The A_y puzzle and the nuclear force

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The nucleon-deuteron analyzing power A_y in elastic nucleon-deuteron scattering poses a longstanding puzzle. At energies E_{lab} below approximately 30 MeV A_y cannot be described by any realistic nucleon-nucleon (NN) force. The inclusion of existing three-nucleon forces does not improve the situation. Because of recent questions about the ^3P_J NN phases, we examine whether reasonable changes in the NN force can resolve the puzzle. In order to do this we investigate the effect on the ^3P_J waves produced by changes in different parts of the potential (viz., the central force, tensor force, etc.), as well as on the two-body observables and on A_y. We find that it is not possible with reasonable changes in the NN potential to increase the three-body A_y and at the same time to keep the two-body observables unchanged. We therefore conclude that the A_y puzzle is likely to be solved by new three-nucleon forces, such as those of the spin-orbit type, which have not yet been taken into account. [S0556-2813(98)01908-6]

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I. INTRODUCTION

The so-called A_y puzzle is a longstanding problem in elastic nucleon-deuteron (Nd) scattering. Since it was first possible to perform rigorous nd scattering calculations [1] it has been known that the nucleon vector analyzing power A_y cannot be described by any realistic nucleon-nucleon (NN) force at energies below ≈ 30 MeV. The same is true for the deuteron vector analyzing power iT_{11}, whereas the deuteron tensor analyzing powers and the differential cross section, for example, can be described very well. Thus one should speak of a vector analyzing power puzzle. But because this problem is known in the literature as the A_y puzzle we will stick to that name. The puzzle remains after the introduction of the latest generation of (nearly) phase-equivalent NN forces [2]. Since it is now possible to calculate elastic proton-deuteron (pd) scattering below the breakup threshold [3] as well, we know that the same problem exists there, too.

A first attempt to solve the A_y puzzle was made in a purely phenomenological study [4]. Because A_y is mainly sensitive to the NN ^3P_J phase shifts [4], the potentials for those partial waves were multiplied by strength factors, keeping the low-energy observables in reasonable agreement with the two-body data, while at the same time increasing A_y predictions towards the experimental data. This could be achieved by introducing large charge-independence breaking (CIB) and charge-symmetry breaking (CSB) into the NN potential. Though such a large CIB and CSB is certainly unphysical, this study suggested that there might be some room for changes in the NN potential.

A similar approach was adopted by Ref. [5] (see also [6] and [7]), where it was claimed that there exists some room for changes in the ^3P_J phase shifts at lower energies. The hope was that one could find modified ^3P_J phase shifts that describe the NN data as accurately as the phase shifts that result from the latest phase-shift analyses [8,9] and at the same time increase A_y.

Another possible solution to the A_y puzzle is a three-nucleon force (3NF). In [10] it became possible for the first time to incorporate a 3NF into Faddeev calculations above the breakup threshold. Since then all available 3NF's have been tried [11,2,3,12,13], but all of them either produce no significant effect on A_y or slightly worsen the situation. Existing 3NF models typically contain only those terms believed most important and least complicated, so the final word on such models has not yet been spoken. We should remember that at the time these models were developed it was not possible to test them in any calculation. Thus it might very well be true that the available forces are missing terms that are essential for the vector analyzing powers.

The aim of this study is to determine which improvements in the A_y problem are possible by changes in the NN potential. A critical discussion of options is given in Sec. II. In our calculations we make use of the AV18 potential [14], which is introduced in Sec. III. The changes we apply to the NN potential are described in Sec. IV. In Sec. V we discuss the size of the changes in the potential that are necessary to keep the two-body observables unchanged and at the same time increase A_y. Section VI deals with the special role of the one-pion-exchange potential (OPEP), which gives the longest-range part of the NN force. In Sec. VII we discuss how the possible changes in the NN potential are influenced by the requirement that the ^3P_J phase shifts should not be changed. We also comment on Ref. [6] and discuss whether any changes in the ^3P_J phase shifts might be able to improve A_y. The question of whether charge independence and charge-symmetry breaking might be able to improve the description of A_y will be answered in Sec. VIII. Finally we summarize and conclude in Sec. IX.

II. OPTIONS

We briefly assess the available dynamical options, necessary assumptions, and uncertainties, and categorize them in the order they will be discussed below.

We assume the existence of a two-body nuclear potential that is independent of the energy. Although that potential is not uniquely defined (because of off-shell ambiguities), we assume that it is as momentum independent as is allowed by the underlying strong-interaction theory (this prescription is called ''minimal nonlocality'' in Ref. [15]). Minimal nonlocality fixes the representation, eliminates off-shell ambiguities, and specifies the form of the dominant part of the potential (such as OPEP). It corresponds most closely to the majority of potentials in existence today. Because off-shell freedom is equivalent to a 3NF, this prescription also defines the 3NF [16,17]. Such a two-body potential *must* be momentum dependent because of special relativity, but in low-momentum applications such as few-nucleon systems that dependence is constrained by the nucleon mass M [viz., the dependence is $\sim(p/M)$, which is small] or by the large QCD scale of the same size as M. We do not expect such momentum dependence to be a critical factor, unless it occurs in combination with the nucleon spin $\vec{s}$ such as $\vec{l}\cdot\vec{s}$ (i.e., a spin-orbit interaction). Although our approach is nonrelativistic, we note that nonlocal interactions (incorporating relativistic corrections in some cases) that have been used in studying A_y produce virtually the same results as local ones.

We assume that any NN potential should produce a good fit to the NN data base. This is our primary principle, and the criterion for rejecting options. The quality of that fit does not have to be the best, but it should not be poor. First-generation potentials (i.e., older potentials that do not fit the data particularly well) do not differ significantly in A_y calculations from newer (second-generation) potentials that have a much better fit. We will assume (and there is no evidence to the contrary) that future-generation potentials that fit the NN data even better than the second-generation potentials that we use (because they incorporate more physics) will not alter this situation.

There is only one exception: the AV14 potential [19] gives a much lower prediction for A_y than all the other potentials [2]. The reason for this behavior is that the ${}^3P_J$ phases of AV14 deviate strongly from those of all other potentials [2] (which means that AV14 does not fit the NN data base well enough).

The fact that all potentials with this one exception (due to differences in the phase-shift parameters) give essentially the same predictions for A_y and iT_{11} strongly argues that the A_y puzzle is not a simple problem of the off-shell behavior of the NN potential. The NN potentials on the market (which were all tried on the vector analyzing powers) vary from strictly local to strongly nonlocal and thus exhibit rather different off-shell behaviors. Experience [2] shows that the analyzing powers are insensitive to the off-shell behavior of existing NN potentials. Thus the assumption above, that it is sufficient that a potential give a reasonable fit to the NN data base, appears justified within the context of ''minimal nonlocality.'' We will comment more on this in Sec. IX.

We conceptually divide the potential into two parts: OPEP plus a shorter-range part. Within this framework we have four possible options for improving the description of A_y without violating our primary principle.

The first option is to change OPEP. These changes could arise from changing the pion-nucleon coupling constant, by modifying the virtual-pion spectral function, by momentum-dependent modifications due to special relativity, and by vertex modifications (i.e., form factors). The current status of the pion-nucleon coupling constant is reviewed in Ref. [20]. The bulk of the phase-shift analyses (including the energy-dependent analyses) favor a common low value. The potentials that we use all have this value. The pion spectral function is a two-loop modification of the propagator and consequently is very tiny [21]. Form factors are a short-range modification, which is discussed below. The effects of relativity have been examined in three-nucleon bound-state calculations, where they are rather small, but no fully relativistic scattering calculations have been performed. Isospin violation is already included in part through the use of different charged- and neutral-pion masses. There is no evidence for different charged- and neutral-pion-nucleon coupling constants [22] at the 1% level. We assume a conventional OPEP.

