Fission Decay of the Isoscalar Giant Monopole Resonance in ^{238}U

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The ^{238}U($\alpha,\alpha' f$) cross section was measured at E_α= 120 MeV for the scattering angle interval 0°–3°. By comparison of the fission-coincident inelastic alpha spectra in the ranges 0°–1.5° and 1.5°–3°, it is possible to deduce the shape of the giant monopole resonance in ^{238}U. It was found to be located at $E_x \sim 77A^{-1/3}$ MeV and to have a width Γ (full width at half maximum) ~ 6 MeV. If one assumes a fission probability similar to that of the giant dipole resonance, it exhausts about 80% of the isoscalar $E0$ energy-weighted sum rule.

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In this Letter we present results on the fission decay of the isoscalar giant monopole resonance (GMR) in ^{238}U. We are able to deduce from our data the shape of the GMR in ^{238}U which is important in connection with the predicted[1,2] and observed[3-5] splitting of the GMR in deformed nuclei.

For the giant dipole resonance (GDR) in the actinide nuclei the observed fission probability[6,7] is the same as for the compound nucleus. For the isoscalar giant resonances the situation seems to be different.[8-16] In inelastic, noncoincident, hadron scattering on ^{238}U a bump located at $E_x \sim 11$ MeV with a full width at half maximum of $\Gamma \sim 3$ MeV is clearly seen, which has been suggested to be due to $L=2$, 4, and 0 excitation.[5] However, this bump has not yet been reproduced in any fission-coincident inelastic hadron scattering experiment. A small bump located at $E_x \sim 10$ MeV with $\Gamma \sim 2$ MeV has been seen but its interpretation is not yet clear.[11-14] The failure to reproduce in the fission-coincident hadron spectra the bump observed in the singles spectrum is in agreement with recent results of an ($e,e'f$) experiment[16] in which it was found that the fission-coincident $[B(E2)+B(E0)]$ strength over the excitation energy interval from 7 to 11.7 MeV is, within the obtained statistical accuracy, flat and featureless. Thus from these experiments one may conclude that some or all of the components making up the giant-resonance-like bump in the singles spectra have lower than normal (~ 0.22) fission probability,[11,12] which makes it important to study the fission decay of the GMR in ^{238}U.

The basic idea of the present experiment is illustrated in Fig. 1, where for different isoscalar multipoles the angular distributions calculated[17] with distorted-wave Born approximation (DWBA) for 100% energy-weighted sum rule (EWSR) at $E_x = 10$ MeV are shown. For $L \geqslant 2$, standard form factors were used, while for $L=0$ version I of Satchler[18] and for $L=1$ the one of Harakch and Dieperink[19] were used. This figure shows that if one finds a bump in a spectrum taken over the angular range from 0° to, for instance, 1.5° which is absent or much more weakly excited in a spectrum taken over the range 1.5° to 3°, it is due to $L=0$ excitation. This is true provided that the observed difference is not due to a difference in the behavior of multistep processes.[20] Such a multistep effect, however, is not likely to result in bumplike structures.

Small-angle, including 0°, inelastic scattering

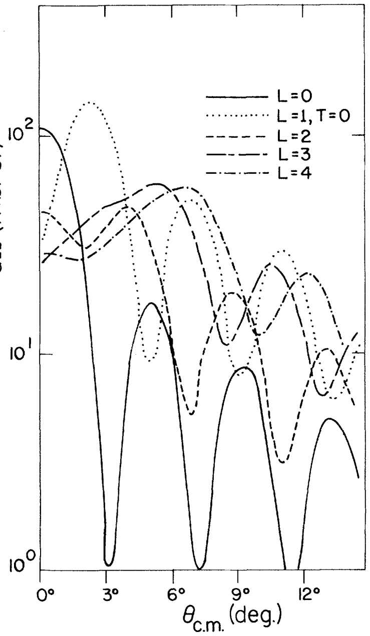


FIG. 1. DWBA-predicted differential cross sections for ^{238}U(α,α') at E_α = 120 MeV for the various isoscalar multipoles indicated, calculated for 100% of the respective isoscalar EWSR strength located at an excitation energy of 10 MeV; see text for more details.

