Negative pion photoproduction from ^{15}N in the region of the Δ resonance

J. Shaw,* H. Choi, T. Kobayashi, and P. Stoler
Physics Department, Rensselaer Polytechnic Institute, Troy, New York 12180

T. Gresko, K. Keeter,† J. H. Mitchell,‡ B. Norum, and T. P. Welch§
Physics Department, University of Virginia, Charlottesville, Virginia 22901

H. T. Chung and J. C. Kim
Department of Physics, Seoul National University, Seoul 151-742, Korea

H. B. van den Brink and W. H. A. Hesselink
Department of Physics and Astronomy, Free University, De Boelelaan 1081, 1081HV, Amsterdam, The Netherlands

J. C. Bergstrom, E. L. Hallin, H. S. Kaplan, D. M. Skopik, and J. M. Vogt
Saskatchewan Accelerator Laboratory, Saskatoon, Saskatchewan, Canada S7N 0W0
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The differential cross section for the reaction ^{15}N $(\gamma,\pi^-)^{15}$O$_{gs}$ has been measured at a photon energy of 220 MeV. We find a discrepancy between our data and a calculation based on the distorted wave impulse approximation which uses phenomenological 1p-shell wave functions. A second calculation, in which higher-shell configurations are included in the wave functions, fails to correct the discrepancy and is even more at odds with the data.

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I. PHYSICS MOTIVATION

Over the past several years, there has been a convergence between theoretical treatments of pion photoproduction from 1p-shell nuclei and the available experimental data. One important exception is the case of ^{13}C$(\gamma,\pi^-)^{13}$N$_{gs}$. This is a single-nucleon mirror transition $(J^\pi=\frac{1}{2}^-,T=\frac{1}{2})\rightarrow(J^\pi=\frac{1}{2}^-,T=\frac{1}{2})$. Thus, two multipoles, $E0$ ($\Delta J=0$) and $M1$ ($\Delta J=1$), may contribute to the overall cross section. (Here, the multipoles refer to the change in the nuclear angular momentum and parity.) The $E0$ piece of the amplitude is dominated by intermediate delta production while the $M1$ piece is primarily nonresonant. The two multipoles separately dominate the overall cross section in different kinematic regions. Thus, by a proper choice of kinematics, it is possible to study the contribution of each multipole.

Data for this reaction were obtained at Bates [1], Tohuku [2], and NIKHEF [3,4]. Theoretical calculations were carried out by Tiator *et al.* [5] using the standard distorted wave impulse approximation (DWIA) formalism. In this treatment, the elementary pion production is treated using the photoproduction operator of Blomqvist and Laget [6], the pion final-state interactions are treated using the optical potential of Stricker, McManus, and Carr [7], and a set of phenomenological 1p-shell nuclear transition densities are used to represent the initial and final nuclear states. Such calculations initially overestimated the experimental data, in the region where the $E0$ multipole dominates, by about a factor of 4. Interestingly, the $M1$ piece of the cross section was underestimated by the calculations at energies near the peak of the resonance.

Calculations performed in the delta-hole framework were carried out by Suzuki [8] and by Takaki and Koch [9]. While these calculations improved the agreement with the experimental data, a factor of 2 discrepancy remained in the region where the $E0$ dominates. These calculations also predicted cross sections below the data in the region where the $M1$ dominates, though the discrepancy was not as pronounced as for the DWIA calculation.

In a recent series of papers [10,11], Bennhold and Tiator have shown that a small admixture of higher-shell configurations can drastically reduce the expected $E0$ contribution to the cross section, while the $M1$ part changes little. Using the $(0+2)\hbar\omega$ wave functions of Wolters *et al.* [12] for the $E0$ part of the cross section, Bennhold and Tiator obtained good agreement with the photoproduction data. These wave functions provide a microscopic description for the p-shell nuclei. They employ an empirical interaction, the parameters of which are found by performing a least-squares fit to various experimental data.

