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^{12}C(γ,p) reaction at $E_\gamma = 60$ MeV

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The ^{12}C(γ,p)^{11}B reaction has been studied using tagged photons and a new type of detector system that allowed proton groups leading to ^{11}B excited states to be resolved for the first time. A comparison between the intensities of states excited in the (γ,p) and (e,e′p) reaction reveals large differences, in particular for the 6.8 MeV doublet of ^{11}B. This may indicate the importance of two-nucleon effects for the (γ,p) reaction which contrasts the single nucleon virtual photon absorption observed for (e,e′p) reactions.

The (γ,p) reaction has been studied for many years and yet the exact mechanism for this most fundamental reaction remains somewhat uncertain. For example, a recent study[1] of the ^{16}O(γ,p) reaction for $E_\gamma = 100$–400 MeV indicates that the incident photon initially interacts mainly with two nucleons, in agreement with conclusions reached previously following measurements of (γ,p)/(γ,n) cross section ratios at lower energies for light nuclei.[2-6] However, a similar study[7] for ^{40}Ca indicates that the mechanism of photons interacting with single protons may be more important. One way that our understanding of the reaction process could be improved is to study the reaction leading to different low excited states of the same residual nucleus. The wave functions of these states can be better related to one another than the very different states associated with a study of A(γ,p)$B_{g.s.}$ reactions using a wide range of targets. So far, however, a detailed study of excited states has not been possible due to a lack of high-quality monoenergetic photon beams. The emergence of tagged photon facilities has now dramatically changed the situation.[8] However, since the usable photon fluxes on such facilities are low, the (γ,p) reaction to discrete states can only be studied if a detector system is constructed which has good energy resolution and large solid angle. In this paper we report the first results of a high resolution ^{12}C(γ,p)^{11}B study using such a special detector system and a tagged photon beam generated from the 100% duty cycle accelerator at the Institut für Kernphysik, Mainz University.

The experiment was conducted by directing a beam of 180 MeV electrons through a 25 μm thick Al radiator which produced a narrow forward cone of bremsstrahlung radiation around 0°. The corresponding energy degraded electrons scattered at ~0° were detected by the magnetic spectrometer that is normally used for electron scattering measurements.[9] The focal plane detector system allowed ~10^7 s^{-1} photons, in the energy range $E_\gamma = 56.5$–63.5MeV, to be "tagged" with a resolution of ~50 keV. The photon beam collimated to ~4 cm diameter impinged on a 10×10 cm carbon target of 20 mg cm^{-2} thickness placed parallel to the beam as shown in Fig. 1. The proton detector, also shown in Fig. 1, comprised a ΔE-ΔE-E system in which the E detector consisted of a cylindrical crystal of intrinsic germanium of area 2000 mm^2 and 1.5 cm thickness, positioned at 90° with respect to the beam direction and a distance of 12 cm from the target. The two ΔE detectors were large area (5×5 cm) silicon strip detectors.[10] These silicon detectors not only provided particle-identification information, but were also used to define the trajectories of the particles from the large illuminated target area. This system enabled a large effective detection solid angle to be subtended at the target (~0.1 sr), and permitted the emitted proton angular distribution to be determined with a resolution of ±5°.

For such a close geometry system it is not very practical to analytically calculate the effective solid angle of the detector. For this reason a Monte Carlo simulation program was used to track through the experimental geometry events emitted randomly over the target area and randomly in emission angle. By this method it was

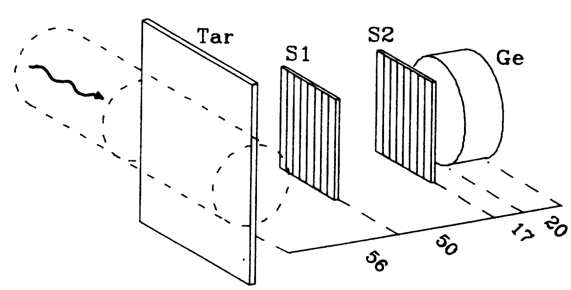

FIG. 1. The geometrical configuration of the detector system. The dashed cylinder represents the incident γ-beam profile incident on the target (Tar). Distances between the ΔE detectors ($S1$, $S2$), the germanium detector (Ge), and the target are given in mm.

possible to determine the effective detector solid angles for different emission angles.

