Multipole Strength Distributions and Form Factors for $E1$, $E2/E0$, and $E3$ from $^{238}U(e,e'f)$ Coincidence Experiments

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A model-independent multipole analysis of $^{238}U(e,e'f)$ coincidence data, taken at four momentum transfers ($0.2 \leq q_{\text{eff}} \leq 0.7$ fm^{-1}; $\omega = 4-22$ MeV) yields both $E1$, $E2/E0$, and $E3$ form factors and strength distributions. The $E2/E0$ strength distribution in the fission channel shows two distinct bumps centered at $\omega \simeq 10$ and 14 MeV, exhausting up to 12 MeV $(19 \pm 2)\%$ of the isoscalar $E2$ sum rule. The extracted form factors can be described within a hydrodynamical model by use of parameters $c_{\text{tr}}/c_0 = 1.2$ and 1.0 for $E1$ and $E2$, respectively.

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Coincidence electron scattering represents the most powerful tool available for the investigation of the decay properties of giant multipole resonances since it makes use of the well-known fundamental advantages of the (e,e') reaction.[1] Additionally, the coincidence between the scattered electron and the nuclear decay product eliminates the radiative tail from elastic scattering.

The fission decay of the isoscalar electric giant quadrupole resonance has been the subject of partially controversial experimental findings[2-8] from various different reactions (inclusive and exclusive hadron and electron scattering, respectively). In order to resolve these long-standing discrepancies, we systematically studied the fission decay of ^{238}U in an $(e,e'f)$ coincidence experiment, using an electron beam of high current and quality at the Mainz Microtron and a more sophisticated fission-fragment detector device with a large solid angle and sufficient angular resolution. Thus, the measurement of complete in- and out-of-plane fission-fragment angular correlations allows a reliable 4π integration of the coincidence cross sections. Furthermore, in the analysis a model-independent multipole decomposition procedure[9] has been applied which model independently yields both multipole strength distributions *and* form factors.

Our experiments were performed at the 185-MeV stage of the Mainz Microtron[10] (MAMI A) using cw electron beams with energies $E_e = 78$, 124, and 183 MeV, respectively, bombarding a uranium-oxide target ($\simeq 170$ μg/cm^2 ^{238}U on a carbon layer of $\simeq 40$ μg/cm^2 thickness) at currents between 10 and 20 μA. The scattered electrons were analyzed with the Mainz 180° double-focusing magnetic spectrometer[11] at scattering angles of $\theta_e = 22°$ (for $E_e = 78$ and 124 MeV), 30°, and 40° (for $E_e = 183$ MeV). Thus, data were taken at four momentum transfers of $q_{\text{eff}} \simeq 0.20$, 0.28, 0.54, and 0.71 fm^{-1}. The fission fragments were detected by the Giessen PPAC Ball,[12] which consists of 32 parallel-plate avalanche counters (PPAC) each subtending a solid angle of $\simeq 60-130$ msr covering the complete angular range $0° \leq \theta_f \leq 180°$ (polar angle) and $90° \leq \Phi_f \leq 270°$ (azimuthal angle) with respect to the q axis and the electron scattering plane, respectively. The 4π integrated coincidence cross sections were then corrected for radiative losses of the scattered electrons in the target by our applying the method of Crannell[13] using Schwinger corrections following Maximon.[14]

In order to disentangle the strength distributions and form factors for different multipoles from the measured 4π-integrated $(e,e'f)$ coincidence cross sections, we applied the model-independent multipole decomposition procedure developed by Kihm *et al.*[9] There is assumed (i) that only the lowest multipole excitations contribute ($E0$, $E1$, $E2$, and $E3$), (ii) that the $E0$ and $E2$ form factors have identical shapes, and (iii) that all nuclear form factors do not depend on excitation energy ω. This multipole extraction method has been expanded in order to extract three different multipole strength distributions and form factors from $(e,e'f)$ coincidence cross sections measured at four momentum transfers q_k ($k = 1-4$), which for every excitation-energy bin ω_j (4 MeV $\leq \omega_j \leq 22$ MeV, of 100-keV width) can be written as a sum over three multipole terms:

$$\frac{1}{\sigma_{\mathrm{Mott}}}\sigma_{\mathrm{expt}}(q_k,\omega_j)=\sum_{EL=E1,E2/E0,E3}\frac{dB(EL;\omega_j)}{d\omega}\frac{\Gamma_f}{\Gamma}\bigg|_{EL}|F_{EL}(q_k)|^2. \qquad (1)$$

This system of equations can be solved by a least-squares fit which then yields both the multipole strength distributions in the fission channel $[dB(EL;\omega_j)/d\omega][\Gamma_f/\Gamma]_{EL}$ and the respective form-factor ratios $|F_{EL}(q_k)|^2/|F_{EL}(q_1)|^2$.

