Application of the Direct-Semidirect Model to the Interpretation of $E1$ and $E2$ Strength in $^{14}C(p_{pol},\gamma_0)^{15}N$†

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Direct-semidirect radiative-capture calculations are compared to new detailed $^{14}C(p_{pol},\gamma_0)^{15}N$ measurements in the giant-dipole-resonance region. The calculations provide a good description of the data by including only direct $E2$ and direct plus collective $E1$. The experimentally determined $E2$ cross section exhausts $(6.8\pm1.4)\%$ of the isoscalar sum rule and shows no sign of a resonance.

A great need exists for a simple reaction model that would describe radiative-proton-capture angular distributions in and above the nuclear giant-dipole resonance (GDR). Such a model is necessary for understanding the general features of the dominant electric dipole ($E1$) capture and for determining the nature of electric quadrupole ($E2$) capture, especially in the general case where even with polarized beams one cannot learn enough experimentally to unravel $E1$ and $E2$ amplitudes and obtain the $E2$ cross section.

In this Letter we make an extension of the direct-semidirect (DSD) capture model[1] to calculate angular distributions for targets of arbitrary spin and for polarized beams. This model has previously been applied only to total nucleon capture cross sections in medium and heavy nuclei, with limited success.[1] We show that the model works extremely well in predicting properly the reaction amplitudes and phases for both $E1$ and $E2$ capture in the GDR region in the reaction $^{14}C(p_{pol},\gamma_0)^{15}N$, by comparing to new data which we present here. This represents a new level of success in understanding the general features of the radiative-capture process and leads us to the expectation that the DSD model, which is very similar to distorted-wave Born-approximation calculations of collective excitations in inelastic scattering, may achieve a similar degree of usefulness in radiative-capture analysis.

The experimental motivation stems in part from the puzzling situation in ^{16}O, where a giant $E2$ resonance was observed[2] in the reaction $^{15}N(p_{pol},\gamma_0)^{16}O$ in the region of the GDR and was found to exhaust $\approx 35\%$ of the $E2$ isoscalar (IS) sum rule in the p_0 channel alone. If this collective resonance is predominantly IS, then it has an exceedingly large ground-state proton branching ratio $\Gamma_{p_0}/\Gamma \gtrsim 0.6$, since it is known[3] that $\geqslant 40\%$ of the IS-sum-rule strength lies at lower energies. If it contains much isovector (IV) strength, then it still must have $\Gamma_{p_0}/\Gamma \gtrsim 0.2$ and it requires IV $E2$ strength at a significantly lower energy than predicted by any theoretical calculation.[4] To pursue this question, we have studied the (p_{pol},γ) reaction over a similar excitation energy region of ^{15}N. Our measurements extend to higher energies and are much more accurate than previous results[5] (thus permitting an accurate determination of the $E2$ cross section).

The $^{14}C(p_{pol},\gamma)^{15}N$ measurements were made using the University of Washington tandem accelerator and a large NaI spectrometer. Targets consisted of ~ 0.4 mg/cm^2 ^{14}C (95%) on 3-mg/cm^2 gold backings. Elastic scattering at $\theta=\pm160°$ from ^{12}C, ^{14}C, and Au in the target was used to monitor the beam polarization continuously and to normalize the γ-ray yields at different angles. Seven-point angular distributions were measured between $\theta_\gamma = 43°$ and $137°$ at thirteen energies from $E_p = 10$ to 18 MeV.

