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Impact of $pp \to pp\pi^0$ data to negative-pion absorption on proton pairs

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Recent data on the reaction $pp \to pp\pi^0$ close to threshold indicate unexpectedly large s-wave pion production, with a possible explanation from a heavy meson exchange contribution to the axial charge. An amplitude with the same quantum numbers appears also in negative-pion absorption on proton pairs in light nuclei. In this paper the effect of this enhancement is estimated and found to be significant in the observables of absorption on ^{3}He. Also some predictions are given for the qualitative effect in $pn \to (pp)_{S\ \rm wave}\pi^-$.

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I. INTRODUCTION

Pion production and absorption in the two-nucleon system has been considered to be "reasonably" well understood [1] either on the basis of the two-baryon formalism or by three-body methods once the most relevant πN resonance, the $\Delta(1232)$, and pion s-wave rescattering are included. However, extensions to more than two baryons are not easy. Also in multinucleon systems there are situations where two-baryon aspects are emphasized and one can expect to be realistic even if the calculation explicitly involves only one pair of nucleons. Such a special case is, for example, pion absorption on a nucleon pair in the quasifree region—i.e., two fast nucleons emerging from the reaction at the so-called conjugate angles have picked up essentially all the energy with the rest of the system staying as a spectator. Even in spite of this simplifying emphasis on the two-nucleon absorption with as little consideration to the rest of the nucleus as possible, one might expect some sensitivity on the nuclear environment. At the very least the relative wave function should be different from the only stable genuine two-nucleon system, the deuteron. Over the last decade cross sections of this process have thus been measured in several experiments in the meson factories [2–4]. A recent review, especially on experimental data, can be found in Ref. [5].

A quasi-two-body model calculation for pion absorption on ^{3}He has been recently attempted for both positive [6] and negative [7] pions. Although in the former process, considered as absorption on a quasideuteron, the angular distribution can be described, the model is not yet successful in predicting the polarization observable P_y [8]. However, the qualitative features of low energy *negative* pion absorption could be produced. Because the neutron-proton pair emerging from π^- absorption on a diproton can have either isospin zero or one and consequently a given spin amplitude can have both parities, there is a forward-backward asymmetry in the cross section. At low energies more protons go backward than forward in the center-of-mass system of these two nucleons. This can be understood in an intuitive picture where the nucleon going forward has picked up the momentum of the absorbed pion as well as its charge. However, this asymmetry was not trivial to produce quantitatively in theory.

In Ref. [7] it was shown that for 62 MeV pions this asymmetry can be satisfactorily explained in terms of mesons and baryons, if the Galilean invariant πNN coupling operator [9]

$$H_{\pi NN} = \frac{f}{\mu}\,\boldsymbol{\sigma}\cdot\left\{\,\mathbf{q}\,\boldsymbol{\tau}\cdot\boldsymbol{\phi}(\mathbf{x}) - \frac{\omega_q}{2M}[\,\mathbf{p}\,\boldsymbol{\tau}\cdot\boldsymbol{\phi}(\mathbf{x}) + \boldsymbol{\tau}\cdot\boldsymbol{\phi}(\mathbf{x})\,\mathbf{p}\,]\right\} \quad (1)$$

is used (the notation is explained in Sec. II). This form arises directly from the relativistic pseudovector coupling (or from the pion coupling to the axial charge and current of the nucleon). Earlier work [10] omitting the second term could not produce the correct forward-backward asymmetry of the differential cross section. With some hindsight this is natural, since the dominant of the two terms was omitted in s wave absorption. Later a quark bag calculation [11] using a similar π-quark coupling as Eq. (1) succeeded in this, raising speculations about the role of quarks in this reaction. Now, in the light of Ref. [7] it is clear that the latter Galilean term produces an s-wave absorption amplitude of the right sign also at the hadron level. Due to the limited angular range the data are not able to determine the magnitude of this amplitude very precisely as compared with the dominant p-wave amplitude [2]. Closer to the threshold the s wave should dominate.

Lacking any data on polarization in π^- absorption, however, an interesting comparison can be made between the polarization P_y of the outcoming protons calculated in Ref. [7] for 62 MeV pions and the analyzing power A_y of $\vec{p}n \to (pp)_{S\ \rm wave}\pi^-$ determined by Ponting *et al.* [12] for incident 400 MeV protons. The energies in the inverse reactions match very closely. The data were qualitatively reproduced, even amazingly well considering that the theory used a bound pp pair, while in the experiment the protons are free. On the other hand, the comparison may actually be more fair here, since the system under discussion in the experiment is a real two-nucleon system vs ^{3}He in Ref. [8]. The pion-"nucleus" interaction would then be less important and be better accounted for in the basically two-nucleon theory. Also, further investigations showed the dependence on the pp-pair wave function to be relatively weak, so that the transition to a free low-energy pp pair may not matter very much as compared with a bound pair calculation.

Although the situation at low energy seems quite good in π^- absorption on pp pairs, at higher energies the theory gives some trends which do not agree with the existing data. Firstly, the calculated asymmetry (with more protons backward than forward) decreases rapidly with increasing energy and reverses already for about 100–120 MeV pions. Experimentally, this trend itself also appears, but is much slower [3]. Only above 200 MeV should the asymmetry become reversed. Also the theory predicted an energy dependence of the polarization P_y (or A_y in the inverse reaction) with the angle where P_y crosses zero, moving backward for increasing energy. This behavior is not seen in the data of the experiment E460 at TRIUMF, where this angle is nearly independent of the energy [13]. Both of these discrepancies indicate that either the p-wave pions take over too fast with increasing energy or the s-wave pion amplitude becomes too small.

