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Azimuthal Angular Distribution of $^{12}C(\gamma,p_0)$*

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The azimuthal angular distribution of the photoprotons produced in the reaction $^{12}C(\gamma,p_0)^{11}C$ by monochromatic polarized gamma rays from $^3T(p,\gamma)^4He$ was measured for gamma-ray energies of 21.3 and 21.6 MeV. The ratio R of the number of photoprotons with directions between 0° and 45° (with respect to the gamma-ray polarization) to the number between 45° and 90° was determined. The average observed ratio for R, 2.8 ± 0.7, is larger than but not inconsistent with that calculated for pure electric-dipole photon absorption, 2.08 ± 0.1.

INTRODUCTION

THE dominant photonuclear absorption in carbon is in the electric dipole "giant resonance" around 22 MeV. According to shell-model calculations[1] this involves primarily the excitation of a $1p_{3/2}$ nucleon to the $1d_{5/2}$ orbit. In addition, there may be excitations involving other multipole absorptions. The uniformity with energy of angular distributions in the inverse (p,γ) reaction on ^{11}B has suggested that any possible other J states are so completely mixed in that the giant resonance is a combination state.[2] This is supported by the observation of a rather uniform a_1 term in the polar angular distribution of the $^{11}B(p,\gamma_0)$ which suggests less than 1% of electric quadrupole mixed in all through the giant resonance. Nevertheless, incipient structure is observed in the cross-section curves[3] with the suggestion that at least there may be variations in the mixing.

Further, the detailed shell-model calculations in ^{12}C predict $J=2$ and $J=0$ states in the giant-resonance region.[4] In an attempt to elucidate this problem we have examined the azimuthal angular distribution of the $^{12}C(\gamma,p_0)$ reaction using monochromatic and polarized gamma rays. In this fashion, it was hoped to detect whether the variations in cross section corresponded to gross variation in azimuthal angular distribution of the emitted photoprotons at the several absorbing energies.

THEORY OF EXPERIMENT

Agodi[5] has calculated the aximuthal angular distribution to be expected for the photoparticles ejected from a nucleus by polarized gamma rays to be

$$I(\varphi)=N(1+p\alpha\cos2\varphi),$$

where p is the fraction of complete polarization of the gamma rays, φ is the aximuthal angle between the ejected particle and the direction of polarization of the gamma ray (see Fig. 1), and α is a coefficient which depends on the multipolarity of the absorption, the spin and parity of the target and reaction products, and the reaction matrix elements. If only a single multipole participates, the reaction matrix elements can be bypassed and α can be expressed in terms of the coefficients of a polar angular distribution (without polarization) of the type

$$I(\Theta)=N(a_0+a_2\cos^2\Theta).$$

Agodi then shows that

$$\alpha=(-)^{\sigma}\frac{(2|L1:L1)}{(2|L1:L-1)}(\sqrt{6})\frac{a_2}{a_0},$$

where σ is zero for magnetic and 1 for electric multipole, L is the angular momentum of the multipole, and the parentheses are Clebsch-Gordan coefficients as used by Agodi, which reduce to

$$\alpha_{E1}=-a_2/a_0,\quad \alpha_{E2}=a_2/5a_0,\quad \text{and}\quad \alpha_{M1}=a_2/a_0.$$

In the case of mixed multipoles, we have extended the calculations of Agodi and have found that, to a good approximation for small mixing, $\alpha_{\text{mixed}}\cong\alpha(1+K\sigma/\sigma_T)$, where σ/σ_T is the fraction of the mixing multipolarity and K is a function of the reaction matrix elements which cannot be evaluated without a nuclear model. K may be expected to be a constant of the order of ±1.

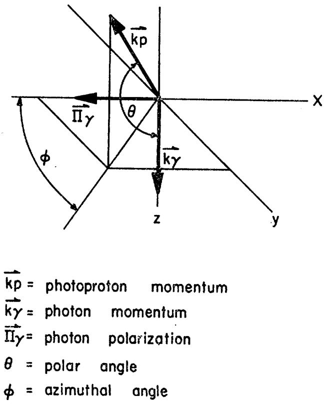

FIG. 1. Diagram showing relation of the photon direction, the polarization direction, and the photoproton direction.

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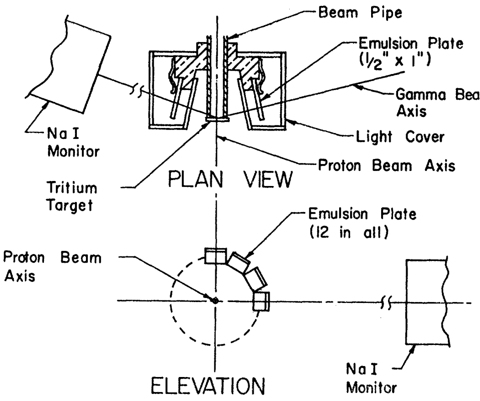

FIG. 2. Diagram of the experimental apparatus.

For larger fractions of mixing, neglected terms may become important and are not easily evaluated.

