Observation of Isoscalar Giant-Resonance Structure in the Fission of ^{238}U Following Inelastic Scattering of ^{6}Li

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Resonance structures are observed in the region of the isoscalar giant quadrupole resonance for the reaction ^{238}U(^{6}Li, ^{6}Li$'f$) at 150 MeV. The ratio between the fission probabilities of resonance and compound-nucleus components appears to be greater than the recently reported value from (α, α') scattering.

Several experiments have been undertaken to investigate the decay modes of the isoscalar giant quadrupole resonance in the actinide nuclei. Electron scattering and photoabsorption have provided indirect evidence that the fission probability for the quadrupole resonance is greater than that for the dipole resonance.[1] A recent study[2] of the $(\alpha, \alpha' f)$ reaction on ^{232}Th and ^{238}U targets arrived at the conclusion that the fission decay of the giant quadrupole resonance is inhibited by at least a factor of 5 as compared with the fission decay of the continuum, since no resonance structure was observed in this channel. We report here the measurement of the fission decay of ^{238}U induced by the inelastic scattering of ^{6}Li where clear resonance structure is observed in the fission channel.

Self-supporting metallic ^{238}U targets of 0.5-mg/cm^2 thickness were bombarded with 150-MeV ^{6}Li^{3+} ions from the 88-in. cyclotron of the Lawrence Berkeley Laboratory. The experiment was performed in two parts. First, singles spectra of inelastically scattered ^{6}Li nuclei were measured with a magnetic spectrograph; this avoids the background problems due to nuclear reactions in solid-state detectors. Second, inelastic ^{6}Li spectra corresponding to coincidences between ^{6}Li nuclei and fission fragments were measured with the experimental arrangement shown in Fig. 1. The fission fragments were detected with large-area parallel-plate proportional detectors A and B and the ^{6}Li nuclei were detected with a solid-state telescope placed either in (I) or out (O) of the horizontal plane. Solid-state detectors could be used for this part of the experiment since the coincidence requirement considerably reduces the background.

An example of a singles ^{6}Li spectrum taken at 16° with the magnetic spectrograph is shown in Fig. 2; the contributions from carbon and oxygen were measured in separate experiments and have been subtracted in Fig. 2. It was discovered that the shape of the energy spectrum did not change

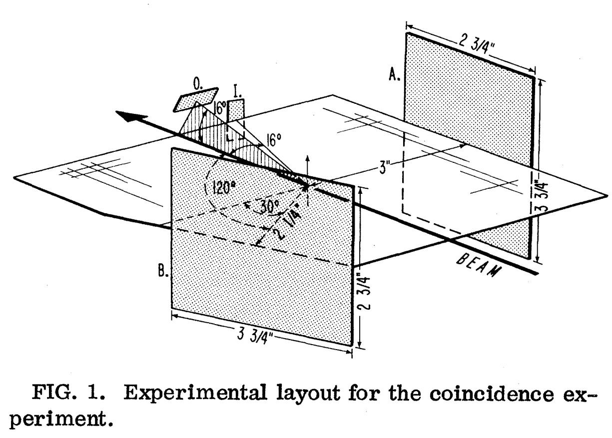

FIG. 1. Experimental layout for the coincidence experiment.

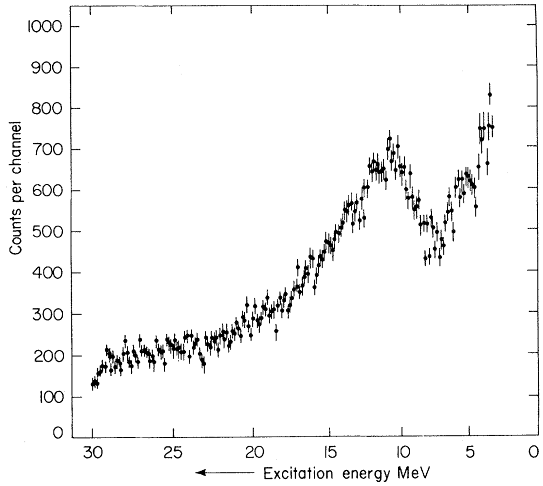

FIG. 2. Energy spectrum measured by the magnetic spectrograph at a scattering angle of 16°.

significantly over the range of angles subtended by the solid-state telescope used for the coincidence experiment. The spectrum shows a clear giant resonant structure centered around 10.5 MeV with a full width at half maximum of 7 MeV. The peak of this structure is close to the value of $63A^{-1/3}$ MeV expected for the isoscalar giant quadrupole resonance. However, the width of this structure is considerably broader than expected for the giant quadrupole resonance, which may indicate that several different multipolarities contribute to the observed structure.[3,4]

