Impact of three-nucleon forces on low-energy $p-^3$He scattering

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Much effort is being currently devoted to the determination of a realistic three-nucleon interaction (TNI) model. Indeed, the very accurate nucleon-nucleon (NN) potential models developed so far, fail to reproduce the binding energy of the trinucleons, signalling the necessity for such an interaction. The most direct testing ground to this aim is represented by the three-nucleon systems. However, it turns out that most of the $A = 3$ scattering observables are not very sensitive to the different models presently available. It is therefore sensible to seek for their effect on the scattering observables in $A = 4$ systems. In particular, $p-^3$He scattering exhibits striking discrepancies between theoretical calculations based on realistic two-nucleon potentials and the very accurate experimental data, the most prominent one being the proton analyzing power A_y, similarly to the well knows A_y puzzle for $N-d$ scattering. Indeed, rapid progress in the techniques required to solve the quantum mechanical 4-body problem in the continuum, has allowed to reach an accuracy of less than 1% in the calculation of $p-^3$He and $n-^3$H phaseshifts, as recently demonstrated by a benchmark calculation [1]. In Ref. [2,3] we used the Kohn variational principle, expanding the inner part of the wave function in Hyperspherical Harmonics functions [4]. We focussed on two models of TNI. The first one, derived in the framework of Chiral Effective Theory, at next-to-next-to-leading order (N2LO) used in association with the two-nucleon potential obtained within the same framework, but at N3LO. The latter accuracy is sufficient to attain a χ^2 very close to 1/d.o.f., on a wide set of nucleon-nucleon scattering data. The development of the chiral expansion on the TNI side is currently in progress. At the order considered the chiral TNI contains two unknown low-energy constants (LECs) which are typically fixed to reproduce the $A = 3$ and 4 binding energies, or alternatively the Gamow-Teller matrix element in the tritium β-decay. The second model of TNI we consider is the Illinois one (IL7), derived in a more phenomenological approach, and used in association with the Argonne V18 potential (AV18). The Illinois model includes specific two-pion and three-pion exchange diagrams among the three nucleons, and is designed to reproduce the spectra of $A = 4 - 12$ nuclei.

We first compared, for the different interaction models, the $p-^3$He phaseshifts with the recent phaseshift analysis [5]. In the energy range considered ($E_p \leq 6$ MeV), $p-^3$He observables are dominated by S-wave and P-wave phase shifts. From this comparison it appears that, with only a NN potential, both S- and P-wave phase-shifts result to be at variance with the PSA. Including the 3N force, we observe a general improvement of the description of the S− and P−wave phase shifts and mixing parameters.

In Fig. 1 we display the comparison for the observables. The two bands collect the results obtained respectively using only NN interaction models, and including also a TNI. The considered observables are the unpolarized differential cross section, two analyzing power observables, and some spin correlation observables. The bands reflect the choice of the potential models, the variation with the cutoff Λ (for the chiral potentials) and the different ways of fixing the two LECs in the chiral N2LO TNI. We note that the unpolarized differential cross section, the ^{3}He analyzing power A_{y0}, and the spin correlation coefficients are not particularly sensitive to the adopted interaction models, and in general we observe a good agreement with the experimental values in all considered cases. The situation is completely opposite for the proton vector analyzing power A_y, shown in the upper central panel: this observable is very sensitive to the inclusion of the 3N interaction. The calculations performed using either the chiral N3LO potential or the AV18, in fact, largely underpredict the experimental points, confirming previous findings. The underprediction of the experimental data is considerably reduced with the inclusion of TNI, at the level of 8-10%.

