UNIVERSIDADE DE SÃO PAULO

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publicações

IFUSP/P-423

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Agosto/1983

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ABSTRACT

A method for the joint analysis of coincident and inclusive electrofission data, in order to minimize effects of the model dependence of data interpretation, is developed. Explicit calculations of the (e,e'f) angular correlations are presented. The potentialities of the method to the study of sub- and near-barrier properties of the fission process, and to the study of the giant resonances fission mode, are discussed.

*Supported in part by the Conselho Nacional de Desenvolvimento Científico e Tecnológico (Brazil).

INTRODUCTION

The nuclear fission phenomenon has been studied extensively over the years, since its discovery in 1939. More recently, since the discovery of the double-humped fission barrier in actinide nuclei, there have been many investigations on the near- and sub-barrier fission properties throughout the actinide region. Even today, however, our understanding of this process leaves much to be desired, mainly because of the latest developments of concepts like two- and three-humped fission barriers (Vandenbosch and Huizenga 1973, Swiatecki and Bjørnholm 1972, Berman 1978). From the experimental side, part of the problem owes its origin to the fact that most of the data bearing upon fission have been obtained via particle--induced reactions wherein the spectra of the transition nuclei are very complicated, when compared to electro- and photofission, and thus the interpretation of the data is much more difficult (making, e.g., the extraction of the characteristics of the final-state fission process uncertain). A type of data eminently suitable for such studies is the angular distribution of fission fragments induced by real (via photofission) and virtual (via electrofission) photons, mainly because of the well-known and direct nature of the electromagnetic interaction and its selection rules. From a theoretical point of view, the electron is the simplest probe because its coupling to nucleons is well-known and the Born approximation is at least reasonable. As has been pointed out (Bertsch and Tsai 1975), inelastic scattering with other projectiles also provides useful data on the nuclear response function, although it is less informative than electron scattering for two reasons. First, the Born approximation is not valid, both because the projectile wave function is strongly altered and because the nucleus does not respond linearly to the large fields made by the projectile. Second, the interaction between projectile and nucleon in the nucleus is not known as well as desired.

A. THE FISSION PROCESS AT LOW EXCITATION ENERGIES

In the last 25 years the study of photofission (Bhandari and Nascimento 1976) and, more recently, the study of electrofission (Arruda-Neto et al 1980, 1982) have proved to be an useful implement for the investigation of properties of fission barriers and for obtaining information on the low-lying levels in the fission spectrum (at the saddle point). Also, sub-barrier electro- and photofission reactions are very important for the investigation of fission isomers because, besides the fact that the electromagnetic interaction is well known, we can probe very low excitation energy regions in the compound system where very few channels are involved. An interesting peculiarity of the sub-barrier energy region, observed in the very low energy fission yields of many actinide nuclei (Zhucko et al 1978, Bowman et al 1978), is the "isomeric shelf" which can be explained, within the picture of a double--humped fission barrier, as a competition of prompt fission and isomeric fission. There are some evidences that the "isomeric shelf" is related to an isomeric resonance of 2^+ states in the second potential well. The second well states have large fission widths and act as "doorway states", intermediate states through which the nucleus may pass on its way to fission (Weigmann 1968, Bjørnholm and Strutinski 1969, Lynn 1968). Recently, Di Toro et al demonstrate that any attempt to reproduce

the available sub-barrier fission yields, for the ^{238}U, only with the isomeric competition leads to a completely unrealistic choice of the barrier parameters. However, because of the low intensities of monochromatic photon beams, all the available data have been obtained with bremsstrahlung beams. The uncertainties in deriving photofission cross sections from bremsstrahlung-induced fission yields come from: (a) the necessity to solve an integral equation by numerical methods, and (b) the unprecise knowledgement of the bremsstrahlung spectrum, especially at low energies. It would seem to us that a solution to these problems needs to be found before one can go too far in the interpretation of the results.

At excitation energies above the fission barrier, but below the pairing gap, the analysis of electrofission--fragment angular distributions has proved to be sensitive in the identification of the low-lying levels of the transition nucleus (Arruda-Neto et al 1980, 1982). Also here, one must face the drawback of dealing with yield curves obtained with a continuous photon spectrum (the virtual photon spectrum).

B. THE FISSION DECAY OF GIANT RESONANCES

The study of the decay properties of the giant resonances can be expected to contribute to our understanding of these fundamental modes of nuclear excitation. In particular, the fission decay mode (which is a large-amplitude collective nuclear motion) and the isoscalar Giant Quadrupole Resonance (GQR) are closely related fields, since they correspond to the same properties of the nuclear Hamiltonian (Weidenmüller 1979). The GQR consists of quadrupole deformation of the nuclear surface, and such deformations play an important role in the fission process, but the excitation energies for the GQR and fission are very different.

The E1 and E2 excitations, of even-even actinide nuclei, populate $J^{\pi}=1^{-}$ and 2^{+} states of the transition nucleus, respectively. The fission probability $P_f(J^{\pi})$ for 1^{-} and 2^{+} states, at excitation energies near the fission barrier, remains an open question. While equality for $P_f(1^{-})$ and $P_f(2^{+})$ is expected at higher excitation energies (Dowell et al 1982), where the density of fission transition states is not related to the energies of the lowest fission barriers, the near-barrier fission process should be strongly dependent on the relative barrier heights and the neutron threshold (Arruda-Neto and Berman 1980). Serious controversies come from electron- and hadron-induced fission data (Arruda--Neto and Berman 1980, Arruda-Neto et al 1982); for example, a recent report on $^{238}U(\alpha,\alpha'f)$ (Plicht et al 1979) finds a complete suppression of the fission decay of transition states populated by E2 excitation in the energy region of the GQR. Such unexpected result [especially taking into account that the GDR and the Giant Monopole Resonance exhibit a substantial fission branching ratio (Caldwell et al 1980, Brandenburg et al 1982)] leads to speculations concerning an enhanced "direct" fission decay from the GQR, as a consequence of its probable overlap with the fission channel. However, the fission process is a large-amplitude collective nuclear motion corresponding to very large deformations, while the giant resonances are small--amplitude collective vibrations about the nuclear ground state (Weindenmüller 1979). Therefore, the amplitude of the GQR is not sufficiently large to drive the fission process (to induce a direct fission width). Also, both photofission and electro-

fission angular-distribution data acquired over the last 25 years show the existence of a significant E2 component at excitation energies near the fission barrier (Vandenbosch and Huizenga 1973, Bhandari and Nascimento 1976, Arruda-Neto et al 1980). By the way, a very recent coincidence electrofission experiment, $^{238}U(e,e'f)$ (Dowell et al 1982), succeed in detecting a sizeable concentration of E2 strength around 6 MeV, despite the poor statistics in this energy region. In this regard, another $^{238}U(\alpha,\alpha'f)$ (Bertrand et al 1981) experiment found a substantial fission branching ratio for the GQR, and speculates about the dominance of K=0 fission decay channels near 10 MeV. However, the photofission and electrofission angular-distribution data are nearly isotropic above 9-10 MeV (Arruda-Neto et al 1982).

