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$^{16}O(\gamma,\pi^+)^{16}N$ reaction at 320 MeV photon energy

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The pion angular distribution for the $^{16}O(\gamma,\pi^+)^{16}N$ reaction leading to the lowest quartet of states in ^{16}N has been measured at 320 MeV photon energy. The results are compared with a distorted-wave impulse approximation calculation.

Recent experimental results on $^{10}B(\gamma,\pi^+)^{10}Be_{(g.s.)}$ (Ref. 1), $^{14}N(\gamma,\pi^+)^{14}C_{(g.s.)}$ (Ref. 2), and $^{13}C(\gamma,\pi^-)^{13}N_{(g.s.)}$ (Ref. 3) in the Δ resonance region have generated renewed interest in the $(\gamma,\pi^\pm)$ reaction. Conventional calculations based on the distorted-wave impulse approximation (DWIA),[4,5] which use the nonunitarized version of the Blomqvist-Laget operator[6] and the phenomenological pion optical potential,[7] have had partial success at lower energies.[8] In the resonance region, however, these calculations have not had good success in fitting the new data. For the ^{14}N case at photon energy $k=320$ MeV, for example, the calculations underestimate the cross sections by a factor of 3. Recently, Wittman and Mukhopadhyay[9] have demonstrated that improvements to the single-nucleon operator and the pion optical potential in the DWIA approach lead to a better description of the ^{14}N data. However, their calculation still remains a factor of 2 below the experiment at $k=320$ MeV. There is some speculation that the failure of the DWIA theory is related to an inappropriate description of the delta dynamics in nuclei.[4,5] The delta-hole model is designed to treat production and propagation of the delta and the pion in the nuclear medium better than the DWIA in the resonance region. However, a recent calculation by Suzuki, Takaki, and Koch[10] with this model also shows similar difficulties as with the improved DWIA calculation[9] in explaining the data. In order to help elucidate this problem, we present in this Brief Report a new angular distribution measurement in the resonance region for the reaction $^{16}O(\gamma,\pi^+)^{16}N$.

Historically, due to the doubly-closed-shell nature of the ^{16}O nucleus, this reaction has attracted the interest of many theorists since the early days of the field.[11] Instead of listing all previous papers, we mention only two calculations by DeCarlo and Freed[12] and by Girija and Devanathan.[13] The customary approach to the (γ,π^+) calculations, as exemplified by these calculations, has used the DWIA in coordinate space. However, as shown recently by Toker and Tabakin[4] and by Tiator and Wright[5] for p-shell transitions, a momentum-space formalism is essential to take the nonlocality in the photoproduction operator properly into account. This is especially important at higher energies. Eramzhyan and co-workers (EGK) (Ref. 14) have also developed a momentum-space formalism, and applied it to several (γ,π^+) reactions including $^{16}O(\gamma,\pi^+)$.

In contrast to the theoretical effort, experimental information on this reaction was rather scarce before the start of this investigation. Full angular-distribution measurements have been limited to lower energies.[15,16] In the resonance region, data points exist at only two angles ($\theta=45°$ and 90°) and have large experimental uncertainties.[17] Since medium effects on the delta production and propagation are believed to be strongly energy dependent, it is of interest to confront theories with full angular-distribution data at a fixed energy near the free-nucleon resonance. The data reported here are the first such results on ^{16}O in the resonance region. As in the previous work, the cross section has been measured for the unresolved sum of the transitions to the four lowest-lying ^{16}N states ($J^P=2^-$, 0^-, 3^-, and 1^-; $E_x=0$, 0.12, 0.30, and 0.40 MeV, respectively).

