†Currently at the Cyclotron Laboratory, University of Manitoba, Winnipeg, Manitoba, Canada.

‡On leave from Institut für Strahlen- und Kernphysik der Universität Bonn, Bonn, Germany.

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Giant Dipole Resonances in ^{12}C Observed with the Polarized Proton Capture Reaction*

H. F. Glavish, S. S. Hanna, R. Avida,† R. N. Boyd, C. C. Chang, and E. Diener
Department of Physics, Stanford University, Stanford, California 94305
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The giant $E1$ resonances of ^{12}C have been studied with the polarized-proton capture reactions $^{11}\mathrm{B}(p,\gamma_0)^{12}\mathrm{C}$ and $^{11}\mathrm{B}(p,\gamma_1)^{12}\mathrm{C}$. The effects of proton polarization on the angular distributions were large and of opposite sign for γ_0 and γ_1. Coupled with the unpolarized measurements the polarized results produce additional significant limitations on the allowed configurations of the giant $E1$ resonances in ^{12}C.

One of the remarkable properties of the El giant dipole resonance (GDR) is the approximate constancy over the resonance of the angular distributions which involve the γ channel.[1] This phenomenon is often in marked disagreement with predictions of the simple particle-hole model and has not been entirely explained by refinements of this model.

In this Letter we report the first polarized-proton capture (p,γ) measurements and their application to a study of the configurations of the GDR. With transverse proton polarization the angular distribution of the capture radiation provides limitations on these configurations in addition to those obtained from the unpolarized measurements. Thus, the polarized measurements represent an important expansion of the experimental information which bears on the nature of the GDR and the question of the constancy of its angular distributions.

Because of its simplicity from both an experimental and theoretical point of view and the relative completeness of existing information on it,[2] the reaction $^{11}\mathrm{B}(p,\gamma)^{12}\mathrm{C}$ was the first one selected for study. Also attractive was the opportunity of obtaining good measurements on both the γ_0 (ground-state) and γ_1 (first-excited-state) transitions.

The polarized proton beam was provided by a polarized ion source of the atomic-beam, sextupole-magnet type,[3] and was then accelerated by the Stanford FN tandem Van de Graaff. Beam currents on target in the range 2–5 nA were available for the experiment. The ^{11}B target used for most of the work was approximately 1 mg/cm^2 thick and consisted of five separate self-supporting foils stacked closely together. The γ rays were detected in the Stanford 24 cm × 24 cm NaI spectrometer.[4] The reaction was monitored by counting particle yields at 35° and at 135° as well as with a current integrator. Although the particle yields are also dependent on the polarization, the reproducibility of the yields for a given polarization helped to establish the reliability of the measurements.

The polarized angular distribution can be written in the form

$$W_P(\theta) = \frac{\sigma_0}{4\pi}\left[1+\sum_{k=1} a_k P_k(\cos\theta)+\vec{\mathrm{P}}\cdot\vec{\mathrm{n}}\sum_{k=1} b_k \sin k\theta\right], \quad (1)$$