C. AIM OF THE PRESENT WORK

The aim of the present work is to show that an answer to all this controversial and somewhat confusing situation can be found by means of a joint analysis of (e,f) and (e,e'f) angular correlation data, obtained with a high beam intensity continuous wave (CW) electron accelerator - now under development in several laboratories. As we will demonstrate below, the inclusive (e,f) data complete the (e,e'f) data in the sense that the formers represent measurements at the "photon point" ($q=\omega$, where q is the momentum transferred to the nucleus and ω is the excitation energy; $\hbar=c=1$), and the latters are measurements at $q>\omega$. Also, we will present an examplifying calculation for the ^{238}U angular correlations and a discussion about the potentialities of the analysis of electrofission angular correlation data.

INCLUSIVE ELECTROFISSION

An inclusive (e,f) measurement integrates over both ω and q, and is dominated by events near the "photon point" (because nearly forward momentum transfers predominate). Electron-induced reactions are quite similar to photon-induced reactions in that both are purely electromagnetic, but the electromagnetic field of the photoexcitation process is transverse, whereas the virtual electromagnetic field associated with the electroexcitation process contains longitudinal components in addition to the transverse components. An important difference between the inclusive photon- and electron-induced reactions is that, e.g., the E2 and M1 virtual-photon spectra are much more intense than E1 (Fig. 1), (Arruda-Neto et al 1982, Soto Vargas et al 1977). This difference may be exploited experimentally to a particular investigation of those aspects of nuclear structure which are inaccessible by means of real photons.

In what follows we consider λL=E1 and E2 excitations of even-even fissioning nuclei (ground state $J^{\pi}=0^{+}$). The differential photofission cross section is defined as

$$\frac{d\sigma_{\gamma,f}}{d\Omega_f}(\omega,\theta_f) = \frac{\sigma_{\gamma,f}(\omega)}{4\pi} \sum_{N=0}^{2L} a_N(\omega)\, P_N(\cos\theta_f) \tag{1}$$

where $\sigma_{\gamma,f}$ is the total photofission cross section; θ_f is the angle between the fission-fragment path and the incident beam direction in the laboratory system; the P_N's are the

Legendre functions, and the a_N's are coefficients which contain all the nuclear physics involved in the photofission process.

Assuming compound nucleus formation leading to fission the interference between different exit channels vanish. Then, in eqn. (1) we have $N = 0,2,$ and 4, because all the phases involved in a_1 and a_3 average out to zero. Writting the Legendre functions explicitly, and grouping terms, we obtain

$$\frac{d\sigma_{\gamma,f}}{d\Omega_f}(\omega,\theta_f) = \sigma_{\gamma,f}(\omega)\Big[\frac{1}{4\pi}\,(a_0(\omega)+a_2(\omega)+a_4(\omega)) + \frac{1}{2\pi}\,(-\frac{3}{4}a_2(\omega)-\frac{5}{16}a_4(\omega))\sin^2\theta_f + \frac{1}{2\pi}\,(-\frac{35}{64}a_4(\omega))\sin^2 2\theta_f\Big] \tag{2}$$

which exhibits the well-known angular dependence of the photofission angular distribution (Vandenbosch and Huizenga 1973, Bhandari and Nascimento 1976).

In even-even actinide nuclei the low-lying transition states at the barriers are rotational bands built upon collective modes characterized by K, the projection of the nuclear angular momentum on the nuclear symmetry axis (along the fission-fragment direction). The E1 and E2 photon-excitations populate (J^{π},K) levels of the transition nucleus with $J^{\pi}=1^{-}$ and 2^{+}, respectively. The photofission coefficients can be expressed in terms of the partial photofission cross sections for the fission channels, $\sigma_{\gamma,f}(J^{\pi},K;\omega)$; we can achieve that by comparing eqn. (2) with eqn. (10) of Arruda-Neto et al 1980. Therefore, for $K=0$ and 1, which is reasonable for near-barrier experiments (Arruda-Neto et al 1982), we obtain

$$a_0(\omega) = a_0(\omega;E1) + a_0(\omega;E2) = 1 \tag{3a}$$

$$a_2(\omega) = a_2(\omega;E1) + a_2(\omega;E2) = \frac{5}{7}\frac{1}{\sigma_{\gamma,f}(\omega)}\left[\sigma_{\gamma,f}(2^+,0;\omega) + \right.$$

$$\left. + \sigma_{\gamma,f}(2^+,1;\omega)\right] - \frac{1}{\sigma_{\gamma,f}(\omega)}\left[\sigma_{\gamma,f}(1^-,0;\omega) - \sigma_{\gamma,f}(1^-,1;0)\right] \quad (3b)$$

$$a_4(\omega) = a_4(\omega;E2) = -\frac{16}{7}\frac{1}{\sigma_{\gamma,f}(\omega)}\left[\frac{3}{4}\sigma_{\gamma,f}(2^+,0;\omega) - \sigma_{\gamma,f}(2^+,1;\omega\right] \quad (3c)$$

The coefficients a_0, a_2, and a_4 may be obtained by a least-squares fit of the expression (2) to the experimentally determined angular distributions. In principle, the four unknown $\sigma_{\gamma,f}(1^-,0)$, $\sigma_{\gamma,f}(1^-,1)$, $\sigma_{\gamma,f}(2^+,0)$, and $\sigma_{\gamma,f}(2^+,1)$ are fully determined from the three equations (3a), (3b) and (3c), and a fourth equation is given by

$$\sigma_{\gamma,f}(\omega) = \sigma_{\gamma,f}(1^-,0;\omega) + \sigma_{\gamma,f}(1^-,1;\omega) + \sigma_{\gamma,f}(2^+,0;\omega) + \sigma_{\gamma,f}(2^+,1;\omega) \quad (4)$$

However, great uncertainties are associated mainly to the obtaintion of the coefficient a_4 at energies ~ 1-2 MeV above the fission barrier, because this coefficient is quite small in comparison to the a_0 and a_2 coefficients (Bhandari and Nascimento 1976, Arruda-Neto et al 1980). On the other hand, in electrofission this drawback is greatly overcame, due to the higher intensity of the E2 virtual-photon spectrum which enhances the E2 component of the electrofission angular distribution (Arruda-Neto et al 1980, 1982).