to locate $E0$ strength has been extensively used by the Texas A & M and the Grenoble groups; see, for instance, Refs. 3 and 4, respectively, and references therein. The main experimental problem for such measurements is to reduce as much as possible the instrumental background due to beam halo and/or slit scattering. In addition, for a target like ^{238}U, peaks due to oxygen and carbon contaminants often prevent an accurate data analysis.[5] In the present fission-coincidence experiment, this background is automatically eliminated.

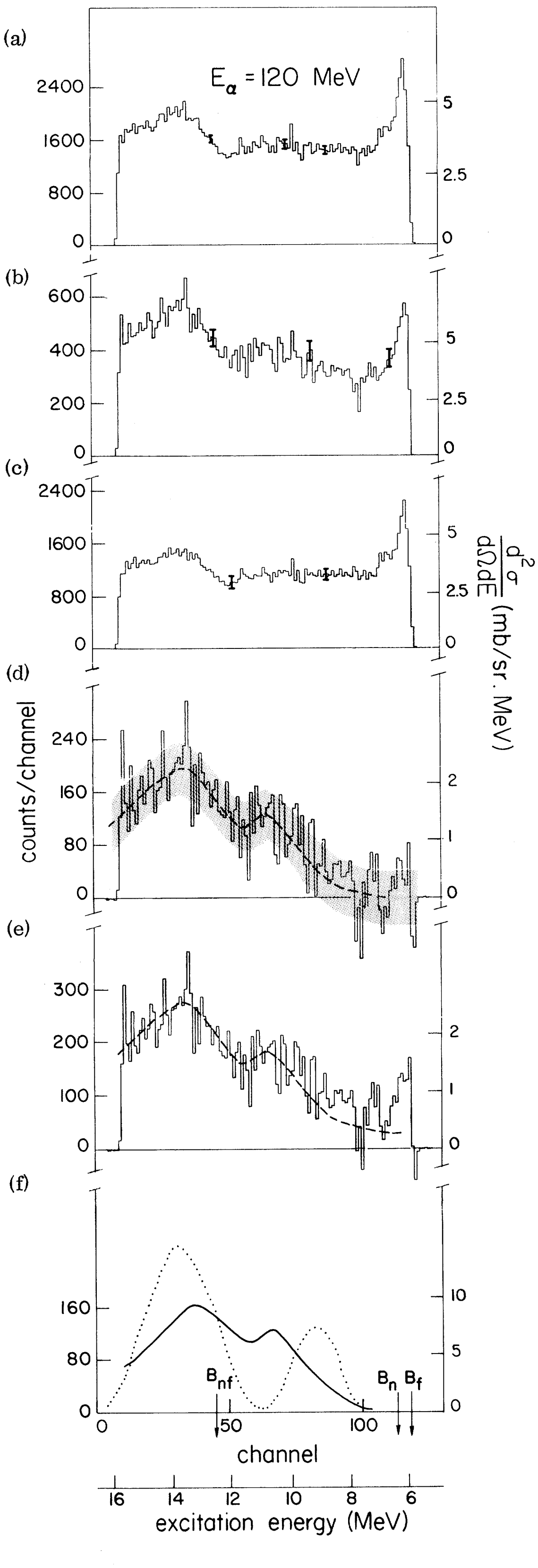
A 120-MeV analyzed alpha beam from the Kernfysisch Versneller Instituut cyclotron was used to bombard a 1.1-mg/cm^2 UO$_2$ target on an 0.1-mg/cm^2 ^{12}C foil. The inelastically scattered alpha particles were detected with the QMG/2 magnetic spectrograph[21] which was at 0° with respect to the beam. The beam was stopped in a Faraday cup in the focal plane of the spectrograph. The solid angle was 10 msr, corresponding to an opening angle of 6°. The detector system covered the excitation energy range between 5.7 and 15.7 MeV and consisted of a sequence of two two-dimensional position-sensitive detectors and a plastic scintillator.[22] With this system it is possible to determine the horizontal and vertical angles of incidence and thus by reconstruction the scattering angles.[22] In an off-line analysis we are thus able to separate the data taken with the full opening angle of 10 msr into two parts, a core part and a lateral one, approximately corresponding to scattering over angular ranges 0° to 1.5° and 1.5° to 3°, respectively—the limit between these two regions being defined to ± 0.2°. The fission fragments were detected in seven parallel-plate avalanche detectors positioned at the angles $\theta_f = -45°$, $-65°$, 105°, 125°, 145°, $-155°$, and 165° with respect to the beam direction. Each fission detector subtended a solid angle $\Delta\Omega_f = 42$ msr with a horizontal opening angle $\Delta\theta_f = \pm 4°$. The normal to the target made an angle of $-25°$ with the beam direction.

