Measurement of $^{14}N(\gamma, \pi^+)^{14}C$(g.s.) at 200 MeV: A Test of the Distorted-Wave Impulse Approximation for Charged-Pion Photoproduction below the $\Delta(1232)$ Resonance

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Differential cross sections for $^{14}N(\gamma, \pi^+)^{14}C(g.s.)(0^+1)$ have been measured for an incident photon energy $E_\gamma = 200$ MeV at laboratory angles of 45°, 60°, 75°, 90°, 120°, and 140°. Momentum-space distorted-wave-impulse-approximation calculations, using a complete treatment of a one-body pion-photoproduction operator, are found to be in excellent agreement with the experimental data. The effect of the momentum-dependent terms in the nuclear photoproduction operator is observed. The reaction is found to be sensitive to input nuclear structure elements not observable in the (e,e') form-factor data.

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We have measured the reaction $^{14}N(\gamma, \pi^+)$-$^{14}C(g.s.)(0^+1)$ at $E_\gamma = 200$ MeV over a wide angular range. This measurement is the first of several (γ, π^+) measurements recently completed on the new medium-energy pion spectrometer (MEPS) at the Bates Linear Accelerator Center. We note that the quality of these data greatly exceeds that obtainable with earlier facilities.[1, 2]

The measurement of $^{14}N(\gamma, \pi^+)^{14}C$(g.s.) was motivated by the need for high-quality (γ, π^+) data which would be especially sensitive to photoproduction dynamics. This transition is of special interest for the understanding of photopion reactions since the β-decay transition rate from the $^{14}C(J^\pi T = 0^+1)$ ground state to the $^{14}N(J^\pi T = 1^+0)$ ground state is anomalously low as a result of the suppression of the allowed Gamow-Teller matrix element. Therefore, we expect that the Kroll-Ruderman[3] (KR) term in the photoproduction operator which is proportional to $\sigma \cdot \epsilon$, usually dominant in (γ, π^+) reactions at this energy, should be suppressed in the $^{14}N(\gamma, \pi^+)^{14}C$(g.s.) reaction, and thus the relative strength of the other terms increased.[2, 4]

Noteworthy features observed from comparison of distorted-wave impulse-approximation (DWIA) calculations to the data reported here are as follows: (1) The effects of the momentum-dependent terms in the pion-photoproduction operator, especially the pion-pole term, are clearly observed for the first time; (2) the results are sensitive to the nuclear structure in a different manner than the analogous (e,e') form-factor data; and (3) DWIA momentum-space calculations are in excellent agreement with the experimental data provided that all aspects of the photoproduction operator are carefully treated.

In some cases previous measurements involving transitions dominated by the KR term have been explained reasonably well by DWIA calculations.[1, 2, 5, 6] However, the dominance of the KR term masks the other interesting contributions to this reaction and no definite conclusions about the basic photoproduction reaction mechanism could be made.

The data were taken at the Bates Linear Accelerator Center by passing 200-MeV electrons first through a 126.6-mg/cm^2 Ta radiator and then through the 365-mg/cm^2 Be_3N_2 sintered wafer target.[7] The pions, produced in the $^{14}N(\gamma,\pi^+)^{14}C$(g.s.) end-point region from the combined bremsstrahlung and virtual photon fluxes, were detected at angles of 45°, 60°, 75°, 90°, 120°, and 140° with the use of MEPS configured with a circular 20.1-msr entrance collimator. Particle position and angle at the focal plane of MEPS were measured by two orthogonal multiwire vertical drift chambers.[8] The focal-plane event trigger was provided by a fourfold coincidence from a scintillator stack located behind the focal plane. A silica aerogel detector ($n = 1.05$),[9] located between the third and fourth scintillators, and pulse-height information from the scintillators were used to eliminate background positron events with an estimated efficiency of 99.99%. The particle momentum determination included corrections for kinematic broadening resulting from the large scattering-angle acceptance of MEPS. Absolute photopion double-differential cross sections $d^2\sigma/d\Omega_\pi dE_\pi$ were obtained by correcting for pion decay, several known instrumental and analysis inefficiencies, and pion absorption in the detectors. The photopion differential cross section, $d\sigma/d\Omega_\pi$, was determined by a Poisson-statistics fit of a spectral function to the data up to 5.0 MeV above the photon end point of the momentum spectrum. The spectral function was defined to be a linear combination of the photon spectrum shape and a constant term which accounted for the flat muon background. The photon spectrum included the contributions from the bremsstrahlung flux produced in the radiator and in the target[10] and the virtual photon spectrum produced by the electron beam traversing the target.[11] Implicit in this procedure is the assumption that the cross section varies slowly over the 5-MeV photon excitation region of the fit. The double-differential cross sections and the resulting fit to the data for the $\theta_\pi = 60°$ measurement are shown in Fig. 1. As an independent check on our methods, elastic $H(e,e')$ and $H(\gamma,\pi^+)n$ cross sections were measured under various experimental conditions. From these results, we estimate a normalization uncertainty of 7% and a relative systematic uncertainty of 6% (90% confidence limits). Errors shown for the differential-cross-section data in Figs. 2 and 3 include both the statistical and relative systematic contributions. The full details of the data analysis may be found in Cottman.[12]

