Brief Reports

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Excitation of giant resonances in ^{92}Zr by inelastic scattering of 115 MeV protons

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The differential cross sections for the excitation of giant resonances in ^{92}Zr have been measured in the angular range 14 to 30° by inelastic scattering of 115 MeV protons. The low energy octupole region $E_x = 5-10.5$ MeV can be explained as due to excitation of $L = 3$ and $L = 4$ multipoles. The composition of the differential cross section for the giant resonance region ($E_x \simeq 10.5-20$ MeV) can be described in terms of the percentage energy-weighted sum-rule strength as $\simeq$63% giant monopole resonance, $\simeq$65% giant dipole resonance, $\simeq$48% giant quadrupole resonance, and $\simeq$20% $L = 4$ resonance.

[NUCLEAR REACTIONS ^{92}Zr(p,p'), $E_p = 115$ MeV; measured $\sigma(\theta)$ for giant resonance excitation; calculated the percentage energy-weighted sum-rule strengths for $L = 0$ to 4 multipoles.]

Inelastic scattering of charged particles from nuclei has been used widely and productively to excite the giant resonances (GR's) and understand their excitation mechanism. Through such experiments, the existence of the giant quadrupole resonance (GQR) (Refs. 1 and 2) and the giant monopole resonance (GMR) (Ref. 3) has been well established. Use of various projectiles at different bombarding energies and intercomparisons of their inelastic spectra will be helpful in establishing the existence of various multipoles in the GR region and in determining reliably their respective strengths. While the presence of GMR, besides GQR and giant dipole resonance (GDR) components in the GR region of the excitation spectrum has been well established at least for medium and heavy nuclei, very little has been done (and less definitive results were obtained) as regards the existence of higher multipole components. In the ongoing program[4] at the Indiana University Cyclotron Facility (IUCF) to study the GR's utilizing inelastic scattering of medium energy protons, we have measured differential cross section angular distributions for the giant resonances excited in ^{92}Zr(p,p') reaction at $E_p = 115$ MeV. While the GR in ^{92}Zr specifically has not been reported so far, considerable work, both experimental[5–11] and theoretical,[12] have been done for the nearby isotope ^{90}Zr. The GR's in ^{90}Zr have been measured utilizing (e,e') (Ref. 5), (p,p') [Refs. 6(a) and 6(b)], $(\vec{p},p')$ (Ref. 7), (d,d') (Ref. 8), (α,α') [Refs. 9(a), 9(b), and 9(c)], (^{3}He, ^{3}He$'$) (Ref. 10), and (^{6}Li, ^{6}Li$'$) (Ref. 11) reactions. We expected the use of ^{92}Zr instead of ^{90}Zr to make some small difference due to isotopic dependence of GR's,[13] but not enough to affect general conclusions concerning GR composition in the $A \sim 90$ region.

The GR region excited in ^{92}Zr has been studied in the present work using the 115-MeV proton beam from the IUCF. Two high-purity intrinsic Ge detectors of thickness 1.5-cm each in a $\Delta E - E$ telescope configuration were used to detect the scattered particles. A ^{92}Zr target (95% isotopic purity) of thickness 25.4 mg/cm^2 was used for these measurements. An overall spectrum resolution of 250 keV was obtained. The data were measured in the angular range 14° to 30° in about 2° intervals. The inelastic scattering spectrum obtained at $\theta = 14°$ is shown in Fig. 1. Broad structures corresponding to low energy octupole resonance (LEOR) and GQR-GMR-GDR complexes are clearly seen in the figure.

In performing distorted-wave Born approximation (DWBA) collective-model analyses of the inelastic scattering data, using the code DWUCK (Ref. 14), the proton optical-model parameters similar to those of Nadasen *et al.*[15] obtained for ^{90}Zr target were used: $V_R = -26.80$ MeV, $R_R = 1.24$ fm, $a_R = 0.716$ fm, $V_I = -8.85$ MeV, $R_I = 1.35$ fm, $a_I = 0.643$ fm,

