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Analyzing power puzzle in low energy elastic *Nd* scattering

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First results of rigorous $3N$ Faddeev calculations including realistic NN and $3N$ forces (3NF) are presented. We compare the theoretical analyzing power A_y in elastic Nd scattering at $E_{\rm lab}^N=3.0$ MeV to recently measured nd data. As 3NF we take the Tucson-Melbourne 2π-exchange model. We study its dependence on the πN form-factor cutoff parameter and also the interplay of three realistic NN forces with that 3NF. The discrepancy between theory and experiment, present for NN forces only, turns out to be aggravated when including that 3NF. Further efforts to be taken are indicated.

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A great amount of proton-proton (pp) and neutron-proton (np) data has been measured over the years and there exist several so-called realistic nucleon-nucleon (NN) potentials, among them meson-theoretical ones, which describe that data set very well. Are those forces also relevant for systems of three and more nucleons? The advent of supercomputers in recent years allowed to solve the $3N$ scattering problem rigorously for any type of NN forces. Our extensive analysis of available three-nucleon ($3N$), proton-deuteron (pd) and neutron-deuteron (nd) elastic scattering data in fact revealed, that the simple dynamical mechanism of three nucleons interacting pairwise with realistic NN interactions clearly dominates this process. The predictions of these modern NN potentials give a very good description of the total cross section for nd scattering, of angular distributions and nearly all polarization data [1] in elastic Nd scattering. Also quite a few Nd breakup data are equally well described by that simple dynamical picture, leaving very little room for additional dynamics. There is, however, an interesting exception in the analyzing power in elastic Nd scattering. While for incident nucleon lab energies of 30 MeV and higher good agreement is found between the theoretical predictions and the A_y data [1], a sizeable discrepancy of about 30% exists in the low energy region, below $E_{\rm lab}^N \approx 30$ MeV, between the theoretical predictions based on modern NN potentials and both pd and nd A_y data. That discrepancy lies in and around the A_y maximum at $\Theta_{\rm c.m.} \approx 125°$ [1]. It exists for energies below as well as above the deuteron breakup threshold. In Fig. 1 we exemplify that discrepancy at a neutron lab energy $E_{\rm lab}^n=3.0$ MeV. The predictions of the currently most prominent four different potentials, AV14 [2], Bonn B [3], Nijmegen [4], and Paris [5], clearly underestimate the recently measured A_y data [6] in the region of its maximum. The deviation of the AV14 prediction from the other ones is due to slight on-shell differences between the AV14 $^3P_{0,1,2}$ NN phase-shift parameters and those phases of the other three potentials. This points to a possible reason for that sizeable discrepancy between theory and data: the great sensitivity of A_y to the ^3P_J NN forces. This has been already emphasized in [7], though at that time a rigorous solution of the $3N$ scattering problem had not been achieved.

As has been displayed at several places in the past [8] and most recently in [6] for $E_{\rm lab}^N=3.0$ MeV the low-energy A_y results mostly from a complicated interference between contributions generated by the ^3P_J ($J=0,1,2$) NN force components. This suggests the possibility that changes in the ^3P_J forces, restricted of course by the requirement to describe always the existing $2N$ data, could probably account for that discrepancy. An attempt to change the ^3P_J forces in this manner showed, that indeed the existing discrepancy for low energy Nd A_y can be significantly reduced [8] and keeping the same quality in the description of pp and np analyzing power data. The price to be paid, however, was the introduction of a significant charge independent breaking (CIB: $pp \neq np$) in those NN force components. The improvement in

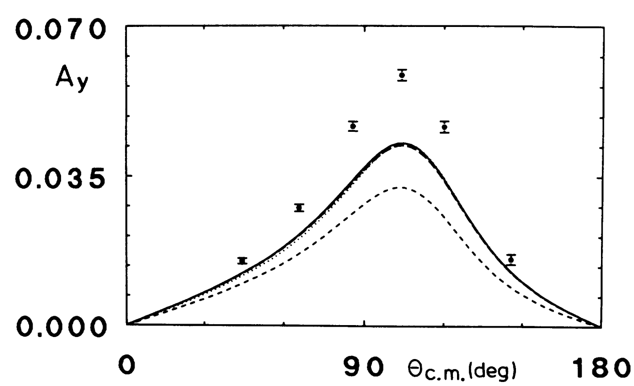

FIG. 1. The neutron-deuteron analyzing power data at $E_{\rm lab}^n=3.0$ MeV [6] (full dots) compared to different potential predictions: Bonn B—solid line, AV14—short-dashed line, Nijmegen—dotted line, and Paris—long-dashed line.

