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Medium effects in photopion reactions

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After discussing the status of distorted wave impulse approximation approaches to the photoproduction of pions from nuclear targets, it is shown that medium effects due to the excitation of particle-hole states by pion propagation are quite significant and serve to improve agreement between coordinate space distorted-wave impulse-approximation calculations and recent data on the reaction $^{14}N(\gamma,\pi^+)^{14}C$. The need to include such medium effects in distorted-wave impulse-approximation photopion calculations is demonstrated, but evidence is given that one must go beyond the local density approximation for evaluating medium effects. The role of recent nuclear structure information and of pion distorted waves on photopion production calculations are also examined.

I. INTRODUCTION

The distorted-wave impulse approximation (DWIA) has been used with considerable success to describe the general features of photopion $(\gamma,\pi^{\pm})$ nuclear reactions.[1-8] The basic Blomqvist-Laget[4] production operator, which has been extracted from the dynamics of pion production from free nucleons, has been used to describe the production of pions even for the case of nucleons within the nucleus.[1-8] With that bold assumption, the motion of the nucleons in the nucleus is incorporated by the use of nuclear wave functions that are consistent with electron scattering information at the requisite momentum transfers and the full coupling of all multipole photons to the nuclear currents is included in a gauge invariant manner. The motion of the produced pion is stipulated by the use of final state distorted waves obtained from analysis of pion elastic scattering data.[3] These calculations include all terms of the production operator, and in several cases terms beyond the $\sigma\cdot\hat{e}_\lambda\tau$ (Gamow-Teller) operator were needed to describe the dynamics.[1,5] For example, from beta decay we know that $A=14$ nuclei have small Gamow-Teller transitions and hence the photopion reaction proceeds through the "higher order terms," especially the pion pole operator, to a greater extent than for other nuclei.[5] For isoelastic transitions, e.g., $^{15}N\rightarrow^{15}O$ (g.s.), it was found that the pion pole and leading $\sigma\cdot\hat{e}_\lambda\tau$ terms interfere destructively to produce qualitative agreement with photopion experiments.[5,6]

Motivated by several successful predictions of the basic features of the early data for photoproduction of charged pions from light nuclei, DWIA methods were developed further by several authors.[7,8] The effects of propagator nonlocalities (i.e., the fact that intermediate nucleons, deltas, and, especially, pions absorb the photon and couple to the final pion at different space points in the basic production dynamics) have been studied in detail by Toker and Tabakin.[7] Recently, impressive momentum space calculations have been performed by Tiator and Wright[8(a)] and by Eramzhayen *et al.*[8(b)] (Momentum space methods are clearly preferred, despite the difficulties with the Coulomb interaction, since the full momentum dependence of the basic photopion operator can be included. On the other hand, momentum space methods involve costly multidimensional integrals.)

Despite these extensive efforts, several serious discrepancies persist both between calculations and experiment and between momentum and essentially equivalent nonlocal coordinate space results. In particular, our coordinate space predictions for $(\gamma,\pi^{\pm})$ differential cross sections for ^{14}N, for ^{13}C, and for ^{10}B targets proved to be larger than much of the subsequent data.[1,20-24] Momentum space results of Tiator and Wright[8(a)] yield better agreement with the ^{14}N 173 and 200 MeV data, but difficulties develop at higher energies[9] for ^{14}N and their predictions are too large for some of the lower energy data sets.[23,24] Nevertheless, both approaches are subject to the criticism of not including medium modification of the basic photoproduction operator. This situation has led us, after exhaustive attempts to salvage the standard impulse approximation for this probe, to embark on a study of medium effects.

The approach we have adopted is to include the renormalization of the basic operators following the ideas developed by Ericson, Delorme, and Chanfray[10] and Mukhopadhyay *et al.*,[11] and applied to $(e,e'\pi)$ and $(\pi,\pi\pi)$ reactions by Cohen and Eisenberg.[12,13] The major motivation is to examine medium effects on the (γ,π) production diagrams (Figs. 1 and 2) which include virtual off mass

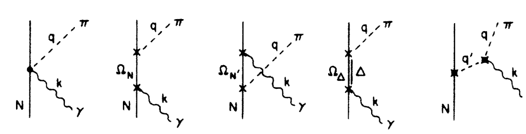

FIG. 1. The basic pion photoproduction processes corresponding to the contact (a), nucleon pole (b), crossed nucleon pole (c), delta (d), and pion pole (e) terms. The associated propagators $\Omega_x(\mathbf{r},\mathbf{r}')$ for $x=$N, N′, Δ, and π, which produce the nonlocalities studied in Ref. 7 are also shown.

