Comparison of the inelastic scattering of protons by ^{144,154}Sm in the region of giant resonances*

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(Received 5 November 1973)

Measurements of the inelastic proton spectrum in the giant-resonance region of the nuclear continuum for ^{144}Sm and ^{154}Sm have been made using 67-MeV protons. The spectra from the spherical and deformed targets are essentially identical in the resonance region above ≈12.8 MeV of excitation. Although the observed resonance peak locations and cross section are consistent with excitation of the giant dipole and giant quadrupole resonances, such an interpretation may lead to inconsistencies with the $E1$ splitting reported for ^{154}Sm in photonuclear reactions.

[NUCLEAR REACTION ^{144}Sm, ^{154}Sm(p,p'), E_p=66.8 MeV, E_x=9–26 MeV; measured $\sigma(E_x,\theta)$ for giant-resonance region; discuss giant quadrupole and giant dipole resonances.]

Recent studies of the inelastic continuum region of nuclear excitation ($E_x \gtrsim S_n$) have provided evidence for giant resonances other than the well-established $E1$ giant dipole resonance (GDR). Such studies have been carried out using a variety of techniques including inelastic electron,[1,2] proton,[3] ^{3}He,[4] and α-particle[4,5] scattering. In particular, broad structure has been observed both at the excitation energy expected for the GDR as established in photonuclear work, and at lower excitation energies. The lower excitation resonance has been recently interpreted[4,6,7] to be a giant quadrupole excitation (GQR) which exhausts most of the expected energy-weighted sum rule (EWSR) for isoscalar-quadrupole states.

Since it has been well established that the GDR is split in deformed nuclei, the present study was undertaken to investigate whether or not the structure in the region of the $E1$ and $E2$ giant resonances would appear different for deformed and spherical nuclei of the same element (i.e., ^{154}Sm and ^{144}Sm, respectively) in inelastic proton scattering.

Measurements were carried out using 66.8-MeV protons from the Oak Ridge isochronous cyclotron and a broad-range magnetic spectrograph with nuclear emulsion plates. Self-supporting targets of ^{144}Sm (20.3 mg/cm^2) and ^{154}Sm (18.2 mg/cm^2) provided by the Isotopes Division at Oak Ridge National Laboratory were used. Data were taken at 20, 25, 30, and 35° in the laboratory system.

For comparative purposes, the data were analyzed in energy bins ≈360 keV wide, and the calculated cross sections have a statistical uncertainty of about 3%. The measured spectra are shown in Fig. 1 where we have plotted the cross sections versus the observed proton energy (and excitation energy of the target nucleus) for both ^{144}Sm and ^{154}Sm at the four angles at which data were obtained. Although the spectra shown cover only the excitation range from ≈9 to ≈26 MeV, the low-lying levels observed in our spectra from both targets agree with the positions of the well-known 2$^+$ and 4$^+$ states in ^{144,154}Sm. Both sets of spectra shown in Fig. 1 exhibit broad structure in the excitation-energy region expected for the GDR and at a lower excitation energy which agrees with the empirical systematics[3] ($E_x \approx 63A^{-1/3}$) for GQR excitation. At excitation energies above ≈19 MeV a structureless continuum is observed for both targets, in accord with other (p,p') continuum measurements.[8] The continuum cross section for the Sm isotopes agrees well with continuum systematics obtained in other measurements.[8]

In Fig. 2 the 20° data from the two Sm isotopes are shown overlaid to exhibit the almost identical shape and magnitude of the spectra from these two nuclei above an excitation energy of about 12 MeV. In the region slightly below this energy, it is apparent that the ^{154}Sm data have a larger cross section than those for ^{144}Sm. The long dashed line shows the assumed shape and magnitude of the underlying continuum.

