Tensor analyzing power A_{yy} for dp breakup in the symmetric constant relative energy configuration

H. Witała and J. Golak
Institut für Theoretische Physik II, Ruhr-Universität Bochum, D-44780 Bochum, Germany and Institute of Physics, Jagellonian University, PL-30059 Cracow, Poland

W. Glöckle, D. Hüber, and H. Kamada
Institut für Theoretische Physik II, Ruhr-Universität Bochum, D-44780 Bochum, Germany

W. Tornow
Department of Physics, Duke University, Durham, North Carolina 27708 and Triangle Universities Nuclear Laboratory, Duke Station, Durham, North Carolina 27708

E. J. Stephenson and D.A. Low*
Indiana University Cyclotron Facility, 2401 Milo B. Sampson Lane, Bloomington, Indiana 47408
(Received 23 January 1995)

The tensor analyzing power A_{yy} in the symmetric constant relative energy geometry for the dp breakup reaction has been calculated using solutions of the three-nucleon Faddeev equations based on the Argonne AV14, AV18, Bonn-B, Nijm78, Nijm93, NijmI, NijmII, and Paris potentials, as well as the Bonn-B potential in conjunction with the Tucson-Melbourne three-nucleon interaction. The comparison with recent dp data at E_d=94.5 MeV revealed a clear discrepancy in the region where the data exhibit a pronounced structure which is not present in the theoretical results.

PACS number(s): 21.45.+v, 24.10.−i, 25.10.+s

I. INTRODUCTION

The three-nucleon (3N) system has always been considered a testing ground for nuclear forces. This is especially true now due to the recent progress in treating the 3N continuum [1,2] in a numerically precise manner that allows one to calculate any 3N scattering observable with arbitrary NN interactions, even including three-nucleon forces (3NF's). Theoretical results achieved along this line demonstrate that the most simple choice of a nuclear Hamiltonian, namely, that composed of only NN forces without 3NF's, describes elastic Nd scattering observables well. These NN forces, however, have to be realistic and describe the NN data very well. As such, they are of course very complicated. Moreover, the description of 3N observables is stable with respect to replacing one NN interaction by another one, as long as they equally well describe the NN data [3]. This is a nontrivial statement, since the NN forces we have studied have different local and nonlocal properties, or softer or harder cores. In spite of large differences off-shell with regard to radial shapes and the balance between local and nonlocal components, the off-shell effects are not significant in the study of the 3N observables that have been investigated previously. If the potentials do not describe the NN data as well as the older of the so-called realistic forces (we have included two examples in this paper), different predictions for 3N observables might arise from their inadequate on-shell properties.

To the good description of elastic Nd scattering observables, there is essentially only one exception, the low energy nucleon analyzing power, where a significant discrepancy exists between the data and the most recent NN force predictions. This is an unsettled problem, which is presumably connected to the detailed properties of the ^3P_j NN force components [4]. This case is restricted to low energies; already above 30 MeV theory and data agree with each other.

The Nd breakup process is potentially even more interesting than elastic scattering. The final momenta of the outgoing nucleons are not integrated over the deuteron wave function, and in addition they can be chosen to some extent arbitrarily by concentrating on a specific kinematical configuration of the three outgoing nucleons. However, the existing database is still rather limited [5], especially in the case of spin observables, which can be both informative and stimulating [6,7].

The aim of this study is to compare theory with recent data for the tensor analyzing power A_{yy} of the $^1\mathrm{H}(\vec{d},pp)n$ reaction observed in the symmetric constant relative energy (SCRE) geometry at an incident deuteron energy of E_d= 94.5 MeV [6]. In this geometry all three nucleons are emitted in the c.m. frame at relative angles of 120° with equal kinetic energy, and both protons emerge symmetrically on either side of a plane defined by the beam axis and the outgoing neutron. Thus, the SCRE final state can be characterized by the outgoing neutron direction that makes an angle α with respect to the beam direction in the c.m. frame. The A_{yy} tensor analyzing power requires that the deuteron quan-

*Present address: Mallinckrodt Institute of Radiology, Department of Radiation Oncology, 510 S. Kingshighway, St. Louis, MO 63110.

0556-2813/95/52(6)/2906(8)/$06.00

tization axis lie in the plane defined by the beam and the outgoing neutron and be perpendicular to the beam direction.

The SCRE geometry was first suggested in Ref. [8] as a good candidate for studying small effects associated with off-shell properties of the NN interaction or three-body forces. In addition to Ref. [6] only one other measurement in the SCRE geometry was performed with polarized deuterons. However, this earlier measurement at $E_d=79.5$ MeV [9] was of poor statistical precision and covered only a limited angular region. The original theoretical analysis of the A_{yy} data of Ref. [6] revealed sensitivities to both the energy and the nucleon-nucleon potentials used in the calculations. In addition, large variations among three different types of calculations were observed [6]. None of the theoretical predictions presented in Ref. [6] could account for the A_{yy} data. However, there exist severe shortcomings in all three types of calculations. The first [10] was based on separable NN interactions which were obsolete, the second used a severely truncated EST representation of the Paris potential [11], and the third [12] used standard NN potentials (Reid [13], Bonn [14], and Paris [15]) to calculate only the S-wave scattering in the Faddeev formalism while the contributions of higher partial waves were treated only as a perturbation. As was shown in Ref. [16], such a perturbation approach is totally unjustified and misleading. In view of these deficiencies, a new theoretical analysis based on rigorous solutions of the 3N-continuum Faddeev equations with realistic NN interactions is required.

In Sec. II we briefly present the underlying theory. Section III is devoted to the theoretical results, their comparison with experimental data, and to a thorough discussion. In Sec. IV we summarize and conclude.

