \equiv \sigma_e(E_o) - \sigma_e^*(E_o) =$$

$$= \int_o^{Eo} \sigma_\gamma^{Add}(E) \left[N^{E2}(E,E_o) - N^{E1}(E,E_o)\right] E^{-1} dE \tag{3}$$

where $$\sigma_\gamma^{Add}(E) = \sigma_\gamma^{E2}(E) + F(E)\sigma_\gamma^{M1}(E) \text{ and } F(E) = \left\langle \frac{N^{M1}}{N^{E2}} \right\rangle . \tag{4}$$

We refer the reader to Ref. 2 for further details and for the justification for inclusion of only the E1, E2, and M1 multipoles in the analysis.

The results for σ_e are shown as the data points in Fig. 1 (a), along with σ_e^* (the solid line), obtained by numerical integration of the product of the measured photofission cross section[9] and the E1 virtual-photon spectrum (see Eq. (3)); σ_e^* represents mostly E1 contributions. Figure 1(b)shows the cross-section difference $\Delta\sigma_e$ (the data points with error flags).Figure 2 shows σ_γ^{Add} obtained by solving the integral equation (3) using the least-structure unfolding method of Cook.[10] The dashed line in Fig. 1 (b) represents the fold-back of the result for σ_γ^{Add} shown in Fig. 2; insofar as this dashed line passes through the data points, the result obtained for σ_γ^{Add} is valid.

At this point, certain aspects of the method employed here (and in previous work[1,2]) should be stressed:

1) The neglect of contributions from the E0 and E3 multipolarities is justified.[2]

2) The photofission cross section is not assumed to be totally E1 (see, for example, the detailed analysis presented in Ref. 1).

3) Above the GDR peak the integral cross section σ_e is no longer sensitive to the E2 cross section σ_γ^{E2}, because above $\sim$ 20 MeV the very large integrated E1 (as compared to E2) strength disguises the E2 contribution. Therefore, the (e,f) cross section need only be known accurately <u>below</u> $\sim$ 20 MeV, down to the fission barrier ($\sim$ 5.5 to 6 MeV[11]).

4) There is no need to make any <u>a priori</u> assumption for the location of the GQR; its peak is determined clearly (see Fig. 1 (b)) by the inflexion of the cross-section difference $\Delta\sigma_e$ (which is a strong function of E_0 at low energies)

5) There is no need to extrapolate the photofission cross section $\sigma_\gamma(E)$ above 18 MeV in order to delineate the isoscalar GQR. For example, from $\sim$20 to 25.4 MeV (the highest-energy experimental point for ^{234}U presented here) the magnitude of the cross-section difference $\Delta\sigma_e$ is insensitive to the choice of $\sigma_\gamma(E)$ at energies above 18 MeV between 0 and $\sim$ 20 mb.

6) Moreover, electrofission experiments above $E_0 \approx 20$ MeV only poorly determine the GQR parameters; for example, in an electrofission study on ^{232}Th, ^{238}U, and ^{237}Np covering the energy range from 20 to 120 MeV, Shotter et al.[12] found substantial concentration of E2 strength in the fission channel but were unable to determine its assignment either to an isoscalar GQR at $\sim$ 9 MeV or to an isovector GQR at $\sim$22 MeV.

From the result for σ_γ^{Add} shown in Fig. 2, and using the same reasoning as in the analysis for ^{238}U and ^{236}U (Refs. 1 and 2), we conclude that the cross section σ_γ^{Add} for ^{234}U represents mostly E2 contributions with some small M1 strength near 6 MeV (according to a preliminary analysis of the fission-fragment angular distributions), represented by the shaded region of Fig. 3; a detailed analysis of the angular distributions will appear elsewhere.[13] The shaded region can be converted to the M1 photofission cross section by dividing the difference between the upper and lower curves by the factor F(E), which is equal to $\sim$3 in this energy region.