Energy spectra of inelastically scattered ^{6}Li nuclei observed in coincidence with fission fragments are shown in Fig. 3 for various detector geometries (for notation, the symbol $A\cdot\bar{B}$ denotes an event in detector A and no event in detector B; see also Fig. 1). The sharp peak observed at 6.1 MeV is due to the fact that the neutron channel opens up at an excitation energy only slightly higher than the fission barrier. At the location of this peak the angular distribution of the fission fragments is highly anisotropic with respect to the recoil direction of the target nucleus,[5] whereas at higher excitation energies the angular distributions are nearly isotropic. This change in anisotropy is clearly evident from Fig. 3 if one notes that, for the in-plane geometry, the detector combination $A\cdot\bar{B}$ selects events close to the recoil axis, whereas the combinations $B\cdot A$ and $B\cdot\bar{A}$ correspond to fission fragments emitted at increasing angles with respect to the recoil direction (the mean value of this angle for each detector configuration is shown in

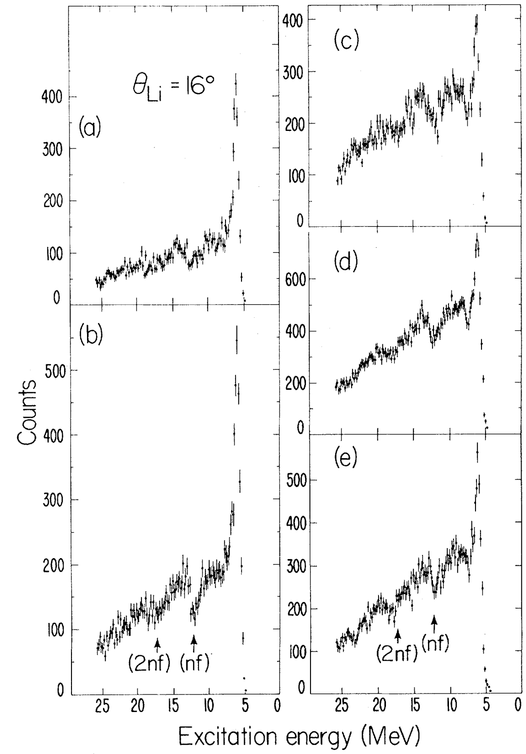

FIG. 3. Coincidence energy spectra for different detector configurations. (a) Li telescope in plane; fission detector configuration $A\cdot\bar{B}$, which corresponds to a mean angle between the recoiling ^{238}U nucleus and the fission detector $\theta_f \approx 0°$ (A and B refer to the fission detectors shown in Fig. 1). (b) Li telescope in plane; fission detector $B\cdot A$, and $\theta_f \approx 20°$. (c) Li telescope in plane; fission detector $B\cdot\bar{A}$, and $\theta_f \approx 65°$. (d) Li telescope out of plane; fission detector B, and $\theta_f \approx 90°$. (e) Li telescope out of plane; fission detector A, and $\theta_f \approx 90°$.

the caption of Fig. 3). The rise in the fission yields at about 12 and 17 MeV excitation energies corresponds to second- and third-chance fission, i.e., fission after the evaporation of one and two neutrons, respectively; in Fig. 3, arrows mark the predicted thresholds. The structure located around 9.5 MeV between the first- and second-chance peaks has not been previously observed. Because of the large anisotropy of the fission fragment angular distribution close to the fission barrier, this structure is difficult to identify if fission fragments are detected close to the recoil direction of the target nucleus [see Fig. 3(a)]. It is most unlikely that this structure could be due to excited states of ^{6}Li, since the only possible candidate is the $T=1$ state at 3.56 MeV which will only be weakly excited since this involves an isospin flip.

The coincidence spectrum corresponding to the sum of all out-of-plane data and the in-plane data for the combination $B\cdot\bar{A}$ is shown in Fig. 4(a). For comparison, the solid curve shown in this figure represents the singles spectrum shown in Fig. 2. Clearly, a one to one correspondence cannot be established between the spectral shapes in the energy region around 10 MeV, since the structure in the coincidence spectrum peaks at a lower excitation energy with a narrower width than the structure observed in the singles spectrum. This difference becomes more apparent in Fig. 4(b) which shows the ratio of these coincidence and singles spectra. The ratio varies strongly as a function of excitation energy of the ^{238}U target nucleus.

An attempt to extract relative fission probabilities from our measurements is presented in Fig. 4(c). The data points of this figure were derived from those of Fig. 4(b) by applying corrections to take account of the incomplete angular range of the fission detectors used to measure the coincidence spectrum in Fig. 4(a). These corrections have been performed by assuming fission angular distributions similar to those of Ref. 5; they are of the order of 60% at the fission threshold and smaller than 10% above 9 MeV excitation energy. Also in Fig. 4(c), the fission probabilities for ^{238}U deduced[6,7] from the reactions ^{236}U(t,pf) and ^{238}U(γ,f) are shown as solid lines. Our data points in this figure have been normalized at 6.1 MeV to the (t,p) data; this is done for diagrammatic comparison purposes only and cannot be considered as a reliable normalization. From our experiment we cannot estimate the fission probability from our experiments to better than 50%. This large uncertainty arises from the difficulties in normalizing data from two experiments using completely different techniques; in particular the tight geometry of the coincidence experiment combined with the rather steep angular distributions means that the normalization is very sensitive to small variations of beam spot position.

