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Giant Resonances in the High-Energy Inelastic Scattering Continuum*

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The details of the structure previously observed in the high-energy proton-scattering continuum are inspected for collective multipole contributions. Evidence is shown that in the $E^* \approx 10$–25-MeV excitation region of the ^{40}Ca continuum, at least dipole, quadrupole, and octupole excitations contribute to the structure of the cross section $[\sigma(\theta, E^*)]$. While the dipole and quadrupole strengths exhaust most of their corresponding sum rules, the octupole component does not. The possible nature of the less structured component at this continuum region is discussed.

In a series of inelastic proton-scattering experiments performed several years ago by Tyren and Maris,[1] the excitation region encompassing the giant dipole state was studied for several light- and medium-weight nuclei. With a bombarding energy of $E_p = 185$ MeV, the authors observed structure in this continuum region which they interpreted as excitation of the giant dipole state. Recently, however, Lewis and Bertrand[2] have shown that structure in the giant resonance region can also be seen in the continuum of proton scattering at $E_p = 62$ and 66 MeV. But the excitation energy (in both the 185- and 60-MeV measurements) and strength (for $E_p = 62$ MeV) are incompatible with a dipole state and a quadrupole interpretation is suggested. Furthermore Satchler[3] has shown that the angular distribution for the whole enhanced region of the continuum is most compatible with an isovector dipole + isoscalar quadrupole interpretation, in which the sum rules for both are essentially exhausted.

It is the purpose of this communication to show that the detailed shape of the continuum structure or scattering cross section $[\sigma(\theta, E^*)]$ reveals the presence of at least three multipoles or resonance states which contribute to the collective strength in the continuum.

Data points from Ref. 1 were extracted[4] and reduced by subtraction of the underlying (slowly energy varying) background. Examples corresponding to the giant dipole region of ^{40}Ca and ^{51}V are shown in Fig. 1. Observation of a few angles shows that marked variations in the energy center occur as a function of angle. In particular the energy centroid of the composite resonance lies at a lower excitation energy for the larger scattering angles. It should be noted that this trend is opposite to that expected from the possible influence of quasifree scattering.

In order to unfold the composite resonance into specific resonance states, it was assumed that the giant dipole state is indeed excited and contributes to the spectral shape. The position of the dipole state is taken from the (γ, n) systematics[5] and the shape is a Lorentz curve with a total width $\Gamma = 4$ MeV. In all cases the dipole is seen to contribute to only the highest excitation region of the composite resonance as illustrated in Fig. 1. Assuming that the remaining strength could be composed of additional resonances with $\Gamma \leq 4$ MeV, at least two more resonances (if $\Gamma = 4$ MeV) were found to be necessary to explain the angle dependence of the spectral shapes. The strongest component resonance occurs about 2–3 MeV below the dipole resonance. This explains why the resonance energies reported by Tyren

