Photon absorption on a proton-proton pair in ^{3}He

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We calculate the total cross sections for different multipole transitions in photon absorption on a $^1S_0$ pp pair embedded in a ^{3}He nucleus. Employing two models, one involving only nucleon degrees of freedom, the other in addition the $\Delta(1232)$ isobar, we show that the Δ gives important effects even in transitions where the photon cannot couple directly to the isobar.

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In two recent papers we have studied quasifree photodisintegration of a quasideuteron in ^{3}He applying the methods and mechanisms developed successfully in free deuteron photodisintegration. Our particular interest in Refs. [1] and [2] was focused on the effect of the quasideuteron wave function being different from the normal deuteron, and indeed causing a large enhancement in all significant transition amplitudes. This effect has been also probed by some recent experiments, e.g., by the TAGX Collaboration [3] extracting a cross section for photon absorption on a "quasideuteron."

However, the use of the term quasideuteron is to some extent inaccurate in this context. Namely, in ^{3}He there is also a component with a neutron-proton pair in the singlet state, $^1S_0(np)$. Experimentally, the contribution arising from this part is, of course, unseparable from the $^3S_1(np)$ disintegration, the actual quasideuteron. The effect of the singlet has also been calculated in Refs. [1,2] and was found to be quite small when compared with the massive magnetic dipole transition of the quasideuteron, dominated by the excitation of the $\Delta(1232)$ isobar. Nevertheless, the difference of the initial pair quantum numbers is a qualitative one and features that are invisible in the quasideuteron case can be seen in absorption on the $^1S_0$ pair. This aspect has been earlier studied in experiments by positive pion absorption on np pairs in ^{3}He and negative pion absorption on pp pairs with qualitatively different results obtained for both cross section [4] and proton polarization [5]. Theoretically they stem from different selections of transition amplitudes, with the prominence of the Δ absent in the negative pion absorption [6].

In contrast to these results with strongly interacting pions, it would be very interesting to find a way to extract the pure $^1S_0$ contribution also in the electromagnetic process. While the experimental extraction of the singlet contribution is clearly impossible for a np pair, it can be done in photon absorption on a correlated pp pair in ^{3}He which only can be in the $^1S_0$ state apart from very small higher partial wave admixtures. The identity of the protons forbids triplet-even final states, so that the magnetic dipole transition is excluded. Also the vanishing electric dipole moment of the pp system strongly suppresses the $E1$ transition because, according to the Thomas-Reiche-Kuhn sum rule, the total $E1$ cross section vanishes for any local pp interaction. In fact, in a recent paper on photon absorption on the pp pair in ^{3}He the TAGX Collaboration argues that the reaction is dominated by the electric quadrupole transition [7].

However, the dominance of $E2$ is not *a priori* clear, since the argumentation above on the $E1$ suppression essentially ignores the spin degrees of freedom of the pp system. Contrary to the case of $M1$ and contrary to the claim in Ref. [7], the $E1$ multipole is not forbidden because the $^3P_1$ final state is accessible by the spin-flip part of the $E1$ operator [8]. In this paper we report a calculation of various multipole strengths arising from the $^1S_0(pp)$ pair in ^{3}He. The allowed transitions are listed in Table I. In particular we will analyze the role of the Δ resonance in $\gamma +^1 S_0(pp) \rightarrow p+p$. Because the S-wave $N\Delta$ states cannot directly contribute, its effect may be expected to be strongly suppressed as compared with absorption on the isoscalar pair in the $^3S_1$ configuration [9,10]. However, it has been shown in Ref. [9] that also $^3\mathrm{He}(\gamma,pp)n$ is completely dominated by the Δ because of a nearly vanishing background from the nucleons. The resulting cross section peaks in the Δ region at $E_\gamma \approx 300$ MeV, contradicting the data [7,10]. In the following it is shown that with a correlated initial pair and a realistic two-nucleon interaction in the pp channel, one obtains also a substantial nucleonic contribution to photon absorption on a pp pair.

Concerning the electromagnetic interaction [11], we consider the nucleonic one-body current which contains a convection (C) and a spin-dependent (S) part consisting of the nonrelativistic spin and the spin-orbit currents as the most important relativistic correction. As isobar current (IC) we include the magnetic dipole excitation of

TABLE I. The final two-proton and $N\Delta$ (in parentheses for $S=2$) configurations contributing to $\gamma +^1 S_0(pp) \rightarrow p+p$ by multipole transitions up to $L=3$. The contributing currents are also listed.