The excitation energy spectrum for $E_\gamma = 60$ MeV is shown in Fig. 2; this spectrum is derived from an event by event analysis of the measured energy of the scattered electron and the energies deposited by the emitted proton in the three detector elements for each event. The energy resolution of the peaks in this spectrum is about 500 keV, and this is mostly determined by the energy loss that the protons suffer when they pass through the carbon target. For the first time, in the study of the (γ,p) reaction, peaks associated with different excitation states are clearly resolved. On the basis of energy, the ground $(J^\pi = \frac{3}{2}^-)$, the 2.1 MeV $(\frac{1}{2}^-)$, and the 5.02 MeV $(\frac{3}{2}^-)$ states of ^{11}B are excited. There is no evidence for populating the $\frac{5}{2}^-$ level of ^{11}B at 4.45 MeV. The strong peak at 6.8 MeV could either be due to feeding the 6.74 MeV $(\frac{7}{2}^-)$ or the 6.79 MeV $(\frac{1}{2}^+)$ state. The continuum above 10 MeV excitation has been ascribed to the quasideuteron mechanism.[11] The angular distributions for each of the observed peaks are shown in Fig. 3. The data are normalized so that the yield at $\theta = 90°$ for the g.s. transition agrees with previous (γ,p_0) measurements.[12]

One possible way to help elucidate the (γ,p) reaction mechanism is to compare spectra, such as shown in Fig. 2, with those obtained from high resolution studies of the (e,e'p) reaction. A recent study[13] of the $^{12}C(e,e'p)^{11}B$ reaction showed that, in common with the present data, the g.s., 2.12, and 5.02 MeV states are excited. There is no evidence for the excitation of the 4.45 MeV state in either reaction, but in contrast to the (γ,p) reaction, the (e,e'p) reaction only weakly excites states at ~6.8 MeV (Ref. 13) at least up to missing momentum, p_m, ~220 MeV/c. The interpretation of the (e,e'p) data is that the g.s., 2.12 and 5.02 MeV states are excited by a one step direct knockout of $1p$ shell nucleons. The absence of any strength[14] for the 4.45 MeV state of ^{11}B indicates that the $1f_{5/2}$ component in the g.s. wave function of ^{12}C is small,

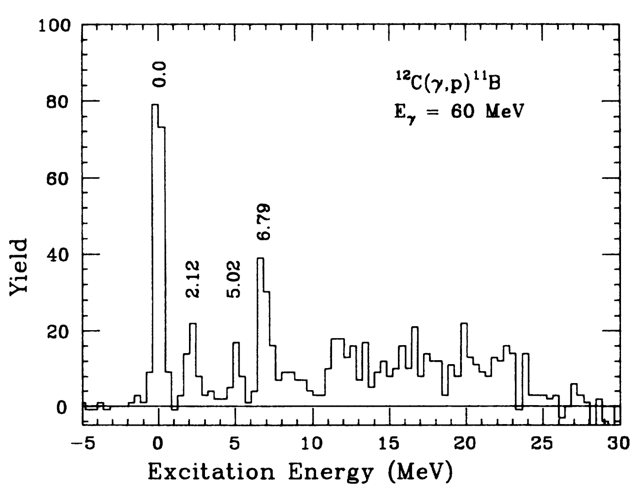

FIG. 2. Excitation energy spectrum of the residual ^{11}B nucleus. This spectrum corresponds to the integrated yield for all emission angles corresponding the detector configuration shown in Fig. 1.

