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Three-body exchange mechanisms in the $^3He(\gamma,p)^2H$ reaction

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The role of three-body exchange currents is investigated in the two-body photodisintegration of ^{3}He.

The two-body photodisintegration[1–4] of ^{3}He and radiative $p\,^2$H capture [5–7] reactions have been widely studied at intermediate energies. However it is only recently that a long standing discrepancy between these two channels has been resolved.[4,6,7] Because of large momentum transfers, the one-body mechanisms are strongly suppressed. Two-body mechanisms dominate the cross section and lead to a fair agreement with a large bulk of experimental data.[8] However, discrepancies systematically remain. While the unpolarized differential cross sections and the spin observables are correctly reproduced at forward angles, strong deviations appear above 60°. This is illustrated in Fig. 1 which shows the excitation function of the $^3He(\gamma,p)^2H$ reaction at $\theta_{p,\mathrm{c.m.}}=90°$. Above $E_\gamma=100$ MeV, the theory underestimates the experimental cross section by at least a factor of 2. This discrepancy is really significant, since the two-body matrix elements have been calibrated against the $^2H(\gamma,p)n$ reaction,[8,9] and since the three-body wave function[10] has been checked, in the same range of momentum, by the analysis[11,12] of the $^3He(e,e'p)^2H$ reaction performed under kinematics which minimize the two-body contributions.

The meson double scattering mechanism depicted in Fig. 2 accounts for a large part of the disagreement between the theory and the experiment. Its contribution becomes more important than the contribution of the two-body mechanisms, when the momentum transfer increases. First, it is more likely to be shared between three rather than two nucleons. Second, one of the exchanged pions is very close to its mass shell (on its mass shell above the pion threshold). Indeed such a mechanism has been found to be sizeable in the $p\,^2H\to T\,^3H\pi^+$ reaction[13] but the $p\,^2H\to {}^3He_\gamma$ channel has the advantage to be opened below the pion threshold. Here both exchanged mesons are off shell and this mechanism is a prototype of three-body exchange currents.

The expression of the cross section has already been given in Refs. 8 and 9. Those of the amplitudes corresponding to all the one-body and two-body graphs have been given in Ref. 14 and fully discussed in Ref. 12: they are not reproduced here. Suffice to say that this analysis is the most complete performed so far. It takes fully into account all Fermi motion effects, and considers all the dominant S and D components of the three-body[10] and deuteron[15] wave functions. It is basically free of parameters, since all the basic matrix elements have been checked independently against relevant reactions induced on the nucleon and the deuteron (see Ref. 8 for a review).

Let $(\omega,\mathbf{k})$, $(E_1,\mathbf{p}_1)$, and $(E_2,\mathbf{p}_2)$ be, respectively, the four momenta of the incoming photon and the outgoing proton and deuteron. The amplitude, corresponding to the graph I in Fig. 2, relates the ^{3}He three-body breakup and the subsequent deuteron recombination matrix elements

$$T=i\int\frac{d^3\mathbf{n}}{(2\pi)^3}\sum_{m_n}T(\gamma\,^3\mathrm{He}\to npp)\left[(\tfrac{1}{2}m_p\,\tfrac{1}{2}m_n\,|\,1m_2)\frac{U_0^D(n-\mathbf{p}_2/2)}{\sqrt{4\pi}}+U_2^D\left(\mathbf{n}-\frac{\mathbf{p}_2}{2}\right)\sum_{m_l}(\tfrac{1}{2}m_p\,\tfrac{1}{2}m_n\,|\,1M_S)(2m_l1M_S\,|\,1m_2)Y_2^{m_l}\left(\mathbf{n}-\frac{\mathbf{p}_2}{2}\right)\right]. \quad (1)$$

where $(\mathbf{n},m_n)$ and $(\mathbf{p},m_p)$ are, respectively, the momenta and magnetic quantum numbers of the neutron and proton which form the final deuteron. To be consistent with the use of nonrelativistic nuclear wave functions, only the positive energy part of the nucleon propagators is retained. The integral over the energy of the neutron picks up the pole in its propagator and puts it on shell. The propagator of the (off-shell) proton is included in the definition of the deuteron wave function, the S and D parts of which are, respectively, U_0^D and U_2^D. The remaining threefold loop integral is performed numerically according to the Gauss-Kronrod[16] rule.