describing *nd* A_y using those modified ^3P_J *pp* and *np* forces is presented in Fig. 2. While here we achieve a nearly perfect description, the improvement, though not perfect, is also very clear at higher energies, 5–14 MeV, where precise recent *nd* data are available [8,9]. Unfortunately the strength and sign of the ^3P_J CIB proposed *ad hoc* in [8] is not supported by a recent meson theoretical study [10] which is based just on pion-mass differences. On the other hand, one should keep in mind that the meson theory of *NN* forces is still basically unsolved as all strong interaction theories. A recent trial by Takemiya [11], whose changes in the ^3P_J components of the Paris potential improve the description of the *Nd* A_y, failed insofar that it spoiled the simultaneous description of both *np* and *pp* A_y data [12].

We think that in view of the realistic calculations presented including the best currently available realistic *NN* forces and in view of the very good agreement of that theory to data for other spin observables and cross sections in elastic *Nd* scattering, that A_y puzzle deserves special attention. Its strong sensitivity to the ^3P_J *NN* forces makes it likely that those *NN* force components are not yet settled, which might be caused by corresponding unsettled ^3P_J *NN* phase-shift parameters. Further efforts on the experimental side, like more dedicated *np* measurements to allow for a phase-shift analysis which is independent of the *pp* data, and possibly even more dedicated *pp* measurements to further confirm the *pp* phase-shift values, appear to be worthwhile, in order to help to clear up that puzzle.

If the reason for that discrepancy will finally turn out not to lie in the *NN* forces one faces an exciting example in 3*N* scattering, where additional dynamics is required, such as the action of three-nucleon forces (3NF). To shed light on that question we solved the 3*N* scattering equations including a 3NF. 3*N* scattering including realistic *NN* forces and 3NF has been solved before at the *Nd* threshold [13] and in the context of *pd* capture [14]. As far as we know 3*N* scattering observables other than scattering lengths based on realistic *NN* forces and 3NF have not been published before. In the present article we show our results at the incoming neutron lab energy $E^N_{\text{lab}}=3.0$ MeV, which is below the deuteron breakup threshold. As 3NF we took the Tucson-Melbourne (TM) 2π-exchange model [15]. It relies on low energy theorems, which makes its essential ingredient, the π-N off-shell scattering amplitude, essentially model independent. This is, however, true only for soft pions. The harder pions, which are induced by the momentum distribution of the nucleons in realistic nuclear wave functions, lead to a relatively strong dependence on the choice of the cutoff parameter in the strong π-N form factor. This is evident from the ^{3}H bound state study [16] and from a more recent one [17]. The question we shall study here is, whether that cutoff dependence is also present for 3*N* scattering observables. As *NN* force we take the one boson exchange Bonn B [3] potential. We solve Faddeev type integral equations

$$\begin{aligned} T &= tP + tG_0T_4 + tPG_0T \ , \\ T_4 &= (1+P)t_4 + (1+P)t_4G_0T \ , \end{aligned} \tag{1}$$

where t is the *NN* off-shell t matrix, G_0 the free 3*N* propagator, P the sum of a cyclic and anticyclic permutation, and t_4 is generated from a chosen 3NF V_4 by an equation of a Lippmann-Schwinger form

$$t_4 = V_4 + V_4G_0t_4 \ . \tag{2}$$

The operator U for elastic *nd* scattering is given as

$$U = PG_0^{-1} + PT + T_4 \ . \tag{3}$$

More details about the formalism and the complex technicalities for the numerical procedure are outlaid in [18, 19]. The fully converged result for the 3*N* analyzing power A_y at $E^n_{\text{lab}}=3.0$ MeV was achieved by allowing both *NN* and 3NF to act in all partial wave states with *NN* total angular momenta $j \leq 2$. The total 3*N* angular momenta had to be kept up to $J_{\text{max}}=9/2$.

