Quasifree π^+ production studied using the $^{12}C(\gamma,\pi^+n)^{11}B$ reaction in the $\Delta(1232)$ resonance region

J. A. MacKenzie,[1] D. Branford,[1] J. Ahrens,[4] J. R. M. Annand,[2] R. Beck,[4] G. E. Cross,[2] T. Davinson,[1] P. Grabmayr,[3] S. J. Hall,[2] P. D. Harty,[2] T. Hehl,[3] D. G. Johnstone,[1] J. D. Kellie,[2] T. Lamparter,[3] M. Liang,[1] I. J. D. MacGregor,[2] J. C. McGeorge,[2] R. O. Owens,[2] M. Sauer,[3] R. Schneider,[3] A. C. Shotter,[1] K. Spaeth,[3] P. J. Woods,[1] and T. Yau[2]

[1]*Department of Physics and Astronomy, University of Edinburgh, Edinburgh, EH9 3JZ, Scotland*

[2]*Department of Physics and Astronomy, University of Glasgow, Glasgow, G12 8QQ, Scotland*

[3]*Physikalische Institut, Universität Tübingen, D-72076, Tübingen, Germany*

[4]*Institut für Kernphysik, Johannes-Gutenberg Universität, D-55099, Mainz, Germany*

(Received 4 December 1995)

Results are presented from a coincidence study of the $^{12}C(\gamma,\pi^+n)^{11}B$ quasifree pion production reaction made in the Δ-resonance region using tagged photons. Cross sections for reactions originating on $1p$-shell protons are found to be significantly larger than predicted by calculations based on quasifree pion production. It is suggested that more sophisticated calculations, perhaps including medium effects, may be required to reproduce the data. [S0556-2813(96)50207-4]

PACS number(s): 25.20.Lj, 13.60.Le, 13.60.Rj 21.30.Fe

A useful method of investigating small systems such as clusters, molecules, atoms, nuclei, and nucleons is to study changes in their properties when placed in different environments. The excitation of nucleons into higher states has been extensively studied using free protons. Here we consider the possibility of studying excitation of protons embedded in nuclei. Excitation of the Δ(3,3) resonance at 1232 MeV is an important non-nucleonic degree of freedom that has to be taken into account when considering intermediate energy photonuclear reactions. Since the decays of Δ's excited at the early stages of photonuclear reactions are known to contribute significantly to quasifree pion photoproduction cross sections [1–3], it is thought that studies of these reactions may provide valuable information on Δ medium modifications. Here, we present first results from an extensive study of quasifree π^+ production on ^{12}C that was made to explore this possibility.

General features of the photoreaction mechanism for light nuclei at Δ-resonance energies have been established by inclusive and semi-exclusive $(\gamma,\pi^\pm)$ and (γ,p) measurements made using tagged photons at Tokyo [4], Bonn [5], and Mainz [6]. These measurements indicate that the main process is quasifree pion production in which a pion and nucleon emerge on opposite sides of the photon beam and the rest of the nucleus mainly acts as a spectator. Qualitatively good descriptions of the results are given by intranuclear cascade calculations made using models [1,5] that assume the process is mainly quasifree pion production followed by final-state interactions (FSI). Photon absorption on nucleon pairs occurs at the $\sim$ 20% level [4].

The development of more refined models clearly requires more exclusive measurements. However, to date, only two exclusive measurements, each covering very limited kinematical regions, have been reported. A measurement of the $^{12}C(\gamma,\pi^-p)$ reaction was made at Tomsk [7] using bremsstrahlung beams with end-point energies of E_γ=350, 370, and 390 MeV. The outgoing particles were detected at θ_π $=120°$ and θ_p=20° with respect to the beam direction. More recently, a measurement of the $^{16}O(\gamma,\pi^-p)$ reaction was carried out at E_γ=360 MeV using the MIT-Bates accelerator [8]. In this case, two pion angles, θ_π = 64° and 120°, were used and the protons were detected by five detectors arranged in a vertical array at correlated polar angles. The resolution of both experiments was such that quasifree events involving the removal of neutrons from $1p$ and $1s$ shells could be separated.

