The $A_y$ Puzzle and the Nuclear Force

D. Hüber and J.L. Friar

Theoretical Division, Los Alamos National Laboratory, M.S. B283, Los Alamos, NM 87545, USA

Abstract

The nucleon-deuteron analyzing power $A_y$ in elastic nucleon-deuteron scattering poses a longstanding puzzle. At energies $E_{\text{lab}}$ below approximately 30 MeV $A_y$ cannot be described by any realistic 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 2-body observables and on $A_y$. We find that it is not possible with reasonable changes in the NN potential to increase the 3-body $A_y$ and at the same time to keep the 2-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 spin-orbit type, which have not yet been taken into account.

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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 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 $\approx 30$ 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. Since it is now possible to calculate elastic proton-deuteron (pd) scattering below the breakup threshold 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. Because $A_y$ is mainly sensitive to the NN $^3P_J$ phase shifts, the potentials for those partial waves were multiplied by strength factors, keeping the low-energy observables in reasonable agreement with the 2-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. (see also and ), 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 and at the same time increase $A_y$.

Another possible solution to the $A_y$ puzzle is a three-nucleon force (3NF). In it became possible for the first time to incorporate a 3NF into Faddeev calculations above the
breakup threshold. Since then all available 3NFs 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 section II. In our calculations we make use of the AV18 potential [14], which is introduced in section III. The changes we apply to the NN potential are described in section IV. In section V we discuss the size of the changes in the potential that are necessary to keep the 2-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 section 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. [3] 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 section VIII. Finally we summarize and conclude in section 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 2-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. [13]). 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 2-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 combinations 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 potentials that have a much better fit.

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 non-local 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 section 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.

The short-range interactions are parameterized 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 charge dependence (CD) 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 2-body observables
unchanged and at the same time increases the 3-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 structural simplicity. The AV18 potential is a semi-phenomenological
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 parameterized 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 2-body angular momentum $\vec{l} = \vec{l}_1 + \vec{l}_2$ and the total 2-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 $\chi^2$ 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 3-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 2-body observables. It is well known that the only 2-body observable sensitive to changes in the $^3P_J$ waves is the analyzing power. In order to distinguish it from the 3-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 potential 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

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

(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 $V_{l2}$ 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 2-body and the 3-body analyzing power. (We shall explain below why this is so.) This implies that, if we want to keep the 2-body prediction unchanged but want to change the 3-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 $E_{lab} = 3$ MeV [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 2-body system than in the 3-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 3-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

\[
.3 \, \delta_C - 1.2 \, \delta_T + 1.7 \, \delta_{ts} - .5 \, \delta_{l2} + [.04 \, \delta_{(ls)^2}] = 0 .
\]  

(2)

The quantities \( \delta \) denote the change (in percent) in the corresponding term of the potential. The factors in front of the \( \delta \)'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.

We based Eq. (2) on the results in Table I at \( E_{lab} = 1 \) MeV for two reasons. First, the results at \( E_{lab} = 10 \) MeV are very similar to the ones at 1 MeV. Second, we concentrate for the moment only on \( A_y \) at \( E_{lab} = 3 \) MeV. The 2-body t-matrix for 2-body energies from 2 MeV to \(-\infty\) are required for Faddeev calculations of nd scattering at \( E_{lab} = 3 \) MeV, so that we can neglect the higher 2-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 2- and 3-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 I is

\[
.4 \, \delta_C - .6 \, \delta_T + 1.6 \, \delta_{ts} - .6 \, \delta_{l2} - [.1 \, \delta_{(ls)^2}] = 30 ,
\]  

(3)

which corresponds to an increase in \( A_y \) of 30%.

Solving Eqs. (2) and (3) for \( \delta_T \) and \( \delta_{ts} \) we obtain

\[
\delta_T = -.22 \, \delta_C + .24 \, \delta_{l2} + 56.7 ,
\]

\[
\delta_{ts} = -.33 \, \delta_C + .47 \, \delta_{l2} + 40 .
\]  

(4)

Obviously \( \delta_T \) and \( \delta_{ts} \) become large numbers if \( \delta_C \) and \( \delta_{ts} \) are chosen to be reasonably small, or, vice versa, if we require \( \delta_T \) and \( \delta_{ts} \) to become reasonably small, \( \delta_C \) and \( \delta_{ts} \) must be chosen