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*Present address: Department of Physics and Astronomy, University of Massachusetts, Amherst, MA 01003.

†Present address: Saskatchewan Accelerator Laboratory, Saskatoon, Saskatchewan, Canada S7N 0W0.

‡Present address: Continuous Electron Beam Accelerator Facility, 12070 Jefferson Avenue, Newport News, VA 23606.

§Present address: Department of Physics, Oregon State University, Corvallis, OR 97331.

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Despite the agreement with the photoproduction data, the calculation of Bennhold and Tiator is not entirely satisfactory for a number of reasons. First, the $M1$ part of the wave function was treated using a phenomenological $1p$-shell-only wave function. The reason for this is that the wave function of Wolters *et al.* cannot reproduce the ^{13}C $M1$ electron scattering form factor and so cannot be expected to accurately describe the $M1$ transition in pion photoproduction. Thus, a different set of wave functions is used to describe each multipole.

Another problem is that the phenomenological $1p$-shell wave functions, on which the $M1$ piece of the amplitude is based, do not reproduce the photoproduction data at a momentum transfer of 1.25 fm^{-1} (where the $M1$ is dominant) except at low photon energy. Finally, the delta dynamics would be more accurately accounted for using the delta-hole formalism rather than the SMC optical potential.

Thus, while it has been shown that the $E0$ part of the amplitude is quite sensitive to higher-shell configurations, a more unified and consistent theoretical treatment is still necessary.

With these considerations in mind, it is important to study the other single-nucleon mirror transition in the $1p$ shell, namely $^{15}N(\gamma,\pi^-)^{15}O_{gs}$. Two data sets exist near threshold [13,14]. The data sets disagree by an amount greater than the combined error bars. The present work extends these measurements to an energy near the resonance peak in the nucleus.

II. EXPERIMENT

The experiment was carried out using the tagged-photon beam of the Saskatchewan Accelerator Laboratory. The experimental setup is shown in Fig. 1. Electrons from the primary beam passed through an aluminum radiator and then were bent by the tagger magnet onto a 62-channel focal plane. The photon energy resulting from a given electron is given simply by $E_\gamma = E_e - E_{e'}$ where E_e is the energy of the primary beam and $E_{e'}$ is the energy of the secondary electron. The photon energy resolution was about 0.5 MeV.

The efficiency of the tagging system was measured periodically throughout the run. This was accomplished by running with a low beam current and placing a 100% efficient lead glass detector in the photon beam. The efficiency is then given by the ratio of the number of detected photons to the number of electrons on the focal plane. Typical efficiencies ranged from about 52–57%.

The target consisted of a pressed disc of urea isotopically enriched to > 99% in ^{15}N. The disc measured two inches in diameter with a thickness of 200 mg/cm^2 in ^{15}N. Pions produced in the target were detected by a pair of scintillator range telescopes, operated in coincidence with the tagger. Each telescope consisted of a stack of sixteen plastic scintillators of size 30 × 50 cm preceded by two three-plane wire chambers. The first two planes were oriented in the horizontal and vertical directions with the third oriented at an angle of 45° relative to the first two. The wire spacing was 6 millimeters. The distance be-