The technique described above for determining $E0$ strength depends crucially on the capability to divide the whole scattering interval of 0° to 3° into a small-angle (core) and a large-angle (lateral) part. We have checked this for the ^{12}C and ^{16}O 0^+ states at 7.65 and 12.05 MeV, respectively, which in the inelastic, noncoincident spectra were, as compared to other (non-$J^\pi = 0^+$) states, more strongly excited in the core than in the lateral part in agreement with DWBA predictions.

Figures 2(a)–2(c) show the fission-coincident inelastically scattered alpha spectra. These spectra were obtained by summing with the appropriate weighting factors the fission-coincident spectra of the individual counters. By this procedure, no details are lost since it was found that over the whole excitation energy range, including the threshold region around $E_x \sim 6$ MeV, the angular correlation of the fission fragments over the interval $15° < \theta_f < 75°$ was approximately isotropic. Especially for the barrier region this is in striking contrast with what was found[11,12] in a similar experiment at $\theta_{\alpha'} \sim 18° \pm 3°$, and shows that in the present experiment only low multipolarities are being excited.

Figure 2(a) shows the coincident inelastic alpha spectrum over the full opening angle, Fig. 2(b) over the core part, and Fig. 2(c) over the lateral part, the last being obtained by subtracting the spectrum in Fig. 2(b) from that in Fig. 2(a). The difference in shapes between the spectra shown in Figs. 2(b) and 2(c) is striking. Whereas the spectrum of Fig. 2(c) is, for the region 7.5 MeV $\leq E_x \leq 12.5$ MeV, approximately flat and featureless, the spectrum of Fig. 2(b) shows a slight rise from about $E_x = 9$ MeV on. As argued above, this difference can be attributed to $L = 0$ strength, that is, to the excitation and subsequent fission decay of the GMR in ^{238}U.

For a quantitative analysis of the shape and the cross section of the GMR some assumptions have to be introduced. The spectrum shown in Fig. 2(d) is based on the assumption that below the giant resonance region ($E_x < 8$ MeV) very little direct excitation of monopole strength is present and that the cross section for fission induced by inelastic alpha scattering for all other excitations is constant for all angles $0° \leq \theta_{\alpha'} \leq 3°$. It was obtained by subtracting one-fourth of the spectrum in Fig. 2(c) from the spectrum in Fig. 2(b), resulting in nearly complete cancellation for $E_x < 8$ MeV. The normalization factor $\frac{1}{4}$ would imply that the angular range corresponding to the core part would be $0° \leq \theta_{\alpha'} \leq 1.35°$, which is very close to the intended range $0° \leq \theta_{\alpha'} \leq 1.5°$. The dotted line in Fig. 2(d) represents an eyeball average of the data. The solid line in Fig. 2(f) shows the $E0$ strength distribution obtained from the fission-coincident spectrum [dashed line in Fig. 2(d)], with the assumption that the fission probability P_f for the GMR has the same shape as the one for the GDR. The $E0$ strength distribution peaks at about $E_x = 12.5$ MeV ($= 77A^{-1/3}$ MeV) and has a width $\Gamma \sim 6$ MeV. If, in addition, we assume that also the magnitude of P_f for the GMR is the same



