^{238}U giant resonances and the ^{238}U(p, p') reaction at $E_p = 66$ MeV†

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Measurements of inelastic proton spectra in the region 0–25-MeV excitation energy have been made for the ^{238}U(p, p') reaction using 66-MeV protons. Two new strongly collective excitation regions of ^{238}U were discovered at $E_x \approx 1.6$–2.0 MeV and $E_x \approx 10$–13 MeV. The ≈ 1.8-MeV excitation region is complex, and its angular distribution is consistent with $L = 3$ and $L = 2$ groups. The collective resonance region at 10–13 MeV appears to have an $L = 2$ angular distribution with strength to exhaust most of the energy-weighted sum rule, although $L = 3$ and 4 components cannot be rigorously excluded. The remaining excitation region accounts for most of the cross-section strength in the reaction and consists of a relatively smooth continuum background. The results are discussed in terms of the Nilsson model.

[NUCLEAR REACTION ^{238}U(p,p'), $E_p = 66$ MeV, $E_x = 0$–25 MeV; measured $\sigma(E_x, \theta)$; discuss giant resonances and other collective states.]

Most studies of direct reaction inelastic scattering on deformed nuclei are concerned only with the lowest excitation regions of the spectra. These measurements, along with others such as Coulomb excitation, have shown that the strongly collective states are of two basic types: (a) those associated with the rotation of the ground state—ground-state band ($K^\pi = 0^+$)—and (b) those associated with rotations about the low-lying collective vibrations—vibrational bands ($K^\pi = 0^\pm, 1^-, 2^\pm$). In a recent calculation by Kammuri and Kusuno[1] in the rare-earth region, predictions are made for new types of higher excitation collective states. These are the $K^\pi = 1^+$ excitations of the $\Delta N = 2$ types (N refers to the major oscillator shell[1] in the Nilsson model). The $K^\pi = 1^+$ vibrations with strong $\Delta N = 0$ components are expected to exist with $E_x \gtrsim 2$ MeV, and the $\Delta N = 2$ components give rise to a number of states having an excitation energy near $E_x = 12$ MeV. In each case, the theory predicts the $J^\pi = 2^+$ member of the $K^\pi = 1^+$ rotational band to have a large $B(E2)$ strength to ground state. In principle, the $B(E2)$ strength in a deformed nucleus is divided into $K^\pi = 0^+$, 1^+, and 2^+ components for both $\Delta N = 0$ and $\Delta N = 2$ states. It is the purpose of the present work to search for $\Delta N = 2$ states, as well as for $K > 2$ levels in ^{238}U via the ^{238}U(p, p') reaction.

The ^{238}U(p, p') reaction was studied at a bombarding energy of 66 MeV at the Oak Ridge isochronous cyclotron (ORIC). The experimental arrangement included detection of the inelastic scattered protons by photographic emulsions in the ORIC broad-range spectrograph. A thick ^{238}U target (≈ 20 mg/cm^2) was used in order to minimize the oxygen-to-uranium ratio. This is particularly important for continuum studies. No appreciable contaminants were found in the spectra. Measurements were made at scattering angles $\theta_{\text{lab}} = 15$, 20, 25, 30, 35, and 40°.

The spectrum obtained at a 20° scattering angle is shown in Fig. 1. (Note scale breaks.) The excitation energy from $E_x = 0.7$–25 MeV is shown. The track density on the photographic emulsions was too high to scan the ground-state rotational band region ($E_x < 0.7$ MeV). However, even in this low resolution (≈ 100 keV) experiment, the well-known $K^\pi = 0^-$, 0^+, and 2^+ bands can be identified near 0.7, 1.0, and 1.1 MeV, respectively. In addition, an unusual strength was found in a cluster of levels near 1.8 MeV.

