Polarized proton capture on ^{59}Co

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The angular distributions of cross section and of analyzing power for the ^{59}Co($\vec{p}$,γ_0) ^{60}Ni reaction have been measured throughout the giant dipole resonance region of ^{60}Ni. In addition, the 90° yield curve has been measured for E_p from 5.8 to 16.5 MeV. The data are analyzed to deduce the amplitudes and phases of the T matrix elements involved. Comparison of the results is made to both the dynamic collective model calculation of Ligensa and Greiner and to a direct-semidirect model calculation. The direct-semidirect calculation indicates that the reaction proceeds predominantly via the radiative capture of $d_{5/2}$ protons. Isospin splitting is also discussed.

[NUCLEAR REACTIONS ^{59}Co($\vec{p}$, γ_0); measured $\sigma(\theta)$ and $A(\theta)$ E_p =6.8–12.8 MeV. ^{59}Co(p, γ_0) measured $\sigma(90°)$, E_p =5.8–16.5. Deduced T-matrix amplitudes and phases. Compared to model calculations.]

I. INTRODUCTION

The giant dipole resonance (GDR) region of ^{60}Ni has been previously studied via the proton-capture reaction.[1] The ^{59}Co (p,γ_0) excitation function obtained in the earlier work was interpreted in terms of the splitting of the $T_< = 2$ and $T_> = 3$ isospin components of the GDR of ^{60}Ni and was compared with the calculations of Akyuz and Fallieros.[2] The identification of the isospin components as two possibly overlapping envelopes of strength is in general very difficult and somewhat speculative because other dynamical effects can also introduce structure into the GDR.[3,4]

In the present experiment, angular distributions of cross section, $\sigma(\theta)$, and analyzing power, $A(\theta)$, have been measured for the capture reaction ^{59}Co (p,γ_0) ^{60}Ni with both polarized and unpolarized beams for energies that encompass the GDR. In addition, $\sigma(90°)$ was measured for proton energies of 5.8 to 16.5 MeV. Following previously developed techniques,[5,6] the angular distributions, $\sigma(\theta)$ and $A(\theta)$, were analyzed to determine the relative amplitudes and phases of the T-matrix elements contributing to the $E1$ decay of the GDR. The results of this analysis are compared to the dynamic collective model calculations of Ligensa and Greiner[7] in which the giant dipole phonons are coupled with surface quadrupole vibrations. The agreement is poor at high excitation energies. On the other hand, the results are in reasonably good agreement with a direct-semidirect model[8] calculation which predicts that the major contribution to the dipole transition is from the $d_{5/2}$ transition matrix element. The results are also examined for evidence of isospin splitting.

II. EXPERIMENTAL DETAILS

Since the experimental details of the present work are similar to those described in a previous paper,[9] only the salient features will be discussed. The γ rays were detected with a 25.4 cm × 25.4 cm NaI crystal assembly incorporating a plastic anticoincidence shield. The threshold of the shield discriminator was set low enough to reject the major portion of the escape peaks and over 99% of the cosmic ray background. Escape-peak rejection was necessary in order to resolve the peaks corresponding to γ-ray transitions to the ground and first excited state at 1.32 MeV. All measurements were made with the front face of the NaI detector 56 cm from the target which corresponded to a total angular acceptance of 18°. Figure 1 shows a typical γ-ray spectrum with an energy resolution of approximately 3.3%. The 4.2 ± 0.4 mg/cm² self-supporting ^{59}Co target used for these measurements was prepared at Oak Ridge National Laboratory[10] from