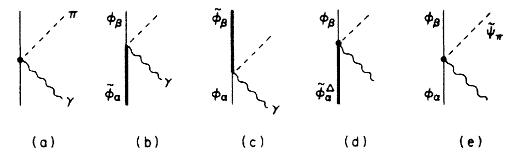

FIG. 2. The equivalent local version of the photoproduction processes. Here the heavy lines represent the effect of the propagators $\Omega_x(\mathbf{r},\mathbf{r}')$ on the associated nucleon (b), crossed nucleon (c), delta (d), and pion pole (e) lines (see Fig. 1). The heavy lines therefore represent the "smeared" orbitals $\tilde{\phi}_\alpha$ and pion wave functions $\tilde{\Psi}_\pi$ [Eqs. (1) and (2)], which are introduced into a local DWIA method (Ref. 1) to include nonlocal propagator effects (Ref. 7).

shell pions; these virtual pions should have the ability to excite nucleon and delta particle-hole pairs while propagating in the nuclear medium (Fig. 3). Consequently, the spin operators to be used for nucleons residing in the nucleus differ from those used to describe the free space dynamics of photoproduction. Following Cohen and Eisenberg,[12,13] we include this medium effect using a local density approximation (LDA), within the framework of the nonlocal calculation of Toker and Tabakin.[7]

There is a considerable literature on the spin-isospin operators in nuclei for a variety of probes.[14–17] The existence of a pion condensate (or even a precursor to such a state), which would magnify such effects by having a large number of zero energy pions, is no longer a promising idea in view of several experiments. Nevertheless, the medium modifications of the spin-isospin operators due to particle-hole excitations by virtual pions remains a subject of great interest. In the case of photoproduction, the lowest order operator is of transverse nature since

$$\sigma\times\mathbf{k}\cdot\hat{\mathbf{e}}_\lambda=\sigma\cdot\mathbf{k}\times\hat{\mathbf{e}}_\lambda=-ik_0\lambda\sigma\cdot\hat{\mathbf{e}}_\lambda \; .$$

An especially interesting part of photopion production involves the pion pole diagram [see Fig. 1(e)] where the photon is absorbed on a virtual pion of almost zero energy. This term involves both longitudinal ($\sigma\cdot\mathbf{k}$) and transverse ($\sigma\times\mathbf{k}$) operators. Hence the photopion process offers the opportunity to study both classes of operators.

The transition ^{14}N$(\gamma,\pi^+)^{14}$C(g.s.) is a particularly significant case and we therefore focus our attention on it. Our calculations show that the differential cross sections for this transition are dominated by the $\sigma\cdot\hat{\mathbf{e}}_\lambda\tau$ and pion pole terms in the photoproduction operator when the final state pion kinetic energy is less than about 70 MeV. That dominance is illustrated in Fig. 4 which shows the contribution of the $\sigma\cdot\hat{\mathbf{e}}_\lambda\tau$ alone and the pion pole term alone to the differential cross section for the reaction ^{14}N$(\gamma,\pi^+)^{14}$C at a photon laboratory energy of 173 MeV. For these results, we use the University of Massachusetts[19] $H1$ nuclear matrix elements and the Stricker, McManus, and Carr (SMC) (Ref. 3) pion optical potential. When the full Blomqvist-Laget operator is used, the full nonlocal result is determined. It is shown as a solid curve in Fig. 4. The additional operators, such as nucleon recoil terms, contribute less than 10% to the result shown here. Thus, this reaction is dominated by the transverse $\sigma\cdot\epsilon_\lambda$ operator plus the longitudinal and transverse pion pole operator, which provides us with a special opportunity to investigate those two operators through their interference. We also see from Fig. 4 that the pion pole contribution (dashed curve) is quite large at smaller angles where it tends to interfere destructively with the $\sigma\cdot\epsilon_\lambda$ term (dotted curve); whereas, at larger angles the $\sigma\cdot\epsilon_\lambda$ term dominates, interferes constructively with the pion pole term, and a large back angle differential cross section results (Fig. 4).

In the same figure, we compare results using the older MIT-NBS (Ref. 18) nuclear matrix elements with a calculation using the more recent University of Massachusetts fitted matrix elements.[19] This current determination used both elastic and inelastic electron scattering form factors for fitting and their results should be more accurate than earlier efforts. Indeed, when used in the (γ,π) calculation, the University of Massachusetts matrix elements give cross sections that are significantly smaller than those obtained from the MIT-NBS values and closer to the data (see Figs. 4 and 5).

The choice of nuclear matrix elements for $A=14$ transitions is complicated because of the "anomalously slow" β-decay lifetime.[17] In our study, we use the University of Massachusetts p-shell model fits to the $M1$ form factors, ground state magnetic moment, and the radiative decay width of the 2.313 MeV level. In that fit the small β-

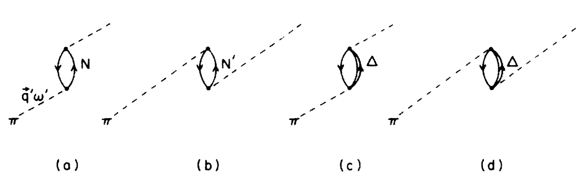

FIG. 3. The renormalization of the pion propagator in the nuclear medium due to the excitation of nucleon-hole and delta-hole states by an off mass shell ($\omega'\approx 0$) pion.

