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Nucleon-deuteron elastic scattering with the Paris nucleon-nucleon potential

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We report on recent advances made in employing realistic nucleon-nucleon forces for nucleon-deuteron elastic scattering. For the first time the Paris potential is used in all relevant partial waves through a separable expansion representing both its on-shell and off-shell properties. Here we present the neutron-deuteron total and differential cross sections below $E_{\mathrm{n}}=20$ MeV as well as the vector-to-vector spin-transfer coefficients of the reaction $^2\mathrm{H}(\vec{\mathrm{N}},\vec{\mathrm{d}})^1\mathrm{H}$ at $E_{\mathrm{N}}=10$ MeV. These results may now be regarded as genuine predictions of the Paris potential for these particular observables of nucleon-deuteron scattering.

I. INTRODUCTION

The three-nucleon problem is of particular importance for studying the properties of nuclear forces. In the past, it became possible to perform accurate calculations of the three-nucleon bound states with modern realistic N-N interactions.[1] Above all, these investigations[2–4] had the merit of revealing that, notably with regard to trinucleon binding energies and electromagnetic form factors, existing experimental data cannot be explained by two-nucleon forces alone, even if the most elaborate N-N potentials are employed.[5] Consequently, these findings initiated many searches for possible effects of three-nucleon forces.[1,3,6–9] Using the presently most advanced meson-theoretical models for the two- and three-nucleon interactions, recent calculations have yielded promising results for the ^{3}H binding energy.[10–12]

On the other hand, studies of three-nucleon scattering have unfortunately not yet reached such an excellent stage. This is due to the higher complexity of the three-body equation for scattering. After angular-momentum decomposition, one is, in general, left with a coupled system of dynamical equations in two variables, which has to be solved in the form of either differential[13] or integral[14,15] equations. Numerical techniques for a direct solution of such two-dimensional equations have still not reached reliable solutions for the case of modern realistic N-N interactions, such as the Paris,[16] Bonn,[17] Nijmegen,[18] or Argonne[19] potentials, which are (more or less) based on meson-exchange theory.

If the two-body input (usually t matrix) can be represented in separable form, the problem is reduced to a coupled system of one-dimensional equations.[20] There is a long tradition in following this approach[21] and the corresponding numerical methods for solving one-dimensional (integral) equations have been matured to yield mathematically stable results.[22–24] Consequently, it is highly desirable to have a separable two-nucleon t matrix for solving the three-nucleon scattering system in a reliable manner.

Modern N-N interactions are not *a priori* separable. For making them amenable to the above approach, one has to find means for expanding them in separable form so that their properties are preserved. This can be done in a number of ways;[21] of course, it has to be guaranteed that the approximation is close enough, so as to achieve convergence to the original case on the two-body as well as three-body level. For certain separable approximation schemes such convergence tests have already been performed (see below) and it has been shown that one can thereby get reliable predictions for three-nucleon observables.

In a series of earlier papers[25–28] we have reported on our first attempts towards introducing realistic models of the N-N interaction into three-nucleon scattering calculations. In our approach we represent some given N-N potentials in separable form such that the on-shell as well as off-shell behavior of the pertinent t matrix is reproduced to the required accuracy. For this purpose we apply a method proposed by Ernst, Shakin, and Thaler (EST).[29] Corresponding separable representations have already been generated for the Bonn and Paris potentials.[28,30] While in the first papers[25,26] we could only use the simplest EST approximations (rank 1) and were able to include only N-N s waves, we later succeeded in employing also the more elaborate separable expansions in the $^1s_0$ and $^3s_1$-$^3d_1$ states and we could, in addition, take into account the effect of p and d waves.[27,28] The latter, however, was done by utilizing purely phenomenological rank-1 separable interactions (from Ref. 31) in the $1\leq l\leq 2$ partial waves, which were then all treated as uncoupled. Furthermore,[32–34] we constructed rank-1 p- and d-wave EST parametrizations of the Paris potential. By applying them together with the rank-3 and rank-4 approximations in $^1s_0$ and $^3s_1$-$^3d_1$, respectively, we could thus avoid the use of phenomenological separable forces throughout.

