Nuclear wave function considerations in pion photoproduction

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We find that the measured values of the angular distributions for the reaction $^{13}C(\gamma,\pi^+)^{13}B_{g.s.}$ can be reasonably well reproduced provided that (i) nuclear wave functions constrained to fit a wide range of weak and electromagnetic data are used and (ii) the Δ-isobar term in the Blomqvist-Laget photoproduction operator is omitted. All calculations were done in the $1p$-shell model space, suggesting that core polarization contributions are much smaller than previously estimated.

Pion photoproduction reactions leaving the nucleus in discrete final states have held the promise of being a valuable tool for the study of pion wave function distortions in the interior of unstable nuclei, and for certain aspects of nuclear structure not ascertainable by other probes. However, in order to fulfill this hope, it is necessary that the nature of the photoproduction operator within the nucleus be well understood. In general, calculations have utilized the distorted wave impulse approximation (DWIA) employing an elementary amplitude obtained by Chew, Goldberger, Low, and Nambu[1] (CGLN) or by Blomqvist and Laget[2] (BL).

These two amplitudes are derived from different approaches and are not without certain deficiencies.[3,4] But in most calculations in coordinate space at low energies ($T_\pi \lesssim 100$ MeV) they result in reasonable agreement with each other and the available data.[4] The origins of this agreement lie in the fact that both elementary amplitudes are dominated at low energies by the simple Gamow-Teller $\boldsymbol{\sigma\tau}$ term with approximately the same strength.

Two specific reactions in which these general conclusions do not hold are $^{14}N(\gamma,\pi^-)^{14}O_{g.s.}$ (Ref. 14) and $^{13}C(\gamma,\pi^-)^{13}N_{g.s.}$ (Refs. 5 and 6) where large disagreements with the data have been reported. It is significant that in each of these two reactions, the measured cross sections are much smaller than those usually obtained in photopion reactions. The explanation for this is that in these two particular reactions, nuclear structure effects have conspired to destroy the dominance of the leading $\boldsymbol{\sigma\tau}$ operator, thus enhancing the importance of the higher order, less well-understood components of the transition operator. This has prompted more careful treatment of these higher order terms (including nonlocal effects) by Tiator and Wright[7] and by Toker and Tabakin.[8]

The reaction $^{13}C(\gamma,\pi^+)^{13}B_{g.s.}$ is interesting for a different reason. The high-quality differential cross-section angular distribution data that have been obtained for $T_\pi=40$ MeV (Ref. 9) and the 90° cross sections for $T_\pi=18$, 29, and 42 MeV (Ref. 10) are *not* anomalously low, suggesting that the $\boldsymbol{\sigma\tau}$ dominance is intact. Hence the reaction is predominantly a *local* one and the nonlocal effects studied in Refs. 7 and 8 are not likely to play a major role. The nuclear transition involved is of a simple ground-state-to-ground-state type that has been successfully calculated in the past using the DWIA approach, with standard $1p$-shell model wave functions and pion distortions constrained to fit pion-nucleus elastic scattering data.[4] Yet the various calculations[9-12] disagreed considerably, raising serious doubts about our understanding of the basic reaction mechanism. The status of the theoretical calculations and the nature of their inputs is summarized nicely by Shoda *et al.*[9] who conclude that no calculations using only $1p$-shell nuclear wave functions can explain both the (γ,π^+) data and the inelastic electron scattering data on ^{13}C to the 15.11 MeV isospin analog state of $^{13}B_{g.s.}$. In the present study, we will examine the effects of the various inputs in the calculation. Our results disagree with the conclusions of Shoda *et al.*[9]

First of all, we will examine the effect of nuclear configuration mixing on this reaction. In a recent study,[13] the states $^{13}B_{g.s.}$, ^{13}C(15.11 MeV), ^{13}N(15.06 MeV), and $^{13}O_{g.s.}$ were treated as members of an isospin quartet while $^{13}C_{g.s.}$ and $^{13}N_{g.s.}$ were treated as an isodoublet. By considering these two isomultiplets as three-hole states within the $1p$ shell their wave functions were determined by requiring them to reproduce accurately measured weak and electromagnetic data involving the two states. Two sets of solutions (A and B) were obtained for the isoquartet while only one (I) was obtained for the isodoublet. The predictions of the resulting wave functions gave good agreement with elastic and inelastic electron scattering form factors for momentum transfer $q \lesssim 2.2$ fm^{-1} (Ref. 13), in contrast to calculations using Cohen-Kurath (CK) wave functions.[14]

Since the $^{13}C(\gamma,\pi^+)^{13}B_{g.s.}$ reaction has a final state which is an isospin analog of that obtained in the inelastic electron scattering reaction, it is of interest to see what effect these new wave functions have on the pion photoproduction reaction. In Fig. 1, we see the results of calculations using four sets of wave functions: (i) extreme *j-j* coupling wave functions; (ii) CK (8–16)POT wave functions;[14,15] (iii) set *IB*; and (iv) set *IA*. The details of such calculations, which use the Blomqvist-Laget photoproduction operator and the Michigan State University (MSU) (1982) optical potential[16] for pion distortions, can be found in Ref. 4. The data are from Shoda *et al.*[9] Extreme *j-j* coupling wave functions mean that $^{13}C_{g.s.}$ is treated as a closed $(1s1p_{3/2})$ core with a valence $1p_{1/2}$ neutron, while $^{13}B_{g.s.}$ is treated as closed $(1s1p_{3/2}1p_{1/2})$ neutron shells and a $1p_{3/2}$ proton hole. All calculations