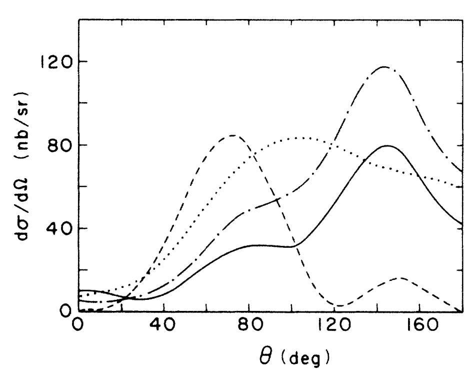

FIG. 4. The differential cross section for the reaction ^{14}N$(\gamma,\pi^+)^{14}$C(g.s.) for incident 173 MeV (laboratory) photons. The full nonlocal calculation (Ref. 7) is shown using MIT-NBS (Ref. 18) (dot-dash) and the recent University of Massachusetts (Ref. 19) (solid) nuclear reduced matrix elements. The latter calculation is also shown for only the $\sigma\cdot\hat{\mathbf{e}}_\lambda\tau$ (dotted) and pion pole (dashed) terms of the photoproduction operator.

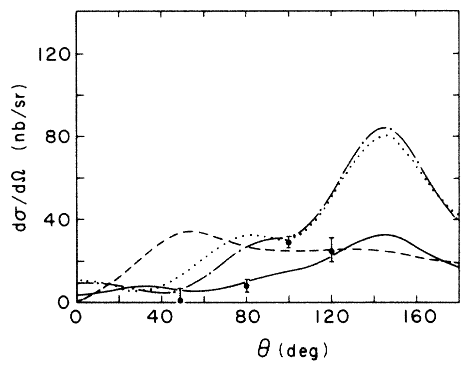

FIG. 5. The differential cross section for the reaction $^{14}N(\gamma,\pi^+)^{14}C(g.s.)$ for incident 173 MeV (laboratory) photons. The data from Mainz[20] are shown along with the renormalized nonlocal results of this work. The dotted curve repeats the nonlocal results (Ref. 7) of Fig. 4 for the University of Massachusetts (Ref. 19) case. Results with renormalization ($g'=0.7$) of only the $\sigma\cdot\hat{\epsilon}_\lambda\tau$ (dash) and only the pion pole (dot-dash) terms are also shown along with the result renormalizing both terms (solid line).

decay matrix element was "not explicitly fit but constrained to be of the order of the uncertainty due to meson exchange currents."[19] Goulard *et al.*[17] suggested that the small β-decay rate arises from a destructive interference between meson exchange (two-body) corrections and the one-nucleon axial current. The meson exchange current involves a type of medium correction to a two-body operator. We deal with a one-nucleon operator description of the (γ,π) process which is also modified by the nuclear medium due, for example, to virtual meson propagation effects, i.e., by a virtual meson exciting nucleon-hole states. A part of such corrections might play the role suggested by Goulard *et al.*[17] and serve to bridge the gap at low momentum transfers between the University of Massachusetts β-decay matrix elements and the small empirical value. The (γ,π) reactions involve higher momentum transfers, where similar cancellations will be reported here. This work is also different from Ref. 17 because in photoproduction virtual pions can be made real by the incident photon [see the pion-pole diagram of Fig. 1(e)].

Disentangling meson, medium, isobar, and nuclear structure effects is an extremely difficult problem which we do not claim to solve, but we feel that the University of Massachusetts fitting procedure provides a reasonable starting point, since it provides room for meson current correction effects. In contrast, when we use another set of University of Massachusetts nuclear matrix elements which are constrained to fit empirical β-decay results, the (γ,π) cross sections were always much higher than the results shown in our paper (although the shapes were generally correct). Hence a direct phenomenological incorporation of the experimental β-decay matrix element does not suffice and we prefer to adopt the philosophy of leaving the requisite room for a microscopic treatment of in-the-medium meson current effects. In the future, a self-consistent treatment is clearly needed, especially in view of the results we present later in this paper.

In Sec. II, the basic alterations of our earlier nonlocal DWIA approach to photopion reactions, required by the renormalization of the above spin-isospin operators, are described. The effect of the medium on the $\sigma\cdot\epsilon_\lambda\tau$ and pion pole terms are shown to yield helpful, significant reductions in the charged pion production for ^{14}N, ^{13}C, and ^{10}B (Sec. III). The earlier results for ^{12}C are seen to also change, in a generally beneficial manner, but lead us to make suggestions for further improvements in the theory in Sec. IV, where we also give our conclusions concerning the need for medium effects in photopion reactions and their relation to that required by other probes.

II. RENORMALIZATION OF SPIN OPERATORS AND DWIA

The photoproduction of pions proceeds via the diagrams shown in Fig. 1. Here we see that the nucleon [Fig. 1(b)], crossed nucleon [1(c)], delta [1(d)], and pion pole [1(e)] propagators involve motion from points $\mathbf{r}$ to $\mathbf{r}'$; whereas, for the contact term [Fig. 1(a)] the nucleon, pion, and photon all interact at one point. To account for the above nonlocal [Figs. 1(b)—1(e)] propagators Toker and Tabakin[7] developed a nonlocal gauge invariant coordinate space DWIA method for photopion reactions. The central idea was to have the nonlocal propagator act on the associated nucleon, delta, or pion lines; a process called "smearing" in Ref. 7. The plane wave nature of the photon permitted one to mathematically translate the photon so that the process could be described by an equivalent local form (see Fig. 2). In this case, the wave functions in the local calculation are replaced by smeared nucleon (N), crossed nucleon (N′), delta (Δ), and pion (π) wave functions defined by

$$\begin{aligned}\tilde{\Psi}_\pi(\mathbf{r})&=\int \Omega_\pi(\mathbf{r},\mathbf{r}')\Psi_\pi(\mathbf{r}')d^3r' ,\\ \tilde{\Phi}_\alpha(\mathbf{r})&=\int \Omega_x(\mathbf{r},\mathbf{r}')\Phi_\alpha(\mathbf{r}')d^3r' ,\\ x&=\text{N, N}', \text{ or } \Delta .\end{aligned} \tag{1}$$