Thus, $\sigma_\gamma^{Add}(E \gtrsim 7.5 \text{ MeV}) = \sigma_\gamma^{E2}(E)$. However, the present technique does not differentiate between first-chance fission $\sigma_{\gamma,f}^{E2}$ and second-chance fission $\sigma_{\gamma,nf}^{E2}$. In order to subtract $\sigma_{\gamma,nf}^{E2}$ from σ_γ^{E2}, we have assumed (as in Refs. 2 and 3) that the ratio $\sigma_{\gamma,f}^{E2}/\sigma_{\gamma,nf}^{E2}$ is the same as that obtained experimentally[14] for E1 transitions for ^{236}U (that ratio is not yet available for ^{234}U). The result of this (tentative) subtraction is shown in Fig. 3.

It should be noted that the subtraction of the second-chance fission cross section does not change the energy of the peak of the GQR, and the total E2 fission strength is reduced by only 10%; however, the width of the GQR is reduced appreciably, from 7.4 MeV to 5.5 MeV. Thus the resulting GQR parameters for the fission decay of ^{234}U are (a) peak energy: 9.5 ± 0.4 MeV; (b) width (FWHM) : 5.5 ± 1.0 MeV; and (c) strength: $87 \pm 14\%$ of the isoscalar-E2 energy-weighted sum rule (EWSR).

The two main sources of uncertainty in the present determination of the GQR parameters (especially the strength) are (a) possibly serious systematic errors between the electrofission cross section σ_e (measured at this Laboratory) and the photofission cross section σ_γ (from Ref. 9), working in opposite directions, which would result in a $\Delta\sigma_e$ with no physical meaning and (b) large uncertainties associated with the DWBA calculations of the vitual-photon spectra N^{E1} and N^{E2}. In order to discard the former possibility we measured the bremsstrahlung-induced fission cross section $\sigma_b(E_o)$ for E_o = 9, 11, 13, 15, and 17 MeV, and compared it to

$$\sigma_b(E_o) = \int_0^{E_o} \sigma_\gamma(E)\, N_b(E,E_o)\, dE$$

obtained from the numerical integration of σ_γ (from Ref.9) in the thin-target bremsstrahlung-spectrum kernel N_b (corrected for the finite thickness of the radiator [2]). The average ratio between the two sets of values for σ_b was found to be close to unity. The latter possibility can be discarded as well, based upon the experimental tests performed for these two spectra.[15,16] The assumption of an upper limit of ~ 20% for the uncertainty in N^{E2}, as established in Ref. 16, results in a lower limit of 60% (of one E2 - EWSR unit) for the GQR fission strength, which still is larger than that for the GDR (~ 45%[9]).

In Fig. 4 the present result for ^{234}U is compared with those for ^{236}U and ^{238}U by plotting the integrated photofission cross sections as a function of the fissility parameter $x = Z^2/50.13A$; also shown are recent E1 photofission results (from Refs. 9 and 14). It can be seen that the strength concentrated in the fission channel increases faster, as a function of x, for E1 transitions than for E2 transitions for the even uranium isotopes. Still, the fission process is more strongly favored in the decay of the GQR than in the decay of the GDR for ^{234}U. A possible explanation for this behavior, at least at low energies (≤ 7 MeV), in terms of the relative location of the lowest 1^- and 2^+ fission barriers, is given in Ref. 3. Clearly, further systematic fission studies, both theoretical and experimental, are needed.

We are pleased to acknowledge the able assistance of A. Vannucci and M. F.B. Monteiro Vannucci in preparing the mica foils and handling the data. We thank Dr. J.T. Caldwell for providing the photofission data in advance of publication. Thanks are due as well to Dr. J.G. Povelites for the manufacture of the fission foils. This work was supported in part by the Fundação de Amparo a Pesquisa do Estado de São Paulo.

REFERENCES

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1) J. D. T. Arruda-Neto, S. B. Herdade, B. S. Bhandari, and I. C. Nascimento, Phys. Rev. C 18, 863 (1978)

2) J. D. T. Arruda-Neto, B. L. Berman, S. B. Herdade, and I. C. Nascimento, Lett. Nuovo Cim. 26, 487 (1979); J. D. T. Arruda-Neto, B. L. Berman, S. B. Herdade, and I. C. Nascimento, Phys. Rev. C 22, 1996 (1980).

3) J. D. T. Arruda-Neto and B. L. Berman, Nucl. Phys. A 349, 483 (1980).