The experiment was performed at the MIT-Bates Linear Accelerator at the same time as other (γ,π^+) measurements on ^{10}B and ^{14}N.[1,2] Details of the apparatus may be found elsewhere.[18] A mixed flux of real and virtual photons was due to the electron beam ($\Delta p/p=\pm 0.15\%$) passing through a 1.86% radiation-length tantalum radiator located 10 cm upstream of a 145 mg/cm^2 beryllium oxide target. The beam position was monitored continuously with a BeO screen on the radiator and with the target itself. The beam intensity was measured with a ferrite-core toroid; average currents were typically 20 μA. The medium energy pion spectrometer (MEPS) was operated with a 20 msr solid-angle collimator, and its momentum acceptance of about 20% was more than wide enough to obtain a pion spectrum for the present purpose with a single magnetic field setting. The focal-plane detector system consisted of a pair of vertical drift chambers followed by a stack of three plastic scintillators, an aerogel Čerenkov counter, and a fourth plastic scintillator. A fourfold coincidence signal between the scintillators served as an event trigger. The position and direction of the particle trajectory at the focal plane were obtained from the drift chamber information. Most of the background, consisting of positrons, was rejected using the Čerenkov counter information in the off-line analysis. From the counting rate information, dead-time corrections for the electronics and the on-line computer were found to vary between 5% and 22%.

The endpoint region of the measured spectra contains muons which come from decays of pions mainly in the quasifree region. At each angle, the muon contribution was estimated by a Monte Carlo simulation[19] using information on the pion distribution in the entire focal plane, and was subtracted from the endpoint yields. The pion spectrum was then fitted with an effective spectral function which consisted of a photon spectrum and a phenomenological background taken to be a straight line. The real photon part of the photon spectrum was calculated according to the prescription of Matthews and Owens,[20] and the virtual part following Tiator and Wright.[21] The spectrum took into account finite-energy spread and straggling effects of the incident electrons and the produced pions. A typical fit to the pion spectrum is shown in Fig. 1 together with the estimated contribution of the muons.

Absolute normalization of the fit results was obtained from $^1H(\gamma,\pi^+)$ measurements with a polyethylene target together with the known cross section values.[22] The resultant cross sections are plotted in Fig. 2 with statistical error bars. The errors in the fitting and the normalization are estimated to be 7% each, giving an overall systematic error of 10% when these are added quadratically. As can be seen in Fig. 2, agreement between the present results and the data at $\theta=45°$ and 90° of Bosted *et al.*[17] is within the errors.

Also shown in Fig. 2 is the momentum-space DWIA calculation of Eramzhyan *et al.*[14,23] Basic ingredients of the calculation are the single-nucleon amplitude of Berends, Donnachie, and Weaver[24] and the $(2s\,1d)(1p)^{-1}$ nuclear wave functions of Donnelly and Walecka[25] with the same reduction factors as are required to reproduce the older (e,e′) data[26,27] (see below for further discussion of the nuclear structure). Effects of pion distortion are taken into account by a multiple scattering formalism. From the individual contributions, also shown in the figure, it is immediately seen that the summed cross section is dominated by the 2^- transition at forward angles and by the 3^- transition at backward angles.

Although the calculation describes the general shape and magnitude of the experimental results, it does not reproduce the detailed shape of the data well. At $\theta=35°$ it overestimates the cross section by about 65%, and at $\theta=60°$ it underestimates the cross section by about 45%. From the individual contributions shown in Fig. 2, we may ascribe the origin of the discrepancies to the dominant contributions at each angle, the 2^- contribution at 35° and the 3^- contribution at 60°. Thus, the good agreement at 45° could be fortuitous, possibly resulting from a calculated 2^- contribution which is too large and a calculated 3^- contribution which is too small.