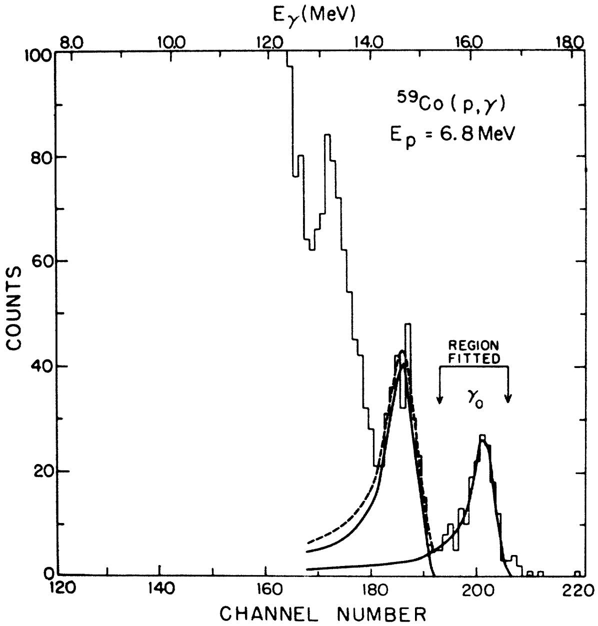

FIG. 1. Typical γ-ray spectrum obtained with the NaI spectrometer.

natural cobalt.

The analyzing power measurements were made with polarized protons from the Triangle Universities Nuclear Laboratory (TUNL) Lamb-shift ion source. Beam currents on target averaged approximately 40 nA. The beam polarization was determined by the quench ratio technique[11] at the beginning and end of each run. Two solid state detectors, mounted at ±160° with respect to the beam direction, were used to monitor the asymmetry of the elastically scattered protons. These measurements were used to verify the fact that the beam polarization was constant during a run. Typical beam polarizations were 0.80 ± 0.02.

The efficiency (probability ϵ that a photon will be recorded if it reaches the crystal) of the detector system was determined by measuring the ^{12}C (p, γ_0) thick target (50 keV for 14.2 MeV protons) yield curve over the 15.07 MeV resonance in ^{13}N. This yield, along with the recent measurement[12] of the number of γ rays per proton (6.83 ± 0.22) $\times 10^{-9}$, was used to determine the efficiency. The value obtained was $\epsilon = 0.168 \pm 0.011$, when the peak was summed in the full-energy region. It is assumed that the efficiency remains constant for all γ-ray energies of the present work.

III. ANALYSIS OF DATA

The yields for the angular distributions for γ-ray transitions to the ground state were determined by fitting a characteristic line shape to the spectrum using a least squares criterion (see Fig. 1). The γ_0 peak was then stripped from the spectrum and a fit was obtained for γ_1, the transition to the first excited state. This procedure was followed to ensure a proper separation of γ_0 and γ_1. A constant line width was used to fit all of the peaks obtained at different angles but at the same proton energy. The data for $\sigma(90°)$ were obtained by summing the region shown in Fig. 1.

The angular distributions for the center of mass cross sections were least squares fitted to an expansion of Legendre polynomials.

$$\sigma(\theta) = A_0 \left[1 + \sum_{k=1} a_k Q_k P_k(\cos\theta)\right],$$

where the coefficients Q_k correct for the finite geometry and $a_0 = 1$. The asymmetry measurements are presented in terms of the quantity $\sigma(\theta)A(\theta)/A_0$, where

$$A(\theta) = \left[\frac{N_+ - N_-}{N_+ + N_-} \frac{1}{P}\right].$$

In this expression P is the beam polarization and N_+ and N_- are the number of counts obtained for spin up and spin down, respectively. This product was fitted by an expansion in associated Legendre polynomials,

$$\frac{A(\theta)\sigma(\theta)}{A_0} = \sum_{k=1} b_k Q_k P_k^1(\cos\theta).$$

Fits were made through $k = 2$ for both the cross sections and asymmetries. Additional fits were also made through $k = 3$, but the inclusion of the $k = 3$ terms for $\sigma(\theta)$ was generally not statistically justified and did not seriously affect the value of a_2. This is in agreement with the Landsdorf suggestion[13] that the angular distributions must extend beyond the zero of $P_k(\cos\theta)$ if a_k is to be determined with statistical significance. Since there is no b_0 and since the zeros of $P_k^1(\cos\theta)$ occur at angles closer to 90° than for $P_k(\cos\theta)$, the $k = 3$ terms for $A(\theta)\sigma(\theta)/A_0$ were statistically significant and will be presented. The generally small values of b_1 and b_3 (relative to b_2), which arise only from the interference of $E1$ radiation with other multipoles, are consistent with the usual assumption that $E1$ radiation dominates this reaction in this energy region.