The differential electrofission cross section (Arruda-Neto et al 1980) is

$$\frac{d\sigma_{e,f}}{d\Omega_f}(E_e,\theta_f) = A_e(E_e) + B_e(E_e)\sin^2\theta_f + C_e(E_e)\sin^2 2\theta_f \quad (5)$$

where E_e is the electron incident energy. It is worth analysing the form of the C_e coefficient, for it contains only E2 contributions, that is

$$C_e(E_e) = -\frac{35}{64}\int_0^{E_e}\frac{\sigma_{\gamma,f}(\omega)}{2\pi}a_4(\omega;E2)N^{(E2,tot)}(\omega,E_e)\frac{d\omega}{\omega} =$$

$$\frac{5}{8\pi}\int_0^{E_e}\left[\frac{3}{4}\sigma_{\gamma,f}(2^+,0;\omega) - \sigma_{\gamma,f}(2^+,1;\omega)\right]N^{(E2,tot)}(\omega,E_e)\frac{d\omega}{\omega} \quad (6)$$

where

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

$$-\frac{1}{4}N^{(E2,2)}(\omega,E_e) \quad (7)$$

and $N^{(\lambda L,M)}(\omega,E_e)$ is the virtual-photon spectrum [calculated, e.g., in DWBA (Soto Vargas et al 1977)] for a λL transition with magnetic substate M. The E2 electrofission yield is greatly enhanced (see eqn. (6)), but now the shortcoming is the necessity to solve an integral equation in order to obtain $a_4(\omega;E2)$. Anyway, inclusive electrofission data can provide more reliable information about the E2 strength, when compared to the photofission data, if accurate virtual-photon spectra are known. At low electron energies ($\lesssim$ 20 MeV), where nuclear size effects are negligible, the (e,f) results exhibit no form factor dependence.

COINCIDENT ELECTROFISSION

Electrofission scattering coincidence experiments provide a new dimension to the study of nuclear structure (Calarco 1980, Carlarco et al 1980, Hanna 1981), and with the advent of the new high energy high duty factor electron accelerator, (e,e'f) electrofission coincidence studies will bring many possibilities for the experimental investigation of the fission phenomenon. It is clear that (e,e'x) measurements, in general, have the potential of becoming the least uncertain way of studying, e.g., the giant resonances and their decay channels (Hanna 1981). As we will discuss next, (e,e'f) experiments can help in the study of isomeric fission, the study and identification of the low-lying levels at the saddle point configuration of fissioning nuclei, and the study of the fission decay of giant resonances. The situation for coincidence electron scattering studies is quite different than the situation in hadron scattering (as illustrated in Fig. 3), which exhibits a background coming from an unknown combination of multistep nuclear excitations and direct excitations of higher multipolarity states. Therefore, such nuclear background cannot be removed by coincident measurement of the nuclear decay. Otherwise, the large background present in the inelastic electron scattering singles spectrum (mainly due to the radiative tail) is effectively removed by the requirement of a coincidence with a nuclear decay product, as can be seen in Fig. 4. In this figure are shown the singles (e,e') and coincident $(e,e'p_0)$ cross sections obtained from ^{12}C, in a recent experiment performed at Stanford (Calarco et al 1980). This experiment was made possible by the high duty factor (up to 100%) of the Stanford Superconducting Accelerator, and the exceptional beam

quality of the accelerator.

The inelastic electron scattering cross section for one emitted nucleon in coincidence with the final electron, in Born approximation (one-photon exchange), is given by (Calarco et al 1980)

$$\frac{d^3\sigma_{e,e'x}}{d\Omega_{e'}\,d\Omega_x\,d\omega} = \frac{2\alpha^2}{q_\mu^4}\,\frac{k_2}{k_1}\,\frac{p_x E_x}{M}\,\frac{1}{4\pi^3}\sum_{\nu\leq N}\sum_{N=0}^{2L} A_N^\nu\,P_N^\nu(\cos\theta_x) \qquad (8)$$

where k_1 and k_2 are the initial and final momenta of the electron, respectively; p_x and E_x are the momentum and energy of the emitted nucleon; $q_\mu^2 = q^2-\omega^2$; M is the mass of the initial nucleus; θ_x is measured with respect to the direction of q (see Fig. 2). In the absence of any direct term the coefficients A_N^ν can be written in the form (Calarco 1980, Calarco et al 1980)

$$A_N^\nu = \sum_{L,L',\ell_j,\ell'_{j'}} K_\nu\,F_\nu^L\,F_\nu^{L'}\,a_{N,\nu}(L,L',\ell_j,\ell'_{j'}) \qquad (9)$$

The factor K_ν contains all the kinematics; the F_ν's are the usual inelastic form factors measured in singles electron scattering; and the coefficients $a_{N,\nu}$ are those obtained from angular distributions following excitation by real photons, as in eqn. (1).

We present here a calculation for the (e,e'f) angular correlation, assuming a kinematic condition where the relevant transitions are of electric character with L=1 and 2. Also, we will write down the equations using a more familiar notation, namely: V_i are the kinematic factors (i = C,T,S, and I, as defined below), and EL(q) and CL(q) stand for the well-

-known transverse and Coulomb form factors, respectively (De Forest 1967). As discussed before, the interference between different exit channels for fission vanish; therefore, the (e,e'f) cross section is

$$\frac{d^3\sigma_{e,e'f}}{d\Omega_{e'}d\Omega_f d\omega} = \sigma\Big[A_0^0P_0(\cos\theta_f) + A_2^0P_2(\cos\theta_f) + A_4^0P_4(\cos\theta_f) +$$

$$+ A_2^1P_2^1(\cos\theta_f) + A_4^1P_4^1(\cos\theta_f)\Big] \qquad (10)$$

where $\sigma \equiv \frac{2\alpha^2}{q_\mu^4}\cdot\frac{k_2}{k_1}\cdot\frac{p_fE_f}{M}\cdot\frac{1}{4\pi^3}$;

after some algebra we get

$$\frac{1}{\sigma}\frac{d^3\sigma_{e,e'f}}{d\Omega_{e'}d\Omega_f d\omega} \equiv W(\theta_f) = A + B\sin^2\theta_f + C\sin^2 2\theta_f +$$

