Differential Cross Sections for $^{16}O(\gamma,\pi^+)^{16}N$ and $^{10}B(\gamma,\pi^+)^{10}Be$ in the $\Delta(1236)$ Region

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Differential cross sections for $^{10}B(\gamma,\pi^+)^{10}Be$ to the ground and first excited states of ^{10}Be separately and $^{16}O(\gamma,\pi^+)^{16}N$ to the sum of the four lowest-lying states in ^{16}N have been measured at laboratory angles of 45° and 90° for pions with kinetic energies from 80 and 210 MeV. The results, which are the first to discrete nuclear final states in the $\Delta(1236)$ region, are in qualitative agreement with several distorted-wave impulse-approximation calculations.

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The photoproduction of pions from complex nuclei has received considerable theoretical and experimental attention in recent years. The first goal of the studies has been to understand the reaction mechanism. The body of data for threshold production has been accounted for, to the 10% level, by parameter-free distorted-wave impulse-approximation (DWIA) calculations.[1] Valuable constraints to these calculations were provided by transverse-electron-scattering data, which give information on the nuclear wave functions, and by pionic atom data, which give phenomenological descriptions of pion wave functions.

At the pion energies spanned by the present experiment, the basic mechanism can be expected to be quite different. Effects due to the production of the $\Delta(1236)$ isobar in intermediate states are important in the understanding of pion scattering data for energies near 150 MeV and should be important for pion photoproduction also.[2] Since (γ,π) reactions test the full pion wave function in a calculation, this data could provide important constraints on the microscopic models for pion reactions presently being developed.

We previously reported (γ,π^-) total-cross-section measurements for $T_\pi = 0$ to 140 MeV for targets (^{12}C and ^7Li) where the nuclear structure was well understood.[3] DWIA calculations, with use of pion wave functions fit to pion elastic-scattering data, were in satisfactory agreement with experiment.[4] Differential-cross-section measurements should provide a more stringent test of the theoretical calculations.

We report in this Letter the first such measurements in the Δ region to discrete states of the final nuclei. We chose two (γ,π^+) cases for which the nuclear structure is well understood from transverse-electron-scattering form-factor measurements, and where large level spacings (>2 MeV) in the residual nuclei make it relatively easy to separate their contributions.

The measurements were made by passing the electron beam of the Bates linear accelerator through a 283-mg/cm^2 BeO target and a 116-mg/cm^2 packed-powder ^{10}B target and detecting the pions produced from the endpoint region of the virtual-photon spectrum. The Bates energy-loss spectrometer was set at 90° and at 45° and the electron beam energy was varied to produce pions of the desired energy. Five 8-cm-thick Lucite Čerenkov detectors and a silica Aerogel Čerenkov detector with an index of refraction of 1.05 behind the spectrometer focal plane were sufficient to reject all positrons. Although each target had material other than the desired element, the contaminants did not contribute to the observed spectra because of their much higher thresholds.

In the case of ^{10}Be, cross sections for the ground state and the first excited state could be determined separately, but the four very closely spaced lowest levels in ^{16}N could not be distinguished and, therefore, only their total contribution was obtained. A typical energy spectrum of pions produced from ^{10}B is shown in Fig. 1. The pions are produced by electroproduction and thus the pion spectrum for a specific state is that of the virtual-photon spectrum over a small range of energies. We have measured the virtual-photon spectrum by comparing the count rate to a given state with and without a 2% Ta radiator 10 cm in front of the target. The results are that the shape of the theoretical plane-wave Born-approximation (PWBA) virtual-photon spectrum[5] is accurate, but the magnitude must be increased by (22 ± 12)%. Photoproduction cross sections were then determined by fitting a spectrum of this shape for each state. This procedure as-

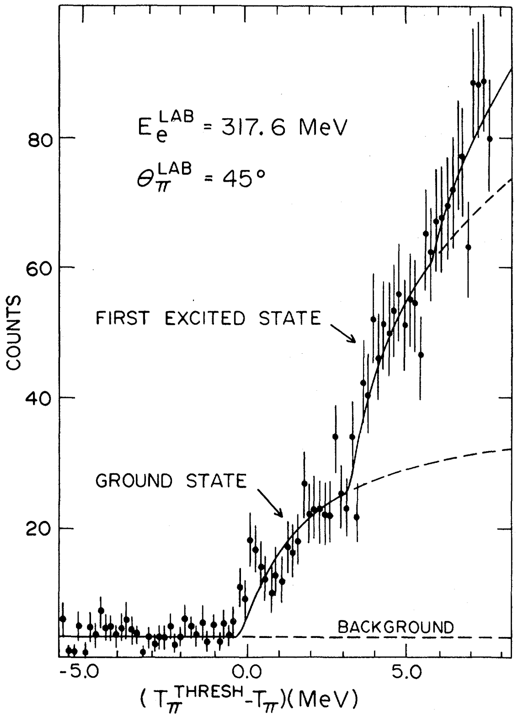

FIG. 1. Typical pion-energy spectrum for $^{10}B(\gamma,\pi^+)^{10}Be$ showing the contributions to the ground, first, and second excited states of ^{10}Be. Most of the background events shown come from pions that decay in flight into muons.