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very large. The inclusion of \( \delta (ls)^2 \) in Eqs. (2) and (3) does not help much. In that case we get

\[
\begin{align*}
\delta_T &= -0.22 \, \delta_C + 0.24 \, \delta l^2 + 0.26 \, \delta (ls)^2 + 56.7, \\
\delta_{ls} &= -0.33 \, \delta_C + 0.47 \, \delta l^2 + 0.16 \, \delta (ls)^2 + 40.7.
\end{align*}
\] (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 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 section 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 \( \delta_T \) and \( \delta_{ls} \) in Eqs. (4) and (5) the multipliers of the
various $\delta$’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 semi-phenomenological 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 2-body and the 3-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
\[ V = V^{SR} + V^{OPEP}, \]  

where \( V^{SR} \) stands for the short-range part and \( V^{OPEP} \) 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 2-body and 3-body analyzing powers. The reason is that the 2-body and 3-body matrix elements of a short-range operator are roughly proportional to each other, as demonstrated in Tables I, II, IV and V. Thus if a change of the strength of a short-range operator causes a certain relative change in the 2-body matrix element, the 3-body matrix element will be changed by roughly the same relative amount.

Thus we find that if we don’t want to change the 2-body analyzing power but want to increase the 3-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 order 30% to 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 $^{3}P_J$ 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 $^{3}P_J$ 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 $^{3}P_J$ 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, $^{3}P_0$ and $^{3}P_2$ by roughly the same amount and $^{3}P_1$ by about half this amount. Because the $^{3}P_J$ 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 $^{3}P_2$ 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 $^{3}P_2$. The central force has a modest effect on $^{3}P_1$.

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

$$ -0.04 \delta_C + 1.4 \delta_T - 1.0 \delta_{ls} - 0.07 \delta_{(ls)^2} = 0, $$

$$ 0.1 \delta_C + 0.8 \delta_T + 0.03 \delta_{ls} + 0.01 \delta_{(ls)^2} = 0, $$

$$ -0.2 \delta_C + 1.4 \delta_T + 0.7 \delta_{ls} - 0.3 \delta_{l^2} - 0.2 \delta_{(ls)^2} = 0. $$

These are

Thus we now have 5 equations for 5 unknowns. The solution of these 5 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 2-body phase shifts and observables unchanged, while at the same time increasing the 3-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 $\epsilon_2$, 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. (4), so that then we would have 7 equations for 5 unknowns. Unless there would be a redundancy within these 7 equations this set would have no solution. Therefore our conclusions would remain the same even if we would consider $^3F_2$ and $\epsilon_2$, too.

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 [5]). 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 $\pi N$ scattering [29]. 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 2-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 multi-energy 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][30]: phase-shift ambiguities at a given energy are removed by performing a multi-energy 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]. Fig. 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 $\chi^2$-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 Figures 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 Figures 2 - 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 (Figure 4). This means that for $^3P_2$ at least, changes below 5 MeV must 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 Figures 2 - 4 that the short-range part of the tensor force $V^{SR}_T$ 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 Figures 2 - 4 the difference (dotted lines) between the phases for AV18 without the short-range tensor force $V_{T}^{SR}$ 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 $V_{T}^{SR}$ to the $^3P_J$ phases exhibits a perfect threshold behavior up to very high energies and thus $V_{T}^{SR}$ is essentially determined by a single parameter for each of the $^3P_J$ waves. In other words, a change in $V_{T}^{SR}$ 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 $V_{T}^{SR}$ 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. (Note that only $^3P_0$, $^3P_1$ and $^3P_2$ were modified at $E_{lab} =1, 5$ and 10 MeV, with the largest modification required at 1 MeV and the smallest modification required at 10 MeV.) Attempts [31] 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 [31] by a weaker pion-nucleon coupling. This is in perfect agreement with our findings above. According to Table VII only a weaker tensor force can decrease $^3P_0$ significantly, and as we see in Table IV this requires a weaker OPEP.

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 [31].

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 [31], 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 $\chi^2$ 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 $\chi^2$ 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.