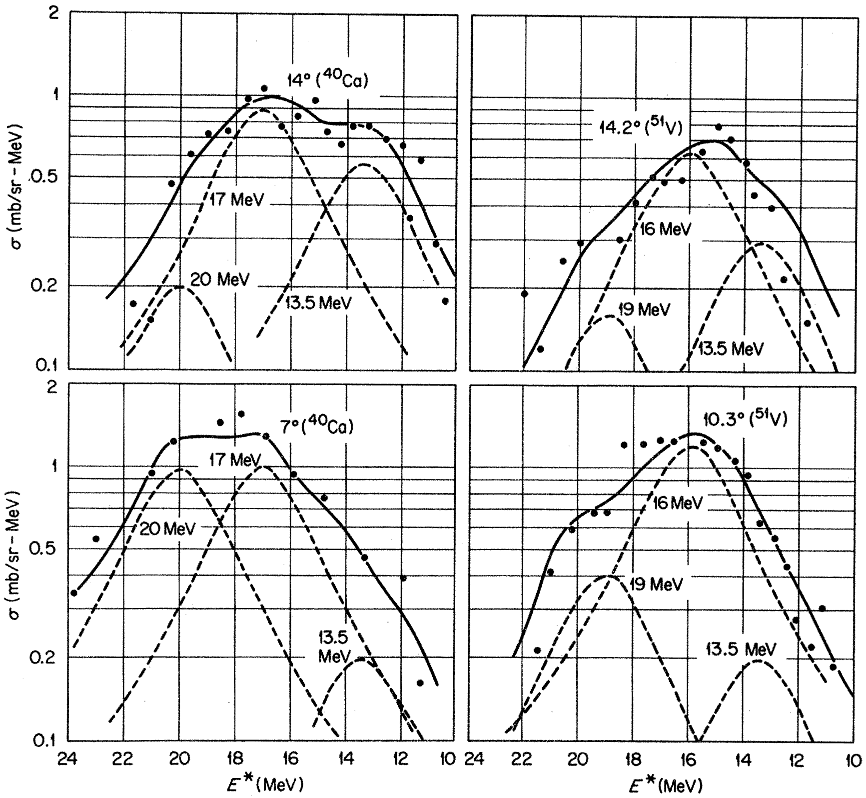

FIG. 1. Results from unfolding typical composite resonances measured in Ref. 1. The dashed curves correspond to constituent resonances assumed to have a Lorentz shape and spreading width Γ = 4 MeV. The solid line is a sum of the composite curves. See also discussion in text.

and Maris[1] were never in agreement with later photonuclear data.[5]

The three-component resonance strengths were adjusted by hand to fit approximately the overall shape of the composite resonance shown by the solid line in Fig. 1 for ^{40}Ca and ^{51}V. The resulting differential cross sections are given in Fig. 2 for ^{40}Ca, and in Table I for ^{51}V since only two small-angle spectra were measured for ^{51}V in Ref. 1. The solid curves in Fig. 2 and the values in parentheses in Table I are distorted-wave Born-approximation (DWBA) estimates based on a sum-rule formula for the deformation or coupling strength β_L discussed in Ref. 3 and previously applied in Refs. 2 and 3. A modification[3] of the usual surface-derivative form factor is required for the dipole case.

TABLE I. Cross sections for the ^{51}V(p,p') reaction at $E_p = 185$ MeV from Ref. 1 as extracted from the unfolding analysis in Fig. 1. The corresponding values in parentheses are DWBA estimates (as discussed in the text) for 100% of the sum rule strength for dipole (19 MeV) and quadrupole (16 MeV) excitation.

E^* \ θ	10.3°	14.2°
13.5	≈ 1	≈ 2
16	7.6 (12)	4.0 (11)
19	2.5 (1.0)	1.0 (0.4)

The data points must be given large uncertainties due to a lack of knowledge of the actual position (E^*) and width (Γ) of the quadrupole and octupole states, and the real shape of the underlying continuum (assumed to be a linear function of energy in this analysis). Nevertheless, each of the three components for ^{40}Ca displays a preference for a unique L transfer: $L = 1$ for the 20-MeV, $L = 2$ for the 17-MeV, and $L = 3$ for the 13.5-MeV resonance. From the magnitude of data points in Fig. 2 and Table I, we find the following:

(a) The isovector DWBA slightly underestimates the dipole data.

(b) The scalar quadrupole strength (when combined with the known 2^+ bound states) is sufficient to exhaust the quadrupole sum rule as discussed

TABLE II. A summary of the distribution of octupole strength in ^{40}Ca.

E_{calc}*	IS_{calc}[a] (%)	E_{expt}*	IS_{expt} (%)
3.84	18	3.73[b]	18[b]
7.15	2.1	6.29[b]	5.0[b]
8.34	1.2	6.58[b]	2.9[b]
10.7			
14.0	14	13.5[c]	24
14.3			
15.3			
17.0			
17.8	15		
20.3			

[a]Results of the random-phase-approximation calculations in Ref. 6. The IS (energy-weighted isoscalar transition strength) is normalized to the (18%) experimental value (see text).

[b]Experimental values taken from Ref. 7.

[c]Results from this analysis.

in Ref. 3.

(c) The octupole strength, though not exhausting the sum rule, is consistent with the $1\hbar\omega$ 3^- continuum states predicted by Gillet and Sanderson.[6] A summary of the measured 3^- states and a comparison with theory is shown in Table II. Since only relative and unweighted transition strengths were given in the random-phase-approximation calculations of Ref. 6, the strengths were weighted and normalized at the measured value[7] for the 3.73-MeV state.

The above analysis raises other questions about the nature of the inelastic-scattering continuum: (i) What contributions to the continuum are made by isovector states of higher multipoles? (ii) To what extent can one describe the full continuum by a collective multipole expansion? Following the DWBA prescription for the dipole,[3] the corresponding estimates for the higher isovector multipoles were made, and the results showed considerably smaller cross-section predictions than for corresponding isoscalar cases. This is illustrated for $L=2$ by the dashed curve in Fig. 2. Isovector states are not expected to make a major contribution to the inelastic proton continuum.