Here the nonlocal operators Ω_x describe the nucleon, crossed nucleon, delta, and pion propagators as they occur in Fig. 1. To carry out this procedure for including nonlocalities for the pion, it was convenient to construct momentum space pion waves [called mock (M) waves in Ref. 7] and to fold in the pion propagator by the integral

$$\tilde{\Psi}_\pi(\mathbf{r})=\int \Omega_\pi(\mathbf{r},\mathbf{q}')\Psi^M_{\pi\mathbf{q}}(\mathbf{q}')d^3q' . \tag{2}$$

Using such techniques, nonlocalities of the production process were studied.[7] Although these nonlocalities proved to be quite significant, particularly for the pion propagator, several discrepancies with the data which originally motivated that extensive development remained unresolved.[1,2,7] Efforts to improve the nuclear structure input information to make it consistent with electron scattering and other data proved to be helpful, but the gap remained. Alternate pion final state interactions were also invoked, but the gap with data remained.

The above study of nonlocalities was still carried out within the philosophy of using the free pion production operator. At this stage it became necessary to go beyond that hopeful assumption and to follow the path required by other nuclear probes[10,14–17] and invoke the effect of the medium. The major medium effect invoked is that virtual off mass pions excite nucleon particle-hole states as they propagate. That effect is illustrated in Fig. 3. As the pion propagates, p-h and Δ-h bubbles are excited, and for a pion of four momentum q' (energy ω' and momentum $\mathbf{q}'$), the propagator is no longer of the free form

$$(\sigma\cdot\mathbf{q}')\hat{\epsilon}_\lambda\cdot(\mathbf{q}+\mathbf{q}')D_\pi(q') , \quad (3)$$

with

$$D_\pi(q')=(q'^2-m_\pi^2)^{-1}=(\omega'^2-\mathbf{q}'^2-m_\pi^2)^{-1} ,$$

but is altered by the medium to the form

$$(\sigma\cdot\mathbf{q}')\hat{\epsilon}_\lambda\cdot(\mathbf{q}+\mathbf{q}')D_\pi(q')/(1+WU) , \quad (4)$$

where $W=\mathbf{q}'^2D_\pi(q')+g'$. For the pion pole diagram Fig. 1(e), the production of the virtual pion at the nucleon vertex is described by the operator $\sigma\cdot\mathbf{q}'$, and the photon couples to the pion current via the operator $\hat{\epsilon}_\lambda\cdot(\mathbf{q}+\mathbf{q}')$. Here, U represents the interaction of the propagating pion with the nucleons in the nucleus. In the medium it has both nucleon (U_N), delta (U_Δ, due to isobar-nucleon hole excitations), and ρ (U_ρ) terms of the form

$$U(q')=U(\mathbf{q}',\omega') =[f^2(q')/m_\pi^2](U_N+4U_\Delta)+U_\rho , \quad (5)$$

where the pion nucleon form factor is given by

$$f^2(q'^2)=f^2(\Lambda^2-m_\pi^2)^2/(\Lambda^2-q'^2)^2 ,\quad f^2/4\pi=0.08,\ \Lambda^2=1 \text{ GeV} . \quad (6)$$

The nucleon and delta interactions in infinite nuclear matter are given by:[12,13]

$$U_N(q')=(M^*p_f/\pi^2)\{1+(p_f/2|\mathbf{q}'|)[L(x_+)-L(x_-)]\} ,\quad U_\Delta(q')=(\tfrac{8}{9})[A\rho\omega_\Delta/(\omega_\Delta^2-\omega'^2)] , \quad (7)$$

where

$$M^*=0.8\ M_N,\ \omega_\Delta=2.3\ m_\pi ,\quad L(x)=[(1-x^2)/x^2]\ln(|1-x|/1+x) ,\quad x_\pm=(p_f/M^*)|\mathbf{q}'|/(E_{q'}\mp\omega') ,\quad E_{q'}=\mathbf{q}'^2/2M^* . \quad (8)$$

The Fermi momentum p_f which enters into Eqs. (7) and (8) can be related to the local density $\rho(r)$ by

$$p_f^3(r)=3\pi^2A\rho(r)/2 . \quad (9)$$

Using the infinite medium and then relating its Fermi momentum to the nuclear density is called the local density approximation (LDA). It was adopted for photopion studies by Cohen and Eisenberg[12] and later subject to critical study by Cohen.[13] We use it here to estimate the effect of the nuclear medium, while recognizing the need for a full random phase approximation (RPA) treatment.[13]

The quantity W_{ij} is related to the associated nucleon-nucleon interaction in the medium, V_{NN}, by the relations

$$W_{ij}=[q_i'q_j'D_\pi(q')+\delta_{ij}g'] , \quad (10)$$

$$V_{NN}(\mathbf{q},\omega)=\tau_1\cdot\tau_2[f^2(q^2)/m_\pi^2]\sigma_i^1W_{ij}\sigma_j^2 =\tau_1\cdot\tau_2(f^2/m_\pi^2)\{[(\sigma^1\cdot\mathbf{q})(\sigma^2\cdot\mathbf{q})/(q^2-m_\pi^2)]+\sigma^1\cdot\sigma^2g'\} , \quad (11)$$

which involve a one-pion exchange potential (OPEP) part plus a constant spin and isospin dependent term which simulates strong, short-range correlation effects. This model has been used in nuclear calculations by many authors.[10–17] The role of an additional term in Eq. (5) (U_ρ) arising from the ρ meson will be mentioned later.

