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Coincident Electrofission Cross Section for ^{238}U from 5 to 11.7 MeV

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The ^{238}U$(e, e'f)$ cross section was measured for excitations between 5 and 11.7 MeV. The sum of the $E2$ and $E0$ strength functions was extracted with the aid of available ^{238}U(γ,f) data. The present results show that the $E2/E0$ strength in the fission channel is spread almost uniformly from 7 to 11.7 MeV. The $E2/E0$ strength that is found in the fission channel corresponds to 10% of the isoscalar $E2$ sum rule; if the fission probability is 0.22, this energy region contains 45% of this sum.

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There have been conflicting reports[1-9] about the magnitude, energy dependence, and fission probability of the isoscalar electric quadrupole giant resonance (GQR) in ^{238}U. The spectra of inelastically scattered protons,[1] alpha particles,[5,6,8] and ^{6}Li ions[7] have a broad bump at energies which vary for the different experiments but are generally in the range between 9 and 13 MeV. This enhanced inelastic scattering was interpreted as a concentration of $E2$ strength by interpolating a "background" in the 9- to 13-MeV excitation-energy region on the basis of the inelastic scattering observed at higher and lower energies. This procedure has been used[10,11] to identify concentrated $E0$ strength near $80A^{-1/3}$ MeV and $E2$ strength near $65A^{-1/3}$ MeV for many nuclei with A between 50 and 209. The separation of $E0$ and $E2$ strength followed the pioneering (α, α') experiments at scattering angles as low as 3° by Youngblood and his collaborators.[12] Our results, which have a better signal-to-noise ratio than did previous experiments for the sum of $E2$ and $E0$ strengths, show a relatively energy-independent distribution of the $E2/E0$ strength between 7 and 11 MeV. Our results make it clear that the assumed background in the (p,p'), (α,α'), and $(^{6}\mathrm{Li},^{6}\mathrm{Li}')$ experiments overestimated the $E2/E0$ strength from 9 to 11 MeV compared to the $E2/E0$ strength from 7 to 9 MeV. This discrepancy raises the question of whether the $E2/E0$ strength is as concentrated in energy as is assumed for nuclei with A between 50 and 209. The background in inelastic hadron scattering comes from an unknown combination of multistep nuclear excitations and direct excitations of higher multipolarity states. Because these backgrounds involve nuclear excitation, they cannot be removed by coincident measurement of the nuclear decay. In contrast, the $(e,e'f)$ cross sections which we measure are due to single-step nuclear excitations that include only low multipoles.

The previous reports of anomalously high[2,3] and low[5,6] fission probability of the GQR in ^{238}U can be clarified by our findings. High fission probability was inferred from electrofission (e, f) experiments[2,3] which can provide reliable information about $E2$ strength only if accurate virtual-photon spectra are known and if accurate absolute cross sections are available both for $E1$ photofission and for electrofission. The large $E2$ component claimed[2,3] has been contradicted by experiments[9] which measured (e^{+},f) as well as (e^{-},f). Our results cast doubt on the high fission probability partly because the reported energy concentration[2,3] conflicts with our results, and partly because our data are consistent with equal $E1$ and $E2$ fission probabilities. This equality of fission probability for 1^{-} and 2^{+} states is expected because the density of fission transition states at high energy is not related to the energies of the lowest fission barriers of states with different spins and parities. The argument in Ref. 3 that higher fission probabilities should be expected for 2^+ than for 1^- states is not generally accepted, and disagrees with a wide variety of measured fission probabilities. The anomalously low fission probability for $E2$ reported from $(\alpha, \alpha' f)$ experiments[5,6] stems from the lack of concentration in energy of $(\alpha, \alpha' f)$ events. The inference that the $E2$ fission probability is low is based on the assumption that the bump observed in (α, α') spectra is $E2$ strength which is concentrated in energy. However, the sum of the $E2$ and $E0$ strengths that we deduce for ^{238}U would not imply a concentration in energy of those $(\alpha, \alpha' f)$ events associated with $E2$ and $E0$. This supports an alternative interpretation of the (α, α') bump as due to a mixture of $L=0$, $L=2$, and higher multipoles.[6] Another $(\alpha, \alpha' f)$ experiment[8] has been interpreted as showing an $E2$ peak near 10.6 MeV but this interpretation conflicts with the more complete $(\alpha, \alpha' f)$ studies[5,6] and with our results. Our data show that the fission fragments are nearly isotropic above 8 MeV which contradicts the speculations[8] about the dominance of $K=0$ fission decay channels near 10 MeV.