In Fig. 3 we compare the cross section for the ^{144}Sm resonance region between $E_x \approx$ 10.5–18 MeV with that calculated by distorted-wave Born approximation (DWBA). The integrated-energy region is broad enough to include the $E1$ and $E2$ resonances. The shape and magnitude of the underlying continuum at each angle were assumed to be similar to that shown in Fig. 2 for the 20° data. The uncertainty in the underlying continuum provides most of the total uncertainty in the cross section shown on Fig. 3. The dipole calculation

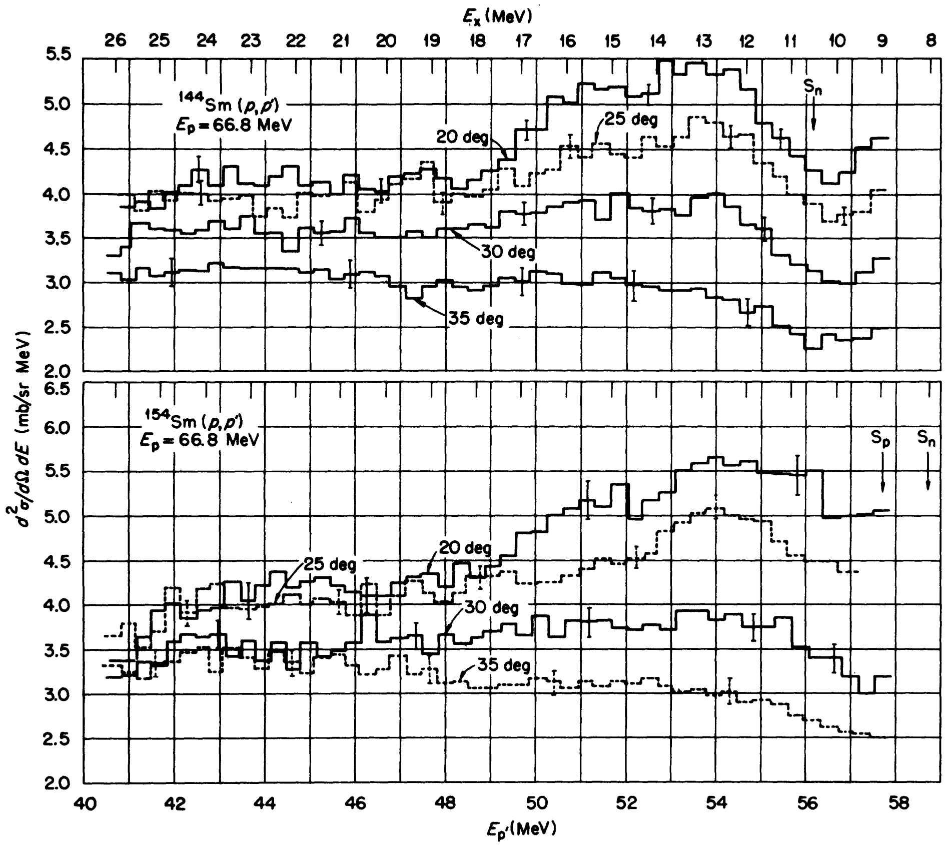

FIG. 1. Inelastic proton spectra from ^{144}Sm and ^{154}Sm at 20, 25, 30, and 35°. $E_{p'}$ is the outgoing proton energy; $E_x \approx$ excitation energy; S_n is the neutron separation energy. The data are plotted in ≈360-keV bins. Typical statistical error bars are shown.

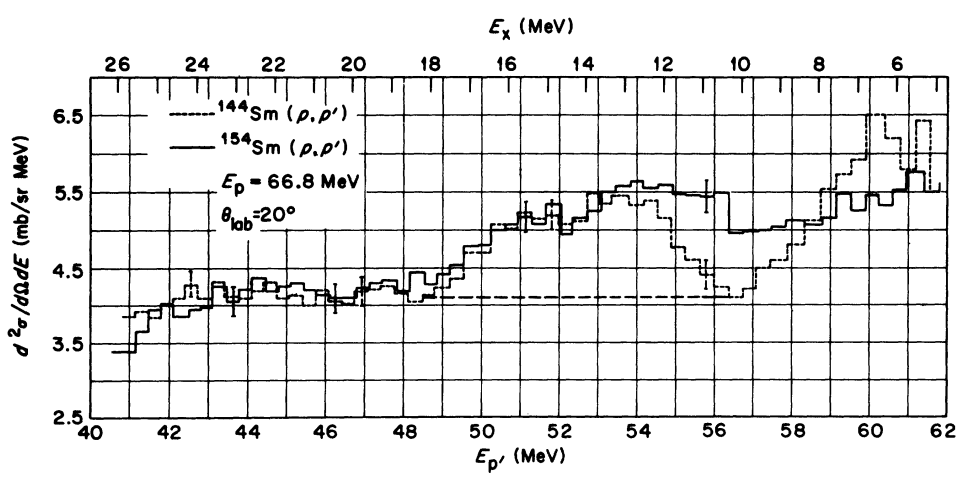

FIG. 2. Inelastic proton spectra from ^{144}Sm and ^{154}Sm compared for $\theta_L = 20°$. The long dashed line shows the assumed underlying continuum shape and magnitude used to extract the resonance cross section. $E_{p'}$ is the outgoing proton energy; $E_x \approx$ excitation energy. The data are plotted in ≈360-keV bins. Typical statistical error bars are shown.

