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ABSTRACT

Experimental results are presented for the electro-and photofission of ^{238}U in the energy range 6 to 60 MeV. The importance of the inclusion of the Coulomb corrections in the calculation of the virtual photon spectrum is emphasized and the relative contributions of the E1 and E2 excitations to the electrofission process are evaluated using the DWBA analysis of the experimental data. A prescription is presented for the extraction of the quadrupole component from the electro-and photo excitation measurements.

KEYWORD ABSTRACT

NUCLEAR REACTIONS, FISSION. Measured electro- and photofission cross sections of ^{238}U in the energy range 6-60 MeV. Deduced relative contributions of E1 and E2 excitations using DWBA analysis of the experimental data.

I - INTRODUCTION

The study of the photonuclear reactions, and of photofission in particular, has been carried out in several laboratories since the discovery of nuclear fission. Although electron induced nuclear reactions have also been studied in the last two decades, there are no data available on the electron induced fission cross sections of ^{238}U in the giant dipole resonance region and only a few investigations [1-3] have been reported for energies above this region.

The use of electrons and that of photons to induce nuclear reactions is equivalent in the sense that in both cases, the nuclei are excited by means of the electromagnetic interaction. In the case of electro excitation, this interaction takes place through the virtual photon spectrum as compared to that through the real photons in the case of photo excitation. The virtual photon spectrum differs from the real photon spectrum mainly in that:

1) it contains both longitudinal as well as the transverse photons, and
2) it depends strongly upon the multipolarity of the photons.

The electro excitation process can therefore, at least in principle, serve as an important tool for the investigation of the multipolarities of the transitions involved.

Using plane waves for the incoming as well as the outgoing electrons, Thie, Mullin and Guth[4] obtained the virtual photon spectrum for the E1, E2 and M1 transitions in the plane wave Born approximation (PWBA). However, Gargaro and Onley(5) have recently calculated the expressions for the virtual photon spectrum for all the multipole orders by using a distorted wave treatment (DWBA). The electron induced fission experiments mentioned earlier were reported before this distorted wave calculation of the virtual photon spectrum became available. Therefore the spectrum calculated in PWBA was used in those investigations to analyse the experimental data. Since these studies were made at very high electron energies (60-1000 MeV), the use of PWBA in the data analysis could be justified. However, in the energy region of the present investigation, it has been shown recently(5,6) that this procedure is subject to large errors depending on the electron bombarding energies and the target atomic numbers.

The interaction of photons with nuclei, in general, exhibits a typical characteristic: a resonance in the photonuclear cross sections at an energy roughly equal to ($80/A^{1/3}$), attributed to the electric dipole (E1) mode of excitation and usually called the "giant resonance". For photofission of ^{238}U, this resonance is located at an energy of 14 MeV. Fission fragment angular distribution studies(7,8) of the heavier actinides, at energies near fission threshold, have indicated the presence of a significant electric quadrupole component. Also, Bohr and Mottelson(9,10) have recently predicted the possible existence of an iso-scalar and of an iso-vector quadrupole giant resonance at energies roughly equal to ($60/A^{1/3}$) and ($135/A^{1/3}$) MeV, respectively. Several experimental evidences have also been reported recently confirming the existence of such resonances. The interest in these new multipole resonances is growing rapidly and for an interim review, the reader is referred to the reference[11].

One of the important characteristicsof the DWBA calculation of the virtual photon spectrum is that it predicts a significantly larger intensity for the electric quadrupole mode as compared to that for the electric dipole mode. This is becausethe Coulomb correction expected for the electric quadrupole and magnetic dipole levels is much greater than that for the electric dipole. This useful property of the virtual photon spectrum then offers an opportunity to use the process of electro excitation as an important tool for studying the otherwise weak quadrupole components in the nuclear spectrum in more detail than is possible with real photons alone.

From the experimental point of view, the cross-sections for the electro excitation processes are roughly$(\frac{1}{\alpha})$ times smaller than the corresponding cross-sections for the photo excitation. Here α is the fine structure constant. Thus the electro excitation yields are much smaller than those for photo excitation. However, it is much easier to obtain well focused intense electron beams than well collimated photon beams. It is also easier to measure electron beam intensities than photon beam intensities.

In the present paper, experimental results are presented for the photofission (20 to 60 MeV)and for the electrofission (6 to 60 MeV) of ^{238}U. The relative contributions of E1 and E2 excitations to the electrofission process are also evaluated using the DWBA analysis of the experimental data.

II - EXPERIMENT

The electron beam was provided by the University of São Paulo Linear Accelerator. Fig. 1 shows a schematic diagram of this facility. It consists of two 3-meter SLAC-type accelerating sections. Electron beam is supplied by a 100 KV pulsed electron gun at a repetition rate of 60 and 120 Hz. After acceleration, the beam is analysed by two deflecting magnets and then focussed on the target using two quadrupole magnetic lenses. The maximum current of the analysed beam is 1 μA, and the electron energy resolution is 1%.