$$+ D\sin\theta_f\cos\theta_f + E\sin\theta_f\cos^3\theta_f \qquad (11)$$

where

$$A = A_0^0 + A_2^0 + A_4^0 \qquad (12a)$$

$$B = -\frac{3}{2}A_2^0 - \frac{5}{8}A_4^0 \qquad (12b)$$

$$C = -\frac{35}{32}A_4^0 \qquad (12c)$$

$$D = 3A_2^1 - \frac{15}{2}A_4^1 \qquad (12d)$$

$$E = \frac{35}{2}A_4^1 \qquad (12e)$$

The coefficients appearing in eqn. (10) are (using the electron scattering notation)

$$A_0^0 = V_C(\theta_{e'})\Big[|C1(q)|^2a_0(E1) + |C2(q)|^2a_0(E2)\Big] \qquad (13a)$$

$$A_2^0 = V_C(\theta_{e'})\Big[-2|C1(q)|^2a_2(E1) + 2|C2(q)|^2a_2(E2)\Big] \qquad (13b)$$

$$A_4^0 = V_C(\theta_{e'})\Big[-\frac{3}{2}|C2(q)|^2a_4(E2)\Big] \qquad (13c)$$

$$A_2^1 = V_I(\theta_{e'},\phi_f)\Big[-\sqrt{2}\,E1(q)C1(q)a_2(E1) + \sqrt{\tfrac{2}{3}}\,E2(q)C2(q)a_2(E2)\Big] \qquad (13d)$$

$$A_4^1 = V_I(\theta_{e'},\phi_f)\Big[\frac{1}{2}\sqrt{\tfrac{3}{2}}\,E2(q)C2(q)a_4(E2)\Big] \qquad (13e)$$

$$A_2^2 = \Big[V_T(\theta_{e'}) - V_S(\theta_{e'},\phi_f)\Big]\Big[\frac{1}{2}|E1(q)|^2a_2(E1) - \frac{1}{2}|E2(q)|^2a_2(E2)\Big] \qquad (13f)$$

$$A_4^2 = \Big[V_T(\theta_{e'}) - V_S(\theta_{e'},\phi_f)\Big]\Big[\frac{1}{12}|E2(q)|^2a_4(E2)\Big] \ . \qquad (13g)$$

The neglecting of A_2^2 and A_4^2 in eqn. (10) is justified below. The kinematic factors (neglecting the mass of the electron) are defined by (De Forest 1967)

$$V_C(\theta_{e'}) = \left(\frac{q_\mu}{q}\right)^4\beta \qquad (14a)$$

$$V_T(\theta_{e'}) = \frac{q_\mu^2}{2q^2}(\beta + q^2) \qquad (14b)$$

$$V_I(\theta_{e'},\phi_f) = \left[(E_e + E_{e'})\left(V_C(\theta_{e'})\frac{q_\mu^2}{2q^2}\right)^{1/2}\right]\cos\phi_f \qquad (14c)$$

$$V_S(\theta_{e'},\phi_f) = \frac{q_\mu^2}{2q^2}(2\beta\cos\phi_f + q^2) \qquad (14d)$$

$$\beta = 2k_1k_2\cos^2\left(\frac{\theta_{e'}}{2}\right) \ . \qquad (14e)$$

The factors V_C and V_T are exactly the same which appear in ordinary electron scattering. In addition, the factor V_S produces terms in the A's, originated from a current which is proportional to the transverse component of $\vec{p}_f$, and the factor V_I produces terms resulting from the interference between the latter and the Coulomb interaction.

In order to perform the analysis of the (e,e'f) angular correlation data, using the formalism presented in this paper, we need to calculate the form factors EL and CL by means of a nuclear model. For illustration purposes we decided to use the generalized hydrodynamical model (Überall 1971), estimated for an experimental condition where $E_e \cong 120$ MeV and $\theta_{e'} = 40°$. The reasons for that are the following:

(a) $|CL|^2 >> |EL|^2$; this approximation simplifies greatly the angular correlations;

(b) it is possible to access quadrupole transitions, because the momentum transferred to the nucleus (q), at this kinematic conditions, maximizes $|C2|^2$ (see Fig. 5);

(c) the above mentioned conditions are quite similar to those used in some recent (e,e'f) experiments carried out at Stanford (Van Bibber 1981) and Illinois (Dowell 1982). Figure 6 shows the curves corresponding to electric dipole and quadrupole excitations leading to the fission of ^{238}U. The curves were generated from the (e,e'f) angular correlation expression (eqn. (11)). The photofission coefficients $a_i(EL)$, i = 0,2, and 4, were obtained from a high resolution photofission angular distribution experiment, assuming that $a_i(E1)/a_i(E2) \cong 20$, i = 0 and 2 (Dowdy and Krysinski 1971), and the form factors were taken from the generalized Goldhaber-Teller model (Überall 1971). A simple visual inspection of

Figure 6 shows that the disentangling of the E1 and E2 components of the fission process can be achieved, once they show markedly differences.

POTENTIALITIES OF THE ELECTROFISSION ANALYSIS

There are many informations to be extracted from a joint analysis of the (e,f) and (e,e'f) data, and I would like to propose some. It is assumed here that the experimental data are of a reasonable quality, which allows the unambiguous determination of the coefficients for (e,f) [A_e, B_e, and C_e (eqn. (5))], and for (e,e'f) [A, B, C, D, and E (eqn. (11))]. The (e,f) angular distributions have been investigated extensively over the last 5 years, using pulsed electron accelerators (Arruda-Neto et al 1980, 1982, Aschenbach et al 1979); the experimental techniques and data analysis procedures are well-known. On the other hand, (e,e'f) experiments require a 100% duty factor CW electron accelerator, with a high beam intensity (100-200 μA). The scattered electrons can be detected by the use of a conventional 180° double focussing electron spectrometer, and for the fission fragments it is possible to use, e.g., parallel plate avalanche fission counters, like those we developed at Stanford (Arruda-Neto et al 1981).

The coefficients C and E (eqns. (12c) and (12e)) contain contributions arising only from E2 excitations, that is (we assume $\theta_{e'}$ fixed for all the runs)

$$C(q,\omega) = \frac{105}{64} \cdot V_C(\theta_{e'}) |C2(q)|^2 a_4(\omega;E2) \quad (15)$$

$$E(q,\omega) = \frac{35}{4} \sqrt{\frac{3}{2}} \; V_I(\theta_{e'},\phi_f) E2(q) C2(q) a_4(\omega;E2) \quad (16)$$

By choosing a kinematic condition where the momentum transferred q maximizes the C2 form factor (Figure 5), as mentioned before, the coefficients C and E are substantially enhanced (when compared to A, B, and D). Therefore, it would be very confortable to obtain C and E with a reasonable confidence. Also, it is possible to contrast in- and out-plane angular correlations; for instance, in out-plane measurements at $\phi_f=90^o$ we have E=0 (see eqns. (12e), (13e), and (14c)) and, therefore, we obtain a more simplified angular correlation.