In spite of these achievements we had to question the reliability of the so far obtained results with respect to the rank of the separable approximations employed. For getting the true predictions of the Paris potential it was therefore also necessary to check the convergence of the EST expansion in the three-body calculation. Recently, we investigated this matter with regard to the $^1s_0$ and $^3s_1$-$^3d_1$ channels.[35] The corresponding convergence tests performed in the three-nucleon bound as well as scattering systems showed that the approach we follow is now of sufficient refinement so as to lead to reliable answers for certain three-nucleon observables. Of course, the effect of higher partial waves also has to be included to the necessary extent. We consider this to be achieved by the present use of the published (rank-2) PEST potentials in higher partial waves (p and d waves),[30] at least with respect to those specific observables which are not so sensitive to these higher partial waves.[24] In the present paper we can thus give, for the first time, reliable predictions of the Paris potential particularly for the n-d differential cross section and spin-transfer coefficients of the reaction $^2\mathrm{H}(\vec{\mathrm{N}},\vec{\mathrm{d}})^1\mathrm{H}$.

In the following section we give a summary of the expansions for the N-N interaction used in the present context, together with specifying technical details of our calculation. In Sec. III we demonstrate our results, which are then, in Sec. IV, discussed in comparison to our earlier or other investigations.

II. METHOD

A. Separable expansion of the Paris potential

In our previous papers[25,30,34] we constructed several EST approximations to the Paris potential[16] of varying complexity. We denoted them by PESTN where N indicates the rank of a particular parametrization in some (coupled or uncoupled) partial-wave state. We represented the form factors resulting from the EST method as rational functions of the type as given in Eq. (3.1) of Ref. 30.

In the course of testing the accuracy and reliability of EST potentials, we designed separable expansions of the Paris potential of even higher rank than in Ref. 30 with alternative representations of the form factors. In particular, these are the EST expansions of rank up to $N=8$, in which the form factors are represented as[35]

$$g_{li}(p)=\frac{p^l}{(p^2+\beta_{li}^2)^{l+\nu_{li}}}[C_{li}+p^2y_{li}(p)] \qquad (i=1,\ldots,N) \qquad (2.1)$$

for some angular momentum l. The parameters C, β and ν are determined such that the difference of the analytical form (2.1) to the numerical EST form factor is minimal. The first term on the right-hand side (rhs) of Eq. (2.1) conveniently describes the threshold behavior. For the remaining term we perform the mapping

$$p^2=\gamma_{li}\frac{1+t}{1-t} \quad t\in[-1,1] \qquad (2.2)$$

and then $y_{li}(p(t))$ is expanded into Gegenbauer polynomials such that the numerical EST form factors are very accurately reproduced up to momenta of $p\approx 10\ \mathrm{fm}^{-1}$. In this range the functions (2.1) can be regarded as practically equivalent to the numerical form factors. Beyond $p\approx 10\ \mathrm{fm}^{-1}$ the approximation is not so accurate, but it was found that in the context of three-nucleon calculations at the energies considered here such deviations are negligible.[26] We call the resulting separable representation PESTN-G. Details of the formalism for applying the EST method to the N-N interaction can be found in Refs. 30 and 36.

In the present work we take into account N-N partial waves up to angular momentum $j=3$. In the different states we use PEST representations as specified in Table I. Their properties can be seen from Refs. 30 and 35.