Assuming the highest-order multipole of importance is quadrupole, we expand the cross section as

$$\sigma(\theta) = A_0\{1+\sum_{i=1}^{4}[a_iP_i(\cos\theta)+Pb_iP_i^{1}(\cos\theta)]\},$$

where $P=\vec{P}\cdot\hat{n}$, $\vec{P}$ is the beam polarization, and $\hat{n}$ is the normal to the reaction plane, $\hat{n}\propto\vec{k}_p\times\vec{k}_\gamma$. Fast flipping of the proton spin, such that $\vec{P}\cdot\hat{n} = \pm P$ at the rate of 1 Hz, was employed to reduce systematic errors due to beam polarization changes. The results are shown in Fig. 1. With the exception of some resonance structure near

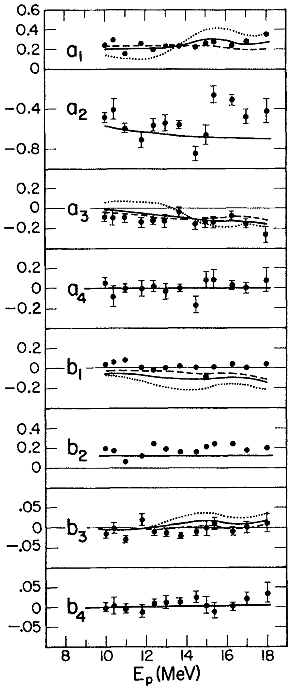

FIG. 1. Measured and calculated angular distribution coefficients for ^{14}C(p_{pol}, γ)^{15}N. Solid curve, $E1$ plus direct $E2$; dashed curve, $E1$, direct $E2$ plus an $E2$ IS resonance; dotted curve, $E1$, direct $E2$ plus an $E2$ IV resonance.

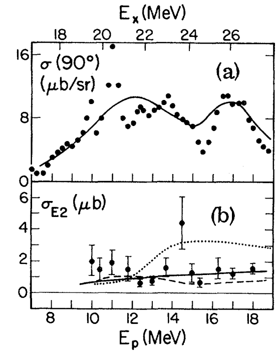

FIG. 2. (a) The 90° cross section (Ref. 6). (b) σ_{E2} derived from the data of Fig. 1 and (a) (see Fig. 1 caption).

$E_p = 15$ MeV in a_2, the angular distribution coefficients vary smoothly with energy and the nonzero a_3 and b_3 show definite evidence for $E2$ radiation at all energies. These results are in agreement with less accurate previous work[5] in the region of overlap. The (p_{pol},γ) measurements permit a model-independent[2] analysis of the nine measured coefficients (A_0, a_1–a_4, b_1–b_4) in terms of $E1$ and $E2$ amplitudes ($M1$ is neglected—see below). The $E2$ cross section obtained in this manner is shown in Fig. 2 along with the 90° cross section (which is mainly $E1$) obtained previously.[6]

A quantitative understanding of these results is greatly aided by comparison to calculations performed with the DSD reaction model. We define a radial matrix element for $E1$ capture which is the sum of a direct and a semidirect (collective) part (the latter is treated in the single-level approximation):

$$R_{lj} = \langle r \rangle_{lj} + \alpha_1 \langle F(r) \rangle_{lj} / (E - E_0 + \tfrac{1}{2} i \Gamma).$$

The numerator in the second term represents the product of proton formation and γ-decay matrix elements with

$$\langle F(r) \rangle_{lj} = \int_0^\infty \frac{\chi_{lj}(r)}{r} F(r) \frac{\varphi_{l'j'}(r)}{r} r^2 \, dr,$$

where $\chi_{lj}(r)$ is the initial proton scattering wave function and $\varphi_{l'j'}(r)$ is the wave function of the valence proton bound in the final state [the normalization of $\varphi_{l'j'}(r)$ is given by the spectroscopic factor $C^2 S_{l'j'}$]. The collective form factor $F(r)$ in the "Steinwedel-Jensen" model is assumed to arise from a transition density proportional to $r\rho_0(r)$, where $\rho_0(r)$ is the ground-state mass density, and is given[7] by $rV_1(r)$ where $V_1(r)/4$ is the real-symmetry term in the optical-model potential with $V_1(0) \approx 100$ MeV. For proton capture, $\alpha_1 = 3\hbar^2 Z \beta_1 / 4M_p A \langle r^2 \rangle E_0$ where β_1 is the fraction of the (classical) dipole sum rule exhausted by the excitation. A simple extension of the model permits one to include direct and collective $E2$ with a form factor for the latter given by $F(r) = r\,dV_0(r)/dr$ and $\alpha_{20} = \hbar^2 \beta_{20} / 2M_p E_0$ for an IS resonance of strength β_{20}, where $V_0(r)$ is the real central potential [$F(r) = r^2 V_1(r)$ and $\alpha_{21} = 5\hbar^2 \langle r^2 \rangle \beta_{21} / 8M_p \langle r^4 \rangle E_0$ for an IV resonance]. The quantities E_0, Γ, and β for the various resonances are unspecified by the model and are to be determined from a comparison of model calculations with experiment.