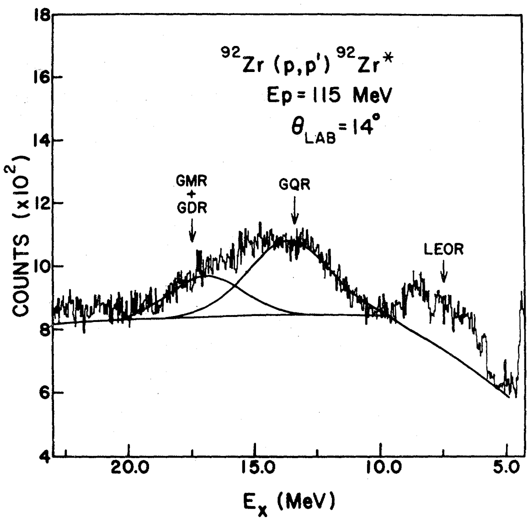

FIG. 1. Energy spectrum for inelastic program scattering on ^{92}Zr covering the GR and LEOR regions. The assumed background for the two regions are indicated by the smooth solid curve. Also shown are the Gaussian fits to the GR regions, one for the GQR and the other for the GDR + GMR region.

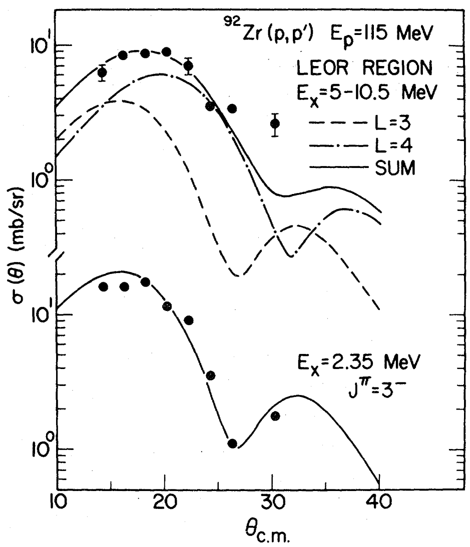

FIG. 2. Measured angular distributions for the low-lying level at $E_x = 2.35$ MeV and LEOR region between $E_x \simeq 5-10.5$ MeV compared with DWBA calculations.

$V_{so} = -3.3$ MeV, $W_{so} = 1.51$ MeV, $R_{so} = 1.052$ fm, $a_{so} = 0.594$ fm. The well known low-lying states of ^{92}Zr were first analyzed to check the reliability of the optical-model parameters and the collective-model assumption. From the data we were able to extract reliably the cross section for the first strong low-lying $J^\pi = 3^-$ state at $E_x \sim 2.35$ MeV, but not for the first $J^\pi = 2^+$ state at $E_x \sim 0.93$ MeV which was riding on the detector reaction tail of the strong elastic peak.

In Fig. 2, we compare the experimental data for $J^\pi = 3^-$, 2.35-MeV state with the collective model predictions; the agreement between the two is seen to be reasonably good. The percentage energy-weighted sum-rule (%EWSR) strength obtained for this state ($10.7 \pm 3.6\%$) agrees very well with the average value of the strength ($10.6 \pm 2.1\%$) obtained from other inelastic scattering studies.[16] The region between 5 and 10.5 MeV in the inelastic spectra was summed to obtain the cross section for the LEOR. A smooth background between 5 and 10.5 MeV (linear or quadratic in shape), similar to the one shown in Fig. 1, was used to subtract the underlying continuum. The angular distribution for the LEOR region and the DWBA prediction, assuming this structure to be a pure $J^\pi = 3^-$ configuration, are shown in Fig. 2. The calculations, normalized to the experimental data forward of $\theta = 20°$, clearly provides a poor description of the shape of the measured angular distributions, indicating that the LEOR region may contain contributions from one or more multipoles other than $L = 3$. Similar conclusions were reached in the low energy (p,p') work of Ref. 7 for ^{90}Zr. However, the (α,α') work of Ref. 9(b) gave a good account of this region assuming a pure $L = 3$ contribution (%EWSR ~ 20). Recently, Fujita *et al.*,[17] in a high-resolution study of $E_x = 5-9$ MeV in ^{90}Zr through (p,p') scattering, established the presence of $L = 4$ strength in this region in addition to $L = 3$. We have fitted the angular distribution data for the LEOR region assuming contribution from $L = 3$ and $L = 4$. The %EWSR strengths for $L = 3$ (6.6 ± 2.5) and $L = 4$ (9.2 ± 1.4) obtained from the present work agree reasonably with those ($L = 3$: $10.8 \pm 1.1\%$; $L = 4$: $5.8 \pm 6\%$) of Ref. 17, though the relative contributions estimated from the two works differ.

