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Excitation of the giant isoscalar monopole resonance in ^{144}Sm and ^{154}Sm via inelastic proton scattering

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Giant resonance spectra for ^{144,154}Sm obtained by 67-MeV (p,p') measurements have been reanalyzed and compared with distorted-wave Born approximation calculations. The calculations use a more recent isovector interaction potential and a modified description of the giant dipole resonance as well as predictions for the splitting of giant resonances in deformed nuclei. The data are shown to be consistent with excitation of isoscalar 0^+ and 2^+ and isovector 1^- resonances which deplete nearly 100% of their respective energy-weighted sum rules.

[NUCLEAR REACTIONS ^{144}Sm, ^{154}Sm(p,p'); $E_p = 67$ MeV; measured $\sigma(E_x, \theta)$. Discuss giant monopole, dipole, quadrupole resonances; deduced L, β_L.]

In a study[1] of the inelastic scattering of 67-MeV protons by ^{144,154}Sm, it was found that the structure in the giant resonance region of both nuclei was remarkably similar at forward angles. For ^{144}Sm, two peaks were observed at energies expected for the excitation of the giant quadrupole (GQR) and dipole (GDR) resonances. It was pointed out[1] that a description of the ^{144}Sm resonance structure as arising from only excitation of the GDR and GQR would lead to difficulties in explaining the ^{154}Sm spectra because photonuclear results[2] show considerable splitting of the GDR peak. On the other hand, it was found that the differential cross section for the sum of the two peaks in ^{144}Sm could be reasonably well described by distorted-wave Born approximation (DWBA) calculations for GDR and GQR excitations using the collective model described[3] by Satchler. Recent direct observations of an *EO* resonance by the (α,α') reaction[4,5] and comparisons[6] between (α,α') and (p,p') excitation of giant resonances in *sd*-shell nuclei suggest that the early DWBA calculations[3] may significantly overestimate the GDR strength expected in the (p,p') reaction. For these reasons we have reevaluated the calculations for $T=1$, $L=1$ excitations.

We have reanalyzed the Sm spectra and shown by comparison with the new DWBA calculations that the results can be explained in terms of the excitation of isoscalar 0^+ and 2^+, giant resonances, consistent with recent ^{144}Sm(α,α') measurements,[5] and isovector 1^- giant resonances. This new analysis of the Sm(p,p') results resolves long-standing questions on the interpretation of these data.

The data have been described[1] previously, except for that[7] at 15°. Incident 66.8-MeV (60.8 MeV at 15°) protons from the Oak Ridge Isochronous Cyclotron, inelastically scattered by Sm targets, were detected on nuclear emulsion plates in the focal plane of a broad-range spectrograph. Spectra in the giant resonance region at 20° are shown in Fig. 1. Additional spectra are given in Ref. 1.

The ^{144}Sm resonance spectra were assumed to consist of two peaks rising above an underlying nuclear continuum as shown in Fig. 1. The peak located at ~12.8 MeV ($\sim 63 \times A^{-1/3}$ MeV) is the GQR[8] and was assumed to have a symmetric shape with full width at half maximum (FWHM) determined to be 2.8 ±0.3 MeV. The energy FWHM are to be compared with values reported by Youngblood *et al.*[5] 12.4 ±0.4 and 2.6 ±0.4 MeV, respectively. The shape and cross section of the second peak were obtained by subtraction of the 12.8-MeV peak from the resonance structure. The energy and FWHM for the second peak were determined from the 15° and 20° data as 15.5 ±0.5 MeV and 2.9 ±0.5 MeV, respectively, in agreement with values recently reported[5] for a GMR in ^{144}Sm observed in small angle (α,α') scattering. From photo-nuclear measurements,[2] the GDR is known to be located at 15.3 MeV with FWHM of 4.45 MeV. Cross sections for the two ^{144}Sm peaks are plotted in Figs. 2(a) and 2(b). The uncertainties arise mostly from a lack of detailed knowledge of the shape and magnitude of the underlying continuum.