Furthermore the modified potential led to very disappointing results in the nd system [32]. Only an improvement of about 3% in $A_y$ was achieved at $E_{lab} = 3$ MeV, instead of the necessary 30%. Similarly, another study contained in [4], 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, as shown above) it would not 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 2-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 [24] and [25] show that the CIB and CSB used in [4] cannot be justified on physical grounds. In [24] and [25] the authors study those CIB and CSB effects that are possible within the conventional meson-exchange model of Ref. [26]. 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 VII and IX we compare the CIB and CSB as calculated in [24] and [25] with the one used in [4] (CIB and CSB effects for the preliminary CD-Bonn99 [27] 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 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 [24] and CD-Bonn99, which has the opposite sign to the modified Bonn B.

The CIB and CSB as calculated in [24] and [25] have been built into a new version of the CD-Bonn potential, the so-called CD-Bonn99 [27]. In addition, the CD-Bonn99 includes CIB effects from irreducible $\pi - \gamma$ exchange as calculated by van Kolck et al. [28]. The CD-Bonn99 potential has the pion-nucleon coupling constant of the Nijmegen PSA, $g_\pi^2/4\pi = 13.6$, whereas the studies [24] and [25] (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 [24] and [25] (see Tables VII and IX). We had a preliminary version [27] 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 $A_y$. 

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at $E_{\text{lab}} = 3$ 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 VII 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*) $t_{\text{eff}} = 1/3 \, t_{np} + 2/3 \, t_{nn(pp)}$, if we neglect isospin $T = 3/2$ channels ($T$ representing the total 3-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 $\delta_{\text{CIB}}$ 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 VII 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 section 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 CD 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 section III. It consists of the OPEP and a phenomenological short-range part. This potential has 5 different operators that contribute to the $^3P_J$ waves (which are the only important ones for $A_y$).

In section IV we showed that it is possible to improve the description of the 3-body $A_y$ and at the same time keep changes in the 2-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 section 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 2-body and 3-body systems, as shown in section 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 section 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 changes 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 multi-energy 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 section 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 2-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 3NFs [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 $^3P_J$ 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 section 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 [31] to fit AV18 to the energy-dependent modified $^3P_J$ phases of Table VII were not possible with a satisfactory value for $\chi^2$ per phase-shift datum [31].

We would like to point out that in order to investigate such 3NFs 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 section 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 3-body binding energy and scattering matrix. In addition, the Hamiltonian $\tilde{H}_1 (H_1 \text{ minus the 3NF})$ and $H_2$ give the same 2-body binding energy and scattering matrix. Thus an off-shell ambiguity in the NN force (needed to define $\tilde{H}_1$) 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 BW-TMO ambiguity arising from energy dependence in the force (discussed in detail in Ref. [38]); (2) $\mu, \nu$ 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 $\mu, \nu$ 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, the remaining short-range forces cannot fix the $A_y$ problem. Because these forces are proportionate in the 2- and 3-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. [6] we find no evidence that prior phase-shift analyses are questionable. In [5] the possibility of a 3NF as an explanation for the $A_y$ discrepancy is ruled out by the argument that “it is very difficult to imagine 3N forces can account for the observed energy dependence of the N-d analyzing power puzzle”. Nevertheless, because every other solution is eliminated by our study, what remains must be the correct answer [39].
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REFERENCES

[1] W. Glöckle, H. Witała, Th. Cornelius, Nucl. Phys. A508 (1991) 115c;
W. Glöckle, H. Witała, Th. Cornelius, Proc. 25th Zakopane School on physics, Vol. 2:
Selected topics in nuclear structure, ed.: J. Styczen and Z. Stachura (World Scientific,
Singapore, 1990) p. 300, and references therein.

[2] W. Glöckle, H. Witała, D. Hüber, H. Kamada, J. Golak, Phys. Rep. 274 (1996) 107.

[3] A. Kievsky, M. Viviani, S. Rosati, Phys. Rev. C52 (1995) R15.

[4] H. Witała, W. Glöckle, Nucl. Phys. A528 (1991) 48.

[5] H. Witała and W. Tornow, submitted for publication.

[6] W. Tornow, submitted for publication.

[7] W. Tornow, H. Witała, and A. Kievsky, Phys. Rev. C57 (1998) 555.

[8] V.G.J. Stoks, R.A.M. Klomp, M.C.M. Rentmeester, J.J. de Swart, Phys. Rev. C48
(1993) 792.