where $\vec{\mathrm{P}}$ is the polarization of the incident proton

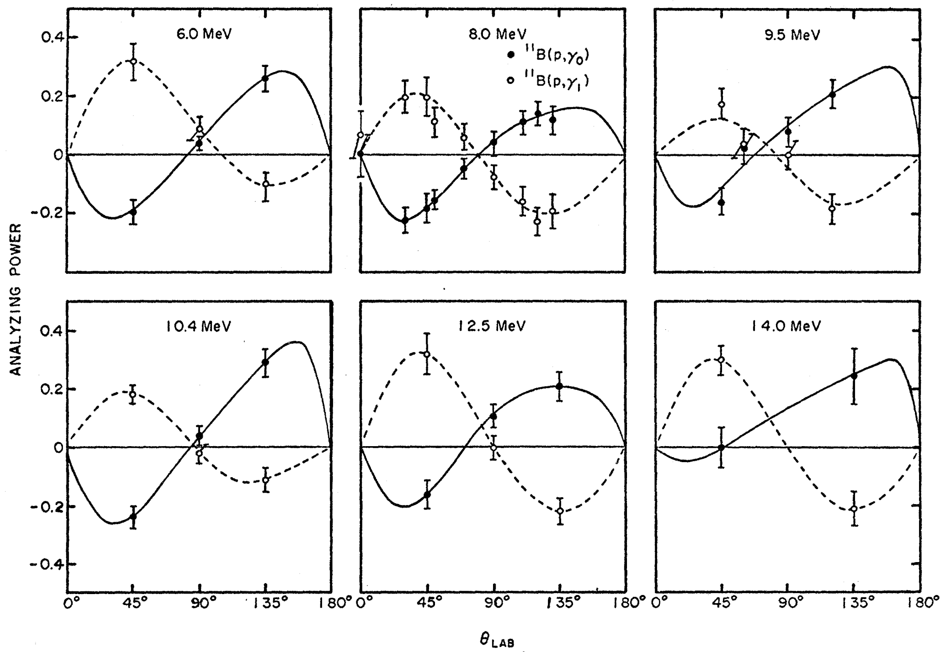

FIG. 1 Measured angular distributions of the polarized-proton reactions $^{11}B(p,\gamma_0)^{12}C$ and $^{11}B(p,\gamma_1)^{12}C$ expressed as the analyzing power $A_1(\theta)$. The curves are fits of Eq. (2) with $k=1$, 2, 3.

beam and $\vec{n}$ is the normal to the reaction plane. The vector analyzing power is defined as

$$A_1(\theta)=(\sum_{k=1} b_k \sin k\theta)[1+\sum_{k=1} a_k P_k(\cos\theta)]^{-1} \qquad (2)$$

and was measured at a given energy and angle by alternating runs with proton spin up with those with proton spin down. If R is the ratio of yields with spin up and spin down, then

$$A_1(\theta)=|\vec{P}\cdot\vec{n}|^{-1}(R-1)/(R+1),$$

where it is assumed that $|\vec{P}\cdot\vec{n}|$ is the same for spin up and down. The polarization $\vec{P}$ was measured several times during a run by observing in a separate scattering chamber the asymmetry in elastic scattering from ^{12}C at $E_p=9.8$ MeV and $\theta_{\mathrm{lab}}=70°$.[5]

In order to investigate the general nature of the (p,γ) reaction with polarized protons and its variation over the GDR in ^{12}C, measurements of $A_1(\theta)$ were made at $E_p=6$, 8, 9.5, 10.4, 12.5, and 14 MeV. At $E_p=8.0$ MeV a complete polarized angular distribution was obtained, as is shown in Fig. 1. At the other energies fewer angles were used since the principal aim was to determine only the $\sin 2\theta$ dependence of $A_1(\theta)$. The data in Fig. 1 clearly show a strong $\sin 2\theta$ dependence and the fact that the b_2 coefficients of γ_0 and γ_1 have opposite signs. The curves fitted to the data points have been generated assuming a $\sin\theta$, $\sin 2\theta$, and $\sin 3\theta$ dependence in $A_1(\theta)$. The fit at 8.0 MeV is exceptionally good and for γ_0 corresponds to the values $b_1=0.0$, $b_2=-0.14$, and $b_3=-0.04$. Nonzero values of b_1 and b_3 (like a_1 and a_3) arise from interference of states of opposite parity. Since b_1 and b_3 are small, it follows that radiations of parity opposite to $E1$ only make a small contribution to b_2.

The values of b_2 shown in Fig. 2 were extracted from the data for $A_1(\theta)$ by fitting with Eq. (2) and using values of a_1 and a_2 determined from unpolarized (p,γ) studies.[2] Shown in the same figure are the values for a_1, a_2, and the total yield σ_0, as measured in Ref. 2.

It is our aim in this Letter to discuss the dominant features of just the γ_0 polarization measurements in terms of the simple particle-hole model[6,7] of the $E1$ excitations of ^{12}C based on j-j coupling. Following the development in Ref. 2 which gives

$$a_2=-0.445\,\mathrm{Re}(\alpha\beta^*)+1.336\,\mathrm{Re}(\alpha\gamma^*)+0.60 \times\mathrm{Re}(\beta\gamma^*)+0.40|\beta|^2-0.40|\gamma|^2, \qquad (3)$$

we obtain

$$b_2=-0.474\,\mathrm{Im}(\alpha\beta^*)-0.947\,\mathrm{Im}(\alpha\gamma^*) -1.061\,\mathrm{Im}(\beta\gamma^*), \qquad (4)$$