Since our limited understanding of the nature of the continuum under the GR region ($E_x \sim 10.5-20$ MeV) does not allow a quantitative determination of the shape of the continuum, we use the procedure universally followed of treating this continuum as a background of arbitrary shape. The main source of error in determining the cross section for the GR region comes from the uncertainty in estimating this background which, in the present work, is ~20% on the average. A typical shape of the background drawn under the GR is displayed in Fig. 1.

After subtracting the background, we fitted this GR region with two Gaussians of widths 4.0 and 3.5 MeV, respectively; the former called the GQR region was centered around 13.7 ± 0.5 MeV and the latter, attributed to GDR + GMR, was assigned a centroid around 17.5 ± 0.5 MeV. In Fig. 3, we have plotted the cross sections for these two regions. We fitted the GQR region assuming contributions arising from $L = 2$, 3, and 4. For this region we found ~50% $L = 2$ strength and ~10% $L = 4$ strength. There was

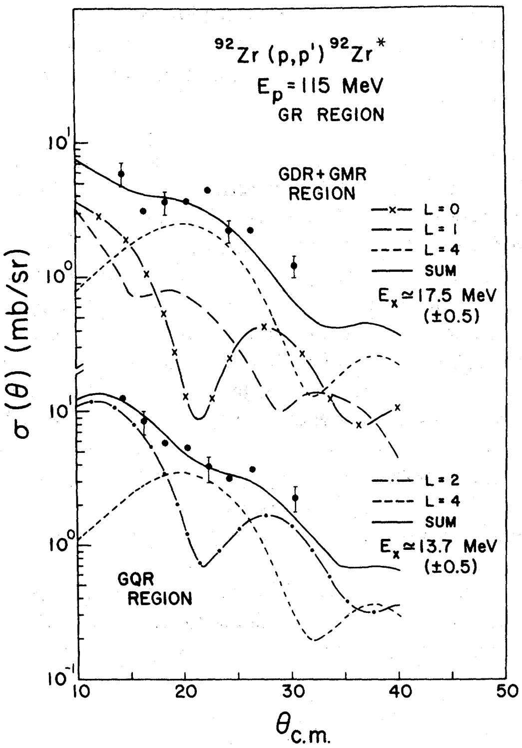

FIG. 3. Angular distributions for the GQR ($E_x \sim 13.7$ MeV) and the GDR+GMR ($E_x \sim 17.5$ MeV) region along with the DWBA calculations. The individual contributions due to various L values are also shown.

negligible $L=3$ contribution. The DWBA calculation obtained following the above mentioned procedure is shown in Fig. 3. The GDR+GMR region was assumed to be free from $L=2$ contribution. The fit obtained using $L=0$, 1, 3, and 4 contributions is also shown in Fig. 3. We assumed that the 65% GDR strength seen in photonuclear measurements[18] was exhausted in this region. We found $\sim 63\%$ GMR and $\sim 9\%$ $L=4$ strengths in this region of excitation. Again, $L=3$ strength was found to be negligible. The strengths obtained for the various multipoles are listed in Table I.

In calculating the GDR and GMR strengths we used the prescriptions of Satchler.[19,20] The GDR cross section was calculated using the Goldhaber-Teller (GT) model[19] starting from the isovector potential obtained both from phenomenological[21] and microscopic[22] nucleon-nucleus optical-model analysis. Cross sections calculated using the microscopic potential were 30 to 50% smaller than those obtained from the phenomenological potential. We used the isovector potential determined from the phenomenological analysis for the final calculations reported here. In calculating the GMR contribution, we used the version II of Satchler's prescription.[20]