[9] R.A. Arndt, R.L. Workman, M.M. Pavan, Phys. Rev. C49 (1994) 2729;
R.A. Arndt, I.I. Strakovskiy, R.L. Workman, Phys. Rev. C52 (1995) 2246.

[10] D. Hüber, H. Witała, W. Glöckle, Few-Body Systems 14 (1993) 171.

[11] H. Witała, D. Hüber, W. Glöckle, Phys. Rev. C49 (1994) R14.

[12] S. Rosati, M. Viviani, A. Kievsky, Few-Body Systems Suppl. 8 (1995) 21.

[13] A. Kievsky, Few-Body Systems Suppl. 9 (1995) 405.

[14] R.B. Wiringa, V.G.J. Stoks, R. Schiavilla, Phys. Rev. C51 (1995) 38.

[15] J. L. Friar, J. Martorell, and D. W. L. Sprung, Phys. Rev. A56 (1997) 4579.

[16] J. L. Friar, Ann. Phys. (N.Y.) 104 (1977) 380.
[17] S.A. Coon and J.L. Friar, Phys. Rev. C34 (1986) 1060. Two-pion-exchange three-nucleon forces (derived from a chiral Lagrangian) that have a spin-orbit character are reported here. These terms are necessary to maintain (approximate) Lorentz invariance.

[18] C. Ordóñez and U. van Kolck, Phys. Lett. B291 (1992) 459;
C. Ordóñez, L. Ray, and U. van Kolck, Phys. Rev. Lett. 72 (1994) 1982;
U. van Kolck, Phys. Rev. C 49 (1994) 2932.

[19] R.B. Wiringa, R.A. Smith, T.L. Ainsworth, Phys. Rev. C29 (1984) 1207.

[20] J.J. de Swart, M.C.M. Rentmeester, R.G.E. Timmermans, Invited Talk at MENU97, TRIUMF Report TRI-97-1 (1997) 96; nucl-th/9802084.

[21] J.L. Friar, Few-Body Systems 22 (1997) 161.

[22] U. van Kolck, J.L. Friar, and T. Goldman, Phys. Lett. B371 (1996) 169.

[23] J.E. McAninch, W. Haeberli, H. Witala, W. Glöckle, J. Golak, Phys. Lett. B307 (1993) 13.

[24] G.Q. Li and R. Machleidt, in preparation.

[25] G.Q. Li and R. Machleidt, in preparation.

[26] R. Machleidt, K. Holinde, Ch. Elster, Phys. Rep. 149 (1987) 1.

[27] R. Machleidt, private communication. The CD-Bonn99 is an update of the CD-Bonn potential presented in: R. Machleidt, F. Sammarruca, Y. Song, Phys. Rev. C53 (1996) 1483.

[28] U. van Kolck, M.C.M. Rentmeester, J.L. Friar, T. Goldman, J.J. de Swart, preprint nucl-th/9710067.

[29] C.N. Yang, in a private communication to E. Fermi quoted in, H.A. Bethe and F. de Hoffmann, Introduction to Meson Theory, Part I, 1954, p. 284ff.
[30] R. Timmermans, Th.A. Rijken, J.J. de Swart, Phys. Rev. C52 (1995) 1145.

[31] R.B. Wiringa and V.G.J. Stoks, private communication.

[32] D. Hübner, private communication.

[33] V.G.J. Stoks, to appear in Phys. Rev. C.

[34] J. Carlson and R. Schiavilla, Few-Body Systems Suppl. 7 (1994) 349.

[35] S. Deister, M.F. Gari, W. Krümpelmann, M. Mahlke, Few-Body Systems 10 (1991) 1;
    D. Plümper, J. Flender, M.F. Gari, Phys. Rev. C49 (1994) 2370;
    J.A. Eden, M.F. Gari, Phys.Rev. C53 (1996) 1510.

[36] W.N. Polyzou, W. Glöckle, Few-Body Systems 9 (1990) 97.

[37] J.L. Friar, Phys. Rev. C22, (1980) 796.

[38] J.L. Friar and S.A. Coon, Phys. Rev. C49 (1994) 1272.