An Uranium target (natural UO_2) was placed in the center of a cylindrical vacuum chamber, making an angle of 45^o with the incident beam direction. The fission chamber used in the experiment was 21 cm. high and had a diameter of 40 cm. The target was prepared by the electrodeposition (12) on a 7 μm aluminium backing. Target thickness, 172μg/cm^2, was measured by absolute alpha particle spectrometry using a surface barrier solid state detector and the uniformity of the UO_2 deposit was checked by irradiating the target with a known neutron flux at the IEA-RI research reactor (at IEA, São Paulo) and by measuring the fission fragment spatial distribution with a mica foil.

The fission fragments were detected using mica foils placed at different angles with respect to the incident beam direction. The mica foils were pre-etched in 50%

Hydrofloric acid for about 20 hours to develop the fossil fission background and for about 10 hours after the irradiations. Fission tracks were counted using an optical projection microscope with a 100X magnification.

For the production of bremsstrahlung, an aluminium radiator with a thickness equal to 2.08×10^{-2} radiation length was placed before the target. The electron beam was monitored by a Faraday cup for the electrofission measurements and by a secondary emission monitor (SEM), placed before the radiator and the target, for the photo - fission experiment.

The possible contamination of the electron beam with bremsstrahlung and neutrons in the electrofission measurements was checked experimentally and was found to be negligible. The bremsstrahlung produced in the SEM aluminium foils during the photofission measurements contributed about 4% of the total bremsstrahlung induced fission yield and this was corrected for. Corrections for the finite thickness of the target and radiator were made using the method described by Barber(13).

III - RELEVANT THEORY AND METHOD OF ANALYSIS

The bremsstrahlung induced fission cross-section as a function of the end point photon energy, Eo, can be written as

$$\sigma_B(E_0) = \int_0^{E_0} \sigma_\gamma(E) \, . \, K^B(E,E_0)dE \qquad (1)$$

where

$$\sigma_\gamma(E) = \sum_{\lambda L} \sigma_\gamma^{\lambda L}(E),$$

is the total photofission cross-section, $\sigma_\gamma^{\lambda L}(E)$ represents the partial cross-section for fission induced by λL photons where L defines the multipole order of the transition and λ its electric or magnetic character. $K^B(E,E_0)$ is the bremsstrahlung spectrum for a thin radiator.

The unfolding of equation (1) allows the determination of $\sigma_\gamma(E)$ from the experimentally measured $\sigma^B(E_0)$. However, as Rabotnov et al.[8] have pointed out, the determination of $\sigma_\gamma(E)$ from this equation is an improperly formulated problem and is subject to uncertainities due to the "swinging" of the solutions. This feature of the unfolding process then calls for caution in the interpretation of any irregular behaviour of $\sigma_\gamma(E)$ at certain energies. The resolution in this method is determined mainly by the uncertainties in the shape of the bremsstrahlung spectrum and those in the unfolding techniques involved. We have used the thin radiator bremsstrahlung spectrum for intermediate screening[14] and the photon difference method[15] for the unfolding of $\sigma_\gamma(E)$ from equation(1). The unfolding technique was satisfactory as is shown later in section IV.

The electron induced fission cross-section $\sigma_e(E_0)$, can be analysed in terms of the photofission cross-section by means of the virtual photon formalism. In this formalism[4], the virtual photon spectrum is defined as

$$\frac{N^{\lambda L}(E,E_0)}{E} = \frac{1}{\sigma_\gamma^{\lambda L}(E)} \times \frac{d\sigma_e^{\lambda L}(E,E_0)}{dE}$$

which reduces to

$$\sigma_e^{\lambda L}(E_o) = \int_o^{E_o} \sigma_\gamma^{\lambda L}(E)\, N^{\lambda L}(E,E_o)\, \frac{dE}{E} \qquad (2)$$

In equation (2), E_o is the incident electron energy, $\sigma_e^{\lambda L}(E_o)$ is the partial cross-section for the fission induced by λL virtual photons and $N^{\lambda L}(E,E_o)$ is the virtual photon spectrum. It is necessary here to use the virtual photon spectrum calculated in DWBA because in PWBA, it is underestimated(5,6). As mentioned earlier, Gargaro and Onley have recently published a DWBA calculation for the virtual photon spectra for all multipole orders. Unfortunately, this calculation requires very long computer times and therefore analytical expressions have been obtained recently(6,16) by a best fit to a few points calculated for each spectrum using the original DWBA program(5). We have used these expressions in the analysis of the experimental data in the present work. The total electrofission cross section is then given by