A collective multipole expansion of the high-energy inelastic proton-scattering continuum cannot be divorced from a quasifree reaction approach. In the latter description the target nucleon, when scattered by the incident nucleons, is ejected directly into the unbound continuum

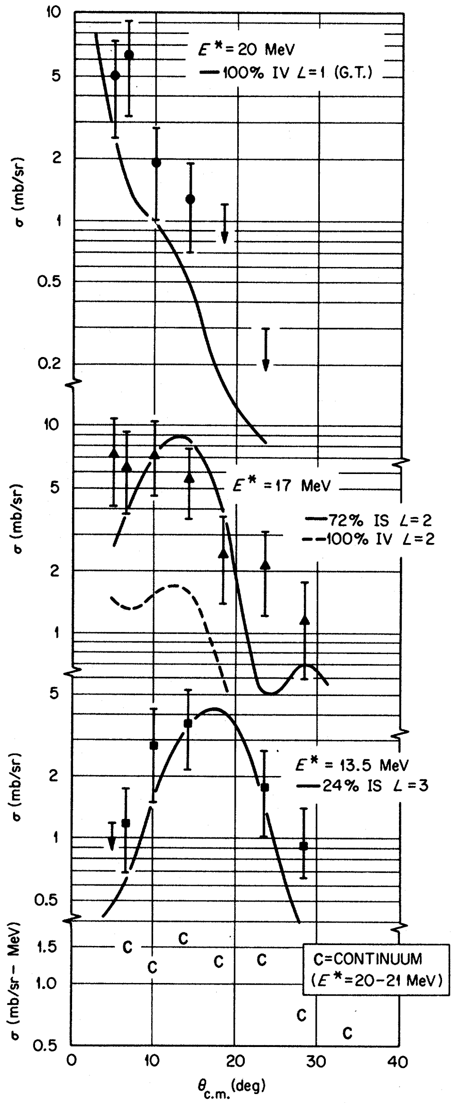

FIG. 2. Angular distributions from the data of Ref. 1 analyzed by the procedure shown in Fig. 1. The solid curves are DWBA estimates. IS and IV are notations for energy-weighted isoscalar and isovector sum-rule estimates for transition strength. G.T. is the Goldhaber-Teller model used for the $L=1$ curve. E* is the excitation energy from Fig. 1. The 18° data for the $L=3$ curve could not be used because the spectral shape near E* = 12 MeV was inconsistent with the remaining data.

without perturbation from outer nuclear shells. This picture could be the asymptotic limit ($L \gg 1$) in a collective multipole expansion.

The approximate angular dependence of the unstructured continuum corresponding to the E* = 20–21-MeV excitation region is shown at the bottom of Fig. 2. The small angles are particularly uncertain because such unstructured regions of the spectra cannot be easily corrected for the incident-beam-degradation component underlying it. The angular dependence does not characterize a unique L transfer in a direct reaction. While the shapes of continuum spectra in Ref. 1 do not clearly manifest the presence of quasifree scattering, neither does the energy nor angle dependence of these data exhibit isotropy. Furthermore, we wish to draw attention to a qualitative similarity between the expected enhancement in the $\sigma(E^*, \theta)$ from quasifree scattering and that from collective excitations ($L \approx 3-6$). The approximate position expected of a quasipeak is determined by $E_{p'} = E_p \cos^2\theta$, where E_p', E_p, and θ are the continuum proton energy, bombarding energy, and scattering angle, respectively. However, for the angular range $\theta \approx 20°-40°$, the position of the quasifree peak, $E^* \approx 20-40$ MeV, would nearly coincide with the maxima expected from DWBA predictions[3] for the collective excitation of the multipoles $L \approx 3-6$.

Finally, we wish to emphasize the need for more high-energy inelastic scattering data. The measurements in Ref. 1 include only one angular distribution for targets $A > 16$ and do not include most of the quasifree scattering region of the spectra. Unfortunately, other measurements[8,9] of quasifree scattering at $E \approx 160$ MeV do not include small-angle data and do not even agree on the existence of quasifree continuum structure at $E = 160$ MeV. The use of high-energy complex projectiles is also important. The inelastic-scattering spectra[10] from 90-MeV α particles and 75-MeV ^{3}He show continuum structure ($E^* \approx 11$ MeV) in heavy nuclei which appears to coincide with that observed in 60-MeV proton spectra.[2]

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