II. THEORY

The theoretical predictions presented in this work are based on solutions of the 3N Faddeev equation with different realistic NN interactions. In one case the Tucson-Melbourne 3NF [17] was included. The treatment of a 3NF in the 3N scattering formalism amounts to solving a set of coupled equations for two operators T and T_4 of the form

$$T=tP+tG_0T_4+tPG_0T,$$
$$T_4=(1+P)t_4+(1+P)t_4G_0T. \quad (1)$$

The two-body t-operator t is driven by the 2N interaction. G_0 is the free 3N propagator, P is the sum of a cyclic and an anticyclic permutation of three nucleons, and t_4 is generated by the three-nucleon interaction V_4 through the Lippmann-Schwinger-type equation:

$$t_4=V_4+V_4G_0t_4. \quad (2)$$

The operators T and T_4 determine the transition operator U_0 for the breakup process

$$U_0=(1+P)T+T_4. \quad (3)$$

Both operators T and T_4 are understood to act on the right on the incoming channel state ϕ composed of the deuteron wave function and a momentum eigenstate of the relative nucleon-deuteron motion. The breakup amplitude is then given by $\langle\phi_0|U_0|\phi\rangle$ where the state ϕ_0 represents the free motion of the three outgoing nucleons.

The iteration of Eq. (1) reveals the underlying physics of multiple scattering in terms of the corresponding pure 2N and genuine 3N transitions. Equation (1) is solved in a perturbation approach in powers of V_4. The various orders in V_4 are summed up by the Padé method. For general background information, details of the formalism, and the numerical treatment and performance we refer to Refs. [1,2,18,19].

We solved Eq. (1) with different NN interactions: Argonne AV14 [20], Argonne AV18 [21], Bonn-B [14], which is an OBE parametrization of the full Bonn potential, Nijm78 [22], Nijm93 [23], which is an updated version of the Nijmegen soft-core potential, the nonlocal Reid-like Nijmegen potential NijmI [23], its local version NijmII [23], and Paris [15]. In all calculations the well-established charge-independence breaking of the NN interaction in the ${}^1S_0$ state was treated exactly by allowing an admixture of total isospin $T=\frac{3}{2}$ [24] related to this particular partial wave state. This isospin violation requires the use of different NN interactions for the np and pp systems. In the case of the Argonne AV14 and Bonn-B potentials, which are fitted to the np ${}^1S_0$ scattering length, we took for the ${}^1S_0$ pp interaction a modified version of the Bonn-B potential which is fitted to the pp-scattering length [14]. For the Nijm78 and Paris potentials, which are adjusted to the pp ${}^1S_0$ scattering length, the np ${}^1\mathrm{S}_0$ interaction was taken from the Bonn-B potential. In the very recently updated NN potentials such as AV18, Nijm93, NijmI, and NijmII, the mixing of different types of NN forces is not necessary due to their inherent dependence on the charge of the NN system. In order to obtain essentially convergent results for A_{yy} at our relatively high energy, all partial wave states with two-nucleon total angular momenta $j\leqslant 3$ had to be taken into account. As has been checked using a Bonn-B calculation, the contribution of $j=4$ NN force components turned out to be negligible. In some cases, when we checked the sensitivities of A_{yy} to different NN force components, the restriction to $j\leqslant 2$ was made in order to save computer time.

In order to study the possible effect caused by a 3NF on A_{yy}, an additional calculation was made with the meson-theoretical Bonn-B potential and the 2π-exchange three-nucleon interaction in the form proposed by the Tucson-Melbourne (TM) Collaboration [17]. The 3NF effects are quite strongly dependent on the ill-determined value for the cutoff parameter Λ_π in the TM 3NF, generally becoming larger with increasing values of Λ_π [2]. Currently, we are only in the position to calculate the influence of the TM 3NF on 3N scattering and breakup observables for a certain range of "reasonable" Λ_π values. We took the recommended "standard" value for the cutoff parameter $\Lambda_\pi=5.8\mu$ ($\mu=139.6$ MeV) and, in addition, $\Lambda_\pi=4.55\mu$. The first value leads, together with the Bonn-B potential, to an overbinding of the triton by about 2 MeV. The second value corresponds to the situation where the Bonn-B potential together with the TM 3NF reproduces the experimental triton binding energy. Thus, the 3NF effects obtained in the latter case, while smaller, are expected to be more consistent with 3N bound-state properties. In the calculations both the 2N and the 3N forces were allowed to act in all partial wave