where α, β, and γ are the reduced T-matrix

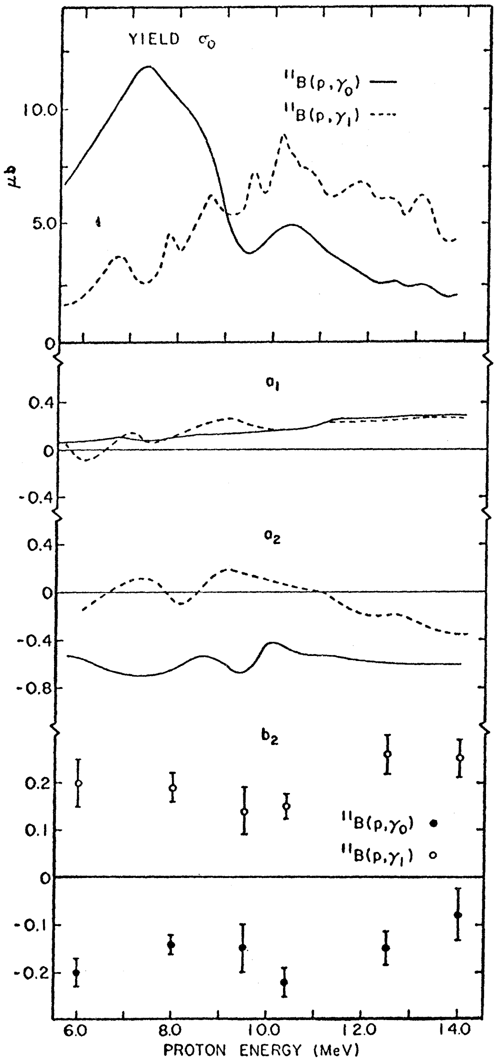

FIG. 2. Summary of existing information on the reactions $^{11}B(p,\gamma_0)^{12}C$ and $^{11}B(p,\gamma_1)^{12}C$ in the giant dipole region of ^{12}C. The curves for σ_0, a_1, and a_2 are from Ref. 2. The values of b_2 are those obtained from the fitted curves in Fig. 1.

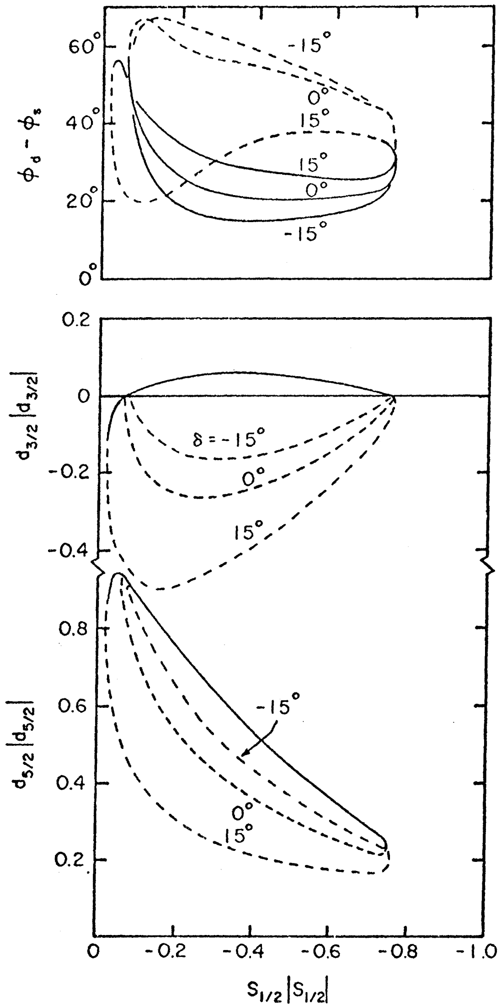

FIG. 3. The configurations in the γ_0 giant resonance of ^{12}C allowed by the data in Fig. 2. The paths in configuration space were obtained for $a_2 = -0.60$, $b_2 = -0.18$, and $\delta = 0, \pm 15°$. The solid and dashed lines represent alternative solutions I and II, respectively. For each allowed value of $s_{1/2}|s_{1/2}|$, the allowed values of $d_{5/2}|d_{5/2}|$, $d_{3/2}|d_{3/2}|$, and $\varphi_d - \varphi_s$ can be read from their respective graphs. Note that for solution I the paths for $d_{5/2}|d_{5/2}|$ and $d_{3/2}|d_{3/2}|$ are almost identical for $\delta = 0, \pm 15°$.

elements for proton capture in the $s_{1/2}$, $d_{3/2}$, and $d_{5/2}$ channels, normalized such that

$$|\alpha|^2 + |\beta|^2 + |\gamma|^2 = 1. \tag{5}$$

Since b_2 depends on the imaginary parts of the interference terms, the polarized (p,γ) data provide additional restrictions on the T-matrix elements and, in particular, on their relative phases.