The results of this model-independent decomposition procedure are shown in Fig. 1 for one momentum transfer: The upper spectrum shows the experimental 4π-integrated $(e,e'f)$ coincidence cross section for $E_e=124$ MeV and $\theta_e=22°$ and, below, the respective multipole cross sections for the fission channel, i.e., the three multipole terms in Eq. (1), for $E1$, $E2/E0$, and $E3$,[15] are plotted. The residual spectrum, i.e., the difference between the fitted right-hand sides of Eq. (1) and the data is equal to zero within its uncertainties for nearly all excitation energies. This can be regarded as a consistency check for the solution of the multipole decomposition procedure. The application of the same extraction method to limited ranges of excitation energies separately yields identical multipole strength distributions and nuclear form factors within their errors—in contrast to the conclusions from previous inclusive electron-scattering work[16]—and establishes the validity of assumption (iii). The observed different onsets of the $E1$ and $E2/E0$ strength distributions can be explained by the different 1^- and 2^+ fission barriers as determined from photofission-fragment angular distributions.[17]

Whereas in analyses[7,8] of previous $(e,e'f)$ experiments the form factors $|F_{EL}(q)|^2$ were calculated within certain nuclear models in order to determine the multipole strength distributions, the above described multipole decomposition procedure extracts model in-

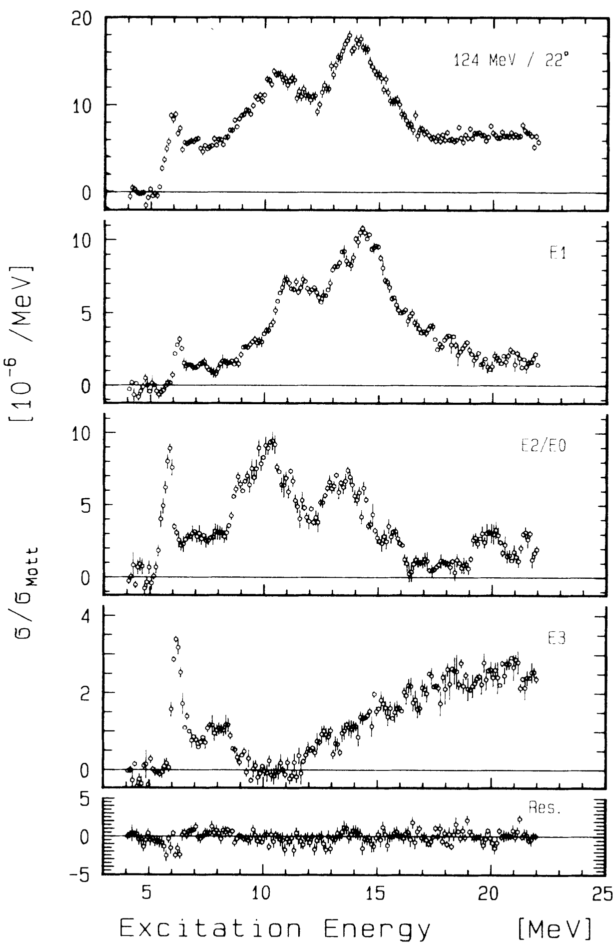

FIG. 1. 4π-integrated $^{238}U(e,e'f)$ coincidence spectrum and its decomposition into $E1$, $E2/E0$, and $E3$ components for $E_e=124$ MeV and $\theta_e=22°$. The residual spectrum is the difference between the measured $(e,e'f)$ cross section and the sum of the deduced $E1$, $E2/E0$, and $E3$ cross sections.