$$\sigma_e(E_o) = \sum_{\lambda L} \sigma_e^{\lambda L}(E_o) \qquad (3)$$

The main modes of photo absorption in the energy range of the present investigation for the heavy nuclei are the electric dipole and the electric quadrupole:

$$\sigma_\gamma(E) = \sigma_\gamma^{E1}(E) + \sigma_\gamma^{E2}(E) \qquad (4)$$

Similarly, for the electro excitation process :

$$\sigma_e(E_o) = \sigma_e^{E1}(E_o) + \sigma_e^{E2}(E_o) \qquad (5)$$

which using eq.^{n}(2), reduces to

$$\sigma_e(E_0) = \int_0^{E_0} \sigma_\gamma^{E1}(E)\, N^{E1}(E,E_0)\frac{dE}{E} + \int_0^{E_0} \sigma_\gamma^{E2}(E)\, N^{E2}(E,E_0)\, \frac{dE}{E} \qquad (6)$$

The relative contribution of the E1 excitation with respect to the total electro excitation process can then be obtained from the ratio

$$R(E_0) = \frac{\sigma_e^{E1}(E_0)}{\sigma_e\ (E_0)} \qquad (7)$$

where $\sigma_e(E_0)$ is the experimentally determined electro-fission yield ($\sigma_e^{exp}(E_0)$) and $\sigma_e^{E1}(E_0)$ can be calculated with a good approximation as

$$\sigma_e^{E1}(E_0) \simeq \int_0^{E_0} \sigma_\gamma(E)\, N^{E1}(E,E_0)\, \frac{dE}{E} \qquad (8)$$

In equation (8), $\sigma_\gamma(E)$ is the photofission cross-section obtained by unfolding the equation (1) and $N^{E1}(E,E_0)$ is the virtual photon spectrum calculated in the DWBA. The value of $\sigma_e^{E1}(E_0)$ obtained in this approximation is overestimated by an amount equal to the integral

$$\int_0^{E_0} \sigma_\gamma^{E2}(E)\, N^{E1}(E,E_0)\, \frac{dE}{E}\ .$$

The value of this integral is of the order of 3% of σ_e^{E1} (as defined in eq.^{n}(2)) at 8 MeV and of the order of 1% above 10 MeV[17]. These values are consistent with the photo absorption estimates for the E1 and E2 excitations as given by P.Axel[18] and by Blatt and Weisskopf[19] respectively.

IV - RESULTS AND DISCUSSION

The experimental results for the bremsstrahlung induced fission cross-section σ_B of ^{238}U as a function of the maximum photon energy E_0 are shown in Fig. 2. Below 18 MeV, since there were only few points actually measured in the present experiment, we have folded Veyssière et al.'s monochromatic photon data[20] with bremsstrahlung for a thin radiator[14] to obtain the yield curve in this energy region. This yield curve, then joined to our yield data above 18 MeV was then unfolded using photon difference method, and the resulting photofission cross-sections in the entire energy range from 6 to 60 MeV are shown in Fig. 3 (solid line). The experimental points shown on the solid line are the original data from Veyssière et al.[20] and the agreement of these points with the solid line provides a check of the unfolding technique used.

The cross-sections shown in Fig.3 have also been folded with the same bremsstrahlung spectrum and the resulting yield curve is shown as a solid line in Fig. 2 with our experimental points. It can be seen that it is in good agreement with our measured bremsstrahlung yield even in the low energy region (6-18 MeV).

The results obtained in the present experiment for the electrofission of ^{238}U, σ_e, as a function of the incident electron energy E_0 are shown in Fig. 4. This diagram also shows a comparison of our experimental results with the semi-theoretical curves El(DW), El(PW) and QD. The El(DW) curve was obtained by evaluating the folding integral of equation (8) with $\sigma_\gamma(E)$ as obtained in the present work (Fig.3) and the virtual photon spectrum as calculated in the DWBA. The El(PW) curve has the same meaning except that the virtual photon spectrum used here was obtained in PWBA.

The curve labelled by QD also refers to σ_e^{El} but with $\sigma_\gamma(E)$ calculated on the basis of the quasi-deuteron model[21, 22] by the expression

$$\sigma_\gamma(E) = \sigma_a^{Q.D.}(E) \; . \; P_f(E) \qquad (9)$$

where $\sigma_a^{Q.D.}(E)$ is the total photo-absorption cross-section given by the quasi-deuteron model and $P_f(E)$ is the relative fission probability obtained from the theoretical expressions given by Nix and Sassi[23]. The results shown in Fig. 4 can be summarized as follows:

a) The σ_e^{El} curve obtained in PWBA underestimate by a large amount the electrofission yield, indicating thereby that PWBA calculation of the virtual photon spectrum is inadequate in analysing the electrofission data in this energy region.

b) The QD curve agrees reasonably with the experimental points above 30 MeV, indicating thereby that the quasi-deuteron process for the photoabsorption may be considered as a possible excitation mechanism to describe the behaviour of the electrofission cross-section above the giant dipole resonance.

c) The E1(DW) curve agrees well with the experimental points in the entire energy region showing the dominance of the E1 giant resonance except at low energies, where for example at 8 MeV, the electric dipole excitation accounts for only about 60% of the total electrofission yield leaving the rest to other excitation modes.