To display this feature we can write $\alpha = s_{1/2} \times \exp(i\varphi_s)$, $\beta = d_{3/2}\exp[i(\varphi_d - \delta)]$, and $\gamma = d_{5/2}\exp(i\varphi_d)$, where $s_{1/2}$, $d_{3/2}$, and $d_{5/2}$ represent the amplitudes of α, β, and γ, respectively. Thus, associated with the giant dipole configuration there are five unknowns, $s_{1/2}$, $d_{3/2}$, $d_{5/2}$, $\varphi_d - \varphi_s$, and δ, which are constrained by Eqs. (3), (4), and (5). Given experimental values for a_2 and b_2, paths in configuration space for these five quantities can be found.

As can be seen in Fig. 2 average values for a_2 and b_2 over the γ_0 giant resonance are $a_2 = -0.60$ and $b_2 = -0.18$. The paths allowed for these values of a_2 and b_2 are shown in Fig. 3 for three values of $\delta = 0, \pm 15°$. There are two solutions corresponding to the solid curve (solution I) and the dashed curve (solution II). When δ varies

TABLE I. New limits on the configuration mixing in the GDR of ^{12}C obtained with the (p,γ_0) reaction using polarized protons, as compared with the old limits derived from the unpolarized reaction.

Data	δ	$\min \lvert s_{1/2}\rvert^2$	$\max \lvert d_{3/2}\rvert^2$	$\min \lvert d_{5/2}\rvert^2$
Unpolarized	0	0.01	0.52	0.10
Polarized included	$-15°$	0.08	0.14	0.23
	0	0.06	0.26	0.21
	15°	0.02	0.49	0.07

from $\delta = 0$, the paths for $d_{3/2}|d_{3/2}|$ and $d_{5/2}|d_{5/2}|$ change substantially for solution II, but there is little change for solution I even for δ as large as $\pm 90°$. The limits on the minimum values for the $s_{1/2}$ and $d_{5/2}$ contributions and the maximum value for the $d_{3/2}$ contribution are shown in Table I and compared with the previous limits based only on the unpolarized data.[2]

If the wave function of the GDR approximates a bound-state wave function, the phases of the T-matrix elements are just the Coulomb phase shifts for the initial channel: $\delta = 0$, $\varphi_d - \varphi_s = 27°$ at $E_p = 6$ MeV and $\varphi_d - \varphi_s = 18°$ at $E_p = 14$ MeV. It is interesting to note that such values are allowed in solution I. Departure from the Coulomb phase shift reflects the extent to which the GDR wave function departs from the bound state form. We note, however, that a Coulomb plus hard-sphere phase shift, as is usually assumed in the literature,[8] produces $\delta = 0$ and $\varphi_d - \varphi_s \simeq 100°$ which is not allowed in either solution I or II.

An analysis of the γ_1 radiation is considerably more complex than that for γ_0, because levels with $J = 1^-$, 2^-, and 3^- can each produce $E1$ radiation to the 2^+ first excited state of ^{12}C. If the $d_{3/2}$ and $d_{5/2}$ phases are nearly equal, then it is not possible to explain the observed asymmetry with a single 1^- or 3^- level. However, a single 2^- level or interferences such as $(1^-, 3^-)$, $(2^-, 3^-)$, and $(1^-, 2^-)$ are able to produce the observed asymmetry.

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†International Atomic Energy Agency Fellow, 1971–1972. Permanent address: Weizmann Institute of Science, Rehovot, Israel.

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Covariant Diastrophic Quantum Field Theory

John R. Klauder
Bell Telephone Laboratories, Murray Hill, New Jersey 07974
(Received 19 January 1972)

Elementary arguments determine the operator superstructure for a special but broad class of covariant field theories. Field operators and generators of interest are shown to be bilinear expressions in conventional creation and annihilation operators. Nontrivial interaction is incompatible with canonical (anti) commutation relations.

Choose any covariant quantum field theory that you like; augment the configuration space variables $\vec{x}$ by an auxiliary real variable w; insist on dynamical independence for all space and time of fields with distinct w values: The result is a covariant "diastrophic" quantum field theory, a