The three-body breakup amplitude $T(\gamma\,^3\mathrm{He}\to npp)$ corresponds to a two-loop diagram, and the integral runs over the four momenta of the two nucleons which do not interact with the incoming photon. Again the energy integration picks up their poles and puts them on shell. The propagator of the third (off-shell) nucleon is included in the definition of the three-body bound-state wave function. After changing the variables of integration, we are left with a sixfold integral over the relative ($\mathbf{q}$) and the total ($-\mathbf{p}'$) three-momenta of these two nucleons

$$T(\gamma\,^3\text{He}\to npp) = -\sqrt{3}\sum_{\Lambda}(1\Lambda\,\tfrac{1}{2}\,m_p'\,|\,\tfrac{1}{2}\,m_i)\int\frac{d^3\mathbf{p}'}{(2\pi)^3}\frac{1}{\sqrt{4\pi}}\frac{\chi_0^{T=0}(\mathbf{p}')}{q_\pi^2-m_\pi^2+i\varepsilon}$$
$$\times T_{\pi^+}(np)_0(\mathbf{q}_\pi,-\mathbf{p}'\Lambda\to\mathbf{p}m_p,\mathbf{p}_1m_1)\,T^B_{\gamma p\to n\pi^+}(\mathbf{k},\mathbf{p}'m_p'\to\mathbf{q}_\pi,\mathbf{n}m_n)\;, \qquad (2)$$

where $(\mathbf{p}',m'p)$ and $(-\mathbf{p}',\Lambda)$ are, respectively, the momenta and magnetic quantum numbers of the proton on which the pion is photoproduced and the pair which absorbs it.

The full antisymmetrized three-body wave function[10] is the solution of the Faddeev equations for the Paris potential. It is expanded on a basis where two nucleons couple to angular momentum L, spin S and isospin T, the third nucleon moving with angular momentum l. (This is only a convenient basis and does not assume any physical cluster in the state.) It is a very good approximation[12] to factorize each component into a product, $\phi^T_{Ll}(p,q) = U^T_L(q)\chi^T_l(p)$, of two wave functions which describe, respectively, the relative motion of the two nucleons inside the pair, and the motion of the third.

Since pion absorption by $T=1$ pair is strongly suppressed[17] only absorption by a $T=0$ pair is retained. The corresponding antisymmetrized matrix element $T_{\pi^+(np)_0}$ is directly deduced from the matrix element of the $\pi^+\,^2\text{H}\to pp$ reaction,[18] by replacing the deuteron wave functions by $U_0^{T=0}$ and $U_2^{T=0}$. Both π and ρ are exchanged and the threefold integration, over the relative momentum in the pair, is done numerically. The matrix element of the Δ formation term is given in the appendix of Ref. 18. All the other πN partial waves, up to D waves, are added in $T_{\pi^+(np)}$ and parametrized by the experimental phase shifts.[19] This improvement leads to a fair agreement with all the observables of the $\pi^+\,^2\text{H}\to pp$ reaction. Below the pion threshold, only the real part of the Δ propagator is retained and the S-wave πN amplitudes are approximated by the corresponding scattering lengths.

In view of the exploratory nature of this work and to avoid the numerical calculation of ninefold integral, the pion photoproduction and reabsorptions amplitudes are factorized out the integral over the proton momentum in Eq. (2), which becomes

$$T(\gamma\,^3\text{He}\to npp) = -\sqrt{3}\sum_{\Lambda}(1\Lambda\,\tfrac{1}{2}\,m_p'\,|\,\tfrac{1}{2}\,m_i)\,T^B_{\gamma p\to n\pi^+}(\mathbf{k},\mathbf{p}'m_p'\to\mathbf{q}_\pi,\mathbf{n}m_n)\,T_{\pi^+(np)_0}(\mathbf{q}_\pi,-\mathbf{p}'\Lambda\to\mathbf{p}m_p,\mathbf{p}_1m_1)$$
$$\times\int\frac{d^3\mathbf{p}'}{(2\pi)^3}\frac{1}{\sqrt{4\pi}}\frac{\chi_0^{T=0}(\mathbf{p}')}{q_\pi^2-m_\pi^2+i\varepsilon}\;. \qquad (3)$$

