Investigation of $E2$ and $E3$ Radiation above the Giant Dipole Resonance in ^{89}Y(p, γ_0)^{90}Zr†

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New detailed angular distribution measurements are presented for ^{89}Y(p,γ_0)^{90}Zr above the giant dipole resonance (14 MeV $\leq E_p \leq$ 27 MeV), which show pronounced effects of higher multipoles. Direct-semidirect calculations provide a good description of the data by including $E2$ and $E3$ as well as $E1$ radiation. The sensitivity of the reaction to a $T=1$ giant quadrupole resonance is demonstrated.

In principle, the measurement of angular distributions in radiative proton capture should prove a useful tool for the investigation of collective resonances which lie high in the continuum and have multipolarity other than $E1$. In practice, there have been few such measurements at high energies because of small cross sections and large background rates, and it is (in most cases) impossible to sort out the contributions of various multipoles without a model for the capture process. Although the direct-semidirect (DSD) model[1-3] provides an appropriate framework for discussing higher multipolarities, heretofore it has been applied almost exclusively to $E1$ total capture cross sections, with reasonable qualitative success. The applicability of the model to the calculation of angular distributions has recently been demonstrated in light nuclei.[4] This Letter presents the first application of the model including the effects of higher multipoles to medium or heavy nuclei, in which strong, localized giant resonances other than $E1$ have been identified by inelastic scattering reactions.

We report herein angular distribution measurements of the reaction ^{89}Y(p,γ_0)^{90}Zr for 14 MeV $\leq E_p \leq$ 27 MeV (22 MeV $\leq E_x \leq$ 35 MeV). This region includes an isovector giant quadrupole resonance at $E_x = 26$ MeV suggested by inelastic electron scattering. This represents the first (p,γ) measurement at energies above the giant dipole resonance (GDR) of sufficient detail to permit determination of the Legendre coefficients through P_5. The DSD calculations show reasonable agreement with the measured coefficients by including direct $E2$ and $E3$ radiation along with the direct plus collective $E1$. Including an isovector giant quadrupole resonance (GQR) with parameters from Fukuda and Torizuka[5] in the calculation substantially improves the agreement, even though the data do not show pronounced structure near $E_x = 26$ MeV. The calculations also show that the (p,γ) reaction is expected to be very insensitive to a concentration of isoscalar $E2$ strength[5,6] in the region of the GDR. A comparison of the model with data at lower energies shows that below $E_p = 8$ MeV a statistical (compound) component must be included to obtain consistency with experiment.

In extending the DSD model to calculate angular distributions, allowing the possibility that the incident beam of nucleons is polarized, we write the differential cross section as

$$\frac{d\sigma}{d\Omega}=A_0\left\{1+\sum_{k=1}^{2L_{\max}}\left[a_kP_k(\cos\theta)+(\vec{p}\cdot\hat{n})b_kP_k^{1}(\theta)\right]\right\},$$

where $\vec{p}\cdot\hat{n}$ represents the polarization of the incident beam normal to the reaction plane. The coefficients A_0, A_0a_k, and A_0b_k are bilinear combinations of radial matrix elements $\langle Q_L\rangle_{l_cj_c,lj}$ taken between the continuum state lj and the bound final state l_cj_c of the captured particle. In the DSD theory, the effective radial operator Q_L for electric multipolarity L in the long-wavelength limit is

$$Q_L=q_Lr^L+\left(\frac{1}{E_\gamma-E_{\rm res}+i\Gamma/2}-\frac{1}{E_\gamma+E_{\rm res}}\right)h_L'(r).$$

