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Isospin character of the giant quadrupole transition in ^{124}Sn

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Use has been made of the interference between the nuclear and Coulomb amplitudes in the scattering of 84 MeV/nucleon ^{17}O ions by ^{124}Sn to study the isospin character of the giant quadrupole transition. The data are well described by assuming the transition is "isoscalar," i.e., $M_n/M_p=N/Z$. This is in disagreement with the results of π^+/π^- scattering on ^{118}Sn and recent $(e,e'n)$ measurements on ^{116}Sn. Cross sections for excitation of the 2^+ state at 1.132 MeV, 3^- state at 2.614 MeV, and giant monopole resonance are included with corresponding coupled-channels calculations.

I. INTRODUCTION

Discrepancies relating to the isospin properties of the giant quadrupole resonance (GQR) persist. Recently, we have reported on the excitation of the GQR in ^{118}Sn by inelastic scattering of ^{17}O ions, and found that this transition is well described by assuming an isoscalar character, i.e., $M_n/M_p=N/Z$ [where $M^L_{n,p}=\int \rho_{\mathrm{tr}}(r)r^{L+2}dr$] [1]. The differential cross sections do not show a minimum predicted at $\theta_{\mathrm{c.m.}}\approx 1.9°$ resulting from a coupled-channels calculation which uses the GQR parameters reported [2] from inelastic π^+/π^- scattering on ^{118}Sn. Although analyses of both the pion and heavy-ion data yielded about the same strength for excitation of the mass GQR [i.e., 56% EWSR (energy-weighted sum rule) and 60% EWSR, respectively], the deduced $B(E2)\uparrow$'s differed by more than a factor of 2. For the pion scattering, $B(E2)\uparrow=0.0676$ $e^2\mathrm{b}^2$ which corresponds to $M_n/M_p=2.38$, whereas the heavy-ion (i.e., isoscalar) value is $B(E2)\uparrow\approx 0.181$ $e^2\mathrm{b}^2$. A recent study [3] of the ^{116}Sn$(e,e'n)$ reaction reports a $B(E2)\uparrow$ which is comparable to that deduced from pion scattering on ^{118}Sn [i.e., corresponds to about 34% of the energy weighted $B(E2)\uparrow$ sum rule]. Both of these results disagree with small-angle (i.e., $\theta\approx 0°$) measurements [4,5] of the ^{116}Sn(α,α') reaction at $E_\alpha\sim 125$ MeV where the GQR is observed to exhaust ~100% EWSR, although they are in better accord with the ~48% EWSR reported [6] from a measurement at $E_\alpha\sim 400$ MeV. The centroid of the giant monopole resonance (GMR) is located at 17.9±0.9 MeV in the $(e,e'n)$ measurement [3], while the three alpha scattering works place it at ~15.7 MeV.

A continuum random-phase-approximation (RPA) calculation for the GQR and GMR in ^{132}Sn was found to reproduce the ^{116}Sn$(e,e'n)$ results for the GMR but to overestimate the GQR by about a factor of 2 [7]. Likewise, an open-shell RPA calculation for ^{118}Sn also overpredicts the GQR strength by about a factor of 2 [8]. Since the agreement [9] between the $(e,e'n)$ data and RPA calculations for ^{208}Pb is quite good, Miskimen *et al* [3]. suggest the need for more theoretical work for the tin nuclei. However, since the open [8] and closed [7] shell RPA calculations for the GQR in the tin isotopes are in excellent agreement, we decided to repeat our heavy-ion scattering measurements on another tin isotope, and chose ^{124}Sn. We present the results of these measurements in this article.

II. EXPERIMENTAL

The measurements were made using a beam of 84 MeV/nucleon ^{17}O ions provided by the Grand Accélérateur National d'Ions Lourds (GANIL) in Caen, France. The scattered ions were detected and analyzed with the energy-loss spectrometer SPEG [10]. The detector system consisted of two multiwire chambers located behind the focal plane, each capable of determining x,y position, an ionization chamber for providing a ΔE signal, and a plastic scintillator for both E and time-of-flight information. For recording inelastic data, the elastic peak was stopped by a beam block which could be moved along the focal plane. The target was a 1.0-gm/cm^2 self-supporting foil of ^{124}Sn enriched to 96.0%. The overall experimental energy resolution was ~700 keV.