One recent remarkable surprise in two-nucleon pion production has been the size of the total cross section of the reaction $pp \to pp\pi^0$ near threshold [14]. Theories based on conventional mechanisms shown in Fig. 1 [direct production by the Galilean term of the πNN vertex, s-wave rescattering, and the $\Delta(1232)$] underpredicted it by factors of 4–5 [14–16]. Since near threshold the single s wave should dominate, one can conclude that these models underpredict exactly this amplitude. In principle, this reaction is so simple that the failure of theory by such a large factor is really spectacular and suggests some important physics to be missing. This underprediction of the s-wave pion production or absorption has its parallel in the above described indications in the three nucleon reactions. It is of great interest to see what implications a satisfactory fit to low energy $pp \to pp\pi^0$ would have in the case of $pp\pi^-$ system, where both isospins are allowed in the np channel.

For the study of the impact of enhanced s-wave pion contribution, the exact origin of the enhancement is to some extent immaterial. A phenomenological fit to $pp \to pp\pi^0$ could be sufficient. However, to be more realistic—especially in the extrapolation of the energy dependence and to take into account the differences due to the different initial nucleonic wave function — a reasonable model for the origin of the amplitude is preferable. Lee and Riska [17] have proposed a heavy meson exchange effect

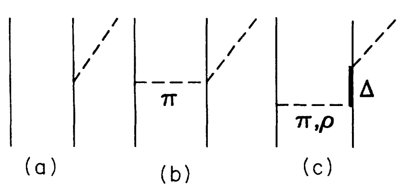

FIG. 1. The conventional mechanisms included in pion production and absorption: (a) direct production, (b) pion s-wave rescattering, and (c) p-wave rescattering via a $\Delta(1232)$ isobar.

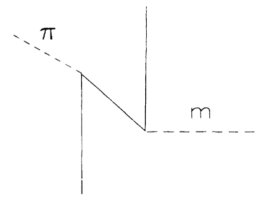

FIG. 2. The nonreducible heavy meson exchange contribution to the axial charge.

as an explanation of the discrepancy between experiment and conventional theories. The two nucleons interact via a heavy meson and with an intermediate nucleon-antinucleon pair state in conjunction with the pion production vertex (Fig. 2). This is a two-body-irreducible mechanism contributing to the two-nucleon axial charge and is not included in the two-nucleon correlations generated by the meson exchanges and the Schrödinger equation. Note, however, that the pion exchange term *is* included in phenomenological treatments of s-wave rescattering. By picking the appropriate combinations of different relativistic invariants [18] forming the Bonn and Paris NN potentials [19, 20] Lee and Riska extract the additional contribution to the axial charge and are able to reproduce the size of the cross section; i.e., they get about a 100 % increase in the s-wave production amplitude from this mechanism.

The meson current effect is made more explicit by Horowitz *et al.* [21], who use directly meson-nucleon-antinucleon couplings to replace the invariants used by Lee and Riska. Taking the couplings, meson masses, and form factors from the Bonn one boson exchange potentials [19] they are able to again reproduce the size of the cross section. Of course, the input is basically the same in both treatments, if the same potential is used as the starting point. The explicit separation of the meson terms in Ref. [21] shows that by far the largest effect arises from the σ meson, an effective scalar-isoscalar particle describing correlated two-pion exchanges (sometimes even crossed pions or the Δ-intermediate state). This term alone is of the same magnitude as the Galilean direct production and adds to it constructively. A smaller contribution arises from the ω, whereas the minor effects of the δ and ρ approximately cancel each other.

This paper incorporates into the earlier calculations of Ref. [7] the meson exchange current effect suggested by Lee and Riska using the relatively simple formalism presented by Horowitz *et al.* The aim is to enhance the s-wave π^- absorption amplitude on a diproton and see if it can solve the present discrepancies in the energy dependence. Because, as was pointed out, the present data at low energies (e.g., 62 MeV) do not constrain the magnitude of this amplitude very strictly, the hope is to obtain a better agreement at high energies, without destroying the existing success below 100 MeV. Also the nomenclature is fixed with this reaction in mind: independent of the actual reaction direction the "final" state (interaction) is that with only two fast nucleons, while the "initial" state has two bound or slow protons and a pion. Section II reviews the model briefly and the results are given in Sec. III.

II. FORMALISM

A. Direct absorption

The formalism of pion production in the two-baryon model has been discussed in detail in Ref. [7] for the case of the pion and two nucleons in the $^1S_0$ state and in Ref. [22] for a pion plus a deuteron. The basic result most relevant for the discussion of this paper is the amplitude of direct absorption of s-wave pions on a diproton arising from the operator (1)

$$\langle \Phi^{SM}|H_{\pi NN}|^1S_0,\pi\rangle = \frac{2\sqrt{8\pi}}{\sqrt{2\omega_q}}\frac{f}{\mu}\frac{q}{p'}\left\{\left(1-\frac{\omega_q}{2M}\right)\int_0^\infty u_{01}^*(r)\,j_1\left(\frac{qr}{2}\right)v(r)\,dr + \frac{\omega_q}{Mq}\int_0^\infty u_{01}^*(r)\,j_0\left(\frac{qr}{2}\right)v'(r)\,dr\right\}. \quad (2)$$

This is the spin amplitude for the final spin S and the magnetic quantum number M truncated at $\ell_\pi = 0$. The general result with higher partial waves is given in Eq. (4) of Ref. [7]. This equation also corrects the isospin factor $\sqrt{3-T}$ appearing earlier, which should not be there. (The effect is basically to lower the total cross section dominated by isospin zero final states by a factor of 3 making its magnitude agree better with experiment at low energies.) Here $\mathbf{q}$ is the pion momentun (relative to the nucleon pair), ω_q the corresponding pion energy, and $\mathbf{p}'$ ($\mathbf{p}$) the relative final (initial) state momentum of the two nucleons. The pion-nucleon coupling constant is taken from the recent analyses [23] to be $f^2/4\pi = 0.075$. The $^1S_0$ nucleon pair wave function is $v(r)$ and its derivative $v'(r) = r\,d/dr[v(r)/r]$, while $u_{01}(r)$ is the radial $^3P_0$ wave function. It may further be noted that in pion absorption on a $^1S_0$-pair conservation of parity and angular momentum forces all final states to be tensor coupled triplet states (including $^3P_0$).