Here the improvement in describing $^3s_1$-$^3d_1$ is certainly the most important progress achieved over our former calculations.[27,28,32–34] The rank-6 expansion PEST6-G cures the shortcoming that to some extent persisted with the mixing parameter ϵ_1 in PEST4 of Ref. 30, i.e., the parametrization employed in our earlier investigations. For the PEST6-G case two additional interpolation points, namely $\{E_i,l_i\}=\{-50,0\},\{-50,2\}$ $(i=5,6)$, were chosen beyond PEST4. This guarantees a mixing parameter ϵ_1, which is practically the same as for the original Paris potential up to $E_{\mathrm{lab}}\approx 200$ MeV. At the same time other quantities, like the $^3d_1$ phase shift, are further improved. In addition, the deuteron wave function of PEST6-G can now be regarded as equivalent—for our purpose—to the wave function from the original Paris potential, due to the new representation (2.1) of the EST form factors.

Another important improvement in the present paper over the previous calculations[27,28,32–34] is the use of higher-rank separable t matrices in higher partial waves. We use rank-2 separable representations in the $^1p_1$, $^3p_{0,1}$, $^1d_2$, and $^3d_2$ partial waves, rank 3 in the $^3p_2$-$^3f_2$ wave, and rank 4 in the $^3d_3$-$^3f_3$ wave, all of which were published in Ref. 30.

From the studies of Refs. 24 and 35 it is clear that the refinement achieved in our present calculation is good enough to obtain the true Paris results for the N-d observables considered here. For example, a five-channel calculation with the PESTN-G potentials of Table I yields the converged result $E_t=-7.31$ MeV for the triton binding energy. This is practically the same as the value obtained by the Hannover group via a different method directly from the Paris potential.[2] Furthermore, it was found in Ref. 35 that, with respect to N-d cross sections, again PEST3-G in $^1s_0$ and PEST6-G in $^3s_1$-$^3d_1$ yield converged results below 50 MeV incident-nucleon energy; higher-rank approximations of these partial waves do not produce any visible differences. With regard to higher N-N partial waves detailed investigations of Ref. 24 together with several convergence tests already performed tell us that their description via rank-2 potentials in uncoupled

TABLE I. Separable EST representations of the Paris potential used.

Partial wave	PEST potential	Reference
$^1s_0$	PEST3-G	35
$^1p_1$, $^3p_0$, $^3p_1$, $^1d_2$, $^3d_2$	PEST2	30
$^3s_1$-$^3d_1$	PEST6-G	35
$^3p_2$-$^3f_2$	PEST3	30
$^3d_3$-$^3g_3$	PEST4	30

states as well as rank-3 and rank-4 interactions in $^3p_2$-$^3f_2$ and $^3d_3$-$^3g_3$, respectively, will be sufficient to lead to reliable N-d results for the Paris potential.

B. Solution of the three-body equations

Since we use separable t matrices in the two-nucleon subsystems, the three-body equations are coupled one-dimensional integral equations. They generally show a complicated singularity structure. In a previous paper[24] we discussed methods for calculating N-d elastic scattering in connection with separable two-nucleon interactions and found the contour deformation to be a rather clear and powerful technique. It allows one to circumvent the singularities in an elegant way, so that very accurate results can be computed.

In our calculations the form factors are always given analytically. Therefore the contour deformation can be applied. However, especially for the PESTN-G form factors, an additional refinement is necessary; it turns out that a simple straight contour as described in Ref. 24 is not so well suited. The reason is the following: These form factors contain many terms, since they consist of an expansion into Gegenbauer polynomials. For realistic interactions the form factors fall off rather rapidly in momentum space as the momentum p goes to infinity.[30] Here, in our case, this is partly achieved by the first factor on the rhs of Eq. (2.1), but more significantly by the cancellation of different terms in the Gegenbauer series. If a straight contour in the complex plane is used, the phases in the complex Gegenbauer polynomials will cause differences compared to the real ones, because the imaginary part in p also tends to infinity as $|p|\to\infty$. These differences in the phases depend on the order of the Gegenbauer polynomials, i.e., they are not the same for each term in the series. This usually destroys the damping, which is due to the cancellation of different terms of the expansion.

