Positive pion absorption on ^{3}He using modern trinucleon wave functions

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(Received 19 September 2002; published 23 April 2003)

We study pion absorption on ^{3}He employing trinucleon wave functions calculated from modern realistic NN interactions (Paris, CD-Bonn). Even though the use of genuine trinucleon wave functions leads to a significant improvement over older calculations with regard to both cross section and polarization data, there are hints that polarization data with quasifree kinematics cannot be described by just two-nucleon absorption mechanisms.

DOI: 10.1103/PhysRevC.67.044003 PACS number(s): 25.80.Ls, 21.45.+v, 24.70.+s, 25.10.+s

I. INTRODUCTION

One hope in building the so-called meson factories towards the end of 1970s was to use mesons, in these facilities pions, as probes of nuclear wave functions and nuclear structure at short distances [1]. However, on the theoretical side it soon turned out that meson interactions even with the two-nucleon systems were quite a challenge and most work concerned these [2]. Pion production physics obtained a new surge with the advent of a new generation of accelerators at IUCF, Celsius, and COSY with a very high-energy resolution making possible accurate measurements at meson thresholds [3,4]. New and even unexpected results also created renewed theoretical activity, concentrated still mainly on two-nucleon meson production at threshold and also at higher energies to understand some puzzles, e.g., in $pp \to pp\pi^0$ threshold production [5]. Nevertheless, there has emerged a general consensus of a fair understanding of at least the main mechanisms in the two-nucleon system, although some problems still remain—within the conventional (meson-exchange) approach [6] as well as in the chiral perturbation treatment of pion production and absorption [7].

New experiments are also performed or in progress on meson production in few-nucleon systems as in $pd \to {}^3\text{He}\,\pi^0$ or $pd \to {}^3\text{H}\,\pi^+$ [8] as well as corresponding η meson production experiments [9]. However, theoretical efforts in this direction with three-nucleon dynamics are very scarce [10,11] and the situation is much less satisfactory as compared with the two-nucleon case. Nevertheless, pionic inelasticities in three- or four-nucleon systems should be the necessary bridge towards understanding them in nuclei and potentially using them as a probe in many-body nuclear physics and for possible effects of nuclear medium on hadrons and their interactions. One may also note that in these phenomena some reaction channels are actually only accessible in absorption.

At the above mentioned new facilities, pion absorption experiments are unlikely due to their low intensities. However, absorption is closely related to production reactions and should be understood in parallel. Furthermore, it may be argued that some absorption processes might be easier to approach theoretically than production. One such process could be quasifree absorption on a pair of nucleons in ^{3}He (or in triton). This is the inverse of two-nucleon pion production in the presence of a (hopefully) inactive spectator. Here the initial state nuclear wave function is known, in principle, exactly from Faddeev calculations and the final state pair is similar to those treated in two-nucleon reactions. Success in this simplest case might open the door to modeling (with explicit inclusion of the spectator) three-nucleon absorption (where data from PSI [12] are available) and the breakup of ^{3}He into a deuteron and a proton—the inverse of the above referred production reactions.

Experimental cross sections of quasifree two-nucleon absorption of pions on helium isotopes have been obtained from the meson factories of LAMPF [13], TRIUMF [14], and PSI [15], but scarce data exist also for the polarization of outcoming fast protons [16,17]. These are obtained at so-called conjugate angles corresponding to kinematics, where it is believed that the spectator is not an active participant and does not absorb momentum from the pion. Then the spectator remains essentially at rest retaining only its Fermi momentum. In Ref. [14] one sees at these angles a massive peaking of the cross section, over an order of magnitude higher than for nonconjugate angles, as a function of the proton energy. The width of this peak may be accounted for with the Fermi motion. The quasifree nature (the spectator having essentially the momentum distribution of the bound state) is even more convincingly established in the kinematically complete experiments of Ref. [15]. Cross sections for positive and negative pion absorption on tritium were obtained in Ref. [18]. Overall, this gives a good amount of data to determine absorption on different nucleon pairs with different isospins in a simple nuclear environment. Also heavier nuclei have been investigated in related contexts [19].

Theoretical work is of old vintage, the most recent serious work probably being in Refs. [20,21] for positive pions, Refs. [22,23] for negative pions, and Ref. [24] for branching ratios in stopped π^- absorption. The angular shapes of the cross sections could be well explained and, roughly, also absolute magnitudes. In fact, for positive pions the shapes do not differ much from $pp \to d\pi^+$ in theory or experiment. However, in absorption of positive pions on ^{3}He or ^{4}He the polarization of the outcoming protons was found to be in qualitative disagreement with the simple theory employed [16,17], which neglected the effect of the spectator and used phenomenological range-corrected deuteron wave functions to describe the active pair as a quasideuteron. The measurements were performed at 120 and 250 MeV and it was possible to reproduce the data qualitatively—however, only when applying different models for the two energies, and not with the same model for both energies.

