Unique Determination of the Amplitude and Phase for the
Population of the Giant Dipole Resonance in
the $^{12}\text{C}(\text{p}, \gamma_0)^{13}\text{N}$ Reaction

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(Received 18 October 1979)

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The interference between the $E_p = 14.23$ MeV $M1(E2)$ $T = 3/2$ resonance and the $E1$ giant dipole resonance "background" in the $^{12}\text{C}(\text{p}_{\text{pol}}, \gamma_0)^{13}\text{N}$ reaction is used to determine uniquely the $E1$ reaction amplitudes. The $E1$ capture is found to be predominantly d-wave, in agreement with the basic shell-model description of the nuclear giant-dipole resonance.

At low energies radiative nucleon capture is dominated by the giant electric dipole resonance (GDR). Measurements of angular distributions in polarized proton capture reactions provide a useful probe of the structure of the GDR. However, existing polarized-proton capture studies do not uniquely determine the reaction amplitudes. Even for the most favorable spin sequences, there is an inherent 2-fold ambiguity¹⁻³ which arises from the quadratic nature of the equations relating the amplitudes to the data. We have, for the first time, resolved the two-fold ambiguity in radiative capture by studying the interference between the $E1$ "background" and a known $M1$ resonance. Our results are in agreement with reaction model calculations and with simple arguments based on the shell model.

The two-fold ambiguity in the case of the $^{12}\text{C}(\text{p}_{\text{pol}}, \gamma_0)^{13}\text{N}$ reaction^{4,5} is illustrated in Fig. 1. The GDR region extends from $E_p \sim 8-30$ MeV. $(\text{p}_{\text{pol}}, \gamma_0)$ angular distribution results are available⁵ for $E_p = 10-17$ MeV.

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For the simple spin sequence of this reaction, only incoming s- and d-wave amplitudes (with $j = 1/2$ and $3/2$, respectively) contribute to E1 capture. The shell model predicts d-waves should dominate. Angular distribution measurements can be fitted equally well with 2 solutions (Fig. 1), one of which is predominantly d-wave (d_{γ}) and the other predominantly s-wave (s_{γ}).

We studied the interference between the $E_p = 14.23$ MeV $M1(E2)$ $T = 3/2$ resonance and the E1 GDR. This $T = 3/2$ resonance is ideal for our purpose since all its important properties (J^{π} , width, strength, mixing ratio, etc.) are well-known.⁶ The dominant M1-E1 interference effects should appear in the A_1 and B_1 coefficients in the Legendre expansion of the cross section and analyzing power, respectively. Hence we chose to measure excitation curves at 90° with a polarized beam, and at 55° and 125° with an unpolarized beam, where

$$[\sigma(55^\circ) + \sigma(125^\circ)]/2 = A_0 - 0.39 A_4 \approx \sigma_{\text{total}}/4\pi$$

$$[\sigma(55^\circ) - \sigma(125^\circ)]/2 = 0.57 A_1 - 0.39 A_3$$

$$\text{and } \sigma A(90^\circ) = [\sigma^{\uparrow}(90^\circ) - \sigma^{\downarrow}(90^\circ)]/2P = B_1 - 1.5 B_3.$$

Excitation function data were measured using a ~ 200 $\mu\text{g}/\text{cm}^2$ natural C target. The polarized beam data were taken with a 25.4 cm $\times$ 25.4 cm NaI spectrometer at 90° and ~ 50 nA of polarized proton beam ($P \approx 0.7$) from the University of Washington tandem Van de Graaff accelerator. The unpolarized data (taken with ~ 350 nA of beam) were measured simultaneously at 55° and 125° in order to avoid spurious effects from small accelerator energy shifts. The large NaI spectrometer was placed at 55° and a 7.5 cm $\times$ 7.5 cm NaI detector at 125° . Representative

on-resonance spectra are shown in Fig. 2. The efficiencies of the two detectors were determined from thick-target resonance yield measurements.

Our resonance measurements for the $55^\circ + 125^\circ$ cross section, the 90° analyzing power $\sigma_A(90^\circ)$ and the 55 - 125° cross section difference are shown in Fig. 3. We fitted these results with a Breit-Wigner resonance (whose width, strength and E2/M1 mixing ratio are given in Ref. 6) interfering with background E1 and E2 amplitudes determined from a model-independent analysis of our off-resonance polarized beam angular distributions. The (asymmetric) energy resolution function and the resonance energy were determined from the shapes of $\sigma(90^\circ)$ and $\sigma(55^\circ) + \sigma(125^\circ)$. $\sigma_A(90^\circ)$ was then fitted with the only free parameter being the phase of the M1/E2 resonance relative to the E1 background. The 2 bands in Fig. 3 indicate the range of d_γ and s_γ solutions consistent with the off-resonance angular distributions at $E_p = 14.00, 14.17, 14.39, \text{ and } 14.49 \text{ MeV}$. Then the corresponding bands for the 55 - 125° cross section difference were calculated with no free parameters. These bands are insensitive to the E2 parameters, which serve only to determine the off-resonance values for $\sigma_A(90^\circ)$ and $\sigma(55^\circ) - \sigma(125^\circ)$. The results clearly select the d_γ solution as the physically correct one.