The short-range interactions are parametrized using as many different forms as there are potentials. The functional forms include Gaussian, Yukawa, and Fermi functions, and combinations thereof. As we shall see, at low energies a single parameter describes this interaction in the P waves. At higher energies and in S waves one or two more may be needed. In effect only a few moments of the potential are required by the NN data, and this is easy to impose on an arbitrary functional form. If OPEP is fixed, this is the primary freedom.

Isospin violation has been suggested as a candidate for solving the A_y puzzle. Because the *same* problem exists for pd (which has no nn interaction) as for nd scattering (which has no pp interaction), it very likely cannot involve CSB (charge symmetry interchanges protons and neutrons). The bulk of the CIB is already included via the different pion masses. What remains should have short range and be rather small in P waves. We will comment further on isospin violation later in the paper.

Finally, introducing a 3NF does not affect the two-nucleon problem. Although those forces used to date have not helped to resolve the puzzle, there are additional components of the two-pion-range 3NF that have a spin-orbit character and have never been included in a calculation [17,18]. In the early days of building force models it was conventional to ignore momentum-dependent forces (and thus anything proportional to $\vec{l}$), because of the complexity.

III. THE NN POTENTIAL

Since earlier attempts to resolve the A_y puzzle (by multiplying the NN potentials in the ${}^3P_J$ waves with strength factors [4,2]) did not lead to satisfying results, we will pursue an alternative approach that introduces more flexibility in changing the potential and thus more possibilities for resolving the puzzle. We apply different strength factors to different parts of the potential, thereby introducing additional freedom (in the form of parameters); this enhances the possibility of finding a set of parameters that leaves the two-body observables unchanged and at the same time increases the three-body analyzing powers A_y and iT_{11} in the desired manner. Our goal will be to relate changes in the NN force to changes in the np and nd analyzing powers. We emphasize that we are not advocating large changes in the potential that are unsupported by the NN data. Rather, our goal is to gain insight into these relationships before drawing any conclusions.

For this purpose we have chosen the AV18 potential [14], which is well suited to use in the study because of its struc-

TABLE I. Effects of changes of $\pm 10\%$ in the various parts of the NN potential in the ^3P_J partial waves on the maximum of the two-body nucleon analyzing power A_2. Δ gives the difference between A_2 for the original AV18 and the changed one, while % gives the change of A_2 in percent. The values of the maxima of A_2 for the original AV18 are 0.00022385 at 1 MeV, 0.012483 at 10 MeV, and 0.42944 at 100 MeV.

E_{lab} (MeV)	Change	A_2	Δ	%	Change	A_2	Δ	%
1	$1.1{*}V_C$	0.00023024	0.00000064	2.85	$0.9{*}V_C$	0.00021773	−0.00000061	−2.73
10		0.012780	0.000297	2.38		0.012198	−0.000285	−2.28
100		0.42389	−0.00555	−1.29		0.43456	0.00512	1.19
1	$1.1{*}V_T$	0.00019673	−0.00002712	−12.12	$0.9{*}V_T$	0.00024655	0.00002270	10.14
10		0.011311	−0.001172	−9.39		0.013454	0.000971	7.78
100		0.42977	0.00033	0.08		0.42889	−0.00055	−0.13
1	$1.1{*}V_{ls}$	0.00026198	0.00003813	17.03	$0.9{*}V_{ls}$	0.00018713	−0.00003672	−16.40
10		0.014207	0.001724	13.81		0.010834	−0.001649	−13.21
100		0.42432	−0.00512	−1.19		0.42641	−0.00303	−0.71
1	$1.1{*}V_{l^2}$	0.00021374	−0.00001011	−4.52	$0.9{*}V_{l^2}$	0.00023491	0.00001106	4.94
10		0.012012	−0.000471	−3.77		0.012999	0.000516	4.13
100		0.43212	0.00268	0.62		0.42585	−0.00359	−0.84
1	$1.1{*}V_{(ls)^2}$	0.00022467	0.00000082	0.37	$0.9{*}V_{(ls)^2}$	0.00022302	−0.00000083	−0.37
10		0.012501	0.000018	0.14		0.012462	−0.000021	−0.17
100		0.43312	0.00368	0.86		0.42558	−0.00386	−0.90

tural simplicity. The AV18 potential is a semiphenomenological potential with a one-pion-exchange tail. This potential is structured around 18 spin-isospin-orbital operators, which are multiplied by different radial functions. In addition to one-pion-exchange components (whose form is well understood and not controversial), those radial functions contain a parametrized short-range component. The operators themselves are constructed from the vectors that are available, such as the distance between the two nucleons $\vec{r}$, the total two-body angular momentum $\vec{l}=\vec{l}_1+\vec{l}_2$ and the total two-body spin $\vec{s}=\vec{s}_1+\vec{s}_2$. The only constraint on the operators that are constructed from these vectors is that they must be scalars. The parameters in the radial functions were fitted to the Nijmegen NN data base with a χ^2 per datum of slightly more than one. Thus, the AV18 potential represents a very general form of the NN potential with a good description of the NN data, and this meets our requirements.

Because we are interested in the ^3P_J waves we have to deal with only 5 of the 18 operators in AV18: the operator 1, which gives the central force V_C, S_{12}, which gives the tensor force V_T, $\vec{l}\cdot\vec{s}$, which gives the spin-orbit force V_{ls}, $\vec{l}^2$, which gives V_{l^2}, and finally $(\vec{l}\cdot\vec{s})^2$, which gives $V_{(ls)^2}$.

IV. CHANGING THE NN POTENTIAL

In order to study the sensitivity of the three-body analyzing power A_y to the above-mentioned five parts of the NN force, we increase and decrease by 10% each of those five parts of the NN force in the ^3P_J waves, without introducing any additional CIB or CSB. All other partial waves remain unchanged. At the same time we study the effect of these changes on the two-body observables. It is well known that the only two-body observable sensitive to changes in the ^3P_J waves is the analyzing power. In order to distinguish it from the three-body analyzing power (A_y) we will call it A_2. Table I shows the effect of the changes on A_2 and Table II on A_y.

Tables I and II demonstrate that the effects of a 10% increase or decrease are roughly the same. Therefore we can conclude that (within roughly 10%) these changes in the po-

TABLE II. Same as Table I, but for the three-body nucleon analyzing power A_y. The value of the maximum of A_y at 3 MeV for the original AV18 is 0.04518.

E_{lab} (MeV)	Change	A_y	Δ	%	Change	A_y	Δ	%
3	$1.1{*}V_C$	0.04685	0.00167	3.70	$0.9{*}V_C$	0.04360	−0.00158	−3.50
3	$1.1{*}V_T$	0.04242	−0.00276	−6.11	$0.9{*}V_T$	0.04716	0.00198	4.38
3	$1.1{*}V_{ls}$	0.05254	0.00736	16.29	$0.9{*}V_{ls}$	0.03829	−0.00689	−15.25
3	$1.1{*}V_{l^2}$	0.04287	−0.00231	−5.11	$0.9{*}V_{l^2}$	0.04775	0.00257	5.69
3	$1.1{*}V_{(ls)^2}$	0.04482	−0.00036	−0.80	$0.9{*}V_{(ls)^2}$	0.04555	0.00037	0.82

tential have a linear effect on A_2 and A_y. In other words, each change of $\pm 1\%$ in V_C causes a change in A_2 of roughly $\pm 0.3\%$ at low energies (regardless of the starting point for that change), as long as the total deviation from the original AV18 potential is less than $\pm 10\%$. For larger deviations from the original AV18 potential this linearity is lost.