Multipole	Current	pp	$N\Delta$
$E1$	S, IC	$^3P_1$	$^3P_1$ ($^5P_1$, $^5F_1$)
$E2$	C, SI, IC	$^1D_2$	$^3D_2$ ($^5S_2$, $^5D_2$, $^5G_2$)
$M2$	S, IC	$^3P_2$, $^3F_2$	$^3P_2$, $^3F_2$ ($^5P_2$, $^5F_2$)
$E3$	S, IC	$^3F_3$	$^3F_3$ ($^5P_3$, $^5F_3$, $^5H_3$)

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the Δ. Two-body currents arising from nonlocal parts of the pp interaction are taken into account in electric multipoles as far as they are covered by the corresponding Siegert operator (SI). Here it might be mentioned that the leading order of the one-pion/rho exchange current (π/ρ-MEC) does not contribute to photon absorption on the pp system. In principle, there is an exchange current contributing to the $\gamma pp \rightarrow N\Delta$ transition, but it is expected to be small as in deuteron photodisintegration. For each multipole the contributing currents are also listed in Table I.

We use two sets of final state NN wave functions, namely, those obtained from a coupled-channel (CC) calculation with $N\Delta$ configuration admixtures and those obtained by solving the Lippmann-Schwinger equation for a pure NN potential (called here the impulse approximation, IA). As NN potential we choose the Bonn one-boson-exchange potential OBEPR of Ref. [12]. In the case of the CC it has to be modified to fit the phase shifts as explained in Ref. [13]. For the initial pp-pair wave function we use the square root of the two-body density correlation function given in Ref. [14]. Many details about the wave functions and mechanisms can be found in Ref. [2].

Looking at Table I it is immediately clear that the $M1$ ($M3$) transition is not allowed since two protons cannot form a 1^+ (3^+) state. The $N\Delta$ partial waves with spin $S=2$ do not couple directly to the photon and are therefore given in parentheses because the magnetic dipole excitation of the Δ cannot generate $\Delta S = 2$ spin-flip transitions. This would not be valid anymore if the electric quadrupole Δ excitation were included. However, it will be seen below that these partial waves can lead to significant effects in comparison with the IA even though the Δ is not directly coupled to the photon there. Moreover, the $E2$ transition via the $^3D_2(N\Delta)$ is also suppressed, because this configuration does not couple directly to the nucleons either, as far as a one-pion exchange NN-$N\Delta$ transition potential is considered. It is connected to the NN sector only through its coupling to the other $N\Delta$ components. Therefore $E2$ gets essentially no *direct* contribution from the isobar. However, there may be an effect from the change of the NN component being modified at short distances due to the $N\Delta$ admixtures, especially the strong $^5S_2(N\Delta)$ partial wave. This can be viewed as a renormalization of the NN part, since the $N\Delta$ component has absorbed some strength. Further, it may be noted that the $^5P_3(N\Delta)$ component of the $^3F_3(NN)$ state, important in both pion [15] and photon [11] absorption on the deuteron, does not couple to the photon here and thus the $E3$ multipole remains quite small.

In Fig. 1 we present the strengths for the $E1$, $E2$, and $M2$ multipoles including only the nucleonic parts of the current and treating the final state in IA (dotted) and in CC (dashed). Since no direct coupling of the photon to the isobar is taken into account here, the changes are exclusively due to the feedback effect of the $N\Delta$ component on the NN wave function at short distances. Since a part of the two-baryon wave function belongs to the nonparticipant $N\Delta$ configuration in the solid curves, they are in general lower than the IA. This depletion is particularly significant in the $E2$ strength, showing even the resonant structure of the $^5S_2(N\Delta)$ component as a function of the incident energy. To our knowledge this may be the only process where it is possible to see such a feedback effect of the $N\Delta$ to the NN state. In deuteron photodisintegration as well as in pion absorption there is always the direct coupling of the probe to the Δ possible, which masks the renormalization.