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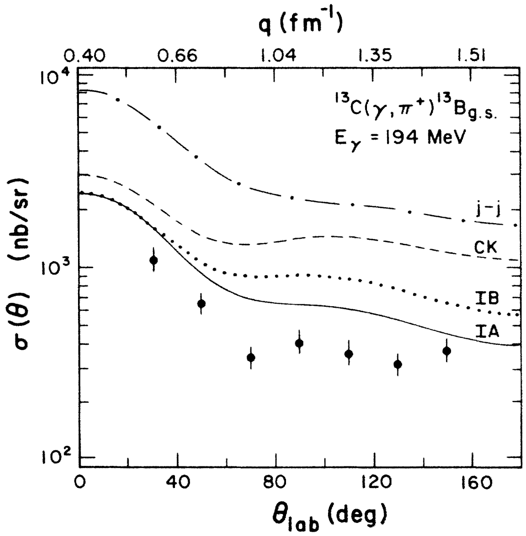

FIG. 1. The effect of different wave function sets on the pion photoproduction reaction. All calculations use the full BL photoproduction operator (Ref. 2) and MSU (1982) pion distortions (Ref. 16). The data are from Shoda *et al.* (Ref. 9). q is the momentum transfer to the nucleus in the barycentric frame.

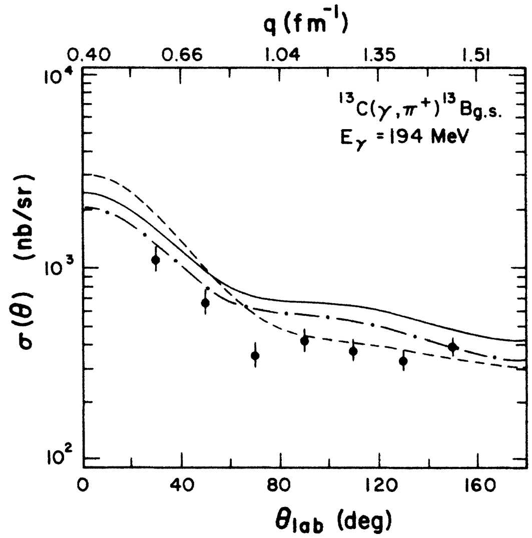

FIG. 2. Solid curve: Full BL operator (Ref. 2) with MSU (1982) pion distortions (Ref. 16) (same as solid curve in Fig. 1). Dash-dot curve: full BL operator with MSU (1979) pion distortion (Ref. 17). Dashed curve: BL operator with no Δ-isobar term and MSU (1982) distortions. The data are from Shoda *et al.* (Ref. 9). q is the momentum transfer to the nucleus in the barycentric frame.

used harmonic oscillator basis wave functions with length parameter $b = 1.59$ fm for (i) and (ii) and $b = 1.73$ fm for (iii) and (iv).

We see that the pure j-j wave functions give cross sections that are too large by nearly an order of magnitude, while the CK wave function predictions are a factor of 3 to 4 too large. The latter is in agreement with the results of Sato-Koshigiri-Ohtsubo (SKO) and Tabakin-Dytman (TD) quoted in Ref. 9 but not with those of Cheon[11] and Maleki[12] who obtain results much closer to the data. [We suspect that the origins of this disagreement lie in Eq. 1.17 of Ref. 11 where the isospin rotation factor $\sqrt{2}$ should really be $\sqrt{3}$. This would scale up the (γ,π^+) calculation of Cheon by 50% while leaving the (e,e′) results unchanged and would bring about rough agreement of all the theoretical calculations that use the CK wave functions and the MSU distortions.] The wave function sets *IA* and *IB* both give much better agreement with the data but even *IA* is still about 50% too large at back angles. To resolve the remaining discrepancy, one has to examine the contribution of the distorted pion waves and the photoproduction operator. But the main point is that most of the discrepancy that existed can be removed by using better nuclear wave functions while still remaining within the $1p$ shell.

The sensitivity of this reaction to pion distortions is seen in Fig. 2 where the calculation has been done with MSU (1979) (Ref. 17) and MSU (1982) optical potentials. Both calculations employed the full BL operator and nuclear wave function set *IA*. The two optical potentials gave almost identical shapes to the cross sections, but the 1979 potential (dash-dot curve) reduces the (γ,π^+) results by about 25% over the 1982 potential (solid curve), resulting in better agreement with the data. In spite of this, we feel that the MSU (1982) potential is to be preferred since it gives much better agreement with the π^+-^{13}C elastic scattering data of Dytman *et al.*[18] (Fig. 3). The ^{13}C$(\gamma,\pi^+)^{13}$B$_{g.s.}$ calculations of Cheon[11] and Maleki[12] used a local Laplacian form of the optical potential which does very poorly with respect to the elastic scattering data, and hence introduces a larger element of uncertainty in their results. In general, the effect of the optical potentials (when compared to plane wave calculations) is to increase the cross sections at back angles by 20% to 30%. The effect of the Coulomb potential is negligible. Hence the use of tightly constrained nuclear wave functions and pion distortions still leaves some disagreement with the data, suggesting that modifications to the photoproduction operator may be necessary.