Next we note that the NN force components that have the largest effect on A_2 are the spin-orbit and tensor forces; the effect of the tensor force on A_y is considerably smaller than the effect of the spin-orbit force, but still fairly large. This is what one expects, since a vector analyzing power is defined by

$$A \equiv \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow}, \tag{1}$$

where $\sigma_\uparrow$ and $\sigma_\downarrow$ denote the differential cross section with the spin of the incoming nucleon (for A_y) or deuteron (for iT_{11}) oriented normal to the scattering plane. Intuitively, such an asymmetry is generated by those potential terms (such as V_{ls} and V_T) that depend on the spin direction. The terms V_C and V_{l^2} do not depend on the spin at all, while $V_{(ls)^2}$ has less influence because it is small. If we set $V_{(ls)^2}$ to zero, A_2 decreases only by 4.6%.

The most important point here is that only the effect of a change in the tensor force is significantly different in the two-body and the three-body analyzing power. (We shall explain below why this is so.) This implies that, if we want to keep the two-body prediction unchanged but want to change the three-body prediction, this must come from a change in the NN tensor force. Changes in the other parts of the NN potential are then needed in order to compensate in A_2 for the change in V_T.

We note that the AV18 prediction for the nd A_y at $E_{\rm lab} = 3$ MeV (Ref. [23]) underestimates the data near the maximum by about 30%. Also, from Tables I and II we learn that the effect of a change in the tensor force is larger in the two-body system than in the three-body system. This means that we first have to *decrease* A_2 and A_y by increasing V_T and then *increase* the analyzing powers again by changes in the other terms until A_2 resembles its original value. A_y will then have a larger value than before because the effect of the decrease by V_T was less for A_y than for A_2. An analogous argument explains why the three-nucleon binding energy increases with decreasing tensor force, if the deuteron binding energy is kept fixed. These changes in A_2 and A_y require large changes in the NN potential.

We next quantify those changes in the potential that are necessary, although only a rough estimate is required. In order to achieve this let us consider the effects of changes in the various terms of the NN potential at 1 MeV (for specificity), as shown in Table I. The requirement that the totality of changes in the potential not affect A_2 leads to the equation

$$0.3\delta_C - 1.2\delta_T + 1.7\delta_{ls} - 0.5\delta_{l^2} + [0.04\delta_{(ls)^2}] = 0. \tag{2}$$

The quantities δ denote the change (in percent) in the corresponding term of the potential. The factors in front of the δ's in Eq. (2) mean, for example, that a change in V_C of 1% leads to a change in A_2 of roughly 0.3%. $V_{(ls)^2}$ has nearly no effect on A_2, but has a small one on A_y, and this is indicated by the brackets. We will first neglect this term and then take it into account later.

TABLE III. Possible solutions of Eqs. (2) and (3). The effects of the changes to A_2 and A_y are given as well.

δ_C	δ_{l^2}	$\delta_{(ls)^2}$	δ_T	δ_{ls}	δ_{A_2}	δ_{A_y}
10	−10	0	52.0	32.0	3.6	54
10	−10	−10	49.4	30.4	5.1	55
22	−22	0	46.4	22.4	6.2	55
22	−22	−22	40.7	18.9	8.5	57
30	−30	0	42.7	16.0	7.4	56
30	−30	−30	34.9	11.2	9.6	57

We based Eq. (2) on the results in Table I at $E_{\rm lab} = 1$ MeV for two reasons. First, the results at $E_{\rm lab} = 10$ MeV are very similar to the ones at 1 MeV. Second, we concentrate for the moment only on A_y at $E_{\rm lab} = 3$ MeV. The two-body t matrix for two-body energies from 2 MeV to $-\infty$ are required for Faddeev calculations of nd scattering at $E_{\rm lab} = 3$ MeV, so that we can neglect the higher two-body energies for the moment. Clearly, this is a very rough procedure. For a real solution of the A_y problem one would have to consider all two- and three-body energies. But because we only require a rough estimate of the size of the necessary changes in the potential, this procedure is good enough for the moment.

The analogue of Eq. (2) that we get from Table II is

$$0.4\delta_C - 0.6\delta_T + 1.6\delta_{ls} - 0.6\delta_{l^2} - [0.1\delta_{(ls)^2}] = 30, \tag{3}$$

which corresponds to an increase in A_y of 30%.

Solving Eqs. (2) and (3) for δ_T and δ_{ls} we obtain

$$\delta_T = -0.22\delta_C + 0.24\delta_{l^2} + 56.7,$$
$$\delta_{ls} = -0.33\delta_C + 0.47\delta_{l^2} + 40. \tag{4}$$

Obviously δ_T and δ_{ls} become large numbers if δ_C and δ_{ls} are chosen to be reasonably small, or, vice versa, if we require δ_T and δ_{ls} to become reasonably small, δ_C and δ_{ls} must be chosen very large. The inclusion of $\delta_{(ls)^2}$ in Eqs. (2) and (3) does not help much. In that case we get

$$\delta_T = -0.22\delta_C + 0.24\delta_{l^2} + 0.26\delta_{(ls)^2} + 56.7,$$
$$\delta_{ls} = -0.33\delta_C + 0.47\delta_{l^2} + 0.16\delta_{(ls)^2} + 40. \tag{5}$$

We give several possible solutions of Eqs. (2) and (3) in Table III together with the effect of these changes on A_2 and A_y. Though for all cases listed in Table III there is a substantial increase of A_2, the increase in A_y is roughly a factor 5 to 10 larger and always far above the required 30%. The reason that the solutions of Eqs. (2) and (3) listed in Table III are so far away from the required 0% and 30% changes (for A_2 and A_y), respectively, is that the parameters in Eqs. (2) and (3) are based on small ($<10\%$) changes in the potential. For the larger changes in the potential that are obviously necessary, the factors in Eqs. (2) and (3) are energy dependent and no longer constants. Thus with some fine tuning it

TABLE IV. Same as Table I, but for the short-range and OPEP parts of the central and tensor force separately.

$E_{\rm lab}$ (MeV)	Change	A_2	Δ	%	Change	A_2	Δ	%
1	$1.1*V_C^{\rm SR}$	0.00023159	0.00000774	3.46	$1.1*V_C^{\rm OPEP}$	0.00022256	−0.00000129	−0.58
10		0.012856	0.000373	2.99		0.012410	−0.000073	−0.58
100		0.42174	−0.00770	−1.79		0.43150	0.00206	0.48
1	$1.1*V_T^{\rm SR}$	0.00022601	0.00000216	0.96	$1.1*V_T^{\rm OPEP}$	0.00019419	−0.00002966	−13.25
10		0.012591	0.000108	0.87		0.011183	−0.001300	−10.41
100		0.42943	−0.00001	0		0.42986	0.00042	0.10

might be possible to reduce the effect on A_2 to an acceptable level and still maintain an increase in A_y of about 30%. But would that be the solution for the A_y problem? Unfortunately not. There are several reasons why this cannot be a solution for the A_y problem and, moreover, why solving the A_y problem with such changes in the NN potential is not possible. We shall discuss this in the following sections.