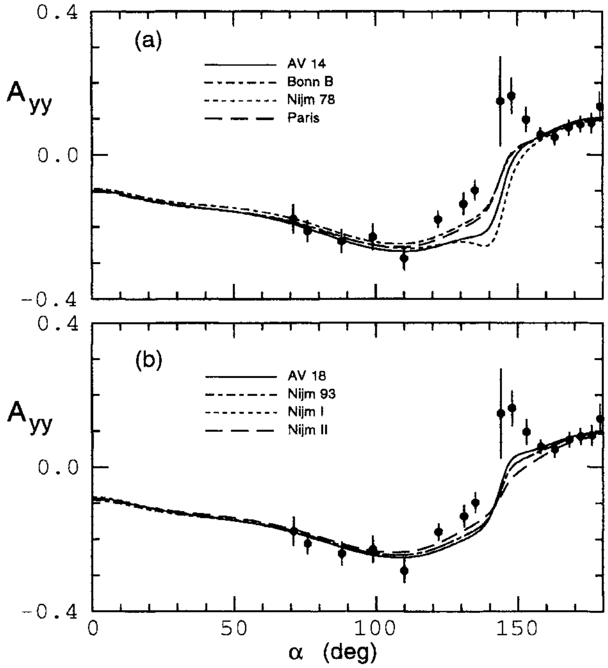

FIG. 1. Tensor analyzing power A_{yy} for the SCRE geometry in the ${}^1\mathrm{H}(\vec{d},pp)n$ reaction as a function of the c.m. angle α between the beam and outgoing neutron directions. The solid circles are experimental data of [6] taken at $E_d=94.5$ MeV. The solid, short-long-dashed, short-dashed, and long-dashed curves are the theoretical predictions obtained at $E_d=95$ MeV with (a) AV14, Bonn-B, Nijm78, and Paris potentials and (b) AV18, Nijm93, NijmI, and NijmII potentials, respectively. All $j\leqslant 3$ NN force components were taken into account.

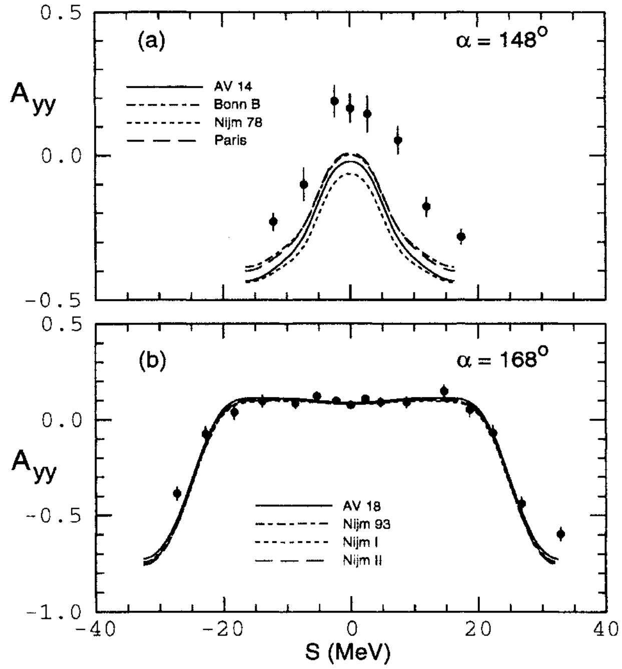

FIG. 2. Tensor analyzing power A_{yy} for the ${}^1\mathrm{H}(\vec{d},pp)n$ reaction as a function of the arclength S for (a) $\alpha=148°$ and (b) $\alpha=168°$. The solid circles are the experimental data of [6] taken at $E_d=94.5$ MeV. For the description of the curves see Fig. 1.

states with total two-body subsystem angular momenta $j\leqslant 2$. As indicated above, such a restriction does not lead to a completely converged result for A_{yy} at the energy of interest in the present work, due to some non-negligible contributions of $j=3$ NN force components. However, this treatment is sufficient in order to obtain information about 3NF effects.

III. COMPARISON OF EXPERIMENT WITH THEORY AND DISCUSSION

In Figs. 1(a) and 1(b) the measured values of the tensor analyzing power A_{yy} from Ref. [6] are compared to our theoretical predictions. In the angular regions of $\alpha\lesssim 110°$ and $\alpha\gtrsim 160°$ the different potentials give practically the same values for A_{yy} and follow nicely the data. However, for angles $110°\lesssim\alpha\lesssim 160°$ they begin to differ among themselves, with especially large deviations exhibited by the AV14 and Nijm78 potentials. In this angular region substantial discrepancies can also be clearly seen between all theoretical calculations and the data. While the A_{yy} data exhibit a strong maximum at angles $\alpha\approx 145°$, no such structure is visible in any of the theoretical predictions presented in Fig. 1.

In order to emphasize the situation even more clearly we present in Figs. 2(a) and 2(b) the comparison of the theory with the data along the full laboratory-frame kinematic energy locus allowed by the limits of the detector. Within these physical limits, a range of energies are accepted for the two-proton final state. Only one position along this locus corresponds to the coplanar, equal-angle SCRE final geometry and the neutron angle α. The horizontal variable S (MeV) measures the energy along this locus from the SCRE point at $S=0$. For the locus associated with $\alpha=148°$ [Fig. 2(a)], which corresponds to the maximum of the discrepancy oberved in Fig. 1, all theoretical predictions for A_{yy} differ drastically from the measured values at all values of S. Thus the SCRE point at $S=0$ is not statistically anomalous. The results evaluated for AV18, Nijm93, NijmI, and NijmII lie within the range of values shown for the somewhat older potentials in Fig. 2(a). In particular, the AV18 prediction nearly coincides with the Paris result. In marked contrast is the case for $\alpha=168°$ [Fig. 2(b)] where a very good description is obtained for almost all values of S. Shown for each plot are only 4 of the 8 calculations available. Calculations not shown lie close to those in Fig. 2, as can be seen at the SCRE point in Fig. 1. In the region of the maximum near $\alpha=148°$, the loci and energy cuts required for extracting the SCRE analyzing powers are well defined (see Ref. [6]). Between $\alpha=120°$ and 140° the compact size of the locus in comparison with the experimental energy resolution may have permitted some contamination from non-SCRE data and shifted the A_{yy} tensor analyzing powers to more positive values in a systematic way [25].