This problem can be avoided by using instead a contour, which approaches the real axis as the three-nucleon momentum q goes to infinity. A possible contour of this type is

$$q=x-\frac{iax(x+b)}{x^4+d^4}\ , \tag{2.3}$$

where x is a new real variable ranging from 0 to ∞. The parameters a,b,d, all being positive, should be chosen so that the contour defined by Eq. (2.3) is far away from any singularities. For the transformation of the variable x, we use the formula[24]

$$x=c\left[\frac{1+t}{1-1}\right]^{1/m}\quad(-1\le t\le 1)\ . \tag{2.4}$$

Then, a standard Gauss-Legendre quadrature procedure is employed for the numerical integration. This finally turns the system of coupled one-dimensional integral equations into a matrix equation (of generally rather high rank).

As before,[27] we have here again avoided the complications with the Coulomb interaction. First of all, there is still no satisfactory solution to this problem[37] and, secondly, the situation is rather controversial with regard to approximate methods describing Coulomb effects.[38] In order to stay on firm ground, we have therefore chosen to take n-d cross sections for comparison, together with those p-d spin observables, where Coulomb effects are generally considered (rather) unimportant.

The latter applies to the ^{2}H($\vec{\rm p}$, $\vec{\rm p}$)^{2}H spin transfers discussed in Refs. 27, 33, and 34 and to the ^{2}H($\vec{\rm p}$, $\vec{\rm d}$)^{1}H vector-to-vector spin transfers considered here.[26,39] Since, especially in the second case, the data come only at backward angles, comparing n-d calculations with p-d measurements should be justified.

III. N-d SCATTERING RESULTS

A. Total n-d cross section

The results for the n-d total cross section in the energy interval $6\le E_{\rm n}\le 20$ MeV are given in Table II. The agreement with the experimental data is perfect up to 12 MeV. Beyond this energy the theoretical result falls slightly outside the experimental error bars; however, the agreement can still be considered satisfactory.

Maybe it would be fair to mention that the total cross section is not very sensitive to details of the the N-N interaction. For instance, the Graz-II interaction,[42] which, contrary to the Paris potential, falls short with respect to some N-N properties, practically leads to predictions of the same quality; they agree with experimental data up to $E_{\rm n}\approx 40$ MeV.[24] Only phenomenological interactions with severe shortcomings or with unrealistic properties can be disqualified on the basis of this observable; cf. the more detailed discussion in Ref. 24.

B. n-d differential cross section

Reproducing the differential cross section of n-d elastic scattering has been a long-standing problem. In particular, at backward angles the calculations employing purely phenomenological (separable) forces did not succeed in matching the experimental data;[24] the same is true for the

TABLE II. Total n-d cross section calculated from the Paris potential in comparison to experimental data.

$E_{\rm n}$ (MeV)	$\sigma_{\rm calc}$ (mb)	$\sigma_{\rm expt}$ (mb) Ref. 40	Ref. 41
6	1469	1478±16[a]	1471±20
7	1330	1296±10[a]	1337±10
8	1225	1207±13	1224±10
9	1129	1118±10[a]	1128±10
10	1047	1055±10	
10.25	1028		1038±10
12	912	913±13	923±10
14	807		824±10
18	650		666±7
20	587	584±10[a]	603±6

[a]These experiments are at slightly different energies $\Delta E_{\rm n}\approx\pm 0.1$ MeV.

p-d case.[23]

We are now sure that in the energy range $E_n \leq 20$ MeV the predictions of the Paris potential for the elastic differential cross section can reliably be obtained with the representations of Table I. With regard to the refinement in the separable expansion, it turned out that the rank-3 and rank-6 EST potentials in $^1s_0$ and $^3s_1$-$^3d_1$ already yield a converged result.[35] The effects of higher partial waves do not exceed 20% for the energies considered here.[24] They can be anticipated to be included to the necessary extent by the corresponding PEST potentials of Table I.