The theoretical calculations used the collective model described in Ref. 3. However, for the GDR

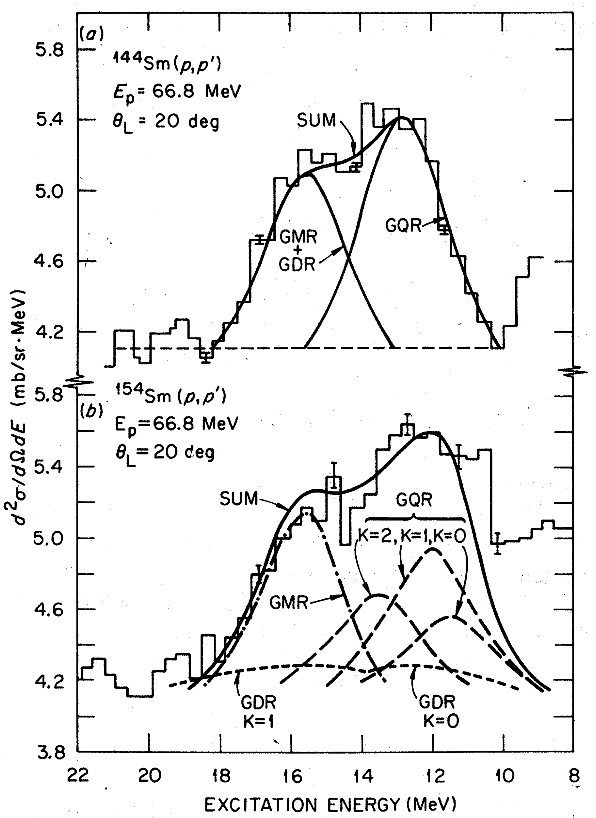

FIG. 1. Giant multipole resonance structure observed in the ^{144}Sm(p,p′) and ^{154}Sm(p,p′) reactions at 20°; E_p = 67 MeV. The data are shown as a histogram. Error bars on the data represent statistical uncertainty only. (a) The resonance structure is assumed to be composed of two separate peaks as shown by the solid curves. The assumed shape and magnitude of the nuclear continuum underlying the resonances are shown by the dashed line. (b) The solid curve is the sum of all the calculated components of the $L=0$, 1, and 2 giant resonances (shown dashed). For the $L=0$ and $L=2$ resonances, a spreading width was assumed to be the same as measured for ^{144}Sm, while the width of the $L=1$ components was taken from photonuclear measurements.

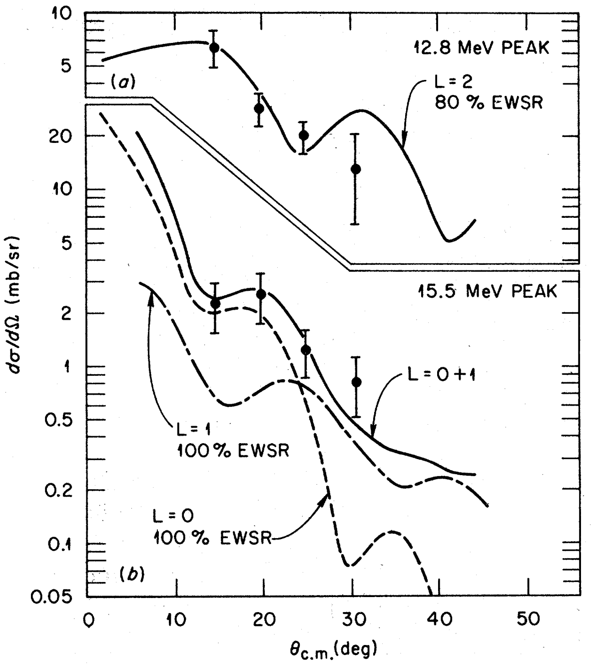

FIG. 2. Cross sections for the two resonance peaks in ^{144}Sm compared with DWBA calculations. (a) 12.8-MeV GQR peak compared with $L=2$ calculations. The best fit between data and calculations yields a $T=0$, $E2$ EWSR depletion of 80 ±15%. (b) 15.6-MeV peak compared with $L=0$ (dashed), $L=1$ (dash-dot), and $L=0+1$ (solid) calculations. The calculations are normalized to 100% EWSR depletion for both multipoles.

we used 40% Steinwedel-Jensen (SJ) and 60% Goldhaber-Teller (GT) as suggested by curve (c) in Fig. 3 of Myers *et al.*[9] The SJ transition potential was taken to be proportional to $j_1(2.08\ r/c)$ $U_1(r)$, where c is the radius of the ground-state density distribution, instead of $rU_1(r)$ as used previously.[3] The effect of this change is rather small, although it tends to make the SJ and GT predictions more nearly equal for small angle scattering.

The $T=1$ interaction $U_1(r)$ has been a major source of uncertainty in previous calculations. Here we used set B of the energy-dependent global optical potentials derived from a recent unified analysis[10] of (p,p) (n,n) and (p,n) data. For excitation of the GDR we chose $U_1(r)$, to correspond to the average of the entrance and exit channel energies. This $U_1(r)$, especially the imaginary part, is much weaker than that used in earlier calculations[3] of the GDR and provides considerably smaller GDR cross sections than the previous calculations. In the present case, the real and imaginary strengths[10] are $V_1=17.7$ MeV and $W_{D_1}=2.8$ MeV, respectively, compared to the $V_1=26$ MeV and $W_{D_1}=15.5$ MeV used in Ref. 3. These choices give a good description of the excitation by 61-MeV protons of low-lying isoscalar states in ^{208}Pb, as well as the elastic scattering. At present, we know of no way to check the validity of the isovector interaction for exciting the GDR, except insofar as it gives consistent results in the present analyses. The isoscalar sum-rule limits were evaluated as before[3] with $R=6.33$ fm (^{144}Sm) and 6.46 fm (^{154}Sm).