In order to find out if contributions of NN force components with higher angular momenta can cure the above discrepancy we present in Fig. 3 a convergence study of theoretical predictions for A_{yy} obtained with the Bonn-B potential at $E_d=99.2$ MeV, with an increasing number of

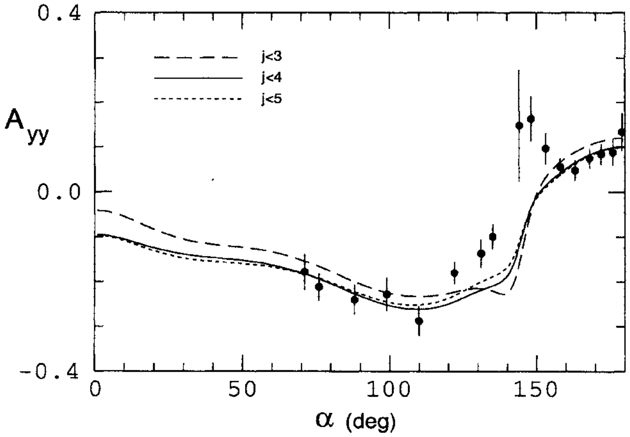

FIG. 3. Same data as in Fig. 1. The long-dashed, solid, and short-dashed curves are the theoretical predictions obtained at E_d=99.2 MeV with the Bonn-B potential taking into account all *NN* force components with $j\leq 2$, $j\leq 3$, and $j\leq 4$, respectively.

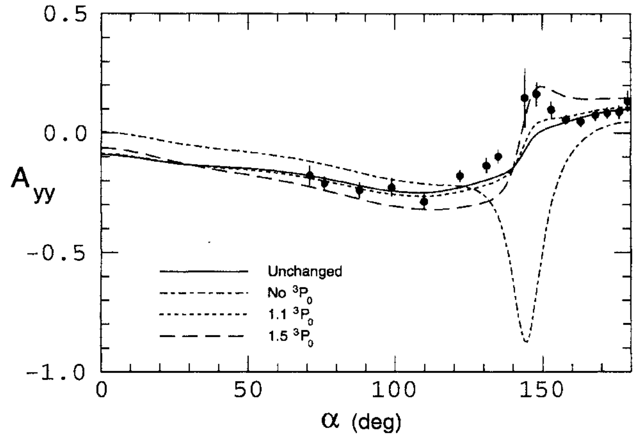

FIG. 4. Same data as in Fig. 1. The solid curve is the theoretical prediction obtained at E_d=95 MeV using the Bonn-B potential and taking all $j\leq 3$ force components into account. Switching off the $^3P_0$ force component "statically" (for explanation see text) results in the short-long-dashed curve. Changing the $^3P_0$ force component "dynamically" by 10% and 50% ($\lambda = 1.1$ and $\lambda = 1.5$, respectively; see text for explanation), and keeping all other force components as in Bonn-B ($j\leq 3$), leads to the short-dashed and long-dashed curves, respectively.

partial waves states. As can be seen, a restriction to states with total two-body angular momenta $j\leq 2$ is not justified. In the angular region around $\alpha\approx 130°$ even $j=4$ *NN* force components contribute slightly and they can change A_{yy} up to about 10%, however, without affecting the large discrepancy observed in the region of the A_{yy} maximum.

In order to locate the source of the large discrepancy between data and calculations near $\alpha\approx 145°$ we checked the sensitivity of A_{yy} to particular *NN* force components. Practically, this was accomplished using the full set of Bonn-B potential ($j\leq 3$) Faddeev amplitudes by switching off all 3N partial waves that contained the particular *NN* partial wave component corresponding to the *NN* force component under investigation. Using such a "static" approach we found that the angular region of the A_{yy} maximum is sensitive predominantly to the $^3P_0$, and to a smaller extent also to the $^1P_1$, $^3S_1-{}^3D_1$, $^1D_2$, $^3D_2$, and $^3P_2-{}^3F_2$ *NN* force components. In Fig. 4 we present, as an example, the case where we switch off the $^3P_0$ force component, which leads to a deep minimum in A_{yy} at $\alpha\approx 145°$.

The "static" switch-off procedure used here is a rather drastic technique and sometimes can give misleading results. A more realistic procedure is to induce a change in the particular *NN* force component and then to use the modified force "dynamically" in the process required to solve the Faddeev equations. In order to see if such dynamical changes of particular *NN* force components could create a maximum in the tensor analyzing power A_{yy} we modified the *NN* forces listed above by multiplying the potential matrix elements $V_{ll'}(p,p')$ by an energy independent factor λ. However, allowing for even unrealistic changes of the Bonn-B potential as large as $\pm 30\%$ (corresponding to $\lambda = 1.3$ and $\lambda = 0.7$, respectively), it turns out to be impossible to produce any significant maximum in the angular region around $\alpha\approx 145°$. As an example, Fig. 4 illustrates the case of the $^3P_0$ force component. Only after allowing for totally unrealistic modifications of this force component by as much as 50% (corresponding to $\lambda = 1.5$) a small maximum in A_{yy} was produced. Unfortunately, this peak is shifted to higher values of α. Simultaneously, such a change totally destroys the previous good agreement between theory and data for smaller and larger angles of α. In summary, from our sensitivity studies we conclude that it is not possible to produce any significant maximum in A_{yy} without drastic modifications to the *NN* interaction which in turn destroy the rather good agreement in the angular regions where the unchanged theory described the data very well.

Another candidate for explaining the existing discrepancy are three-nucleon force effects. However, comparing the predictions for A_{yy} obtained with the Bonn-B potential in conjunction with the TM 3NF using a cut-off parameter $\Lambda_\pi = 5.8\mu$ shows only a small shift with respect to the pure Bonn-B potential result (see Fig. 5), without any indication of a possible maximum in A_{yy}. The value $\Lambda_\pi = 4.55\mu$ drastically reduces the TM 3NF effects. As can be seen from Fig. 5, they are practically negligible. Unless the TM 3NF provides totally wrong dynamics for the interaction of three nucleons, 3NF effects cannot explain the present discrepancy for A_{yy}.