To test this, the calculation using nuclear wave function set *IA* and MSU (1982) was repeated but with the s-

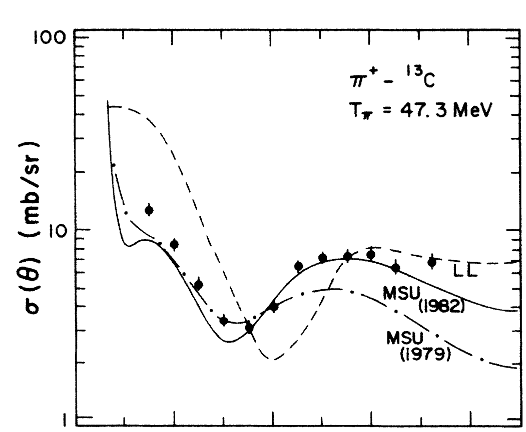

FIG. 3. π^+-^{13}C elastic scattering cross section with different optical potentials. The data are from Dytman *et al.* (Ref. 18). The local Laplacian curve (LL) is taken from Ref. 11.

channel Δ-isobar term in the BL transition amplitude omitted. The presence of this isobar term has been criticized previously on general theoretical grounds as leading to possible double counting[4,8] and calculations for $^{13}C(\gamma,\pi^-)^{13}N_{g.s.}$ by Toker and Tabakin[8] as well as Tiator and Wright[7] have found that the omission of this term gives better agreement with the data for that reaction. The result of the present calculation is shown in Fig. 2 by the dashed curve. We see that the omission of this term gives much better agreement with the data, especially at larger angles. The situation at 90° for $T_\pi = 18$, 29, and 42 MeV is given in Table I where it is again seen that the use of the BL amplitude without the Δ isobar reduces the calculated values considerably, bringing them much closer to the data.[10] The experimental values of LeRose *et al.* at 90° are still about 40% lower with respect to the present calculations. But the datum of Shoda *et al.* at 40 MeV is also 40% larger than the value obtained by LeRose *et al.* at 42 MeV, suggesting that some uncertainty exists about the normalization of the latter data. This has previously been suggested by Stoler *et al.*[5] for the (γ,π^-) reaction. It is unlikely that two-body reaction mechanisms in which a π^0 is produced off one nucleon which then charge exchanges with another nucleon can explain the discrepancy with data. This is because the *amplitude* for (γ,π^0) reactions from a nucleon is an order of magnitude less than for $(\gamma,\pi^\pm)$ reactions, a result that is consistent with partially conserved axial-vector current (PCAC), current algebra, and experiment.[22] Hence such two-body contributions should be small.

TABLE I. The 90° measurements of LeRose *et al.* (Ref. 10) are compared with the theoretical calculations of this study obtained using (i) the full BL operator and (ii) BL without the Δ-isobar contribution. All calculations used the *IA* nuclear wave functions and MSU (1982) (Ref. 16) pion distortions.

T_π		$\sigma(90°)$ in nb/sr	
(MeV)	Expt.	(i) Full BL	(ii) BL (no Δ)
18	178±9	393	325
29	230±4	527	396
42	325±10	692	457

In summary, we find that the available data on the reaction $^{13}C(\gamma,\pi^+)^{13}B_{g.s.}$ can be understood provided that (i) one uses nuclear wave functions that have been constrained to fit weak and electromagnetic data involving those states or their isospin analogs and (ii) the Δ-isobar term in the BL pion photoproduction amplitude is omitted. This is the dashed curve in Fig. 2. It should be recalled that these calculations have been done using the impulse approximation entirely within the $1p$ shell, suggesting that core polarization effects are much smaller than previously thought.[9] (There is, however, always the possibility that these wave functions are effectively absorbing the core polarization effects and conspiring to give the right transition densities for the weak, electromagnetic, and strong transitions.) It also underscores the point that has been forcefully made by Eramzhyan *et al.*[19] in their study of $A = 12$ nuclei that the use of carefully constrained nuclear wave functions is an essential prerequisite to any meaningful studies of the pion photoproduction transition operator. In our calculation, the use of nuclear wave functions constrained to fit a *wide array* of weak and electromagnetic data gave a significant improvement in the calculations of the (γ,π^+) reaction while still remaining within the $1p$ shell. The use of these same wave functions also results in better (though not complete) agreement with the data for the reaction $^{18}C(\gamma,\pi^-)^{13}N_{g.s.}$ (Refs. 20 and 21) suggesting that these wave functions provide an overall consistency that makes them useful for the study of reaction mechanisms involving these states.

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