Data were taken with SPEG set to an angle of 2.47° with respect to the incident beam. The left horizontal entrance slit of SPEG was used to stop the incident beam. This slit is not a Faraday cup, and a correction factor was determined by comparing elastic-scattering data for several targets with DW optical model calculations. In order to fit the calculated curves, the elastic cross sections based upon the entrance slit beam current determination had to be renormalized by a factor of 1.5. Calibrations of both in-plane (θ) and out-of-plane (ϕ) angles were accomplished by means of a slotted plate. Absolute calibration of the θ angle was done by moving the left-hand slit out until the current reading was reduced by a factor of 2 which established the incident beam direction. The presence of a peak in the elastic spectra which was due to scattering from a small hydrogen impurity in the target served as a check of the θ calibration.

The elastic data were measured over an angular range $\theta_L = 0.55-4.66°$ and for the inelastic $\theta_L = 1.14-3.64°$. Angle bins of $\Delta\theta = 0.1°$ were used to determine differential cross sections.

III. DATA ANALYSIS AND DISCUSSION

A. Elastic scattering

The elastic data were fitted using the computer program PTOLEMY [11] and an optical model potential with Wood-Saxon form factors, i.e.,

$$V(r) = -Vf(x_v) - iWf(x_w) ,$$

with

$$f(x_i) = (1+e^{x_i})^{-1}, \quad x_i = (r-R_i)/a_i ,$$

$$R_i = r_i(A_p^{1/3} + A_t^{1/3}) ,$$

and $i = V, W$. The Coulomb potential was taken as that between a point charge and a uniform charge distribution with radius $R_c = 1.20(A_p^{1/3} + A_t^{1/3})$ fm. The real and imaginary geometrical parameters were set equal.

The fit to the elastic data as shown in Fig. 1 was attained with $V = 50.0$ MeV, $W = 49.465$ MeV, $r = 1.0641$ fm, and $a = 0.7429$ fm. These parameters are similar to those obtained by fitting the ^{118}Sn data [1].

B. Inelastic scattering

The inelastic data were analyzed in a similar manner as is described in our ^{118}Sn paper [1]. At each angle, the nuclear continuum was parametrized as a third-order polynomial above an excitation energy of 16 MeV which was matched to a Guassian peak centered at 16 MeV. The low-energy side of the Gaussian has an energy-dependent amplitude which tends toward zero at the neutron separation energy. The parameters that describe the polynomial were determined by fitting the data above $E_x = 45$ MeV. The results are shown for an inelastic spectrum for $\theta_{\text{c.m.}} = 2.26°$ in Fig. 2(a). The spectrum that results after subtracting the continuum is shown in Fig. 2(b).

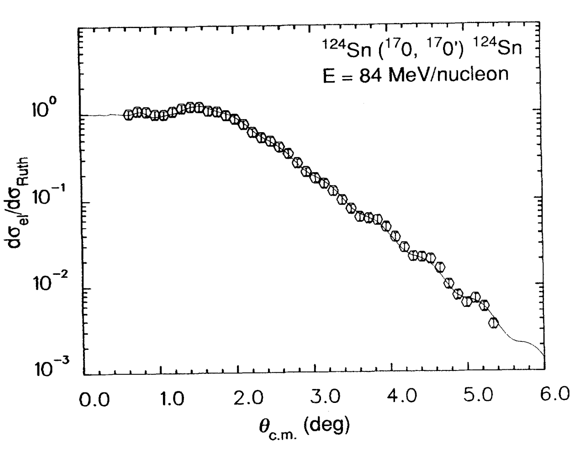

FIG. 1. Optical model fit to the ratio of the differential elastic cross section to Rutherford cross section vs $\theta_{\text{c.m.}}$ for the ^{124}Sn(^{17}O,^{17}O$'$)^{124}Sn reaction at 84 MeV/nucleon. The optical model parameters are given in the text.

The photonuclear data of Fultz *et al.* [12] were used to generate the shape distribution for the giant dipole resonance (GDR). Because of the strong Q dependence of the Coulomb excitation, the shape distribution of the GDR varies markedly with angle. The photonuclear cross section [12], $\sigma_\gamma(E_x)$, was converted to an effective $B(E1)\uparrow$ per unit energy by the relation

$$b_{E1}(E_x) = \frac{0.09\hbar c}{16\pi^3}\sigma_\gamma(E_x)/E_x \ e^2\text{b/MeV} .$$

This expression was used to calculate double-differential cross section $d^2\sigma/d\Omega\,dE$ for the GDR at several excitation energies assuming only a Coulomb interaction and using the optical model parameters given above which were obtained from fitting the elastic data. This calculational procedure has been shown to reproduce measured ^{208}Pb(^{17}O,^{17}O$'\gamma$) cross sections for the GDR [13]. The GDR shape distribution at each angle was then determined by averaging the double-differential cross section over the corresponding center-of-mass solid angle defined by the software cuts. The GDR shape distribution and the experimental spectrum resulting after subtraction of the continuum for $\theta_{\text{c.m.}} = 2.26°$ are shown in Fig. 2(b). Note that the effect of the Q dependence is to shift the GDR shape distribution toward lower energy.