The GQR strength obtained in the present work, $\sim 48 \pm 9\%$ agrees well with that obtained from low energy (p,p') [Ref. 6(a)], (α,α') [Refs. 9(a) and 9(c)] (^{3}He, ^{3}He') (Ref. 10), (d,d') (Ref. 8), and (e,e') (Ref. 5) results. The low energy $(\vec{p},p')$ (Ref. 7) and high energy [Ref. 6(b)] (p,p') experiments yielded 18 and 30% strengths, respectively, for the GQR, which are significantly lower than the results of the present work and of Refs. 5, 6(a), 8, 9(a), 9(c), and 10. The theoretical calculation from Ref. 12 predicts a $B(E2)$ value of 1292 e^2fm^4 for this excitation energy region which is on the high side of the value of 900 ± 174 e^2fm^4 obtained in the present work. The GMR strength of $63 \pm 18\%$ determined in the present work compares well with the results of Refs. 6, 9(a), 9(c), and 10. However, this result is strongly dependent on the GDR estimation. As the GDR cross section calculated varies considerably depending on the choice of the model, viz., Goldhaber-Teller (GT) or Jensen-Steinwedel (JS) and also on the set of optical parameters used, the GMR strength extracted is expected to have larger uncertainty. The $L=4$ strength, determined to be around $\sim 20\%$ for the GR region of excitation in the present work, is in good agreement with the value 16% obtained from the low energy $(\vec{p},p')$ work.[7] Our result for $L=4$ strength is high compared to that

TABLE I. Results of DWBA analysis for the GR region in ^{92}Zr. S: %EWSR strengths.

E_x (MeV)	J^π	S [a]	S [b]	S [c]	S [d]	S [e]	S [f]	S [g]	S [h]
GQR region	2^+	48 ± 9	18	60 ± 15	30 ± 8	66 ± 17	65–75	51	44–50
($E_x = 13.7 \pm 0.5$ MeV)	4^+	10 ± 2	8		≤ 4				
GDR+GMR region	0^+	63 ± 18	<20	60 ± 25		90 ± 25	80–180	60	19–25
($E_x = 17.5 \pm 0.5$ MeV)	4^+	9.5 ± 2.5	8						

[a] Present work; $E_p = 115$ MeV; (p,p').
[b] Reference 7; $E_p = 57.5$ MeV; $(\vec{p},p')$.
[c] Reference 6(a); $E_p \simeq 61$ MeV; (p,p').
[d] Reference 6(b); $E_p \simeq 200$ MeV; (p,p').
[e] Reference 9(a); $E_\alpha \simeq 120$ MeV; (α,α').
[f] Reference 9(c); $E_\alpha = 152$ MeV; (α,α').
[g] Reference 10; $E_{^3\mathrm{He}} = 108$ MeV; (^{3}He, ^{3}He').
[h] Reference 8; $E_d \simeq 108$ MeV; (d,d').

of Bertrand *et al.*[6(b)] The $B(E4)$ value $\simeq (10\pm2)\times10^5\ e^2\mathrm{fm}^8$ obtained in the present work falls short of the theoretical prediction[12] of about $20\times10^5\ e^2\mathrm{fm}^8$. It should be noted that the above mentioned comparisons assume that the results for ^{90}Zr and ^{92}Zr are sufficiently similar. It has been suggested[23] that, for higher proton energies, use of the standard prescription relating transition rate and deformation parameter will lead to poor agreement with the data. One way of taking care of this effect is to normalize strengths obtained for low-lying states to the results from (e,e') experiment, and use these constants to normalize strengths in the GR region.

In the present work we find that the %EWSR obtained for the low-lying 3^- state agrees well with that obtained from low energy hadron scattering experiments. In view of the experimental difficulties mentioned earlier, we have not been able to make this type of comparison for the low-lying 2^+ state. One notices a gradual reduction in %EWSR value for the GQR from (p,p') experiments as one goes from low to high proton energy (see Table I). It would be of interest to measure systematically angular distributions for the low-lying states of known J^π and compare with collective-model calculations and to establish the proton energy dependence of the sum-rule strengths.

In the present work, we have determined the strengths of the various multipoles excited in ^{92}Zr. It is found that the GQR strength obtained here is in good agreement with the average results of other experiments. The GMR strength obtained here is less certain in view of the problem of estimating the GDR contribution mentioned above. The $L=4$ strength found here is not inconsistent with the presence of measurable strength for this multipole predicted from theoretical calculation. The present work confirms the conclusions of low energy (p,p') (Refs. 7 and 17) analyses that the LEOR cannot be explained as arising from a pure $L=3$ excitation in contrast to results of the (α,α') work.[9(b)] We find noticeable $L=4$ strength in this region, in agreement with Ref. 17.

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