Cross sections calculated using the distorted wave impulse approximation (DWIA) code of Li, Wright, and Bennhold (LWB), which includes some effects of Δ propagation [2], have been compared to the Tomsk data. These non-local DWIA calculations are found to be in good agreement with the $1p$-shell data although they are less successful in describing the $1s$-shell data. The MIT data were compared initially to DWIA calculations made with the code THREEDEE [9], which uses the Blomqvist-Laget operator [10] for pion production on a free nucleon to describe the initial interaction. FSI are treated using optical model potentials. Although good agreement is observed with the data at θ_π = 120°, the calculations for θ_π = 64° are $\sim$3 times larger than the data. This was thought to be a consequence of the fact that Δ-propagation effects are not included in the THREEDEE code. However, more recent calculations [3] made by Sato and Takaki using the Δ-hole model, which effectively includes Δ-propagation effects, also give cross sections for θ_π=64° that are $\sim$3 times larger than the data. It was concluded therefore, that perhaps some hitherto unknown effect gives rise to strong absorption of pions that are emitted at relatively small θ_π.

The results presented here are the first to come from a study of the exclusive $^{12}C(\gamma,\pi^+n)$ reaction. This study is aimed at producing a much expanded data set which will help in refining the theoretical models, especially their Δ-excitation content. Measurements were made with photons in the range E_γ=114–792 MeV produced using the Glasgow

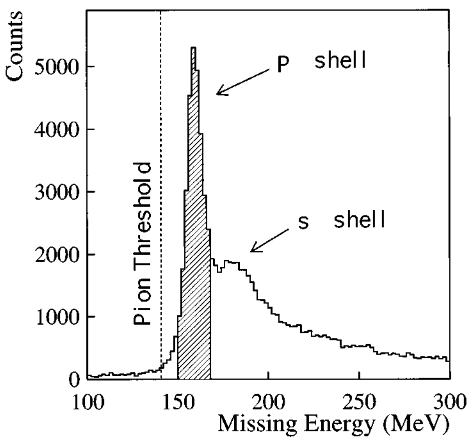

FIG. 1. Missing energy spectrum for the $^{12}C(\gamma,\pi^+n)$ reaction. The hatched area contains events selected for analysis of $1p$ proton removal.

photon tagging spectrometer [11,12] at the 855 MeV electron microtron accelerator MAMI of the Institut für Kernphysik, Mainz [13]. Positively charged pions were detected in a large position sensitive plastic scintillator hodoscope PiP [14] over the angular range $\theta_\pi = 50°$ to 130° and $\Delta\phi_\pi = 46°$, and the neutrons by an array of plastic scintillator time-of-flight (TOF) detectors [15] on the opposite side of the beam covering $\theta_n = 10°$ to 150° and $\Delta\phi_n = 40°$. The π^+ particles were selected using ΔE-E information and requiring that an afterpulse was present from the 2.2 μs decay of the μ^+ particle produced at the end of the track. The detector response (peak to total ratio) was improved by rejecting events where the energy deposited in any PiP layer was significantly different from that expected from purely electronic stopping [16].

The system was energy calibrated using cosmic rays and particles from the two-body reaction $p(\gamma,\pi^+n)$ produced in a CH_2 target. A measurement of the detection efficiency was made by comparing our coincidence $p(\gamma,\pi^+n)$ counting rates to rates calculated using the Blomqvist-Laget free-pion photoproduction operator [10] that gives results in good agreement with established measurements [17]. Simulations made of the PiP detector response for pions with the code GEANT [18] give an efficiency that agrees within 15%. All the results presented below were determined using the experimentally obtained efficiency that is effectively based on the well-established $p(\gamma,\pi^+n)$ cross section.