At $k=200$ MeV, the quality of agreement between a similar calculation and the data[15,28] is comparable to the

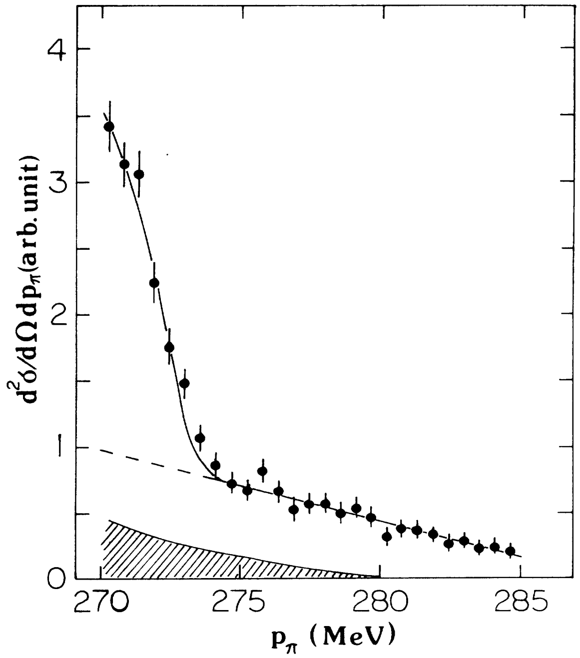

FIG. 1. Result of fit at $\theta=45°$. Lines represent contributions of the background and transitions to the ground-state complex. Shaded area indicates the calculated muon contribution which is subtracted from the measured spectrum prior to the spectral-function fit (see the text).

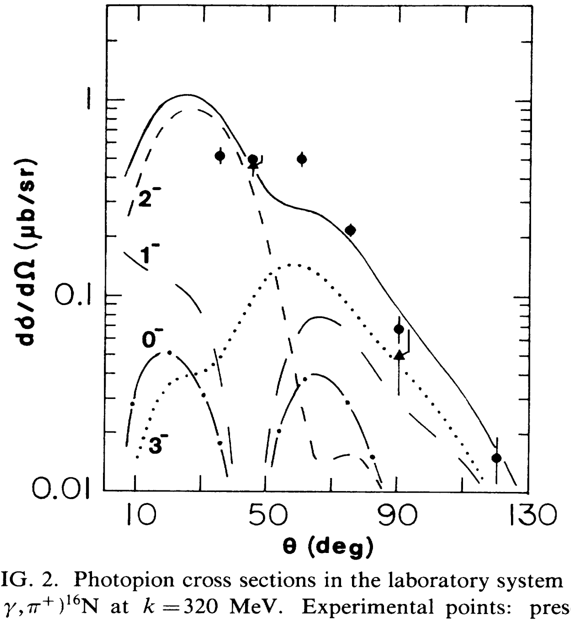

FIG. 2. Photopion cross sections in the laboratory system for $^{16}O(\gamma,\pi^+)^{16}N$ at $k=320$ MeV. Experimental points: present work (circles), and Bosted *et al.* (Ref. 17) (triangles). Theoretical curves of Eramzhyan *et al.* (Refs. 14 and 23): contributions from the $J^P=2^-$ (dashed), 0^- (dash-dotted), 3^- (dotted), and 1^- (long-dashed) states, and their sum (solid).

320 MeV case, but at 200 MeV the calculation tends to underestimate the cross sections at forward angles, where the 2^- transition is dominant.[14]

The overall agreement of the general trend in Fig. 2 is the first qualified success of a momentum-space DWIA calculation in the resonance region. As mentioned earlier, for the other transitions studied recently, the DWIA calculations[4,5] generally fail to reproduce experiment,[1–3] even though it should be noted that the treatments of the nonlocality (and the final-state interaction) in these theories are not the same. In cases where there are small nonlocality effects in the calculations, e.g., the $^{12}\mathrm{C}(\gamma,\pi^+)^{12}\mathrm{B}_{(\mathrm{g.s.})}$ reaction at $T_\pi = 32$ and 42 MeV, the results of Eramzhyan *et al.*[29] and Toker and Tabakin[4] are similar. For the $^{16}\mathrm{O}(\gamma,\pi^+)^{16}\mathrm{N}$ reaction at $k = 320$ MeV, the reasonable agreement obtained between the EGK nonlocal[14] and the DeCalro-Freed local[12] calculations implies small nonlocal effects in this reaction also.[14] (The discrepancy of a factor of 2—3 with the Girija-Devanathan local calculation[13] was attributed to an inappropriate choice of the nuclear wave functions in Ref. 13.) Nevertheless, it is desirable as an additional check to apply the other nonlocal theories[4,5] to the $^{16}\mathrm{O}$ case and/or to apply the EGK calculations to other cases such as $^{14}\mathrm{N}$.