The first term represents direct capture; q_L is the recoil effective charge factor ($e_{\rm eff}/e$) for single-particle EL capture.[7] The coupling to the giant-resonance intermediate states appears as a correction to the single-particle radial operator. The first energy denominator arises from polarization of the core by the incident nucleon; the second denominator, corresponding to core polarization by the captured nucleon in the final state,[8] has heretofore been neglected. We retain it here because its relative contribution to the dipole cross section is significant at the highest energies of interest ($E_\gamma \approx 2E_{\rm GDR}$). The shape factors $h_L'(r)$ are derived from the hydrodynamic prescriptions of Satchler,[9] which relate the factors h_L' to the optical potential via shape and charge deformations of the nuclear density. The result for isovector excitations, based on the Steinwedel-Jensen (S-J) model for the giant resonances, is

$$h_L'(r) = -\tau_3 \frac{\hbar^2}{m}\frac{f_{\rm sum}}{E_{\rm res}} L(2L+1)\frac{NZ}{A^2}\frac{\langle r^{2L-2}\rangle}{\langle r^{2L}\rangle} r^L U_1(r).$$

The quantity U_1 is to be identified with the symmetry part of the full optical potential defined by $U(r) = U_0(r) + \tau_3 U_1(r)(N-Z)/A$. The normalization is provided by assuming that the giant resonance exhausts a fraction $f_{\rm sum}$ of an energy-weighted sum rule.[10] The quantity τ_3 is 1 and -1 for neutrons and protons, respectively, and m is the nucleon mass. In the calculations we have approximated the averages $\langle r^N\rangle$ by the value $3R^N/(N+3)$ appropriate to a uniform-density sphere of radius R, where R is obtained from the real-well radius in the Becchetti-Greenlees potential.[11] An analogous shape factor, proportional to $r\,dU(r)/dr$, was derived for the isoscalar GQR. Although such a resonance has been identified[6] slightly below the GDR in ^{90}Zr, including it in the present calculation yielded negligible effects on the total cross section and very small changes ($\lesssim$ 10%) in the angular distribution coefficients.

The continuum wave functions were calculated with the Becchetti-Greenlees optical potential, and the bound $2p_{1/2}$ state with Woods-Saxon parameters suggested by Bohr and Mottelson.[12] A spectroscopic factor from the reaction[13] ^{89}Y(^{3}He, d_0) was included in the calculation. The shape of U_1 was taken from the real volume term of the Becchetti-Greenlees potential, and the strength (in the equation for h_L') adjusted to approximately fit the total cross section in the region 12–15 MeV. This value was 48 MeV, compared with 24 MeV in Ref. 11. Such an increase appears typical in heavy nuclei for the S-J model with the real coupling; the reason for this is not understood. The position (E_x = 16.7 MeV) and width (4.2 MeV) of the GDR were taken from ^{90}Zr(γ, n) experiments.[14] The coupling strength for the isovector GQR was assumed the same as for the GDR; the position, width, and sum-rule fraction were taken as 26 MeV, 7 MeV, and 0.73, respectively.

New data above E_p = 14 MeV from the University of Washington and Lawrence Livermore Laboratory (LLL) taken with anticoincidence-shielded NaI spectrometers are compared with the calculations in Fig. 1, together with Stanford measurements[15,16] in the range 6–14 MeV. The quantities $\alpha_{0,1,2}$ are related to differential cross sections Y_θ at 55°, 90°, and 125° by the expressions $\alpha_0 = (Y_{55}+Y_{125})/2$; $\alpha_1 = 0.872(Y_{55}-Y_{125})/\alpha_0$; $\alpha_2 = 2(\alpha_0 - Y_{90})/\alpha_0$. These quantities reduce to A_0, a_1, a_2 if the a_n are negligible for $n \geqslant 3$. Figure 2 shows coefficients through a_5 extracted from the LLL data. We note that proton capture, in contrast to neutron capture, exhibits analog resonances, which are not included in the model. Such resonances appear prominently[15] near 6.1 and 8.0 MeV. Additional resonances ascribed to the $T_>$ component of the GDR[15] occur between 10 and 14 MeV. We have neglected the isospin split-