In Fig. 1 the differential cross sections are shown at several energies below 20 MeV incident-neutron energy. The agreement with experimental data is very satisfactory, especially also in the delicate region at very backward angles. There is only some deviation from the 1983 Karlsruhe data.[41] It must be remarked, however, that these data are at variance with the Uppsala measurement,[43] as well as with a very recent experiment of the Karlsruhe group itself.[44] They are therefore questionable, especially at backward angles.

An adequate reproduction of the n-d differential cross section is not easily achieved. Above all, the region of backward angles, which is mainly governed by the quartet state, requires an elaborate description of the $^3s_1$-$^3d_1$ N-N partial waves and notably of the deuteron. Both on-shell and off-shell properties play a role. For instance, a striking dependence on the asymptotic normalization A_s of the s-state wave function of the deuteron (and linked to that on the triplet effective-range parameters) was observed, especially at lower energies.[24] Furthermore, the deuteron binding energy, d-state probability, and quadrupole moment are important.

In the series of our former investigations we could gradually refine the calculation of the differential cross section. In the first instance we replaced the phenomenological p- and d-wave potentials applied in Ref. 27 by the rank-1 PEST parametrizations, which already brought a slight improvement.[34] The present calculation is further refined by the more complete description of the higher partial waves and notably also by employing the rank-6 PEST representation in $^3s_1$-$^3d_1$. As compared to the previously used rank-4 potential, the PEST6-G expansion gives rise to a much better mixing parameter ϵ_1, which might be important in connection with the backward differential cross section. The curves in Fig. 1 indicate a convincing prediction of the Paris potential for the n-d differential cross section.