It is interesting to examine the effect of the same interaction models in $p-d$ scattering. The

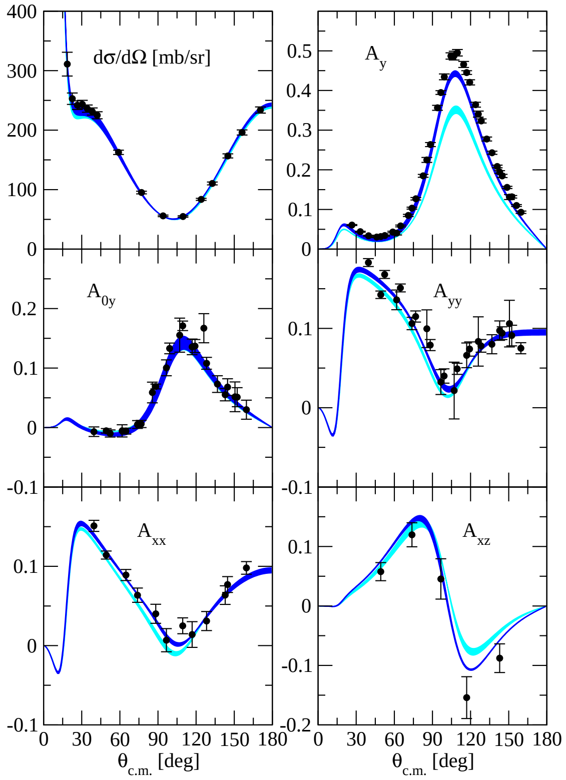

Figure 1. $p{-}^3$He differential cross section, analyzing powers and various spin correlation coefficients at $E_p = 5.54$ MeV calculated with only the NN potential (light cyan band) or including also the 3N interaction (darker blue band), compared to experimental data.

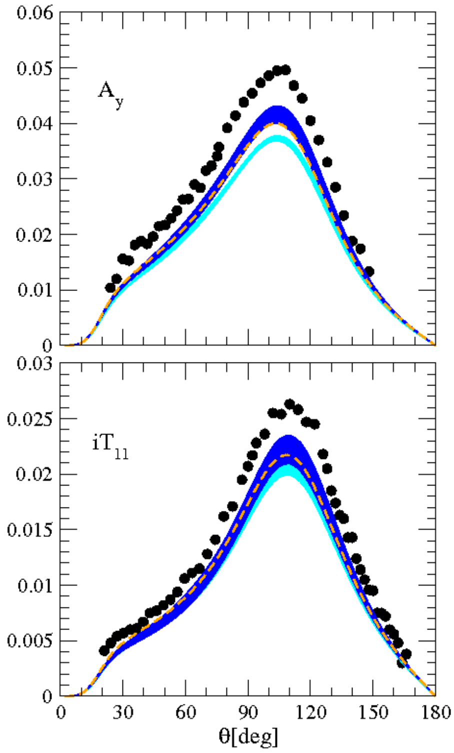

Figure 2. Comparison to experimental data for $p-d$ vector polarization observables at $E_p = 3$ MeV calculated with only the NN potential (cyan band) or including also the 3N interaction (blue band). The results obtained with the AV18/IL7 interaction models are reported as the dashed orange line.

results for two vector polarization observables at $E_p = 3$ MeV are shown in Fig. 2. The cyan band has been obtained using the NN chiral interaction only for $\Lambda = 500$ and 600 MeV, whereas the blue one takes also into account the corresponding N2LO TNI. The orange lines represents the results with the AV18 potential supplemented by the Illinois model of TNI. The underprediction of both observables (the "A_y puzzle") is reduced by the inclusion of TNI, but is still of the order of 18-20%, now somewhat larger than for the $p{-}^3$He A_y observable. It should be kept in mind, however, that the above $p-d$ asymmetries are rather tiny, and therefore more sensitive to small effects, as those due to additional spin-orbit terms which in the chiral 3N potential would appear at next-to-next-to-next-to-next-to-leading order (N4LO) [6]. Conversely, the $p{-}^3$He A_y is large and probably more sensitive to other missing parts of the interaction, as the contribution of the N3LO 3N force.

As an interesting outcome of the present investigation, we observe that the results obtained with the N3LO/N2LO models and AV18/IL7 model are always very close with each other. In view of the differences in the frameworks used to derive these TNI models, this outcome is somewhat surprising.

Finally, it will be certainly very interesting to test the effect of the inclusion of the N3LO and N4LO 3N forces derived from the effective field theory. Work in this direction is in progress.

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