4) J. R. Calarco, Proc. RCNP International Symposium on Highly Excited States in Nuclear Reactions, Osaka (1980).

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

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

7) F. E. Bertrand, J. R. Beene, C. E. Bemis, Jr., E. E. Gross, D. J. Horen, J. R. Wu, and W. P. Jones, Oak Ridge National Laboratory preprint (1980).

8) W. W. Gargaro and D. S. Onley, Phys. Rev. C 4, 1037 (1971).

9) J. T. Caldwell, E. J. Dowdy, B. L. Berman, R. A. Alvarez, and P. Meyer, private communication.

10) B. C. Cook, Nucl. Instrum. Methods 24, 256 (1963).

11) R. Vandenbosch and J. R. Huizenga, Nuclear Fission (Academic Press, New York, 1973); J. D. T. Arruda-Neto, S. B. Herdade, and I. C. Nascimento, Nucl. Phys. A334, 297 (1980).

12) A. C. Shotter, D. Branford, J. C. McGeorge, and J. M. Reid, Nucl. Phys. A290, 55 (1977).

13) J. D. T. Arruda-Neto, B. L. Berman, S. B. Herdade, and I. C. Nascimento, to be submitted to Nucl. Phys.

14) J. T. Caldwell, E. J. Dowdy, B. L. Berman, R. A. Alvarez, and P. Meyer, Phys. Rev. C 21, 1215 (1980).

15) I. C. Nascimento, E. Wolynec, and D. S. Onley, Nucl Phys. A246, 210 (1975).

16) J. D. T. Arruda-Neto, B. L. Berman, S. B. Herdade, and I. C. Nascimento, Phys. Rev. C 22, 1794 (1980).

FIGURE CAPTIONS

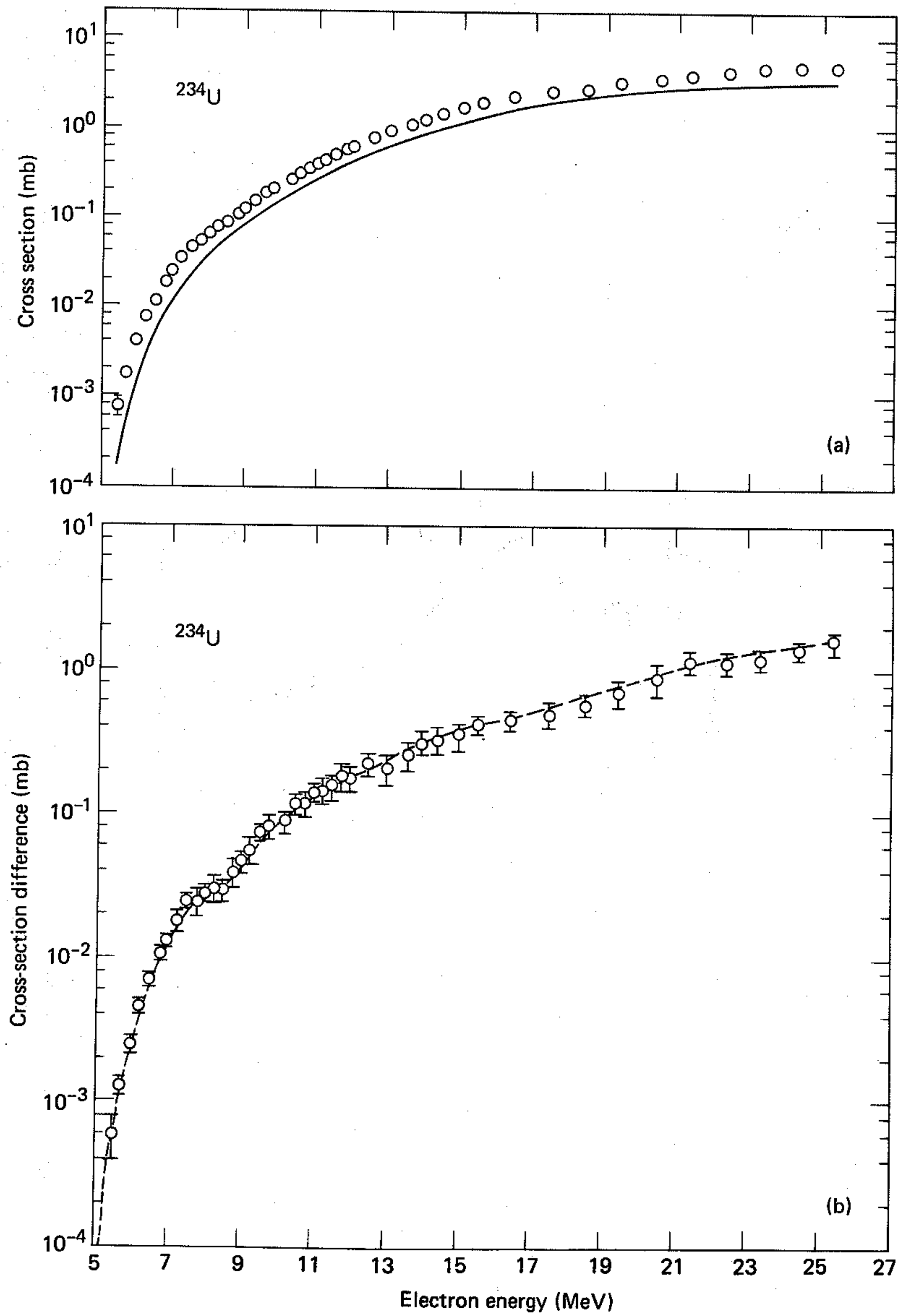
1. (a) The data points are the present measured electrofission cross-section $\sigma_e(E_o)$ for ^{234}U. Except for the point at 5.5 MeV, the statistical uncertainties are smaller than the plotted symbols. The solid curve is $\sigma_e^*(E_o)$, which was obtained by integrating the measured photofission cross section of Ref. 9 with the E1 virtual-photon spectrum of Ref. 8; it represents mainly the E1 component.

