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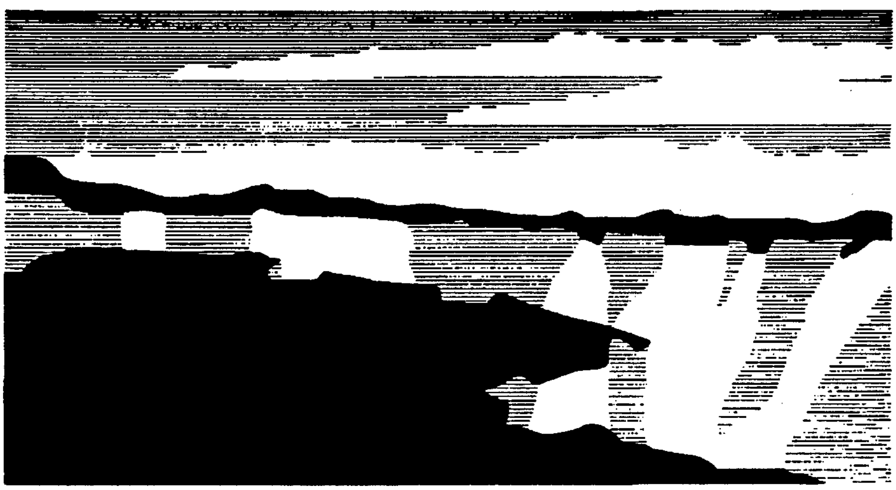

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Recent Progress in the 3N System Including Three-Nucleon Forces

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A new single Faddeev equation for the inclusion of a three-nucleon force (3NF) into the three-nucleon (3N) continuum and a new partial wave decomposition of a 3NF is presented. This allows for the first time in momentum space calculations the inclusion of a 3NF in higher angular momenta. We present converged calculations including a 3NF up to $j_{max} = 6$ for the three-nucleon bound state and $j_{max} = 3$ in the 3N continuum, where j is the total nucleon-nucleon angular momentum. Several 3N Hamiltonians are generated based on modern nucleon-nucleon (NN) forces and properly adjusted 3NFs, which give the correct triton binding energy. They are used to analyze recent measurements of spin transfer coefficients in elastic nucleon-deuteron scattering. We show that $K_y^{y'}$ scales with the triton binding energy, whereas $K_y^{z'z'}$ does not.

Three-nucleon forces (3NF) were included into three-nucleon (3N) continuum calculations above the deuteron breakup threshold for the first time in [1]. The algorithms and techniques introduced in [1] have been used for calculations up to total 2N angular momenta in the 3NF $j_{max} = 2$ only [2]. In order to be able to take into account also higher partial waves of a 3NF new algorithms and techniques have been developed recently [3][4].

In [3] we introduced a new single Faddeev equation for the inclusion of a 3NF in the 3N continuum:

$$
\begin{aligned}
T &= tP\phi + (1+tG_0)V_4^{(1)}(1+P)\phi \\
&+ tPG_0T + (1+tG_0)V_4^{(1)}(1+P)G_0T
\end{aligned}
\tag{1}
$$

In that equation occur the NN t-operator t, 3-body permutation operator P, the initial nd channel state ϕ, the free 3N propagator G_0, and $V_4^{(1)}$, one of the three cyclical pieces of a 3N force. The pp Coulomb force is not taken into account. The solution T is part of the 3N breakup operator. Its knowledge allows to calculate all processes by quadrature, since the transition operators for elastic scattering, U, and for the breakup process, U_0, are given by

$$
\begin{aligned}
U &= PG_0^{-1} + PT + V_4^{(1)}(1+P)\phi + V_4^{(1)}(1+P)G_0T \\
U_0 &= (1+P)T
\end{aligned}
\tag{2}
$$

potential	p_d [%]	E_t^{NN} [MeV] $t = 1/3\ t_{np} + 2/3\ t_{pp}$	Λ/m_π	E_t^{NN+3NF} [MeV] $t = 1/3\ t_{np} + 2/3\ t_{pp}$
CD-Bonn	4.83	7.953	4.856	8.483
Nijm II	5.65	7.709	4.990	8.477
Reid 93	5.70	7.648	5.096	8.480
Nijm I	5.68	7.731	5.147	8.480
Nijm 93	5.76	7.664	5.207	8.480
AV18	5.78	7.576	5.215	8.479

Table 1
Triton binding energies E_t for various realistic NN potentials in charge dependent calculations without total isospin $T = 3/2$ states. Deuteron d-state probabilities p_d, the adjusted cut-off parameters Λ in the 3NF and the resulting triton binding energies.