as for the GDR[6,7] (P_f is ~ 0.22 from E_x ~ 7 MeV to E_x ~ 12.5 MeV and then gradually increases to ~ 0.39 at E_x ~ 14 MeV[6]) then the fission coincidence spectrum of Fig. 2(f) corresponds to about (80 ± 20)% of the $E0$ EWSR. The uncertainty of ± 20% is estimated from the uncertainties in the normalization factor of the angular range and in the DWBA analysis. The excitation energy E_x corresponds to what may be expected from systematics, but its width is considerably larger than the one for spherical nuclei.[23] This broadening can be attributed to a splitting of the GMR strength in deformed nuclei; in fact, a real splitting is suggested from our data in Fig. 2(f). Evidence for broadening has been obtained before in the deformed nuclei around $A = 150$.[3,4] The shape and magnitude of the GMR thus deduced are not too sensitive to the choice of the normalization factor used in the subtraction of Fig. 2(c) from Fig. 2(b). For instance, Fig. 2(e) shows a spectrum which is obtained by using a normalization factor of $\frac{1}{5}$ instead of $\frac{1}{4}$. The effect is that approximately the same fission-coincident GMR bump is observed as in Fig. 2(d) but now superposed on an approximately flat continuum. Similarly a larger normalization factor would result in a fission-coincident GMR bump sitting on a negative base line.

Finally, Fig. 2(f) shows our results obtained as discussed above, together with the ones recently obtained by Morsch *et al.*[5] from a comparison of (α,α') spectra obtained at $E_x = 100$ and 172 MeV. The data of Ref. 5 suggest a clear splitting of the GMR, while our data indicate that this splitting is smaller, so that its main effect is only a broadening of the GMR in ^{238}U. A calculation on the splitting of the GMR in deformed nuclei has been per-

FIG. 2. (a) Fission-coincident inelastic alpha spectrum at $\theta_{\mathrm{lab}} = 0^\circ$ for the full opening angle of the spectrograph, $-3^\circ \leq \theta_{\alpha'} \leq 3^\circ$. (b) Same as (a) but for a core opening angle of $-1.35^\circ \leq \theta_\alpha \leq 1.35^\circ$. (c) Same as (a) but for the remaining lateral angular part [spectrum in (a) minus the spectrum in (b)]. (d) Spectrum obtained by subtracting $\frac{1}{4}$ spectrum in (c) from spectrum in (b) (dashed line represents eyeball fit of the data; shaded area represents error limits). (e) Spectrum obtained by subtracting $\frac{1}{5}$ spectrum in (c) from spectrum in (b) (dashed line represents eyeball fit of the data). (f) Giant monopole strength distribution (solid line) as obtained from our fission-coincident spectrum (d) with the assumption of a fission probability similar to that of the GDR. The dotted line is the monopole strength distribution as expected from the data of Morsch *et al.* (Ref. 5). (See text for details and discussion.)

formed, for instance, by Abgrall *et al.*[2] For a deformation parameter $\beta = 0.3$ their predictions correspond closely to what Morsch *et al.*[5] have found experimentally for ^{238}U. Since the actual value of $\beta \approx 0.23$ in ^{238}U, their predicted splitting would be smaller than that found by Morsch *et al.*[5] and in better agreement with our results.

In conclusion, by measuring the fission-coincident inelastic alpha spectrum over the angular range 0° to 3° and making reasonable assumptions for the fission probability, we have been able to determine the shape of the isoscalar giant monopole resonance in ^{238}U. The data suggest that the GMR is located at $E_x \sim 77A^{-1/3}$ MeV and has a width $\Gamma \sim 6$ MeV. Moreover the data are consistent with an $(80 \pm 20)\%$ exhaustion of the $E0$ EWSR if a fission probability similar to that of the GDR is assumed.

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