Investigation of the $^{12}C(\gamma,pn)$ Reaction Using Tagged Photons

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(Received 23 March 1988)

Tagged-photon measurements of the $^{12}C(\gamma,pn)$ reaction in the photon energy range 83–133 MeV are reported. The measurements have achieved a good angular resolution, $\simeq 4°$, and a better missing-energy resolution, $\simeq 8$ MeV, than any previous measurement. This has allowed events to be selected in which both the neutron and proton are ejected from the $1p$ shell of the ^{12}C nucleus. The correlation of the momenta of the outgoing nucleon pairs is quantitatively explained by the quasideuteron mechanism.

PACS numbers: 25.20.Lj, 27.20.+n

At energies between the giant dipole resonance and the threshold for pion photoproduction, the two-nucleon contribution to photoreactions is strongly favored[1] because of the large momentum mismatch between the incident photon and the outgoing nucleon, which is typical of one-nucleon interactions. Previous investigations of the (γ,pn) reaction[2-5] showed the importance of the emission of proton-neutron pairs and established their strong back-to-back angular correlation. This left little doubt as to the qualitative correctness of the two-nucleon absorption mechanism, which found a natural explanation in the quasideuteron model,[1] in which the photon interacts with a proton-neutron pair in close proximity, while the rest of the nucleus acts as a spectator. However, technical limitations have generally prevented a convincing quantitative investigation of this type of reaction. Where this has been attempted, the agreement with theory has not been entirely satisfactory.

In early bremsstrahlung experiments,[2-5] where the incident photon energy was unknown, it was necessary to make assumptions about the mean excitation energy of the residual nucleus and, therefore, reconstruction of the reaction kinematics was not possible. More recently, systematic investigations with tagged photons over a wide photon-energy range and with a series of targets[6,7] have allowed the kinematic reconstruction of each event. These studies confirmed the dominance of the (γ,pn) channel over the (γ,pp) channel. However, the best overall energy resolution achieved, $\simeq 30$ MeV, was insufficient to determine the initial shells of the emitted nucleons, so that the source of problems encountered in trying to fit the angular correlation could not be traced. In two special cases, a kinematic reconstruction and a detailed comparison with theory have been achieved. In a $^{6}Li(\gamma,pn)$ bremsstrahlung measurement[8] at low photon energies (35–65 MeV), the production of a residual α particle was assumed so that the photon energy could be reconstructed from three-body kinematics. The observed angular correlation is only in moderately good accord with the shape calculated under the assumption of harmonic-oscillator wave functions for the two $1p$ nucleons. More recent results[9] with 80-MeV tagged photons suggest that the residual nucleons remain in the form of an α particle with less than 50% probability, although it is not obvious that this is responsible for the discrepancy. Cloud-chamber[10] and diffusion-chamber[11,12] techniques have also been used to study the (γ,pn) reaction. These experiments have been used to give an estimate of the initial momentum distribution of the p-n pairs emitted from the $1p$ shell in ^{12}C, but suffered from poor momentum resolution and statistics.

The study of the two-body photon absorption mechanism has been advocated as a method of investigating the short- and medium-range nucleon-nucleon correlations in nuclei. Gottfried[13] has shown that the (γ,pn) cross section can be expressed as a product of two factors, one being the distribution of momenta of the initial p-n pair, $F(P)$, and the other dependent on the nucleon-nucleon correlations. However, before information on nucleon-nucleon correlations can be extracted, a more quantitative understanding of the reaction mechanism must be established.

The present measurements used the tagged-photon technique, which holds great promise for future photonuclear work with its obvious advantages of determining both the incident photon energy and the photon flux. The tagged-photon spectrometer[14] on the Mainz 100%-duty-cycle 180-MeV electron microtron has an energy resolution of 0.5 MeV, and a count-rate capability of up to $\sim 10^8$ tagged photons per second. Photons were tagged from 83 to 133 MeV in a single spectrometer setting. The photon beam was incident on a 215-mg/cm^2 CD_2 target. Protons were detected over the angular range 55° to 125° in a position-sensitive plastic-scintillator telescope[15] with a solid angle of 0.7 sr. Measurements of neutron energies relied on the time-of-flight technique with an array of eight 1 m×20 cm×20 cm plastic-scintillator detectors, placed 4 m from the target and covering the 67° to 127° angular range on the opposite side of the target. The neutron detectors did not have any charged-particle veto detectors in front of them. However, an analysis of the neutron pulse height versus energy spectra gave an upper limit of 3% for $\sigma(\gamma,pp)/\sigma(\gamma,pn)$. The overall energy resolution was $\simeq 8$ MeV and the total angular resolution was $\simeq 4°$, which are much improved over earlier experiments. The data were recorded event by event and the detailed analysis was carried out off-line. Most of the detector background was rejected electronically, with the remainder being reduced off-line by careful selection of events according to their timing and pulse-height characteristics. Full details of the data reduction are given elsewhere.[16]