In a recent paper [25], a convenient parametrization was presented, which approximates analytically exact three-nucleon bound-state wave functions resulting from Faddeev calculations based on realistic nucleon-nucleon (NN) interactions. This parametrization is similar in philosophy to that of Ref. [26] but deviates from it in two important ways. First, it releases its single-term separability in the two relative momenta p and q of the pair and the spectator (or the corresponding coordinates r and ρ). This gives more freedom for reproducing the behavior of the wave function better when both momenta are large—as one would expect, for example, that one particle which is far off shell would influence the others. In contrast, the parametrization of Ref. [26] treats the dependence of the wave function on the two momenta p and q as being totally independent of each other. There are actually significant differences between the wave functions at momenta relevant for mesonic inelasticities [25]. It is interesting to see what impact these may have to physically observable quantities, in particular, whether the pair-spectator correlation could correct the above mentioned energy-dependent discrepancy seen in the pion absorption reactions.

A second and more significant difference is that, instead of parametrizing the single Faddeev amplitudes only, corresponding to different permutations of the three nucleons, as done in Ref. [26], we parametrized directly partial wave projections of the total antisymmetrized wave function. Also this expansion was seen to be well convergent and was applied in calculations of low-momentum quantities such as the probabilities of the trinucleon wave function components and the π^3He scattering length in Ref. [25].

It may be mentioned that the Faddeev wave function of Ref. [26] has been used for pion absorption on nucleon pairs in Ref. [27]. However, that paper did not include pion *s*-wave rescattering which is essential for the cross section at threshold and for the polarization at all energies. The latter is a major topic of the present work.

In the present paper, we apply the above quoted parametrization to study quasi-two-body absorption of pions on ^{3}He. Thereby, the aim is twofold. First, we want to test the reliability and convergence of our parametrization of the three-nucleon bound-state wave function in calculations of observables involving higher momenta. Second, we want to see how one can fare with such improved wave functions in this specific reaction physically, without explicit participation of the spectator nucleon. In the following section we shortly outline the most essential features of the parametrization and provide some details of the ingredients and technical aspects of our calculation of pion absorption, while Sec. III deals with the actual results of our pion absorption calculation. The paper ends with some concluding remarks.

II. FORMALISM

A. Faddeev amplitudes in ^{3}He

Aiming at extreme simplicity, the model of Ref. [20] considered quasifree absorption of positive pions as simply absorption on a quasideuteron with a wave function more compressed than the free deuteron (because the binding energy is larger) and with kinematics compatible with 10 MeV more binding than in the normal deuteron (5 MeV for the actual binding energy difference *plus* 5 MeV for the average kinetic energy of the spectator from its momentum distribution). A similar approach was adopted also later for negative pion absorption on a singlet proton pair [22,23] and actually was able to explain such features of the differential absorption cross section as the asymmetry about 90° and also of the analyzing power in the closely related process $\vec{p}n \to (pp)_{S\text{-wave}}\pi^-$.

The trinucleon wave functions adopted were basically of two kinds. Initially, phenomenological functions based on a range-modified deuteron wave function following an old idea of Ref. [28] or on a calculated correlation function [29] were used in Ref. [20]. Later, also Faddeev pair wave functions $v(r)$ from the separable form $\psi^\nu(r,\rho)=v^\nu(r)w^\nu(\rho)$ parametrized by Hajduk *et al.* [26] were used in Refs. [22,23], where

$$\psi^\nu(r_{ij},\rho_k)=\langle r_{12}\rho_3\nu_{12}|\psi[(12)3]\rangle =\langle r_{23}\rho_1\nu_{23}|\psi[(23)1]\rangle=\langle r_{31}\rho_2\nu_{31}|\psi[(31)2]\rangle \tag{1}$$

and the total antisymmetric wave function is

$$|\Psi\rangle=|\psi[(12)3]\rangle+|\psi[(23)1]\rangle+|\psi[(31)2]\rangle. \tag{2}$$

However, these calculations used for absorption on each pair ij only the wave function component above with the particular permutation $(ij)k$ and considered only the corresponding Jacobian coordinate r_{ij} in the absorption process. With a single-term separable parametrization [26] or with a completely phenomenological pair wave function, this left the role of the spectator to a mere normalization integral. Plausibly, the use of the square root of the correlation function as the pair wave function may take the other two terms in Eq. (2) effectively into account to some extent. Evidently, this issue will now be addressed more explicitly with the new wave functions.

In the above functions the index ν labels the partial wave structure of the three nucleons. In the following calculations, we only consider the states with zero spectator orbital angular momentum, so that this index trivially just symbolizes the quantum numbers of the pair wave functions, in the singlet spin state $^1S_0$ and in the triplet $^3S_1$ or $^3D_1$. The two additional states with the spectator angular momentum 2 considered in Refs. [25,26] have much less weight and are assumed to be of little importance for the present kinematics where the spectator remains essentially at rest.