One of the main goals of the data analysis is the obtention of the photofission coefficients, and in particular $a_4(\omega;E2)$ from C and/or E. However, it is necessary to know the form factors since, e.g., $a_4 \sim \frac{C}{|C2|^2}$. The usual way to obtain the form factors is by means of singles (e,e') measurements, but for high-Z nuclei the huge radiative tail makes the results uncertain. For example, ~1% of the counting rate in the ^{238}U(e,e') spectrum is due to nuclear excitation (Dowell et al 1982); then, a reliable extraction of the form factors from such (e,e') data is questionable. Thus, it is necessary to obtain the form factors from a specific nuclear model; this is an inevitable source of uncertainty which itself can amount ~25%, as in the case of a recent ^{238}U(e,e'f) data interpretation (Dowell et al 1982). Inelastic electron scattering data, found in the literature, are frequently analysed by the assumption that the q dependence of the form factors is given by the Tassie model, and that the transition radii are independent of the excitation energy. A detailed discussion of the uncertainties associated to these assumptions is given in Pitthan et al 1980, which demonstrate that up to the first minimum of the form factors the cross sections are predominantly determined by the transition radii.

Our proposition to avoid part of the uncertainties, arising from the model dependence of the form factors, is to cross-check the photofission coefficients obtained from the (e,e'f) data with the inclusive (e,f) data. To be more specific, the coefficient $a_4(\omega;E2)$ deduced from the experimentally determined C (eqn. (15)) is folded-back into the inclusive C_e coefficient,

$$C_e(E_e) = -\frac{35}{128\pi}\int_0^{E_e} \sigma_{\gamma,f}(\omega)\,a_4(\omega;E2)\,N^{(E2,tot)}(\omega,E_e)\,\frac{d\omega}{\omega} \quad .$$

The shape of $a_4(\omega;E2)\times\omega$ acquired at a fixed q, from $C/|C2|^2$ (eqn. (15)), does not depend on the particular model chosen to describe the form factor C2(q), provided the excitation energy interval is restricted to a few MeV. Now, the magnitude of a_4 is substantially affected by the model dependence and thus, the coefficient C_e can help in the determination of a "normalization factor".

For (e,e'f) data got at an electron spectrometer set-up where $E_e-E_{e'}=\omega<5$ MeV, it will be possible to detect directly, e.g., the ^{238}U isomeric resonance (which manifests itself as a "shelf" in the bremsstrahlung yield) predicted at $\omega=3.55$ MeV with a total width of 130 keV, by means of a simple visual inspection of the (e,e'f) spectrum. The multipolar character of this resonance can be revealed by the analysis of the angular correlation coefficients, in order to confirm if this resonance is related to 2^+ states in the second well; the C and E coefficients should play an essential role in such assignment. Also, the fission barrier parameters can be delineated from the partial photofission cross sections, given by

$$\sigma_{\gamma,f}(J^{\pi};\omega) = \sigma_{\gamma}(\lambda L;\omega)\ \frac{\alpha(J^{\pi};\omega)\Gamma_f(J^{\pi};\omega)}{\Gamma_f(J^{\pi};\omega) + \Gamma_{\gamma}(J^{\pi};\omega)} \qquad (17)$$

assuming that a compound nucleus is formed, and for excitation energies below the neutron threshold. $\sigma_{\gamma}(\lambda L;\omega)$ is the photo-absorption cross section; $\alpha(J^{\pi};\omega)$ are the relative populations of compound states in the first potential well of spin and parity J^{π} ; Γ_f and Γ_{γ} are the partial fission and γ-decay widths, respectively, of the first well states. There are many possibilities for the data analysis. For example, the barrier parameters can be extracted assuming that both the "class II" fission widths (at the second well) and the coupling widths of the class II doorway states to the "class I" states can be related to the penetrability of the intervening barriers through the Bohr-Wheeler relationship for Γ_f (Bohr and Wheeler 1939), using the Hill-Wheeler expression (Hill and Wheeler 1953) for the penetrability of a single parabolic barrier (Auchampaugh and Bowman 1973, Auchampaugh and Weston 1975). For the study of the 2^+ fission barrier, in particular, we use the $\sigma_{\gamma,f}(2^+;\omega)$ cross section given by (eqn. (3c), for K=0 channels)

$$\sigma_{\gamma,f}(2^+;\omega) = -\frac{7}{12}\,\sigma_{\gamma,f}(\omega)a_4(\omega;E2) \qquad (18)$$

Our understanding of the GQR (and other giant multipole resonances) fission decay mode can be greatly improved by (e,e'f) studies of actinide nuclei. The (e,e'f) cross section integrated over the fission fragment angles Ω_f , in the first Born approximation and for an individual and well--separated level, is given by (Überall 1971, Arruda-Neto et al 1982)

$$\frac{d^2\sigma_{e,e'f}}{d\Omega_{e'}d\omega} = \int \frac{d^3\sigma_{e,e'f}d\Omega_f}{d\Omega_{e'}d\Omega_f d\omega} = \sum_{EL} 4\pi\sigma_M\left[\frac{1}{B(EL)}\frac{dB}{d\omega}\ (EL,\omega)\right] \times$$

$$\times\ |F^{EL}(q)|^2 \cdot \left[\frac{\Gamma_f(\omega)}{\Gamma}\right]_{EL} \qquad (19)$$

where σ_M is the Mott cross section; $dB/d\omega$ is the "strength function", that is, the reduced transition probability per unit excitation energy interval evaluated at the photon point $q=\omega$; and

$$|F^{EL}(q)|^2 \equiv \frac{q_{\mu}^4}{q^4}\,|CL(q)|^2 + \left[\frac{q_{\mu}^2}{2q^2} + \tan^2\left(\frac{\theta_{e'}}{2}\right)\right]|EL(q)|^2 \qquad (20)$$

Thus, for measurements performed at a given q which maximizes the form factor for a particular EL-transition, it is easy to obtain the correspondent strength function concentrated in the fission channel (using some nuclear model to calculate the form factor), that is

$$\frac{1}{4\pi\sigma_M|F^{EL}(q)|^2}\cdot\frac{d^2\sigma_{e,e'f}}{d\Omega_{e'}d\omega} = \frac{1}{B(EL)}\frac{dB}{d\omega}\ (EL,\omega)\ \cdot \left[\frac{\Gamma_f(\omega)}{\Gamma}\right]_{EL} \qquad (21)$$