This behaviour of the decreasing dominance of the electric dipole excitation mechanism in the low energy region can be better visualized in Fig. 5 where we have shown the ratio $R(E_0)$ as defined in equation (7), as a function of the incident electron energy E_0. The ratio fluctuates around unity in the energy region above 15 MeV but decreases rapidly in the low energy region. This provides a quantitative evidence for the existence of a significant electric quadrupole component in the low energy photofission of ^{238}U and is consistent with similar evidence obtained from the fission fragment angular distribution studies[7,8]. Whether this quadrupole component is distributed uniformly over a wide energy region or is concentrated in a specific energy interval to qualify as a quadrupole giant resonance remains to be seen. As mentioned earlier, Bohr and Mottelson[9,10] have predicted the existence of an iso-scalar quadrupole giant resonance at an energy roughly equal to $(60/A^{1/3})$ MeV (~9.6 MeV for ^{238}U).

V - A PRESCRIPTION FOR EXTRACTING THE QUADRUPOLE COMPONENT FROM THE ELECTRO-AND PHOTO EXCITATION MEASUREMENTS:

We would like to briefly describe here a prescription which can be used to extract the quadrupole component from the electro-and photo excitation measurements. We define

$$\Delta(E_o) = \sigma_e(E_o) - \int_o^{E_o} \sigma_\gamma(E)\, N^{E1}(E,E_o)\, \frac{dE}{E} \qquad (10)$$

where $\sigma_e(E_o)$ is the experimentally measured electro fission yield $(\sigma_e^{exp}(E_o))$, $\sigma_\gamma(E)$ is the photofission cross-section obtained from the unfolding of equation (1) (or obtained independently from monochromatic photon data etc.) and $N^{E1}(E,E_o)$ is the electric dipole virtual photon spectrum calculated in the DWBA. Thus one can determine $\Delta(E_o)$.

Using equations (2), (4) and (5), we can also rewrite equation (10) as

$$\Delta(E_o) = \int_o^{E_o} \sigma_\gamma^{E2}(E) \,.\left[N^{E2}(E,E_o) - N^{E1}(E,E_o)\right] \frac{dE}{E} \qquad (11)$$

Knowing $\Delta(E_o)$ from the electro-and photo excitation measurements using eq^n(10), and $N^{\lambda L}(E,E_o)$ from the DWBA calculation, one can then unfold the quadrupole component of the photofission cross section using equation (11). A detailed analysis using this prescription for extracting the quadrupole component in the low energy photofission of ^{238}U will be the subject of a forthcoming paper.

A C K N O W L E D G E M E N T S

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FIGURE CAPTIONS

Fig. 1: A schematic diagram of the University of São Paulo electron linear accelerator. L1, L2 represent the magnetic lenses, C the collimator and S is a slit. Q1, Q2 are the two quadrupole magnetic lenses. K and M represent respectively the klystrons and the modulators.

Fig. 2: Bremsstrahlung induced fission yield, σ_B, of ^{238}U as a function of the maximum photon energy E_o. The solid line represents the yield curve obtained by folding in the photofission cross section of ^{238}U (as shown in Fig. 3) with the bremsstrahlung spectrum for a thin radiator[14].

Fig. 3: Photofission cross section $\sigma_{\gamma f}$ of ^{238}U as a function of photon energy E_γ is shown by the solid curve obtained by the unfolding of the bremsstrahlung induced fission yields as described in the text. The experimental points shown are the monochromatic photon data of Veyssière et al.[20].

Fig. 4: Electron induced fission yield, σ_e, of ^{238}U as a function of the incident electron energy E_o. The solid lines labelled by E1(DW), E1(PW) and QD are the semi-theoretical curves as explained in the text.

Fig. 5 : The relative contribution of the E1 excitation with respect to the total electro-excitation process, as defined in eq.^{n}(7) of the text by the ratio R, is plotted as a function of the incident electron energy E_0.