In Ref. [25], a considerably different parametrization was given for the wave functions. First, the simple separability used in Ref. [26] was generalized to more terms of separable form with a systematic improvement in the approximation. The structure of the wave function remained basically simple but allowed correlation between the momenta or the corresponding coordinates, which is not present in the simple product ansatz. Physically one might expect that, if in a bound three-body system either the spectator or the pair is far off shell, then it would be less likely to find also the other ones far off shell. A parametrization as a sum of two products was seen to offer sufficient freedom and to allow a reasonable fit in the sense that inclusion of a third term did not have much effect. It is worth noting that at large momenta, relevant to meson production and absorption, the inclusion of the second term changed the wave function significantly (see Fig. 1 in Ref. [25]).

The second essential difference is that in Ref. [25] a parametrization for the fully antisymmetrized wave function was provided, and not only for its individual Faddeev amplitudes as in Ref. [26]. This is a nontrivial extension, including also the two other amplitudes of Eq. (2) in the projection on angular momentum eigenstates, and has the advantage that all permutations enter automatically into the calculation of each pair absorption but still with simple wave functions for a given coordinate pair. For example, if the form of Eq. (2) is used in absorption on the pair 12, the first term is simple, but in the other terms the "proper" simple pair coordinate would be $\mathbf{r}_{23}=-1/2\,\mathbf{r}_{12}-\boldsymbol{\rho}_3$ or $\mathbf{r}_{31}=-1/2\,\mathbf{r}_{12}+\boldsymbol{\rho}_3$. These terms would be quite complicated functions of the coordinates $\mathbf{r}_{12}$ and $\boldsymbol{\rho}_3$. However, once the full antisymmetric wave function is parametrized directly in terms of $\mathbf{r}_{12}$ and $\boldsymbol{\rho}_3$, the calculation is greatly simplified. The choice of the pair does not matter, since physically absorption on any pair should give the same result, anyhow.

In practice, the full antisymmetric Faddeev wave function [calculated using the charge-density–Bonn (CD-Bonn) [30] and Paris [31] potentials] was expressed as a product of functions of the pair and spectator momenta p and q, where each function is given by expansions in terms of Lorentz functions

$$\tilde{v}_1^{\nu}(p)=\sum_i \frac{a_i^{\nu}}{p^2+(m_i^{\nu})^2}, \quad \tilde{w}_1^{\nu}(q)=\sum_i \frac{b_i^{\nu}}{q^2+(M_i^{\nu})^2}, \tag{3}$$

for the five most important Faddeev amplitudes. In the coordinate representation these functions will transform into Yukawa functions and (for D waves) their derivatives,

$$v_1^{\nu}(r)=\sqrt{\frac{\pi}{2}}\sum_i a_i^{\nu}e^{-m_i^{\nu}r}$$

or

$$v_1^{\nu}(r)=\sqrt{\frac{\pi}{2}}\sum_i a_i^{\nu}e^{-m_i^{\nu}r}\left(1+\frac{3}{m_i^{\nu}r}+\frac{3}{(m_i^{\nu})^2r^2}\right), \tag{4}$$

with similar expressions for the (spectator) ρ dependence. The denominator r is canceled against the volume element.

Up to this point the procedure would have been equivalent to Ref. [26], except that the fit was performed to the exact total (antisymmetrized) wave functions. However, in Ref. [25] another similar product term $v_2^{\nu}(p)w_2^{\nu}(q)$ was added in order to improve the quality of the analytical representation of the wave function. Thus the wave function was presented as

$$\Psi^{\nu}(p,q)=v_1^{\nu}(p)w_1^{\nu}(q)+v_2^{\nu}(p)w_2^{\nu}(q), \tag{5}$$

with the normalization

$$\sum_{\nu}\int_0^{\infty}dp\;\; dq\;\; p^2q^2|\Psi^{\nu}(p,q)|^2=1. \tag{6}$$

The parameters of the fit(s) were given in Ref. [25] and will not be repeated here, but the importance of the additional freedom will be studied in the differential cross section and polarization of the protons in quasifree absorption on positive pions on quasideuterons. At this stage it is worth remembering that for a specific low-momentum observable, the $\pi^-\,{}^3$He scattering length, the effect of the second term in Eq. (5) was seen to be only about the order of 1% [25].