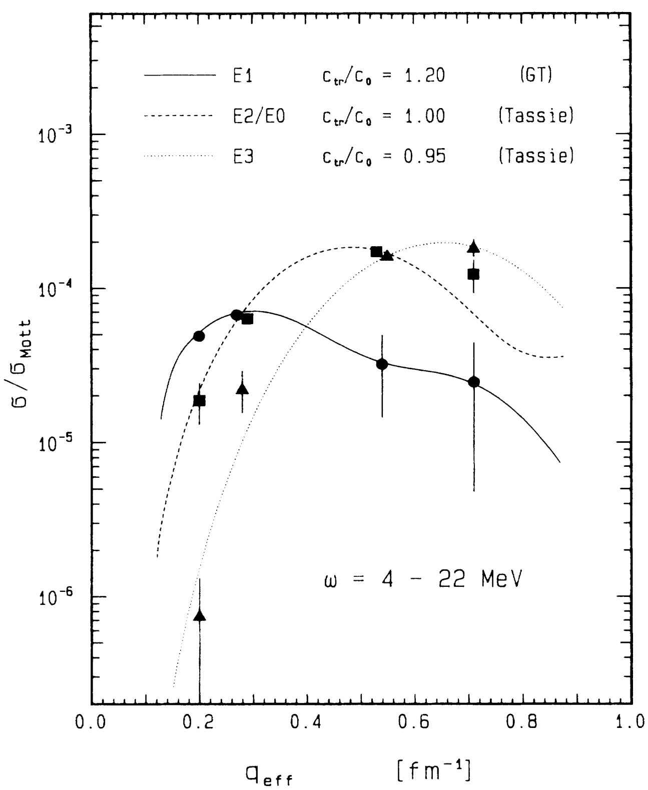

FIG. 2. Deduced $E1$ (circles), $E2/E0$ (squares), and $E3$ (triangles) form factors compared with fits of corresponding distorted-wave Born-approximation calculations (Ref. 18) (curves).

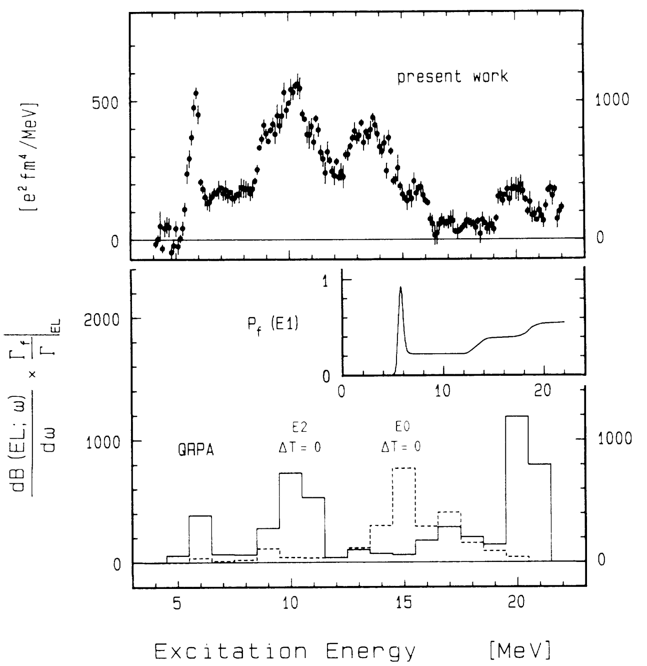

FIG. 3. Comparison between decomposed total $E2/E0$ strength distribution and a QRPA prediction (Ref. 25) ($E2$, solid line; $E0$, dashed line) which was multiplied by the $E1$ fission probability (Ref. 26), shown in the inset; left scale for $E2$, right scale for $E0$.

dependently both the multipole strength distributions and the shapes (i.e., the q dependence) of the nuclear form factors, which is of crucial importance in particular in the case of the $E1$ form factor.[16] In order to scale the extracted form factors the ratios $|F_{EL}(q_k)|^2/|F_{EL}(q_1)|^2$ ($k=1-4$) were fitted by the distorted-wave Born-approximation calculations[18] by adjustment of the radius parameter c_{tr} of the transition charge density. Different values of c_{tr} cause an evident change of both the shapes and magnitudes of the calculated form factors (for 100% exhaustion of the corresponding sum rule[19]). The fit to our data yields for c_{tr}, in units of the radius parameter c_0 of the ground-state charge density, for $E1$, 1.20, for $E2/E0$, 1.00, and for $E3$, 0.95, by use of predictions of the Goldhaber-Teller[20] model (GT) for $E1$ and the Tassie[21] model for $E2$ and $E3$ shown in Fig. 2 in comparison with the extracted experimental data integrated over the whole investigated excitation-energy range.

