Giant Resonances in the High-Energy Helium Inelastic Scattering*

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An analysis of earlier reported cross-section data from ^{208}Pb(α,α'), (^{3}He,^{3}He'), and ^{197}Au(^{3}He,^{3}He') reactions at $E_\alpha=90$ MeV and $E_{^3\mathrm{He}}=75$ MeV confirms the discovery of a new giant resonance at $E^*\approx 11$ MeV in heavy nuclei. From the magnitude of the cross sections and theoretical sum-rule prescriptions, it is found that the resonance may be interpreted as a giant-quadrupole state but not, as recently suggested, a giant-monopole state.

Recent studies[1–4] of the giant resonance region ($E^*\approx 10$–20 MeV) of the nuclear continuum by direct reaction inelastic scattering have demonstrated the existence of a new giant resonance. The excitation energy of the resonance is 2–3 MeV lower than the giant-electric-dipole resonance, the latter having been well-established in photon absorption (γ, n) or (γ, p) measurements. The multipolarity of the new resonance is more difficult to establish. Whereas in the (γ, n) reactions only dipole excitations are strongly excited, in the inelastic scattering reactions such as (p, p') and (e, e') strong multipole selectivity does not generally exist. Since the widths of giant resonances may be large ($\Gamma\approx 4$ MeV), at least the dipole and perhaps other resonances overlap the region of the new resonance. Thus in the scattering experiments, the extracted angular distribution data for the new resonance have relatively large uncertainties accruing from the unfolding of the composite resonance into neighboring component resonances.[3,4]

Nevertheless, angular distributions for the new resonance have been extracted for ^{40}Ca(p, p') at $E_p=182$ MeV[3] and ^{90}Zr(e, e') at $E_e=180$ MeV[4] and analyzed with available reaction theories. For ^{40}Ca(p, p') data, collective models discussed by Satchler[2] for $L\geqslant 1$ were examined, and $L=2$ with a strength of about 73% of isoscalar sum rule was the preferred multipole assignment. Concurrently the ^{90}Zr(e, e') data for the new resonance could be equally well described by either a giant quadrupole (≈75% of the isoscalar sum-rule strength) or giant monopole (100% of the isoscalar strength). Also studies[5] of the ^{208}Pb(e, e') reaction at $E_e=65$ MeV have identified $E2$ resonances at $E^*=10.2$, 10.6, and 11.2 MeV which are believed to correspond to fine structure seen on the low excitation side of the giant $E1$ resonance in the (γ, n) reaction. More recently Satchler[6] has suggested a nuclear scattering model for a giant-monopole excitation. From the predictions of the model he finds that in the case of the currently available inelastic proton data, it is not possible to resolve clearly the ambiguity between a monopole and a quadrupole assignment to the resonance.

While some of the small angle differential cross-section data and the positive polarization value from the 180-MeV scattering experiment[7] on ^{40}Ca(p, p') appear to favor an $L=2$ rather than an $L=0$ assignment[6] for the resonance, more corroborating evidence is needed to resolve the quadrupole-monopole ambiguity. We show below that more evidence can be found in the helium scattering data of Chenevert and collaborators.[8]

α and helion inelastic scattering data[8] have been taken on targets ^{208}Pb, ^{197}Au, and ^{181}Ta. With bombarding energies of $E_\alpha=90$ MeV and $E_{^3\mathrm{He}}=75$ MeV, resonances can be identified which apparently correspond in excitation energy ($E^*\approx 11$ MeV) with those systematically measured in Ref. 1. It is important to distinguish between these resonances and the so-called "mesa" resonance.[8] The latter is believed to exist only in the (α, α') spectra and to be the effect of the in-flight decay of ^{5}He ($^5\mathrm{He}\rightarrow\alpha+n$) formed in the $(\alpha, {}^5\mathrm{He})$ pickup reaction. The position of the "mesa" resonance in the α spectra is such as to interfere with the observation of the collective resonance unless the bombarding energy is sufficiently large, $E_\alpha\approx 90$ MeV.[8] Examples of the resonances[9] in the ^{208}Pb(α, α') and ^{197}Au(^{3}He, ^{3}He$'$) reactions are shown in Fig. 1. The shape of the resonance region of the spectra can be fitted with the approximations that the resonance has a Lorentz shape with width $\Gamma=3$ MeV, and that a linearly energy-dependent background continuum underlies the resonance. The clear observation of the resonance is limited to scattering angles $\theta\approx 20$–30°. At smaller angles the interference of elastic or collimator scattering is significant while at larger angles the differential cross section becomes small compared to background continuum. With the currently available data, we were able to analyze only a couple of angles in a given reaction. Examples of the cross sections one obtains in this kind of analysis are summarized in Table I for ^{208}Pb and ^{197}Au.