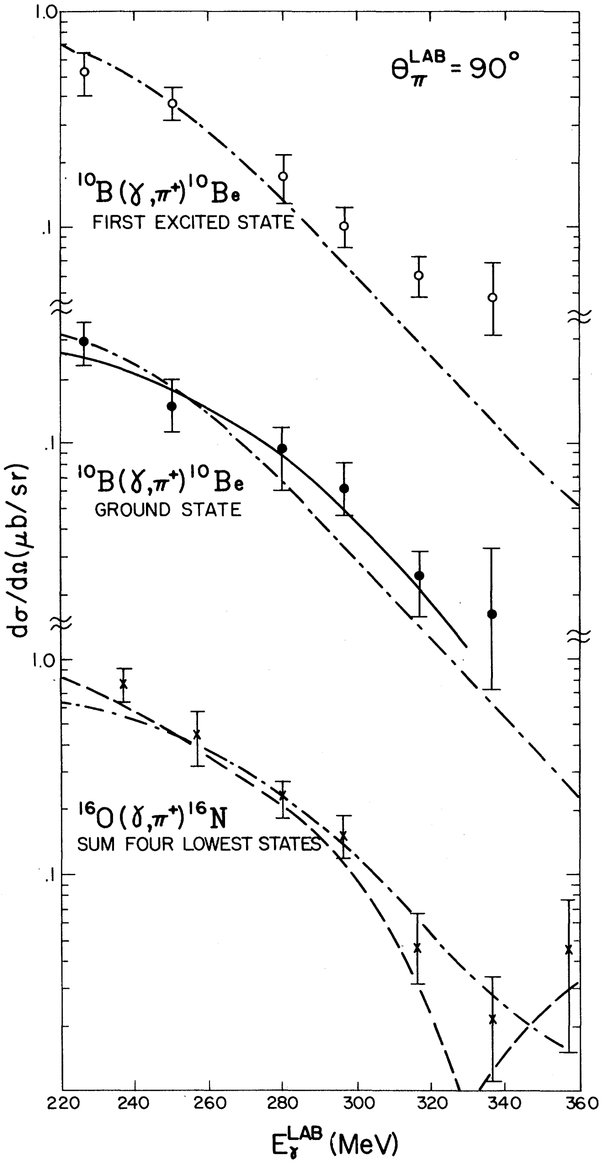

FIG. 2. Differential cross sections for $^{16}O(\gamma,\pi^+)^{10}Be$ at 90°. The solid circles represent the contributions from the ground state of ^{10}Be, the open circles are for the first excited state of ^{10}Be, and the crosses are for the sum of the four lowest-lying levels in ^{16}N. The solid line is the calculation of Singham and Tabakin (Ref. 8), the dashed line that of Devanathan *et al.* (Ref. 9), and the dot-dashed lines are from Nagl and Uberall (Ref. 10). Pion energies can approximately be found by subtracting 140 MeV from the photon energies.

sumes that the photoproduction cross section is constant over the observed range of pion energies. Further details can be found in Ref. 6. The solid line in Fig. 1 shows a fit of the first three levels in ^{10}Be plus a linear background.

The overall efficiency of the detection system as a function of pion energy was determined by measuring the well-known reaction $p(\gamma,\pi^+)n$ at several energies.[7]

Comparison with theory is made in Figs. 2 and 3. Three sets of calculations, all performed within the framework of the DWIA, are presently available to us: that of Singham and Tabakin[8] (ST) (solid lines) for the pure $M3$ transition from the 3^+ ground state of ^{10}B to the 0^+ ground state of ^{10}Be, that of Devanathan, Girija, and Prasad[9] (DG) (dashed lines) for the sum of the transitions from the 0^+ ground state of ^{16}O to the low-lying 0^-, 1^-, 2^-, and 3^- states in ^{16}N, and those of Nagl and Überall[10] (NU) (dot-dashed lines) for all of the cases that we have measured. The NU code was run at the Massachusetts Institute of Technology (MIT) with use of the Helm-model[11] parameters fitted by the authors.

Differences between the calculations lie in details of the elementary operator, nuclear wave functions, and pion optical potentials used. Differences in the elementary operators (Blomqvist-Laget[12] for ST, Chew *et al.*[13] with no pion gradient

