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# Effect of the tensor force on gamma-ray de-excitation angular distributions from dipole states populated in the $^{12}C(p,p')$ reaction

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Angular distributions have been measured for the de-excitation gamma rays from the isoscalar and isovector $1^+$ states populated in the $^{12}C(p,p')$ reaction at $E_p(\text{lab}) = 22\text{–}27$ MeV. Fluctuations in the $A_0$ coefficients, which measure the total excitation cross sections, are observed to decrease with energy toward the high end of the region investigated. The $a_2$ coefficients are still fluctuating at 27 MeV, but exhibit reasonably well-defined average values of about $-0.40$ and 0.15 for the $T=0$ and $T=1$ levels, respectively. Microscopic distorted-wave calculations based on a realistic $G$ matrix interaction, while not sufficient to completely describe the present data, suggest that the isospin dependence of the $a_2$ coefficients is associated with the tensor force. The theoretical calculations have been extended to 50 MeV and this effect of the tensor force persists.

[NUCLEAR REACTIONS $^{12}C(p,p'\gamma)$ $E_p = 22\text{–}27$ MeV; measured gamma-ray angular distribution; $M1$ states miscroscopic DWBA analysis.]

## I. INTRODUCTION

Recent experiments[1-5] have demonstrated the existence of a definite isospin dependence in the proton spin-flip probabilities and proton analyzing powers for the excitation of the $1^+$ $T=0$ and $T=1$ levels in $^{12}C$ at $E_x = 12.7$ and 15.1 MeV. The incident proton energies in the experiments of Refs. 1–5 ranged from 22–65 MeV. Microscopic distorted-wave calculations[1-3] based on realistic $G$ matrix interaction[6] and the $p$-shell wave function of Cohen and Kurath[7] indicate that the spin-flip probabilities and analyzing powers for these $0^+ \to 1^+$ transitions in $^{12}C$ are sensitive to the details of the effective interaction, particularly the tensor interaction component. The comparison[1-3] between theory and experiment has been inconclusive so far because two-step processes may also make significant contributions to these transitions.[8]

The angular distributions of de-excitation gamma rays for these dipole transitions also contain information on the effective interaction. The shapes of these distributions in the center of mass (c.m.) are characterized by the coefficients $A_0$ and $a_2$ in the Legendre expansion[9]

$$\frac{d\sigma}{d\Omega} = A_0[1 + a_2 P_2(\cos\theta)].$$

Gamma-ray angular distributions for the de-excitation of both the $1^+$ $T=0$ and $T=1$ levels have been previously measured for incident proton energies up to 22 MeV.[10] The $A_0$ and $a_2$ coefficients exhibit a strong energy dependence in this region. In the present paper we report new data on the gamma-ray distributions in the (22–27)-MeV energy region. These data are examined within the framework of the microscopic distorted-wave approximation. The theoretical results are extended to incident energies of 50 MeV.

## II. EXPERIMENT

The present data were obtained by bombarding a natural carbon target with protons from the Lawrence Livermore Laboratory cyclograaff. Gamma rays were detected in a 25.4×25.4 cm NaI detector[11] surrounded by a plastic anticoincidence shield. The counts in the 12.71- and 15.11-MeV gamma peaks appearing in each spectrum were extracted with a fitting program in which standard line shapes were placed at 10.67, 12.71, and 15.11 MeV, and the counts in the peaks as well as the over-all system gain were varied. The counts assigned to the 12.71-MeV gamma depend on the shape of the 15.11-MeV peak in the region of the 12.71-MeV peak. The line shape for 15.11 MeV was measured as an adjunct to another experiment[3] in which a carbon target was bombarded by 25-MeV protons, and the gamma spectra in coincidence with inelastically scattered protons were recorded. The line shapes for the 10.67- and 12.7-MeV gammas were taken to be the same as for 15.11 MeV. An example of the resultant fit is shown in Fig. 1. Only the spectra of events

 

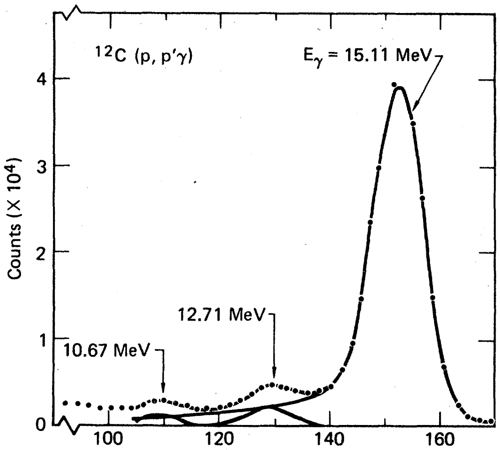


FIG. 1. Typical pulse height spectrum proton bombardment of $^{12}$C taken with the large NaI gamma-ray detector at $E_p$ = 27 MeV (lab). The solid line passing through the data is the fit including contributions from the excitation of the 15.11- and 12.7-MeV states. The curves below this data show the contributions from the three gamma lines indicated.