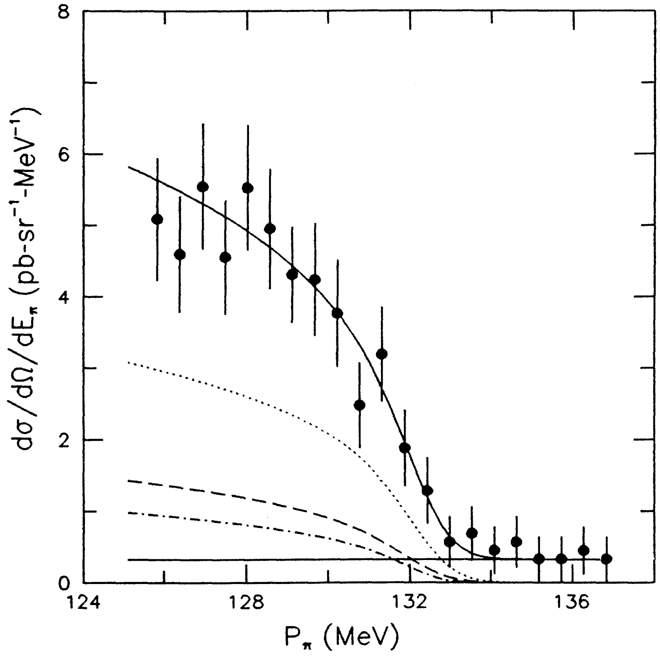

FIG. 1. Momentum spectrum of $^{14}N(\gamma,\pi^+)^{14}C$(g.s.) at 60° and resulting fit of data. The dotted and dashed-dotted curves represent the radiator and target bremsstrahlung contributions, respectively. The virtual photon contribution is shown as a dashed curve. The flat background contribution is shown as a solid curve while the sum of the real and virtual photon and background contributions is also shown as a solid curve. Error bars are statistical.

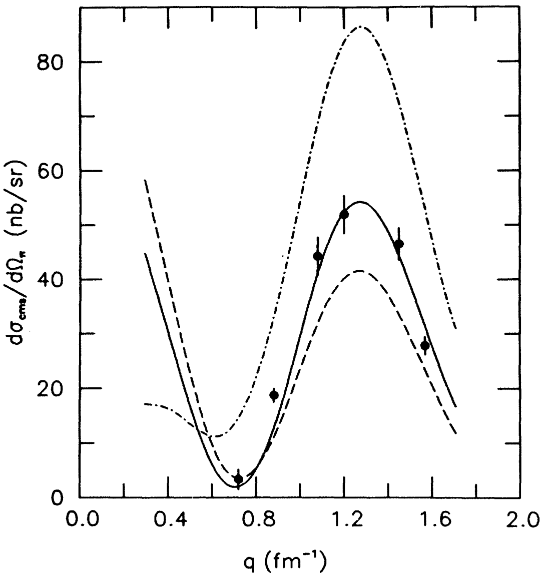

FIG. 2. Comparison of $^{14}N(\gamma,\pi^+)^{14}C$(g.s.) data at $E_\gamma = 200$ MeV to DWIA calculations using different nuclear structure inputs. The DWIA calculation using the full BL photoproduction operator, the SMC (Ref. 14) pion optical potential, and the H1 nuclear wave functions (Ref. 15) is shown as a solid curve. The DWIA calculations using the H2 set (Ref. 15) and the Ensslin set (Ref. 16) for the nuclear structure input are shown as dashed and dot-dashed curves, respectively.

Comparisons between the experimental data and DWIA calculations using various possible nuclear structure inputs are shown in Fig. 2. The theoretical formalism is described in an earlier paper.[6] These calculations used the full Blomqvist-Laget (BL) pseudovector photoproduction operator[13] and the phenomenological optical potential of Stricker, McManus, and Carr[14] (SMC) to parametrize the pion-nucleus final-state interaction. These DWIA calculations are executed in a momentum-space basis and thus avoid the difficulties encountered by a coordinate-space basis in fully incorporating the behavior of the pion and nucleon momentum-dependent propagators in the photoproduction operator. The H1 and H2 p-shell wave functions of Huffman *et al.*[15] have been fixed by empirical fits to the $M1$ form factors for the electron elastic scattering and the inelastic scattering to the 2.313-MeV state of ^{14}N. The wave functions of Ensslin *et al.*[16] were chosen to be consistent with selected electromagnetic and weak properties of the $A=14$ system and empirical fits to the $^{14}\mathrm{N}(e,e')^{14}\mathrm{N}(0^+)$ data available at that time. Both the Huffman and Ensslin wave functions fit the inelastic electron scattering data in the momentum transfer range considered. However, the H1 and H2 solutions result in better fits to both the (e,e') elastic scattering data and the (p,p') inelastic scattering data[17] for the same states in ^{14}N. The Ensslin wave functions fit the experimental $\log(ft)$ of the ^{14}C beta decay with a correspondingly small Gamow-Teller matrix element. In view of recent speculation about the sizable contributions of meson-exchange-current corrections to the ^{14}C beta decay,[18] Huffman *et al.* have chosen a finite Gamow-Teller matrix element having opposite sign to the meson-exchange-current corrections.