V. THE SIZE OF THE REQUIRED CHANGES IN THE NN POTENTIAL

Table III shows that each solution of Eqs. (2) and (3) requires quite remarkable changes in the several terms of the NN potential. For each of the tabulated solutions at least one term of the NN potential has to be changed by more than 35%. Changes of up to 50% are required. Other solutions of Eqs. (2) and (3) than those shown in Table III would obviously result in similarly large changes in the NN potential. As mentioned in Sec. IV, in order to satisfy Eqs. (2) and (3) a huge change in the tensor force is unavoidable. This is illustrated by the fact that in the expressions for δ_T and δ_{ls} in Eqs. (4) and (5) the multipliers of the various δ's on the right-hand sides are smaller by a factor of 100 than the last summand on each right-hand side.

Such large changes in the NN potential can be ruled out. Though the AV18 potential is a semiphenomenological potential, the strengths of its various terms are not free. The radial functions in the AV18 potential are fit to the NN data. Moreover, OPEP has been properly implemented and plays a large role, as we discuss below.

The different terms in the potential were multiplied by constant strength factors. One might argue that more freedom results if one changes the shape of the radial functions in the potential, as well. Unfortunately, this will not help much. Because the radial function for the one-pion-exchange potential (OPEP) is well known, such a change could only be made for the radial functions associated with the short-range operators in the potential. But it is demonstrated in Tables I, II, IV, and V (for an explanation of Tables IV and V, see below) that such a modification will result in roughly the same changes for A_2 and A_y and will thus not be able to solve the A_y problem. In fact, as we shall see in the next section, the freedom to change the NN potential is even much more tightly constrained.

VI. THE ONE-PION-EXCHANGE POTENTIAL

As already mentioned there is one piece of the phenomenological AV18 potential that comes from an important and well-recognized physical process—the OPEP. The OPEP makes up the longest-range part of this potential, whereas the short-range part is phenomenological. The OPEP has a tensor and a (weaker) central part. As we shall see below, the pion tail in the tensor force is the reason why the tensor force has a significantly different effect on the two-body and the three-body analyzing powers.

Let us first regard Tables IV and V. These tables show the different effects of the short- and long-range parts of the central and tensor forces on the analyzing powers. We accomplish this by separating the long- and short-range parts into the form

$$V = V^{\rm SR} + V^{\rm OPEP}, \tag{6}$$

where $V^{\rm SR}$ stands for the short-range part and $V^{\rm OPEP}$ for the pion tail of the potential. The latter also includes the short-range regulator that makes it finite at the origin. Choosing a different regulation scheme is equivalent to changing the short-range part.

Tables IV and V demonstrate that all the sensitivity of the analyzing powers to the tensor force comes from the pion tail. The short-range tensor force has nearly no effect on the analyzing powers.

For the central force the pion tail is much less important than the short-range part, which is well known. What is important here is that changes in all short-range operators cause roughly the same change in the two-body and three-body analyzing powers. The reason is that the two-body and three-body matrix elements of a short-range operator are roughly proportional to each other, as demonstrated in Tables I, II,

TABLE V. Same as Table II, but for the short-range and OPEP parts of the central and tensor force separately.

$E_{\rm lab}$ (MeV)	Change	A_y	Δ	%	Change	A_y	Δ	%
3	$1.1*V_C^{\rm SR}$	0.04732	0.00214	4.74	$1.1*V_C^{\rm OPEP}$	0.04473	−0.00045	−1.00
3	$1.1*V_T^{\rm SR}$	0.04552	0.00034	0.75	$1.1*V_T^{\rm OPEP}$	0.04200	−0.00318	−7.04

TABLE VI. Same as Table I, but for the np ^3P_J phases at $E_{\rm lab}=1$ MeV. The values for the original AV18 are 0.18045 for $^3P_0$, -0.10737 for $^3P_1$, and 0.022529 for $^3P_2$.

Phase	Change	Phase	Δ	%	Change	Phase	Δ	%
$^3P_0$	$1.1*V_C$	0.17980	−0.00065	−0.36	$0.9*V_C$	0.18111	0.00066	0.37
$^3P_1$		−0.10831	−0.00094	0.88		−0.10644	0.00093	−0.87
$^3P_2$		0.022130	−0.00040	−1.77		0.022951	0.00042	1.87
$^3P_0$	$1.1*V_T$	0.20495	0.02450	13.58	$0.9*V_T$	0.15680	−0.02365	−13.11
$^3P_1$		−0.11575	−0.00838	7.80		−0.09891	0.00846	−7.88
$^3P_2$		0.025649	0.00312	13.85		0.019527	−0.00300	−13.33
$^3P_0$	$1.1*V_{ls}$	0.17883	−0.00162	−0.90	$0.9*V_{ls}$	0.18217	0.00172	0.95
$^3P_1$		−0.10768	−0.00031	0.29		−0.10706	0.00031	−0.29
$^3P_2$		0.024190	0.00166	7.37		0.021003	−0.00153	−6.77
$^3P_0$	$1.1*V_{l^2}$	0.18042	−0.00003	−0.02	$0.9*V_{l^2}$	0.18049	0.00004	0.02
$^3P_1$		−0.10735	0.00002	−0.02		−0.10740	−0.00003	0.03
$^3P_2$		0.021871	−0.00066	−2.92		0.023253	0.00072	3.21
$^3P_0$	$1.1*V_{(ls)^2}$	0.17921	−0.00124	−0.69	$0.9*V_{(ls)^2}$	0.18173	0.00128	0.71
$^3P_1$		−0.10751	−0.00014	0.13		−0.10724	0.00013	−0.12
$^3P_2$		0.022001	−0.00053	−2.34		0.023070	0.00054	2.40

IV, and V. Thus if a change of the strength of a short-range operator causes a certain relative change in the two-body matrix element, the three-body matrix element will be changed by roughly the same relative amount.

Thus we find that if we do not want to change the two-body analyzing power but want to increase the three-body analyzing power we must modify the long-range force. Because the only long-range NN force is the OPEP, this is the part that must be changed. The required increase is of the order 30–50 % in order to get the 30% increase in A_y, and this is unreasonable. Thus, all the solutions for Eqs. (2) and (3) are inconsistent with the OPEP and therefore out of the question.

In summary, the only way to keep A_2 unchanged and simultaneously raise A_y would be a very large strengthening of the one-pion-exchange potential, and this would not be credible. Thus a solution of the A_y problem by such changes in the NN potential is not possible. In the next section we shall also demonstrate the importance of OPEP for the ^3P_J phase shifts.

VII. THE ^3P_J PHASE SHIFTS

Up to now we have looked at observables, but we have not checked what effects the changes that we made in the NN potential have on the ^3P_J phase shifts. Table VI gives an overview.

The first noticeable thing in Table VI is that each of the different terms of the potential affects the ^3P_J partial waves in very different ways. The tensor force has the largest effect on the phases, although it does not dominate A_2. The tensor force changes all three phases in the same direction, $^3P_0$ and $^3P_2$ by roughly the same amount and $^3P_1$ by about half this amount. Because the ^3P_J phases influence A_2 in different ways, the changes in the phases partially cancel each other in A_2.

The spin-orbit force changes essentially only the $^3P_2$ phase, and by roughly half the amount that the tensor force changes this phase. Because there is no cancellation from the other two phases, the effect of the spin-orbit force on A_2 is larger than that of the tensor force. The other three terms have only a small influence on the phases and on A_2; they primarily affect $^3P_2$. The central force has a modest effect on $^3P_1$.