A remaining possibility for explaining the observed discrepancy are Coulomb force effects. All the calculations presented here take into account only the nuclear part of the *NN* potential, totally neglecting the Coulomb interaction between the two protons. Until now, no rigorous solutions of the 3N continuum above the deuteron breakup threshold have been presented with the Coulomb interaction included exactly. Only very recently a first calculation based on a simple, rank-one *S*-wave *NN* interaction has appeared [26]. However, with such simplified *NN* dynamics, practically nothing can be concluded about the Coulomb force effects for the tensor analyzing power A_{yy}, which depends significantly on higher *NN* force components. One can only very roughly and qualitatively estimate the importance of Coulomb force ef-

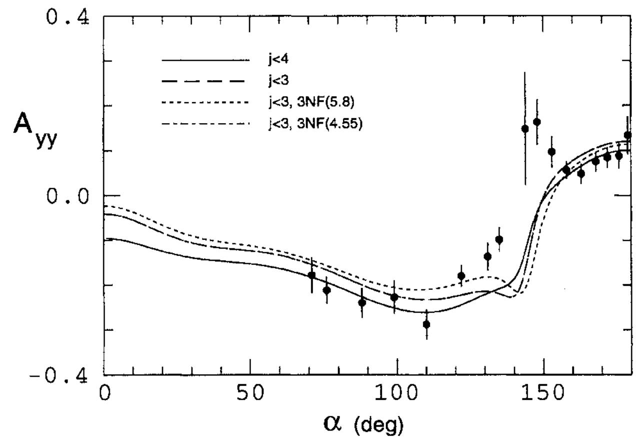

FIG. 5. Same data as in Fig. 1. The solid and long-dashed curves are the theoretical predictions obtained at $E_d=99.2$ MeV with the Bonn-B potential taking into account all $j\leqslant 3$ and $j\leqslant 2$ NN force components, respectively. The short-dashed and short-long-dashed (which practically overlaps the long-dashed) curves result when in addition to the Bonn-B potential ($j\leqslant 2$) the TM 3NF is included with cut off parameters of $\Lambda_\pi=5.8\mu$ and $\Lambda_\pi=4.55\mu$, respectively.

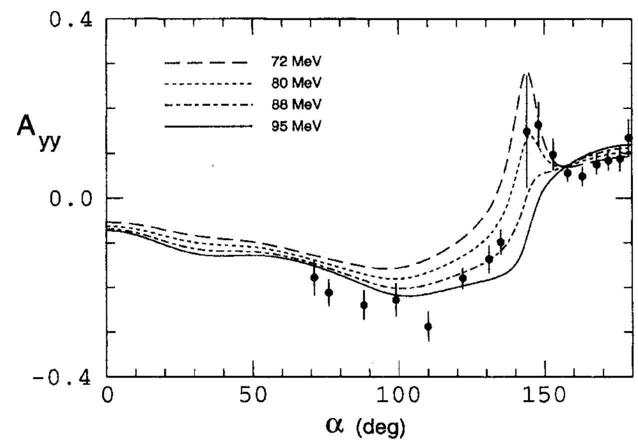

FIG. 6. Same data as in Fig. 1. The long-dashed, short-dashed, short-long-dashed, and solid curves are the theoretical predictions obtained with the Bonn-B potential ($j\leqslant 2$) at $E_d=72$, 80, 88, and 95 MeV, respectively.

fects by studying the energy dependence of the tensor analyzing power A_{yy} and then applying the "slowed-down" hypothesis presented in Ref. [27]. According to this hypothesis the incoming proton is slowed down in the Coulomb field of the deuteron and this leads to the fact that the breakup process takes place at an effectively smaller energy. In Fig. 6 we present the predictions for A_{yy} obtained at four incident energies ranging from $E_d=72$ MeV to $E_d=95$ MeV. It is very astonishing that the calculation with $E_d=80$ MeV brings the Bonn-B theory much closer to the data. The curves presented in Fig. 6 correspond to $j\leqslant 2$. The associated nearly convergent results obtained at 80 MeV with $j\leqslant 3$ using different NN interactions, in particular Bonn-B, are presented in Fig. 7. A simple estimate in the framework of the slowed-down hypothesis predicts an expected shift in the incoming energy of $\Delta E_d\approx -0.8$ to -1.6 MeV [27]. This result is far too small to resort to Coulomb force effects in order to explain the nice agreement between theoretical calculations at $E_d=80$ MeV using the Bonn-B and Paris potentials and experimental data obtained at $E_d=95$ MeV. A theoretical study of the continuous formation of the A_{yy} maximum with decreasing incoming deuteron energy suggests that measurements performed at lower energies are expected to be very important in explaining the present disagreement.

