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Angular distributions of π^+ in the $^{10}B(\gamma,\pi^+)$ reaction leading to low-lying states of ^{10}Be

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Differential cross sections for the reactions $^{10}B(\gamma,\pi^+)^{10}Be_{(g.s.)}$ and $^{10}B(\gamma,\pi^+)^{10}Be_{(1st)}$ have been deduced from measured electroproduction yields at $E_e=185$ MeV and $\theta_\pi=30°-150°$. The experimental results are compared with a calculation made in distorted wave impulse approximation. Substantial discrepancies between the theory and the experiment are observed.

Despite extensive experimental and theoretical effort in recent years, the reaction mechanism of the charged-pion photoproduction from nuclei is not fully understood. Even at low energies ($T_\pi=10-50$ MeV), the distorted wave impulse approximation (DWIA), which describes total cross sections at threshold reasonably well, has turned out to be only partially successful in explaining differential cross sections. For example, the latest calculation by Tiator and Wright[1] reproduces the $^{14}N(\gamma,\pi^+)^{14}C_{(g.s.)}$ data quite well at photon energies $k=173$ and 200 MeV,[2] but fails very badly for the reaction $^{13}C(\gamma,\pi^-)^{13}N_{(g.s.)}$ at $k\approx170-190$ MeV.[3] Many attempts have been made to remove these discrepancies both within and beyond the DWIA framework (employing various nuclear wave functions,[4–6] medium effects on the propagators,[6] meson exchange effects,[5] etc.). However, none of them appears to be consistently successful in explaining all the existing data. The failure of the DWIA theory seems more serious in the Δ resonance region,[7] which may be partly due to the increased importance of the delta formation and propagation in the process,[8] as has been demonstrated by the delta-hole approach in other pion- and photon-induced reactions.[9] Nevertheless, it is desirable to enlarge the data base of the photopion reaction to obtain better knowledge of the systematics.

We report here new experimental cross sections for the reactions $^{10}B(\gamma,\pi^+)^{10}Be_{(g.s.)}$ and $^{10}B(\gamma,\pi^+)^{10}Be_{(1st)}$ at $T_\pi\approx40$ MeV. Because the ground-state transition (pure $M3$) includes well-known nuclear structure and proceeds via almost pure spin flip, we believe this is one of the most important cases to test theories in the low energy region. In spite of the importance, only one full angular distribution measurement for the transition has been published previously at $T_\pi=12.3$ MeV.[10] Two other earlier experiments are limited to fixed pion angles at relatively low[11] and high[12] energies. Our measurement extends the angular distribution measurement of Ref. 10 to higher energy and is supplementary at $\theta_\pi=90°$ to the data of Refs. 11 and 12.

The experiment was performed at the Tohoku University electron linear accelerator. The target was bombarded by electrons of total energy $E_e=185$ MeV. Positive pions emitted from the target were analyzed by a double-focusing magnetic spectrometer and detected by an array of 33 threefold-coincidence telescopes located at the focal plane of the spectrometer. Each telescope consisted of three 1-mm-thick Si(Li) detectors, and pulse-height criteria in the three Si(Li) detectors were used to identify pions. As methods of the data taking and analysis were similar to our earlier experiments, any details not described here may be found in the literature.[13] The measurements were made at laboratory angles $\theta_\pi=30°-150°$ in 20° steps, which covers the momentum transfer range $q=0.5-1.4$ fm^{-1} for the $^{10}B(e,\pi^+)^{10}Be_{(g.s.)}$ reaction.

The targets used were fabricated by pressing boron powder, enriched to 96.5% in ^{10}B, to form self-supported disks, and had a thickness of either 162 or 131 mg/cm^2. The target thickness and the geometry of the apparatus were checked by measuring elastic electron scattering. Energy resolution of the pion spectra due to energy spread of the incident electrons and straggling of pion energy loss was about 0.5 MeV and 0.8 MeV (full width at half maximum) for the measurements at $\theta_\pi=30°-110°$ and 130°–150°, respectively. Thus, we could easily separate the transitions to the ground and the first excited ($E_x=3.37$ MeV) states from those to the higher-lying ($E_x\geq5.96$ MeV) states and the continuum.

Because of the difference in Q values, no pions from the $^{11}B(e,\pi^+)$ reaction are expected in the measured spectra. Contamination of the measured spectra by pion-decay products, μ^+ and e^+, was negligible under the geometry and the pulse-height criteria employed. As shown in Fig. 1, we generally observed clean breaks in the pion spectrum due to the transitions to discrete final states. At $\theta_\pi=30°$, however, the large positron background combined with the small cross sections was a rather serious problem. At each angle, a flat background was assumed and estimated from the number of counts lying beyond the $^{10}B(e,\pi^+)$ end point.