Above the excitation energy of approximately 2 MeV, the "discrete" spectrum becomes "continuous". Due to the finite resolution (≈ 100 keV) of the measurements, the density of collective levels above about 2 MeV is sufficiently large to generate the properties of a subthreshold continuum. There appears to be no particular "concentration" of collective levels in the subthreshold continuum as can be seen by the absence of resonance-like structure below $E_x = S_n = 6.2$ MeV. Furthermore, the subthreshold continuum smoothly joins to the neutron escape continuum ($E > S_n$), and except for the 10–13-MeV region, this true continuum is relatively smooth throughout the spectra. In the 10–13-MeV region a "bump-like" resonance appears. At angles 20, 25, and 30°, the resonance is large enough that it can be separated from a smooth background continuum with confidence. The resulting shapes, as a function of position (energy) given in Fig. 2, seem to indicate an approximately constant shape for the resonance over this limited angular range. On the other hand, the remaining continuum shape changes as a function of angle, becoming "negatively" sloped at larger angles, as shown in a relative way by the dashed curves in Fig. 2.

It is known from photonuclear studies that the dipole $B(E1)$ strength is split in ^{238}U so that most of this strength is centered about 14-MeV excitation.[2] None of our spectra show an appreciable resonance at 14-MeV excitation (≈90 mm on center plate in Fig. 1). Thus, either the giant dipole resonance (GDR) is very weakly excited in the (p, p') at $E_p = 66$ MeV, or other collective states above and below the GDR "wash out" the appearance of this resonance in this kind of reaction spectrum.

The "resonances" at 1.6–2.0 MeV and 10–13 MeV were investigated by studying their angular distributions. In Fig. 3 are shown the angular distributions for the 1.6–2.0-MeV group (solid points), as well as the vibrational bands at ≈1.1 and 0.7 MeV. All of these groups have similar average angular distribution "slopes," indicating that they have similar L (angular momenta) strengths. The group of levels at $Q \approx -0.73$ MeV (shown by triangles) is expected[3] to contain mostly $L = 3$ and $L = 5$ transfer strengths, corresponding to the known $K^\pi = 1^-$ band. The group of levels at $Q \approx -1.1$ MeV (shown by circles) is expected[3] to contain mostly $L = 2$ and $L = 4$ transfer strengths exciting the known $K^\pi = 0^+$ and 2^+ "$\beta + \gamma$" vibrational bands in ^{238}U. The curve through the solid data points is a distorted-wave Born-approximation (DWBA) prediction based upon equal strengths of $L = 2$ and 3. While the data are consistent with this $L = 2 + 3$ mixture, other combinations cannot be rigorously excluded. The optical-model parameters[4] used in the DWBA prediction are those measured for ^{208}Pb.

The relevant distorted-wave calculations were also carried out for the 10–13-MeV resonance and are shown by the curves in Fig. 4. Each multipole curve in Fig. 4 is normalized to represent 100% of the isoscalar (isovector for $L = 1$) strength for $Q = -11$ MeV based upon the energy-weighted sum rules.[5] It may be noted that while the $L = 3$ and $L = 2$ curves are qualitatively similar, the $L = 0$ and $L = 2$ curves are quite different in their average slope.

By assuming a simple background continuum such as that given by the dotted lines in Figs. 1 and 2, the angular distribution for the 10–13-MeV resonance was extracted, and the results are shown in Fig. 5. The cross-section uncertainties for $\theta > 30°$