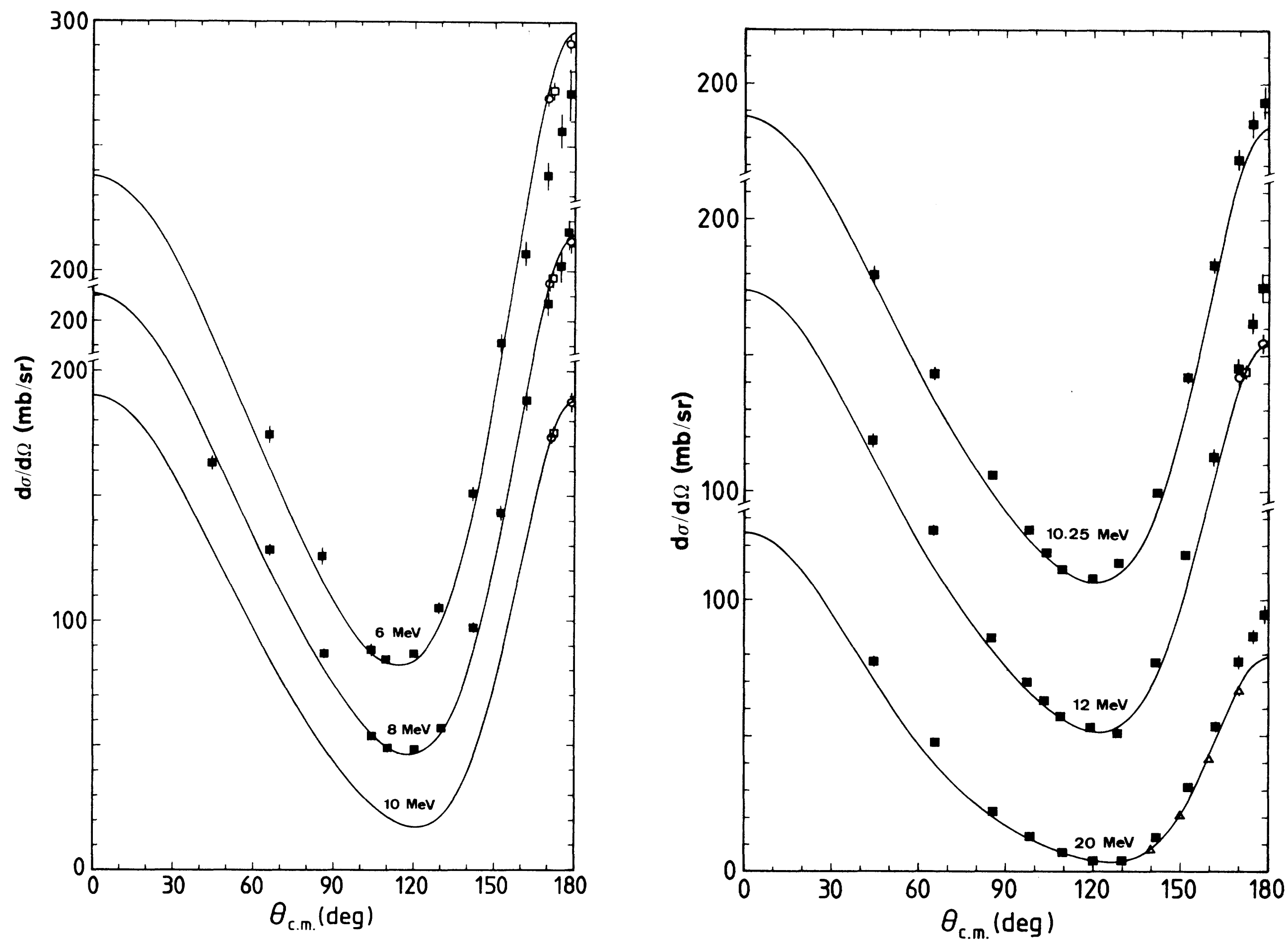

FIG. 1. Paris potential predictions for n-d differential cross section as calculated with the separable representations of Table I. The experimental data are □ and ○, Uppsala group (Ref. 43); ■, Karlsruhe group (Ref. 41); and △, Hofmann (Ref. 44).