To enable an investigation to be made of the shells from which the nucleons are ejected, the spectrum of missing energies $E_m = E_\gamma - E_p - E_n - E_{\text{recoil}}$ shown in Fig. 1 was calculated. The width of the peak at 2.2 MeV, produced by the photodisintegration of deuterium contained in the CD_2 target, gives a good estimate of the overall missing-energy resolution. However, the data do not exhibit structure which would allow a totally unambiguous separation of events in which two $1p$ nucleons are emitted from those in which a more tightly bound $1s$-shell nucleon is ejected. Nevertheless, the peak centered at $E_m = 28$ MeV, close to the $^{12}C(\gamma,pn)$ reaction threshold (27.4 MeV), has a width only slightly greater than the overall resolution and indicates a large probability of leaving the residual ^{10}B in its ground or low-lying states. For the purpose of further analysis, events with 15 MeV $< E_m <$ 40 MeV were assumed to result from the emission of two $1p$ nucleons.

The next step in the analysis is to test the quasideuteron mechanism quantitatively. This is done by our reconstructing the momenta of the recoil nuclei, $\mathbf{p}_{\text{recoil}} = \mathbf{p}_\gamma - \mathbf{p}_p - \mathbf{p}_n$, from the event-by-event data. In the absence of any final-state interaction, the initial momentum of the p-n pair $\mathbf{P}$ is simply equal to $-\mathbf{p}_{\text{recoil}}$. The distribution $F(P)$ is then compared with a quasideuteron calculation using Woods-Saxon wave functions for the two $1p$ nucleons. In making this comparison, account must be taken of the finite solid-angle and energy acceptance of the detectors used, which tend to preferentially select higher-energy events in which the p-n pairs are emitted back to back in the laboratory frame. The bias produced by this sampling was treated in a Monte Carlo calculation. Figure 2 shows the deduced distribution of initial pair momenta, compared with the calculated distribution, after allowance for the detector sampling bias (solid line). The calculated

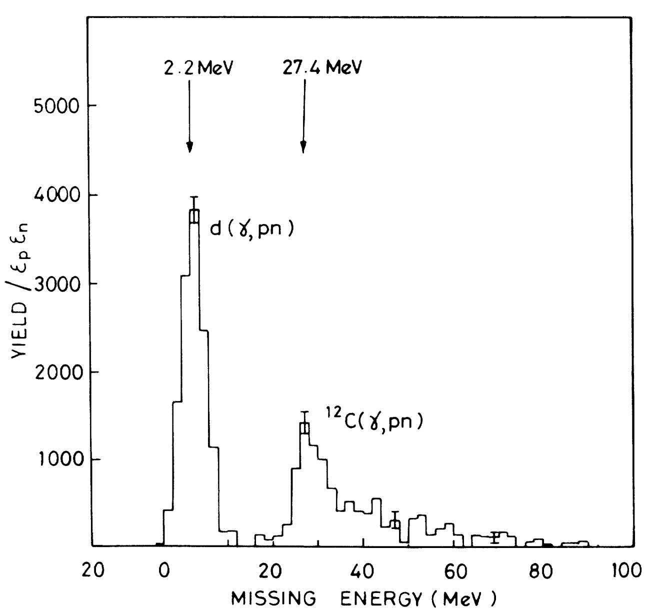

FIG. 1. Missing-energy spectrum from a CD_2 target. The arrows indicate the threshold energies for the $d(\gamma,pn)$ and $^{12}C(\gamma,pn)^{10}B$ reactions.

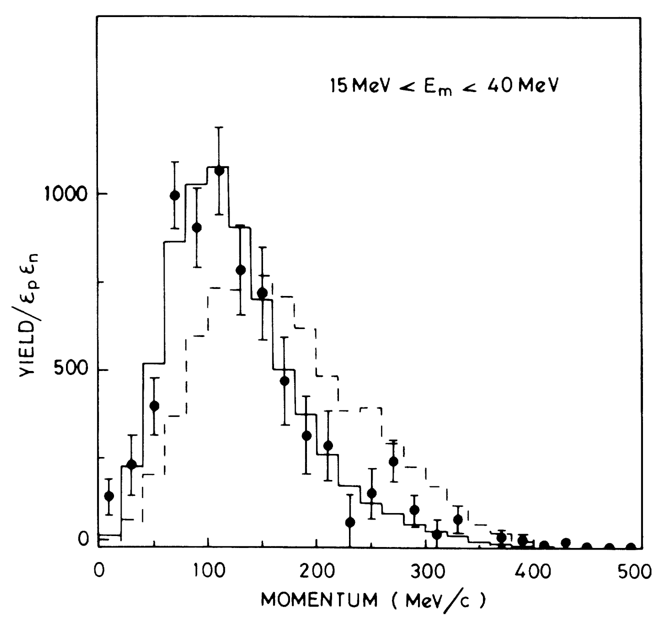

FIG. 2. Experimental distribution of the deduced initial p-n pair momenta, for nucleons emitted from the $1p$ shell of ^{12}C. The solid line is the prediction of the quasideuteron model after allowance has been made for detector bias. The dashed line is the phase-space prediction after allowance for detector bias.