In spite of the suppression factor ω_q/M the latter term dominates s-wave absorption close to threshold. The first term (opposite in sign) is suppressed there by a factor of q^2 and the less favorable radial dependence. In p-wave absorption it would be the dominant effect with the spherical Bessel function $j_0(qr/2)$ in the integral. The factor in front of this term includes the effect of changing the symmetric operator ($\mathbf{p}+\mathbf{p}'$) to operate only on the initial state nucleon wave function $v(r)$. In the s-wave amplitude near threshold this correction is negligible and this whole non-Galilean term is, in fact, omitted in Ref. [21]. At higher energies also this axial current term becomes significant and tends to cancel the Galilean term.

In the present calculation of π^- absorption, $v(r)$ is mainly taken to be the same as in the basic most realistic results of Ref. [7], i.e., the square root of the isospin zero S-wave correlation function in ^{3}He [24] calculated from the Reid soft-core potential [25]. When the pair is two free protons in the $^1S_0$ state in $pp \to pp\pi^0$, this is the scattering solution also including the Coulomb interaction. The final state wave function $u_{01}(r)$ is also calculated using the Reid potential. The calculation of the higher pion partial waves exactly follows the lines of Ref. [7] for π^- absorption. For example, in the dominant p-wave absorption the same kind of modified form of the Reid potential is used for the $^3S_1$-$^3D_1$ final state. It gives a better fit to the mixing parameter ϵ_1 than the original potential. Although the $\Delta(1232)$ effect in s-wave absorption was moderate in the calculations of Refs. [7],[16], it will be relatively smaller once the enhancement of the s-wave amplitude is achieved and it will be neglected in the present work. Except for the ρ exchange (small in Ref. [21]) the Δ contribution would be unaffected by the addition of the exchange current effect.

B. Pion rescattering

It has been known for a long time [9] that the dominant mechanism in $NN \leftrightarrow d\pi$ near threshold is s-wave pion rescattering from the second nucleon, contributing mainly to s-wave pion production or absorption. In Ref. [16] it was noted that it is a significant contributor to pion production in $pp \to pp\pi^0$, although in this particular reaction this mechanism is greatly suppressed as compared with reactions where a change of the nucleonic isospin is allowed. This rescattering is phenomenologically achieved by the operator [9]

$$H_s = 4\pi\frac{\lambda_1}{\mu}\boldsymbol{\phi}\cdot\boldsymbol{\phi} + 4\pi\frac{\lambda_2}{\mu^2}\boldsymbol{\tau}\cdot\boldsymbol{\phi}\times\boldsymbol{\pi}. \quad (3)$$

The λ_2 term corresponds to charge exchange rescattering and eventually gives a two-nucleon operator proportional to $\boldsymbol{\tau}_1\times\boldsymbol{\tau}_2$ [22], which necessarily changes the isospin of the two-nucleon system. Therefore, in s-wave pion absorption on $^1S_0$ pairs it is forbidden leaving only the much weaker first term to contribute. It is allowed but a minor effect (10%) in the p-wave absorption amplitude.

The s-wave contribution from the operator (3), combined with the pion absorption vertex (1) gives two extra terms to the expression within the braces in Eq. (2)

$$I_s = \frac{\lambda_1}{\mu q}\left[\left(2-\frac{\omega_q}{2M}\right)\int_0^\infty u_{01}^*(r)\,f'(r)\,j_0(qr/2)\,v(r)\,dr - \frac{\omega_q}{M}\int_0^\infty u_{01}^*(r)\,f(r)\,j_0(qr/2)\,v'(r)\,dr\right]. \quad (4)$$

The first of these terms is more important, since the multiplying factor is larger and the function $f'(r) = df/dr$ is also larger than $f(r) = \exp(-\mu' r)/r$ with $\mu'^2 = (3\mu^2 - q^2)/4$ (also a monopole form factor with $\Lambda = 700$ MeV is included in these functions). Further, the overlap with $v(r)$ is more favored than with $v'(r)$, which changes sign at about 1 fm.

The strength parameters λ_1 and λ_2 in Eq. (3) can be related at threshold to the isospin I pion-nucleon s-wave scattering lengths a_{2I+1} by

$$\lambda_1 = -\frac{1}{6}\mu\,(a_1 + 2a_3),$$
$$\lambda_2 = \frac{1}{6}\mu\,(a_1 - a_3). \quad (5)$$

The latter of these, the dominant λ_2 is relatively well determined from pion scattering data. The Panofsky ratio between the charge exchange reaction $\pi^- p \to \pi^0 n$ at rest and π^+ photoproduction directly gives

$$3a^-_{0+} \equiv a_1 - a_3 = (0.263 \pm 0.005)\mu^{-1}$$

(Ref. [26]), whereas the Karlsruhe-Helsinki scattering analysis KH80 [27] gives the value $(0.274 \pm 0.005)\mu^{-1}$. The later KA85 [28] results are similar. The above difference may give an estimate of uncertainties involved in the scattering lengths. Due to chiral invariance the isospin symmetric scattering length, related to λ_1 and defined by $3a^+_{0+} = a_1 + 2a_3$, is suppressed by an order of magnitude to values (0.026) – (–0.035) [29]. Unfortunately, there is no observable directly related to this combination of scattering lengths and the relative uncertainty arising from individual errors of the larger a_1 and a_3 will be much enhanced in the small a^+_{0+}. Therefore, this quantity is very badly known and weakly constrained by pion scattering analyses, which are also difficult to extrapolate down to threshold from pion energies typically above 50 MeV.