Before going into any details of the pion absorption mechanisms, we want to test the significance of nonseparability anticipated above for physical reasons. Therefore, we explore extreme momentum transfers corresponding to the highest energy at which polarization data in pion absorption are available, namely, $T_{\pi}=250$ MeV. Our results for the differential absorption cross section on a quasideuteron and transverse polarization[1] of an outcoming proton are shown in Fig. 1 utilizing a systematic expansion of the wave function up to three separable terms, i.e., beyond Eq. (5). It can be seen that nonseparability does play a visible role. However, given the quality of the data and the model uncertainties this sensitivity is not really significant. Nevertheless, it is encouraging to see that just one additional term of products is sufficient to account for the nonseparability and that the expansion has converged quite well already at the two-term level. In the calculations presented in Fig. 1 the Faddeev wave

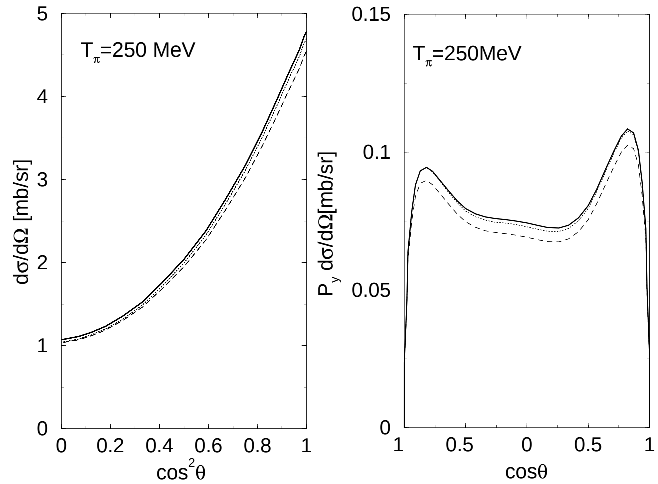

FIG. 1. The differential absorption cross section and its "asymmetry" $P_y\, d\sigma/d\Omega$ at $T_{\pi}=250$ MeV using different fits to the CD-Bonn trinucleon wave function. Dashed: single-term separable fit. Solid: two-term fit. Dotted: three-term fit.

[1]To facilitate better comparison this is multiplied by $d\sigma/d\Omega$. In meson production this would correspond to the asymmetry of the cross section of the two-nucleon reaction with a polarized beam.

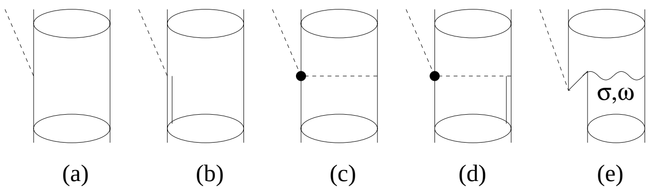

FIG. 2. The mechanisms included in pion production (as well as in absorption) on two nucleons: (a) direct production, (b) "direct" production involving the $\Delta(1232)$ isobar, (c) pion-nucleon s-wave rescattering, (d) s-wave rescattering of a pion originating from a Δ, and (e) heavy meson exchange.

functions from the CD-Bonn potential are used. We want to mention, however, that the convergence features for those based on the Paris potential were found to be the same.

B. Absorption formalism

The mechanisms in pion absorption on two nucleons have been discussed in detail elsewhere [20,22,23] and will not be repeated here in depth.[2] They are depicted in Fig. 2 for the time reversed reaction corresponding to pion production. The first one [Fig. 2(a)] is the standard direct production due to the Galilean invariant πN interaction arising from the pseudovector coupling (with obvious notation) [32]

$$H_{\pi NN}=\frac{f}{m_\pi}\sum_i \boldsymbol{\sigma}_i\cdot\left\{\mathbf{q}\boldsymbol{\tau}_i\cdot\boldsymbol{\phi}-\frac{\omega_q}{2M}[\mathbf{p}_i\boldsymbol{\tau}_i\cdot\boldsymbol{\phi}+\boldsymbol{\tau}_i\cdot\boldsymbol{\phi}\mathbf{p}_i]\right\}. \tag{7}$$

Here the first term would give predeominantly p-wave pions (relative to nucleon i), while the second term when operating on the NN wave function facilitates also (mainly) s-wave production. The direct production is generalized to include also resonant p-wave πN rescattering [Fig. 2(b)] via the $\Delta(1232)$ resonance. Note that this contribution is treated on the same footing as the direct production by generating first the ΔN admixture by the coupled channels method in the initial state. Subsequently, the Δ decays by an operator similar to Eq. (7) (with the spin and isospin operators replaced by the ΔN transition operators and the πNN coupling constant $f^2/4\pi=0.076$ by the $\pi\Delta N$ coupling constant $f^{*2}/4\pi=0.35$ from the decay width of the Δ). This produces the well known prominent cross section peak at pion energies around 150 MeV for $\pi^+d\to pp$.

The NN interaction of the high-energy nucleon pair is based on the Reid soft core potential [33]. At high energies the details of the potential are not expected to be very important. Moreover, within a coupled channels treatment the NN part must be modified, anyway, to avoid doubly counting the attraction generated by the coupling to ΔN intermediate states [32].