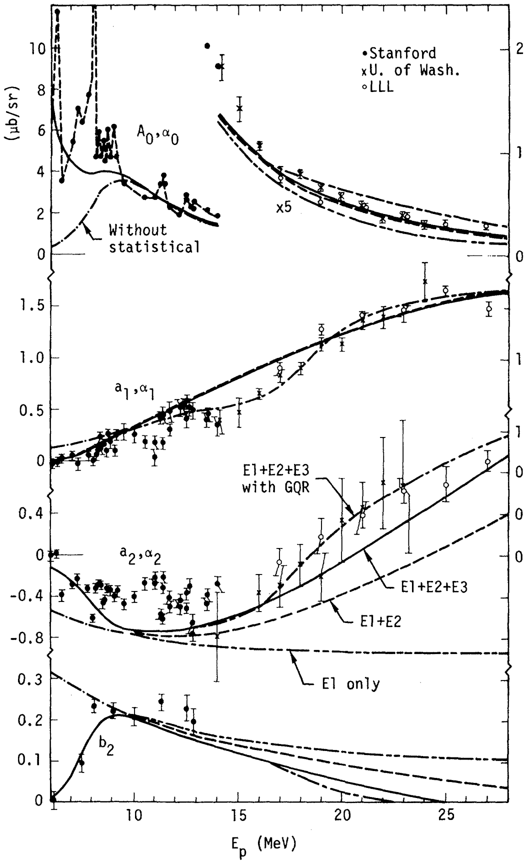

FIG. 1. Angular distribution coefficients for ^{89}Y(p, γ_0)^{90}Zr. Crosses and open circles, present measurements of α_i(see text); solid dots, previous measurements of A_0, a_i, and b_2 (Refs. 14 and 15) ($A_0 \cong \alpha_0$ and $a_i \cong \alpha_i$ for $E_p \lesssim 14$ MeV). The curves represent calculated α_i; the $E1$ curve includes both direct and semidirect (GDR); $E2$ and $E3$ are direct only, except where semidirect $E2$ (GQR) is indicated.

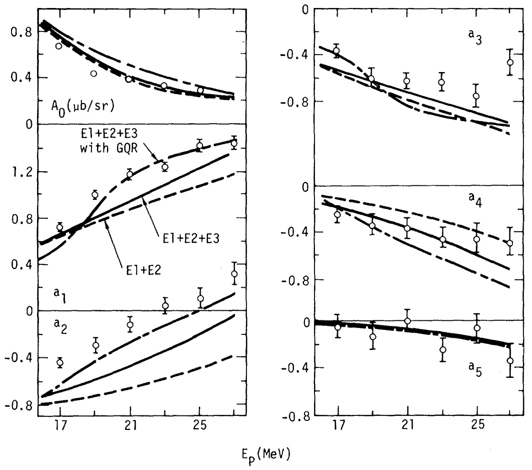

FIG. 2. Angular distribution coefficients extracted from LLL data. See text and Fig. 1 caption for significance of curves.

ting of the GDR, which is probably reasonable since the absorption strength of the $T_>$ GDR has been estimated at about 15% of the Thomas-Reiche-Kuhn sum rule.[15] Below 9 MeV compound gamma emission appears to be significant. A Hauser-Feshbach calculation[17] was made using gamma transmission coefficients derived from the observed total photoneutron yield[14] by detailed balance, and Gilbert-Cameron level densities[18] in the competing ^{89}Zr$+n$ system.

The curves in Figs. 1 and 2 represent (a) $E1$ only (direct+GDR); (b) direct $E2$ added; (c) direct $E3$ added to (b); (d) isovector GQR added to (c). The curves are the sum of the DSD and statistical calculations, except for the dash-dotted curve below 10 MeV, which is the same as (c) without the statistical component. The data are compatible with the GQR parameters of Ref. 5. The calculated resonance effect is strongly damped by the large value of the width (7 MeV) given in Ref. 5. Use of a complex coupling for the resonances, as introduced for the GDR by Potokar,[19] yields qualitatively similar results, except that the GQR strength must be reduced to ≈40% of the sum rule to be compatible with the data; this will be discussed in a subsequent paper. More detailed understanding of the coupling to the $T=1$ GQR will require a systematic study of nucleon capture in additional nuclei. The calculation indicates that $E3$ radiation becomes significant at the higher energies, appearing mainly by $E1$–$E3$ interference in a_2 and a_4. This conclusion is supported by nonzero measurements of a_5, which require multipolarity $\geqslant 3$.

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