TABLE I. Measured and calculated cross sections for the resonance seen in α and helium-3 inelastic scattering at $E^* \approx 11$ MeV in ^{208}Pb and ^{197}Au. Columns 5 and 6 are estimates for giant-scalar-monopole and quadrupole resonances, respectively. See text for further details.

Target	Projectile	θ_{lab} (deg)	σ measured (mb/sr)	100% $\sigma_{DW}(L=0)$ (mb/sr)	85% $\sigma_{DW}(L=2)$ (mb/sr)
^{208}Pb	α	25	2.8 ± 1.4	0.66	2.3
^{nat}Pb	α	30	1.5 ± 0.7	0.08	1.1
^{208}Pb	^{3}He	22	9 ± 5	0.55	3.8
^{208}Pb	^{3}He	40	$\approx 0.7 \pm 0.4$	0.12	0.45
Au	^{3}He	22	4.3 ± 2.1	0.55	3.8
Au	^{3}He	30	1.9 ± 0.9	0.31	1.4

The cross sections obtained are, of course, only approximately corrected for the low excitation end of the known giant-dipole[10] state ($E^* \approx 13.5$ MeV). The uncertainties given for the cross sections in Table I are believed to be large enough to include such background errors; thus these uncertainties are not statistical but represent limits of the resonance cross section. It is interesting to note that, as in the 60-MeV proton scattering data,[1] the giant-dipole state is not strongly excited in the (^{3}He, ^{3}He′) at 75 MeV or (α, α') at 90 MeV. This fact implies a relatively weak symmetry term in the ^{3}He optical potential. Other analyses of ^{3}He potentials have led to similar conclusions.[11]

Distorted wave (DWBA) estimates for isoscalar-quadrupole and isoscalar-monopole excitations were calculated. The prescription for the monopole radial form factor was taken to be that given by Satchler[6] (version 2),

$$F(r) = -XU(r) - R\,\frac{\partial U(r)}{\partial r}\,. \tag{1}$$

$U(r)$ is the usual complex optical model potential $U(r) = V(r) + iW(r)$, and X is a constant defined in Ref. 6 and determined by volume conservation.