[39] The most familiar version of this statement is contained in: The Sign of Four, by Sir
    Arthur Conan Doyle.
| $E_{lab}$ [MeV] | change | $A_2$ | $\Delta$ | $\%$ | change | $A_2$ | $\Delta$ | $\%$ |
|----------------|--------|-------|--------|-----|--------|-------|--------|-----|
| 1              | $1.1 \times V_C$ | .00023024 | .00000064 | 2.85 | $0.9 \times V_C$ | .00021773 | -.00000061 | -2.73 |
| 10             |        | .012780 | .000297 | 2.38 |        | .012198 | -.000285 | -2.28 |
| 100            |        | .42389 | -.00555 | -1.29 |        | .43456 | .00512 | 1.19 |
| 1              | $1.1 \times V_T$ | .00019673 | -.00002712 | -12.12 | $0.9 \times V_T$ | .00024655 | .00002270 | 10.14 |
| 10             |        | .011311 | -.001172 | -9.39 |        | .013454 | .000971 | 7.78 |
| 100            |        | .42977 | .00033 | 0.08 |        | .42889 | -.00055 | -0.13 |
| 1              | $1.1 \times V_{ls}$ | .00026198 | .00003813 | 17.03 | $0.9 \times V_{ls}$ | .00018713 | -.00003672 | -16.40 |
| 10             |        | .014207 | .001724 | 13.81 |        | .010834 | -.001649 | -13.21 |
| 100            |        | .42432 | -.00512 | -1.19 |        | .42641 | -.00303 | -0.71 |
| 1              | $1.1 \times V_{l2}$ | .00021374 | -.00001011 | -4.52 | $0.9 \times V_{l2}$ | .00023491 | .00001106 | 4.94 |
| 10             |        | .012012 | -.000471 | -3.77 |        | .012999 | .000516 | 4.13 |
| 100            |        | .43212 | .00268 | 0.62 |        | .42585 | -.00359 | -0.84 |
| 1              | $1.1 \times V_{(ls)}^2$ | .00022467 | .00000082 | 0.37 | $0.9 \times V_{(ls)}^2$ | .00022302 | -.00000083 | -0.37 |
| 10             |        | .012501 | .000018 | 0.14 |        | .012462 | -.000021 | -0.17 |
| 100            |        | .43312 | .00368 | 0.86 |        | .42558 | -.00386 | -0.90 |

**TABLE I.** Effects of changes of ±10% in the various parts of the NN potential in the $^3P_J$ partial waves on the maximum of the 2-body nucleon analyzing power $A_2$. $\Delta$ 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 .00022385 at 1 MeV, .012483 at 10 MeV and .42944 at 100 MeV.
| $E_{lab}$ [MeV] | change | $A_y$ | $\Delta$ | % | change | $A_y$ | $\Delta$ | % |
|-----------------|--------|-------|---------|---|--------|-------|---------|---|
| 3               | $1.1 \times V_C$ | .04685 | .00167 | 3.70 | $0.9 \times V_C$ | .04360 | $-0.00158$ | $-3.50$ |
| 3               | $1.1 \times V_T$ | .04242 | $-0.00276$ | $-6.11$ | $0.9 \times V_T$ | .04716 | $0.00198$ | $4.38$ |
| 3               | $1.1 \times V_{ls}$ | .05254 | .00736 | 16.29 | $0.9 \times V_{ls}$ | .03829 | $-0.00689$ | $-15.25$ |
| 3               | $1.1 \times V_{l2}$ | .04287 | $-0.00231$ | $-5.11$ | $0.9 \times V_{l2}$ | .04775 | $0.00257$ | $5.69$ |
| 3               | $1.1 \times V_{(ls)^2}$ | .04482 | $-0.0036$ | $-0.80$ | $0.9 \times V_{(ls)^2}$ | .04555 | $0.0037$ | $0.82$ |

**TABLE II.** Same as Table I, but for the 3-body nucleon analyzing power $A_y$. The value of the maximum of $A_y$ at 3 MeV for the original AV18 is .04518.

| $\delta_C$ | $\delta_{l2}$ | $\delta_{(ls)^2}$ | $\delta_T$ | $\delta_{ls}$ | $\delta_{A_2}$ | $\delta_{A_y}$ |
|-----------|--------------|-----------------|-----------|-------------|---------------|---------------|
| 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            |