What happens if we require that our changes to the potential leave not only A_2 unchanged, but also the ^3P_J phases? Obviously we will get three additional equations to be fulfilled together with Eqs. (2) and (3). These are

$$-0.04\delta_C+1.4\delta_T-0.1\delta_{ls}-0.07\delta_{(ls)^2}=0,$$
$$0.1\delta_C+0.8\delta_T+0.03\delta_{ls}+0.01\delta_{(ls)^2}=0, \tag{7}$$
$$-0.2\delta_C+1.4\delta_T+0.7\delta_{ls}-0.3\delta_{l^2}-0.2\delta_{(ls)^2}=0.$$

Thus we now have five equations for five unknowns. The solution of these five equations is unique and gives $\delta_C=177$, $\delta_T=-19$, $\delta_{ls}=141$, $\delta_{l^2}=577$, and $\delta_{(ls)^2}=-681$. Changes of this order are totally out of question, and therefore we can conclude that reasonable changes in the NN potential cannot keep the two-body phase shifts and observables unchanged, while at the same time increasing the three-body analyzing power by the amount required by the data.

In the discussion above we left out the $^3F_2$ phase and the $^3P_2$-$^3F_2$ mixing parameter ϵ_2, because they are less important for the analyzing powers. These parameters are also changed by the modifications we made to the different potential terms. Requiring these two parameters to be unchanged as well would lead to two additional equations besides the three Eqs. (7), so that then we would have seven equations for five unknowns. Unless there would be a redundancy within these seven equations this set would have no solution. Therefore our conclusions would remain the same even if we would consider $^3F_2$ and ϵ_2, too.

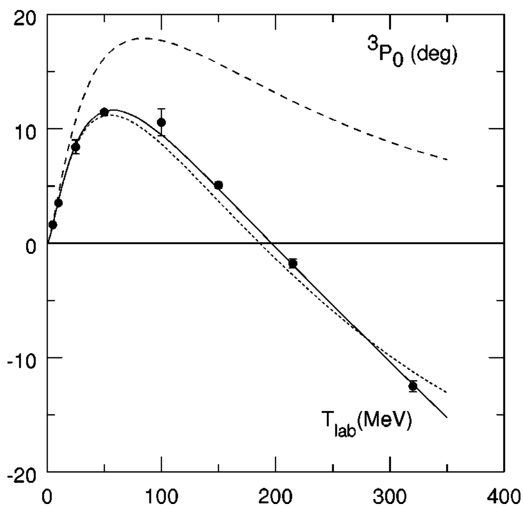

FIG. 1. The $^3P_0$ phase from the Nijmegen PSA [8]. The dashed line is the prediction for the OPEP only, the dotted line is the result of the PSA with one parameter, and the solid line is the final result of the Nijmegen PSA with three parameters. The filled circles denote results of the single energy analysis.

Heretofore we have made two assumptions: that there is no CIB and CSB in the ^3P_J waves and that the ^3P_J phase shifts should not deviate from the results of the Nijmegen phase-shift analysis (PSA) (with which the AV18 potential is commensurate).

The second assumption was questioned very recently by the author of [6] (see also Table III of [7]). He shows that there is room for some changes in the ^3P_J phase shifts at lower energies due to the fact that there are not enough NN data to determine the low-energy ^3P_J phases uniquely. In fact, in [6] the Fermi-Yang ambiguities were rediscovered, which were first found for πN scattering [24]. If a set of two or more phase shifts shows sensitivity in only one observable, Fermi and Yang discovered that there is a continuous ambiguity in the determination of those phase shifts by a single-energy analysis. (If a second observable shows sensitivity, the ambiguities become discrete.) That is exactly the situation we face: the only two-body observable showing strong sensitivity to the ^3P_J phases at lower energies is the analyzing power A_2. In a low-energy approximation it can be written in the form

$$A_2(\theta)=f(\theta)(-2\delta_{^3P_0}-3\delta_{^3P_1}+5\delta_{^3P_2}+c). \tag{8}$$

The constant c includes the dependence of partial waves other than ^3P_J, which play only a minor role. It is obvious from Eq. (8) that any combination of the ^3P_J phases that leaves the sum $(-2\delta_{^3P_0}-3\delta_{^3P_1}+5\delta_{^3P_2})$ unchanged will do equally well in the description of A_2.

Thus these ambiguities are clearly there, but do they give any freedom for changes in the ^3P_J phase shifts as determined in the Nijmegen PSA? They do not, as we shall show next.

First of all one can argue that in a multienergy phase-shift analysis the low-energy ^3P_J phases are not only determined by low-energy NN data but by other constraints (continuity and analyticity), whereas the analysis done in [6] is equivalent to a single-energy phase-shift analysis and lacks these constraints. Thus even if it is possible to describe the NN data at a single energy with several sets of different ^3P_J phases (as it is clearly shown in [6]), it is virtually certain that all but one are ruled out in a multi-energy phase-shift analysis.

Indeed, this is the longstanding position of the Nijmegen group [20,25]: phase-shift ambiguities at a given energy are removed by performing a multienergy analysis and by adding additional physics.

Physics in our case means OPEP. The inclusion of OPEP indeed restricts the possible freedom for changes in the ^3P_J phases drastically. This is demonstrated in Fig. 1, which is taken from Ref. [8]. Figure 1 shows that the prediction for $^3P_0$ by OPEP alone already gives the correct shape of this phase. Adding one more parameter into the PSA for shorter-range effects gives essentially the correct result. For a perfect χ^2 fit only two additional parameters are needed. In other words, *all* short-range effects in $^3P_0$ can be explained reasonably well with one parameter only, which leaves very little room for changes in this phase.

Even if we assume that it is justified to modify the ^3P_J phases at low energies within the limits given in [6], one can show that this cannot solve the A_y problem. In Figs. 2–4 we show the ^3P_J phase shifts as they change with energy. We have divided the phase shifts by $E^{3/2}$, because the threshold behavior for phase shifts at low energies is given by $\delta_l \propto k^{2l+1}$. From Figs. 2 and 3 we see that $^3P_0$ and $^3P_1$ start to deviate from the threshold behavior at 1 MeV, although not very strongly. The $^3P_2$ phase on the other hand exhibits a nearly perfect threshold behavior up to 10 MeV (Fig. 4). This means that for $^3P_2$ at least, changes below 5 MeV must

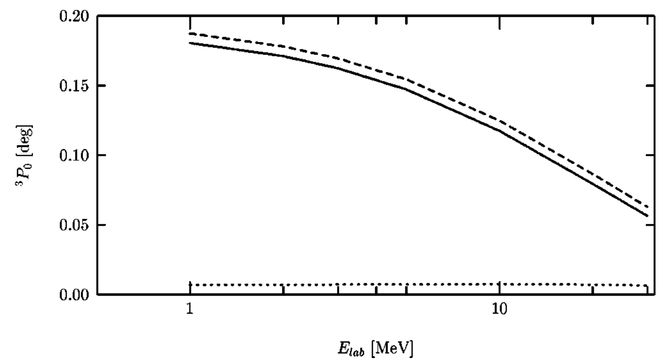

FIG. 2. The $^3P_0$ phase shift divided by $E^{3/2}$. The solid line denotes AV18, the dashed line AV18 with $V_T^{\rm SR}$ set to zero, while the dotted line is the difference between the dashed and solid lines.

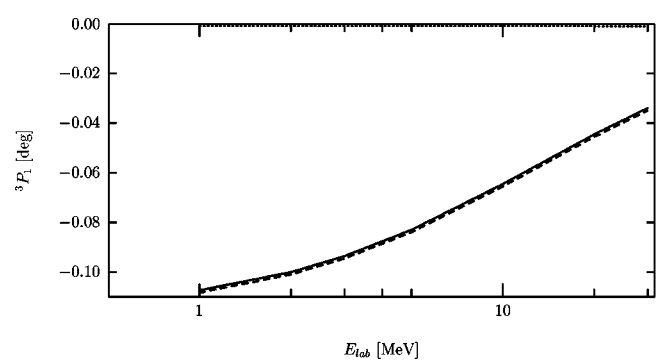

FIG. 3. Same as Fig. 2 but for $^3P_1$.