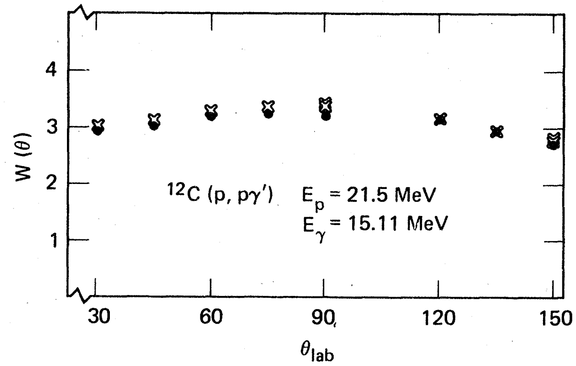


FIG. 2. Laboratory angular distribution of the deexcitation gamma rays from the 15.11-MeV state, taken at $E_p$ = 21.5 MeV (lab). Data from separate measurements are indicated. The slight fore-aft asymmetry is the effect of the forward recoil of $^{12}$C* in the laboratory frame.

with no coincidence between the NaI detector and the plastic shield were analyzed in this way. The fraction of events in the NaI detector rejected by coincidence in the shield was measured for events in the range of pulse heights between 13.5–17 MeV and extrapolated to lower energies with the line shapes determined in the experiment of Ref. 3. The maximum variation in the rejection rate with angle was about 10%.

With the exception of a few energies for which data were taken at many angles, the angular distribution coefficients were determined from the ratio of yields at 90 and 30°. The coefficients obtained from the data were $A_0 = (4+5r)/9r$ and $a_2 = 8(1-r)/(4+5r)$, where $r$ is the ratio of yields $W_{90°}/W_{30°}$, after normalization to elastic proton counts in an Si monitor detector placed at 135° to the incident beam. The calculated quantities do not exactly coincide with the $A_0$ and $a_2$ Legendre coefficients of the c.m. angular distribution because of a slight forward peaking of the angular distribution due to the forward recoil of the decaying $^{12}$C* nucleus. A precise c.m.-laboratory conversion is not convenient because the correction is reaction-model dependent due to the three-body final state. A full laboratory gamma-ray angular distribution is shown in Fig. 2. The ratio of 30 and 150° yields is about 1.08, which is in acceptable agreement with an estimate of 1.06 calculated by ignoring the distribution of momentum carried off by the inelastically scattered proton, which indicates that $a_2$ in the c.m. is smaller than the laboratory $a_2$ by about 0.03 to 0.04 throughout the energy range studied. These differences are small with respect to the observed values of the $a_2$ coefficients.

The $a_2$ coefficients are shown in Fig. 3. The uncertainties shown are representative of the statistical uncertainties for each point. The differences between the present work in the region around 22-MeV proton energy and that of Ref. 10 are generally less than the errors assigned to the data. The strong variation with energy which is evident in the lower energy data continues up to the highest energy obtained in the present study.

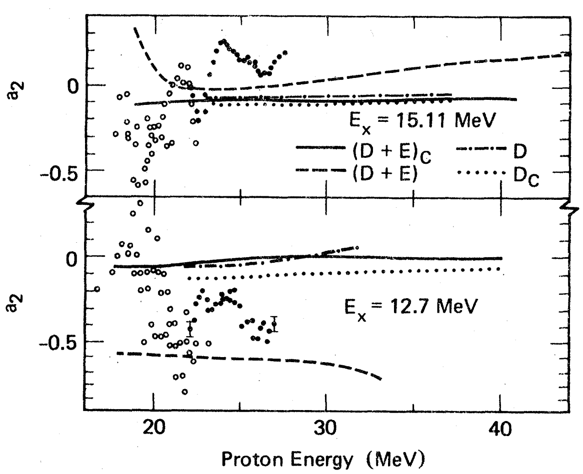


FIG. 3. Values of the $a_2$ coefficient for both excitations as a function of incident energy in the laboratory. The closed circles are data from the present experiment, the open circles from Ref. 10. Calculations are all distorted-wave approximations; $D$ indicates that only the direct term is plotted, $D+E$ indicates that exchange is included, and the subscript $c$ signifies that only the central parts of the interaction were used.

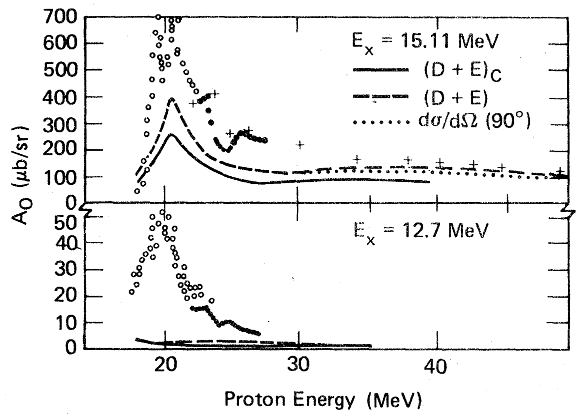


FIG. 4. Values of the $A_0$ coefficient for both excitations as a function of incident energy in the laboratory. The identification of data and calculation is the same as Fig. 3 except the crosses which are the differential cross sections at 90° gamma-ray angle from Ref. 12. The dotted line is the calculated 90° gamma-ray cross section with the complete interaction and knockout exchange. This is quite close to the theoretical results for $A_0$.