At threshold, both production and absorption are, however, dominated by $2N$ mechanisms such as πN s-wave rescattering, Fig. 2(c), with also a substantial contribution from Fig. 2(d). This rescattering is described by a phenomenological πN interaction

$$H_s=4\pi\frac{\lambda_1}{m_\pi}\boldsymbol{\phi}\cdot\boldsymbol{\phi}+4\pi\frac{\lambda_2}{m_\pi^2}\boldsymbol{\sigma}\cdot\boldsymbol{\phi}\times\boldsymbol{\pi}, \tag{8}$$

where the parameters λ_1 and λ_2 depend on the πN on-shell momentum and are fitted to pion-nucleon scattering data [23]. As far as the relative importance in positive and negative pion absorption is concerned one should note that, due to chiral invariance, λ_1 is suppressed close to threshold by a factor of m_π/M_N as compared with λ_2. Indeed λ_1 is very small at threshold, but it becomes comparable to λ_2 for pion momenta q_π corresponding to $\eta=q_\pi/m_\pi\geqslant 0.5$. A monopole form factor is included in the meson exchange interaction. The value of the cutoff mass is crucial in fitting the analyzing power A_y at some given energy. Its effect is small on the total cross section except close to threshold.

It is known that the above mechanisms are not sufficient to explain the size of the cross section of the reaction $pp\to pp\pi^0$ [5]. The remaining strength could be explained by short-range contributions from the NN interaction to the axial charge of the two nucleons, most importantly by exchanges of the σ and ω mesons as shown in Fig. 2(e) [34–36].[3] Consequently its effect was seen to be important also in negative pion absorption on $^1S_0$ pp pairs in ^{3}He [23]. In $pp\to d\pi^+$ and the inverse reaction (i.e., the present consideration with a quasideuteron) the effect of the heavy meson exchange was seen to be much less important [36]. However, in the present context the wave functions are more condensed than in the deuteron and it is of interest to include also this short-range effect. Further, motivation for taking it into account here is provided by the possibility that the active pn pair can appear also in the $^1S_0$ state.

As a starting point Fig. 3 shows the results for the transverse analyzing power A_y in the basic input reaction $pp\to d\pi^+$ at two energies close to the energies of the data in π^+ absorption on ^{3}He. If the quasifree ansatz is correct and the employed wave functions are realistic, one would expect a similar degree of agreement also in the latter reaction. Please, note that in the calculations of the $pp\to d\pi^+$ observables the s-wave rescattering form factor has been adjusted individually for each deuteron wave function to reproduce the depth of the dip at 90° as shown by the data at 515 MeV [39] (the cutoff mass used is $\Lambda=3m_\pi$ for CD Bonn, $4m_\pi$ for Paris and $5m_\pi$ for Reid). These form factors will be used also in the following calculations for the pion and three-nucleon system.

It is interesting to observe that there are differences between the results at the higher energy—even after the above described fitting—and that the data may favor the newer wave functions based on the Paris and CD-Bonn potentials

[2] Many of the existing calculations are actually done for pion production, but time reversal is trivial.

[3] As an alternative to this heavy meson exchange mechanism also πN off-shell rescattering has been proposed [37]. Reality may be a combination of both [38].

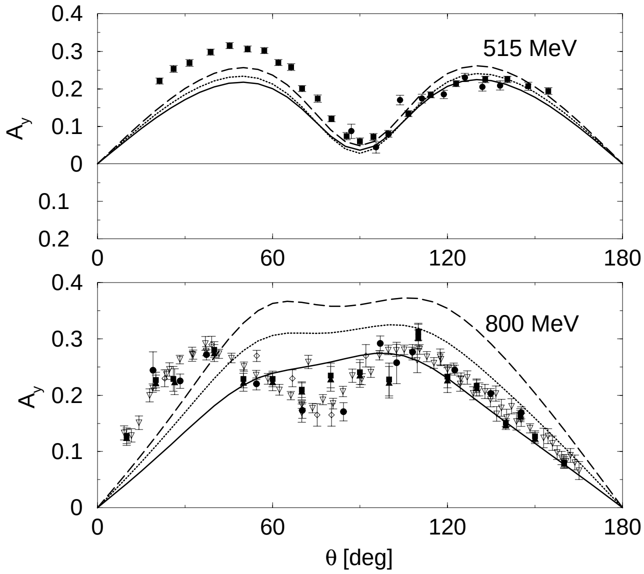

FIG. 3. The analyzing power A_y in the reaction $pp \to d\pi^+$ at two energies closely corresponding to the π^+ ^{3}He absorption energies of Ref. [16]. The different deuteron wave functions used are: CD-Bonn (solid curve), Paris (dotted curve), Reid soft core (dashed curve).

vs the older Reid soft core model. Without this fixing of the interactions at 515 MeV the differences with different wave functions would be even larger. Also, we want to point out that the magnitude of A_y at the higher energy is strongly correlated with the D-state probability in the employed deuteron wave function, with A_y becoming larger with increasing P_D. None of the wave functions is able to reproduce correctly the dip in the data at 800 MeV. In these calculations (as in those for absorption, that will be presented in the following section) all the partial wave amplitudes up to $J=5$ were included, which was found sufficient also at 800 MeV.