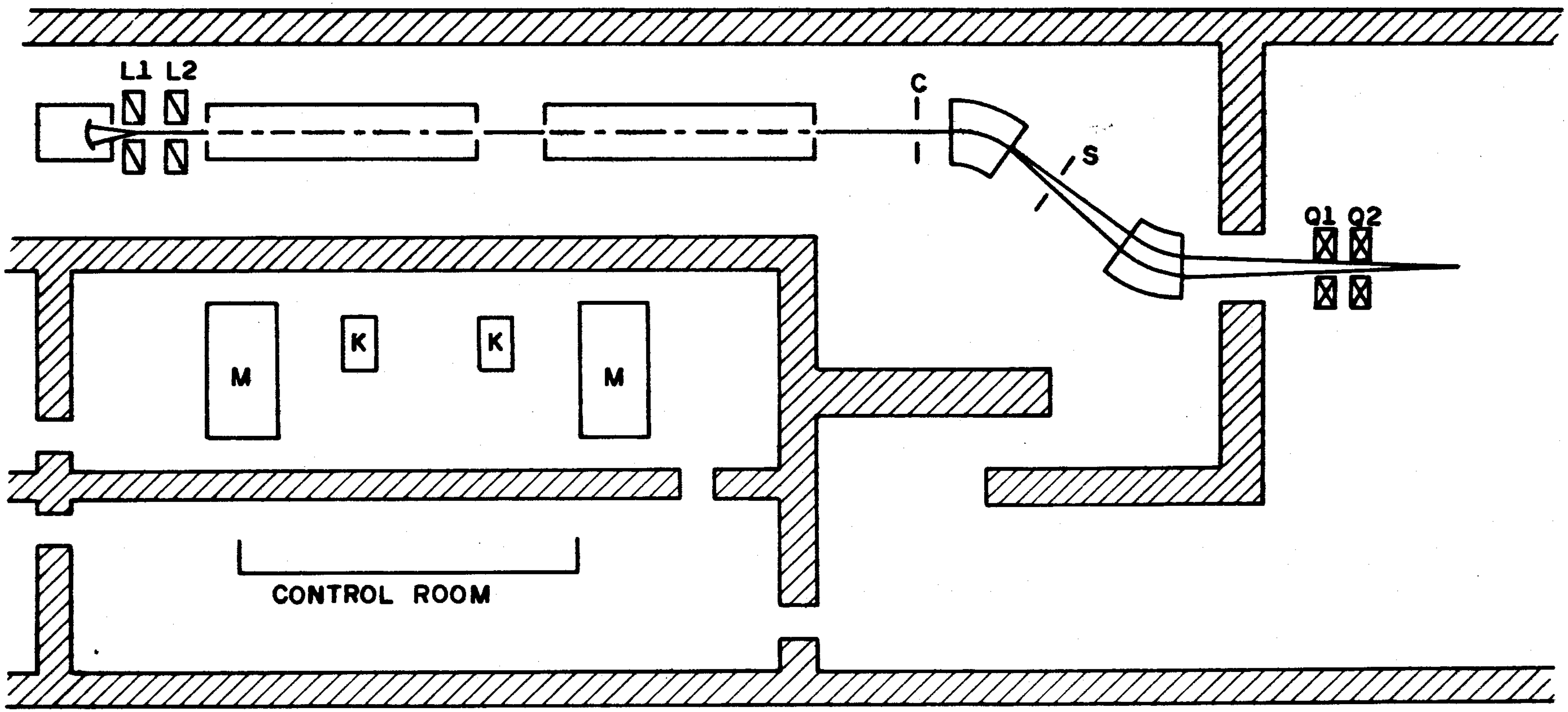

Fig. 1

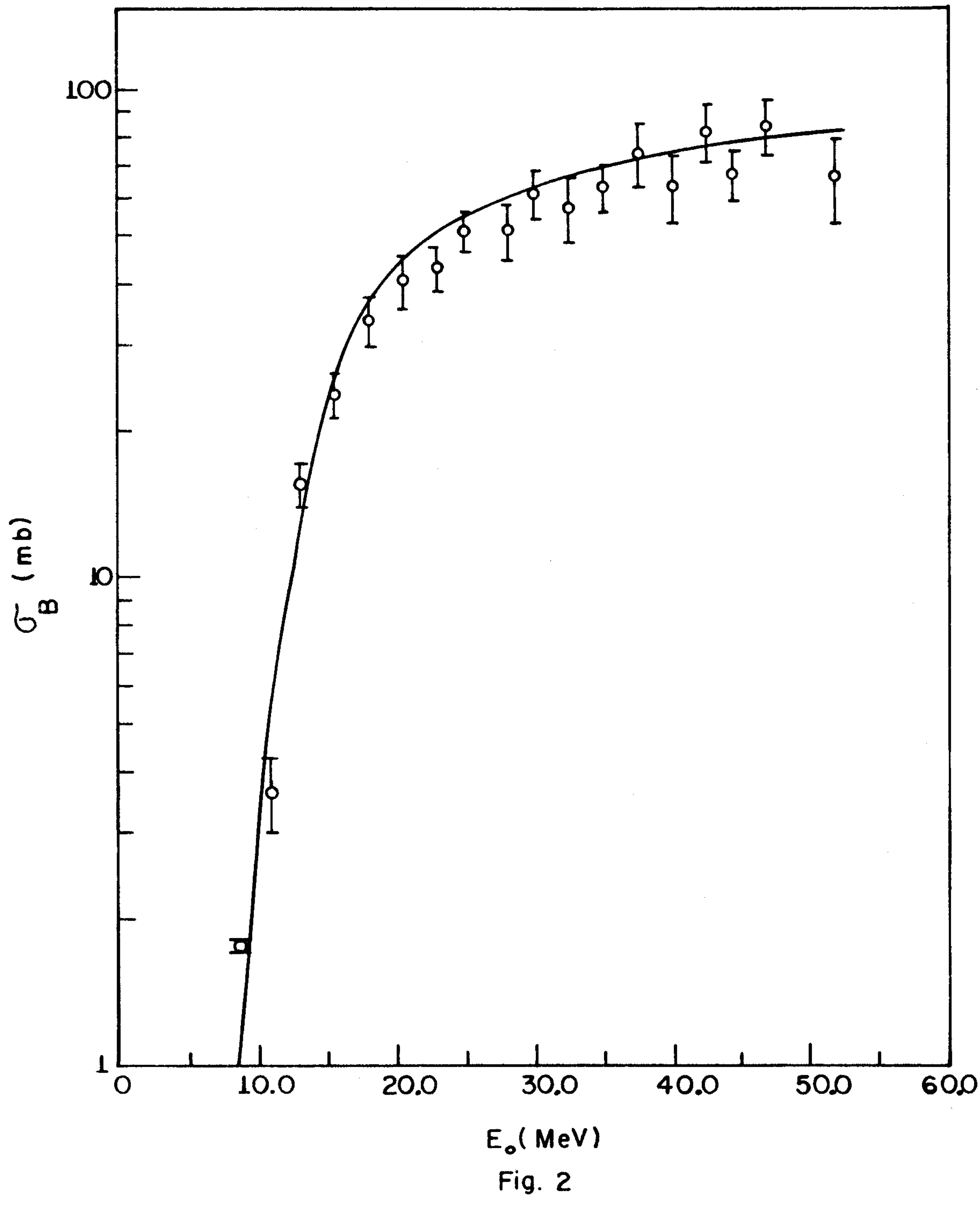