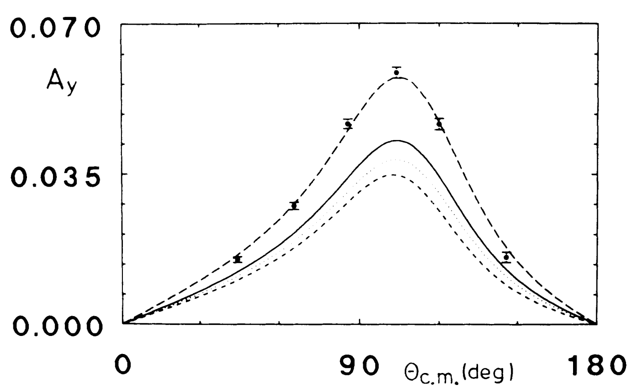

FIG. 2. The neutron-deuteron analyzing power data at $E^n_{\text{lab}}=3.0$ MeV [6] (full dots) compared to theoretical predictions obtained with 2*N* and 2*N* + 3*N* forces. The solid line is the prediction of the Bonn B potential. The dotted and short-dashed lines result by adding to Bonn B the 2π-exchange 3*N* force with $\Lambda_\pi=4.1m_\pi$ and $5.8m_\pi$, respectively. The result obtained with the charge-dependent *pp-np* modification of the Bonn B potential in ^3P_J waves, as proposed in Ref. [8], is shown by the long-dashed line.

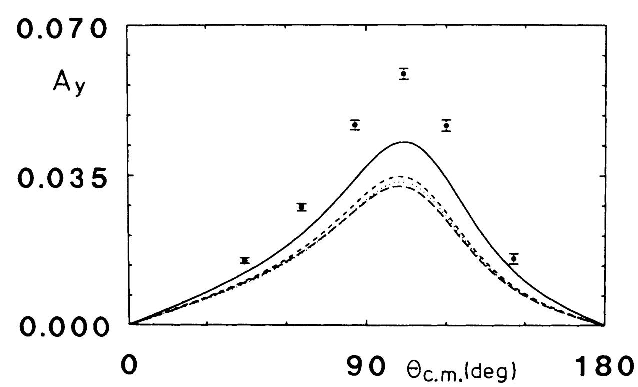

FIG. 3. The neutron-deuteron analyzing power data at $E^n_{\text{lab}}=3.0$ MeV [6] (full dots) compared to different theoretical predictions. The solid line is the prediction of the Bonn B potential. The short-dashed, dotted, and long-dashed lines result when to the Bonn B, Nijmegen, and Paris 2*N* interactions the 2π-exchange 3*N* force with $\Lambda_\pi=5.8m_\pi$ is added, respectively.

In Fig. 2 we compare the results based on the Bonn B potential and the TM 3NF choosing two values for the cutoff parameters, $\Lambda_\pi = 4.1 m_\pi$ and $5.8 m_\pi$ ($m_\pi = 139.6$ MeV). The bigger value is considered to be more realistic [15]. We see indeed a cutoff dependence, but the main point is, that the inclusion of the 3NF increases the discrepancy in the region of the maximum. This result could depend on the specific choice of the *NN* force. In case of the ^{3}H bound state the 3NF effects on the binding energy depend in size to some extent on the particular *NN* force model used [20]. Therefore we solved the set (1) including the TM 3NF ($\Lambda_\pi = 5.8 m_\pi$) together with two more *NN* forces: the Nijmegen and the Paris potential. Figure 3 shows our result. We see that changing the *NN* interaction leads only to small changes of the 3NF effects for A_y. Therefore we can state that standard current *NN* forces together with the 2π-exchange TM 3NF are not able to explain the low energy analyzing power in elastic *Nd* scattering. Further investigations are necessary, including other 3NF mechanisms (π-ρ,ρ-ρ,Δ propagation), before final conclusions on 3NF effects and the origin of the A_y discrepancy can be drawn. Right now the puzzle remains.

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