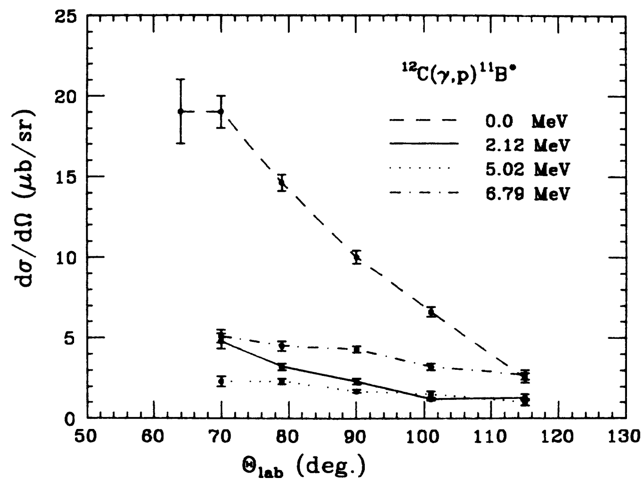

FIG. 3. Angular distributions for ground state and discrete excited states of ^{11}B.

so resulting in a small direct knockout component. This result is apparently consistent[14] with shell model calculations for the ground-state configuration of ^{12}C.

Since the (γ,p) reaction strongly excites the same low-lying negative parity states it could be concluded that the (γ,p) reaction proceeds mainly by direct proton knockout. This conclusion is supported by the fact that the yields of each of these states measured in this work, Table I, are correlated with the spectroscopic factors determined from reactions that are single particle in nature, e.g., (e,e'p). However, with a knockout model it is difficult to account for the ratio $(\gamma,p_0)/(\gamma,n_0) \sim 1$ observed for light nuclei.

The most striking difference between the $^{12}C(\gamma,p)^{11}B$ and $^{12}C(e,e'p)^{11}B$ spectra is the intensity of excitation in the region of the 6.8 MeV doublet (6.74 MeV, $\frac{7}{2}^-$; 6.79 MeV, $\frac{1}{2}^+$). This doublet is only seen in the (e,e'p) spectra for low transferred momentum to the knocked-out proton.[13] Indeed, the yield of this peak as a function of p_m is maximum at $p_m = 0$ and falls off rapidly (at $p_m = 100$ MeV/c the yield is ~0.1 of the maximum) which is characteristic of proton knockout from an s shell, suggesting that the yield of the 6.8 MeV peak is mostly due to the 6.79 MeV $(\frac{1}{2}^+)$ state. Even at $p_m = 0$ however, the yield of this state is still very weak (~0.03) when compared to the ground-state transition. At $p_m \sim 250$ MeV/c appropriate for the (γ,p) reaction studied here it would be

TABLE I. Comparison of cross-section ratios to spectroscopic factor ratios. $\sigma_i(\exp) \equiv 2\pi\int_{60°}^{120°}(d\sigma/d\Omega)_i \sin\theta d\theta$; $(C^2S)_i \equiv$ spectroscopic factor for state i (Ref. 19).

State i (MeV)	$\frac{\sigma_i(\exp)}{\sigma_{g.s.}(\exp)}$	$\frac{(C^2S)_i}{(C^2S)_{g.s.}}$
g.s.	1.0	1.0
2.1	0.26	0.17
4.45	<0.02	. . .
5.05	0.16	0.11
6.7	0.35	. . .

expected that the yield from $1s$ knockout would be very much smaller. It is possible that $2s$ proton knockout makes a contribution to the excitation of this state, since the $2s$ proton wave function has a second maximum at ~ 250 MeV/c. However, a calculation of the spectroscopic factors for ($1s$) and ($2s$) knockout leads to the conclusion the $2s$ contribution is very small.[13] If the reaction mechanism for (γ,p) to excite the 6.79 MeV state is similar to that for (e,e′p), it is difficult to understand why this state is excited so strongly for the (γ,p) reaction.

One possible explanation is that the 6.8 MeV state in the (γ,p) reaction is the $\frac{7}{2}^-$ state rather than the $\frac{1}{2}^+$ state. However, there is little evidence that this state is excited in the (e,e′p) reaction. That this state is not observed in (e,e′p) is consistent with shell model calculations which ascribe a small $1f_{7/2} \sim 0.1$ wave function amplitude component to the ground state of ^{12}C.[13] It is possible that the $\frac{7}{2}^-$ state could be excited by two step mechanisms such as those proposed to explain the excitation of this state in hadron induced reactions, e.g., (p,2p), (d,^{3}He), (t,^{4}He).[15–17] However, such a mechanism would also lead to the excitation of the 4.45 MeV ($\frac{5}{2}^-$) state as indeed is observed in the hadron reactions. The absence of the $\frac{5}{2}^-$ state therefore indicates that the two-step processes are not very probable for this (γ,p) reaction. A similar conclusion has also been reached for the (e,e′p) reaction.[14]