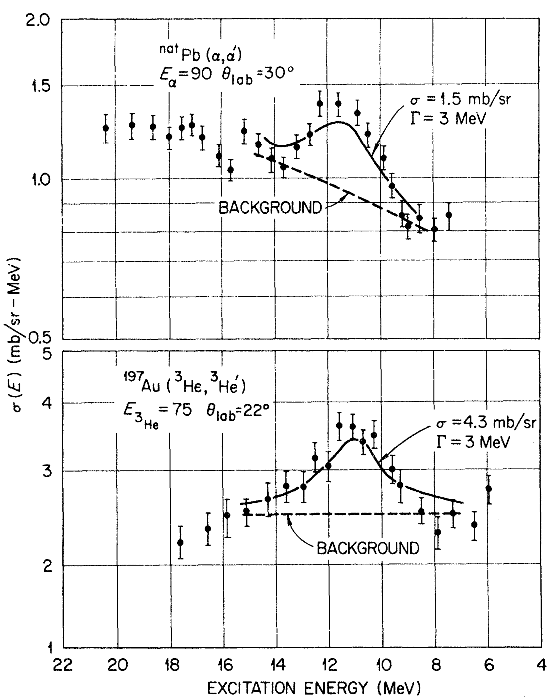

FIG. 1. Portions of the inelastic scattering spectra in the excitation energy $E^* = 6–20$ MeV. Data points with the uncertainties are from Ref. 8. The solid line is a fit to the data based on a linear background continuum and Lorentz resonance of width $\Gamma = 3$ MeV. The structure in the (α, α') spectra at $E^* \gtrsim 17$ MeV is believed to be the "mesa" resonance discussed in Ref. 8.

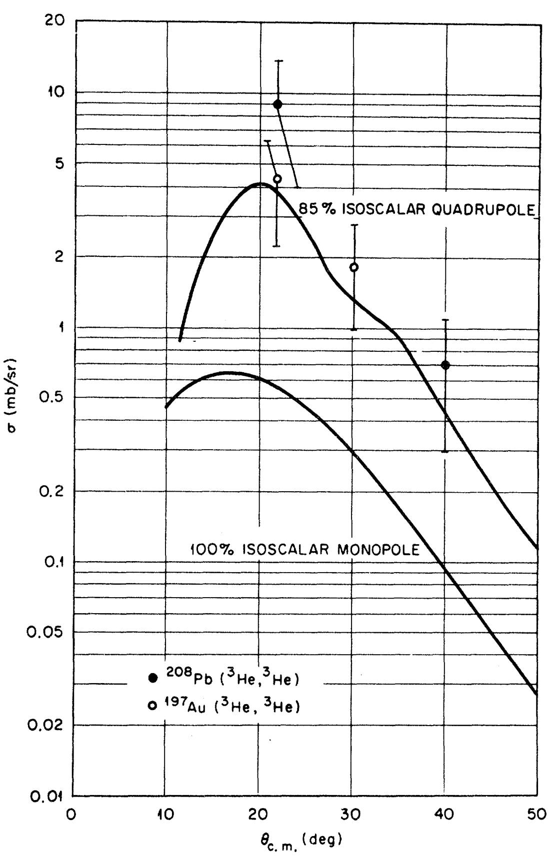

FIG. 2. A comparison of angular distribution predictions for monopole and quadrupole resonances. The multipole strengths are indicated by the percentages of the energy weighted isoscalar sum rule. Measured cross sections from Table I are seen to be inconsistent with a monopole interpretation. The data were found to be consistent with predictions for multipoles $L \geq 2$.

The second term in the form factor is used in the quadrupole case. While this kind of analysis gives comparable differential cross sections for monopole and quadrupole excitations in the case of ^{208}Pb(p, p') at $E_p = 60$ MeV, it predicts quite different angular distributions in the case of ^{3}He and α scattering. Such a difference might be expected from the relatively strong nuclear absorption and large momentum transfers characteristic of the scattering of complex projectiles.

The DWBA predictions for quadrupole and monopole excitations are given in Table I and Fig. 2. Optical model parameters are from Satchler, Parkinson, and Hendrie.[12] Corrections to the predicted cross sections for the finite solid angle of the particle detectors are included. It can be seen that while a quadrupole (85% of isoscalar sum-rule strength) interpretation of the resonance data can explain most of the observed cross section, a monopole (100% of isoscalar sum-rule strength) assignment would account for only about 10% of the resonance strength.

Furthermore, it was found that the relatively small cross sections predicted for the $L = 0$ angular distribution was a property of the ^{3}He scattering, not very sensitive to the magnitude of $XU(r)$, the monopole interfering term in the form factor (Eq. 1). Thus we feel that in spite of the uncertainties in both the measured cross sections and the DWBA analysis, it is unreasonable that a giant-monopole state could account for the existing data; multipoles $L \geq 2$ with their larger sum-rule strengths are required. More extensive helium scattering data would be very useful in further clarifying the nature of the giant resonance region in nuclei; higher-resolution experiments are needed to verify the fine structure reported in Ref. 5.

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