Our experiment[13] used the 100%-duty-cycle electron beams available from the University of Illinois MUSL-2 accelerator. Cross sections were measured at a scattering angle, θ_e, of 60° for electron beam energies, E, of 46.5, 56.9, and 67.1 MeV, and at $\theta_e = 80°$ with the 67.1-MeV beam. The corresponding effective elastic momentum transfers varied from 0.36 to 0.59 fm^{-1}. Spectra were taken for excitation energies, ω, of 5 to 12 MeV. The electrons scattered from a 1.07-mg/cm^2 uranium target were detected in a magnetic spectrometer which subtended 5 msr, and had an energy resolution of 0.1%. The fission fragments were detected by two 500-μg/cm^2 films of NE-102 plastic scintillator. Each detector subtended a solid angle of about 500 msr, and was centered at an angle θ_f of either 90° or 180° relative to the momentum transfer axis.

Figure 1 illustrates how the coincidence measurement removes experimental backgrounds. The upper spectrum shows the ^{238}U(e,e') energy-loss spectrum. It is dominated by the elastic peak and its radiative tail. The lower spectrum shows the inelastically scattered electrons in coincidence with a fission fragment. Clearly visible in this spectrum are the opening of the fission channel

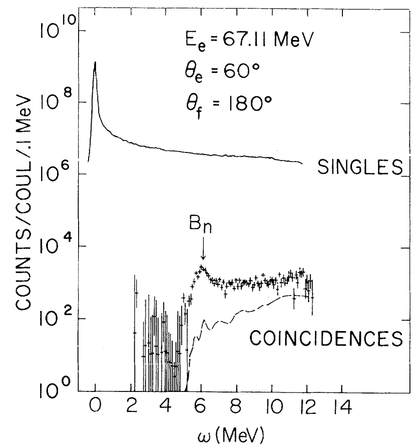

FIG. 1. Electron scattering spectra from ^{238}U observed with and without the requirement of coincident detection of a fission fragment. The dashed line indicates the estimated $E1$ contribution to the coincidence spectrum (see text) and the arrow indicates the opening of the neutron channel.

near 5.3 MeV, the effect of neutron competition above 6.15 MeV, and a relatively smooth, featureless cross section from 8 to 12 MeV. The fission-fragment angular distribution was measured to be isotropic for nuclear excitation energies above 8 MeV. Each of the two fission-fragment detectors had about an 8% chance of detecting one of the fission fragments. If the fission probability were 22% above 8 MeV, the total nuclear excitation would be a factor of 60 greater than the observed coincidence counting rate, implying that less than 1% of the counting rate in the ^{238}U(e,e') spectrum in this energy region was due to nuclear excitation. The quantitative extraction of the nuclear excitation cross section from such (e,e') data would require very accurate knowledge of the radiative tail and experimental backgrounds. Our measured cross sections are about a factor of 2 lower than the reports from a similar experiment,[14] but agree with the preliminary results of a later experiment.[15] The effects of radiative processes on the inelastic scattering, typically ~20%, were unfolded from the data using standard techniques.

The multipole strength functions were extracted from the data by a combined analysis of $(e,e'f)$ and (γ,f) data. Ignoring the angular correlations and interference, the coincident form factor can be written as

$$\frac{1}{\sigma_{\text{Mott}}} \frac{d^3\sigma(E, \theta_e, \theta_f, \omega)}{d\Omega_e \, d\Omega_f \, d\omega} = \frac{1}{4\pi} \sum_\lambda \frac{dB(E\lambda, \omega)}{d\omega} \frac{\Gamma_f}{\Gamma}(E\lambda, \omega) |F(E\lambda, E, \theta_e, \omega)|^2. \tag{1}$$

Here $dB(E\lambda,\omega)/d\omega$ is the reduced transition probability strength per megaelectronvolt for $E\lambda$ transitions in units of $e^2\cdot\text{fm}^{2\lambda}$, and Γ_f/Γ is the branching ratio for fission decay. The form factor $|F(E\lambda, E,\theta,\omega)|^2$, which is normalized to unit reduced transition probability, contains the dependence of the cross section on the radial behavior of the transition matrix element. Only electric multipoles contribute at the forward scattering angles used. The low q values of our experiment limit the sum in Eq. (1) to multipoles $\lambda \leq 2$. The $E0$ and $E2$ form factors are indistinguishable at low q; these two are treated together and will be referred to as $E2/E0$. We measure the product of the strength and the branching ratio. On the basis of these considerations, Eq. (1) can be simplified:

$$\frac{1}{\sigma_{\text{Mott}}}\frac{d^3\sigma(E,\theta_e,\theta_f,\omega)}{d\Omega_e\, d\Omega_f\, d\omega} = \frac{1}{4\pi}[A(\omega)|F(E1,E,\theta,\omega)|^2 + B(\omega)|F(E2/E0,E,\theta,\omega)|^2]. \qquad (2)$$