Figure 1 shows a missing energy spectrum for the $^{12}C(\gamma,\pi^+n)$ reaction using the definition

$$E_m = E_\gamma - T_\pi - T_n - T_{\mathrm{recoil}} = E_X - Q, \quad (1)$$

where T_{recoil} and E_X are respectively the kinetic energy (calculated using momentum conservation) and excitation energy associated with the recoiling $A=11$ system. Q is the Q value for the reaction in which the residual nucleus is left in the ground state. Random counts have been subtracted from this spectrum and all other results presented here. The spectrum has almost identical features to those previously observed using proton knockout reactions such as $^{12}C(e,e'p)^{11}B$ [19] and $^{12}C(p,2p)^{11}B$ [20]. Based on a comparison with these data, the large sharp peak and smaller

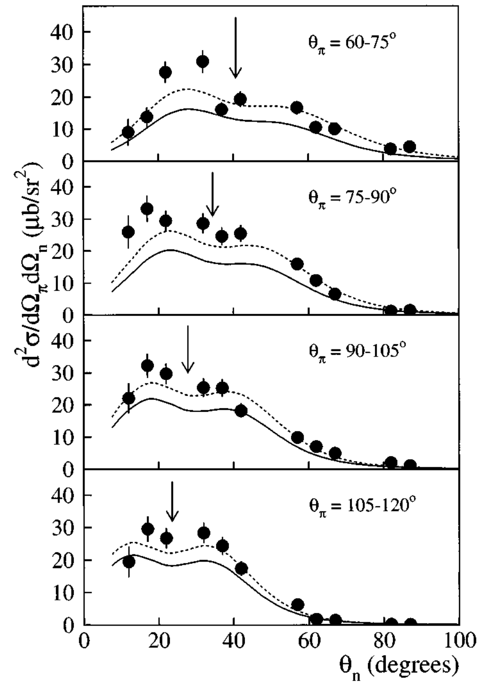

FIG. 2. Double differential cross sections for the $^{12}C(\gamma,\pi^+n)^{11}B$ reaction for E_γ=280–320 MeV versus neutron angle. The relative pion and neutron azimuthal angles are restricted to 180±10°, which selects essentially coplanar events. The pion energy acceptance is 20–180 MeV and the neutron energy threshold is 15 MeV. The curves are from THREEDEE calculations made using two different neutron optical potentials, Nadasen *et al.* (solid line) and Abdul-Jalil–Jackson (dashed line).

broad peak are assumed to be due to quasifree (γ,π^+n) events involving the removal of a $1p$ and $1s$ proton, respectively. The tail leading to higher missing energies is most likely due to events involving significant FSI or non-quasifree processes, where in either case one or more of the final-state particles is not detected. Since the large $1p$ peak is made up of events involving only moderately weak FSI, these events provide a window into the early stages of the reaction [2].

The large peak occurs at $E_m = 160 \pm 2$ MeV and has a full width at half maximum of $\sim$12 MeV that is noticeably broader than that observed for the $p(\gamma,\pi^+n)$ reaction (FWHM = 8 MeV). These results are consistent with the view that the large peak corresponds to the removal of a $1p$-shell proton. By analogy with the $^{12}C(e,e'p)$ measurement [21], which has better resolution, the $^{12}C(\gamma,\pi^+n)$ reaction would be expected to leave ^{11}B in the three low-lying single-hole states at 0.0 MeV ($J^\pi = 3/2^-$), 2.12 MeV ($J^\pi = 1/2^-$), and 5.02 MeV ($J^\pi = 3/2^-$) (E_m = 156.8, 158.9, and 161.8 MeV, respectively) and therefore give rise to a broader peak than that observed in the $p(\gamma,\pi^+n)$ measurement (E_m = 140.8 MeV). In the following, we present an analysis of the events corresponding to $1p$ proton removal that occur in the region $E_m = 150 - 165$ MeV.