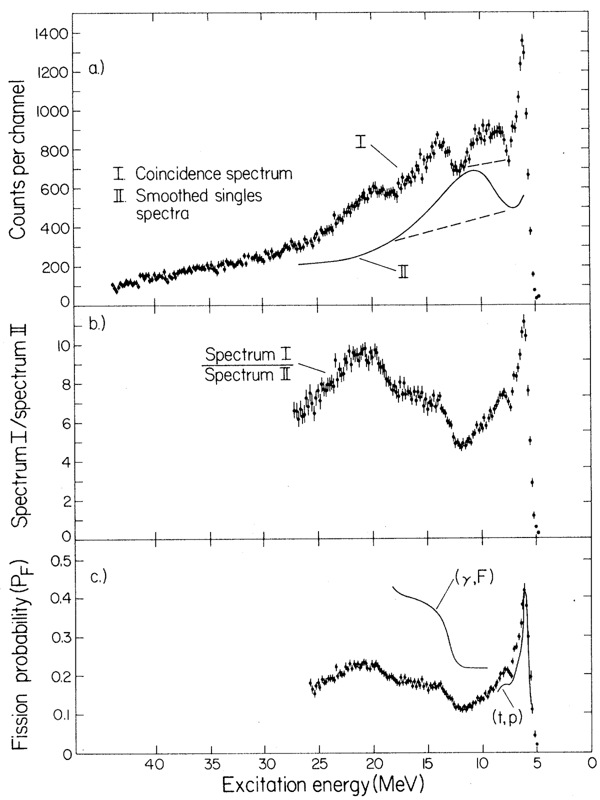

FIG. 4. Comparison between the singles and coincidence energy spectra.

It is evident that the energy dependence of the fission probabilities for the charged-particle-induced fission is very similar below about 8.5 MeV. Unfortunately, no data on charged-particle-induced fission of ^{238}U are published for excitation energies above this energy. It should, however, be noted that the rise of the fission probability in the region of the second- and third-chance fission is very similar for the ^{6}Li-induced reaction and the photofission.

The results from this experiment are different from those obtained using the (α,α') reaction reported in Ref. 2, since clear resonant structures are observed in the present coincidence spectra. It is not clear whether this difference could be due to the excitation of different states in the two reactions, or to the detection of fission fragments preferentially in the recoil direction of the target nucleus reported in Ref. 2, where structure may be obscured by the strong peak at the fission threshold. The absence of resonance structure reported in Ref. 2 leads to the conclusion that the fission probability of the giant quadrupole resonance is smaller by at least a factor of 5 compared with that of the continuum. From our data we feel that we cannot deduce the fission probability with any confidence because the identification of resonance and background is highly uncertain for the coincidence spectrum. Nevertheless, by adopting the extreme simplification of defining a smooth background [see dashed lines in Fig. 4(a)] we find that the resonant structure observed in the coincidence spectra has to be associated with an integral fission probability of at least half the value of the fission probability of the underlying continuum. This value was deduced by taking a ratio of areas above and below the dashed lines in Fig. 4(a) for the singles and coincidence spectra. It should be kept in mind, however, that such a choice of background for the coincidence spectrum would mean that the ratio of the fission probabilities between the resonance structure and background would vary between 1.3 and 0 for the energy range 7.5–11.5 MeV, and be 0 for the remaining resonance region between 11.5 and 17.5 MeV, which is clearly unreasonable. We therefore feel that this simple choice of background for the coincidence spectrum represents an upper limit and, consequently, the quoted ratios of fission probabilities should be taken as lower limits, with the probable values being considerably above these limits. The division between resonance and compound-nucleus contributions is therefore likely to be lower than drawn in Fig. 4(a), and so would lead to a higher value than $\frac{1}{2}$ quoted above for the ratio between fission probabilities of the resonance and compound-nucleus components.

The fission probability varies strongly over the energy region of the resonance structure observed in the singles spectra. For excitation energies above about 13 MeV this energy dependence is mainly due to the occurrence of second- and third-chance fission. Additional structure might be caused by the contribution of several multipolarities[3,4] to the resonant structure and the splitting of the quadrupole resonance[8] into its $K=0$, 1, and 2 components. It is possible that different fission probabilities have to be associated with these various contributions. To pursue further this interesting question it will be necessary to compare directly the fission probabilities for a reaction condition in which the resonance is strongly excited with a reaction condition where it is only weakly excited, over an extended energy range.

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Determination of the Asymptotic *D*- to *S*-State Ratio of the Deuteron Wave Function

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Cross sections and tensor analyzing powers in *dp* elastic scattering, measured at 35 and 45 MeV, are used to determine the asymptotic *D*- to *S*-state ratio of the deuteron wave function. The results agree with the value determined at lower energies and provide a considerably more precise averaged value: $\rho_D = 0.0263 \pm 0.0013$.

Recent reviews of the deuteron[1,2] have emphasized the importance of the determination of its *D*-state probability, P_D, and/or its asymptotic *D*- to *S*-state ratio, ρ_D. More precise knowledge of these basic deuteron properties would establish significant constraints on the nucleon-nucleon in-