Table I shows some determinations of a_1, a_3, a^+_{0+}, and a^-_{0+}. Clearly, there is a significant difference between the various Karlsruhe-Helsinki type analyses, which are constrained by analyticity and consider the relevant singularities, and the VPI (SAID) results based directly on the data. With the underestimation of the total cross section, to fit the data a large enhancement of s-wave rescattering was found necessary in Ref. [16], which used a form of λ_1 reducing to $3a^+_{0+} \approx 0.014\mu^{-1}$ at threshold. From Table I it can be seen that use of the Karlsruhe results could obviously give an enhancement by a factor of 2, even 3 from Ref. [31]. This would bring the threshold cross section from the present 30% of the experimental value up to 50–70 %. One might still want to find some plausible justification for further enhancement, since the Karlsruhe-Helsinki errors refer only to the part estimated from deviations from the internal consistency of the method [26]. There are some recent low-energy pion scattering data that somewhat contradict that analysis and are causing controversy in the field [32]. Also several recent analyses [23] tend to yield a significantly lower value 0.075–0.076 for the pion-nucleon coupling constant for which 0.079 from Ref. [27] has long been the canonical value and is used in all Karlsruhe analyses. It is not out of the question that the results of these analyses might change somewhat with new physical input.

The direct determination of the $\pi^- p$ scattering length by the energy shift in pionic hydrogen obtained in Ref. [33] from x-ray transitions gave at first

$$a^{\pi^- p}_{0+} = \frac{1}{3}(2a_1 + a_3) = (0.059 \pm 0.006)\mu^{-1}$$

in apparent contradiction with the closest Karlsruhe result $(0.079 \pm 0.004)\mu^{-1}$. This result could have given a chance to increase the isospin symmetric scattering length much higher. If it were combined with the other rather direct experimental value for the isospin-odd scattering length given above, one would get $3a^+_{0+} = (-0.085 \pm 0.018)\mu^{-1}$. This would be enough enhancement for a succesful theory of the reaction $pp \to pp\pi^0$ at threshold. Of course, the pure isospin scattering lengths would then be outside the range from partial wave analyses. This contradiction between the amplitude analysis and pionic hydrogen result discussed, e.g., by Koch [34] seems now to be resolved by the new value of the s-wave energy shift obtained by the same group [35], which yields $a^{\pi^- p}_{0+} = (0.086 \pm 0.004)\mu^{-1}$ in agreement with the Karlsruhe prediction. Combined with the Panofsky ratio result above, this would give now the negligible $3a^+_{0+} = (-0.005 \pm 0.011)\mu^{-1}$. It seems clear then that such large enhancement factors as required to reproduce the $pp \to pp\pi^0$ data are excluded even in the scattering lengths.

The relative uncertainty in the scattering amplitudes is further reduced a great deal at energies well above threshold. To allow energy dependence above threshold, the scattering lengths a_{2I+1} in the above expressions for λ_i are replaced by $\tan\delta_{2I+1}/q$. As seen in Fig. 3, the energy dependence is very strong in the case of the presently relevant parameter λ_1. There the boxes and circles show the results for λ_i from the Karlsruhe-Helsinki analysis [27] and the solid curves the fit to be used in this work. The dashed curves show the values used in Ref. [16] and were based on the amplitudes obtained by the interactive program SAID [30]. Since the uncertainty about the amplitude decreases above threshold (different analyses agree with each other quite well above, for example, $q = 0.5\,\text{fm}^{-1}$), the exact value of the scattering length becomes less and less important with increasing energy. Even though the isospin symmetric amplitude becomes comparable to the isospin asymmetric one (which is virtually independent of energy), the cross section of $pp \to pp\pi^0$ will still be underestimated. Only if λ_1 shown by the dashed curve were arbitrarily multiplied by 4.7, could the 290 MeV cross section be fitted resulting also in a qualitative agreement with the available data over the energy range 300–700 MeV and with variation of three orders of magnitude in the cross section be achieved [16]. That calculation included also

TABLE I. Pion-nucleon s-wave scattering lengths in units of μ^{-1}.

a_1	a_3	$3a^+_{0+}$	$3a^-_{0+}$	Ref.
0.171 ± 0.004	-0.105 ± 0.003	-0.039 ± 0.007	0.276 ± 0.005	[31]
0.173 ± 0.003	-0.101 ± 0.004	-0.029 ± 0.009	0.274 ± 0.005	[27]
0.175	−0.100	−0.025	0.275	[28]
0.16	−0.077	0.007	0.24	[30]
0.174 ± 0.004	-0.089 ± 0.005	-0.005 ± 0.011	0.263 ± 0.005	2 expt.