An investigation of the reaction mechanism was made by examining the angular distributions of the emitted particles. Figure 2 shows a subset of the differential cross sections we obtained using this missing energy cut for the $^{12}C(\gamma,\pi^+n)$

reaction at a range of E_γ covering the $\Delta(3,3)$ resonance region. The errors shown are the statistical errors. Systematic errors are estimated to be on average approximately $\pm 10\%$, which includes a $\pm 7\%$ estimated uncertainty in the $p(\gamma,\pi^+n)$ cross section results [17] used in the determination of the detection efficiency. There is probably some scatter in the data due to the detection efficiencies having more structure than the fitted smooth curves used in the analysis. This is a consequence of the segmented nature of the detectors. It can be seen that the differential cross sections are centered around the angles expected for quasifree pion production that are indicated by arrows on the plots. The data are distributed over a relatively large range of θ_n as would be expected due to the Fermi motion of the struck proton. Furthermore there is weak evidence of the expected minimum at zero nucleon momentum in the initial $1p$ shell proton momentum distribution. The full data set shows that the cross sections are at their maxima at $E_\gamma = 340 \pm 20$ MeV, which corresponds to the energy at which the $\Delta(3,3)$ resonance in the $p(\gamma,\pi^+n)$ reaction is known to peak.

To consider our data on a more quantitative basis, we compared the results to DWIA calculations carried out using the code THREEDEE [9]. The proton $1p_{3/2}$ bound-state wave function was generated from a mean-field Woods-Saxon potential that reproduced the observed binding energy. In the case of the π^+ particle, distorted outgoing pion waves were generated using the Cottingame-Holtkamp pion nucleus optical potential [22], which was extracted from data obtained by scattering pions with energies greater than 100 MeV from several nuclei including ^{12}C. Two nucleon-nucleus optical potentials were employed to describe the outgoing neutrons, the Abdul-Jalil and Jackson potential [23] and that of Nadasen *et al.* [24]. The Abdul-Jalil–Jackson potential was extracted from proton scattering on ^{12}C at incident energies of 50–150 MeV. The Nadasen potential is a global parametrization based mainly on proton scattering at 80–180 MeV from the heavier isotopes of Ca, Zr, and Pb. It has nevertheless been used satisfactorily in a recent $^{12}\mathrm{C}(e,e'p)^{11}\mathrm{B}$ analysis [21]. All the theory results were multiplied by a spectroscopic factor of $S=2.6$ as used in LWB [2].

In general, the shapes of the calculated curves agree with experiment, although on average the experimental values are significantly larger. This result differs from that obtained for the $^{16}\mathrm{O}(\gamma,\pi^-p)^{15}\mathrm{O}$ reaction where the experimental results for pions at $\theta_\pi = 64°$ were a factor of three below the THREEDEE calculation [8]. It is difficult to reconcile the two experiments since (γ,π^+n) and (γ,π^-p) reactions on self-conjugate nuclei are, apart from relatively small Coulomb effects, expected to have similar characteristics. Since the data at forward and backward pion angles presented here were obtained simultaneously, which was not the case for the $^{16}\mathrm{O}(\gamma,\pi^-p)^{15}\mathrm{O}$ experiment, we conclude that the previous results may be in error, and the previously postulated strong attenuation of forward emitted pions [3], which would be difficult to explain, is not required.

The most interesting result to come out of our work is the fact that the data lie above the THREEDEE calculations. To investigate this further we have determined cross sections integrated over the neutron detection angles for the data and the two calculations at four energies spanning the $\Delta(3,3)$ resonance region. These results, shown in Fig. 3, clearly indicate that the $^{12}\mathrm{C}(\gamma,\pi^+n)^{11}\mathrm{B}$ cross section systematically exceeds the calculations. The most up-to-date analysis [25] by Ireland and van der Steenhoven of NIKHEF $^{12}\mathrm{C}(e,e'p)^{11}\mathrm{B}$ data gives the spectroscopic factor $S_0 = 2.3$ for the removal of a $1p$ proton leading to the ground state of ^{11}B. Furthermore, a recent $^{12}\mathrm{C}(e,e'p)^{11}\mathrm{B}$ measurement made at Mainz [26] suggests that S_0 is 16% lower than that reported in Ref. [25]. Assuming that this 16% reduction also applies to the excited states of ^{11}B we deduce that the spectroscopic factor appropriate for multiplying our THREEDEE results could be as small as $S=2.2$. Use of these lower spectroscopic factors would lead to even greater differences between the data and the calculations.