IV. RESULTS

The 90° yield curve, shown in Fig. 2, was measured from 5.8 to 8.0 MeV in 100 keV steps, from 8.0 to 11.0 MeV in 150 keV steps, and from 11.0 to 16.5 MeV in 200 keV steps. The errors shown are purely statistical, while the absolute cross section determined from the efficiency, target

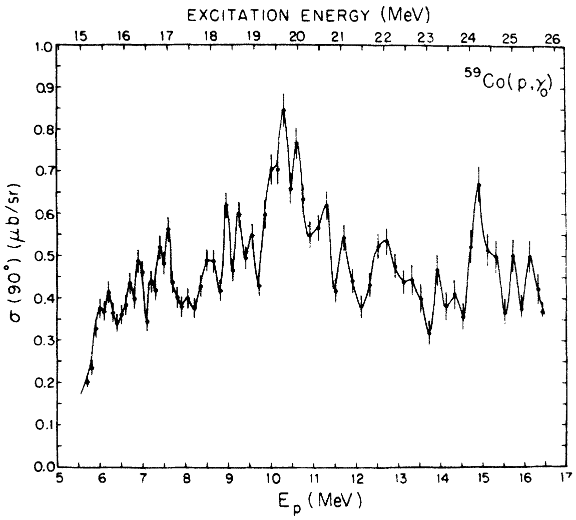

FIG. 2. The 90° yield curve for the ^{59}Co(p, γ_0) ^{60}Ni reaction. The error bars represent the statistical error associated with the data points and the solid curve is a smooth line drawn through the data points.

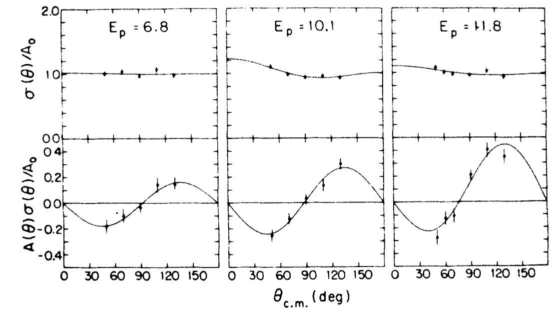

FIG. 3. Typical data at three energies for the quantities $\sigma(\theta)/A_0$ and $\sigma(\theta)A(\theta)/A_0$. The errors bars represent the statistical errors associated with the data points. The solid curves are the result of fitting the data as described in the text.

thickness, and beam current integration has an uncertainty of ±11%. The agreement of these data with those of Diener *et al.*[1] is fair; the general shapes of the two $\sigma(90°)$ yield curves are similar, and the absolute cross sections obtained in the two experiments agree within the errors quoted.

A sample of the angular distribution data is shown in Fig. 3 where $\sigma(\theta)/A_0$ and $A(\theta)\sigma(\theta)/A_0$ are presented for three different energies. Data were taken at five angles for each proton beam energy. The solid curves are the fits as previously described. The a_k and b_k coefficients obtained from all the fits are tabulated in Table I along with the a_k's from Ref. 1.

Since the ground state spin and parity of ^{59}Co is $\frac{7}{2}^-$, there are three amplitudes that can contribute to the formation of the 1^- dipole state. Each of these can be represented by a transition matrix element labeled by the total angular momentum brought in by the proton. Each of these T-matrix elements will have an amplitude and a phase which can be denoted by $d_{5/2}$, $g_{7/2}$, and $g_{9/2}$ and $\phi(d_{5/2})$, $\phi(g_{7/2})$, and $\phi(g_{9/2})$, respectively. With the assumption of pure $E1$ radiation and neglecting the possibility of statistical compound nuclear effects, the a_0, a_2, and b_2 coefficients can be expressed in terms of the three amplitudes and phases as