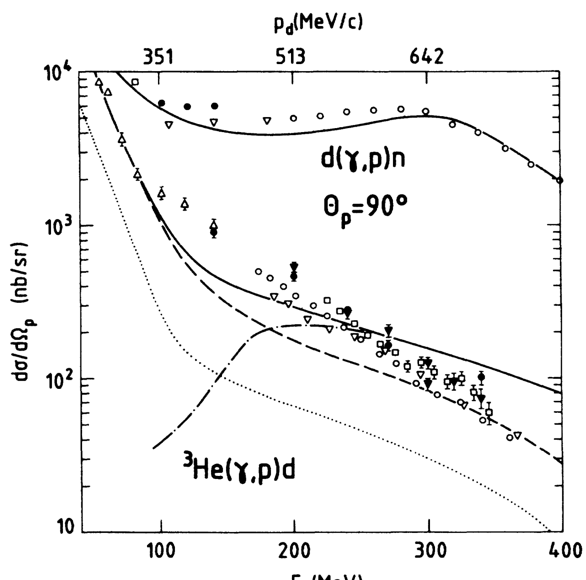

FIG. 1. The excitation functions, at $\theta_{p,\text{c.m.}}=90°$, of the $^2\text{H}(\gamma,p)n$ reaction (Refs. 3 and 8) and the $^3\text{He}(\gamma,p)^2\text{H}$ reaction (Refs. 1–7) are plotted against the in-coming photon energy. The momentum of the outgoing deuteron is also plotted on abscissa. The dotted-line curve is the contribution of the one-body mechanism alone. The dashed-line curve includes also the two-body mechanisms. The full line curve takes also into account the meson double scattering mechanism. Its contribution is the dash-dotted line curve.

The remaining integral is computed in a compact analytical form according to Ref. 20. Above the pion threshold, its logarithmic singularity, associated with the on-shell propagation of the first pion, enhances the contribution of this three-body mechanism. It selects the low momentum components of the proton wave function, makes more likely the contribution of its S-wave part $\chi_0^{T=0}$, which is retained in Eqs. (2) and (3), and justifies the factorization procedure. This approximation has been found to be quite accurate in a very similar problem; the pion-nucleon scattering in the $^2\text{H}(\gamma,p\pi^-)p$ reaction.[20]

Contrary to the three-nucleon breakup channel,[11] the dominance of pion-absorption by $T=0$ pairs prevents the formation of the Δ in the first pion photoproduction amplitude, since the total isospin of the pd final state is $T=\frac{1}{2}$. Indeed both π^+ and π^0 are reabsorbed and the combination of the elementary amplitudes leads to Eq. (2). Only Born terms are relevant, and the two dominant graphs are depicted in Fig. 2; the pion photoelectric and the contact terms.[20] The Born terms due to the exchange of a nucleon are of minor importance and are not retained. (They are already included in the nuclear wave function if three-body forces are taken into account in the potential.)

Below the pion threshold, both mesons are off-shell and these two graphs really represent basic three-body exchange currents. Their amplitudes have the same expression as above threshold, where only on-shell elementary amplitudes enter the calculation. Therefore the excitation function, shown in Fig. 1, offers us the opportunity to start

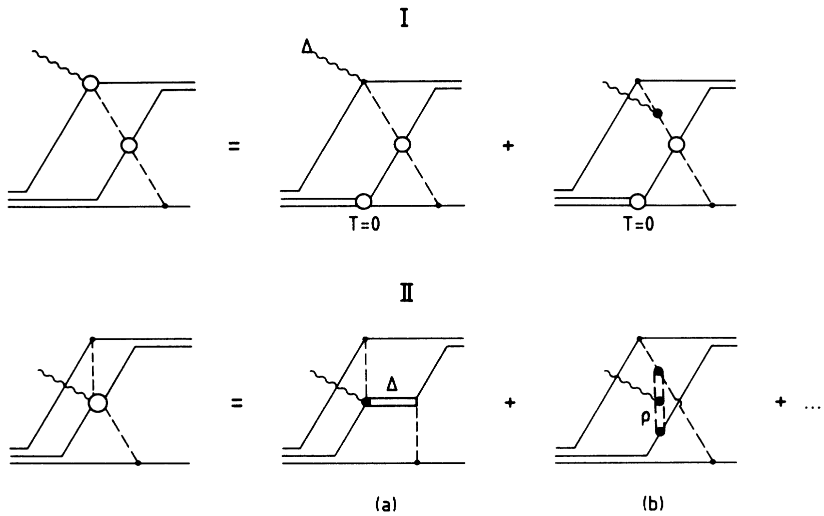

FIG. 2. The three-body exchange currents. I: the meson double scattering mechanism is decomposed into its two dominant parts. II: the two relevant graphs which do not reduce to a sequential meson scattering.

