THE ANGULAR DISTRIBUTION OF PROTONS FROM THE $^{12}C(\gamma, p_0)^{11}B$ REACTION IN THE GIANT RESONANCE REGION

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Summary

Proton spectra from the $^{12}C(\gamma, p_0)^{11}B$ reaction have been obtained at angles of 30°, 50°, 70°, 90°, 110°, 130°, and 150° using semiconductor detector telescopes. From these spectra the angular distribution of the $^{12}C(\gamma, p_0)^{11}B$ reaction has been determined every 250 keV throughout the excitation energy region between 20 and 27 MeV. The observed energy dependence of the angular distribution is compared with that expected from the collective correlations model description of ^{12}C.

I. Introduction

Since ^{12}C is a self-conjugate closed subshell nucleus, it is particularly suited to application of the particle–hole model and, consequently, numerous descriptions of its E1 photo-excitation have been based on this model. These descriptions (e.g. Gillet 1962; Vinh-Mau and Brown 1962) were able to account for the major resonance in the photo-absorption cross section at about 22 MeV, but they were unable to account for the higher energy subsidiary resonance found at about 25·5 MeV. However, the recent collective correlation calculations of Drechsel, Seaborn, and Greiner (1966) and Kamimura, Ikeda, and Arima (1967) which have taken into account the coupling of the 1^- states of ^{12}C with its quadrupole surface vibration have provided a much better description of the photo-absorption cross section.

As the collective correlations model also describes the photo-absorption cross sections of ^{32}S (Webb, Spicer, and Arenhövel 1968), ^{28}Si, and ^{60}Ni (Drechsel, Seaborn, and Greiner 1967) better than previous models, it is important to establish whether the success of this model is fortuitous or is of a substantial nature. Any theoretical description of a nucleus involves a calculation of the nuclear wavefunctions, the nature of which affects the predicted angular distribution of the photonucleons. Therefore, a comparison between the predicted and experimentally observed angular distributions of photoprotons from ^{12}C should provide a good test of the model.

Many studies of the angular distribution of the photoprotons from ^{12}C had been made at the time the present work was contemplated (see Toms 1967 for references). Of these the most thorough was that of Allas *et al.* (1964), who obtained the energy dependence of the angular distribution of the $^{12}C(\gamma, p_0)^{11}B$ reaction throughout the giant resonance region. Unfortunately these workers only recorded data at five angles and were therefore unable to assess the precision of their angular distributions. Since it is important that both the angular distribution and its precision be known it was decided to remeasure the $^{12}C(\gamma, p_0)^{11}B$ angular distribution over the giant resonance region taking data at a greater number of angles.

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II. Experimental Details

As facilities were available for simultaneously recording data taken at four angles, and data taken at six or more angles would be sufficient, proton spectra were measured at laboratory angles of 30°, 50°, 70°, and 90° and then at 90°, 110°, 130°, and 150°, the detectors having an angular acceptance of $\pm 10°$. Bremsstrahlung with an endpoint energy of 31·5 MeV was used to irradiate a 2·75 mg cm^{-2} polyethylene target. This was mounted at an angle of 45° to the γ-ray beam in the 20 in. internal diameter duralumin scattering chamber described by Stewart (1968). A thick walled ionization chamber, which is a replica of that described by Pruitt and Domen (1962), was used to measure the integrated γ-ray flux producing the spectra.

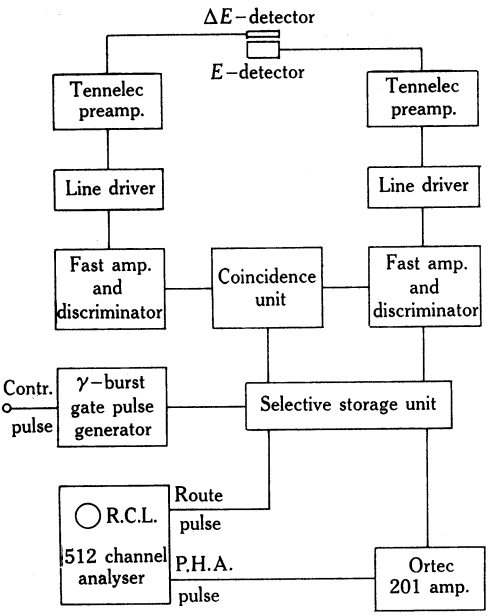

Fig. 1.—Block diagram of electronics.