Using eq. (1) is substantially more efficient than the two coupled Faddeev equations applied up to now [1][2]. Whereas in the old approach one had to solve a set of two coupled Faddeev equations in every order of $V_4^{(1)}$, the iteration of eq. (1) in T automatically generates all orders of $V_4^{(1)}$ together with the ones of t.

The second decisive step forward is a new partial wave decomposition (PWD) for the 3NF [4]. The PWD used up to now leads to untractable numerical difficulties for partial waves with $j > 2$. Our results achieved with the old PWD and $j_{max} = 2$ are not affected by that defect. The basic idea for the new PWD is to break $V_4^{(1)}$ into two quasi 2-body operators, whose PWD in a proper basis of 3-body partial wave states becomes as simple as for an one-meson exchange NN potential. Then the matrix elements of the 2-body operators in the different basis states have to be linked together and to the basis states in which we solve eq. (1). This is done by the application of permutation operators $P_{i\leftrightarrow j}$:

$$V_4^{(1)} = P_{1\leftrightarrow 2}\, W^2\, P_{2\leftrightarrow 3}\, W^3\, P_{3\leftrightarrow 1} \qquad (3)$$

Here W^2 and W^3 denote the two quasi 2-body pieces of $V_4^{(1)}$. The three types of basis states are labeled by the numbers 1, 2 and 3 of the corresponding spectator particles. Most of the complexity of the 3NF is now carried by the permutation operators. In [4] we exemplified this new PWD for the 2π-exchange Tuscon-Melbourne (TM) 3NF [5].

As a first application [6] we calculated triton binding energies for NN and 3N forces acting in partial waves up to $j = 6$, which is sufficient to reach convergency. We found that the TM 3NF slows down the convergence of the triton binding energy in the number of partial waves. Next we generated a set of phenomenological 3N Hamiltonians based on the most modern phase-equivalent NN forces and that TM 3NF, which are adjusted individually to the triton binding energy by a proper choice of the strong form factor parameter Λ in that 3NF. We show in Table 1 the fully converged triton binding energies for this modern NN forces including charge independence breaking and the various cut-off parameters Λ, which guarantee 8.48 MeV theoretical triton binding energy. The variations of the Λ values, especially for the NN forces which by themselves give nearly the same triton binding energy, can be qualitatively linked to the properties of the NN correlation

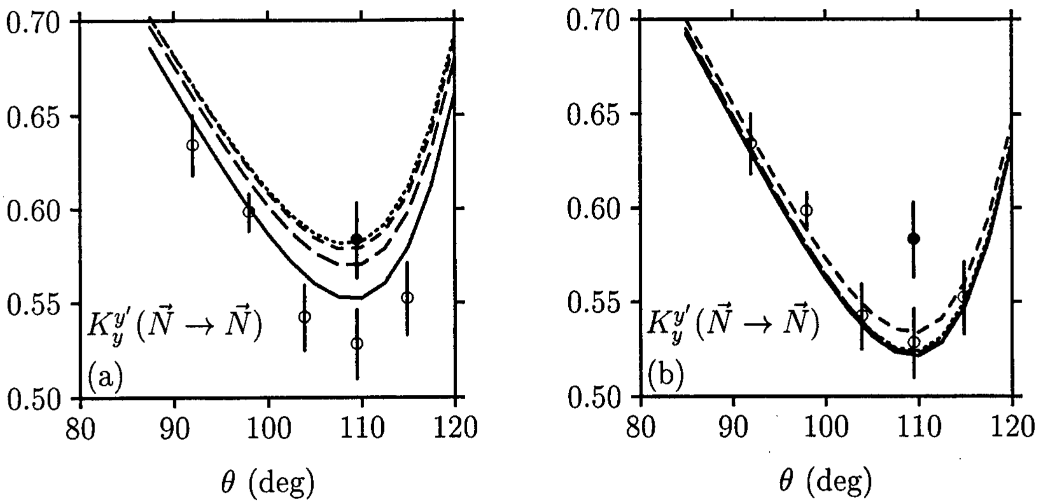

Figure 1. The nucleon to nucleon spin transfer coefficient $K_y^{y'}$ in elastic Nd scattering at $E_{lab} = 19$ MeV. Curves are predictions for CD-Bonn (solid), Nijm I (long dashed), Nijm II (short dashed) and AV18 (dotted). Subfigure (a) shows predictions based on NN forces only, whereas in subfigure (b) the corresponding 3NFs are included. • is a nd datum from [4], ○ are pd data from [5].

functions in the triton as generated by the various NN forces [6].