**TABLE III.** Possible solutions of Eqs. (2) and (3). The effects of the changes to $A_2$ and $A_y$ are given as well.
| $E_{lab}$ [MeV] | change | $A_2$ | $\Delta$ | % | change | $A_2$ | $\Delta$ | % |
|----------------|--------|-------|---------|---|--------|-------|---------|---|
| 1              | 1.1 * $V_{SR}^C$ | .00023159 | .00000774 | 3.46 | 1.1 * $V_{OPEP}^C$ | .00022256 | -.00000129 | -.058 |
| 10             | .012856 | .000373 | 2.99 | | .012410 | -.000073 | -.058 | |
| 100            | .42174  | -.00770 | -1.79 | | .43150  | .00206  | 0.48 | |

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

| $E_{lab}$ [MeV] | change | $A_y$ | $\Delta$ | % | change | $A_y$ | $\Delta$ | % |
|----------------|--------|-------|---------|---|--------|-------|---------|---|
| 1              | 1.1 * $V_{SR}^T$ | .00022601 | .0000216 | 0.96 | 1.1 * $V_{OPEP}^T$ | .00019419 | -.00002966 | -13.25 |
| 10             | .012591 | .000108 | 0.87 | | .011183 | -.001300 | -10.41 | |
| 100            | .42943  | -.00001 | 0 | | .42986  | .00042  | 0.10 | |

TABLE V. Same as Table II, but for the short-range and OPEP parts of the central and tensor force separately.
\begin{table}
\centering
\begin{tabular}{|c|c|c|c|c|c|c|c|c|}
\hline
phase & change & phase & Δ & % & change & phase & Δ & % \\
\hline
\textsuperscript{3}P\textsubscript{0} & .11 * \textit{V}_C & .17980 & -.00065 & -0.36 & .9 * \textit{V}_C & .18111 & .00066 & 0.37 \\
\textsuperscript{3}P\textsubscript{1} & -.10831 & -.00094 & 0.88 & -.10644 & .00093 & -0.87 \\
\textsuperscript{3}P\textsubscript{2} & .022130 & -.00040 & -1.77 & .022951 & .00042 & 1.87 \\
\hline
\textsuperscript{3}P\textsubscript{0} & .11 * \textit{V}_T & .20495 & .02450 & 13.58 & .9 * \textit{V}_T & .15680 & -0.02365 & -13.11 \\
\textsuperscript{3}P\textsubscript{1} & -.11575 & -.00838 & 7.80 & -.09891 & .00846 & -7.88 \\
\textsuperscript{3}P\textsubscript{2} & .025649 & .00312 & 13.85 & .019527 & -.00300 & -13.33 \\
\hline
\textsuperscript{3}P\textsubscript{0} & .11 * \textit{V}_l & .17883 & -.00162 & -0.90 & .9 * \textit{V}_l & .18217 & .00172 & 0.95 \\
\textsuperscript{3}P\textsubscript{1} & -.10768 & -.00031 & 0.29 & -.10706 & .00031 & -0.29 \\
\textsuperscript{3}P\textsubscript{2} & .024190 & .00166 & 7.37 & .021003 & -.00153 & -6.77 \\
\hline
\textsuperscript{3}P\textsubscript{0} & .11 * \textit{V}_l^2 & .18042 & -.00003 & -0.02 & .9 * \textit{V}_l^2 & .18049 & .00004 & 0.02 \\
\textsuperscript{3}P\textsubscript{1} & -.10735 & .00002 & -0.02 & -.10740 & -.00003 & 0.03 \\
\textsuperscript{3}P\textsubscript{2} & .021871 & -.00066 & -2.92 & .023253 & .00072 & 3.21 \\
\hline
\textsuperscript{3}P\textsubscript{0} & .11 * \textit{V}_{(ls)}^2 & .17921 & -.00124 & -0.69 & .9 * \textit{V}_{(ls)}^2 & .18173 & .00128 & 0.71 \\
\textsuperscript{3}P\textsubscript{1} & -.10751 & -.00014 & 0.13 & -.10724 & .00013 & -0.12 \\
\textsuperscript{3}P\textsubscript{2} & .022001 & -.00053 & -2.34 & .023070 & .00054 & 2.40 \\
\hline
\end{tabular}
\caption{Same as Table I, but for the np \textsuperscript{3}P\textsubscript{J} phases at \textit{E}_{lab} = 1\,\text{MeV}. The values for the original AV18 are .18045 for \textsuperscript{3}P\textsubscript{0}, -.10737 for \textsuperscript{3}P\textsubscript{1}, and .022529 for \textsuperscript{3}P\textsubscript{2}.}
\end{table}
\begin{table}
\centering
\begin{tabular}{ccccccccc}
\hline
$E_{lab}$ & $^3P_0$ & & $^3P_1$ & & $^3P_2$ & & $\epsilon_2$ & \hfill $^3F_2$ \\
& AV18 mod. & ach. & & AV18 mod. & ach. & & AV18 mod. & ach. & \hfill AV18 mod. & ach. \\
\hline
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 & -2.0 & 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 & -4.9 & 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 & -8.0 & 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 & -12.9 & 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 & -17.2 & 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 & -21.2 & 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 & -24.938 & -24.921 & -24.9 & 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 & -28.5 & 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 & -31.8 & 16.69 & 16.686 & 16.646 & -0.2 & -1.88 & -1.879 & -1.786 & 5.2 & 0.14 & 0.137 & 0.062 & -21.0 \\
\hline
\end{tabular}
\caption{Phase shift parameters of the original AV18 potential [14] compared to phases which were modified in the spirit of [6] in order to give an increased prediction for $A_y$. Also given are the phases which could be achieved by the potential refitted to the modified phases [31]. 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.}
\end{table}
TABLE VIII. CIB effects in degrees for the preliminary CD-Bonn99 potential [27] and from [24] compared to CIB in the modified Bonn B of [4]. $E_{lab} = 10$ MeV refers to CD-Bonn99 and [24], and 12 MeV to the modified Bonn B. The CIB effect is defined as $\delta_{CIB} \equiv \delta_{np} - 0.5 \times (\delta_{nn} + \delta_{pp})$.

