Tuning the three-nucleon interaction from three-nucleon data

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Despite long-lasting efforts in the determination of a realistic three-nucleon force (TNF), none of the presently available models leads to a satisfactory description of bound and scattering states of the $A = 3$ system [1]. It seems natural to ascribe the above situation to the fact that these models include a very small number of adjustable parameters, compared to the two-nucleon interaction case. For example, in the framework of the chiral expansion, only 2 low-energy constants (LECs) enter up to and including N3LO [2].

In Ref. [3] we have classified all subleading three-nucleon contact operators, which involve two powers of nucleon momenta. These terms would show up at the N4LO of the low-energy expansion, but they represent the first correction to the TNF in the pionless version of the effective theory. The resulting three-nucleon potential, which depends on 10 LECs ($E_{1,\dots,10}$) whose values should be fitted to experimental data, can be cast in a local form in coordinate space,

$$
\begin{aligned}
V = \sum_{i\neq j\neq k} \quad & (E_1 + E_2 \boldsymbol{\tau}_i\cdot\boldsymbol{\tau}_j + E_3 \boldsymbol{\sigma}_i\cdot\boldsymbol{\sigma}_j + E_4 \boldsymbol{\tau}_i\cdot\boldsymbol{\tau}_j \boldsymbol{\sigma}_i\cdot\boldsymbol{\sigma}_j)\left[Z_0''(r_{ij}) + 2\frac{Z_0'(r_{ij})}{r_{ij}}\right] Z_0(r_{ik}) \\
& +(E_5 + E_6 \boldsymbol{\tau}_i\cdot\boldsymbol{\tau}_j) S_{ij}\left[Z_0''(r_{ij}) - \frac{Z_0'(r_{ij})}{r_{ij}}\right] Z_0(r_{ik}) \\
& +(E_7 + E_8 \boldsymbol{\tau}_i\cdot\boldsymbol{\tau}_k)(\mathbf{L}\cdot\boldsymbol{S})_{ij}\frac{Z_0'(r_{ij})}{r_{ij}} Z_0(r_{ik}) \\
& +(E_9 + E_{10} \boldsymbol{\tau}_j\cdot\boldsymbol{\tau}_k)\boldsymbol{\sigma}_j\cdot\hat{\mathbf{r}}_{ij}\boldsymbol{\sigma}_k\cdot\hat{\mathbf{r}}_{ik} Z_0'(r_{ij}) Z_0'(r_{ik}) \qquad (1)
\end{aligned}
$$

where S_{ij} and $(\mathbf{L}\cdot\boldsymbol{S})_{ij}$ are respectively the tensor and spin-orbit operators for particles i and j, and the function $Z_0(r)$ is the Fourier transform of the cutoff function, chosen of gaussian type. The 10 additional LECs parametrize the short-range component of the TNF, and are unconstrained by chiral symmetry. As such, they could provide the necessary flexibility to arrive at a truly realistic model for the TNF. In order to put such conjecture to quantitative scrutiny, we examine [4] to which extent the AV18 NN interaction, supplemented by the leading and subleading contact-range TNF, provides a satisfactory fit to $N-d$ scattering data.

As an example, we show in Fig. 1 the result of a 4-parameter fit (the leading order c_E and 3 out of the 10 subleading E_i's) to $p-d$ scattering observables at 3 MeV laboratory energy. The LECs have been rescaled by inserting appropriate powers of F_π and Λ according to naive dimensional analysis, so that they become adimensional and should be of order 1, if natural. The calculation have been carried on using the Kohn variational principle expanding the wave function on the hyperspherical harmonics basis [5]. The description of the polarization observables is much improved, in particular the well-known A_y and T_{11} discrepancies are much decreased, until a χ^2 of about 3 per degree of freedom. The resulting LECs are natural suggesting that, at N4LO, the chiral expansion could naturally provide a realistic TNF.