An interesting point seen in Fig. 1 is the fact that the AV18, Bonn-B, Nijm93, NijmI, NijmII, and Paris potential predictions are very similar for all values of α. This set of potential model predictions differs most in the region of the A_{yy} maximum from the Nijm78 potential and, to a smaller degree, also from the AV14 potential prediction. Among all the NN force components to which the tensor analyzing power A_{yy} is mainly sensitive at the energies studied in the present work, the largest on-shell difference exists for the phase shift $\delta_{^1P_1}$ and the mixing parameter ϵ_1 between the Nijm78 potential and the set of potentials referred to above. Both quantities are shown in Figs. 8 and 9. The phase shift $\delta_{^1P_1}$ is practically the same for the Bonn-B and the Paris potentials, but differs somewhat from the nearly identical values found for the AV14, AV18, Nijm93, NijmI, and NijmII potentials. The $\delta_{^1P_1}$ values of the Nijm78 potential are considerably less negative than the values for all other potentials. Also, the values for the mixing parameter ϵ_1 of the Nijm78 potential differ clearly from those of the other potentials. This observation implies that the differences between the values for A_{yy} obtained with the Nijm78 potential and those calculated from the other potentials could be a result of different $^1P_1$ and $^3S_1-^3D_1$ force components. This conjecture is supported by Fig. 10. Here, the prediction of the Nijm78 potential practically overlaps in the region of the A_{yy} maximum with the result based on a modified Bonn-B potential where the original Bonn-B $^1P_1$ and $^3S_1-^3D_1$ forces were replaced by those of the Nijm78 interaction. Similarly, when the Bonn-B $^1P_1$ and $^3S_1-^3D_1$ forces were replaced by those of the AV14 potential, the full AV14 prediction was practically reproduced. These exercises show that the $^1P_1$ and $^3S_1-^3D_1$ force components of the Nijm78

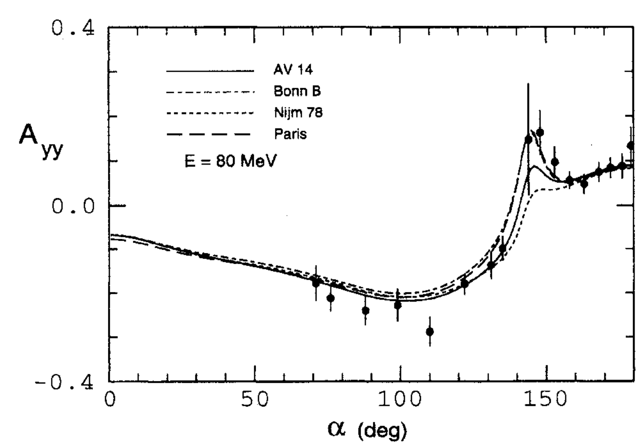

FIG. 7. Same data as in Fig. 1, but with theoretical predictions obtained at $E_d=80$ MeV.

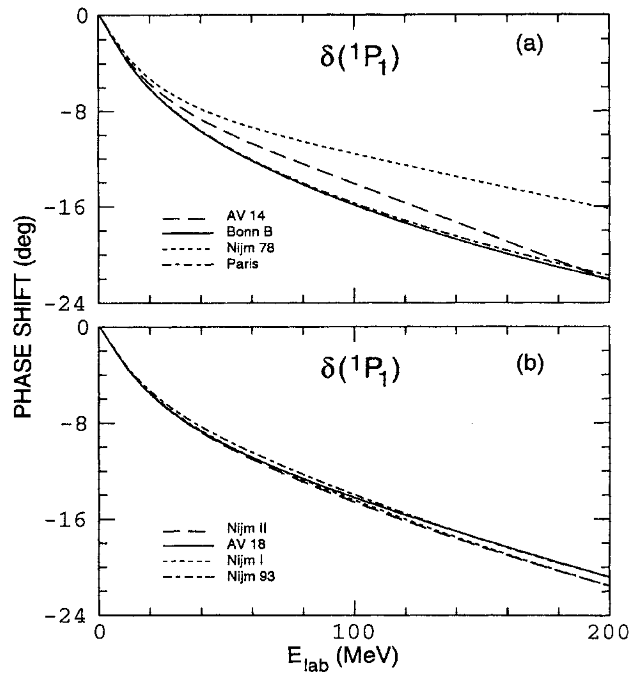

FIG. 8. The energy dependence of the phase shift $\delta_{^1P_1}$. The long-dashed, solid, short-dashed, and short-long-dashed curves correspond to the (a) AV14, Bonn-B, Nijm78, and Paris potentials and (b) NijmII, AV18, NijmI, and Nijm93 potentials, respectively.

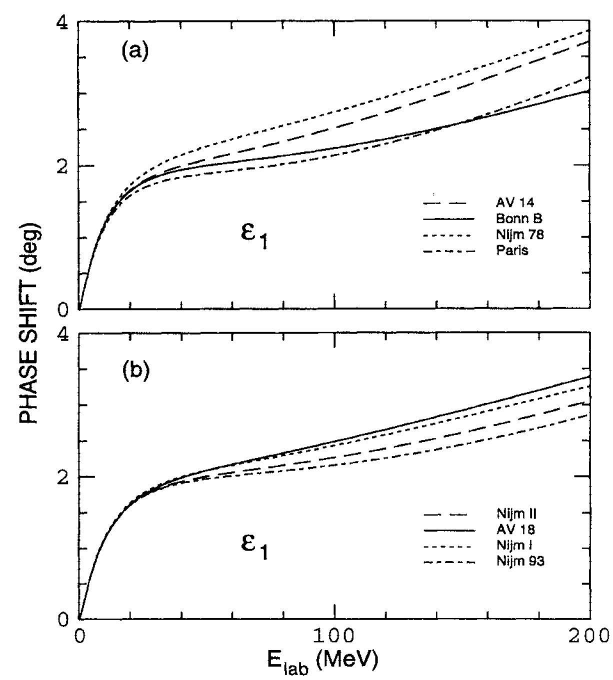

FIG. 9. The energy dependence of the mixing parameter ϵ_1. For the description of the curves see Fig. 8.