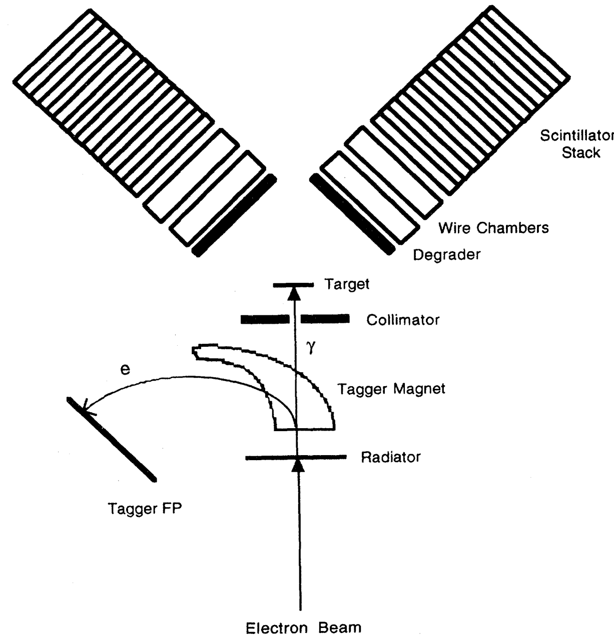

FIG. 1. A schematic of the experimental setup.

tween the target and the outer wire chamber was varied between 40 and 65 centimeters, depending on the angle of the detector, in order to maximize the solid angle while avoiding obstacles in the experimental hall.

The scintillators ranged in thickness from 2 to 10 millimeters. Metal degraders consisting of 0.5 inch of steel and 0.25 inch of copper were also placed in front of the telescopes in order to moderate the high-energy pions so that they would stop within the scintillator stack. The degraders also served to reduce the number of low-energy electrons resulting from pair production in the target. Pions were identified by their energy-loss pattern in the telescope. By measuring the amount of material traversed by a given pion, and from the known photon energy, it has possible to reproduce the entire reaction kinematics. Data on ^{15}N were taken at four pion scattering angles, 32.5°, 45°, 58°, and 70°. Data were also taken for the reaction $^1H(\gamma,\pi^+)n$ to provide an absolute normalization for our detectors. The target consisted of a sheet of polyethylene with thickness 294 g/cm^2.

Since each scintillator in our range telescopes was viewed by a phototube at only one end, it was necessary to correct for the position dependence of the light output. This was accomplished by dividing each scintillator into an 8 × 5 grid and measuring the ADC value in each cell for high-energy, monoenergetic protons. Protons were used for this purpose since they were copiously produced and thus allowed for extremely good statistics. The high-collection efficiency varied typically by less than 10% in the horizontal direction. In the vertical direction, it varied by about 10–20 % for the thin scintillators and by up to 50% for the thick scintillators.

During the analysis phase of the experiment, it was discovered that the incident photon energy differed from that given by the tagger calibration, being about 5 MeV

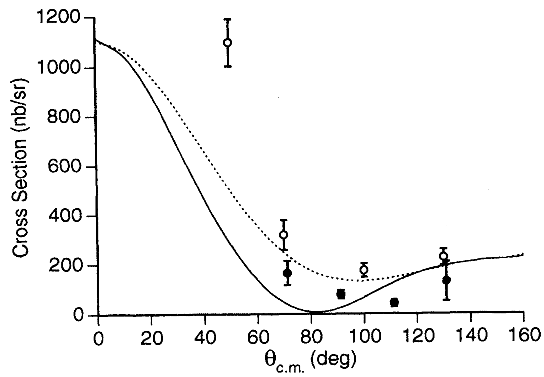

FIG. 2. The ^{15}N cross section at 170 MeV. Open circles: data of Liesenfeld *et al.* [13]. Solid circles: data of Kobayashi *et al.* [14]. Solid curve: calculation of Bennhold *et al.* [15] using $(0 + 2\hbar\omega)$ wave functions. Dashed curve: calculation using 1p-shell only wave functions.

lower. This was later confirmed by a subsequent tagger calibration. This discrepancy greatly reduced the available statistics since many of the pions produced lacked sufficient energy to be detected in our range telescopes.

III. RESULTS

The results of the two low-energy measurements are shown in Fig. 2 while the results of the present study are shown in Fig. 3. As in the ^{13}C case, the calculations performed with the wave functions of Wolters *et al.* cannot reproduce the $M1$ electron-scattering form factor for ^{15}N. Thus, the $M1$ contribution to the cross section is again calculated using the phenomenological 1p-shell only wave functions while the $E0$ part is calculated in the $(0 + 2)\hbar\omega$ basis.