$$\begin{aligned} a_0 &= 1 = d_{5/2}^2 + g_{7/2}^2 + g_{9/2}^2 , \\ a_2 &= -0.143 d_{5/2}^2 - 0.247 d_{5/2} g_{7/2} \cos(d_{5/2}, g_{7/2}) \\ &\quad + 1.464 d_{5/2} g_{9/2} \cos(d_{5/2}, g_{9/2}) + 0.476 g_{7/2}^2 \\ &\quad + 0.282 g_{7/2} g_{9/2} \cos(g_{7/2}, g_{9/2}) - 0.333 g_{9/2}^2 , \qquad (1) \\ b_2 &= 0.289 d_{5/2} g_{7/2} \sin(d_{5/2}, g_{7/2}) \\ &\quad + 0.488 d_{5/2} g_{9/2} \sin(d_{5/2}, g_{9/2}) \\ &\quad + 0.423 g_{7/2} g_{9/2} \sin(g_{7/2}, g_{9/2}) , \end{aligned}$$

TABLE I. The a_k and b_k coefficients obtained from least squares fits to the data as described in the text. Also presented are the a_k coefficients from Ref. 1.

E_p (MeV)	a_1	a_2	χ_2	b_1	b_2	b_3	χ_2
6.70 [a]	0.02 ± 0.03	0.03 ± 0.05	1.5				
6.80	0.01 ± 0.05	0.01 ± 0.07	1.8	−0.01 ± 0.03	−0.12 ± 0.02	0.00 ± 0.02	0.5
7.20	0.06 ± 0.03	0.15 ± 0.06	0.4	0.05 ± 0.02	−0.15 ± 0.02	0.04 ± 0.02	1.3
7.55 [a]	0.08 ± 0.05	0.16 ± 0.07	1.5				
7.60 [a]	−0.01 ± 0.02	0.28 ± 0.03	0.6				
7.75	0.02 ± 0.04	0.10 ± 0.08	6.1	0.02 ± 0.03	−0.10 ± 0.02	0.01 ± 0.02	0.1
8.75	0.05 ± 0.03	0.26 ± 0.05	1.5	0.04 ± 0.02	−0.10 ± 0.02	0.00 ± 0.02	0.9
10.00 [a]	0.22 ± 0.03	0.07 ± 0.04	1.5				
10.10	0.11 ± 0.03	0.12 ± 0.06	0.7	0.02 ± 0.02	−0.17 ± 0.02	0.01 ± 0.02	1.1
10.60	0.11 ± 0.04	0.12 ± 0.06	0.4	0.04 ± 0.02	−0.18 ± 0.02	−0.01 ± 0.02	8.1
11.80	0.06 ± 0.04	0.05 ± 0.06	1.2	0.14 ± 0.03	−0.23 ± 0.02	−0.05 ± 0.02	0.8
12.80	0.12 ± 0.03	−0.03 ± 0.06	2.8	0.05 ± 0.02	−0.14 ± 0.02	−0.02 ± 0.02	1.8

[a] From Ref. 1.

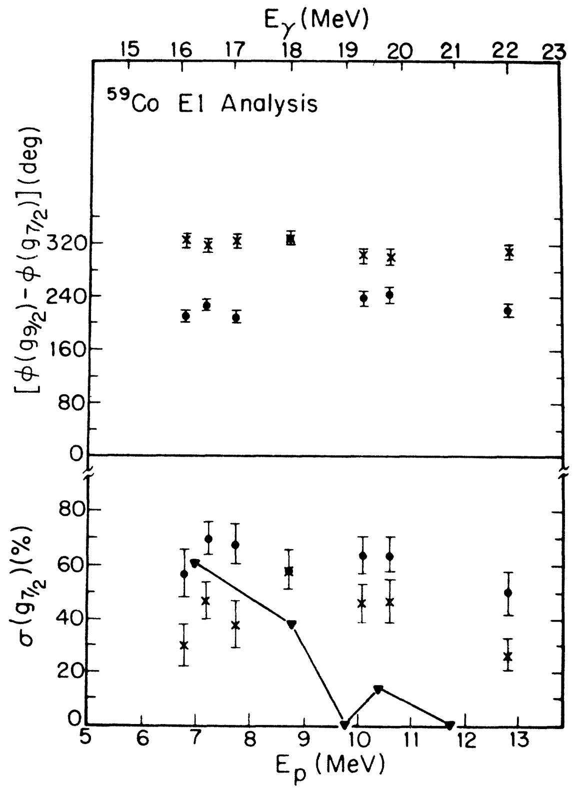

FIG. 4. Comparision of the transition matrix element amplitudes extracted from the present data with those calculated at five energies by Ligensa and Greiner. The dots and crosses represent the two mathematical solutions at each energy as mentioned in the text. The solid curve connects the five calculated values. The results are presented as a percentage of the cross section, $\sigma(g_{7/2}) + \sigma(g_{9/2})$, where $\sigma(g_{7/2}) = g_{7/2}^2$, etc. It should be noted that no mathematical solution was found for the data at $E_p = 11.8$ MeV. The error bars represent the statistical errors associated with the data.