was normalized to 100% depletion of the $T=1$ EWSR. An 80% depletion of the $L=2$, $T=0$ EWSR was then found to be consistent with the data. The parameters used in the DWBA calculations are listed in Table I. The disagreement at 30° could easily be due to a low resonance cross section produced by overestimation of the underlying continuum. While the closeness in excitation energy of the GDR and GQR would make extraction of separate cross sections highly suspect, it would appear that the integrated data are at least consistent with an $E1+E2$ interpretation. As can be seen from Figs. 1 and 2, the $E1+E2$ cross sections for ^{154}Sm would agree very closely with those for ^{144}Sm and thus with the predicted $E1+E2$ strength.

While the GDR itself seems clearly identified in high-energy electron scattering,[2] it has not been conclusively demonstrated that the GDR is, in fact, excited in inelastic proton scattering. However, the peak shape and energy of part of the resonance structure observed in proton scattering[3,6] consistently agree with GDR systematics established in photonuclear reactions. In addition, it has been suggested in an analysis of the 185-MeV proton scattering that the GDR can be identified in spectra taken at angles $\lesssim 10°$.[9] Relatively small nuclear-scattering cross sections for the GDR are expected[10] from the isospin dependence of the nuclear potential.

After considerable examination of the spectral shapes for ^{144,154}Sm in order to detect differences, we unfortunately find that a unique interpretation of the spectra is not possible. However, enumeration of some possible modes of analysis and interpretation seems pertinent. In attempting to analyze this type of data, one is confronted with three major problems. The first is defining the background of the continuum underlying the "resonances." Second, at the peak positions the resonances rise only about 20% above the cross section of the underlying continuum. Third, the full widths at half maximum for the resonances are comparable to or greater than the energy separating them. This means that the tail of one resonance cannot be ignored when trying to fit the other with an assumed shape.

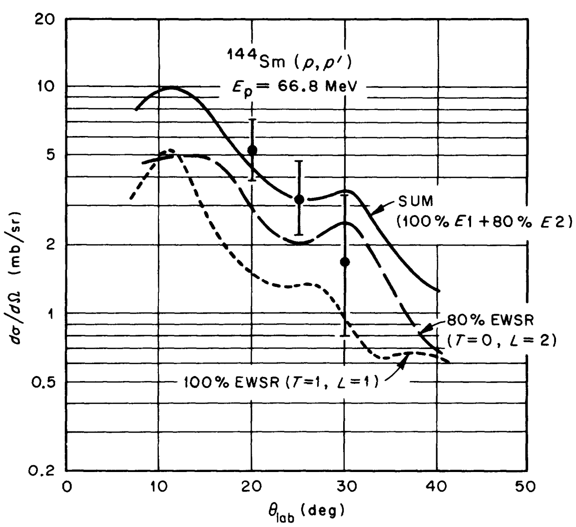

FIG. 3. Cross sections in the giant-resonance region ($E_x \approx 10.5$–18 MeV) for ^{144}Sm compared to DWBA predictions. The error bars shown represent uncertainties from all sources, but are dominated by the uncertainty in the magnitude and shape of the underlying continuum.

The position of the smaller "peak" in the resonance structure from the (p,p') results (see Fig. 2) corresponds to a nuclear excitation energy of ≈ 15.4 MeV for both nuclei. In a study of the photonuclear reaction on ^{144}Sm, Bergere *et al.*[11] observed an $E1$ resonance which could be fitted by a single Lorentzian with a peak energy of 15.3 ± 0.1 MeV. For ^{154}Sm they found that the resonance is split and exhibits peaks at 12.4 ± 0.1 and 16.1 ± 0.1 MeV. The integral cross section in ^{154}Sm was found to be about equal to that for ^{144}Sm and distributed about equally between the two segments.