In the present context, the above two-nucleon mechanisms are embedded in ^{3}He for which we use the parametrization of the full antisymmetric wave function [25]. Since then, absorption on any pair should give the same results as on the others, we can assume the coordinate r (e.g., r_{12}) to be the active one and particle 3 to be the spectator. With the above described parametrization the wave function $\Psi^\nu(r,\rho)=\Sigma_\lambda v_\lambda^\nu(r)\, w_\lambda^\nu(\rho)$ would give, for example, for the cross section the result

$$\frac{d\sigma}{d\Omega}=\mathrm{Tr}\sum_{\lambda\lambda'\nu\nu'}(M_{\lambda'}^{\nu'})^* M_\lambda^\nu \mathcal{W}_{\lambda'\lambda}^{\nu'\nu}\delta_{\nu\nu'}, \tag{9}$$

where M_λ^ν stands for the two-nucleon transition matrix calculated for the state component ν and for a specific term λ of the parametrization of the $3N$ wave function. The trace is over spin orientations. Here the minor effect in kinematics from the variation of the spectator kinetic energy is neglected. Now the spectator effect has reduced to mere overlap integrals

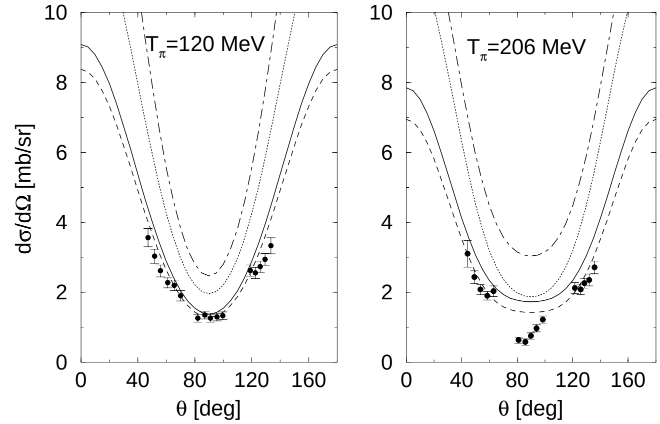

FIG. 4. The bound-state wave function dependence of the differential absorption cross section at $T_\pi=120$ and 206 MeV. Solid: CD-Bonn; dashed: Paris; dash-dotted: CD-Bonn single Faddeev amplitude (normalized to one) used instead of the fully antisymmetric wave function; and dotted: result using a wave function based on the correlation function as described in Ref. [20]. The data are from Ref. [15].

$$\mathcal{W}_{\lambda'\lambda}^{\nu'\nu}=\int d\rho\, w_{\lambda'}^{\nu'}(\rho) w_\lambda^\nu(\rho). \tag{10}$$

Similar expressions with different ν assignments hold also for other spin dependent observables.

III. RESULTS

In Figs. 4 and 5 we show the differential cross sections and proton polarizations for pion absorption on ^{3}He at two energies for the trinucleon wave functions of the Paris and CD-Bonn potentials using the two-term separable fits given in Ref. [25]. Our aim is to study the behavior of the proton polarization for different wave functions and compare the results with the data of Ref. [16]. In particular, we want to explore the influence of using either the fully antisymmetric wave function or just the Faddeev amplitude. In addition to the quasideuteron, in the present calculations also absorption on the $^1S_0$ np pair is included. This study is motivated by

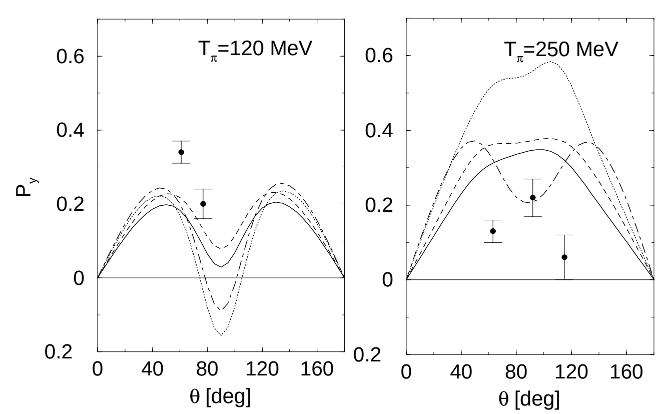

FIG. 5. The bound-state wave function dependence of the polarization P_y at $T_\pi=120$ and 250 MeV. Notation as in Fig. 4; the data from Ref. [16].

the inclusion of heavy meson exchange Fig. 2(e), which should enhance this contribution as it did in *s*-wave absorption of negative pions on ^{3}He [23].