The above considerations lead to the conclusion that the (γ,p) reaction mechanism contains components that originate from processes other than direct knockout. As mentioned in the Introduction, one possibility is that a photon interacts with two correlated nucleons where one nucleon is ejected while the other absorbs momentum into the residual $A-1$ nucleus. Such a model to describe ground state transition was first introduced by Schoch[18] to account for (γ,n)/(γ,p) cross section ratios. The reason why this process may provide an explanation for exciting the 6.8 MeV ($\frac{1}{2}^+$) state, is that the momentum balance involves two particles in the final channel instead of just one. For this two-particle channel $\mathbf{k}_n+\mathbf{k}_p+\mathbf{k}_\omega=\mathbf{k}'_n+\mathbf{k}'_p$ where $\mathbf{k}_n,\mathbf{k}_p,\mathbf{k}_\omega$ are the momenta of the neutron, proton, and photon, respectively. Therefore, the momentum of the initial proton that can contribute to the γ absorption spans a much wider momentum range than for the case where only the proton is involved in the interaction. For example, if we assume the γ ray interacts with a $1s_{1/2}$ neutron proton pair, leading to a proton ejection of momentum ~ 250 MeV/c, then there is an appreciable probability that the neutron can absorb ~ 150 MeV/c between its initial and final states, i.e., $\mathbf{k}_n-\mathbf{k}'_n \sim 150$ MeV/c. In this case the proton in its initial state would only need $p_m \sim 100$ MeV/c compared to $p_m \sim 250$ MeV/c if the neutron did not participate in the interaction. Since the $s_{1/2}$ momentum wave function is larger at this lower momentum, the yield of such two nucleon processes could be expected to be significantly greater than for the one-particle process.

Although this interpretation offers an attractive explanation of the observed 6.8 MeV state there is a possible problem when the nucleon pair originate from the $1p$ shell. Proton ejection from the $1p_{3/2}$ accompanied by neutron excitation from $1p_{3/2} \rightarrow 1p_{1/2}$ would give rise to excited ^{11}B states $J^\pi = \frac{1}{2}^-, \frac{3}{2}^-, \frac{5}{2}^-$, and $\frac{7}{2}^-$. Although the observed 2.14, 5.02, and 6.8 MeV peaks could be due to exciting the $J^\pi = \frac{1}{2}^-, \frac{3}{2}^-$, and $\frac{7}{2}^-$ states respectively by this mechanism it is difficult to understand the absence of the 4.45 MeV ($\frac{5}{2}^-$) state in the data. This observation could be understood if the probability for the neutron to remain in its initial orbit (while still absorbing momentum) is much larger than for it to change orbit because then the yields of the $\frac{5}{2}^-$ and $\frac{7}{2}^-$ states would be suppressed. Clearly, a detailed calculation is needed within the two nucleon absorption model of the probabilities for the neutron remaining in its initial state or being excited.

For the reasons given above it is not easy to decide the relative importance of one- or two-particle reaction mechanisms for the (γ,p) reaction for ^{12}C. However, the strong yield of the 6.8 MeV state suggests a dominant two-particle mechanism for exciting this particular state. This initial study therefore indicates the value of determining the (γ,p) yield to different final states, because the reaction mechanism may involve one- and two-particle processes to different degrees for different states of the residual nucleus. In order to gain a deeper understanding of the mechanism it would be clearly helpful to study the (γ,p) reaction for targets corresponding to filling different shells.

The emergence of tagged photon facilities, coupled to state of the art semiconductor charge particles detectors provide a unique opportunity to study with high precision one of the most fundamental nuclear reactions, i.e., (γ,p). The results of the present study of this reaction for ^{12}C shows that the (γ,p) reaction studied at high resolution, is not simply an appendix to the impressive data obtained with the (e,e′p) reaction, but rather is a complementary reaction valuable in its own right.

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