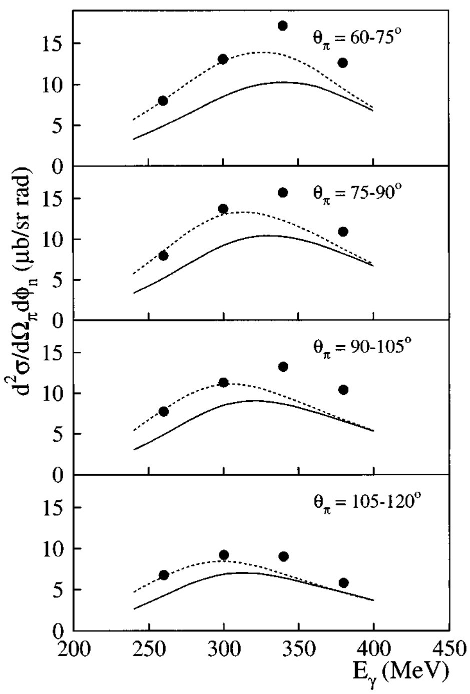

FIG. 3. Cross section results integrated over neutron polar angle (weighted by $\sin\theta_n$) versus photon energy. The photon energy bins are 40 MeV wide. The curves are as described in Fig. 2.

A possible explanation of these results is that the data contain a significant fraction of events from removal of $1s$ protons that are not adequately resolved from the $1p$ peak. It is unlikely though that this could explain fully the observed differences since the $(e,e'p)$ results indicate that the $1s$ strength is broadly distributed around 25 MeV ^{11}B excitation with only a small fraction extending down to $E_X < 10$ MeV. Based on these $(e,e'p)$ results, we estimate that not more than 10% of the events included in the missing energy cut could be due to $1s$ proton removal. However, a similar number of valid $1p$-shell events are expected to be shifted outside the selected missing energy region by resolution effects. Taking these considerations together, it seems unlikely that contamination of the results by events corresponding to $1s$ proton removal can explain the high experimental cross sections.

A more exciting possibility is that the above effects may be related to medium modifications that are not included in the THREEDEE model. Changes of the cross section could arise from modifications to the pion-production operator brought about by the nuclear environment or collective effects. Additionally, Δ's excited in the nucleus need not necessarily decay into $N+\pi$, since other channels such as $N+\Delta\rightarrow N+N$ are open. This however would not explain our results as it would reduce the Δ contribution to the exclusive quasifree (γ,π^+n) reaction. Clearly, investigation of the above effects requires the use of more sophisticated models such as that developed by LWB [2], which includes some medium effects. It is hoped that the results presented here will stimulate such investigations.

In conclusion, we have carried out the first extensive study of an exclusive reaction involving charged pions produced on a complex nucleus. The missing energy resolution is sufficiently good to allow $^{12}C(\gamma,\pi^+n)^{11}B$ events involving the removal of a $1p$ proton to be selected. Qualitative arguments and comparisons with calculations made using the code THREEDEE strongly support the assumption that the yield arises predominantly from quasifree pion production. No evidence is obtained for strong nuclear absorption of forward moving pions as suggested by $^{16}O(\gamma,\pi^-p)\,^{15}O$ measurements. The observation that the measured cross sections lie on average above the THREEDEE calculations highlights the need for more sophisticated calculations.

[1] R. Carrasco and E. Oset, Nucl. Phys. **A536**, 445 (1992); R. Carrasco, E. Oset, and L. L. Salcedo, *ibid.* **A541**, 585 (1992); R. Carrasco, M. J. Vicente Vacas, and E. Oset, *ibid.* **A570**, 701 (1994).

[2] Xiaodong Li, L. E. Wright, and C. Bennhold, Phys. Rev. C **48**, 816 (1993)

[3] T. Sato and T. Takaki, Nucl. Phys. **A562**, 673 (1993).