Integrating the resonance peak under investigation we get the mean branching ratio weighted in $dB/d\omega$, namely

$$\left\langle \left[\frac{\Gamma_f(\omega)}{\Gamma}\right]_{EL} \right\rangle = \frac{1}{B(EL)}\int \frac{dB}{d\omega}\ (EL;\omega)\ \cdot \left[\frac{\Gamma_f(\omega)}{\Gamma}\right]_{EL} d\omega \qquad (22)$$

Here again we face the same shortcoming mentioned before, namely, the model dependence of the data interpretation. The same prescription suggested for the normalization of the coefficient a_4 can be used for the fission strength function (eqn. (21)), that is, to fold-back the, e.g., GQR strength function into the model independent expression for the inclusive (e,f) cross section (Arruda-Neto et al 1982),

$$\sigma_{e,f}(E_e) = \int_0^{E_e} \sigma_{\gamma,f}(\omega) N^{E1}(\omega,E_e) \frac{d\omega}{\omega} + \frac{4\pi^3}{75}\alpha \int_0^{E_e} \frac{dB}{d\omega}(E2,\omega) \times$$
$$\times \left[\frac{\Gamma_f(\omega)}{\Gamma}\right]_{E2} \cdot \left[N^{E2}(\omega,E_e) - N^{E1}(\omega,E_e)\right]\omega^2 \, d\omega \qquad (23)$$

where $\sigma_{\gamma,f}$ was obtained experimentally with monoenergetic photons (Caldwell et al 1980). Therefore, the (e,e'f) data are sensitive to the shape of the strength function, while the (e,f) data provide a valuable check of its area (the total strength) in a model independent way.

The present controversy regarding the fission branching ratio of the GQR (see the "Introduction") clearly suggests that we need both better experimental data and better data interpretation. In this sense, hadron scattering experiments are unable to sample all the strength of a giant resonance, particularly that portions of the strength concentrated near the fission barrier and at the tail of the giant resonance. Such strength has to be missed in hadron works since there the backgrounds are drawn to exclude everything except the narrower structures sticking out beside these backgrounds. The (e,e'f) experiments need some improvement too. For instance, while the ^{238}U(e,e'f) spectra obtained at Stanford (Van Bibber 1981) exhibit a clear structure around 9 MeV, a similar (e,e'f) experiment carried out at Illinois (Dowell et al 1982) shows nearly structureless spectra.

FINAL REMARKS

This paper proposes a method for the analysis of coincidence (e,e'f) data, using inclusive (e,f) data in order to minimize the effects of the model dependence of data interpretation. An examplifying calculation of (e,e'f) angular correlation is presented, and the necessity of model calculations for the form factors is shown. It is also shown that this formalism is very adequate to the study of sub- and near-barrier properties of the fission process, and should help to elucidate the characteristics of the fission decay mode of the giant resonances. Finally, the purpose of this paper is to motivate studies of the fission phenomenon, using the tremendous potentialities of the new CW machines.

ACKNOWLEDGMENTS

We want to thank Dr. J.R. Calarco and Dr. K. Wienhard for useful discussions, during our stay at the HEPL - Stanford University where this work were initiated. Also, we wish to thank the able assistance of Mrs. Sonia Maria A.P. Cavalcante in revising the English version of the manuscripts.

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FIGURE CAPTIONS

Fig. 1 - E1, E2, and M1 virtual-photon spectra calculated in DWBA for electrons having energy E_e = 9.5 MeV incident upon uraniun (Z=92) nuclei.

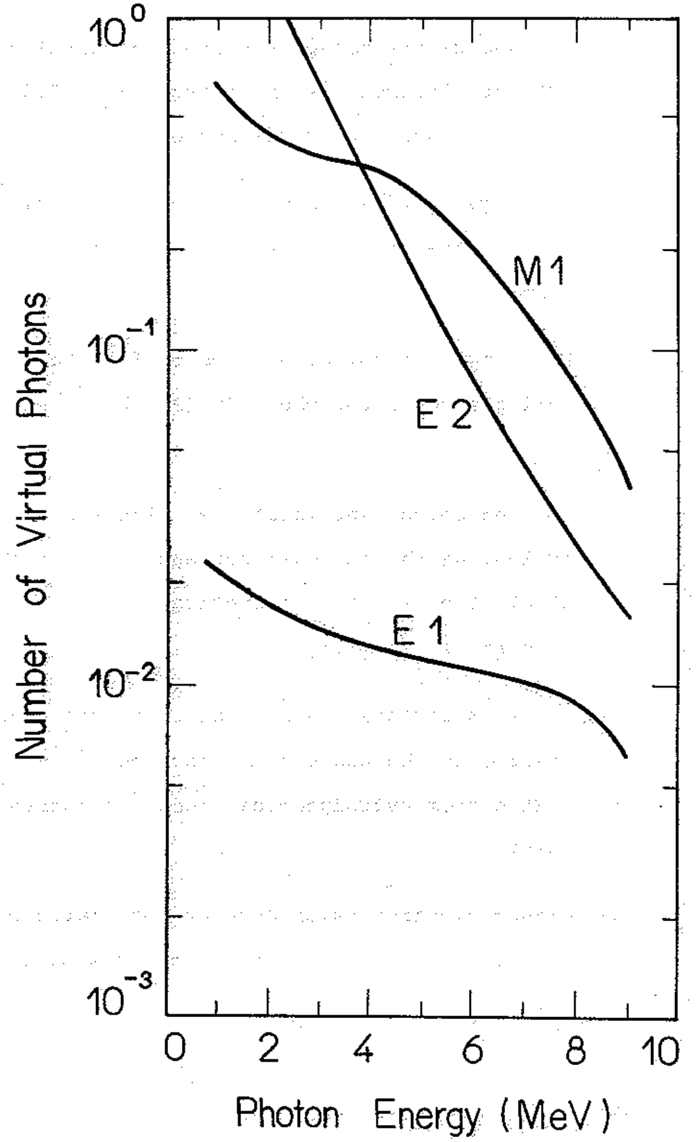
Fig. 2 - Kinematic quantities associated to the coincident electron scattering (the symbols are defined in the text).

Fig. 3 - Singles (top) and coincident (bottom) alpha scattering spectra for the ^{238}U (Plicht et al. 1979).

Fig. 4 - Singles and coincident (scattered electron with a proton leaving the residual nucleus on the ground state) electron scattering spectra for the ^{12}C (Calarco et al. 1980).