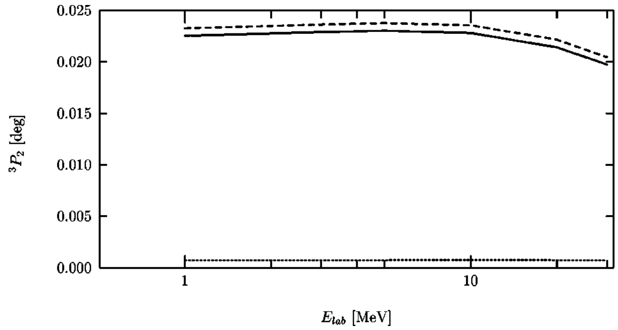

FIG. 4. Same as Fig. 2 but for $^3P_2$.

be accompanied by corresponding changes up to 10 MeV and possibly higher. But at those higher energies there is no room for changes in $^3P_2$ [6]; thus it cannot be changed at lower energies either.

We next notice from Figs. 2–4 that the short-range part of the tensor force $V_T^{\rm SR}$ has only a very small effect on the ^3P_J phases. This fact repeats our findings from Tables IV and V that the effect of the tensor force is almost exclusively in the one-pion-exchange part. Thus any major changes in the tensor force (which are necessary for any improvement in the A_y problem, as we have seen above) must be made in the OPEP, which will not accommodate a drastic change.

One might still argue that for small changes in the ^3P_J phases at low energies a change in the short-range tensor force might be sufficient. In order to show that this cannot be true, we have plotted in Figs. 2–4 the difference (dotted lines) between the phases for AV18 without the short-range tensor force $V_T^{\rm SR}$ and for the full AV18, again divided by $E^{3/2}$. These lines are virtually constant for all three phases. This means that the contribution of $V_T^{\rm SR}$ to the ^3P_J phases exhibits a perfect threshold behavior up to very high energies and thus $V_T^{\rm SR}$ is essentially determined by a single parameter for each of the ^3P_J waves. In other words, a change in $V_T^{\rm SR}$ leads necessarily to a change of the phase shifts for all energies, and this change is proportional to $E^{3/2}$ up to very high energies. It is impossible to change the phases at low energies via $V_T^{\rm SR}$ without disagreement with data at higher energies.

Let us go even one step further. Let us follow [6] and take ^3P_J phases that are modified at low energies in the spirit of [6] as shown in Table VII, and refit the AV18 potential to them. These modified phases were merely an exercise to test the flexibility of realistic NN potentials against the constraints of the data, rather than an attempt to improve the description of A_y. (Note that only $^3P_0$, $^3P_1$, and $^3P_2$ were modified at $E_{\rm lab}=1$, 5, and 10 MeV, with the largest modification required at 1 MeV and the smallest modification required at 10 MeV.) Attempts [26] to fit the potential to these modified ^3P_J phases were unsuccessful, unless the pion-nucleon coupling was weakened. The reason for the necessity of weakening the pion coupling was that Table VII requires a weakening in $^3P_0$ by 5% at the lowest energy, and this could only be achieved [26] by a weaker pion-nucleon coupling. This is in perfect agreement with our findings above. According to Table VI only a weaker tensor force can decrease $^3P_0$ significantly, and as we see in Table IV this requires a weaker OPEP.

TABLE VII. Phase-shift parameters of the original AV18 potential [14] compared to phases which were modified in the spirit of [6] (see text). Also given are the phases which could be achieved by the potential refitted to the modified phases [26]. Note that the pion-nucleon coupling constant was only allowed to change slightly during the refit process. The difference in percent between the modified and the achieved phases is given as well.

	$^3P_0$				$^3P_1$				$^3P_2$				ϵ_2				$^3F_2$			
$E_{\rm lab}$	AV18	Mod.	Ach.	%	AV18	Mod.	Ach.	%	AV18	Mod.	Ach.	%	AV18	Mod.	Ach.	%	AV18	Mod.	Ach.	%
1	0.18	0.171	0.178	4.1	−0.11	−0.105	−0.107	1.9	0.02	0.024	0.023	−4.3	−0.00	−0.001	−0.001	0	0.00	0.000	0.000	0
5	1.64	1.581	1.619	2.4	−0.93	−0.913	−0.921	0.9	0.26	0.267	0.262	−1.9	−0.05	−0.049	−0.049	0	0.00	0.002	0.002	0
10	3.71	3.616	3.649	0.9	−2.04	−2.021	−2.026	0.2	0.72	0.738	0.733	−0.7	−0.19	−0.185	−0.184	−0.5	0.01	0.011	0.011	0
25	8.32	8.320	8.167	−1.9	−4.82	−4.819	−4.778	−0.9	2.57	2.570	2.601	1.2	−0.77	−0.768	−0.762	−0.8	0.08	0.086	0.083	−3.6
50	10.99	10.993	10.801	−1.8	−8.15	−8.145	−8.079	−0.8	5.86	5.863	5.895	0.5	−1.68	−1.678	−1.657	−1.3	0.28	0.280	0.259	−8.1
100	8.69	8.691	8.595	−1.1	−13.07	−13.065	−12.998	−0.5	11.00	10.998	10.980	−1.6	−2.69	−2.692	−2.653	−1.5	0.67	0.668	0.590	−13.2
150	3.78	3.780	3.788	2.1	−17.28	−17.284	−17.238	−0.3	14.12	14.120	14.065	−0.4	−2.95	−2.946	−2.910	−1.2	0.98	0.979	0.863	−13.4
200	−1.43	−1.426	−1.350	−5.6	−21.22	−21.221	−21.189	−0.2	15.86	15.862	15.799	−0.4	−2.82	−2.822	−2.792	−1.1	1.15	1.149	1.030	−11.6
250	−6.41	−6.410	−6.299	−1.8	−24.95	−24.953	−24.921	−0.1	16.70	16.694	16.640	−0.3	−2.54	−2.539	−2.503	−1.4	1.10	1.097	0.997	−10.0
300	−11.06	−11.056	−10.935	−1.1	−28.49	−28.495	−28.450	−0.2	16.91	16.908	16.863	−0.3	−2.21	−2.207	−2.149	−2.7	0.77	0.766	0.688	−11.3
350	−15.36	−15.358	−15.245	−0.7	−31.85	−31.851	−31.783	−0.2	16.69	16.686	16.646	−0.2	−1.88	−1.879	−1.786	5.2	0.14	0.137	0.062	−21.0

TABLE VIII. CIB effects in degrees for the preliminary CD-Bonn99 potential [31] and from [28] compared to CIB in the modified Bonn B of [4]. $E_{\mathrm{lab}}=10$ MeV refers to CD-Bonn99 and [28], and 12 MeV to the modified Bonn B. The CIB effect is defined as $\delta_{\mathrm{CIB}} \equiv \delta_{np} - 0.5*(\delta_{nn}+\delta_{pp})$.