   (b) The data points (with error flags) are the electrofission cross-section differences $\Delta\sigma_e(E_o)$ between the data points and the curve of part (a). The dashed curve is the fold-back of σ_γ^{Add} (shown in Fig. 2) in Eq. (3).

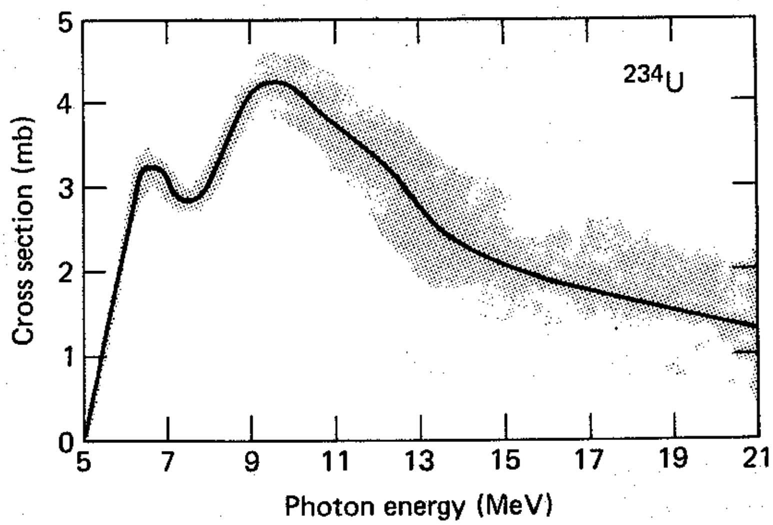
2. The solid curve is the "additional" cross section $\sigma_\gamma^{Add}(E)$ for ^{234}U, which represents contributions from multipolarities other than E1, and was obtained by solving the integral equation (3) using the least-structure unfolding method of Ref. 10. The shaded error band contains both systematic and statistical uncertainties.

3. The upper curve is σ_γ^{Add} from Fig. 2. Subtraction of the M1 contribution, represented by the shaded region (see text) yields the lower curve below $\sim$8 MeV. Subtraction of the second-chance photofission cross section $\sigma(\gamma,nf)$ from the total photofission cross section $\sigma(\gamma,F)$ yields the first-chance photofission cross section $\sigma(\gamma,f)$ which is the lower curve above the (γ,nf) threshold B_{nf} = 12.3 MeV. Thus, the lower curve represents the fission-decay branch of the GQR.