The spectrum resulting from subtraction of the continuum and the GDR is shown in Fig. 2(c). This spectrum (as well as those at other scattering angles) was decomposed using Gaussian peaks with energies and widths given in Table I. The peaks at 1.132 and 2.614 MeV correspond to excitation of the well-known first 2^+ and 3^- states, respectively, in ^{124}Sn. The peaks at 4.20, 4.90, 6.20, and 7.85 MeV are located in the region dominated by the low-energy octupole resonance (LEOR) reported by Moss *et al* [14]. In this excitation energy region, an underlying broad structure was observed upon which were superimposed some narrow peaks which had other than an $L = 3$ angular distribution [14]. This is similar to what we observed for ^{118}Sn [1]. The peak at 12.50 MeV corresponds to the GQR, and that at 15.25 MeV to the GMR. In the following we will be concerned with only the 1.132-, 2.614-, 12.50-, and 15.25-MeV peaks whose differential cross sections are shown in Fig. 3, plotted with our total experimental uncertainties.

Inelastic differential cross sections were calculated using the deformed potential model [15,16] and the program PTOLEMY [11] to solve the coupled channels (ground state to one excited state) equations exactly. Details of the interaction potential and form factors can be found in Refs. [1], [15], and [16].

In the calculations for the 1.132-MeV, 2^+ state cross sections, we used the adopted [17] $B(E2)\uparrow = 0.166\ e^2\text{b}^2$