| $E_{lab}$ [MeV] | $3P_0$ | $3P_1$ | $3P_2$ |
|-----------------|--------|--------|--------|
|                 | $\delta_{CDB99}$ | $\delta_{mod. BB}$ | $\delta_{CDB99}$ | $\delta_{mod. BB}$ | $\delta_{CDB99}$ | $\delta_{mod. BB}$ |
| 5               | -.237  | -.250  | .515   | .112   | .117   | 0.    | -.011  | -.011  | 0.   |
| 10(12)          | -.466  | -.492  | 1.405  | .198   | .206   | -.015 | -.032  | -.032  | .005 |
| 25              | -.822  | -.858  | 2.575  | .314   | .322   | -.025 | -.103  | -.101  | .015 |
| 50              | -.943  | -.960  | 3.275  | .368   | .366   | -.035 | -.188  | -.184  | .045 |

TABLE IX. CSB effects in degrees for the preliminary CD-Bonn99 potential [27] and from [24] compared to CSB in the modified Bonn B of [4]. $E_{lab} = 10$ MeV refers to CD-Bonn99 and [24], and 12 MeV to the modified Bonn B. The CSB effect is defined as $\delta_{CSB} \equiv \delta_{nn} - \delta_{pp}$.

| $E_{lab}$ [MeV] | $3P_0$ | $3P_1$ | $3P_2$ |
|-----------------|--------|--------|--------|
|                 | $\delta_{CDB99}$ | $\delta_{mod. BB}$ | $\delta_{CDB99}$ | $\delta_{mod. BB}$ | $\delta_{CDB99}$ | $\delta_{mod. BB}$ |
| 5               | .008   | .009   | -.23   | -.002  | -.002  | -.02  | .002   | .003   | 0.   |
| 10(12)          | .018   | .019   | -.63   | -.003  | -.002  | -.07  | .006   | .007   | .01  |
| 25              | .040   | .042   | -1.15  | -.001  | 0.     | -.13  | .022   | .025   | .03  |
| 50              | .056   | .057   | -1.49  | .006   | .010   | -.11  | .051   | .056   | .09  |
FIG. 1. The $^{3}P_0$ phase from the Nijmegen PSA [8]. The dashed line is the prediction for 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 3 parameters. The filled circles denote results of single energy analysis.
FIG. 2. The \( ^3P_0 \) phase shift divided by \( E^{3/2} \). The solid line denotes AV18, the dashed line AV18 with \( V_{T}^{SR} \) set to zero, while the dotted line is the difference between the dashed and solid lines.

FIG. 3. Same as Figure 2 but for \( ^3P_1 \).
FIG. 4. Same as Figure 2 but for $^3P_2$. 

$E_{lab}$ [MeV]