Since the $^{11}B(p,\gamma)^{12}C$ inverse reaction has been carefully studied in the giant resonance region and the polar angular distribution determined,[2] we can use those results to determine that $a_2/a_0=-0.55\pm0.05$ near 21.5 MeV. This determines the aximuthal coefficients for carbon photoprotons in this energy region to be

$$\alpha_{E1}=0.55\,,\ \alpha_{E2}=-0.11\,,\ \alpha_{M1}=-0.55\,,$$
$$\alpha(E1,E2)\cong0.55(1+K\sigma_q/\sigma_T)\text{for small }\sigma_q\,,$$
$$\alpha(E1,M1)\cong0.55(1+K\sigma_m/\sigma_T)\text{ for small }\sigma_m.$$

In analyzing experimental results, it is convenient to use a ratio R defined as

$$R=\frac{\int_0^{\pi/4}(1+\alpha\cos2\varphi)d\varphi}{\int_{\pi/4}^{\pi/2}(1+\alpha\cos2\varphi)d\varphi}=\frac{\frac{1}{2}\pi+\alpha}{\frac{1}{2}\pi-\alpha}.$$

This is particularly advantageous if the photoproton yield is limited and the statistical uncertainties are large. For pure transitions in carbon at these energies R should be $R_{E1}=2.08\pm0.1$, $R_{M1}=0.48\pm0.02$, and $R_{E2}=0.87\pm0.08$. For slightly mixed transitions, the ratio will not depart much from that for pure $E1$. Experimentally, R can be determined by the ratio of photoprotons with φ between 0° and 45° to those with φ between 45° and 90° without regard to the + or − direction of either the polarization or the proton.

EXPERIMENT

The monochromatic and polarized gamma rays were provided by bombarding with protons a target of tritium gas absorbed in a thin layer of titanium evaporated on a platinum backing. The target was estimated to be 70 keV for the protons of 2 MeV with which they were bombarded. The Doppler polar angle of the gamma rays used was 90° to 106°. Hence, the energy width of the gamma rays was about 70 keV at 21.3 MeV and very nearly the same at 21.6 MeV.[6] The polarization of these gamma rays at these energies is practically complete, as evidenced by the angular distribution.[7]

Because of the small available intensity of these gamma rays, the reaction was observed in nuclear emulsions with the carbon of the gelatin providing the sample and the developed emulsion supplying the detection of the photoproton. Ilford K2×2 plates of 200-μ thickness were used and disposed around the source of gamma rays as shown diagrammatically in Fig. 2. The gamma rays were monitored by a $4\frac{1}{2}$-in. diam by 6-in. long sodium iodide scintillation crystal whose pulses were stored in a 400-channel analyzer during the run. The photo-peak was used to establish the numbers of photons bombarding the nuclear emulsions by our previous calibration.[8]

Background was of several kinds. Photoelectrons were most numerous and electron tracks had to be elimiated or reduced. This was accomplished by developing the plates with a two-temperature method[9] which discriminated against electron tracks compared with proton tracks. Short proton recoils from the $T(p,n)$ neutrons limited the exposure to that amount of darkening which could be seen through. Photoprotons from other reactions were not expected in the energy region examined, as Table I indicates.

The developed nuclear-emulsion plates were scanned and the range and orientation of the photoproton tracks

TABLE I. Proton tracks produced by 21.3-MeV gamma rays in $K2\times2$ nuclear emulsion.

Isotopic Constituent of emulsion	Concentration (10^{21} atoms/cc)	Photoproton energy (MeV)	Neutron-induced proton energy (MeV)
^{1}H	31.0	...	1.1(recoil)
^{2}D	0.004	8.5[a]	1.0(recoil)
^{12}C	20.0	4.85[c],2.95	0.3(recoil)
^{13}C	0.2	3.5[a]	0.3(recoil)
^{14}N	4.9	12.9,9.45[b]	1.2(n,p)
^{15}N	0.02	11.1,4.7[a]	0.3(recoil)
^{16}O	8.6	8.6,2.7	0.2(recoil)
^{17}O	0.003	(a)	0.2(recoil)
^{18}O	0.014	(a)	0.2(recoil)
^{32}S	0.15	12.4···[a]	0.1(recoil)
^{79}Br	4.0	evap. peak∼6[2.5–14.7]	1.3(np)
^{81}Br	4.0	peak∼6[2.5–13.7]	0.1(np)
^{107}Ag	4.0	peak∼7[3–15.5]	1.4(np)
^{127}I	0.2	peak∼8[a]	0.4(np)

[a] Neglect due to low concentration.
[b] Prominent groups are: 0.51, 1.63, and 2.92 MeV. I. F. Wright, D. R. O. Morrison, J. M. Reid, and J. R. Atkinson, Proc. Phys. Soc. (London) **A69**, 77 (1956).
[c] These are the tracks measured in this experiment.