Thus a rule for renormalizing the spin operator is derived in Refs. 11 and 12 to be

$$\tilde{\sigma}_i=\sum_{j=1,3}\mu_{ij}\sigma_j , \quad (12)$$

$$\mu_{ij}=(1+g'U)^{-1}\{\delta_{ij}-[D_\pi(q')U_{q_i'q_j'}/(1+WU)]\} , \quad (13)$$

where $q'(\omega',\mathbf{q}')$ is the four-vector of the propagating pion which is determined by [see Fig. 1(e)]

$$\mathbf{q}'=\mathbf{k}-\mathbf{q} \quad (14)$$

and

$$\omega'=k_\gamma-E_\pi=(\text{small}) . \quad (15)$$

The effect of the medium due to the off mass shell pion propagation in the nucleus is thus given by the matrix μ_{ij}. Note that the medium modification of the pion propagator affects not only the pion pole term, but also the other diagrams since intermediate nucleons and deltas interact with the nucleus via exchange of off mass shell pions.

The result of applying the above rule to the pion pole term has already been given in Eqs. (3) and (4); when applied to the $\sigma\cdot\hat{\epsilon}_\lambda$ term the result is

$$\sigma\cdot\hat{\epsilon}_\lambda\rightarrow(1+g'U)^{-1}\{\sigma\cdot\hat{\epsilon}_\lambda-[D_\pi(q')U(\sigma\cdot\mathbf{q}')(\mathbf{q}'\cdot\hat{\epsilon}_\lambda)](1+WU)^{-1}\} . \quad (16)$$

In this paper we focus on the medium renormalization of the $\sigma\cdot\hat{\epsilon}_\lambda$ and pion pole terms, which we find to be the dominant operators for the $A=14$ reaction under study for $T_\pi \leq 70$ MeV. Inclusion of this medium effect using the LDA requires only simple modifications of the integrals needed to calculate the photopion amplitudes. For example, to introduce the above medium effects into the nonlocal DWIA photopion code of Ref. 7, the integrals involving the operator $G_1\sigma\cdot\hat{\epsilon}_\lambda$ now include an additional factor:

$$G_1\sigma\cdot\hat{\epsilon}_\lambda \rightarrow G_1\sigma\cdot\hat{\epsilon}_\lambda f_1(r) \; . \tag{17}$$

For the operator (of pion-pole—type) the associated integrals are modified by the replacement:

$$G_3\sigma\cdot\mathbf{q}'\hat{\epsilon}_\lambda\cdot(\mathbf{q}'+\mathbf{q}) \rightarrow G_3\sigma\cdot\mathbf{q}'\hat{\epsilon}_\lambda\cdot(\mathbf{q}'+\mathbf{q})f_2(r) \; . \tag{18}$$

The two functions f_1 and f_2 are defined by:

$$\begin{aligned} f_1(r) &= [1/(1+g'U)] \; , \\ f_2(r) &= f_1(r)[(1+g''U)/(1+WU)] \; , \\ g'' &= g' - [G_1/(2G_3)] \\ &\approx g' - 0.75 \text{ at } E_\gamma = 173 \text{ MeV} \; , \end{aligned} \tag{19}$$

where the dependence on r arises from the LDA [Eq. (9)] and ensures that at the nuclear surface both f_1 and f_2 approach 1. The repulsive nature of U_N usually decreases the amplitude arising from each of the affected diagrams.

Several approximations, beyond the use of the LDA, are used to facilitate our estimate of medium effects; namely: (1) the medium effects are assumed to involve only real terms, (2) the renormalization of other operators are being ignored, and (3) angle dependences which occur in Eq. (19) are being treated in an angle-averaged approximation. The potential used to describe the U_Δ [Eq. (7)] interaction of the virtual pion with the nucleus should have an absorptive part, which arises both from the delta channel's width and from loss of pion flux by annihilation and excitations. Inclusion of such effects would essentially rotate our amplitudes by complex phases and further alter the interference between various terms of the total photopion amplitude. The ρ-meson term U_ρ of Eq. (5) should also be included to describe realistic, short-range meson effects.[13] Nevertheless, for simplicity, we ignore these complicated aspects and simply modify the integrals for the $\sigma\cdot\hat{\epsilon}_\lambda\tau$ and pion pole operators using Eqs. (17)—(19).