The $E1$ photofission cross section, which was deduced from the decomposed $E1$ strength distribution by use of the extracted nuclear $E1$ form factor, is in good agreement with recent photofission data[22-24] reported from different laboratories, in particular with those from Saclay[22] and Giessen.[24] Furthermore, the agreement with the photofission data establishes the reliability of our analysis.

In Fig. 3 the decomposed total $E2/E0$ strength distri-

TABLE I. Comparison of integrated strengths from the present work with results from previous $(e,e'f)$ experiments (Refs. 7 and 8) and QRPA predictions (Ref. 25) in terms of percentage exhaustion of the isovector $E1$ energy-weighted sum rule (EWSR) and the isoscalar $E0$ and $E2$ EWSR, respectively (Ref. 19). [The following sum-rule-values were used: $S(E0,\Delta T=0)=1.01\times10^5$ MeV fm^4, $S(E1,\Delta T=1)=839$ MeV fm^2, $S(E2,\Delta T=0)=1.00\times10^5$ MeV fm^4.] Numbers in parentheses refer to strengths in total absorption with the assumption of the same fission probability for $E0$ and $E2$ as for $E1$ (Ref. 26).

Reference	ω (MeV)	$E1$	$E0^a$	$E2^b$
QRPA[c]	5.5–17.5	(87)	(66)	(84)
$(e,e'f)$[d]	5.7–7.0			3.7 (8)
	7.0–11.7			10 (45)
$(e,e'f)$[e]	<6.5			1.5 ± 0.2 (2.2)
	<12			10.7–14.1 (44–59)
	<17.5	(87 ± 0.4)	39–63 (140–221)	20–32 (70–111)
	12–17.5		18–35 (52–103)	
Present work	<6.5			2.0 ± 0.2 (3.8 ± 0.7)
	8–12			15 ± 1 (69 ± 5)
	<12			19 ± 2 (80 ± 6)
	12–16.4		32 ± 3 (100 ± 9)	
	<17.5	24 ± 1 (81 ± 4)		

[a]All total $E2/E0$ strength is assumed to be only $E0$ (except for QRPA).
[b]All total $E2/E0$ strength is assumed to be only $E2$ (except for QRPA).
[c]Reference 25.
[d]Reference 7.
[e]Reference 8. The reported data are taken from a constrained fit by photofission data, depending on the form factors used in their analysis.

bution is compared with recently reported predictions from quasi-random-phase-approximation (QRPA) calculations[25] performed by Zawischa and Speth (multiplied by the $E1$ fission probability[26]) which show a fairly good agreement concerning the excitation energies and strengths of the resonance structures observed in our experiment. From the energetic locations of the two resonance structures in comparison with the results from QRPA[25] and recent hadron-induced reactions,[27,28] the bump around 10 MeV should be ascribed to the isoscalar giant quadrupole resonance and the bump around 14 MeV might be due to the fission decay of the isoscalar electric giant monopole resonance.

In Table I the integrated strengths observed in our experiment are summarized and compared to previous $(e,e'f)$ data[7,8] and the QRPA prediction.[25] If we assume that the total $E2/E0$ strength for excitation energies (i) up to 12 MeV corresponds only to $E2$ and (ii) between 12 and 16.4 MeV is only due to $E0$, our integrated $E2$ strengths are in good agreement with the QRPA calculation.[25] On the other hand, our results concerning the exhaustion of the $E2$ energy-weighted sum rule[19] are higher than those derived from both previously performed $(e,e'f)$ experiments[7,8] although the magnitudes of the 4π-integrated coincidence cross sections, taken at slightly different momentum transfers, are in fair agreement. Therefore, the discrepancy in the extracted $E2$ strengths should be ascribed to the applied analysis. Our model-independent analysis, furthermore, showed the crucial importance and good high-q data for a reliable separation of contributions from higher multipoles ($\geq E3$).

With the assumption of a fission probability for $E2$ as for $E1$,[26] which is $\simeq 22\%$ for ^{238}U in the excitation-energy range below the second-chance fission threshold, this yields in total absorption an exhaustion of the isoscalar $E2$ energy-weighted sum rule of $(80 \pm 6)\%$ up to 12 MeV. Thus, we can conclude from our analysis that the giant-quadrupole resonance neither decays strongly enhanced[5] nor shows a suppressed[3,7,9] coupling to the fission channel, as compared with the isovector giant dipole resonance which is known to decay predominantly statistically.

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