	$^3P_0$			$^3P_1$			$^3P_2$		
E_{lab} (MeV)	$\delta_{\mathrm{CIB}}^{\mathrm{CDB99}}$	$\delta_{\mathrm{CIB}}^{[28]}$	$\delta_{\mathrm{CIB}}^{\mathrm{mod.}\,BB}$	$\delta_{\mathrm{CIB}}^{\mathrm{CDB99}}$	$\delta_{\mathrm{CIB}}^{[28]}$	$\delta_{\mathrm{CIB}}^{\mathrm{mod.}\,BB}$	$\delta_{\mathrm{CIB}}^{\mathrm{CDB99}}$	$\delta_{\mathrm{CIB}}^{[28]}$	$\delta_{\mathrm{CIB}}^{\mathrm{mod.}\,BB}$
5	−0.237	−0.250	0.515	0.112	0.117	0	−0.011	−0.011	0
10(12)	−0.466	−0.492	1.405	0.198	0.206	−0.015	−0.032	−0.032	0.005
25	−0.822	−0.858	2.575	0.314	0.322	−0.025	−0.103	−0.101	0.015
50	−0.943	−0.960	3.275	0.368	0.366	−0.035	−0.188	−0.184	0.045

It is also interesting to note from Table VII that the attempt to fit the phases that were modified at the lower energies led to changes in the phase-shift predictions of the potential at all energies. The most dramatic changes in the phase-shift prediction of the refitted potential (in comparison to the original potential) are found at the higher energies for $^3F_2$. Most of the predictions of the refitted potential for $^3F_2$ fall outside the error bars of the Nijmegen PSA [8]. We based this judgment on the error bars that are given in [8] for the pp phases; unfortunately Ref. [8] gives no error bars for the np isovector phases. The refit procedure for the potential was also based on these error bars [26].

This shows that a refit of the AV18 potential to the energy-dependent modified phases of Table VII within the error bars for the phase shifts as given in Ref. [8] is not possible, though the required changes for the ^3P_J phases are very moderate. Also, because in the refit process the pion-nucleon coupling constant was allowed to change only slightly [26], the refitted potential fails to reproduce the modified phases below 10 MeV for all three ^3P_J phases. In other words, the changes in the phases we aimed for could be achieved only partially, at the price of unwanted changes. The χ^2 per phase-shift datum of Table VII for the refitted potential is 23, mainly because of the bad description of the modified ^3P_J phases below 10 MeV and of $^3F_2$ at the higher energies. Nevertheless, the χ^2 per np datum did increase only by about 3% for the refitted potential compared to the original potential. This reflects the fact that the $^3F_2$ phase is very small and therefore has not much influence on the np data.

Although the modified phases of Table VII are not chosen specifically to give an improvement in A_y, the fact that they force the pion-nucleon coupling constant in the potential to become smaller indicates that the refitted potential will give an improvement in A_y. However, this improvement turned out to be far too small [27], namely only 3% instead of the required 30%. Similarly, another study contained in [2], where the Nijmegen ^3P_J phases where changed by up to 3%, showed that within this restriction a solution of the A_y problem is not possible. From this we conclude that even if a modification of the low-energy ^3P_J phase shifts could be justified and a fit of the potential to those modified phases would be possible (which it is not for the case above) it is not likely to solve the A_y problem.

VIII. CHARGE INDEPENDENCE AND CHARGE-SYMMETRY BREAKING

The first of the two assumptions mentioned in the previous section, namely that there is no CIB and CSB in the ^3P_J waves, might be questioned because it was shown in [4] that the introduction of a very strong CIB and CSB in the Bonn B NN potential makes it possible to keep the two-body observables unchanged while increasing the nd A_y by the necessary amount. However, the ^3P_J phases were strongly changed. The $^3P_0$ pp phases, for example, were changed by about 15% at all energies. This is in clear contradiction with that Nijmegen phase, which has a statistical uncertainty below 1% at the energies considered here. Moreover, two very recent studies [28] and [29] show that the CIB and CSB used in [4] cannot by justified on physical grounds. In [28] and [29] the authors study those CIB and CSB effects that are possible within the conventional meson-exchange model of Ref. [30]. In the meson-exchange picture CIB and CSB are primarily caused by the differences between the neutral- and charged-meson masses, as well as the different nucleon masses. In Tables VIII and IX we compare the CIB and CSB as calculated in [28] and [29] with the one used in [4] (CIB and CSB effects for the preliminary CD-Bonn99 [31] are shown as well for later use). For $^3P_0$ the CIB and CSB used in [4] is not only much stronger than can be explained by the meson-exchange picture (the CSB is a factor of 20 too

TABLE IX. CSB effects in degrees for the preliminary CD-Bonn99 potential [31] and from [29] compared to CSB in the modified Bonn B of [4]. $E_{\mathrm{lab}}=10$ MeV refers to CD-Bonn99 and [29], and 12 MeV to the modified Bonn B. The CSB effect is defined as $\delta_{\mathrm{CSB}} \equiv \delta_{nn} - \delta_{pp}$.

	$^3P_0$			$^3P_1$			$^3P_2$		
E_{lab} (MeV)	$\delta_{\mathrm{CSB}}^{\mathrm{CDB99}}$	$\delta_{\mathrm{CSB}}^{[29]}$	$\delta_{\mathrm{CSB}}^{\mathrm{mod.}\,BB}$	$\delta_{\mathrm{CSB}}^{\mathrm{CDB99}}$	$\delta_{\mathrm{CSB}}^{[29]}$	$\delta_{\mathrm{CSB}}^{\mathrm{mod.}\,BB}$	$\delta_{\mathrm{CSB}}^{\mathrm{CDB99}}$	$\delta_{\mathrm{CSB}}^{[29]}$	$\delta_{\mathrm{CSB}}^{\mathrm{mod.}\,BB}$
5	0.008	0.009	−0.23	−0.002	−0.002	−0.02	0.002	0.003	0
10(12)	0.018	0.019	−0.63	−0.003	−0.002	−0.07	0.006	0.007	0.01
25	0.040	0.042	−1.15	−0.001	0	−0.13	0.022	0.025	0.03
50	0.056	0.057	−1.49	0.006	0.010	−0.11	0.051	0.056	0.09

strong), but both also have the wrong sign. The same is true for CSB in the $^3P_1$ partial wave, whereas for the CIB in the $^3P_1$ and $^3P_2$ waves we note the far larger effects for [28] and CD-Bonn99, which has the opposite sign to the modified Bonn B.

The CIB and CSB as calculated in [28] and [29] have been built into a new version of the CD-Bonn potential, the so-called CD-Bonn99 [31]. In addition, the CD-Bonn99 includes CIB effects from irreducible $\pi-\gamma$ exchange as calculated by van Kolck *et al.* [32]. The CD-Bonn99 potential has the pion-nucleon coupling constant of the Nijmegen PSA, $g_\pi^2/4\pi=13.6$, whereas the studies [28] and [29] (as well as Bonn B) use a larger pion-nucleon coupling constant of $g_\pi^2/4\pi=14.4$. Thus the CIB and CSB effects in CD-Bonn99 are generally smaller than those given in [28] and [29] (see Tables VIII and IX). We had a preliminary version [31] of this potential at our disposal, which we tested in the 3N analyzing powers. For simplicity we restricted CIB and CSB to the partial waves that are essential for our problem (i.e., $^1S_0$ and ^3P_J). In all other partial waves we used the np force only. This calculation is to be compared to one where the CD-Bonn99 np force is used in all partial waves. The CIB and CSB built into CD-Bonn99 gives an increase in the maximum of A_y at $E_{\rm lab}=3$ MeV of about 4% and in iT_{11} of about 10%. The increase in A_y is far too small to come close to the nd data. For iT_{11} there are no nd data, but a comparison of a pd calculation using the AV18 potential with pd data at 3 MeV [13] shows a 50% discrepancy. Thus we can conclude that although the CIB and CSB effects as built into the CD-Bonn99 potential go in the correct direction, they are much too small to explain the discrepancies in the vector analyzing powers.