Photons of less than 32 MeV energy excite states in ^{12}C which decay almost exclusively by proton emission to the ground state of ^{11}B (Hayward 1963). Moreover the cross section for photoproton emission by ^{12}C is much larger than that for other charged photoparticles at excitation energies below 31·5 MeV, so that for practical purposes it was assumed that the only charged particles produced were electrons and protons from the $^{12}C(\gamma, p_0)^{11}B$ reaction. Semiconductor detector telescopes, comprising a 50 μ transmission ΔE-detector and a 1000 μ E-detector, were used to discriminate against electron pulses.

A block diagram of the circuitry associated with one of the detector telescopes is presented in Figure 1. Since only protons of less than 12·3 MeV can be stopped in the telescopes, and these lose more than 320 keV in the ΔE-detector, whereas electrons lose less than 100 keV, a bias of 320 keV was applied to the ΔE-discriminator. Also, a bias of 700 keV, which corresponds to the minimum energy loss of an electron

in the E-detector, was applied to the E-discriminator. The coincidence requirement also eliminated pulses caused by protons from $^{28}Si(n, p)$ reactions initiated in the detectors by background neutrons.

In order to minimize pile-up effects, the time duration of the γ-ray burst was lengthened to about 150 μsec and the pulse length in the circuitry where both electron and proton pulses were present was kept below $0 \cdot 5$ μsec. To eliminate background outside the beam interval the pulse height analyser was gated on only during beam bursts. A typical charged particle spectrum is presented in Figure 2.

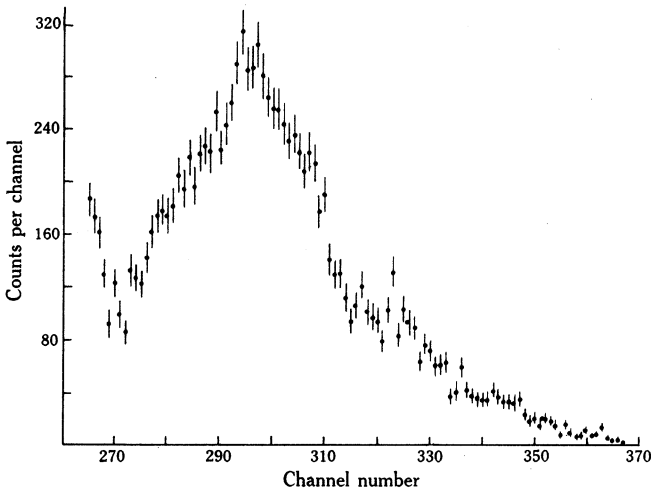

Fig. 2.—Charged particle energy spectrum for ^{12}C at 50°.

The stability of each of the detection systems was checked every 2 hr by feeding standard pulses into the preamplifiers. Both the temperature and pressure were monitored to enable corrections to be applied to the ionization chamber readings. Before and after each run the energy calibrations of the detection systems were measured using the α-particles from a ThC+C′ source.

III. Analysis of Data

All the spectra were normalized to a common integrated γ-ray flux. Electron background, evident only in the 30° and 50° spectra, was estimated by fitting an exponential through the data in the lowest channels. The background spectra were also subtracted. Corrections were made for different detection efficiencies due to the slightly different geometry at each angle. Using the range–energy data given in the ORTEC (1965) manual, a correction was made for the energy lost by protons in travelling through the ΔE-detectors.

The two 90° spectra were summed and divided by the bremsstrahlung number distribution function to produce the 90° differential cross section for the $^{12}C(\gamma, p_0)^{11}B$ reaction as presented in Figure 3. The errors are simply statistical standard deviations of the composite spectrum.

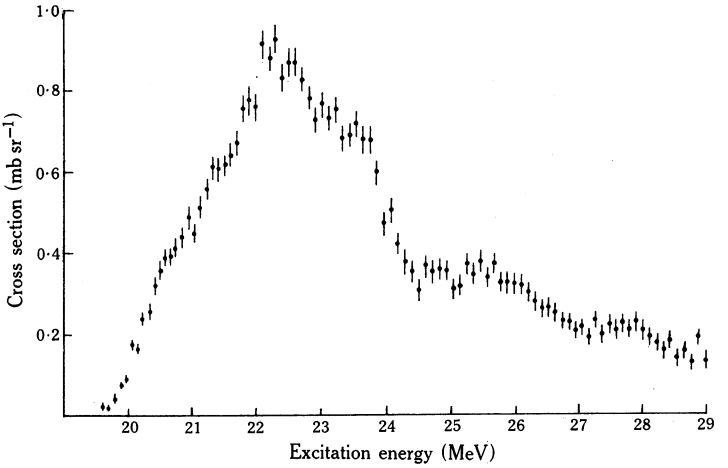

Fig. 3.—Differential cross section at 90° for $^{12}C(\gamma, p_0)^{11}B$.