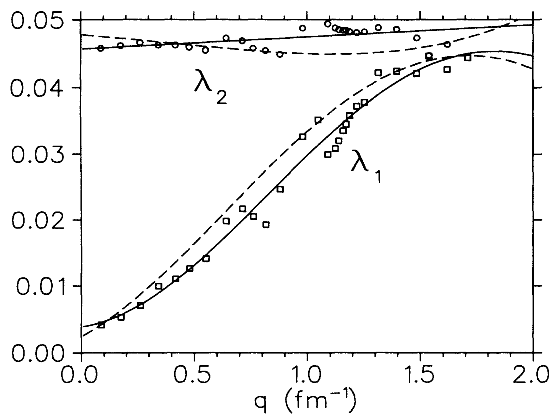

FIG. 3. The s-wave scattering parameters λ_1 and λ_2 as functions of the pion momentum as defined in the text. Solid: the fit to the KH80 solution results [27] shown by the boxes and circles; dashed: the fit used in Ref. [7].

the effect of the $\Delta(1232)$. With the fit to the Karlsruhe-Helsinki analysis (solid curve) the factor needed is found to be 6 using purely nucleonic wave functions. Clearly, this factor cannot be justified by the πN data and therefore s-wave rescattering alone cannot account for the discrepancy with the data in $pp \to pp\pi^0$.

The parameters described above, also shown in Fig. 3, are literally scattering amplitudes. To take into account the relation between an interaction and scattering amplitude properly, in the scattering potential these λ's are further multiplied by $(M+\omega_q)/M$ as shown, e.g., in Ref. [36].

C. Exhange current effect

The proposal of Lee and Riska [17] introduces to $pp \to pp\pi^0$ a new short-ranged axial charge mechanism shown in Fig. 2. The short range (or finite range) of this contribution actually helps the integral to survive the otherwise oscillatory behavior of the integrand. The first maximum of the integrand will not then be cancelled by the next maximum of opposite sign. The couplings of the heavy mesons are large enough to give a sizable effect, even more than pion rescattering. Of course, in absolute terms the contribution is not large, as the elusive exchange current effects are not elsewhere either. However, in the present case also the "main" term is small and so the relative enhancement of the cross section is visible and so far not as clearly observed by any other mechanism.

Following Ref. [21] the scalar-isoscalar σ meson gives an operator similar to the Galilean term in Eq. (1) only weighted by the propagator of the σ, its coupling, and also divided by M (from the nucleon-antinucleon propagator). Finally, one gets the σ-meson exchange current contribution to the integrals inside the braces in Eq. (2) in the lowest order of the nonrelativistic limit

$$J_\sigma = \frac{\omega_q}{Mq}\int_0^\infty \left[u_{01}^*(r)\, j_0\left(\frac{qr}{2}\right)\left(\frac{g_\sigma^2}{4\pi}\frac{e^{-m_\sigma r}}{Mr}\right) v'(r) + u_{01}'^*(r)\, j_0\left(\frac{qr}{2}\right)\left(\frac{g_\sigma^2}{4\pi}\frac{e^{-m_\sigma r}}{Mr}\right) v(r)\right] dr. \qquad (6)$$

Here the final $^3P_0$-state wave function derivative is defined as

$$u_{01}'(r) = (d/dr + 1/r)\, u_{01}(r).$$

Other mesons, notably the ω, give similar results differing only in some details. It was shown in Refs. [17, 21] that the combined effect of all heavy mesons (or corresponding relativistic invariants) was enough to fit the total cross section below $\eta = q/\mu = 0.6$ using the Bonn potentials A and B. The Reid soft and hard core potentials as the distorting interactions yielded somewhat lower results.

From the above it should be rather clear that, for applications elsewhere, since the σ and vector meson ranges are rather similar, it is then reasonable to take phenomenologically just one representative meson current contribution, fix its strength with the $pp \to pp\pi^0$ cross section and finally calculate its effect to the amplitudes in that other application. In any event, such meson exchange currents have been shown in Refs. [17,21] to be able to fit the low-energy data. The details should not be important once the magnitude of the effect has been justified, and one could simulate the whole effect by one adjustable meson. Because the σ contribution is the largest by a factor of 2, it is the preferred choice. In this paper the mass $m_\sigma = 4\mu$ is used with an additional monopole form factor in the potential of Eq. (6) with $\Lambda = 9$ fm^{-1}. This is close to the σ-meson mass 550 MeV used in the Bonn potentials [19]. Fitting the $pp \to pp\pi^0$ cross section at 290 MeV ($\eta = 0.26$) gives the effective coupling $g_\sigma^2/4\pi = 15$, half of which is the same as the actual σ coupling in the Bonn potentials. The rest is mainly due to the strong ωNN coupling and to the fact that the use of the Reid soft-core potential to generate the distortions originally gives a smaller cross section than the Bonn potentials in Ref. [21].

To establish that this is, indeed, a reasonable phenomenological fit and that the actual meson content of the mechanism is not crucial, Fig. 4 shows a comparison of the $pp \to pp\pi^0$ total cross section calculated in this way (solid curve) against the data. The energy dependence is indistinguishable from that of [21] including explicitly the σ, ω, δ, and ρ exchange currents, so that apparently the sum of the mesons can be well simulated with a single term in this context. Only low-energy data can be fitted well in this way indicating that other mechanisms and partial waves are involved above, for example, 350 MeV ($\eta \approx 0.7$). Below this energy the magnitude of the s-wave amplitude is then directly experimentally verified and fixed. The phase of the amplitude is determined by the nucleon-nucleon scattering phases. If only the $^1S_0$ wave is considered in the $pp\pi$ state, its phase is immaterial in observables. Presumably, the model for s-wave pion production can also be extended to other energies and reactions, in particular to pion absorption involving a different pp wave function.