Over the energy interval from 23–27 MeV the $a_2$ coefficients have averaged values of −0.4 and 0.15 for the $T=0$ and $T=1$ excitations, respectively.

Values for the $A_0$ coefficient are shown in Fig. 4. The values of $A_0$ were normalized to those of Ref. 10 near 22-MeV proton energy for the 15.11-MeV state. This method gives rise to consistent but slightly smaller $A_0$ values for the 12.7-MeV state from the present work when compared to Ref. 10 for overlapping proton energies. The variation in $A_0$ with energy appears to become smoother at the top of the range for both excitations. Also shown in Fig. 4 are 90° $\gamma$-ray cross section data from Ref. 12. Since the values for $a_2$ are small, the 90° cross section and $A_0$ values are not expected to differ greatly.

## III. THEORETICAL RESULTS

The curves in Figs. 3 and 4 are the $a_2$ and $A_0$ coefficients obtained from microscopic distorted-wave calculations which used the $G$ matrix interaction of Ref. 6 and the $p$-shell wave function of Ref. 7. The calculations were made with the code DWBA70[13] which allows for exact inclusion of the knockout exchange amplitudes. The optical model parameters were taken from Ref. 1, 5, and 14. The $S=1$, $T=1$ parts of the $G$ matrix interaction were reduced by 40% as suggested by recent studies[15–17] of the $(p,n)$ reaction on light nuclei.

The theoretical results for the $A_0$ coefficients, obtained by normalizing the integrated inelastic $(p,p')$ cross sections by gamma-ray branching ratios from Ref. 18, fall below the experimental data for both transitions over the entire energy region of the present experiment. These are shown in Fig. 4. The noncentral interaction components (mainly tensor) give an important contribution to the theoretical $A_0$ at all energies. The peak at about 21 MeV in the calculated $A_0$ for the $T=1$ state depends sensitively on the values of the optical potential. The match between the peak and the data is fortuitous. The theoretical $A_0$ values for the $1^+$ $T=1$ excitation become comparable to the experimental data around 35 MeV and remain in agreement up to 50 MeV. Although no experimental $A_0$ values are available for the $1^+T=0$ excitation at higher energies, a comparison of the theoretical results of this work with the $(p,p')$ cross sections for the $T=0$ excitation given in Ref. 8 indicates that the $G$ matrix interaction does a better job in reproducing the experimental data at energies above 35 MeV than it does below this energy. The essential conclusion from these calculations is that the experimental $A_0$ values below 35 MeV cannot be understood in terms of a direct one-step process alone.

The theoretical results for the $a_2$ coefficients shown in Fig. 3 exhibit a marked sensitivity to the knockout exchange amplitude of the noncentral interaction components. The theoretical values obtained with the central interaction components alone satisfy $|a_2| \leq 0.1$ for both transitions over the entire energy region investigated. With the noncentral interaction components and knockout exchange amplitudes included, the $a_2$ coefficient for the $T=1$ excitation tends toward positive values and $a_2$ for the $T=0$ excitation is negative. The difference between $a_2$ $(T=1)$ and $a_2$ $(T=0)$ is $\geq 0.6$ for the lower energies and tends to increase with increasing energy. The tensor exchange amplitudes are responsible for the bulk of this effect. If the fluctuating experimental results for $a_2$ in the (22–27)-MeV energy region are viewed as varying about some underlying values typical of the direct process alone, it can be concluded that the theoretical and experimental $a_2$ coefficients are in closest agreement when all the amplitudes are included in the calculation.

## IV. SUMMARY

In summary, new experimental data have been presented for the angular distributions of $\gamma$ rays produced by the de-excitation of the lowest $1^+$ levels populated in the $^{12}C(p,p')$ reaction at 22–27 MeV. These data have been combined with other available data at both lower and higher energies. The results of microscopic distorted wave calculations for the $A_0$ and $a_2$ coefficients which characterize the $\gamma$-ray angular distributions have also been presented. In these theoretical calculations we have investigated a wider energy region, i.e., 20–50 MeV, than that covered by the present experimental measurements. The theoretical results underestimate the experimental $A_0$ for energies below 35 MeV, but seem to be reasonable for energies above this value. The calculations predict significant differences in the $a_2$ values for the $1^+$ $T=0$ (12.7-MeV) and $1^+$ $T=1$ (15.1-MeV) transitions. This effect is primarily due to the tensor knockout exchange amplitudes. The experimental $a_2$ values vary with proton energy but the average values over the energy interval are close to the distorted-wave approximation results. The large differences between the $a_2$ values for these two transitions are predicted to persist at higher energies. It would be interesting to extend the $a_2$ measurements to these higher energies where the one-step microscopic model seems adequate to describe the integrated inelastic cross sections as well.

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