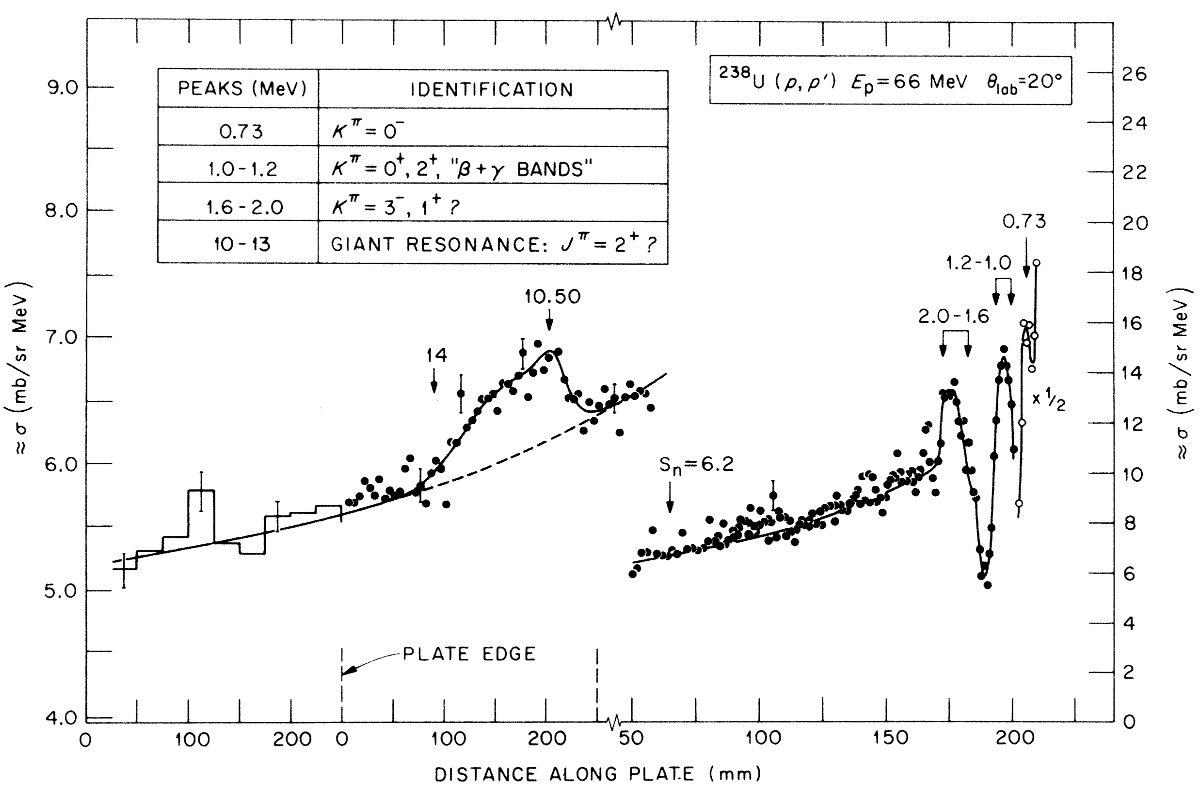

FIG. 1. An excitation energy spectrum of the ^{238}U(p, p') reaction ($E_x \approx 0.7$–25 MeV). The neutron threshold is given by S_n. The energy dispersion along the photographic plates (horizontal axis) is ≈33 keV/mm. Various energy points are shown (in MeV) above the data. The broken line is an estimate of the background continuum underlying the resonance structure.

are quite large because the resonance is not well defined against the background continuum. The measured angular distribution was compared with theoretical predictions for "giant" isoscalar-quadrupole and monopole resonances. Only the quadrupole interpretation was found to be consistent with the data, as shown in Fig. 5. If the resonance consists of only quadrupole strength, then ≈85% of the isoscalar $E2$ sum rule is exhausted by the resonance (the absolute uncertainty in this figure is about 50%). However, octupole and hexadecapole strength might contribute to the total observed strength without changing the average slope of the angular distribution.