In the present calculation, we employ the individually adjusted amplitudes for the basic reaction $pp \to d\pi^+$ (in order to get agreement with the analyzing power A_y at 515 MeV) as discussed in Sec. II B. We find that, even with the adjusted amplitudes, the CD-Bonn (solid) and Paris (long dashes) potentials give somewhat different results for both the absorption cross section and polarization on ^{3}He (although the angular distributions are rather similar). The difference in the total cross section is about 10%, but without the adjustment it would be 20–30 %, i.e., comparable to the spread obtained in Ref. [40] for the two-nucleon reaction $pp \to d\pi^+$ using several different deuteron wave functions.

In order to compare with earlier more phenomenological investigations we repeated the calculation using a wave function based on the correlation function of the two protons in ^{3}He given in Ref. [29]. This yields results shown by the dotted curves, which are very similar to those obtained earlier in Refs. [16,20] using this wave function. However, one should note that our calculation utilizes the mechanisms and interactions described above (including adjusting the analyzing power of $pp \to d\pi^0$), so that any difference here is due to the differences in the bound-state wave functions. With the new trinucleon bound-state wave functions we find a much better agreement with data than in earlier studies [20]. However, one may note that for the higher energy the differential cross section seems to have a problem at 90°.

Contrary to Ref. [16], the qualitative shape of the polarization can now be roughly reproduced with the new bound-state wave functions (solid and dashed curves) also at the higher energy 250 MeV (Fig. 5). The slight minimum in the old calculation has all but vanished and the top is much lower. This result may be related to the smaller deuteron *D*-state probability, as in the earlier calculations neglecting the quasideuteron *D* state reproduced the high-energy data [16]. (However, then the 120-MeV result was unacceptable.) In any case, in spite of this apparent success in the case of the three-nucleon system, comparison with two-nucleon data in Fig. 3 could give some reason for a different interpretation as discussed in the Conclusion.

The results discussed above were all obtained with the parametrization of the full antisymmetric wave function. The result using single-permutation Faddeev amplitudes from Ref. [25] for the CD-Bonn potential [normalized to one; see Eqs. (1) and (2)] is given as the dash-dotted curve. This wave function has a significantly different short-range behavior including a node at about 0.3 fm and is similar to the functions provided in Ref. [26] [however, we also include the second term to the expansion as in Eq. (5)]. Also it is overall shorter ranged than the full antisymmetrized wave function. It is a very striking result that the single Faddeev amplitude gives a qualitatively unacceptable polarization. The result for the cross section is qualitatively much closer to the dotted curve based on the correlation function of protons, which is also of short range. The longer range of the full antisymmetrized wave function obtained in Ref. [25] is clearly reflected in the present results, perhaps most directly in the decrease of the

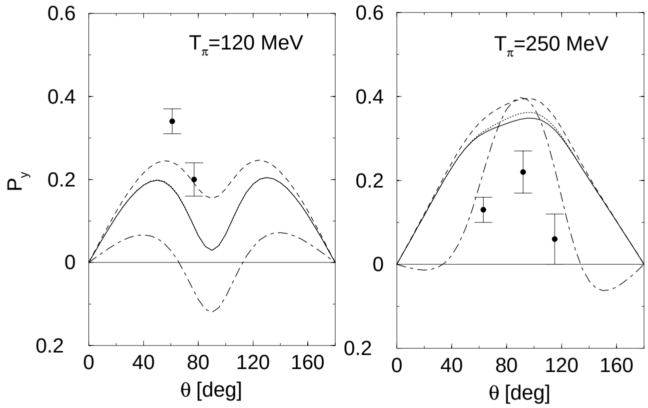

FIG. 6. The effect of different interaction components on the polarization P_y at 120 and 250 MeV. Solid: CD-Bonn full result as in Fig. 5; dotted: absorption on the $^1S_0$ pair neglected; dashed: heavy meson exchange mechanism neglected; and dash-dotted: the *D*-state of the quasideuteron omitted. The data are from Ref. [16].

cross section. As another reason for the largeness of the cross section in the Faddeev-amplitude calculations it is worth noting that in those cases the fraction of the more active triplet state is significantly larger than in the antisymmetrized wave functions.

To further test the dependence on the bound-state wave function the above calculation with the single Faddeev amplitude was repeated for the cases of the Paris potential and the Reid soft core potential (using the parametrization of Ref. [26] and an antisymmetrized version of the latter). In these calculations two clear trends emerged. The cross sections and polarizations were very similar in all antisymmetrized calculations in one hand and in all Faddeev-amplitude calculations on the other hand (e.g., in each case the Reid cross section was nearly indistinguishable from the corresponding Paris result). The structure of the results using the correlation wave function is apparently associated to its overall shorter range rather than the direct use of the Reid potential. To some extent, the present results also confirm the rather moderate dependence of the total cross section on the detailed structure of the bound-state wave functions found by Ohta *et al.* [27].