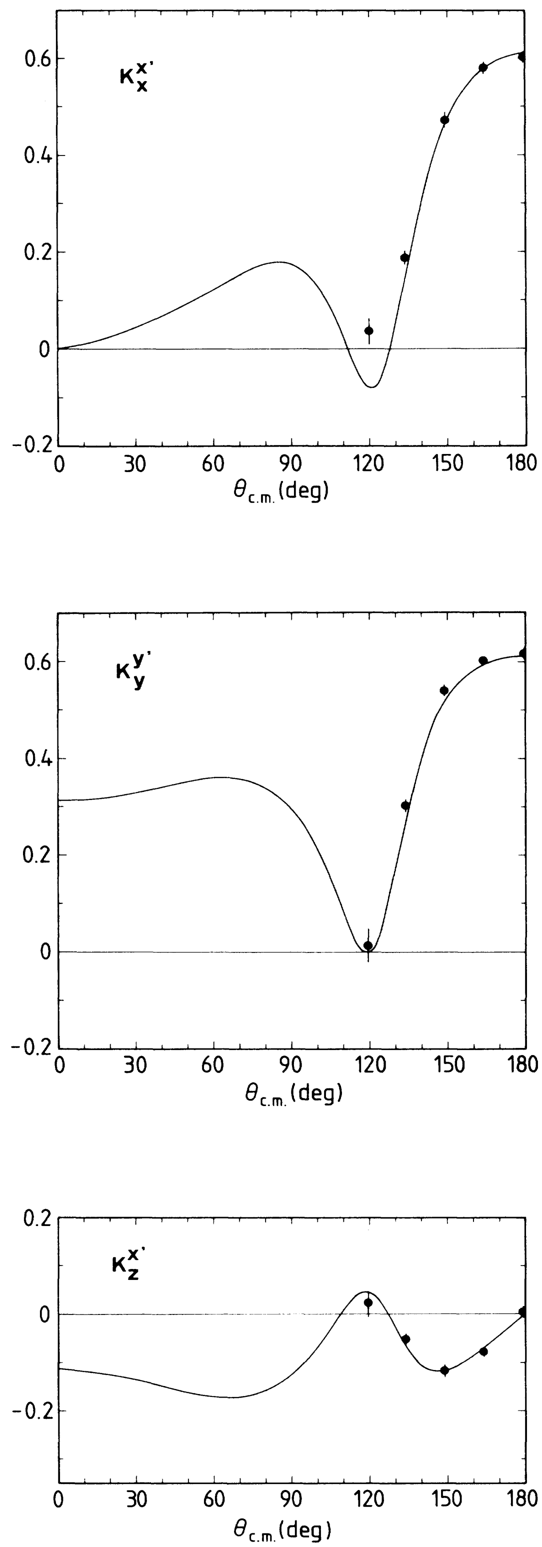

FIG. 2. $^2H(\vec{p},\vec{d})^1H$ vector-to-vector spin-transfer coefficients. The predictions of the Paris potential are calculated with the separable representations of Table I neglecting all Coulomb effects. Experimental data are for p-d scattering taken from Ref. 39.

C. $^2H(\vec{N},\vec{d})^1H$ vector-to-vector spin transfer

Next, let us consider nucleon-to-deuteron vector-to-vector spin-transfer coefficients, for which p-d data exist from the ETH-Zürich group.[39] It is worthwhile to add this comparison in the present context, because (i) these measurements are very accurate, and (ii) except for forward angles Coulomb effects are considered negligible in such observables. Therefore, as was done before in the case of nucleon-to-nucleon spin transfers,[27] we can without harm compare the n-d calculation with p-d data, especially since the latter exist at backward angles.

Figure 2 shows the spin transfers $K_x^{x'}$, $K_y^{y'}$, and $K_z^{z'}$ at $E_N=10$ MeV. The agreement of the theoretical predictions with the experimental data is very satisfactory. Our calculation shows some improvement over that of Doleschall in Ref. 38. This, however, is not surprising in view of the refinement achieved in the N-N interactions introduced here.

IV. SUMMARY

We have reported on our presently most advanced n-d scattering calculation with the Paris potential. Our approach relied on separable expansions such that the on-shell and off-shell properties are reproduced to the extent required for the three-nucleon applications in question. We have now reached a stage at which we can present reliable predictions for the total and differential cross section below $E_n=20$ MeV as well as for vector-to-vector spin transfers of the $^2H(\vec{N},\vec{d})^1H$ reaction at $E_N=10$ MeV. From the comparison to existing experimental data, we can conclude that the Paris potential is, so far, in agreement with the phenomenology of the three-nucleon scattering system. Thus meson-exchange N-N dynamics proves to be a reliable concept in this context. The off-shell behavior it implies for the long- and intermediate-range N-N potential may be considered as quite reasonable. Several observables of N-d scattering that are sensitive to these characteristics[24,26,27] have been improved by introducing the corresponding potential properties into three-nucleon calculations. To this end the method of separable expansions has been essential. In following this approach, however, one must always make sure that the separable approximation is accurate enough in order to yield reliable three-body results. For the case of the Paris potential such convergence tests have been performed for the elastic scattering, especially with respect to the $^1s_0$ and $^3s_1$-$^3d_1$ states, the ones which are most important for the observables considered here. In addition, analogous checks have shown that the separable expansions used here lead to the same results for the triton binding energy as other methods using the Paris potential directly.

Though the present results already prepare a firm basis for evidence on the three-nucleon scattering system, one must not forget that there remain several open questions. For example, we have not addressed the problem of deuteron vector and tensor polarizations. Further substantial refinements, above all with regard to Coulomb effects, are necessary for these aspects. Likewise, an even more careful description of the higher N-N partial waves with higher rank representations might be required, especially for predicting observables such as the analyzing power A_y or vector-to-tensor $^2H(\vec{p},\vec{d})^1H$ spin transfers, which are known to be highly sensitive to *p* waves.

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