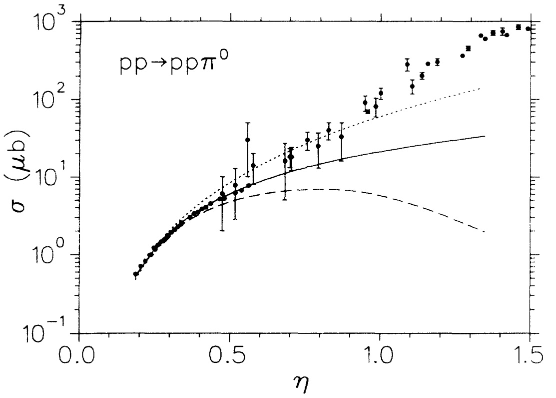

FIG. 4. The $pp \to pp\pi^0$ total cross section as a function of the maximum pion momentum (in units of μ). The theoretical results have been fitted to the low-energy data of Meyer *et al.* [14] at 290 MeV. Solid: with the heavy meson contribution; dashed: with the Galilean term multiplied by 2.4, dotted: with s-wave rescattering multiplied by 6. The high-energy data from Ref. [39].

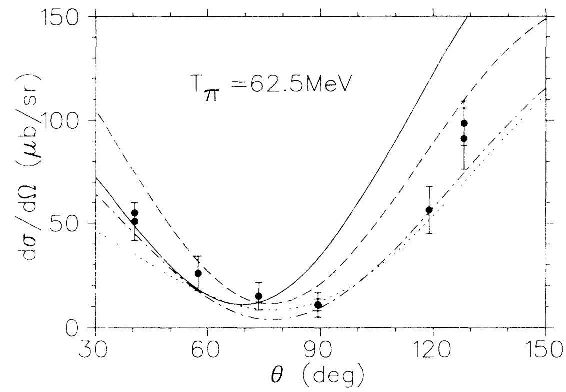

FIG. 5. The differential cross section of negative pion absorption on a diproton in ^{3}He at $E_\pi = 62.5$ MeV. Dashed: no heavy meson contribution; solid: with the heavy meson contribution; dash-dot: with the heavy meson contribution but using the pair wave function of Ref. [37]. The dotted curve is the experimental fit at 64 MeV [3] and the data points from Ref. [2].

For a comparison, it may be also of interest to compare this result and its energy dependence with arbitrary scaling of the amplitude to fit the 290 MeV cross section. The dashed curve shows the result of multiplying the Galilean term by 2.4. The high energy behavior is not even qualitatively reproduced. This is understandable, since earlier work has shown that this amplitude becomes small above 400 MeV. It even changes sign. Enhancing s-wave rescattering, instead, by a factor of 6 prevents this destruction in the same way as the meson current does — even after the sign change, the direct Galilean term and the non-Galilean term never reach the dominant term now. The result is now significantly larger at high energies, reflecting the artificially enhanced energy dependence of the λ_1 parameter shown in Fig. 3. Of course, such a change is not physically justified and is outside the error limits.

III. RESULTS

Figure 5 shows the differential cross section for the absorption of 62 MeV pions. As one would expect, the larger mixture of s-wave amplitude results in more asymmetry about 90°. Although the data would allow some freedom, the result including the exchange current effect (solid) seems significantly worse than without (dashed). Therefore, it seems worthwhile to also attempt another realistic initial pair wave function, namely, a direct parametrization of the Faddeev wave function of ^{3}He in a form factorized to the motion of the pair and the motion of the third spectator relative to the pair [37]. The result of this calculation is shown by the dash-dot curve in a good agreement with the cross-section data. The main reason for the weaker s-wave absorption in this case is the existence of a node in the pair wave function at $r \approx 0.5$ fm. (The appearance of a short-range node in the pair function presentations is typical in three-body wave functions.) The dotted curve shows the three-term Legendre polynomial fit to the 64 MeV data of Ref. [3]. It may be worth noting that here no adjustment is made to fit the total cross section as was done earlier in Ref. [7]. However, as a cautionary measure in considering the success or failure of different wave functions one should keep in mind that the quasifree mechanism might not be a complete description of absorption in the presence of extra nucleons. Also, here only a single term has been used of the three different pairings of the Faddeev wave function.

The polarization P_y is given in Fig. 6 along with the data of Ponting *et al.* [12] for $\vec{p}n \to (pp)_{S\ \mathrm{wave}}\pi^-$ at $E_{\mathrm{lab}} = 400$ MeV. The zero crossing angle has moved further from 90° somewhat closer to the experimental value with the addition of the heavy meson exchange (solid vs dashed curve). However, the theoretical result is still not as dramatically sharply varying with the angle as the data. On the other hand, the result using the Faddeev parametrization is sharp enough, but its zero-crossing an-

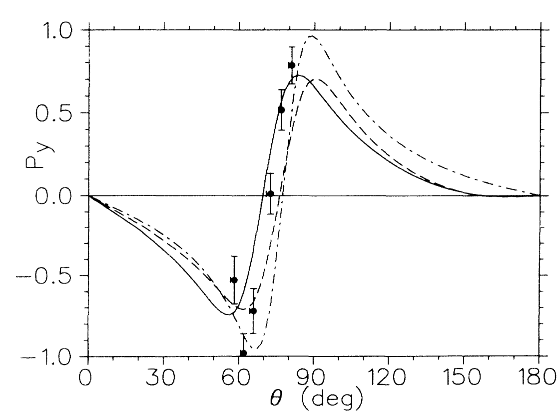

FIG. 6. Polarization in π^- absorption at 62.5 MeV vs the analyzing power data in production at $E_p = 400$ MeV [12]. The curves have the same notation as in Fig. 5. The nucleon lab energy corresponding to the pion energy is 390 MeV.

gle is further from the data (dotted curve). Of course, use of any Faddeev wave-function presentation in comparison with a two-body reaction is unjustified. The reason for its display is only that it reveals some interesting sensitivities of this observable on the corresponding amplitudes.