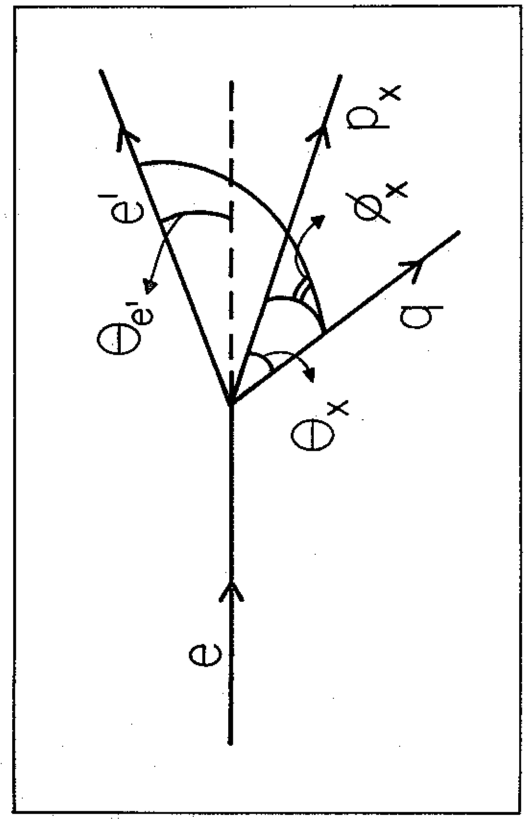
Fig. 5 - Nuclear form factors, as a function of the momentum transferred to the nucleus q , for the ^{238}U calculated from hydrodynamical models (Pitthan et al. 1980).

Fig. 6 - Coincident electrofission angular correlations for the ^{238}U , calculated in the center of mass (CM) system.



10^{0}
10^{-1}
10^{-2}
10^{-3}
Number of Virtual Photons
M 1
E 2
E 1
0
2
4
6
8
10
Photon Energy (MeV)

Fig. 1



e
e'
p_x
ϕ_x
q
$\Theta_{e'}$
Θ_x

Fig. 2

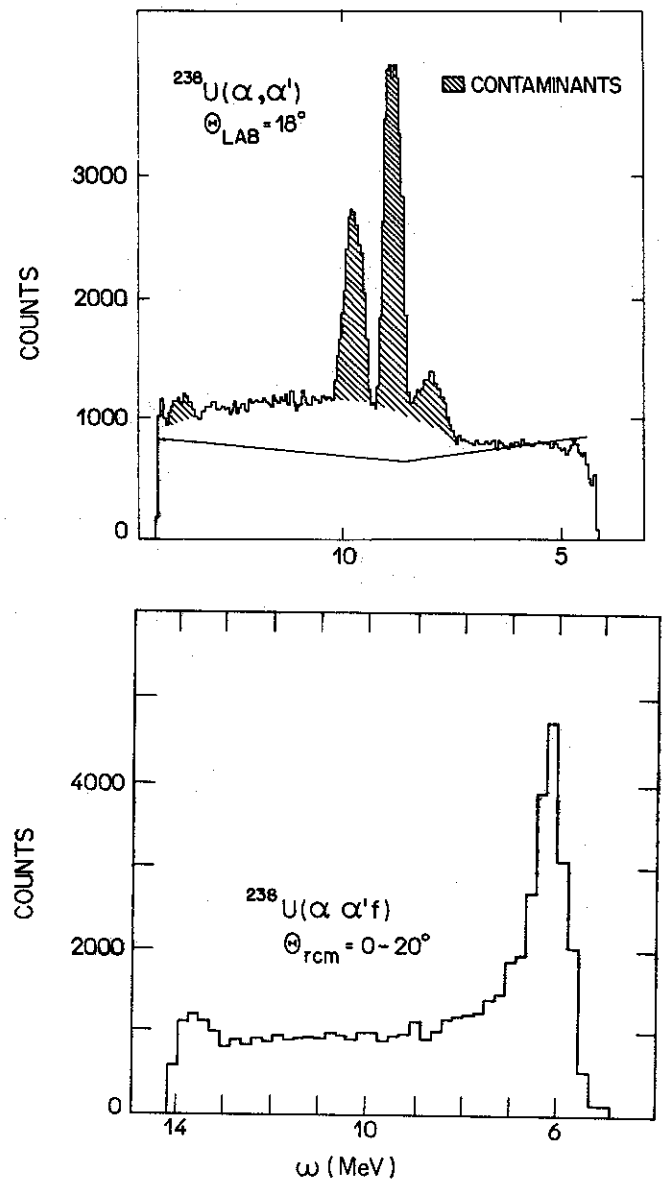

$^{238}U(\alpha,\alpha')$
$\Theta_{LAB} = 18°$
CONTAMINANTS
COUNTS
3000
2000
1000
0
10
5
$^{238}U(\alpha\ \alpha' f)$
$\Theta_{rcm} = 0-20°$
COUNTS
4000
2000
0
14
10
6
ω (MeV)