As mentioned already, the success of the calculation in this energy region is unexpected and we cannot rule out the possibility that it is due to a fortuitous cancellation of disagreements between experiment and theory for the individual transitions. However, the calculation may indeed be accounting for the individual transitions approximately correctly, and medium correction effects may be relatively small for the dominant transitions. Suzuki *et al.* have in fact pointed out that in the delta-hole framework, even at the resonance energies, the medium effects on the resonant part are masked by the nonresonant $\sigma\cdot\epsilon$ part, if the transition is dominated by the latter.[10] It may well be that the most important transitions here, to the 2^- and 3^- states, have dominant $\sigma\cdot\epsilon$ contributions, since they proceed mainly via the predominantly spin-flip $1p_{1/2}\rightarrow 1d_{5/2}$ single-particle transition, and that therefore they involve small medium corrections. Furthermore, it was also shown in Ref. 10 that in some other cases, e.g., $^{14}\mathrm{N}(\gamma,\pi^+)^{14}\mathrm{C}_{(\mathrm{g.s.})}$, the medium effects in the longitudinal and transverse parts, while large, cancel each other within the resonant part. In any event, it will be interesting to carry out a delta-hole calculation for these transitions to see the size of the resonant medium effects. In addition, medium effects on the nonresonant part[30] should be studied for the $^{16}\mathrm{O}(\gamma,\pi^+)$ reaction.

Finally, we note that it will be important in the future to check any model wave functions for the $^{16}\mathrm{O}(\gamma,\pi^+)$ calculation against the new high-q and high-resolution (e,e′) measurement of Hyde-Wright.[31] Previously, the form factors for the individual states were available only at low momentum transfers ($q \lesssim 1\ \mathrm{fm}^{-1}$),[26] and the high-$q$ form factors were given only for the unresolved complex.[27] As was shown by Hyde-Wright,[31] this complex has important contributions from the $T=0$ (3^- and probably 2^+) states, and therefore cannot be used to test the $T=1$ wave functions reliably. The Donnelly-Walecka wave functions[25] used in the EGK calculation are in good agreement with the low-q (e,e′),[26] the muon capture,[32] and the beta decay data. However, at $q \gtrsim 1.3\ \mathrm{fm}^{-1}$, which corresponds to $\theta \gtrsim 50°$ in $^{16}\mathrm{O}(\gamma,\pi^+)$ at 320 MeV, the 2^- and the longitudinal 3^- form factors calculated with these wave functions do not appear to agree with the new (e,e′) data,[29] suggesting that improvements of the wave functions may be necessary. Use of the appropriate wave functions will be especially essential when one proceeds to an evaluation of the medium effects in the resonance region, because the resonant part of the effects in particular depends strongly on the nature of the nuclear structure involved.[10]

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[1] J. A. Nelson *et al.*, Bates Linear Accelerator Center, Massachusetts Institute of Technology Annual Report, 1985, p. 138, and unpublished data.

[2] P. K. Teng *et al.*, Phys. Lett. **177B**, 25 (1986).

[3] J. H. Koch *et al.*, submitted to Phys. Rev. Lett.

[4] G. Toker and F. Tabakin, Phys. Rev. C **28**, 1725 (1983).

[5] L. Tiator and L. E. Wright, Phys. Rev. C **30**, 989 (1984).