The above features of the polarization or analyzing power are connected with the relative importances of the different s- and p-wave amplitudes, because their mixing causes both the cross-section asymmetry and the deviation of the P_y zero-crossing angle from 90°. The zero-crossing angle is primarily related to the amount of s-wave amplitude vs p wave. With the Faddeev wave function the s-wave absorption amplitude has become smaller than with the correlation function, which causes the zero-crossing angle to be closer to 90°. The sharper structure, instead, results from the ratio of the p-wave amplitude with the asymptotic D-state to that with the asymptotic S-wave being smaller, 1.5 vs the value 3 using the correlation function and 3–5 without the meson current [7]. Apparently, this ratio can to some extent and more transparently be regulated by the strength of the tensor force or the ${}^3S_1$-${}^3D_1$ mixing parameter ϵ_1. Here is a sensitive test of the relative importance of the S and D states of the fast np pair. Also in the analysis of the pion absorption cross section data by Piasetzky *et al.* [38] this ratio was found to be crucial for the qualitative behavior of P_y, separating the two main solutions 1 and 2 where the dominances of the S and D states were inverted.

So there seems to be some systematic sensitivity to the final and initial states in the detailed fine structure of P_y via these three amplitudes, although the qualitative features are quite robust [7]. At the level of these details one may expect that absorption (with the bound pair) and production (with a free pp pair in the ${}^1S_0$ state) should be considered as different reactions and incompatible for a common analysis, even if the quasifree assumption were valid. On the other hand, the differences can be used for benefit. The two-nucleon production reaction can fix the basic mechanism (as has been done above in Sec. II) and, after application of these mechanisms to the multinucleon situation, the differences are due to the presence of spectators either as active participants or as modifying the pair wave functions.

This being the case, a calculation using the free pp-pair wave function is needed for an actual detailed comparison with the $\vec{p}n \to pp\pi^-$ polarization measurement of Ponting *et al.* [12] or of the TRIUMF experiment E460 [13]. However, Figs. 7 and 8 still give the results using the bound-state pair at energies relevant to this experiment. In the kinematics here just a nominal binding of 1 MeV is used for the pair to better simulate the free situation. The wave function is still the square root of the ^{3}He correlation function. The total cross section would depend on the exact value of the pp-pair energy cutoff used in the experiment to extract the S-wave final state (i.e., on the fraction of the phase space taken into account). Therefore, only the angular distribution is meaningful and the units should be considered arbitrary in Fig. 7. The angular distribution shows a change from the addition of the short-range meson exchange effect at a level that could be seen in the data of an accurate experiment [13]. Also, the change in the polarization (analyzing power in the experiment) is measurable.

The energy dependence in a wider range is shown in Figs. 9–11. In Fig. 9 the angular distribution without the short-ranged meson exchange current is given by the

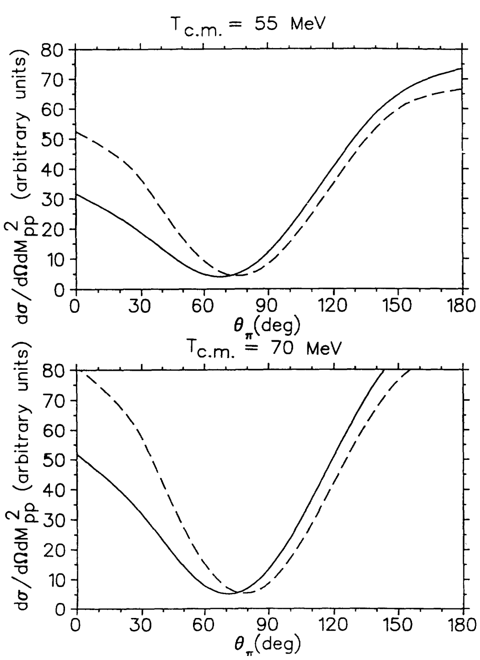

FIG. 7. The angular distribution of $pn \to (pp)_{S\ \mathrm{wave}}\pi^-$ as a function of the pion angle at two energies (total C.M. kinetic energies above the pion threshold) corresponding to the TRIUMF experiment E460 [13]. The solid and dashed curves as in Fig. 5. The units are arbitrary.

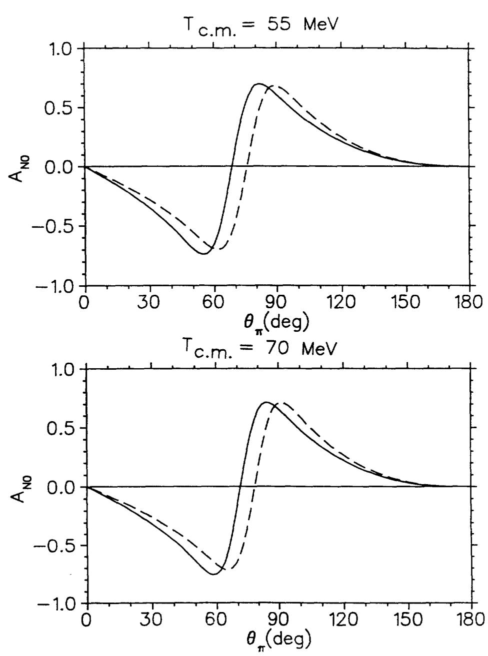

FIG. 8. The polarizations P_y or analyzing powers A_y at two energies corresponding to the TRIUMF experiment E460. Curves as in Fig. 7.