III. RESULTS

As discussed in the Introduction, the ^{14}N$(\gamma,\pi^+)^{14}$C(g.s.) transition is dominated by the $\sigma\cdot\hat{\epsilon}_\lambda\tau$ and pion pole terms in the photoproduction operator for pion kinetic energies less than about 70 MeV. This reaction therefore provides a good testing ground for the renormalization procedure introduced in Sec. II. We now present results for this and other transitions for which recent data are available.[20–24] All calculations use all terms of the Blomqvist-Laget[4] production operator (Fig. 1) and the energy-dependent optical potential of Stricker, McManus, and Carr.[3]

The nonlocal results (without renormalization) for 173 MeV photons are presented in Fig. 5 along with the Mainz[20] data; clearly, aside from perhaps one point, the result based on the nonlocal DWIA approach (dotted curve) is too large at all angles, even when the best available nuclear[19] and pion-nucleus[3] information is used. Invoking the LDA renormalization of the pion pole and $\sigma\cdot\hat{\epsilon}_\lambda\tau$ terms are described earlier (choosing $g'=0.7$), the renormalization of the pion pole term alone [Eq. (4)] (dot-dash curve) has little effect on the differential cross section (one sees only a slight decrease at large angles and a bigger, but still small, buildup at forward angles). In contrast, the renormalization of the $\sigma\cdot\hat{\epsilon}_\lambda\tau$ term alone has a dramatic effect; namely, it suppresses the back angle and increases the forward angle differential cross section (see the dashed curve in Fig. 5). When both the $\sigma\cdot\hat{\epsilon}_\lambda\tau$ and pion pole terms are renormalized according to Eqs. (17)—(19) (solid curve), the cross section is suppressed at all angles to produce excellent agreement with the data. At forward angles the suppression is a consequence of the renormalization of both terms, while at back angles the dramatic decrease of the $\sigma\cdot\hat{\epsilon}_\lambda\tau$ contribution is the dominant effect. We see here a large reduction of the transverse operator at back angles, plus a fortunate destructive interference at forward angles which leads to overall good agreement with these data.

The sensitivity of the above results to the value of g', which is used to describe strong short-range correlation effects, is shown in Fig. 6. The dot-dashed curve is again our result using Toker's nonlocal DWIA procedures[7,19] and the dashed curve is the local DWIA result of Singham and Tabakin,[1] which shows that the nonlocalities made the disagreement worse for this case. For a range of values of g' (0.5 to 0.9), the medium LDA renormalization effect yields the curves shown in Fig. 6. There is apparently little sensitivity to g', with all values in this range being consistent with the Mainz data.[20]

Encouraged by the beneficial result described above

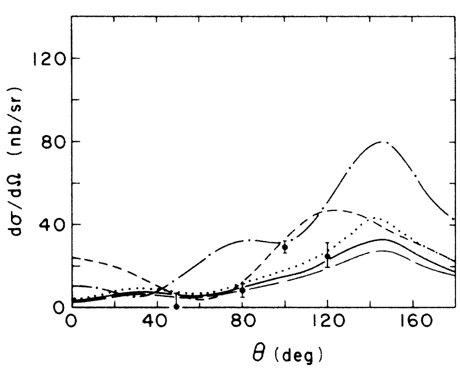

FIG. 6. The differential cross section for the reaction ^{14}N$(\gamma,\pi^+)^{14}$C(g.s.) for incident 173 MeV (laboratory) photons. The data from Mainz (Ref. 20) are shown along with the results of an earlier (Ref. 1) local DWIA calculation (short dashed curve). We also show our nonlocal DWIA results (Ref. 7) using the University of Massachusetts (Ref. 19) $H1$ nuclear matrix elements for the unrenormalized case (dot-dash curve) and for $\sigma\cdot\hat{\epsilon}_\lambda\tau$ and pion pole renormalized cases with g' values of 0.5 (dotted), 0.7 (solid), and 0.9 (long dashed).

when the effect of the nuclear medium was included, we now examine the results for the same transition at a photon laboratory energy of 200 MeV (Fig. 7). Again the net effect of renormalizing the pion pole term alone is slight; whereas, for the $\sigma\cdot\hat{\epsilon}_\lambda\tau$ term alone we have a large renormalization. When both operators are renormalized the interference mechanism described earlier occurs and, for a value of $g'=0.7$, a greatly suppressed differential cross section results (see the solid curve in Fig. 7). The Bates data[21] are larger than our $g'=0.7$ results, which suggests that lower g' and U values are needed to lessen the suppression and improve agreement with the data. In any case the LDA renormalization is clearly a significant and helpful effect.

The procedure described in Sec. II can be readily applied to any (γ,π) transition as long as the LDA is used to calculate the medium effects. We have examined the effects of renormalizing just the $\sigma\cdot\hat{\epsilon}_\lambda\tau$ and pion pole operators in other nuclei for which data have recently been published. These transitions include the following:

^{12}C$(\gamma,\pi^+)^{12}$B(g.s. and 2$^+$), 32 MeV pions (Ref. 22) ,

^{13}C$(\gamma,\pi^-)^{13}$N(g.s.), 48 MeV pions (Ref. 23) ,

^{10}B$(\gamma,\pi^+)^{10}$Be(g.s.), 200 MeV photons (Ref. 24) .