$A(\omega)$ and $B(\omega)$ are the reduced transition probability strength functions in the fission channel for $E1$ and $E2/E0$ transitions. In analyzing the data we adopted the technique[16] of using a nuclear model for the form factors $F(E\lambda,E,\theta,\omega)$ and then determining the strength functions $A(\omega)$ and $B(\omega)$ by a least-squares fit. The hydrodynamic model[17] was used in the distorted-wave Born-approximation code HEINEL[18] to calculate the $F(E\lambda,E,\theta,\omega)$. This model adequately describes the low-q (e,e') data for a broad variety of nuclear bound-state studies.[19] The transition radii used were the values which fit the $^{238}\text{U}(e,e')$ giant resonance data.[4] Previously reported (γ,f) data[20-22] were included in the fit on an equal footing with the $^{238}\text{U}(e,e'f)$ data. The data were averaged over fission-fragment angle and divided into 100-keV bins; the (γ,f) and $(e,e'f)$ cross sections for each energy bin were fitted by adjusting A and B. The photon data essentially determine the $E1$ strength function $A(\omega)$. The $E1$ contribution as a function of ω is shown for the 67-MeV, 60° data as a dashed line in Fig. 1. The best-fit $E2/E0$ strength function is shown in Fig. 2(a). The ratio of $E2/E0$ strength functions extracted separately for the $\theta_f = 180°$ and 90° data is shown in Fig. 2(b). The $E1$ contribution to the measured $(e,e'f)$ cross sections, and the $E2/E0$ strength function inferred from the fit to the data, are sensitive to the q dependence of the model form factors used in the analysis. If we restrict the model transition densities to variations observed in low-q bound-state studies,[19] the $E2/E0$ strength function inferred varies by about 25% of its value. This 25% uncertainty is a reasonable estimate of the model dependence of our interpretation of our data.

The sharp rise in the $E2/E0$ strength at 5.3 MeV is due to the opening of the fission channel. The threshold of the $E2/E0$ strength is observed to be about 200 keV below the corresponding $E1$ threshold.[21] At 6 MeV Γ_f/Γ probably has a value close to 1 (Ref. 21); the neutron channel opens at 6.15 MeV. If Γ_f/Γ is similar for $E2/E0$ and $E1$ excitation, the fission probability decreases between 6.15 and 7 MeV, and remains constant at a value of 0.22 until the threshold for second-chance fission (about 12.6 MeV in ^{238}U). There is evidence for a plateau in the $E2/E0$ strength at about 5.7 MeV. A similar plateau has been observed in (γ,f),[21] (t,pf),[23] and $(\alpha,\alpha'f)$[24] reactions, where it has been interpreted in terms of a double-humped fission barrier. The large anisotropy

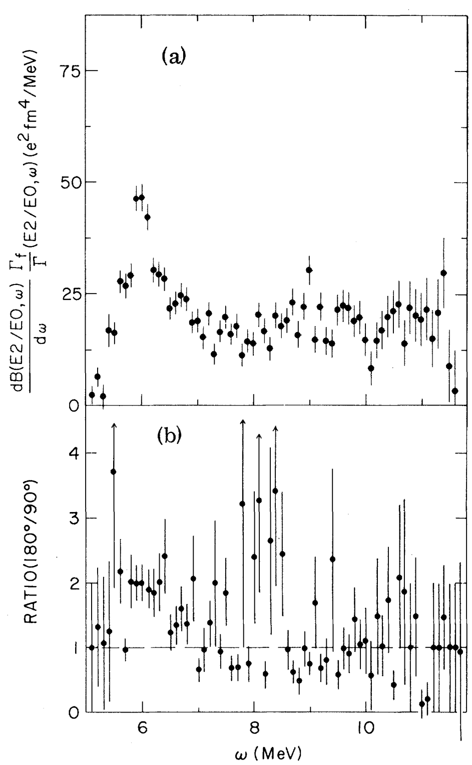

FIG. 2. The $E2/E0$ strength in the fission channel as determined from the present experiment, and the measured angular asymmetry.

visible in Fig. 2(b) below 7 MeV shows that the strength in this region is predominantly $E2$ rather than $E0$. The isotropy above 8 MeV might be due either to $E2$ strength decaying through an equal population of K states, or to $E0$ strength.

The $E2/E0$ strength function in the fission channel is surprisingly flat above 7-MeV excitation; there is evidence for a small bump near 9 MeV. About 3.7% of the isoscalar $E2$ sum rule is observed in the threshold region (i.e., $5.7 < \omega < 7$ MeV). An estimated average fission branch of 0.5 in this energy region suggests that 8% of the $E2$ energy-weighted sum rule might be located below 7 MeV. The fission strength function between 7 and 11.7 MeV is 10.0% of the isoscalar $E2$ sum rule. If we assume a fission probability of 0.22, the strength between 7 and 11.7 MeV accounts for an additional 45% of the isoscalar $E2$ sum rule. The $E2/E0$ strength inferred from our experiment presents no distinctive concentrated resonant behavior to assist in separating it from the featureless backgrounds present in hadron scattering.

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