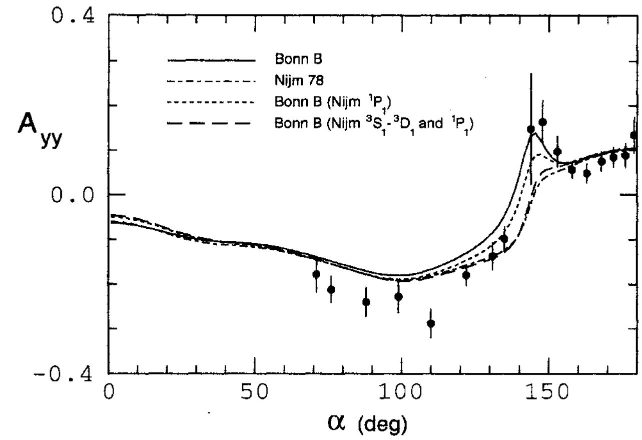

FIG. 10. Same data as in Fig. 1. The solid and short-long-dashed curves are the theoretical predictions obtained at $E_d = 80$ MeV with the Bonn-B and Nijm78 potentials taking into account all $j \leq 2$ force components. The short-dashed curve results when, in the Bonn-B calculation, the $^1P_1$ force is replaced by that of the Nijm78 potential. The long-dashed curve represents the prediction when, in the Bonn-B calculation, the $^1P_1$ and $^3S_1-{}^3D_1$ forces are replaced by those of the Nijm78 potential.

potential are responsible for the low values of A_{yy} found in Fig. 1. This appears to be connected to the different on-shell properties of the Nijm78 potential in these force components in relation to the other NN forces. On the other hand, the fact that AV14 and AV18 with essentially equal on-shell properties for $^1P_1$ and $^3S_1-{}^3D_1$ forces also lead to different A_{yy} predictions indicates that other NN force properties influence that observable. However, we would not like to point here to off-shell effects, since AV14 and AV18 are not strictly phase equivalent and, for instance, have slightly different ^3P_j NN phases. We have included the predictions of the older potentials, Nijm78 and AV14, only to express a warning that predictions of 3N observables using potentials that do not describe NN data with very high accuracy have to be taken with great caution. Even among the most modern NN forces, AV18, NijmI, and NijmII, which reproduce NN data with a reduced chi square close to one, do not have phases that agree fully. For AV18, some large phases deviate by as much as 2–4 % from those of the Nijmegen potentials. (For the very small phases, the percentage deviations are even larger.) Nevertheless, their predictions for A_{yy} agree more closely among themselves than do the predictions from the older group of potentials (whose reduced χ^2 for NN data exceeds two). The spread of the predictions around $\alpha = 150°$ [see Fig. 1(b)] for even the most modern potentials should not be overemphasized since these angles correspond to the smallest cross sections [6] and have to be sensitive to the details of the forces. In any case, the different NN force predictions shown in Fig. 1 in the region of the experimental maximum indicate that A_{yy} is dynamically interesting and should be pursued experimentally with higher precision in the future.

IV. SUMMARY AND CONCLUSIONS

A recent measurement of the tensor analyzing power A_{yy} in the dp breakup process performed with polarized incident deuterons of energy $E_d = 94.5$ MeV in the symmetric constant relative energy geometry has been analyzed. The data were compared to theoretical predictions based on solutions of the 3N Faddeev equations with different realistic NN interactions: AV14, AV18, Bonn-B, Nijm78, Nijm93, NijmI, NijmII, and Paris. All potentials describe the data very well for the SCRE configurations corresponding to values for the angle (α) between the outgoing neutron and the incident beam direction of $\alpha \lesssim 110°$ and $\alpha \gtrsim 160°$. In the angular region $110° \lesssim \alpha \lesssim 160°$ a large discrepancy was found between the data and all theoretical predictions. None of the potentials used can reproduce the distinct maximum seen in the data in this angular region. Sensitivity studies using modified NN force components revealed that even drastic, totally unrealistic changes of particular NN force components cannot remove this discrepancy. Also, possible 3NF effects cannot be made responsible for the disagreement. By adding the Tucson-Melbourne 3NF, generated with two different cut-off parameters to the Bonn-B potential, only insignificant changes in A_{yy} were found in comparison to the pure Bonn-B potential prediction. The effect amounts to a slight shift with respect to the pure Bonn-B result without creating any maximum in A_{yy}. Unless the dynamics of the three nucleon interaction as given by the TM 3NF are totally wrong, three nucleon force effects cannot explain the failure of pure NN interactions to describe the A_{yy} data studied in the present work.

The Coulomb interaction between the two protons, which was totally neglected in our calculations, is not expected to account for the observed disagreement. In view of the present lack of 3N breakup calculations with both realistic NN interactions and an exact treatment of the Coulomb force, we performed only a very qualitative estimate of possible Coulomb force effects on A_{yy} using a "slowed-down" hypothesis. The estimated shift of the incoming deuteron energy is $\Delta E_d \approx -0.8$ to -1.6 MeV. Suprisingly, we found that lowering the incoming deuteron energy to $E_d = 80$ MeV resulted in a good description of the present A_{yy} data using the AV18, Bonn-B, Nijm93, NijmI, NijmII, and Paris potentials. However, this energy difference of 14.5 MeV is much too large to make the Coulomb interaction of the two protons responsible for the present disagreement between data and theory.

The deuteron laboratory energy of 94.5 MeV corresponds to a nucleon laboratory energy of 47 MeV. This is rather low and we therefore do not expect relativistic effects to play a significant role. Many other observables in elastic scattering and the breakup process agree very well with theory even at nucleon laboratory energies as high as 65 MeV [3].

The effects of possible Δ admixtures are unknown for 3N scattering, except for the specific 3NF effect of the TM force, which contains an intermediate Δ part. The whole effect turned out to be insignificant for this case.