For these cases, we do not have the interesting dominance of the $\sigma\cdot\hat{\epsilon}_\lambda\tau$ and pion pole terms seen in the ^{14}N$(\gamma,\pi^+)^{14}$C reaction. For $A=12$ the $\sigma\cdot\hat{\epsilon}_\lambda\tau$ term is dominant for the transition to the ground state at pion energies less than about 50 MeV. As shown in Fig. 8, the nonlocal results are suppressed too much by the medium effects, when applied to the $\sigma\cdot\hat{\epsilon}_\lambda\tau$ and pion pole terms using the local density approximation. In Fig. 8 one sees that the local[1] and nonlocal[7] DWIA calculations are in fair agreement with the Mainz data;[22] however, the strong renormalization of the $\sigma\cdot\hat{\epsilon}_\lambda\tau$ term reduces the calculated LDA result to an unacceptable value (solid curve) below the data. In contrast, the local and nonlocal results[1,7] are too high for the final 2$^+$ 0.95 MeV state of ^{12}B, and the medium suppression with $g'=0.7$ brings the calculation closer to the Mainz data. These three results are shown in

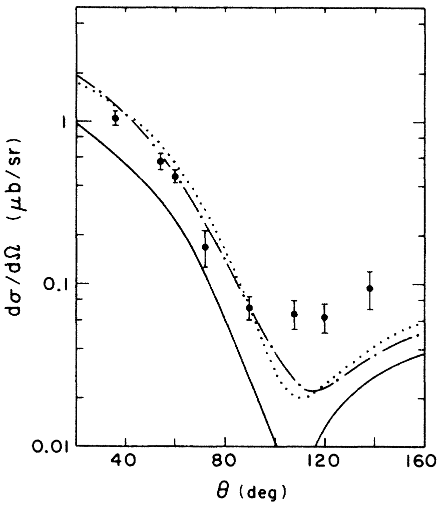

FIG. 8. The differential cross section for the reaction ^{12}C$(\gamma,\pi^+)^{12}$B(g.s.) for final 32 MeV (laboratory) pions. The data from Mainz (Ref. 22) are shown along with earlier DWIA local (Ref. 1) (dotted curve), and nonlocal (Ref. 7) (dot-dash) calculations before renormalization using the Cohen-Kurath (Ref. 25) nuclear matrix elements. The solid curve shows the same nonlocal case after renormalization of the $\sigma\cdot\hat{\epsilon}_\lambda\tau$ and pion pole terms using $g'=0.7$ (solid curve).

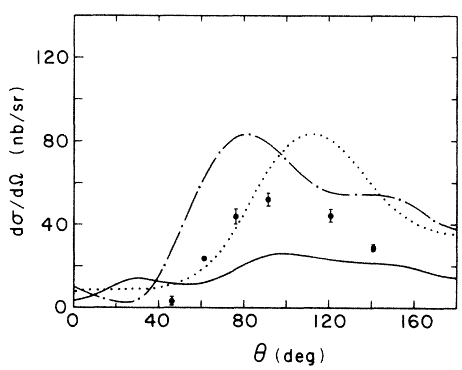

FIG. 7. The differential cross section for the reaction ^{14}N$(\gamma,\pi^+)^{14}$C(g.s.) for incident 200 MeV (laboratory) photons. The data from Bates (Ref. 21) are shown along with the local DWIA results (dotted curve) (Ref. 1), our nonlocal DWIA (Ref. 7) calculations before renormalization using the University of Massachusetts (Ref. 19) $H1$ nuclear matrix elements (dot-dashed curve), and after renormalization of the $\sigma\cdot\hat{\epsilon}_\lambda\tau$ and pion pole terms using $g'=0.7$ (solid curve).

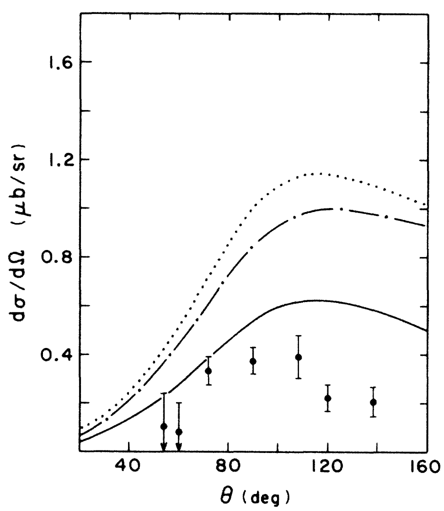

FIG. 9. The differential cross section for the reaction ^{12}C$(\gamma,\pi^+)^{12}$B$(2^+,0.95$ MeV) for final 32 MeV (laboratory) pions. The data from Mainz (Ref. 22) are shown along with earlier DWIA local (dotted curve) (Ref. 1) and nonlocal (dot-dash) (Ref. 7) calculations before renormalization using the Cohen-Kurath (Ref 25) nuclear matrix elements. The solid curve shows the same nonlocal case after renormalization of the $\sigma\cdot\hat{\epsilon}_\lambda\tau$ and pion pole terms using $g'=0.7$ (solid curve).

Fig. 9. For this case the $\sigma\cdot\hat{\epsilon}_\lambda\tau$ is supplemented by sizable contributions from the isobar and other operators.