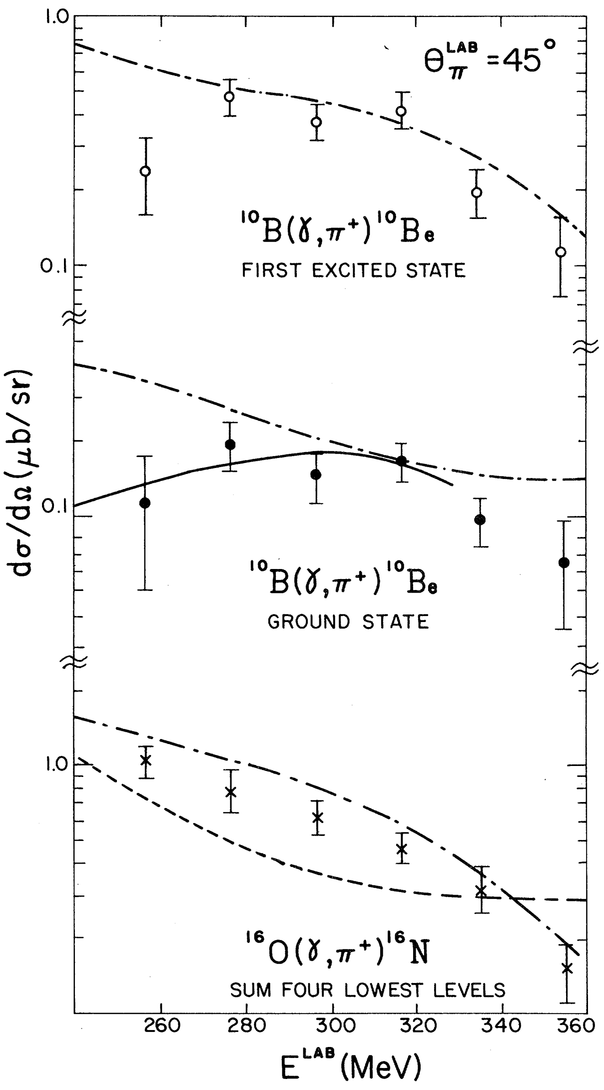

FIG. 3. Same as for Fig. 2, but at a pion laboratory angle of 45°.

terms used for DG, and Berends[7] for NU) probably do not account for more than 15% differences in the photopion cross sections since they all describe the elementary vertex well and nuclear off-shell effects seem to be small in the Δ region in the framework of the DWIA.

Calculated photopion cross sections are sensitive to the nuclear-structure inputs which therefore should be constrained to fit transverse-electron-scattering form factors to the analog states. In the case of ^{10}B, both the Cohen-Kurath[14] (used by ST), and the Helm model[11] (used by NU) do a good job in describing the data of Ansaldo *et al.*[15] In the case of the 1^-, 2^-, and 3^- $T=1$ analog levels in ^{16}O grouped near 13 MeV, electron scattering data exist for each state separately for $q<1$ fm^{-1} and for their sum at higher momentum transfers. Recent data[16] from MIT have been measured for each state separately for $0.8<q<2.4$ fm^{-1}, with only the 2^- results finalized. NU used the Helm model to fit all available data, while DG's calculation used the wave functions of Rho,[17] which have not yet been compared to electron scattering data, but which agree with muon capture rates.

All three calculations use a first-order Kisslinger potential with the addition of s- and p-wave absorption, Pauli suppression, and the Lorentz-Lorenz Ericson-Ericson effect. A study of the applicability of this potential form to pion scattering was carried out by Stricker, McManus, and Carr.[18] Many parameters, few of which can be determined independently, are required to fit experimental data, causing some arbitrariness in their choice. They derived a set of parameters that fit ^{16}O, ^{40}Ca, and ^{208}Pb data quite well except near minima and for angles greater than 90°. ST use this parametrization, NU use the same form for their potential, fitted to the same data, but with somewhat different parameters. DG ignore absorption and isovector terms and their fit to older ^{16}O data is only good to about 30%.

No studies have been done to test the validity of these potentials for nuclei such as ^{10}Be and ^{16}N. Although apparently small for these nuclei, the spin-flip and isovector terms are not well understood. Furthermore, scattering from the quadrupole moments of the relevant states has been ignored. Overall, it seems that this part of the calculation is the least understood.

We conclude by remarking that the present level of qualitative agreement between calculations and data is of the same order as the differences between the calculations. Clearly more work will be needed to constrain reliably the inputs to DWIA calculations before one can ascertain whether more exotic effects, such as medium modifications to the propagating Δ, will be important. We hope to be taking soon high-quality angular distributions for several transitions, which should help further pinpoint inadequacies in the theories presently being developed.

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Evolution of Projectile Double-*K*-Vacancy Fractions with Target Thickness in Ion-Atom Collisions

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The dependence of projectile double-*K*-vacancy (hypersatellite) x-ray yields on target thickness for ions moving in thin solid targets is examined. For 2.3-MeV/amu Cl ions incident on C foils, the double- to single-*K*-vacancy x-ray yield ratio increases by a factor of 3.5 over the range of thicknesses investigated, reaching values as high as 0.3. A quantitative explanation of the observed results is obtained using a formulation based on *K*-vacancy production and filling cross sections.

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The production of ions with two K vacancies is of fundamental interest in ion-atom collisions.[1-3] Previously, double-K-vacancy production has been inferred from the ratio $R=\sigma_x{}^h/\sigma_x$ of hypersatellite to single-K-vacancy x-ray yields, if we assume the fluorescence yields for single- and double-K-vacancies are the same.[1] This ratio has been used to determine double-K-vacancy sharing ratios between target and projectile in near symmetric collisions[3] and to determine branching ratios for two-electron-one-photon transitions.[4,5] In these works, it was tacitly assumed that R does not depend upon the target thickness.