Application of the model to (p,γ) in and above the GDR of ^{16}O shows that a good fit to the total cross section is obtained with $E_0 = 22.5$ MeV, $\Gamma = 4.2$ MeV, and $V_1(0)\beta_1 = 110$ MeV (here $E2$ is negligible). Since $\beta_1 \approx 1$ (neglecting the high-energy photoabsorption tail[8]) the value of $V_1(0)$ obtained here agrees with other expectations. The fragmentation of $E1$ strength in ^{15}N precludes a single-level fit; however, the introduction of a second single-level $E1$ amplitude permits the fit shown in Fig. 2(a) (solid curve) with $E_0 = 21.0$ (25.5) MeV, $\Gamma = 6$ (2) MeV, and $V_1(0)\beta_1 = 115$ (25) MeV for the two resonances. The solid curves in Figs. 1 and 2 contain direct $E2$ and provide a good description of the observed coefficients, thus justifying the neglect of $M1$ in the model-independent extraction of σ_{E2} from the data [Fig. 2(b)]. The good agreement shown here means that the model properly gives both the magnitude *and* phases of the complex s- and d-wave $E1$ and p- and f-wave $E2$ amplitudes.

In order to gauge the sensitivity of (p_{pol},γ) to possible collective $E2$ strength, we also show in Figs. 1 and 2 model predictions for an IS excitation at $E_0 = 22$ MeV, $\Gamma = 4$ MeV exhausting 50% of the IS sum rule ($\beta_{20} = 0.5$), and a prediction for a similar IV excitation exhausting 100% of the IV sum rule ($\beta_{21} = 1.0$). No theoretical calculation[4] places much IV strength at these low energies and indeed a concentrated IV resonance such as is shown in Fig. 2 would be in clear disagreement with the data. However, the DSD model predicts that the (p_{pol},γ) reaction is relatively insensitive to a concentration of IS $E2$ strength at these energies.

The integral of σ_{E2} from $E_x = 19.5$ to 27.0 MeV is $\int \sigma_{E2}(\gamma,p_0)dE/E^2 = 0.48 \pm 0.11$ μb/MeV corresponding to $(6.8 \pm 1.4)\%$ of the IS sum rule[9] (the integral of the calculated direct capture is 3.9%). Thus the reaction ${}^{14}\mathrm{C}(p_{\text{pol}},\gamma){}^{15}\mathrm{N}$ shows no sign of a collective $E2$ resonance, although the integral of the observed $E2$ cross section is somewhat in excess of direct capture. This is in sharp contrast to the situation in ${}^{16}\mathrm{O}$ where the integral of the observed σ_{E2} yields ≈35% of the IS sum and σ_{E2} appears to have a resonance shape (here the direct capture integral is 7%). Now over the same energy range $\int \sigma_{E1}(\gamma,p_0)dE$ drops in going from ${}^{16}\mathrm{O}$ to ${}^{15}\mathrm{N}$ but by a much smaller factor (14% versus 7% of the $E1$ sum rule, respectively). Thus there appears to be a strong difference in the concentration of $E2$ strength in these two nuclei.