from a kinematical domain where the calculation is founded on solid grounds, and to extrapolate below the pion threshold where the usual problems, due to the virtual nature of the exchanged mesons (form factors, exchange of heavy mesons), come into the game.

While this meson double scattering amplitude leads to a fair agreement with the data between $E_\gamma = 200$ and 300 MeV, it overestimates them above and underestimates them at the pion threshold and below. Figure 3 shows two angular distributions in the Δ energy range. Here again, the theoretical cross section is too large at backward angles.

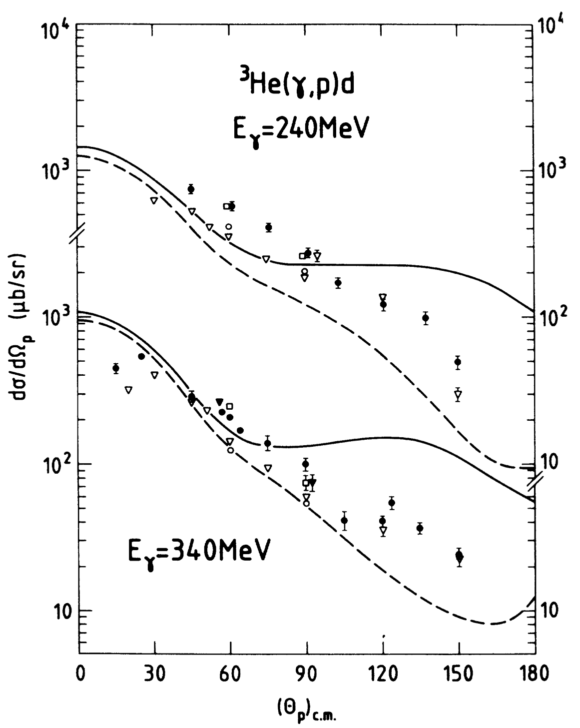

FIG. 3. The angular distributions of the $^3He(\gamma,p)^2H$ reaction (Refs. 1–7) at $E_\gamma = 240$ and 340 MeV. The full-line curves include the meson double scattering diagrams. They are not included in the dashed-line curves.

The agreement with the experiment is not as good as in the analysis of the $p\,^2H \rightarrow {}^3H\pi^+$ reaction.[13] Presumably this is a hint that other mechanisms, which do not occur in pion induced reactions, must be considered in photon induced reactions. Two examples are depicted in Fig. 2 (diagram II). It is well known[21] that ρ exchange contributes significantly to the πN S-wave scattering amplitudes. While the coupling of the photon to the pion is accounted for by diagram I(b), the direct coupling to the exchanged ρ, diagram II(b), must also be considered, especially near the pion threshold and below. It is also well known[20] that two-pion photoproduction proceeds primarily through the emission of a $\pi\Delta$ system in a relative S wave. When these two pions are virtual [diagram II(a)] the amplitude extrapolates smoothly below the $\pi\Delta$ threshold, and the corresponding three-body exchange current might interfere with the meson double scattering amplitude. Since both mesons are highly virtual, the evaluation of these two amplitudes requires the full calculation of a ninefold integral and is beyond the scope of this note, which is a first attempt to evaluate the size of the most obvious three-body exchange currents.

To summarize, meson double scattering appears to be a capital ingredient of the cross section of the $^3He(\gamma,p)^2H$ reaction at high momentum transfer. However, it cannot alone reproduce all the data, and other three-body exchange currents must be considered before any definite conclusion can be reached. All these different mechanisms must be singled out and extensively studied. The flexibility of the three-body kinematics of the $^3He(\gamma,2p)n$ reaction[11] will provide us with the way to achieve this goal.

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