In order to study our model results in more detail let us switch on and off different interaction components. Corresponding results are shown in Fig. 6 for the polarization. The solid curve is the same as in Fig. 5 (CD Bonn), while in the dotted curve absorption on the $^1S_0$ np pair is neglected. Although heavy meson exchange [Fig. 2(e)] enhances this contribution, its effect is still negligible. However, heavy meson exchange can also take place in absorption on the quasideuteron. It has been included in the results of this work so far and is switched off in the dashed curve. Due to the more condensed bound-state wave function, its effect is somewhat larger than in $pp \to d\pi^+$ [36], but still does not change the results qualitatively.

Finally, the dash-dotted curve shows results where the quasideuteron $^3D_1$ component has been completely neglected. Now the shape of the polarization at 250 MeV is well reproduced but then the results at the lower energy are strongly at variance with the data—even qualitatively, as was also seen in Ref. [16] for a wave function based on an Argonne potential calculation. Although there is some uncertainty in the *D*-state component (in particular its probability is unknown), it is obvious that it cannot be made small enough for a perfect agreement with the higher-energy data.

IV. CONCLUSION

In this paper, we have employed parametrizations of genuine three-nucleon wave functions, obtained from Faddeev calculations with realistic *NN* models, with the aim of investigating the crucial observables of quasifree pion absorption on two nucleons in a three-nucleon environment. The most essential new points were the use of a total antisymmetrized wave function of the target and a nonseparable fitted form of its wave function to allow for correlations between the two relative canonical coordinates (or momenta). Both were seen to have an effect, but nonseparability was of minor importance. In contrast, the full antisymmetrized wave function was necessary for a quantitative agreement with the experimental cross section and a qualitatively successful description of the polarization. Also it was seen that heavy meson exchange had a significant, though not qualitative, effect in particular at intermediate or low energy.

Although an essential improvement is found, these results confirm to some extent the earlier result (which used less sophisticated bound-state wave functions) that conventional two-nucleon calculations cannot be easily accommodated with the polarization data of Refs. [16,17]. In these earlier works, a somewhat poorer description was obtained for pair wave functions calculated with the Reid potential and having a sizable $^3D_1$ component (quasideuteron). However, if the effect of the *D* state was neglected, the high-energy polarization could be reproduced at the expense of the agreement at 120 MeV as seen in Fig. 6. The present improvement over the old results may be partly seen as a compromise with somewhat smaller *D*-wave components in the new deuterons and quasideuterons. However, it is hardly realistic to assume an arbitrarily low *D*-state probability only in order to agree with the higher-energy results.

For further improvements, one might have to consider either some energy-dependent mechanism yet not included (and possibly not necessary in two-nucleon reactions) or admit some influence, probably active participation, of the spectator even in the quasifree kinematics of the conjugate angles. An argument for this may be found indirectly from a comparison of the true two-body and quasi-two-body results even, though admittedly the agreement with two-body data at high energies is not perfect. However, in our model calculations the characteristic basic structure of the *calculated* polarization in $pp \to d\pi^+$ (see Fig. 3) is carried over to pion absorption on ^{3}He for a variety of deuteron and quasideuteron wave functions. The similarity of the shapes of the polarization in the two cases is partly due to the smallness of the $^1S_0$ pair contribution. To establish its smallness it was necessary also to study the impact of heavy meson exchange in the preceding section.

Some success in absorption on ^{3}He was achieved perhaps, because the dip in the polarization data at 800 MeV is not reproduced even in the basic $pp \to d\pi^+$ reaction. From the calculated structural similarity of the two-body and quasi-two-body results one can deduce that, *if* the assumption of quasifree mechanisms is valid *and* the abundant two-nucleon data for A_y at 800 MeV are used, then it is hard to understand why the dip structure should not be found also in the polarization of pion absorption on quasideuterons. Since the existing data at 250 MeV clearly do not indicate such a dip, they lend support for the need of other mechanisms.

The latter possibility would make nuclear physics with mesonic inelasticities even more involved than previously believed. On the other hand, this could be a tool to study the effect of the ‘‘medium’’ on pionic inelasticities. Therefore, it would be desirable to have more data to investigate in detail the development of $P_y(\theta)$ for energies intermediate to 120 and 250 MeV and also to confirm the structural difference seen in the data at 250 MeV. Also it may be useful to apply the new wave functions in π^- absorption on the singlet pp pair in ^{3}He or π^+ on the nn pair in a triton [41]. In this case the two-body absorption is strongly suppressed making the possible (but also small) $3N$ background more visible.

ACKNOWLEDGMENTS

Financial support for this work was provided in part by the international exchange program between DAAD (Germany, Project No. 313-SF-PPP-8) and the Academy of Finland (Project No. 41926).

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