In conclusion, we have presented evidence that the general shape of the inelastic scattering spectra in the ^{238}U(p,p') reaction with $E_p = 66$ MeV implies new types of vibrations in deformed nuclei. The angular distribution of the 1.6–2.0-MeV group is consistent with $K^\pi = 3^-$ and $K^\pi = 1^+$ bands expected in ^{238}U near the measured energy. Other evidence for high-excitation 3^- states has been found in low bombarding energy measurements.[6] Above 2-MeV excitation, the $K > 3$ bands might be expected to increase significantly the level density which explains in part the "subthreshold continuum." However, the onset of this "continuous spectrum of

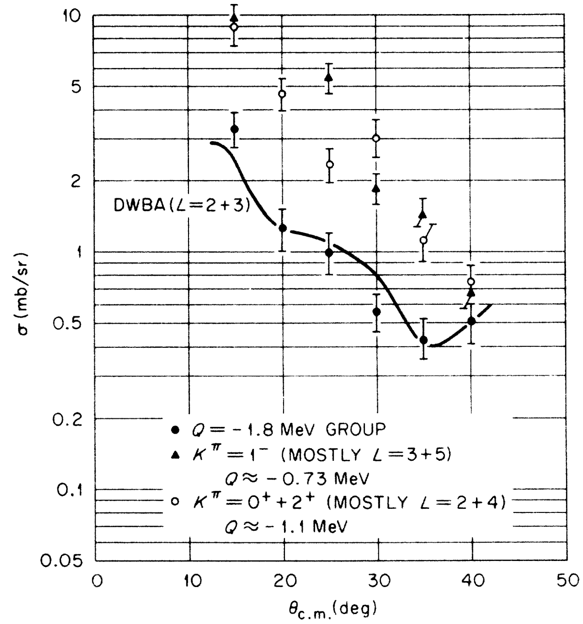

FIG. 3. Angular distributions of the three bound-state groups shown in Fig. 1 and identified by Q value. The solid curve is arbitrarily normalized but contains equal strengths of $L=2$ and $L=3$.

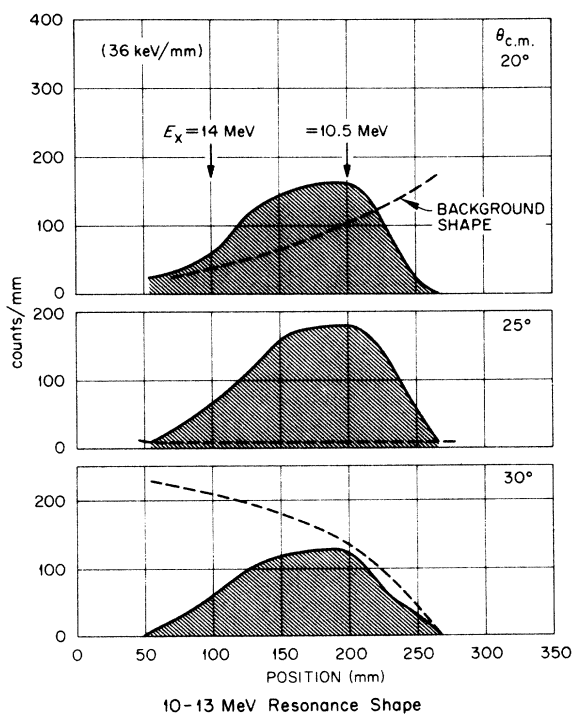

FIG. 2. Shapes of the high-energy resonance region of the spectra after background subtraction as shown in Fig. 1. The broken lines are the (arbitrarily normalized) background shapes.