An examination of these data reveals no evidence for the type of $E0$ suppression seen in the ^{13}C case. At low energy, the Mainz data set seems to agree with the older calculation, based on the phenomenological 1p-shell wave functions with the interesting exception of the forward-angle point. The $E0$ piece of the amplitude is important here while the $M1$ part should be well constrained by Gamow-Teller beta decay. The present results overshoot

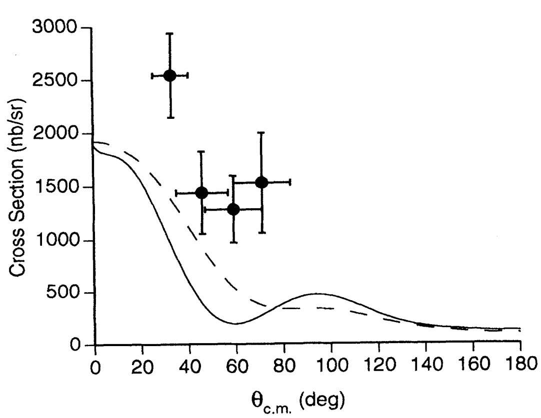

FIG. 3. The present results at a photon energy of 220 MeV. Curves: same as for Fig. 2.

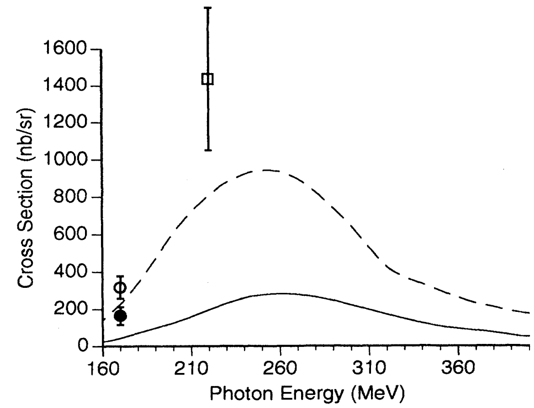

FIG. 4. The ^{15}N cross section as a function of photon energy for a fixed momentum transfer of 0.7 fm^{-2}, where the $E0$ multipole dominates. The data points at 170 MeV are from Liesenfeld *et al.* [13] (open circle), and Kobayashi *et al.* [14] (solid circle). The point at 220 MeV is from the present results. Note that this latter point is actually at a momentum transfer of 0.62 fm^{-2}. The curves are the same as for Fig. 2.

even the 1p-shell only calculation.

Figure 4 shows the two calculations plotted against photon energy for a constant momentum transfer $Q^2 =$ 0.7 fm^{-2}, where the $E0$ multipole dominates the cross section. Clearly, the effect of adding the higher-shell configurations is to drive the theory away from the experimental data. These results may indicate that the delta-nucleus dynamics are not being properly treated in the calculation.

Unfortunately, it is not possible to offer a definitive interpretation of these results at the present time. Further studies—both experimental and theoretical—are needed to clarify the situation. First, it would be desirable to obtain a complete energy distribution from threshold through the delta peak for the present reaction at values of the momentum transfer where the $M1$ and $E0$ transition are separately dominant. Second, it would be extremely interesting to have data for the reaction $^{14}C(\gamma,\pi^-)^{14}N_{2,3}$. This reaction is unique among the p-shell nuclei in that it is a pure $E0$ transition. Thus, an $E0$ suppression (or lack thereof) should manifest itself prominently in this case. Data near the pion production threshold have been obtained at Saskatoon. The data analysis is still underway.

On the theoretical side, we need a set of wave functions which include the most important higher shells and which can provide a satisfactory description of the electron scattering $M1$ form factor. In addition, the calculation in the resonance region should be carried out in the delta-hole formalism rather than the DWIA in the resonance region.

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