In view of these studies, it seems to be impossible to describe the present A_{yy} data using realistic NN interactions and present-day three nucleon forces. Also, it seems rather unlikely that an exact treatment of the Coulomb interaction could account for such a substantial discrepancy. Since the calculations performed at considerably lower energy describe the present data well, it would be interesting and very helpful to have high accuracy A_{yy} data available at lower energies in order to solve the present puzzle.

We showed that in the region of the A_{yy} maximum, where discrepancies between the theory and the data have been observed, the very recently updated NN potentials, AV18, Nijm93, NijmI, and NijmII with low reduced χ^2 values for reproducing the NN data, give nearly identical results (except where the cross section is small), while the older forces, AV14 and Nijm78, deviate from them. For Nijm78, this is very likely caused just by the different on-shell properties in the $^1S_1$ and $^3S_1-^3D_1$ states. For AV14 we did not carry through a corresponding study, but it has on-shell differences with AV18, in particular in the ^3P_j forces.

The discrepancy with the most modern four NN potentials is an interesting fact that justifies more experimental efforts to determine precisely values for A_{yy} in the region of the maximum at this and neighboring energies.

ACKNOWLEDGMENTS

This work was supported by the Maria Skłodowska-Curie II FUND under Grant No. MEN/NSF-94-161, the EC under Grant No. CI1*-CT91-0894, the U.S. Department of Energy, Office of High Energy and Nuclear Physics, under Grant No. DEFG05-91-ER40619, the Deutsche Forschungsgemeinschaft and the U.S. National Science Foundation. The numerical calculations have been performed on the CRAY Y-MP of the Höchstleistungsrechenzentrum in Jülich, Germany, and on the CRAY Y-MP of the North Carolina Supercomputing Center at Research Triangle Park, North Carolina.

[1] H. Witała, Th. Cornelius, and W. Glöckle, Few-Body Systems **3**, 1 (1988).
[2] D. Hüber, H. Witała, and W. Glöckle, Few-Body Systems **14**, 171 (1993).
[3] W. Glöckle, H. Witała, H. Kamada, D. Hüber, and J. Golak, in *Proceedings of the 14th International IUPAP Conference on Few Body Problems in Physics*, Williamsburg, Virginia, 1994, AIP Conf. Proc. No. 334 (AIP, New York, 1995), p. 45; and references therein.
[4] H. Witała and W. Glöckle, Nucl. Phys. **A528**, 48 (1991).
[5] M. Allet *et al.*, Phys. Rev. C **50**, 602 (1994).
[6] D. A. Low, E. J. Stephenson, C. Olmer, A. K. Opper, B. K. Park, P. Schwandt, and S. W. Wissink, Phys. Rev. C **44**, 2276 (1991).
[7] J. Jourdan *et al.* (unpublished).
[8] M. Jain, J. G. Rogers, and D. P. Saylor, Phys. Rev. Lett. **31**, 838 (1973).
[9] P. Schwandt, W. W. Jacobs, H. O. Meyer, E. J. Stephenson, J. Q. Yang, R. E. Brown, N. Jarmie, P. Doleschal, and W. T. H. van Oers, Indiana University Cyclotron Facility Scientific and Technical Report, 1983, p. 61.
[10] P. Doleschall, W. Grüebler, V. König, P. Schmelzbach, F. Sperisen, and B. Jenny, Nucl. Phys. **A380**, 72 (1982).
[11] J. Haidenbauer and W. Plessas, Phys. Rev. C **30**, 1822 (1984).

[12] C. Stolk and J. A. Tjon, Nucl. Phys. **A295**, 384 (1978).
[13] R. V. Reid, Jr., Ann. Phys. (N.Y.) **50**, 411 (1968).
[14] R. Machleidt, Adv. Nucl. Phys. **19**, 189 (1989).
[15] M. Lacombe, B. Loiseau, J. M. Richard, R. Vinh Mau, J. Côté, P. Pirés, and R. de Tourreil, Phys. Rev. C **21**, 861 (1980).
[16] H. Witała, W. Glöckle, and T. Cornelius, Nucl. Phys. **A491**, 157 (1989).
[17] S. A. Coon, M. D. Scadron, P. C. McNamee, B. R. Barrett, D. W. E. Blatt, and B. H. J. McKellar, Nucl. Phys. **A317**, 242 (1979); S.A. Coon and W. Glöckle, Phys. Rev. C **23**, 1790 (1981).
[18] W. Glöckle, *The Quantum-Mechanical Few-Body Problem* (Springer, Berlin, 1983).
[19] W. Glöckle, *Lecture Notes in Physics* (Springer, Berlin, 1986), Vol. 273, p. 3.
[20] R. B. Wiringa, R. A. Smith, and T. L. Ainsworth, Phys. Rev. C **29**, 1207 (1984).
[21] R. B. Wiringa (private communication).
[22] M. M. Nagels, T. A. Rijken, and J. J. de Swart, Phys. Rev. D **17**, 768 (1978).
[23] V. Stoks, R. A. M. Klomp, C. P. F. Terheggen, and J. J. de Swart, Phys. Rev. C **49**, 2950 (1994).
[24] H. Witała, W. Glöckle, and H. Kamada, Phys. Rev. C **43**, 1619 (1991).
[25] D.A. Low, Ph.D. thesis, Indiana University, 1988.
[26] E. O. Alt and M. Rauch, Few-Body Systems, Suppl. **7**, 160 (1994).
[27] W. Tornow, C. R. Howell, R. L. Walter, and I. Slaus, Phys. Rev. C **45**, 459 (1992).