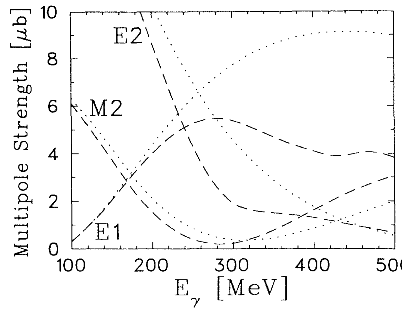

FIG. 1. Contributions of $E1$, $E2$, and $M2$ multipoles including only nucleonic currents and treating the final state in the IA (dotted) and in the CC with $N\Delta$ admixtures (dashed).

Figure 2 shows the additional effect of direct photoexcitation of the Δ within the CC approach. One observes in $E1$ a destructive interference of the nucleonic and Δ current contributions, while for $E2$ both results are indistinguishable as anticipated above. Above 300 MeV the $E1$ transition always dominates over $E2$. It is remarkable that $\gamma+{}^1S_0(pp) \rightarrow {}^1D_2(pp)$ seems to work as a nearly perfect spin filter with respect to the small elementary $E2$ excitation of the Δ resonance since it strongly suppresses its elsewhere dominant $M1$ excitation.

In Fig. 3 a comparison is made with the available data of Ref. [7]. According to our model for the ^{3}He state, the probability for a particular pair in ^{3}He to be a pp pair in the $^1S_0$ state is 1/3 [2]. Also the final state with three identical particles in the isospin formalism requires a statistical factor. Therefore the results in Figs. 1 and 2 for the integrated strengths have to be divided by 3.

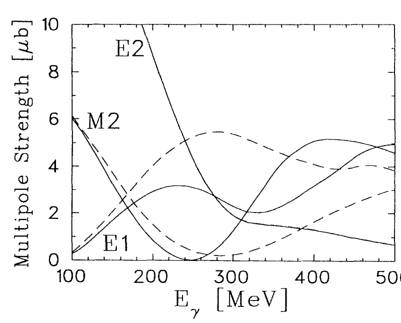

FIG. 2. Contributions of $E1$, $E2$, and $M2$ multipoles for the CC with (solid) and without (dashed) the Δ excitation current.

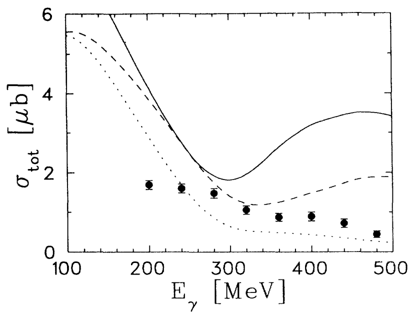

FIG. 3. Various multipole contributions to the total cross section for ^{3}He$(\gamma, pp)n_{spec}$: $E2$ (dotted), $E1 + E2$ (dashed), and $E1 + E2 + M2$ (solid). The data are from Ref. [7].

The magnitude and slight energy dependence of the data are fairly well reproduced by the sum of the $E1$ and $E2$ contributions. The addition of the $M2$ multipole gives an increasing cross section at high energies in clear contrast to the data which do not show any maximum in the Δ region as in Ref. [9]. Here a major contributor is the $N\Delta$ admixture in the $^3P_2$ state. Finally, we emphasize that the total cross section arising from the IA would be far too high in comparison with experiment due to the lack of the renormalizing effect discussed above.

In summary, we have shown that the Δ isobar is important also in photon absorption on *pp* pairs, where *a priori* one could expect its effect to be suppressed. Both the indirect effect of the *pp* wave function renormalization due to the existence of $N\Delta$ components and the direct photoexcitation of the Δ are significant. In the case of the $E2$ transition, the former is the only effect. The excitation of the Δ tends to suppress our earlier overestimate of the cross section with purely nucleonic states [8]. However, at high energies it introduces trends in the energy dependence that are not seen in experiment [7]. The remaining overestimation can likely be cured by use of a slightly longer ranged wave function, which is reasonable because of the less attractive *pp* force than the isospin zero *np* force which corresponds to the wave function used here. About the reason for the high energy behavior one may at present speculate whether it is due to the lack of some higher isobars in our model or to unknown off-shell effects in the photon vertices. It may be noted that the consideration of the explicit pion exchange current involving the Δ^{++} excitation helps slightly by decreasing the cross section at high energies by 10%. Further study of the model dependence of this reaction is in progress.

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