Fig. 2

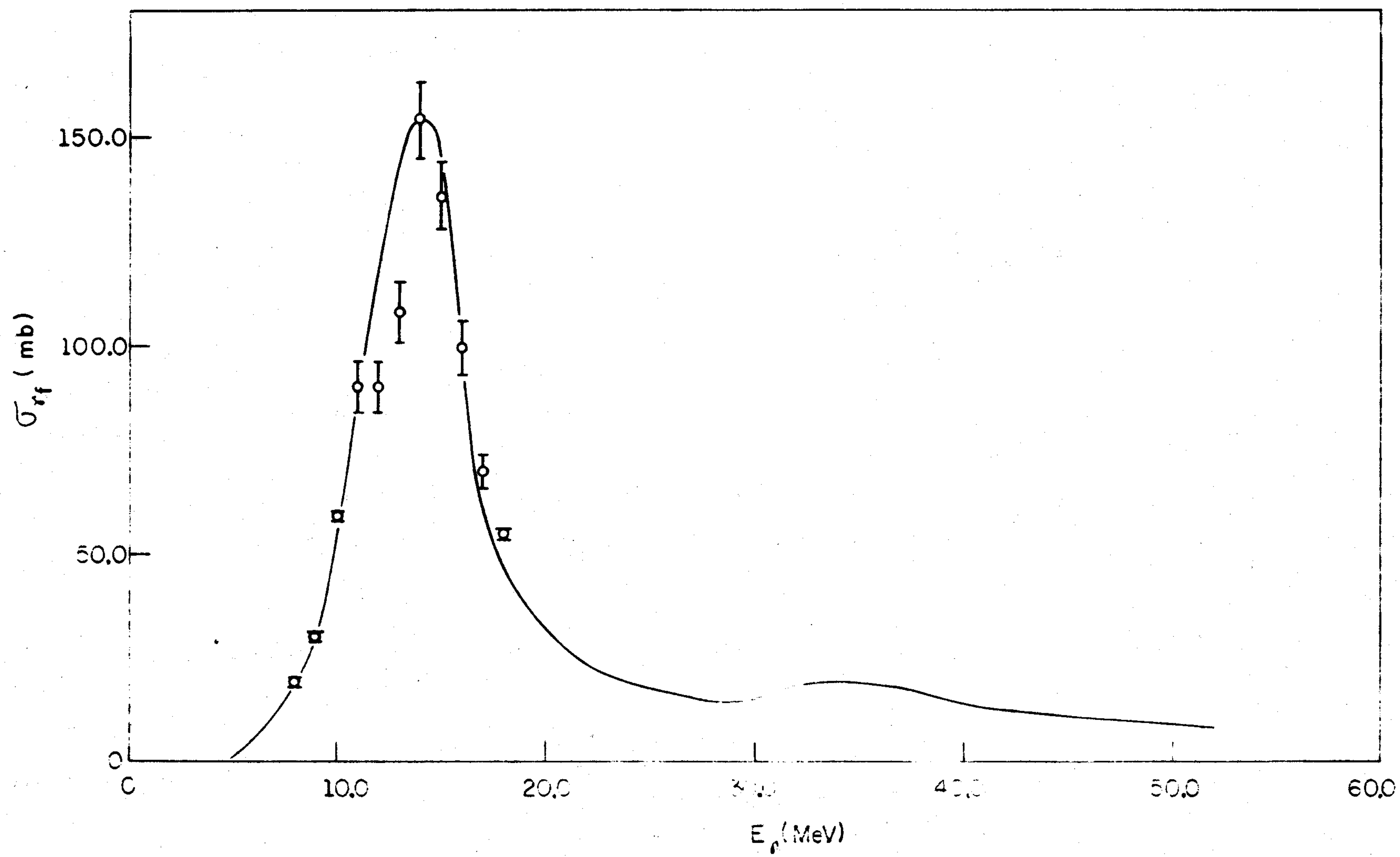

Fig. 3

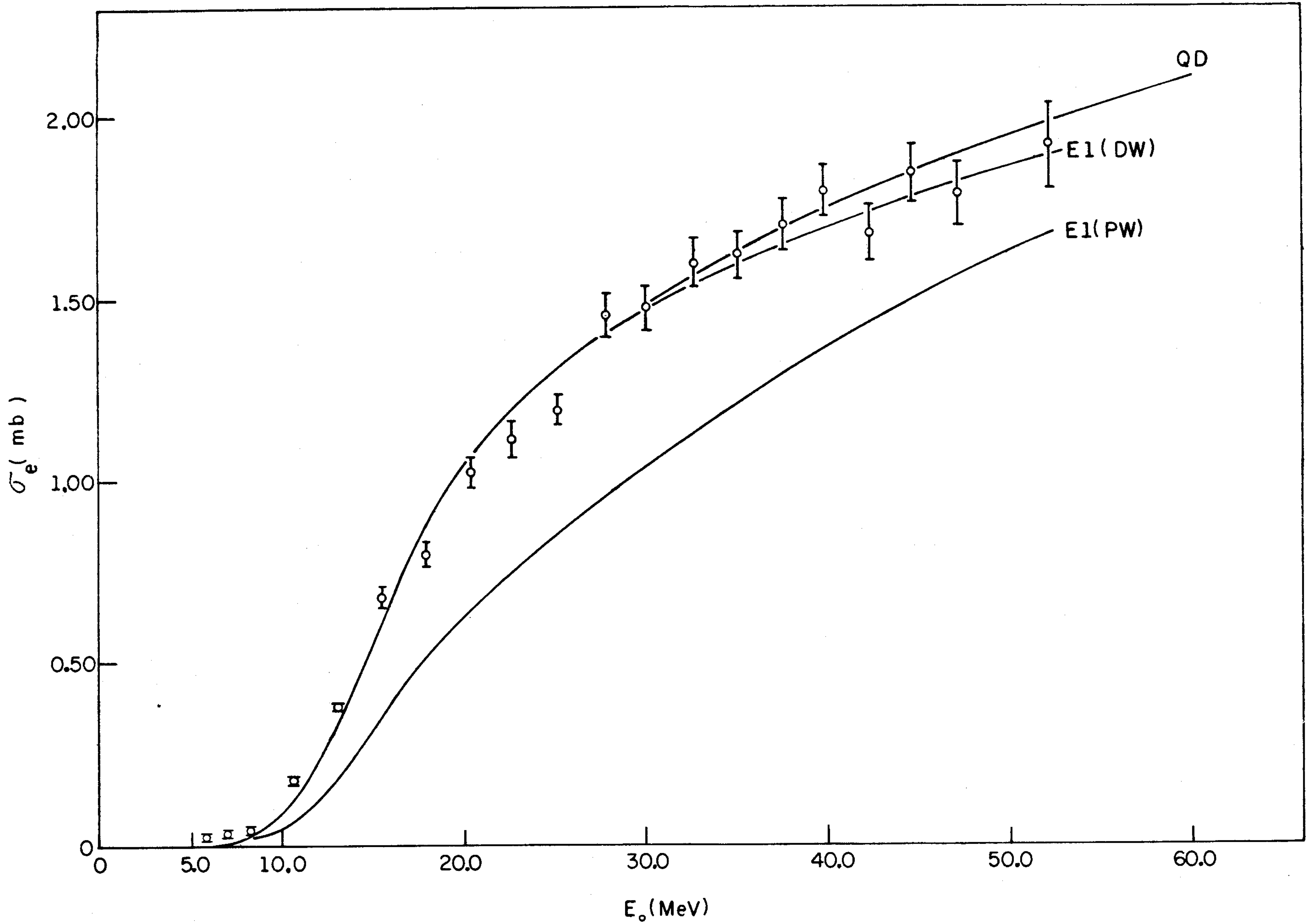
QD
E1 (DW)
E1 (PW)
2.00
1.50
1.00
0.50
0
0
5.0
10.0
20.0
30.0
40.0
50.0
60.0
σ_e (mb)
E_o (MeV)