Huffman *et al.* report that H1 and H2 were found to be almost equivalent in describing the measured form-factor data. We find a definite preference for the H1 set in comparison to our data. The major difference between H1 and H2 is the nonzero $(L=1, S=1)$ component of the single-particle transition matrix elements of the H1 set. This component is not observed in the (e,e') form-factor data as it is forbidden for a $M1$ transition. However, this same component is allowed for a pion-photoproduction $M1$ transition.

In Fig. 3 the sensitivity of $^{14}\mathrm{N}(\gamma,\pi^+)^{14}\mathrm{C}(\mathrm{g.s.})$ to all the different aspects of the photoproduction operator is demonstrated for calculations using the H1 wave-function set. The calculated cross sections, using only the KR term which is usually dominant in $(\gamma,\pi^\pm)$ reactions at this energy, are clearly too large. Singham and Tabakin,[2] and Figureau and Mukhopadhyay,[4] have suggested that the KR term is suppressed because of the vanishingly small Gamow-Teller matrix element and thus the other terms play a more important role.[2] In particular, the studies of Toker and Tabakin imply that a proper treatment of the pion-pole term is necessary for any successful calculation of the $^{14}\mathrm{N}(\gamma,\pi^+)^{14}\mathrm{C}(\mathrm{g.s.})$ reaction.[5]

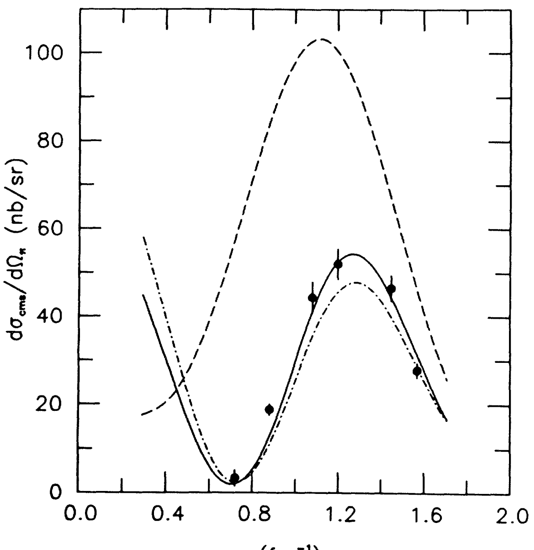

FIG. 3. Comparison of $^{14}\mathrm{N}(\gamma,\pi^+)^{14}\mathrm{C}(\mathrm{g.s.})$ data at $E_\gamma = 200$ MeV to DWIA calculations using different forms of the photoproduction operator. The DWIA calculation using the full pseudovector BL photoproduction operator with (solid) and without (dot-dashed) the s-channel Δ term, the SMC pion optical potential, and the H1 set are shown. The same DWIA calculation, using only the KR photoproduction term, is shown as a dashed curve.

We find that only when the full operator is used are the theoretical cross sections reconciled with the measured data. This sizable reduction can be traced to the destructive interference between the KR term and the pion-pole term at angles backward of the interference minimum near $\theta_\pi = 40°$. Also shown in Fig. 3 is a calculation in which the Δ term in the photoproduction operator has been omitted. This omission results in a relatively small change in the calculated cross section indicating that this reaction is fairly insensitive at these energies to the Δ term.

To summarize, we have seen direct evidence that an elementary impulse photoproduction operator offers an accurate description of the (γ,π^+) reaction process in a complex nucleus below the $\Delta(1232)$-resonance region. In particular, we are able to confirm that the $^{14}\mathrm{N}(\gamma,\pi^+)^{14}\mathrm{C}(\mathrm{g.s.})$ reaction is unusually sensitive to the pion-pole term of the photoproduction operator and that proper treatment of the momentum-dependent terms of the operator is demanded. Of further note is the fact that the excellent agreement between the DWIA calculations and the data implies that the interaction of the final-state pion with the nucleus at this energy can be adequately described by a pion optical potential whose parameters are determined from pion-nucleus scattering data. Finally, the observed sensitivity of this reaction to the nuclear structure input leads us to conclude that the comparison of a carefully constructed theory with a new generation of high-quality pion-photoproduction data can yield new insight into nuclear structure which is complementary to that obtained from other reaction studies.

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