As a second application we studied elastic Nd scattering for various observables and energies. Recently two new experiments have been performed for elastic Nd scattering: the Bonn group using a neutron beam [7] measured the spin transfer coefficient $K_y^{y'}$ at $E_{lab} = 15.0$, 17.0, 19.0 and 25.8 MeV and the Cologne group using a proton beam [8] measured various spin transfer coefficients at $E_{lab} = 19$ MeV. First we show the spin transfer coefficient $K_y^{y'}$ at $E_{lab} = 19$ MeV, which has been measured by both groups. The comparison of the nd and pd data in fig. 1 shows a significant Coulomb effect in the minimum of $K_y^{y'}$. This indicates that one should not compare nd calculations with pd data if one is looking for subtle effects in the NN force or for 3NF effects.

In its minimum $K_y^{y'}$ varies with the d-state probability p_d, the lower the minimum the smaller the p_d. Therefore in the past the value of the minimum was proposed to be used to discriminate between the different d-state probabilities of the various NN potentials. As shown in fig. 1a and regarding table 1 the predictions of the four NN potentials used spread indeed according to their different p_d's. But if we switch on the TM 3NF with Λ fitted to the experimental triton binding energy according to table 1 we see in fig. 1b that the predictions of all potentials come very close together (only Nijm II is a bit off): $K_y^{y'}$ scales with the triton binding energy. This precludes the possibility to use $K_y^{y'}$ as a tool to get additional knowledge about the deuteron d-state probability.

Surprisingly our most advanced results including the 3NF agree with the pd data but not with the nd datum as one would expect. This discrepancy is not yet understood.

We also studied wether the phenomenon of scaling with the triton binding energy occurs for other elastic scattering observables. Thereby the individual predictions of the various

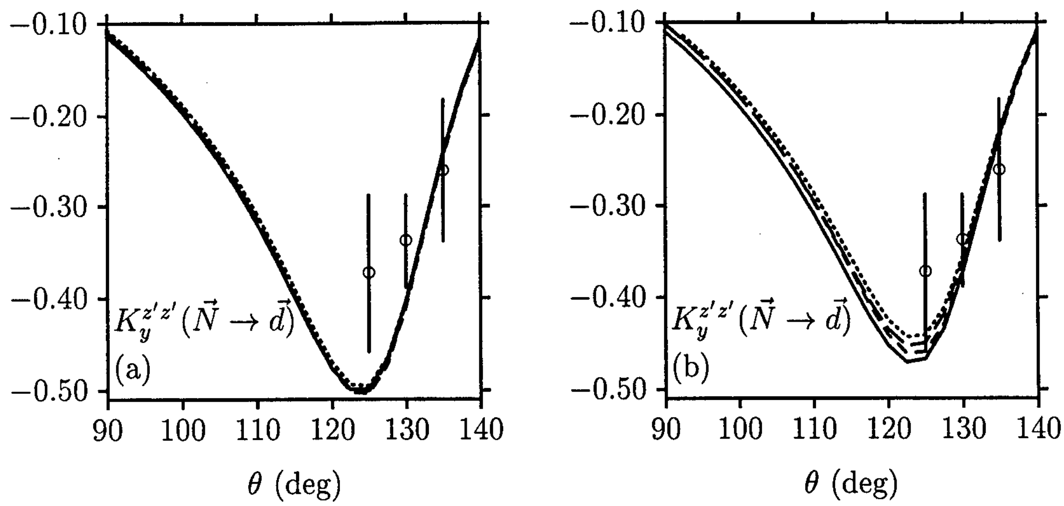

Figure 2. The nucleon to deuteron spin transfer coefficient $K_y^{z'z'}$ in elastic Nd scattering at E_{lab} = 19 MeV. Curves are predictions for CD-Bonn (solid), Nijm I (long dashed), Nijm II (short dashed) and AV18 (dotted). Subfigure (a) shows predictions based on NN forces only, whereas in subfigure (b) the corresponding 3NFs are included. ∘ are pd data from [5].

NN forces alone and then together with the properly adjusted 3N forces according to table 1 were evaluated. We found cases where the individual NN force predictions deviate from each other and coincide after inclusion of the 3NF (scaling phenomena) and also the extreme opposite behaviour that the NN force only predictions coincide and diverge after inclusion of the 3NF. Cases somewhere in between result, too [9].

One example for non-scaling is shown in fig. 2, the nucleon to deuteron spin transfer coefficient $K_y^{z'z'}$. Here the predictions of the four NN forces alone agree very well (see subfigure 2a), whereas the predictions when the adjusted 3NFs are included deviate (see subfigure 2b). Interestingly the predictions with the more complete dynamics encompassing 3NFs are somewhat closer to the data. However again caution is needed because we compare pd data with nd calculations.

Further investigations on the scaling phenomenon for breakup processes and the inclusion of other types of 3NFs are planned.

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