curves have been normalized to have the same area as the data. The agreement is excellent. Comparison is also made with the distribution expected if the final-state kinematics were determined purely by phase-space considerations (dashed line), again with allowance for the detector sampling bias. This distribution is significantly different from that arising from the quasideuteron mechanism. Figure 2 provides strong evidence that the quasideuteron description is quantitatively correct.

Data obtained at higher missing energies, 40 MeV $< E_m <$ 65 MeV, where the nucleons are likely to be ejected, one each, from the 1s and the 1p shells, were also analyzed to produce the momentum distribution, shown in Fig. 3. However, the statistical accuracy is much poorer, as a larger proportion of events are lost below the detector biases. Again the data agree with the quasideuteron prediction, but the accuracy of the data is too poor for this to be taken as significant. In order to obtain reliable results in this region, data taken with higher photon energies would be required. At higher energies fewer events would be lost below the detector biases and the differences between the quasideuteron and phase-space predictions become more pronounced.

Experiments of this type will certainly be affected by final-state interactions of the outgoing nucleons. The extent to which these might affect the shape comparison in Fig. 2 is now considered. The proportion of events which are completely lost from the selected missing-energy range, 15 MeV $< E_m <$ 40 MeV, is estimated to be $\simeq$35% by comparing the measured cross section, after Monte Carlo correction for the detector acceptances, with that obtained from the Levinger quasideuteron model.[1] This should be regarded as an upper limit, as

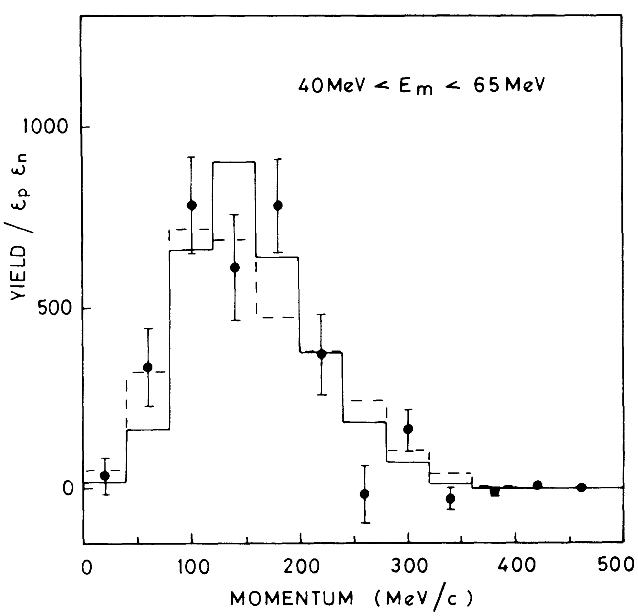

FIG. 3 As Fig. 2, for events with 40 MeV $< E_m <$ 65 MeV.

the Levinger model may overestimate the cross section at the present low-photon energies. Those (γ,pn) events which are recorded may still be affected by final-state interactions which could weaken the angular correlation between the outgoing nucleons, giving larger deduced values for P and a distribution closer to the phase-space prediction. The first sign of this would be a tail in the experimental distribution on the high-P side. This is not evident in Fig. 2, suggesting that the bulk of the data is unaffected and that the agreement of the data with the calculated shape remains valid. It is likely that all of the missing p-n pairs are to be found at high missing energies, but to determine this is beyond the scope of the present measurement.

This experiment has obtained data with a missing-energy resolution, $\simeq$8 MeV, which has not previously been achieved. An accurate kinematic reconstruction of each event has allowed a quantitative analysis of the reaction mechanism to be made. The quasideuteron model gives an excellent description of the distribution of initial p-n pair momenta. This represents an important advance in the quantitative understanding of photonuclear interactions in the intermediate-energy region. It may now be possible to use (γ,pn) reactions to study the systematics of nucleon-nucleon correlations for each shell, by dividing out the $F(P)$ dependence of the cross section from the data.

The authors are grateful to the Deutsche Forschungsgemeinschaft and the United Kingdom Science and Engineering Research Council for supporting this work. The United Kingdom members of the collaboration also wish to thank the Institut für Kernphysik, Mainz University for the use of their facilities and for the assistance received during the course of this experiment. Three of us (S.N.D., P.A.W., and S.V.S.) are grateful to the Science and Engineering Research Council for providing financial support in the form of research studentships during the period of this work.

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