Fig. 4

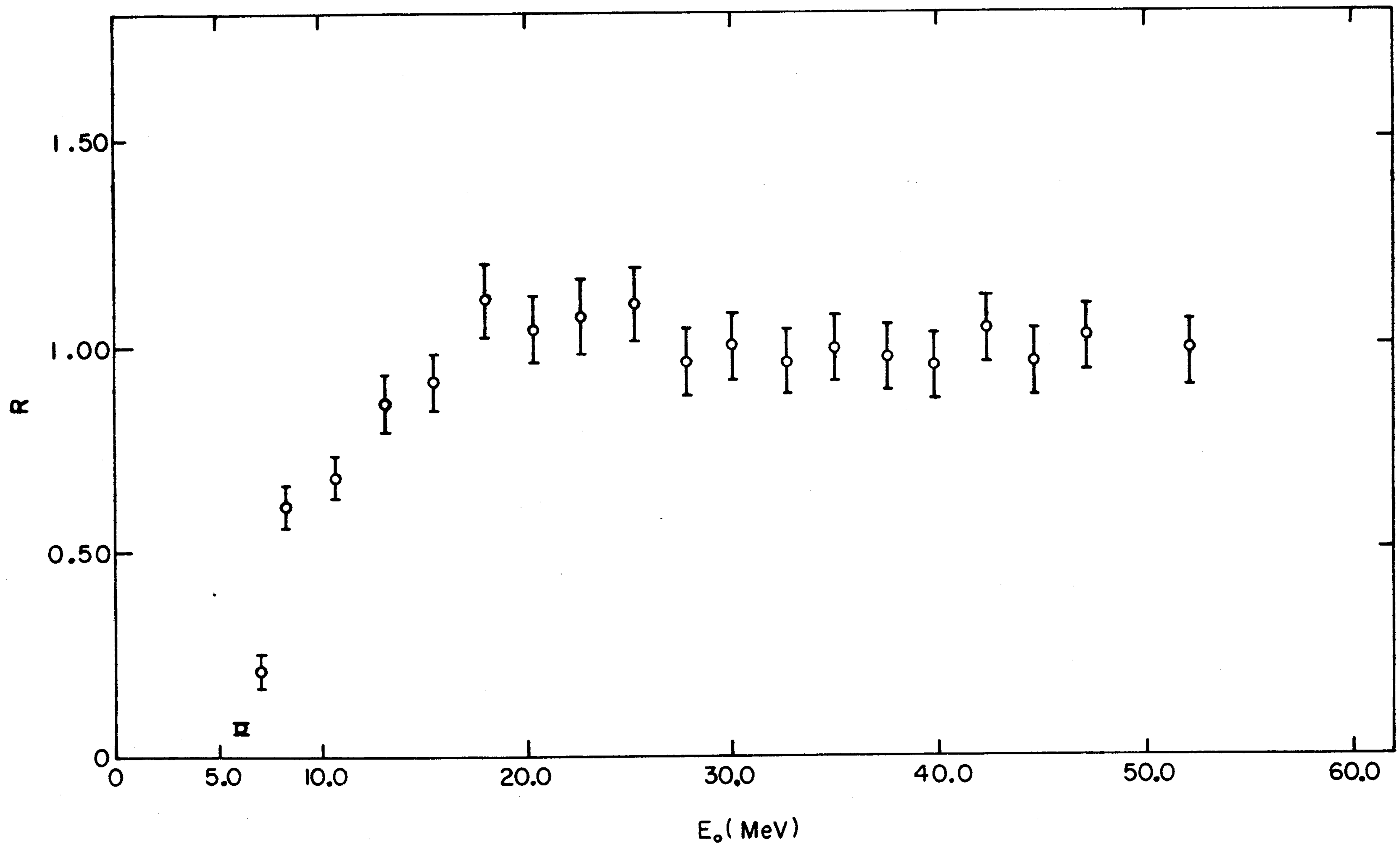

Fig. 5