At first sight it might be surprising that the CD-Bonn99 potential gives an increase in the analyzing powers (as does the modified Bonn B), because all CIB effects of the two potentials have opposite signs. But a closer look at Table VIII shows that there is no inconsistency. Let us remember first that in order to increase A_y one has to decrease $\delta_{^3P_0}$ and increase $\delta_{^3P_1}$ and $\delta_{^3P_2}$ (that is, the magnitude of those phases; $\delta_{^3P_1}$ has a negative sign). We also remember that in a charge-dependent Faddeev calculation the CIB effect can be taken into account via an effective t matrix (or with the potential *mutatis mutandis*) $t_{\rm eff}=1/3\ t_{np}+2/3\ t_{nn(pp)}$, if we neglect isospin $T=3/2$ channels (T representing the total three-body isospin). Thus if we want to get an increase in A_y in a charge-dependent calculation in comparison to a charge-independent calculation (which uses the np force only), we need a $\delta_{\rm CIB}$ for $^3P_0$ and $^3P_1$ with positive sign (again note that $\delta_{^3P_1}$ is negative) and of negative sign for $^3P_2$. So we see from Table VIII that the modified Bonn B of Ref. [4] has the correct CIB in $^3P_0$ in order to increase A_y, but the wrong CIB in the other two phases. But the CIB effects of the modified Bonn B in these other two phases can be neglected against the huge CIB in $^3P_0$. Thus the large increase in A_y of the modified Bonn B in comparison to the original Bonn B comes only from $^3P_0$. For CD-Bonn99, on the other hand, we find the correct CIB for an increase of A_y for $^3P_1$ and $^3P_2$ and the wrong CIB for $^3P_0$. Also the CIB effects in all three phases are of the same order of magnitude. So for CD-Bonn99 we have an interference of opposite effects, and the increasing effects just overcome the decreasing one.

We also note that the A_y problem exists in pd scattering [12], as well, and this involves the well-known pp interaction rather than the poorly known nn force. Thus for all of these reasons we can exclude CIB and CSB as a solution of the A_y problem.

IX. SUMMARY AND CONCLUSIONS

In Sec. II we laid down the principles and options of our study of the A_y puzzle. Any NN potential should fit the NN data reasonably well, and if it does so, it gives the same answer for A_y as all other potentials. The NN potential has an OPEP as the long-range part, which is very well known. There is, however, much more uncertainty in the short-range parts of the NN potential. We argue that CIB must be a small effect. Current 3NF models do not help in A_y.

In order to study the possibilities of changes in the NN force we chose the AV18 model, which is introduced in Sec. III. It consists of the OPEP and a phenomenological short-range part. This potential has five different operators that contribute to the ^3P_J waves (which are the only important ones for A_y).

In Sec. IV we showed that it is possible to improve the description of the three-body A_y and at the same time keep changes in the two-body A_2 small, but that huge changes (at least in the tensor force) are necessary in order to achieve this. As pointed out in Sec. V such huge changes in the NN potentials can be ruled out, and there is only very little room for changes in the NN potential at all.

Indeed, the tensor force acts largely through OPEP, and that is the reason why only the tensor force has a significantly different effect in the two-body and three-body systems, as shown in Sec. VI. Thus the only way to increase A_y and keep A_2 unchanged at the same time is to change OPEP by 30–50 %. This is impossible.

Moreover, as we see in Sec. VII, the additional requirement of keeping the ^3P_J phases unchanged, as well, leads to the requirement of even more drastic changes in the NN potential.

We also comment in this section on Ref. [6], where it is claimed that there is much room for change in the low-energy ^3P_J phases. Unfortunately this is true only if additional constraints are not applied. The ambiguities for the ^3P_J phases found in [6] can be removed by performing a multienergy analysis and by including additional physics (i.e., OPEP).

Finally we excluded CIB and CSB as a possible explanation of the A_y puzzle in Sec. VIII. Although we did not comment on the effects of long-range electromagnetic forces, it was shown in a recent paper [33] that they have no major effect on A_y.

Thus we have eliminated all possibilities for solving the A_y puzzle on the two-body level. Therefore we come to the conclusion that the only possible solution for the A_y puzzle must be a 3NF. This 3NF must be a term that has not yet been taken into account [17]. Because of the nature of the analyzing power as a difference between cross sections with different spin direction for one of the incoming particles, it must be a spin-dependent 3NF. Likely candidates are spin-orbit-type 3NF's [17]. We also note that there is a similar problem with the ^{5}He energy levels, where the $P_{1/2}-P_{3/2}$ splitting is 20–30 % too small [34]. This seems likely to have the same origin as the A_y puzzle and, if so, would have the same solution.

Another strong hint that a 3NF is the solution of the A_y puzzle is the fact that in [6,7,5] only energy-dependent changes (changes in shape) of the $^{3}P_J$ phases are considered as possible solutions and energy-independent changes are ruled out. But an energy-dependent change in the NN force (which we do not accept as a possibility, see Sec. II) is very likely equivalent to adding a 3NF (in the three-nucleon systems). This point is also supported by the fact that the attempts [26] to fit AV18 to the energy-dependent modified $^{3}P_J$ phases of Table VII were not possible with a satisfactory value for χ^2 per phase-shift datum [26].

We would like to point out that in order to investigate such 3NF's it is desirable to have a consistent description of the NN and 3N force. Otherwise the complicated interplay between inconsistent NN and 3N forces might lead to wrong conclusions. A consistent description of NN and 3N forces, such as realized in the Ruhrpot model [35], also has the advantage that the 3NF is essentially parameter-free (i.e., all parameters occurring in the 3NF are already given by the NN force and its fit to the NN data base).

We mentioned in Sec. II that an off-shell ambiguity is equivalent to a 3NF. Is this a serious consideration for our problem? In principle it might be, but in practice it is not. The depth of the problem is illustrated in Ref. [36], where a theorem is proven that any Hamiltonian H_1 that contains a 3NF can be replaced by a Hamiltonian H_2 that does not contain a 3NF, with H_1 and H_2 giving the same three-body binding energy and scattering matrix. In addition, the Hamiltonian $\overline{H}_1$ (H_1 minus the 3NF) and H_2 give the same two-body binding energy and scattering matrix. Thus an off-shell ambiguity in the NN force (needed to define $\overline{H}_1$) is equivalent to *the whole* 3NF.

In practice the problem is much less dramatic. In our experience [37] field-theoretic exercises to define potentials such as OPEP suffer from only three types of ambiguity: (1) the Brueckner-Watson–Taketani-Machida-Ohnuma (BW-TMO) ambiguity arising from energy dependence in the force (discussed in detail in Ref. [38]); (2) μ,ν unitary ambiguities due to chiral representation and choice of quasipotential (defined and discussed in [17]); (3) ''form'' ambiguities, where the entire structure of the quasipotential equation is altered, such as by squaring the relativistic Schrödinger equation [see Eqs. (103) and (104) of Ref. [16]]. In each case, specifying the form of OPEP eliminates the ambiguity by fiat. Moreover, the Bonn potentials differ from most others in their μ,ν parameters and this makes little difference in the A_y problem, as was shown in Ref. [2], for example.

We succinctly summarize by stating that if OPEP is not dramatically changed and if long-range electromagnetic forces are unimportant [33], the remaining short-range forces cannot fix the A_y problem. Because these forces are proportionate in the two- and three-nucleon systems up to quite high energies and are fixed by all the NN data in this range, they cannot be altered to resolve the puzzle. This conclusion is in clear disagreement with the authors of Ref. [5]. Also, unlike the conjecture of Ref. [7] we find no evidence that prior phase-shift analyses are questionable. If modifications of the NN potential are ruled out (as we have argued), only additional (or modified) 3NF components remain as a possible solution to the A_y puzzle.

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