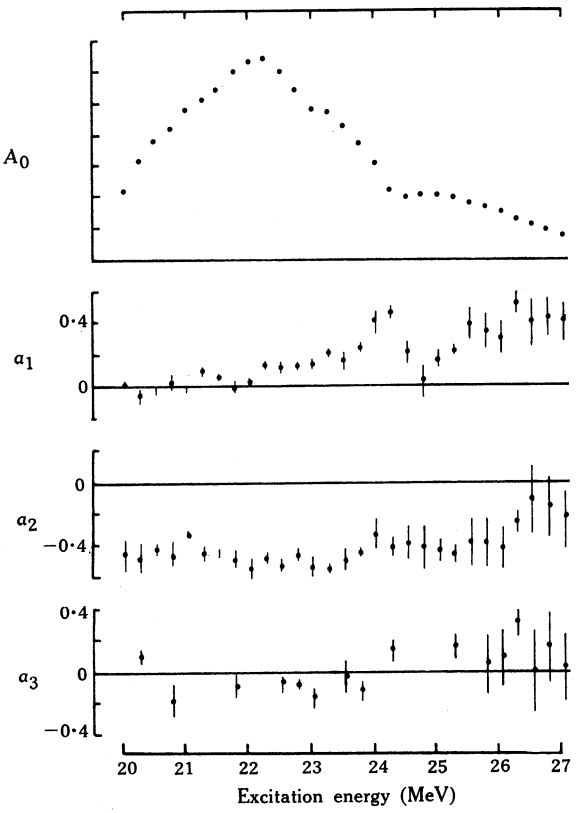

Fig. 4.—Angular distribution coefficients.

The differential cross section, which is a function of energy and angle, may be written

$$\frac{\mathrm{d}\sigma(E,\theta)}{\mathrm{d}\Omega} = \frac{k}{E}\sum_{tt'} W_{tt'}(\theta)\, S_t(E)\, S_{t'}(E)\,, \tag{1}$$

where k is a constant, the $S_t(E)$ are matrix elements which are independent of angle, the $W_{tt'}(\theta)$ contain the angular dependence, t and t' are the quantum numbers defining the reaction channels, and the summation extends over all values of t and t' compatible with the conservation laws. As shown by Biedenharn, Blatt, and Rose (1952), the $W_{tt'}(\theta)$ can be written as a function of Legendre polynomials and Racah coefficients, which may be expressed in the form

$$W_{tt'}(\theta) = A_0\left(1+\sum_{l=1}^{n} a_l \mathrm{P}_l(\cos\theta)\right). \tag{2}$$

As it is unlikely that radiation with a multipolarity higher than quadrupole will participate, n may take a maximum value of four in equation (2).

The spectral data were summed in 250 keV bins, each of which was assigned a weight inversely proportional to its variance. The angular distribution of each interval was determined by least-squares fitting the weighted data to the function defined by equation (2) for all values of n from 1 to 4. The coefficients A_0 and a_l for the most significant fits, with confidence limits calculated from their variances, are presented in Figure 4. The a_4 coefficient has been omitted, since it did not significantly improve the fit.

IV. Discussion

The behaviour of a_1 and a_2 as found in the present work agrees fairly well with that found by Allas *et al.* (1964), and also with the preliminary results by Frederick (personal communication). However, there are some significant differences. The rapid fluctuation in a_1 between 23·5 and 25·0 MeV seen in the present work was less pronounced in Frederick's results, and was not found by Allas *et al.* On the other hand, the fluctuation which Frederick found at about 25 MeV is not evident in either the present work or that of Allas *et al.* The behaviour of a_3 is similar in all three studies.