Figure 2(a) shows that the 12.8-MeV peak for ^{144}Sm is fit by an $L=2$ DWBA calculation normalized to 80% depletion of the $T=0$, $L=2$ energy-weighted sum rule (EWSR) in agreement with 85 ±15% given in Ref. 5. Our experimentally extracted GQR cross section probably contains a negligible contribution from the GDR. Figure 2(b) compares the 15.5-MeV peak with calculations for $L=0$, $L=1$, and $L=0+1$. GDR excitation alone with 100% depletion of the EWSR distributed in accordance with the photonuclear measurements[2] cannot account for the experimentally observed cross section at any angle. Although the calculation for $L=0$ with 100% EWSR can account for the cross sections at 15° and 20°, it falls far short at 25° and 30°. However, the sum of $L=0$ (100%) and $L=1$ (100%) agrees well with the measured cross sections at all angles. We conclude that the 15.5-MeV peak excited in 67-MeV proton scattering arises from excitation of both the GMR ($100\pm 20\%$, in agreement with Ref. 5) and the GDR (100%).

As pointed out in Ref. 1, the shape of the spectra at 20° (and 15°, see Ref. 8) above about 13 MeV of excitation is almost identical for the two Sm isotopes. This can now be explained since from Fig. 2(b) the GMR dominates at these angles and is not expected to split in a deformed nucleus. Recent calculations predict[11-13] the splitting of the GQR to be relatively small, and hence not to have much effect in the vicinity of the 15.5-MeV peak. However, at 25° the measured cross section for the 15.5-MeV peak in ^{154}Sm is only $\approx 60\%$ as large as that for ^{144}Sm. From Fig. 2(b), the GDR is predicted to dominate at 25°. From the photonuclear measurements[2] it is known that although the integrated GDR cross sections are the same for ^{144}Sm and ^{154}Sm, the resonance is split nearly equally into components centered at 12.4 and 16.1 MeV. Hence, the angular behavior of the ^{154}Sm spectra, relative to the ^{144}Sm, is consistent with our conclusion that scattering of 67-MeV protons by these nuclei excites the GMR, GDR, and GQR and that the magnitude of the GMR and GDR are correctly predicted by the DWBA calculations.

Comparison of the ^{154}Sm and ^{144}Sm spectra in Fig. 1 shows that the GQR peak for ^{154}Sm is shifted to lower excitation energy and appears somewhat broadened. We have incorporated into our DWBA calculations for ^{154}Sm deformation corrections as described[12] by Suzuki and Rowe, both for the transition density shapes and the distribution of the sum-rule strength among the various K components of the resonances. To provide a comparison with the ^{154}Sm data, we used the ansatz of Ref. 12 and scaled the radii of the transition potentials proportionally with the nuclear deformation δ. (We set $\delta=0.3$ for ^{154}Sm.) We find that the various K components have somewhat different angular distributions. For the GQR, the overall effect is to enhance the $K=0$ and $K=1$ components, relative to the $K=2$.

We distributed the DWBA calculated cross section for each component as follows: (a) The position and width for the GMR were as derived from the ^{144}Sm data. (b) The positions and widths of the GDR were taken from the photonuclear measurements.[2] (c) Each component of the GQR was assumed to have the same width as that found for ^{144}Sm. The sum of the component cross sections (100 % GDR and GMR and 80% GQR) provides excellent agreement with the data [see Fig. 1(b)], considering the uncertainty in both the experimental and theoretical analyses.

In conclusion, we find that the giant resonance structure observed in ^{144,154}Sm through the (p,p') reaction can be explained in a consistent manner in terms of excitations of a GMR, GDR, and GQR, each of which nearly depletes its EWSR. Such an interpretation explains several previously unresolved aspects of the Sm(p,p') measurements. In addition, our results offer more credence to the isovector potential used here than that employed earlier and show that the ^{154}Sm spectra can be well reproduced by calculations based on a recently published prescription for the splitting of giant resonances in deformed nuclei.

Note added in proof. A recent (e,e') measurement[14] on the deformed nucleus ^{181}Ta also shows splitting of the GQR which is reproduced by calculations based on the formalism of Ref. 12.

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