Our experiment has proven that the d_γ E1 solution is the correct one at $E_p = 14.23 \text{ MeV}$. Furthermore it is very probable that d-wave capture dominates over the entire region from $E_p = 10$ - 17 MeV because the two solutions are well separated and nearly independent of energy in this region (see Fig. 1). Although (p_{pol}, γ) results are not available for the $17 < E_p < 30 \text{ MeV}$ region where the bulk of the E1 absorption strength lies, the measured $a_2 (= A_2/A_0)$ suggests that the capture amplitudes here are similar to those in the lower energy region.

More importantly the $^{12}\text{C}(p_{\text{pol}}, \gamma_0)$ data are very similar to other lp-shell capture results such as $^{14}\text{C}(p_{\text{pol}}, \gamma_0)^7$ and $^{15}\text{N}(p_{\text{pol}}, \gamma_0)^{1,3}$ over similar ranges of E_p (encompassing the GDR in these latter cases). Thus it is reasonable to infer that d-wave dominance is a common feature of (p, γ_0) reactions in the upper lp-shell.

These results provide a basic test of reaction model calculations such as the direct-semidirect (DSD)^{3,7} model (see Fig. 1), and the doorway-state model⁸ which predict in the above cases that d-wave capture should dominate over s-wave capture, in agreement with our experiment. However, one does not need a detailed calculation to understand the observed d-wave dominance. It follows from the basic argument that dipole matrix elements are largest when the initial and final state wave functions have the same number of nodes. Hence the GDR is expected⁹ to be dominated by nucleon excitations of the form $n\ell \rightarrow n'\ell'$ where $n\ell$ and $n'\ell'$ are occupied and unoccupied shell model orbits, respectively (n = principal quantum number, ℓ = orbital angular momentum) and $n' = n$ and $\ell' = \ell + 1$. The same argument leads one to expect that the GDR amplitudes in the p_0 channel should be dominated by $\ell' = \ell + 1$ (and $n' = n$) when the target nucleus is related to the final nucleus by the removal of a nucleon from orbital $n\ell$. Since $n = 1$ and $\ell = 1$ for lp-shell nuclei, d-wave radiative capture should dominate in the GDR.

Our results also provide restrictions on the E2 contributions to the $^{12}\text{C}(p_{\text{pol}}, \gamma_0)$ reaction. In Ref. 5, it is shown that if one can neglect background M1 contributions, then small E2 cross sections $\lesssim 0.5 \mu\text{b}$

(roughly consistent with calculated direct E2 capture) are derived from fits to the angular distribution data. However, at some energies much larger E2 cross sections are also compatible with the data. These solutions with large E2 cross sections have E1 amplitudes with large s/d ratios (~ 0.7). If the E1 amplitudes are roughly energy-independent, then our resonance data reject these large E2 solutions.

More extensive measurements could lead in principle to a unique determination of the background E2 amplitudes and phases near this resonance. Also, this technique can (and should) be applied to other nuclei where (p, γ) resonances with known multipolarity occur at sufficiently high excitation energies to be used for unique determinations of giant resonance amplitudes and phases.

It is a pleasure to acknowledge the participation of T.A. Trainor in the early stages of this experiment.

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Figure Captions

- 1 Upper Part: σ_{total} for $^{12}\text{C}(p_{\text{pol}}, \gamma_0)$ for $E_p = 5-30$ MeV (Refs. 4 and 5).
Lower Part: The d-s phase difference and the relative d-wave intensity for $E_p = 10-17$ MeV (ref. 5 plus present work for $14 < E_p < 15$ MeV). The points and crosses correspond to the 2 different solutions. The solid lines are DSD calculations described in Ref. 5.
- 2 On-resonance γ -ray spectra for the large NaI spectrometer at 55° (bottom) and the 7.5×7.5 cm NaI at 125° (top). The vertical bars show the region summed for the γ_0 analysis.
- 3 Excitation curves taken near the lowest $T = 3/2$ resonance in $^{12}\text{C}(p, \gamma_0)^{13}\text{N}$. The solid curve in the top part is a calculated fit. The bands in the lower 2 parts represent the spread of calculated curves for the $d_>$ and $s_>$ solutions, consistent with the off-resonance angular distributions.