The intensity and interference terms which may be present in the angular distribution under various circumstances were evaluated using the tables of Sharp *et al.* (1954), and are presented in Table 1. Since nonzero values of a_1 and a_3 were found, it is obvious from Table 1(*c*) that E1–E2 or E1–M1 interference, or both, must occur. The experimental values of four angular distribution coefficients will not allow the structure of the contributing states to be determined uniquely. However, some information about their structure can be obtained.

Since the coefficients a_1 and a_3 are small, interference effects must be small, so the value of a_2 is due primarily to E1 absorption. According to the calculations of Boeker (1963), there is no initial phase difference between emitted s- and d-wave protons; hence it is clear from Tables 1(*a*) and 1(*b*) that the 1^- states decay predominantly via channel spin 1 with the emission of d-wave protons.

The detailed wavefunctions given by the collective correlations model have not been published. However, above 20 MeV the 1-particle–1-hole states in both the simple particle–hole and collective correlations models are $[(1p_{3/2})^{-1}(1d_{3/2})]$ and $[(1p_{3/2})^{-1}\ (1d_{5/2})]$. These should decay predominantly by d-wave emission.

TABLE 1

CALCULATED ANGULAR DISTRIBUTION FUNCTIONS FOR $^{12}C(\gamma, p_0)^{11}B$ REACTION

J^π is for the intermediate state, s is the channel spin, and l_p and l'_p are the proton angular momenta

(*a*) *Intensity Functions*

Radiation	J^π	s	l_p	Intensity Function
E1	1^-	1	0	$3P_0$
		1	2	$(3/2)(2P_0-P_2)$
		2	2	$(3/2)(2P_0+P_2)$
M1	1^+	1	1	$(3/2)(2P_0+P_2)$
		2	1	$(3/10)(10P_0-P_2)$
		2	3	$(3/5)(5P_0-2P_2)$
E2	2^+	1	1	$(5/2)(2P_0+P_2)$
		1	3	$(5/7)(7P_0+4P_2-4P_4)$
		2	1	$(5/2)(2P_0-P_2)$
		2	3	$(5/7)(7P_0+P_2+6P_4)$

(*b*) *Interference Functions* (*I*)

Radiation	J^π	s	l_p	l'_p	Interference Function
E1	1^-	1	0	2	$(-3/\sqrt{2})P_2$
M1	1^+	2	1	3	$(-9\sqrt{3}/5\sqrt{2})P_2$
E2	2^+	1	1	3	$(5\sqrt{3}/7\sqrt{2})(P_2-8P_4)$
		2	1	3	$(5/7)(3P_2+4P_4)$

(*c*) *Interference Functions* (*II*)

s	Radiation	l_p	Radiation	l'_p	Interference Function
1	E1	0	M1	1	$(-3\sqrt{3}/\sqrt{2})P_1$
		2		1	$(3\sqrt{3}/2)P_1$
2	E1	2	M1	1	$(9\sqrt{3}/2\sqrt{5})P_1$
		2		3	$(-9/\sqrt{10})P_1$
1	E1	0	E2	1	$(3\sqrt{5}/\sqrt{2})P_1$
		0		3	$(-\sqrt{15})P_3$
		2		1	$(3/2\sqrt{5})(P_1-6P_3)$
		2		3	$(\sqrt{3}/\sqrt{10})(9P_1-4P_3)$
2	E1	2	E2	1	$(9/2\sqrt{5})(P_1+\frac{2}{3}P_3)$
		2		3	$(9/\sqrt{5})(P_1+\frac{2}{3}P_3)$
1	E2	1	M1	1	$(-3\sqrt{15}/2)P_2$
		3		1	$(3\sqrt{5}/\sqrt{2})P_2$
2	E2	1	M1	1	$(3\sqrt{3}/2)P_2$
		1		3	$(-3/\sqrt{2})P_2$
		3		1	$(3\sqrt{3})P_2$
		3		3	$(-3\sqrt{2})P_2$

The energies of the observed states agree reasonably well with the predictions of the collective correlations model. This latter model also predicts that the γ-ray absorption strength of the 25·5 MeV "state" comes from strength that has been transferred from the 1-particle–1-hole dipole state at 22 MeV by means of the core–particle–hole coupling. Therefore this state at 25·5 MeV should decay by emission of d-wave protons, a prediction which is well borne out by the experimental data.

The collective correlations model has not been developed to include states other than 1^- in the giant resonance region, and it is therefore not yet able to account for the behaviour of coefficients other than a_2.

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