Relative efficiencies of the telescope channels have been obtained by measuring a flat pion spectrum of similar energy. Corrections have also been applied for pion loss due to the decay in flight and the energy loss of the electrons and the pions. Absolute normalization has been obtained from an additional $^1H(e,\pi^+)$ run at $E_e=190$ MeV and $\theta_\pi=40°$, where the pion energy $T_\pi=40$ MeV matches

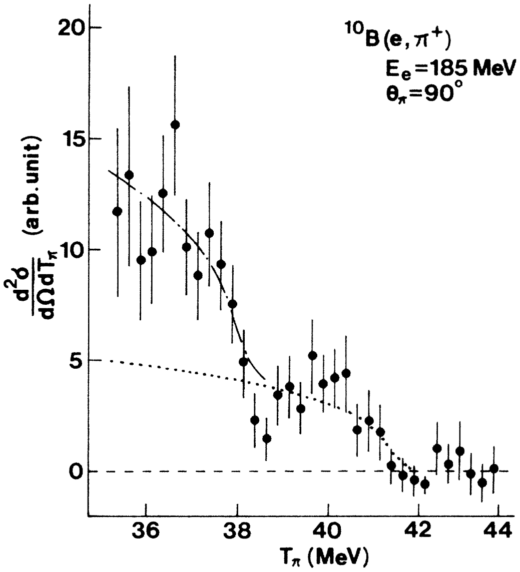

FIG. 1. Typical π^+ spectrum in the ^{10}B(e,π^+) reaction at $E_e = 185$ MeV and $\theta_\pi = 90°$. Lines show contributions of the background (dashed), the ground-state transition (dotted), and the sum of the ground-state and the first-excited-state transitions (dash-dotted).

that in the ^{10}B(e,π^+) runs, and the known ^{1}H(γ,π^+) cross section.[14]

Photoproduction cross sections for the two transitions were obtained with the virtual photon spectrum of Tiator and Wright[15] from an about 3-MeV interval of the pion spectrum at the tip of each transition. A correction for a real photon contribution, which comes from bremsstrahlung by the incident electrons in the target, of about 5% was also included in the analysis. The lines in Fig. 1 show the individual contributions to the pion spectrum. Systematic errors in the resultant cross sections are estimated to be about 15%, and dominated by the uncertainty in the hydrogen normalization of about 10%.

In Fig. 2, we compare our results at selected angles with the earlier works by Zulkoskey *et al.*[10] and by Rawley *et al.*[11] at different energies. Only statistical errors are indicated in this and subsequent figures. We can see that the photon energy dependence is generally smooth except for the ground-state transition at $\theta_\pi = 90°$. It is possible that the set of Ref. 11 is systematically smaller than a combined set of the present work and Ref. 10, although the error bars of Ref. 11 and our measurement overlap around $T_\pi = 40$ MeV.

The curves in Fig. 2 are results of a DWIA calculation made with the computer code of Singham and Tabakin.[16] The code includes the single-nucleon amplitude by Blomqvist and Laget[17] (BL), and the pion-nucleus optical potential by Stricker, McManus, and Carr.[18] We used as the nuclear structure input the p-shell transition densities by Cohen and Kurath[19] [(8–16)POT version] with an oscillator parameter $b = 1.66$ fm. It is known that these transition densities describe the analogous (e,e′) data at the relevant momentum transfers very well.[20] Though the code is based on the coordinate-space formulation, it gives similar cross sections (at a 10% level) to the momentum-space calculation by Tiator and Wright[1] for the ground-state transition at low energies. It is because the nonlocality effects are small in p-shell $M3$ transitions at low energies.[1] We can see that the calculation is compatible with the experimental points at $\theta_\pi = 50°$ for the ground-state transition, but it overestimates the cross sections at $\theta_\pi = 90°$ for both the transitions.

In Fig. 3, the full angular distributions at $k \approx 155$ and 183 MeV are compared with the same DWIA calculation. Again, the calculation generally overestimates the cross sections for both the transitions. The discrepancies for the ground-state transition are about 60% at the backward angles of $k \approx 183$ MeV, but much less at the forward angles and at $k \approx 155$ MeV. We note that the preliminary result at $k \approx 200$ MeV by Nelson *et al.* shows similar deviations from the calculation to the 183 MeV case.[21] Since the nonlocal approximation loses its footing at higher energies even for this transition,[1] the previously reported agreement of the nonlocal calculation with the fixed-angle data in the delta region[12] may be regarded as fortuitous.