where $(d_{5/2}, g_{7/2})$ stands for $\phi(d_{5/2}) - \phi(g_{7/2})$, etc.[14] Since these three equations involve five variables, there are many possible solutions for the amplitudes and relative phases. In an earlier study at this laboratory of the GDR in ^{55,57,59}Co, Cameron *et al.*[15] found that restrictions on one of the phase differences proved useful in limiting the range of the solutions. In this case, however, such restrictions are of little help, and hence the guidance of model calculations in the reduction of the number of amplitudes is necessary to proceed further with the analysis.

Ligensa and Greiner[7] (LG) have made detailed calculations for ^{60}Ni. They described the GDR as a coupling of the 1p-1h states to quadrupole surface vibrations. These states were then coupled to the continuum via a residual interaction. The calculated particle widths obtained with this model indicate that the $d_{5/2}$ amplitude is small and can be neglected. If only the $g_{7/2}$ and $g_{9/2}$ amplitudes and their relative phase are included in Eq. 1, the resulting quadratic equation can be solved exactly. Errors for the solutions were derived from the error matrix and reflect the proper statistical errors.[16] At each energy, two mathematical solutions are obtained and Fig. 4 shows a comparison between these solutions (dots and crosses) from the present analysis with the solutions calculated by LG. Note that $\sigma(g_{7/2}) = g_{7/2}^2$, etc. At the lower excitation energies there is some agreement, but at the higher energies there are large discrepancies.

A reaction model which has been used to predict angular distributions for radiative capture is the direct-semidirect (DSD) capture model.[8] The required radial matrix element for $E1$ capture is

$$\left\langle \phi_{nlj}(r) \left| r + \frac{V_1(r)}{E_\gamma - E_d + i\Gamma_d/2} \right| \phi_{l'j'}(r) \right\rangle ,$$

where $V_1(r)$ is the radial part of the form factor. The kets $|\phi_{l'j'}\rangle$ and $|\phi_{nlj}\rangle$ are the proton continuum and bound state wave functions, respectively. If the form factor is taken to be that suggested by Brown,[8] the predicted angular distributions (that is, the relative amplitudes and phases of the T-matrix elements) will be identical[17] to those obtained from a pure direct calculation, i.e., $V_1(r) = 0$, if the resonance parameters are taken to be the same for all matrix elements. Other versions of the form factor have been used[17–19] but, in fact, Likar *et al.*[17] have concluded (for $l \leq 3$ and medium weight nuclei) that all approaches using real form factors give approximately the same energy dependence for the a_2 coefficient. Consequently, for pure $E1$ radiation it is only necessary to perform a direct calculation[20] though the calculation can be considered to be either pure direct, or direct-semidirect (DSD) with the Brown form factor.[8]

The continuum single particle wave functions were calculated with the optical model parameters of Becchetti and Greenlees.[21] The bound state single particle wave function was obtained by integrating the Schrödinger equation with a Woods-Saxon potential including a spin-orbit term with $V_{so} = 6.2$ MeV. The experimental binding energy of 9.53 MeV for the proton was used to determine the well depth of 57.3 MeV. The matrix elements are simply related to the transition amplitudes through a Clebsch-Gordan coefficient. The resulting calculation indicates that all three matrix elements ($d_{5/2}$, $g_{7/2}$, and $g_{9/2}$) have approximately the same magnitude, but the Clebsch-Gordan coefficient reduces the relative $g_{7/2}$ amplitude by a factor of almost 40.