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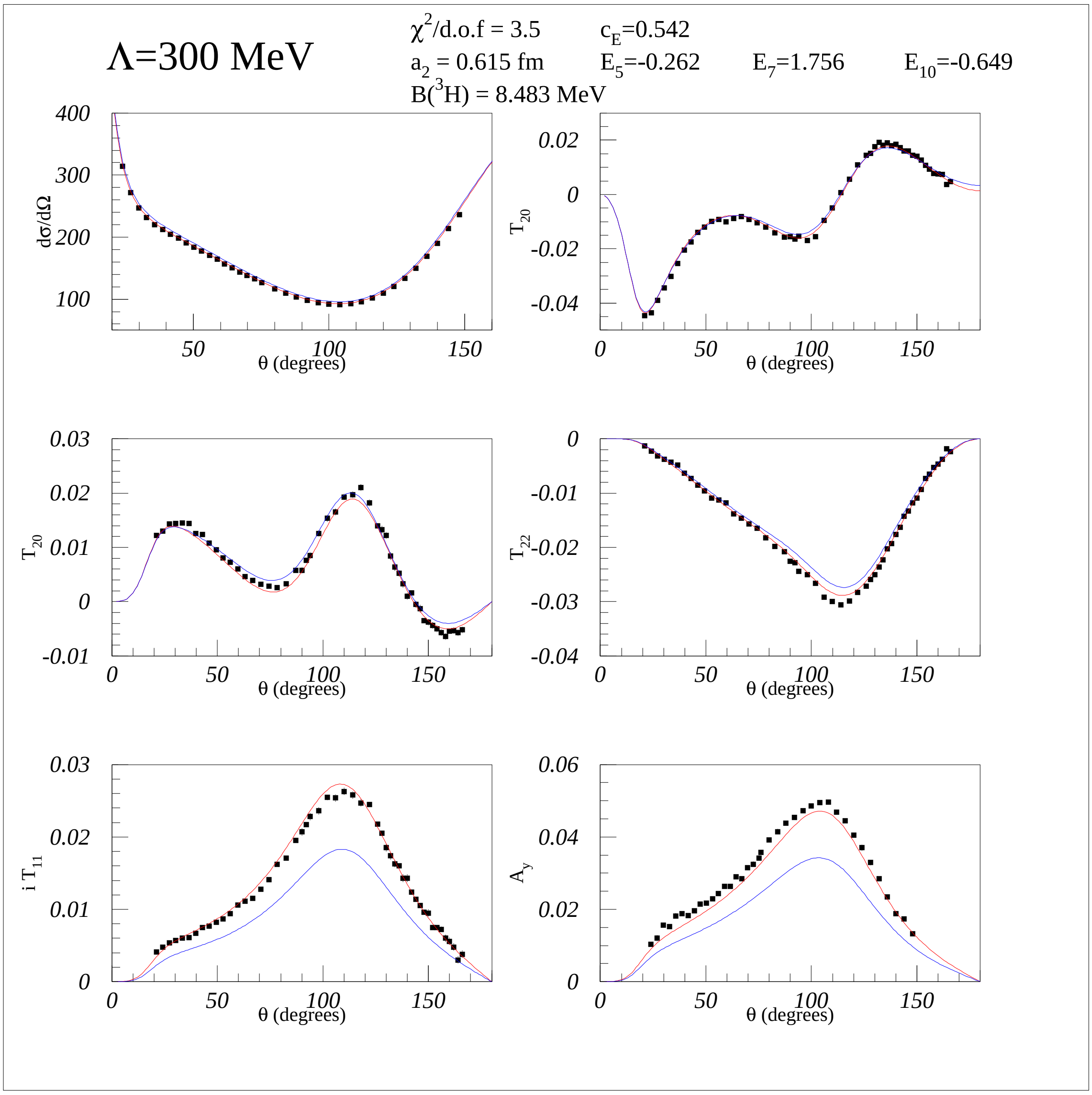

Figure 1. Results of a 4-parameter fit to $p-d$ scattering observables at 3 MeV laboratory energy. Blue lines denote the AV18 prediction, while the red lines include a subset of the contact-range TNF, with the cutoff $\Lambda = 300$ MeV. Also fitted are the triton binding energy $B(^3\mathrm{H})$ and the doublet scattering length a_2.