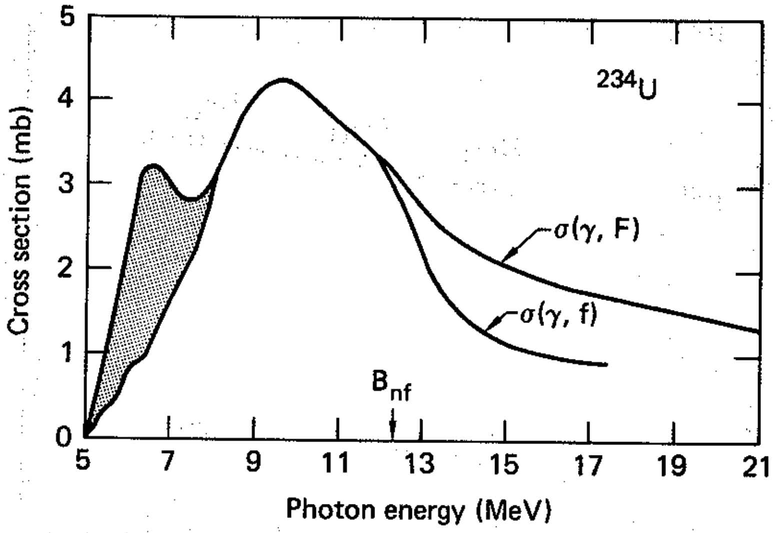
4. The data points are the integrated photofission cross sections for the E1 and E2 multipolarities for the even uranium isotopes, as labeled. The lines illustrate the steeper dependence of the E1 strength on the fissility Z^2/A than that of the E2 strength.



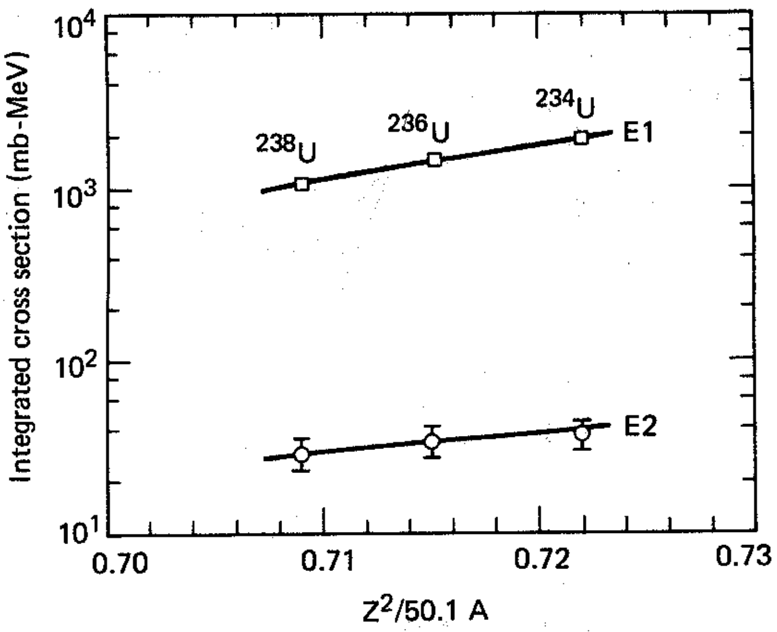
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Cross section (mb)
^{234}U
(a)
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Cross-section difference (mb)
^{234}U
(b)
5
7
9
11
13
15
17
19
21
23
25
27
Electron energy (MeV)



234U
Cross section (mb)
Photon energy (MeV)
0
1
2
3
4
5
5
7
9
11
13
15
17
19
21



Cross section (mb)
Photon energy (MeV)
^{234}U
$\sigma(\gamma, F)$
$\sigma(\gamma, f)$
B_{nf}
0
1
2
3
4
5
5
7
9
11
13
15
17
19
21



Integrated cross section (mb-MeV)
10^4
10^3
10^2
10^1
238U
236U
234U
E1
E2
0.70
0.71
0.72
0.73
Z^2/50.1 A