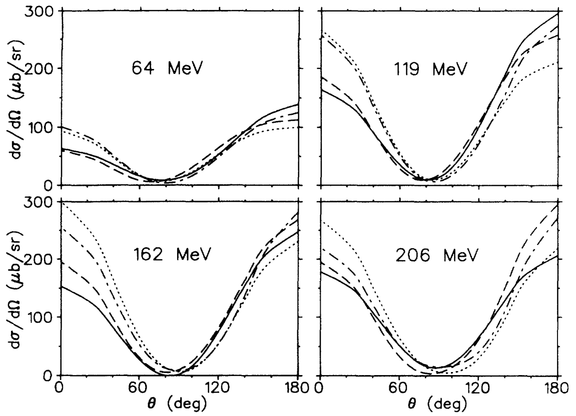

FIG. 9. The energy dependence of the angular distributions: Solid: fit to the data of Ref. [3]; dashed: with the heavy meson effect; dotted: without the heavy meson effect; dash-dot: with the heavy meson but using the wave function of Ref. [37]. For an easier comparison these are scaled to give the experimental total cross section.

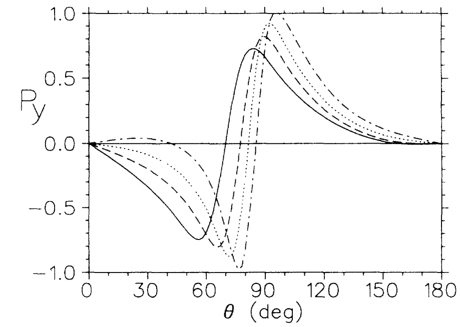

FIG. 11. The energy dependence of the polarization P_y including the heavy meson effect: solid: 64 MeV; dashed: 119 MeV; dotted: 162 MeV; dash-dotted: 206 MeV.

dotted curve while that including it is the dashed curve. The solid curve presents a fit to the experimental data [5]. In this figure the theoretical results are scaled to produce the total cross section correctly, i.e., present only the angular distribution. The scaling factor can be estimated from Fig. 10 which shows the energy dependence of the total absorption cross section. The discrepancies here may be due to the pion initial state interaction with the ^{3}He nucleus. Again, it can be seen that the results are improved from those of Ref. [7] or the dotted curves. The trends in the energy dependence of the angular distribution are much better produced with the short-range exchange effect included. Over the wider energy range and with the scaled angular distribution either *pp*-pair wave function seems to work well as compared with the available data.

The polarization in Fig. 11 shows a similar energy dependence as in Ref. [7] but presents a 20% smaller spread and all the curves are shifted towards forward direction by about 10° (as in Figs. 6 and 8). It will be interesting

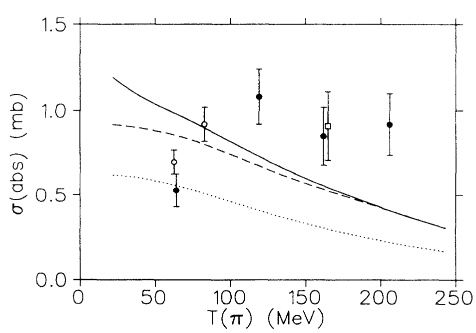

FIG. 10. The total absorption cross section of negative pions on *pp* pairs in ^{3}He. Solid: with the heavy meson exchange; dashed: without heavy mesons; dotted: with the heavy meson exchange but using the wave function of Ref. [37]. The data are from Refs. [2] (open circles), [3] (full circles) and [4] (square).

to see whether this energy dependence at higher energies is actually confirmed by experiment. Only the new results including the heavy meson current are shown here. Without it the result can be found in Ref. [7] which would be indistinguishable from the present one using the Karlsruhe-Helsinki πN amplitudes. The effects of varying other quantities like the pair wave function, final state interaction and omitting some of the partial waves or mechanisms (other than the heavy meson effect of interest here) can also be found there. As to the *pp*-pair wave function, these calculations should obviously be extended to the free pair case to better correspond to the experiments of Refs. [12, 13].

IV. CONCLUSION

In this work I have shown that the drastic enhancement of the *s*-wave pion production amplitude in $pp \to pp\pi^0$ has also necessarily significant and measurable effects in the absorption reaction of negative pions on a diproton, where a similar amplitude is also essential though not dominant. The mechanism proposed to increase the axial charge in the two-nucleon system [17, 21]—heavy meson exchange—is short ranged and therefore one can expect it to be particularly important in the tightly packed three- or four-nucleon systems. Quasifree calculations confirm this expectation. At low energy the new *s*-wave contribution does not necessarily improve the already existing good agreement of the angular distribution with data, but at higher energies the improvement is significant.

The total cross section at high energies becomes still too small. A possible reason could be lack of some *p*-wave strength. One could well ask about the importance of the heavy meson mechanism in *p*-wave absorption. The short range could even be of more advantage there since one can have the overlap of both initial and final states in an S state. However, the effect to axial current is small in nuclei and so probably also in pion interactions at low energy [40]. The reason for this smallness is an additional relativistic factor of the scale p/M as compared with the axial charge correction [18]. On the other hand, the strong dominance of the $p \to {}^3D_1$-${}^3S_1$ amplitude over the ${}^3S_1$-${}^3D_1$ final state (or rather the smallness of the latter) is due to a cancellation of the first two maxima in the latter. [Due to the existence of the bound state (deuteron) in this wave there is a node at a relatively short distance in the scattering state.] Therefore, it would be interesting to investigate whether even the relativistically suppressed short-ranged contribution could change this precarious balance. Earlier in Fig. 6 we also saw that the polarization had some sensitivity on the ratio of these two final states.

The effect arising from this mechanism is also most likely large enough to be seen in the angular distributions and polarization asymmetries of the production reaction $pn \rightarrow (pp)_{S\text{ wave}}\pi^-$. However, the present results indicate so much sensitivity on the initial and final states that a truly meaningful comparison with an accurate experiment would require an actual calculation of the free reaction rather than simulation by a bound pair, which works surprisingly well at a qualitative level. This kind of calculation is a natural extension of the present results and is underway.

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