If we assume that the results of Ref. 11 are really too

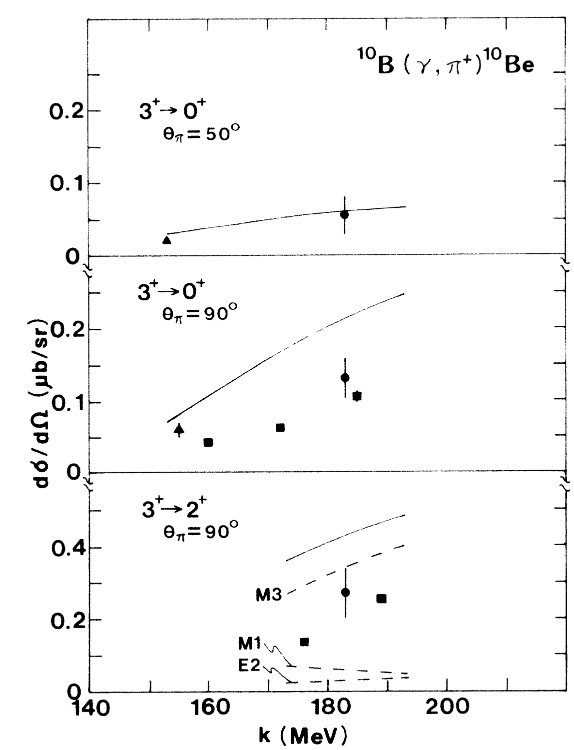

FIG. 2. Photon energy dependence of the ^{10}B(γ,π^+)^{10}Be differential cross sections: the ground-state transition at $\theta_\pi = 50°$ (top) and at $\theta_\pi = 90°$ (middle), and the first-excited-state transition at $\theta_\pi = 90°$ (bottom). Data are from the present work (circles), Zulkoskey *et al.* (Ref. 10) (triangles), and Rawley *et al.* (Ref. 11) (squares). Solid curves are results of a DWIA calculation made with the code of Singham and Tabakin (Ref. 16). Dashed curves in the bottom part of the figure indicate individual multipole components of the transition. In the top part of the figure, the point of Ref. 10 is for $\theta_\pi = 40°$, and the curve is for $\theta_\pi = 45°$.

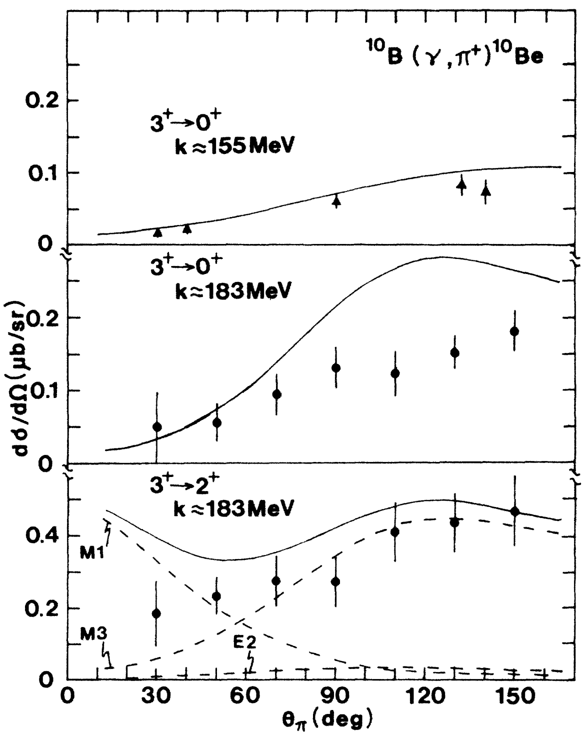

FIG. 3. Angular dependence of the $^{10}B(\gamma,\pi^+)^{10}Be$ differential cross sections: the ground-state transition at $k \approx 155$ MeV (top) and at $k \approx 183$ MeV (middle), and the first-excited-state transition at $k \approx 183$ MeV (bottom). Meanings of symbols and curves are the same as in Fig. 2.

small, we may take as a general trend for the ground-state transition that the theoretical estimates are closer to the data at the lower energies and at the smaller pion angles. These are the regions where the contributions from the delta term in the single-nucleon amplitude are diminishing. Indeed, we can reduce the size of the discrepancies for the ground-state transition to about half at the backward angles of $k \approx 183$ MeV by performing a calculation without the delta term as in the case of the forward-angle $^{13}C(\gamma,\pi^-)^{13}N_{(g.s.)}$.[3] Though this procedure is incompatible with the DWIA concept, it may imply that something missing in the theory is related to the delta. A rather surprising fact here is that the reaction is not completely dominated by the $\sigma\cdot\epsilon$ term as expected from the multipole structure of the transition and the closeness of the energy to the threshold. Nevertheless, the case studied here still has the $\sigma\cdot\epsilon$ term as a major contributor, and should be considered as complementary to other $\sigma\cdot\epsilon$ suppressed cases.

The DWIA calculations with the single-nucleon amplitude by Chew *et al.*[22] and by Berends *et al.*,[23] respectively, give smaller[24,25] and larger[26] cross sections than those with the BL amplitude shown here. These amplitudes have different (delta-related) unitarity properties as pointed out by Wittman *et al.*[27] At present, however, we are unable to ascribe the differences in the results entirely to the effects of unitarity, because these calculations are not consistent with each other in other ingredients. It is interesting to pick up the effects of the unitarity in the BL amplitude, and see if it improves the description of the nuclear photopion reactions.[28]

In addition to the unitary problem, other aspects (e.g., medium effects) of the DWIA theory have to be extensively investigated. The delta-hole model will also offer a possible direction of studying the role played by the delta in this reaction.[8]

Finally, we remark that it has to be checked if the deformation of the ^{10}B nucleus affects the nuclear-structure and pion-distortion parts of the calculation. The latter has been observed in the pion elastic scattering.[29]

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