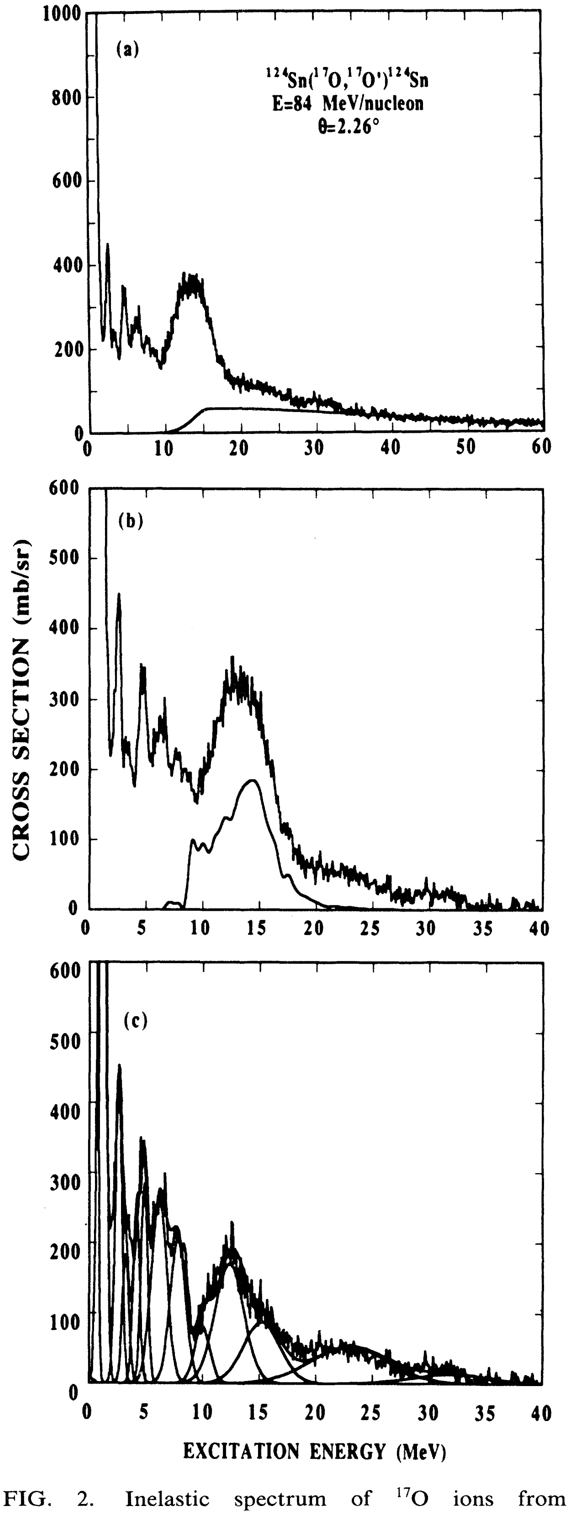

FIG. 2. Inelastic spectrum of ^{17}O ions from the ^{124}Sn(^{17}O,^{17}O$'$)^{124}Sn reaction at $\theta_{\mathrm{c.m.}}=2.26°$ plotted as a function of excitation energy of the target. (a) The thin solid curve represents the assumed underlying continuum to be subtracted from the data. (b) The continuum subtracted spectrum and the calculated GDR response function. (c) The spectrum resulting from subtraction of the continuum and GDR and the fitted Gaussian distributions. The fixed energies and widths of the Gaussians used in the fit are given in Table I.

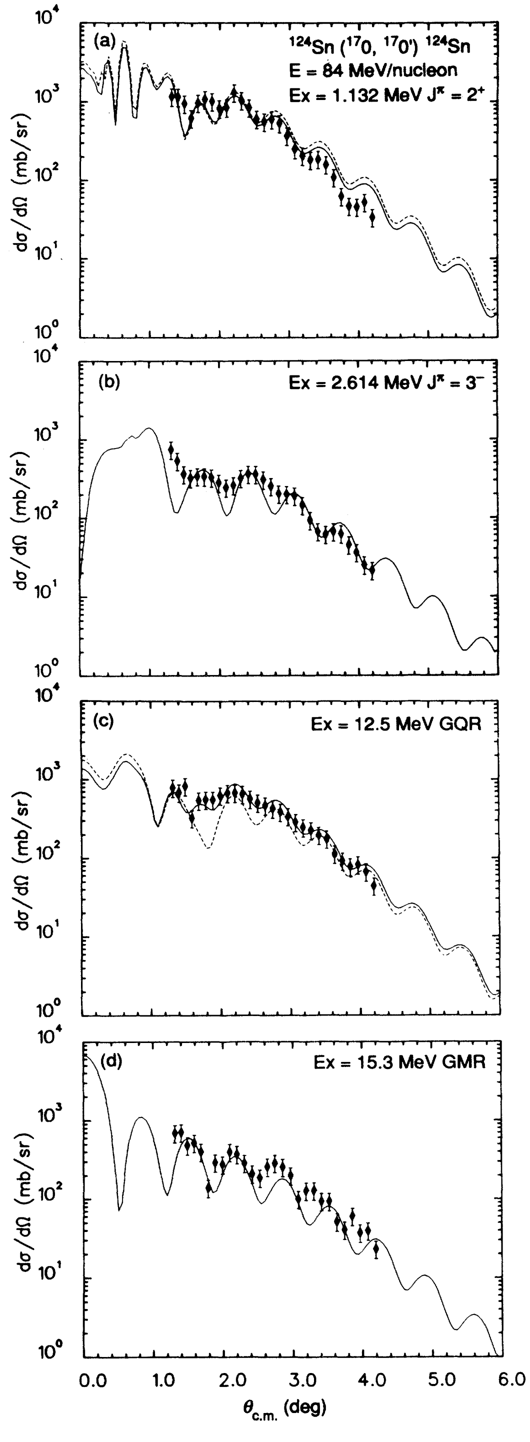

FIG. 3. Comparison of differential inelastic cross sections with coupled-channels calculations for excitation of states in ^{124}Sn by ^{17}O ions at $E=84$ MeV/nucleon. (a) The first 2^+ state at 1.132 MeV. The solid curve assumes an isoscalar excitation ($M_n/M_p=1.48$) and the dashed curve $M_n/M_p=1.78$. (b) The first 3^- state at 2.614 MeV. The calculated curve is for an isoscalar transition, (c) the GQR. The solid curve is for an isoscalar transition, whereas the dashed curve used the parameters from π^+/π^- scattering. (d) The GMR. The calculated curve represents exhaustion of 125% EWSR.

TABLE I. Energies and widths (FWHM) of Gaussian distributions which were held fixed in the analysis of ^{124}Sn(^{17}O,^{17}O$'$)^{124}Sn spectra.