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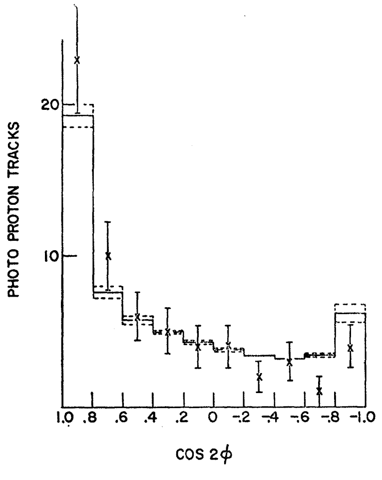

FIG. 3. Numbers of observed photoprotons plotted against cos2φ for $E_\gamma=21.6$ MeV. The distribution to be expected for pure $E1$ is shown as a histogram.

with projected ranges between 80 and 300 μ were recorded. This included the expected $^{12}C(\gamma,p_0)$ peak at 4.85-MeV proton energy. The tracks were corrected for shrinkage and analyzed. The energy, Θ, and φ distributions were plotted, and within statistical uncertainties were reasonable. Figure 3 shows the cos2φ distribution observed for $E_\gamma=21.6$ MeV. The histogram is the predicted distribution for pure $E1$ absorption ($\alpha=0.55$). The x's are the measured numbers of tracks.

RESULTS

The values of R determined from the observed numbers of tracks are: $R_{21.3}=2.22\pm0.6$ and $R_{21.6}=3.43\pm0.7$. If these two results are averaged, the $R_{\mathrm{av}}=2.82\pm0.7$. Such a value is higher than but not inconsistent with the value $R_{E1}=2.08\pm0.1$ calculated for pure electric dipole using the alpha calculated from the polar angle distribution found in the inverse reaction. The value of R found at 21.6 MeV is rather larger. An examination of Fig. 3, however, suggests that the departure from the distribution expected from pure $E1$ may still be due to statistical fluctuation. This interpretation is also consistent with the results of the polar angular distribution of the inverse reaction.[2] There the $\sin^2\Theta$ distribution is found to be peaked slightly forward of 90°, giving an a_1 coefficient of approximately 0.1. That would imply only a fraction of 1% of electric quadrupole mixed into the dominant electric dipole.

The absolute cross section of the $^{12}C(\gamma,p_0)^{11}B$ reaction was measured to be 9.4 ± 3 mb at 21.3 MeV and 8.9 ± 2 mb at 21.6 MeV. This compares well with the values 9.0 ± 1.1 mb and 7.8 ± 1 mb observed by Shin[3] (see Fig. 4). All of these values are somewhat higher than those deduced[2] from the inverse reaction $^{11}B(p,\gamma_0)$-^{12}C by detailed balancing; 6.2 ± 1 and 6.5 ± 1 mb, respectively, but are, perhaps, within the uncertainties of the different measurements. Many of the measurements[2,3,10] seem to show an undulation in the cross-section curve at these points but differ in the magnitude of the anomaly.

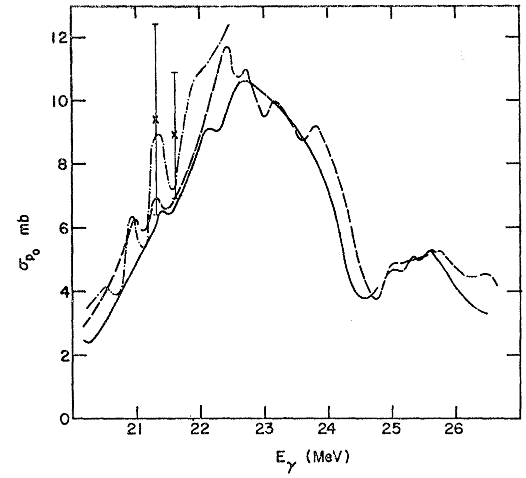

FIG. 4. Photoproton cross section as a function of photon energy. Solid line derived by detailed balance from the $^{11}B(p,\gamma_0)$ work of Allas *et al.* (Ref. 2). Dashed curve from the $^{12}C(e,pe')$ results of Dodge and Barber (Ref. 10) assuming ground state transitions and $1+1.5\sin^2\Theta$ angular distribution. Dot-dashed curve shows the $^{12}C(\gamma,p_0)$ results of Shin and Stephens (Ref. 3). The crosses represent the present results.

DISCUSSION

Since we cannot understand a value of R much larger than that predicted for a pure electric dipole transition, we suspect that the large value of R found at $E_\gamma=21.6$ MeV is due to statistical fluctuations. If this is so, then the angular distributions at both 21.6 and 21.3 MeV are probably consistent with electric dipole and not magnetic dipole or electric quadrupole. Hence, these results do not furnish any evidence for gross difference in angular-momentum character between the peak and dip of the cross-section variation at 21.45 MeV in the giant-resonance excitation of $^{12}C(\gamma,p_0)$. To this extent then, these results agree with the interpretation of Allas *et al.*[2] that the giant resonance in ^{12}C is a well mixed set of states with rather uniform angular-momentum characteristics.

There nevertheless remain discernible differences in the excitation of ^{12}C in this energy region. The $(\gamma,p)/(\gamma,n)$ ratio appears to vary appreciably in this region,[11] presumably because of a slight variation in isotopic-spin admixture. Also, the transition probability to excited states in ^{11}C with the emission of photoneutrons seems to vary,[11,12] perhaps because of the presence of localized two-particle–two-hole excitations.[11]

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