Fig. 3

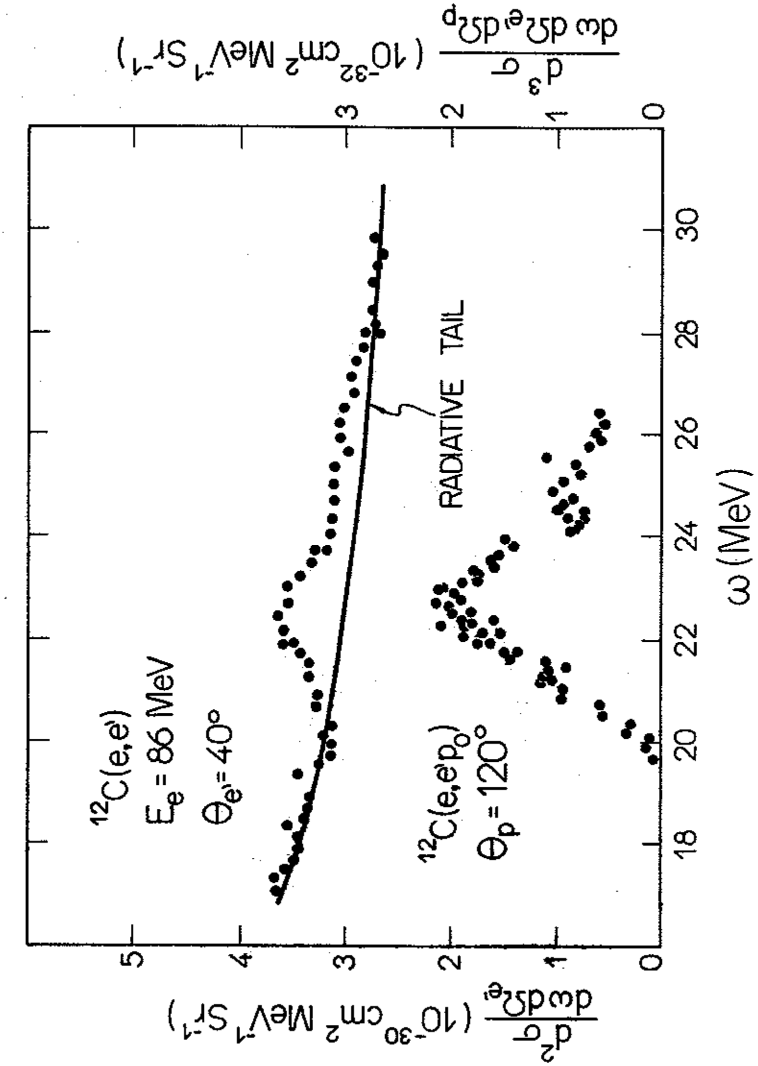
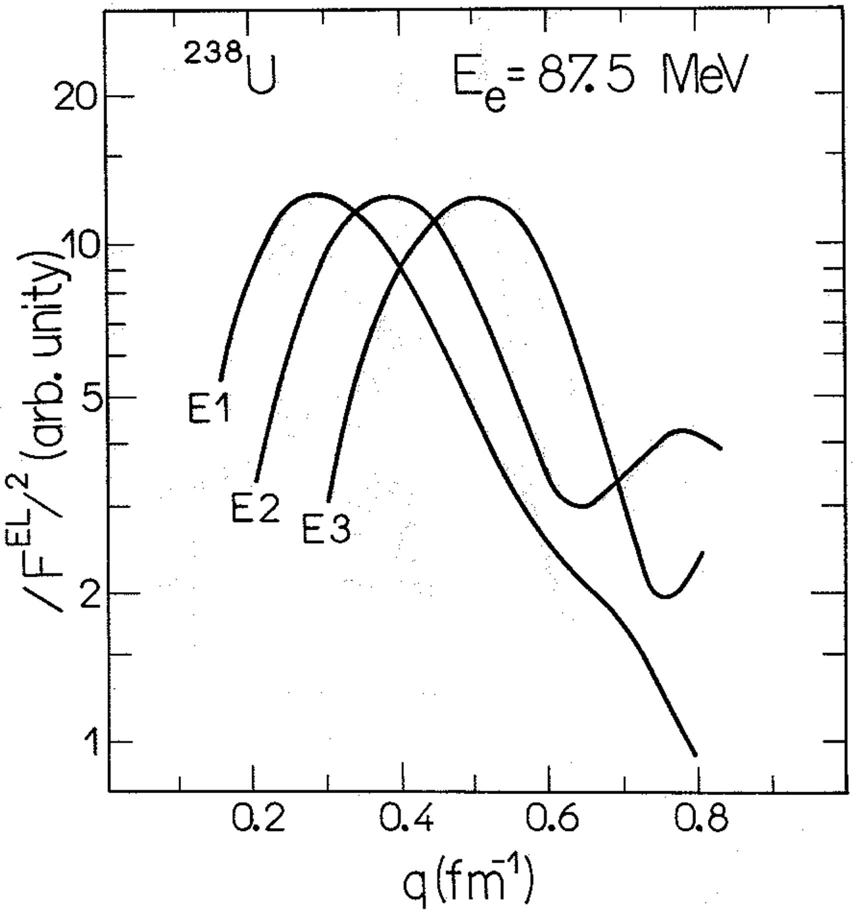
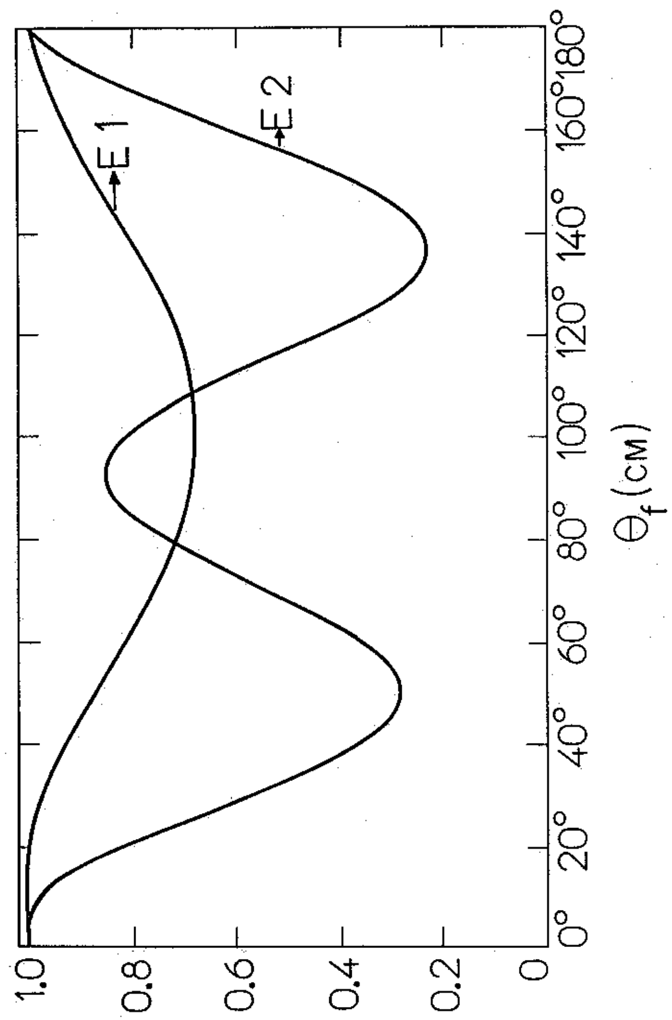

$^{12}C(e,e')$
$E_e = 86$ MeV
$\Theta_{e'} = 40°$
$^{12}C(e,e'p_o)$
$\Theta_p = 120°$
RADIATIVE TAIL
ω (MeV)
$\frac{d^2\sigma}{d\omega d\Omega_{e'}}$ (10^{-30} cm^2 MeV^{-1} Sr^{-1})
$\frac{d^3\sigma}{d\omega d\Omega_{e'} d\Omega_p}$ (10^{-32} cm^2 MeV^{-1} Sr^{-1})

Fig. 4



^{238}U
E_e = 87.5 MeV
E1
E2
E3
$|F^{EL}|^2$ (arb. unity)
20
10
5
2
1
0.2
0.4
0.6
0.8
q(fm^{-1})

Fig. 5



E 1
E 2
1.0
0.8
0.6
0.4
0.2
0
0°
20°
40°
60°
80°
100°
120°
140°
160°
180°
Θ_f (CM)

Fig. 6