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

[7] K. Stricker, H. McManus, and J. A. Carr, Phys. Rev. C **19**, 929 (1979); J. A. Carr, H. McManus, and K. Stricker-Bauer, *ibid.* **25**, 952 (1982).

[8] See, for example, B. H. Cottman *et al.*, Phys. Rev. Lett. **55**, 684 (1985); K. Röhrich *et al.*, Phys. Lett. **153B**, 203 (1985).

[9] R. Wittman and Nimai C. Mukhopadhyay, Phys. Rev. Lett. **57**, 1113 (1986).

[10] T. Suzuki, T. Takaki, and J. H. Koch (unpublished).

[11] V. Devanathan, M. Rho, K. Srinivasa Rao, and S. K. Nair, Nucl. Phys. **B2**, 329 (1967); L. M. Saunders, *ibid.* **B7**, 293 (1968).

[12] V. DeCarlo and N. Freed, Phys. Rev. C **25**, 2162 (1982).

[13] V. Girija and V. Devanathan, Phys. Rev. C **26**, 2152 (1982).

[14] R. A. Eramzhyan, M. Gmitro, S. S. Kamalov, and R. Mach, J. Phys. G **9**, 605 (1983); R. A. Eramzhyan, M. Gmitro, and S. S. Kamalov, Phys. Lett. **128B**, 371 (1983).

[15] K. Shoda *et al.*, J. Phys. Soc. Jpn. **52**, 3355 (1983).

[16] P. Jennewein, B. Schoch, and F. Zettl, Phys. Lett. **130B**, 369 (1983).

[17] P. E. Bosted *et al.*, Phys. Rev. Lett. **45**, 1544 (1980).

[18] P. K. Teng, Ph.D. thesis, Rensselaer Polytechnic Institute, 1985 (unpublished); J. A. Nelson, M.S. thesis, Massachusetts Institute of Technology, 1986 (unpublished).

[19] D. C. Carey, K. L. Brown, and Ch. Iselin, computer code

DECAY TURTLE, Stanford Linear Accelerator Center, Report SLAC-246, 1982.

[20] J. L. Matthews and R. O. Owens, Nucl. Instrum. Methods **111**, 157 (1973).

[21] L. Tiator and L. E. Wright, Nucl. Phys. **A379**, 407 (1982).

[22] H. Genzel, P. Joos, and W. Pfeil, *Zahlenwerte und Funktionen aus Naturwissenschaften und Technik,* Vol. 8 of Landolt-Börnstein, edited by H. Schopper (Springer, Berlin, 1973).

[23] R. A. Eramzhyan (private communication).

[24] F. A. Berends, A. Donnachie, and D. L. Weaver, Nucl. Phys. **B4**, 1 (1967); **B4**, 54 (1967).

[25] T. W. Donnelly and J. D. Walecka, Phys. Lett. **41B**, 275 (1972).

[26] M. Stroetzel, Z. Phys. **214**, 357 (1968); J. C. Kim, R. P. Singhal, and H. S. Caplan, Can. J. Phys. **48**, 83 (1970).

[27] I. Sick, E. B. Hughes, T. W. Donnelly, J. D. Walecka, and G. E. Walker, Phys. Rev. Lett. **23**, 1117 (1969).

[28] B. H. Cottman, Ph.D. thesis, Rensselaer Polytechnic Institute, 1985 (unpublished).

[29] R. A. Eramzhyan, M. Gmitro, S. S. Kamalov, T. D. Kaipov, and R. Mach, Nucl. Phys. **A429**, 403 (1984).

[30] S. A. Dytman and F. Tabakin, Phys. Rev. C **33**, 1699 (1986).

[31] C. Hyde-Wright, Ph.D. thesis, Massachusetts Institute of Technology, 1984 (unpublished).

[32] F. R. Kane *et al.*, Phys. Lett. **45B**, 292 (1973); P. Guichon *et al.*, Phys. Rev. C **19**, 987 (1979).