The success of the model calculations in describing the capture process in these nuclei lends confidence that it can be applied to other light nuclei and used as an aid in understanding $E2$ capture. Calculations show,[10] for example, that the large a_1 and a_3 angular distribution coefficients observed[11] in the reaction ${}^{11}\mathrm{B}(p,\gamma){}^{12}\mathrm{C}$ above the GDR (and below $E_p = 30$ MeV) can be quantitatively understood in terms of $E1$–direct-$E2$ interference. The fact that the DSD model including $E1$ and direct $E2$ correctly[10] yields A_0 and a_1 above the GDR in ${}^{11}\mathrm{B}(p,\gamma_0){}^{12}\mathrm{C}$ and ${}^{15}\mathrm{N}(p,\gamma_0){}^{16}\mathrm{O}$ means that the quantity[12] $a_1^2A_0$ is dominated by direct $E2$ contributions for $15 < E_p < 30$ MeV [$\sigma_{E2}(\text{direct}) \lesssim 1.1$ μb for both reactions in this energy range]. A study of the applicability of the model to medium and heavy nuclei is under way.[10,13]

Details of the calculations and measurements in ${}^{15}\mathrm{N}$ will be published separately. The authors are pleased to thank E. G. Adelberger, G. Bertsch, and F. S. Dietrich for valuable discussions, and J. L. Gallant for technical assistance in the preparation of the ${}^{14}\mathrm{C}$ targets.

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[1] M. Potokar *et al.*, Nucl. Phys. A213, 525 (1973), and references therein.

[2] S. S. Hanna *et al.*, Phys. Rev. Lett. 32, 114 (1974), and in *Proceedings of the International Conference on Nuclear Structure and Spectroscopy, Amsterdam, The Netherlands, 1974*, edited by H. P. Blok and A. E. Dieperink (Scholar's Press, Amsterdam, 1974), Vol. 2, p. 249.

[3] K. A. Snover, E. G. Adelberger, and D. R. Brown, Phys. Rev. Lett. 32, 1061 (1974).

[4] See, e.g., S. Krewald *et al.*, Phys. Rev. Lett. 33, 1386 (1974).

[5] H. R. Weller *et al.*, Phys. Rev. C 13, 922 (1976). Data from this reference, the present work, and M. H. Harakeh *et al.*, Phys. Rev. C 12, 1410 (1975), are in reasonable agreement with one another, but not with H. R. Weller *et al.*, Phys. Rev. Lett. 32, 177 (1974). Also the $E2$ cross section determination in the first reference mentioned here is incorrect since it ignores f-wave capture, which we find to be essential.

[6] Harakeh *et al.*, Ref. 5.

[7] G. R. Satchler, Nucl. Phys. A195, 1 (1972). Optical-model potentials were derived from B. M. Skwiersky *et al.*, Phys. Rev. C 9, 910 (1974), using the N and Z dependence given in B. A. Watson *et al.*, Phys. Rev. 182, 977 (1969).

[8] J. Ahrens *et al.*, in *Proceedings of the International Conference on Photonuclear Reactions and Applications, Pacific Grove, California, 1973*, edited by B. L. Berman, CONF-730301 (Lawrence Livermore Laboratory, Livermore, Calif., 1973), Vol. 1, p. 23.

[9] M. Gell-Mann and V. L. Telegdi, Phys. Rev. 91, 169 (1953). We use $\langle r^2\rangle = 7.30$ fm^2 for ${}^{15}\mathrm{N}$ as given from electron scattering: C. W. deJager *et al.*, At. Data Nucl. Data Tables 14, 479 (1974).

[10] K. A. Snover and K. Ebisawa, to be published.

[11] R. G. Allas *et al.*, Nucl. Phys. 58, 122 (1964); C. Brassard *et al.*, Phys. Rev. C. 6, 53 (1972); P. Paul *et al.*, to be published.

[12] P. Paul, in *Proceedings of the International Symposium on Highly Excited States in Nuclei, Jülich, Federal Republic of Germany, 1975*, edited by A. Faessler C. Mayer-Boericke, and P. Turek (Kernforschungsanlage Jülich GmbH, Jülich, Federal Republic of Germany, 1975).

[13] F. S. Dietrich, K. A. Snover, and K. Ebisawa, to be published.