The above results show that the effect of the medium cannot be included for all nuclei in the simple manner that led to helpful results for ^{14}N. Another problem with the transition to the 2^+ state involves the nuclear structure information. DWIA studies by Eramzhyan *et al.*,[8(b)] without medium effects, but with careful attention to the continuity equation, give good agreement with both the $A=12$ photoproduction and electron scattering data. Thus, we conclude that the physical effect of the medium must depend sensitively on the nucleus and its state. Also the recent finite nucleus RPA calculations of Cohen[13] go beyond the LDA in treatment of the nuclear medium and could provide such a selectivity. Hopefully, the needed suppression occurs for some ($A=14$) and not for other reactions (say, $A=12$ for the final nucleus in its ground state). The ^{13}C(γ,π^-)^{13}N(g.s.) results for $T_\pi=48$ MeV are shown in Fig. 10. The Toker[7] nonlocal DWIA result using the Cohen-Kurath[25] nuclear matrix elements (dashed curve) is contrasted in Fig. 10 with the nonlocal DWIA result using Singham's phenomenological matrix elements.[26] These improved matrix elements move the DWIA results closer to the data as shown by the dot-dashed curve in Fig. 10, but are not the whole story. A further reduction occurs when the LDA renormalized $\sigma\cdot\hat{\epsilon}_\lambda\tau$ and pion pole operators are introduced (using $g'=0.7$ and the nuclear structure information of Singham[26] as input), shown as the solid curve in Fig. 10. For this reaction the renormalization of just the $\sigma\cdot\hat{\epsilon}_\lambda\tau$ and pion pole terms yields a beneficial suppression as in the ^{14}N case.

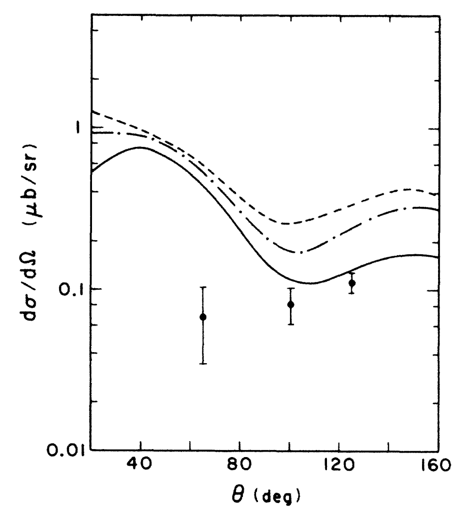

FIG. 10. The differential cross section for the reaction ^{13}C(γ,π^-)^{13}N(g.s.) for final 48 MeV (laboratory) pions. The data from NIKHEF (Ref. 26) are shown along with nonlocal DWIA calculations before renormalization using the Cohen-Kurath (Ref. 25) (dashed curve) and Singham's recent (Ref. 26) (dot-dash) nuclear matrix elements. The solid curve shows the same nonlocal case after renormalization of the $\sigma\cdot\hat{\epsilon}_\lambda\tau$ and pion pole terms using Singham's nuclear matrix elements and $g'=0.7$.

Finally, for the reaction ^{10}B(γ,π^+)^{10}Be, several calculations yield excessive cross sections compared to preliminary Bates data,[24] i.e., the local and even the various nonlocal DWIA results of Refs. 1, 7, and 8(a) are too high. Tiator and Wright[8(a)] note that a fit to the data can be achieved by simply omitting the delta contribution. A renormalization of the $\sigma\cdot\hat{\epsilon}_\lambda\tau$ and pion pole terms only (i.e., the bare delta is kept) also yields a dramatic reduction. Indeed, for that case the suppression is excessive compared to the preliminary Bates data, which suggests that a full study of the effect of the medium on all of the photopion operators is really necessary (especially the Δ piece which is shown to be important by Tiator and Wright[8(a)]).

IV. CONCLUSION

The local density approximation has been used to estimate the effect of the nuclear medium on the $\sigma\cdot\epsilon_\lambda\tau$ and pion pole photopion production operators, which are the dominant operators for ^{14}N(γ,π^+)^{14}C for incident 173 and 200 MeV photons. The suppression and interference of the nonlocal DWIA amplitudes arising from these operators yield a beneficial reduction in the cross section (Fig. 5). For other targets (Figs. 8—10) the results of renormalizing only the above two operators also indicate a strong medium effect, but the results are mixed.

Although the quality of photopion calculations has greatly improved in the last few years, several effects not yet completely studied could influence results possibly at the same level as the medium corrections examined here. For example, the delta resonance needs to be included correctly with appropriate delta nucleus interaction effects, the photopion amplitude needs to be properly unitarized, and alternate nuclear structure and pion distorted waves should be examined to completely isolate effects of meson origin. The restrictions of current continuity should also be monitored. Because of these complications, we have confined our main study to cases where simple operators dominate and where the delta is known to be a small influence. We use the most recent nuclear reduced matrix elements, but the basic nuclear transitions are limited to particle-hole states in the p shell.

Based on our estimates of the effect of the medium on photopion DWIA operators, we conclude that a detailed and complete study is warranted, along the lines of the RPA studies of Cohen[13] combined with the full momentum space techniques developed by Tiator and Wright[8(a)] and by Eramzhyan *et al.*[8(b)] The dependence of the renormalization effects on the particular finite nucleus state and the inclusion of the full momentum dependence and nonlocalities of the basic photopion process will then be understood and hopefully explain the new photopion experimental results.

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