Considering first the ^{144}Sm proton data, we observe two peaks in the resonance region. As mentioned above, the peak located at ≈ 15.4 MeV occurs at an energy corresponding to the location of the GDR, while we interpret the 12.9-MeV peak as the GQR. If these resonances are, in fact, correctly interpreted as the GDR and GQR, we are led to the interpretations discussed below.

We first *assume* that the shapes and energies of $E1$ excitations in proton scattering are the same as reported in the photonuclear measurements.[11] In addition, we utilize the theoretical DWBA calculations of Satchler[10] for predicting the $E1$ strength that should be observed in inelastic proton scattering. We are then confronted with two possible situations:

(1) If the DWBA calculation correctly predicts the $E1$ strength, then we find considerable additional cross-section strength superimposed upon the GDR (15.4-MeV) peak in ^{144}Sm.

(2) If the DWBA calculation underestimates the $E1$ strength that should be observable in ^{144}Sm so that most of the peak located at ≈ 15.4 MeV is in fact

TABLE I. Table of DWBA parameters (notation of Ref. 1). $V_1 = 10$ MeV; $4W_{D1} = 62$ MeV.

V (MeV)	W (MeV)	$4W_D$ (MeV)	r (fm)	r_w (fm)	a (fm)	a_w (fm)
47.6	6.7	17.7	1.16	1.37	0.750	0.464

$E1$, then it is difficult to reconcile the identical spectral shape of ^{144}Sm and ^{154}Sm found in the proton scattering with photonuclear results. To do so would seem to imply that the $E2$ resonance in ^{154}Sm is split to compensate the expected $E1$ splitting in just such a way as to make the two spectra essentially identical above ≈ 12 MeV (see Fig. 2).

Torizuka *et al.*[12] have proposed that qualitative differences between an $E2$ isoscalar giant resonance, as observed in spherical and deformed nuclei in similar mass regions, are expected. They argue: (a) that since the low-lying (or rotational) 2^+ state in deformed nuclei has a large $B(E2)$ value, such a state might deplete the $E2$ sum rule leaving any GQR weakly excited, and (b) that differences might occur since, in a deformed nucleus the vibrational mode can be split into two types, so-called β and γ vibrations. However, since the $B(E2)$ is energy weighted in the sum rule, we find that the fraction of the EWSR absorbed by the low-excitation highly collective 2^+ state is small ($\approx 3\%$ in ^{154}Sm). In addition, it has been found[13] that the low-lying 2^+ state in ^{154}Sm is split by only ≈ 200 keV and strongly weighted toward the γ vibration. Thus, we feel there is no *a priori* reason to expect large splitting of an isoscalar GQR in a deformed nucleus.

Before concluding, we should make a few comments pertaining to the excess of cross section below the 12.8-MeV peak in ^{154}Sm relative to ^{144}Sm. At first glance, one would be tempted to consider this region as either part of the GQR or some other type resonance. However, when one compares the ^{154}Sm and ^{144}Sm data further, it is noted that just below ≈ 9 MeV of excitation the ^{144}Sm has an excess of cross section. One possible explanation for these differences may be that because of rotational bands the density of states in this region of ^{154}Sm is greater than in ^{144}Sm, and tails resulting from the spread due to damping extend toward the giant-resonance region and create an appreciably higher "background" in the ^{154}Sm in the region below 12.8 MeV. In any event, the $\approx 20\%$ cross-section enhancement below the $E2$ region of the ^{154}Sm spectra is not completely understood.

In summary, we have found that in the scattering of 67-MeV protons on ^{144,154}Sm the structure above about 12.8 MeV is essentially identical in both shape and magnitude for the spherical and deformed nuclei studied here. Unfortunately, the present data are not sufficient to uniquely characterize the observed resonances. However, assignment as $E1$ of a major portion of the cross section observed in ^{144}Sm at the location of the known GDR would make difficult a consistent interpretation of the ^{154}Sm data unless the GQR is assumed to split. Further experiments which might uniquely identify the character of the resonances observed in this work are in order.

The authors would like to acknowledge the efficient plate scanning of M. P. Haydon and the help rendered by the cyclotron operations staff.

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*Research sponsored by the U. S. Atomic Energy Commission under contract with the Union Carbide Corporation.

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