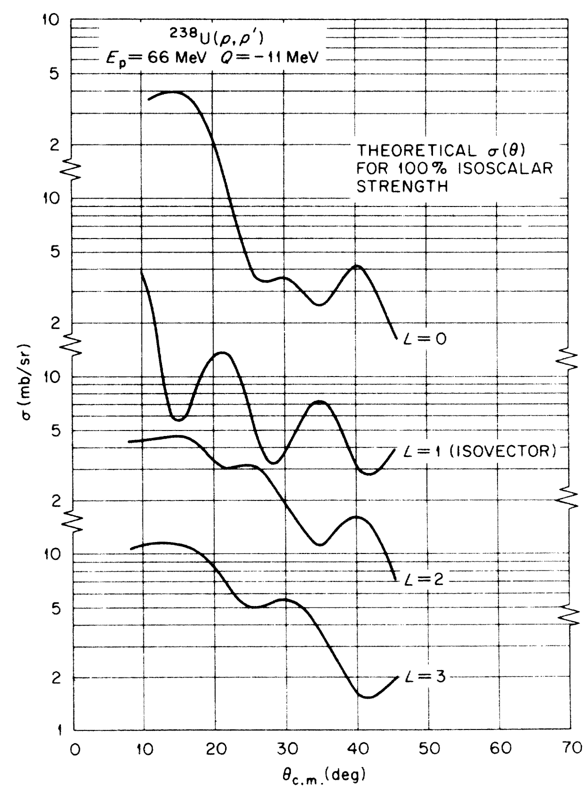

FIG. 4. Theoretical angular distributions calculated by distorted-wave estimates using energy-weighted sum rules as described in Ref. 5.

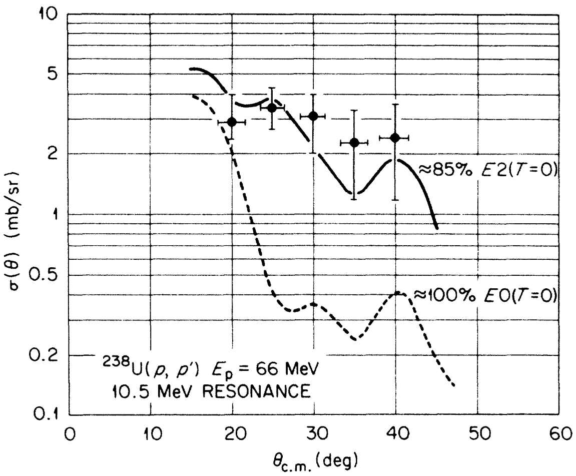

FIG. 5. Angular distributions of the 10–13-MeV resonance (after background subtraction). Data are compared with the $L=2$ and $L=0$ curves taken from Fig. 4.

bound states" appears to occur rather suddenly as a function of excitation energy, and this fact demands further consideration. Another possible explanation to this continuum effect at 2 MeV is via the fission decay width of these highly excited states. From this point of view, the average fission widths of the collective levels might rapidly increase above about 2- or 3-MeV excitation energy, which implies that the fission barrier rapidly decreases. While details of fission barrier shapes are not well known,[7] there is at present no reason to believe that the fission barrier suddenly decreases in the energy region 2–3 MeV.

The 10–13-MeV structure observed in the ^{238}U(p,p') spectra might be compared to the corresponding energy regions in the ^{208}Pb(p,p')[8] and, more recently, the ^{154}Sm(p,p')[9] spectra. The excitation energies of the structure in the ^{208}Pb and ^{238}U are very similar, although some "fine structure" was observed in the ^{208}Pb case near 10–11 MeV. While the excitation energy of the resonance in deformed ^{238}U is lower than that for deformed ^{154}Sm, as expected from the inverse mass law ($E_x \approx 63A^{-1/3}$),[8] the spectra are similar in that the background continuua near the threshold of the resonances are larger than the corresponding case in spherical nuclei in neighboring mass regions. Since the calculations of Kammuri and Kusuno[1] predict an excitation energy of ≈12 MeV for the $\Delta N=2$ states in the rare-earth nuclei, it is reasonable to associate the high-excitation resonance observed in deformed ^{154}Sm and ^{238}U spectra with these $\Delta N=2$ vibrations, as was previously done in the case of spherical nuclei.[8]

Finally, it is important to point out that our results help to resolve the ambiguity found[9] in the samarium inelastic scattering, namely, whether the cross section for the excitation of the GDR is large enough to manifest a resonance in the ≈66-MeV (p,p') spectra. We find no evidence to support this and suggest that nearly the entire resonance seen in the (p,p') spectra is isoscalar excitation.

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