E (MeV)	Γ (MeV)	Comment
1.132	0.700	2^+
2.614	0.700	3^-
3.250	0.700	
4.200	0.700	
4.900	0.700	
6.200	1.60	
7.850	1.60	
10.00	1.60	
12.50	3.80	GQR
15.25	3.80	GMR
23.00	8.00	
32.00	8.00	

or $\delta_p = 0.5703$ fm for a uniform charge of radius $1.20A^{1/3}$ fm. The curves shown in Fig. 3(a) correspond to $M_n/M_p = N/Z = 1.48$ (solid) and $M_n/M_p = 1.78$ (dashed), i.e., $\delta_H = \delta_p$ and $\delta_H = 1.12\delta_p$, respectively. The latter value was predicted from a no-free parameter schematic model [18,19], and is close to a value of 1.71 predicted [8] by a nondegenerate RPA calculation for the 1.23-MeV, 2^+ state in ^{118}Sn. As can be seen in Fig. 3(a), the calculated differential cross section for the first 2^+ state in ^{124}Sn is not very sensitive to the ratio of M_n/M_p for the ^{124}Sn(^{17}O,^{17}O$'$)^{124}Sn reaction at 84 MeV/nucleon.

Comparison of the coupled-channels calculation with the cross section for the 2.614-MeV, 3^- state of ^{124}Sn is shown in Fig. 3(b). The transition was assumed to be pure isoscalar, and from normalization of the calculation to the data we deduce $B(E3)\uparrow = 0.051 \pm 0.013\ e^2\mathrm{b}^2$. This value is about 30% smaller than that reported by Jonsson *et al.* [20] from a Coulomb excitation experiment. For ^{118}Sn our[1] deduced $B(E3)\uparrow$ for the 2.327-MeV, 3^- level was about 15% smaller than the Coulomb excitation value [20].

The data for the GQR are compared with coupled-channels calculations which assume $M_n/M_p = N/Z$ (solid curve) and the parameters deduced from pion scattering [2] on ^{118}Sn (dashed curve) in Fig. 3(c). From normalization of the isoscalar calculation to the data, we find that the GQR exhausts 60±15% of the EWSR. The pion parameters give 56% of the EWSR with $B(E2)\uparrow = 0.0676\ e^2\mathrm{b}^2$. As can be seen in the figure, the data do not indicate a minimum near $\theta_{\mathrm{c.m.}} \approx 1.9°$ as predicted by calculations using the parameters deduced from pion scattering. This is similar to what we have found in the case of ^{118}Sn [1].

Our results for the GMR are also similar to those observed [1] for ^{118}Sn, i.e., normalization of the coupled channels calculation to the data gives 125% of the EWSR. This comparison is shown in Fig. 3(d).

The similar characteristics of the GQR and GMR in ^{118,124}Sn are consistent with expectations from the nuclear structure calculations [7,8]. Reasons for the small $B(E2)\uparrow$ values reported for the GQR in the pion [2] and $(e,e'n)$ [3] reactions are not clear. Recently, the validity of using Coulomb-nuclear interference and the deformed potential model for bound states in ^{204,206,208}Pb has been examined [21]. It was found that the model deduced M_n/M_p values in good accord with theory, even for the first 2^+ states of ^{204,206}Pb which have considerable isospin mixing [21].

Our parametrizations for the GQR in ^{124}Sn differ somewhat from those reported in the most recent small angle (α,α') study [5]. Sharma *et al.* [5] give $E_x = 13.02 \pm 0.13$ MeV, $\Gamma = 2.80 \pm 0.30$ MeV, and 127±31% EWSR. For the GMR, these authors give $E_x = 15.35 \pm 0.16$ MeV, $\Gamma = 3.40 \pm 0.35$ MeV, and 108±22 % EWSR which are in better agreement with our values.

IV. CONCLUSIONS

We have studied the ^{124}Sn(^{17}O,^{17}O$'$)^{124}Sn reaction at 84 MeV/nucleon and find that the GR region is excited in a manner similar to what we observed for ^{118}Sn. In particular, we find that the cross sections for exciting the GQR and GMR can be well reproduced by assuming the transitions are isoscalar and exhaust 60% and 125% EWSR, respectively. The differential cross section for the GQR does not exhibit a minimum at $\theta_{\mathrm{c.m.}} \sim 1.9°$ as is predicted by coupled-channels calculations employing the parameters reported for ^{118}Sn from a study [2] of π^+/π^- scattering. The qualitative agreement between the $(e,e'n)$ data [3] for ^{116}Sn and the pion results [2] for ^{118}Sn are somewhat disconcerting in light of our ^{118,124}Sn studies. Based upon our previous results [13,22] for the GQR in ^{208}Pb and the bound states [21] in ^{204,206,208}Pb, we believe that the determination of M_n/M_p with heavy ions is a valid technique.

Although the GQR has been a subject of investigation for almost twenty years there remains considerable disagreement pertaining to its salient characteristics as deduced from studies using different probes.

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