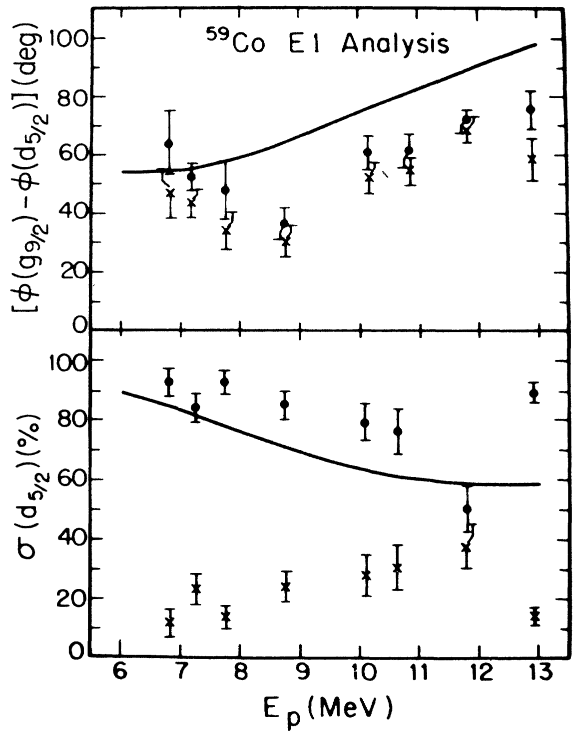

FIG. 5. Comparison of the transition matrix elements extracted from the present data with those from a direct-semidirect reaction model calculation as described in the text. The solid curve shows the results of the calculation. The results are presented as a percentage of the cross section, $\sigma(d_{5/2})+\sigma(g_{9/2})$, where $\sigma(d_{5/2})=d_{5/2}{}^2$, etc. The error bars represent the statistical errors associated with the data.

This result can be examined by considering the transformation between the amplitudes in the LS and jj coupling schemes which are given by[22]

$$d_{13}=d_{5/2},$$

$$g_{13}=-0.167g_{7/2}+0.986g_{9/2},$$

$$g_{14}=0.986g_{7/2}+0.167g_{9/2}.$$

The notation here is L_{JS}, where L is the letter assigned to the orbital angular momentum, J is the total angular momentum, and S is the channel spin. These equations show that the $g_{7/2}$ amplitude is nearly identical to the g_{14} "spin flip" amplitude. Neglect of this amplitude seems reasonable.

If in Eq. (1) the $g_{7/2}$ amplitude is set equal to zero, and if only the $d_{5/2}$ and $g_{9/2}$ amplitudes are included, two mathematical solutions are obtained from the data at each energy. The results of this analysis (dots and crosses) are shown in Fig. 5. The errors shown are derived from the error matrix as mentioned above. The DSD predictions, also shown in Fig. 5, were normalized for plotting purposes such that $\sigma(g_{9/2})+\sigma(d_{5/2})=100\%$, where $\sigma(d_{5/2})=d_{5/2}{}^2$, etc. In fact, the calculations predict that $\sigma(g_{7/2})$ typically accounts for <6% of the cross section. This normalization procedure, of course, does not affect the relative $d_{5/2}$ to $g_{9/2}$ strength. The calculations are in good agreement with the predominantly $d_{5/2}$ solution and hence remove the ambiguity of the two solutions. This result indicates the importance of considering the particle decay channel in evaluating the transition matrix elements. So, despite the fact that the $E1$ transition rate is larger for the $g_{9/2}$ than for the $d_{5/2}$ single particle state, the coupling to the proton channel results in the predominance of the $d_{5/2}$ transition matrix element.

The relative amplitudes obtained from the experiment change slowly across the GDR except for the single point at $E_p=12.8$ MeV, while the relative $g_{9/2}$ to $d_{5/2}$ phase changes smoothly except for a small inflection near $E_p=8.8$ MeV, a point about midway between the proposed isospin components. The results of these data and calculations appear to imply that isospin effects do not significantly affect the relative amplitudes and phases. Therefore, no definitive evidence for isospin splitting has been observed in this experiment. If any effect of isospin splitting is present in these results, it would appear that it is in the relative phase of the T-matrix elements. This observation requires further investigation.

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