[4] S. Homma, M. Kanazawa, Y. Murata, and H. Okuno, Phys. Rev. C **27**, 31 (1983); S. Homma, M. Kanazawa, M. Koike, Y. Murata, H. Okuno, F. Soga, and N. Yoshikawa, Phys. Rev. Lett. **52**, 2026 (1984).

[5] J. Arends, J. Eyink, H. Hartmann, A. Hegerath, B. Mecking, G. Nöldeke, and H. Rost, Z Phys. A **305**, 205 (1982).

[6] G. E. Cross *et al.*, Nucl. Phys. **A593**, 463 (1995).

[7] I. V. Glavanokov, Sov. J. Nucl. Phys. **29**, 746 (1979).

[8] L. D. Pham *et al.*, Phys. Rev. C **46**, 621 (1992).

[9] N.S. Chant and P. G. Roos, Phys. Rev. C **15**, 57 (1977).

[10] I. Blomqvist and J. M. Laget, Nucl Phys. **A280**, 405 (1977).

[11] I. Anthony, J. D. Kellie, S. J. Hall, G. J. Miller, and J. Ahrens, Nucl. Instrum. Methods **A301**, 230 (1991).

[12] S. J. Hall, G. J. Miller, R. Beck, and P. Jennewein, Nucl. Instrum. Methods **A368**, 698 (1996).

[13] H. Herminghaus, A. Feder, K. H. Kaiser, W. Manz, and H. v. d. Schmitt, Nucl. Instrum. Methods **A138**, 1 (1976).

[14] I. J. D. MacGregor, in Proceedings of the Workshop on Future Detectors for Photonuclear Experiments, Edinburgh, 1991, edited by D. Branford (unpublished).

[15] P. Grabmayr *et al.*, in Proceedings of the Workshop on Future Detectors for Photonuclear Experiments, Edinburgh, 1991, edited by D. Branford (unpublished).

[16] D. Branford, Nucl. Phys. News **4.4**, 28 (1994).

[17] C. Betourne, J. C. Bizot, J. Perez-Y-Jorba, D. Treille, and W. Schmidt, Phys. Rev. **172**, 1343 (1968).

[18] R. Brun, M. Hansroul, and J.C. Lassalle, ''*GEANT User's Guide,*'' Report No. DD/EE/82 CERN (1982).

[19] J. Mougey, M. Bernheim, A. Bussiere, A. Gillebert, Phian Xuan Ho, M. Priou, D. Royer, I. Sick, and G. J. Wagner, Nucl. Phys. **A262**, 461 (1976).

[20] S. L. Belostotskii, S. S. Volkov, A. A. Vorob'ev, Yu. V. Dotsenko, L. G. Kudin, N. P. Kuropatkin, O. V. Miklukho, V. N. Nikulin, and O. E. Prokof'ev, Sov. J. Nucl. Phys. **41**, 903 (1985); Y. V. Dotsenko and V. E. Starodubskii, *ibid.* **42**, 66 (1985).

[21] G. van der Steenhoven, H. P. Blok, E. Jans, M. de Jong, L. Lapikas, E. N. M. Quint, and P. K. A. de Witt Huberts, Nucl. Phys. **A480**, 547 (1988); **A484**, 445 (1988).

[22] W.B. Cottingame and D.B. Holtkamp, Phys. Rev. Lett. **45**, 1828 (1980).

[23] I. Abdul-Jalil and Daphne F. Jackson, J. Phys. G **5**, 1699 (1979).

[24] A. Nadasen, P. Schwandt, P. P. Singh, W. W. Jacobs, A. D. Bacher, P. T. Debevec, M. D. Kaitchuck, and J. T. Meek, Phys. Rev. C **23**, 1023 (1981).

[25] D. G. Ireland and G. van der Steenhoven, Phys. Rev. C **49**, 2182 (1994).

[26] K. I. Blomqvist *et al.*, Z. Phys. A **351**, 353 (1995).