Three-nucleon reactions with chiral dynamics

H. Witała\textsuperscript{1,a}, J. Golak\textsuperscript{1,b}, R. Skibiński\textsuperscript{1,c}, and K. Topolnicki\textsuperscript{1,d}

\textsuperscript{1}M. Smoluchowski Institute of Physics, Jagiellonian University, PL-30-059 Kraków, Poland

\textbf{Abstract.} Faddeev calculations using the chiral three-nucleon force at next-to-next-to-next-to-leading-order show that this force is not able to provide an explanation for the low-energy $A_y$ puzzle. Also the large discrepancies between data and theory for the symmetric-space-star and for the neutron-neutron quasi-free-scattering cross sections in low energy neutron-deuteron breakup cannot be explained by that three-nucleon force. The discrepancy for the neutron-neutron quasi-free-scattering cross section seems to require a modification of the $^1S_0$ neutron-neutron force.

\section{Introduction}

Recent progress in the construction of chiral nucleon-nucleon (NN) and three-nucleon forces (3NF) allows one to test chiral dynamics in 3N reactions up to the next-to-next-to-next-to-leading-order ($N^3$LO) of the chiral expansion. It provides also an opportunity to check if consistent two- and three-nucleon forces are able to explain the low-energy $A_y$ puzzle.

The large disagreement between theory and data for the symmetric-space-star (SST) and for the neutron-neutron quasi-free scattering (nn QFS) cross section in low energy neutron-deuteron (nd) breakup reaction provides another example where consistent application of $N^3$LO chiral forces is desirable. The strong dominance of S-waves on the cross section in those configurations indicates the possibility that two neutrons interaction in a $^1S_0$ state should be modified.

\section{$A_y$ puzzle and the $N^3$LO chiral three-nucleon force}

In order to describe the 2N system with the same high precision as provided by standard semi-phenomenological NN potentials one needs to go to $N^3$LO in chiral expansion [1, 2]. In the following, results of 3N Faddeev calculations [3, 4] based on five versions of chiral $N^3$LO potentials, which use different cut-offs for the Lippmann-Schwinger equation and spectral function regularization [1] and which equally well describe the 2N system, will be presented. In that order of the chiral expansion...
six topologies contribute to the 3NF: 2π-exchange, 2π − 1π-exchange, ring, 1π-exchange-contact, 2π-exchange-contact and a purely contact term. In addition, there are also leading relativistic corrections. The first three topologies belong to long-range contributions [5], while others are of short-range character [6]. These terms do not involve any unknown low-energy constants and the full N^3LO 3NF depends on two parameters, D and E, coming with the 1π-exchange-contact and the purely contact term, respectively. A recently developed efficient method of partial wave-decomposition [7] allowed us to apply the N^3LO 3NF in 3N Faddeev calculations. First results presented in the following were obtained without leading relativistic corrections in that 3NF. In the left column of Fig.1 the A_y puzzle is exemplified for nd data taken at 10 MeV. High-precision semi-phenomenological NN potentials (light shaded band) cannot describe the data and including the 2π-exchange Tucson-Melbourne (TM) 3NF (dark shaded band) only partially fills out the discrepancy in the maximum of A_y. Taking the next-to-leading order (NLO) chiral NN potential overestimates the data for A_y (upper band in the right column of Fig.1), while next-to-next-to-leading order (N^2LO) potentials describe the A_y data quite well (middle band in the right column of Fig.1). Such behavior can be traced back to the large sensitivity of A_y to the \(^3P_2\) NN force components and to a poor description, especially for \(^3P_2\), of the experimental phase-shifts by the NLO and N^2LO chiral potentials [1]. Only with the N^3LO NN potentials is the A_y puzzle again regained (lower band in the right column of Fig.1) and predictions for A_y become similar to those obtained with semi-phenomenological potentials.

The chiral N^3LO 3NF is not able to explain the A_y puzzle (see Fig.2). It lowers the A_y maximum and even increases the discrepancy to data. A resolution of the A_y puzzle might be achieved either with the N^4LO chiral 3NF [9] or/and using NN forces with corrected low-energy \(^3P_2\) phase-shifts.

3 Low energy breakup

Cross sections for the symmetric-space-star (SST) and quasi-free-scattering (QFS) configurations of the nd breakup are extremely stable with respect to the underlying dynamics. Different potentials,
Figure 2. (color online) The neutron analyzing power $A_y$ in elastic nd scattering. In the left and right column the solid (red) line shows predictions of N$^3$LO chiral NN potentials alone and the dashed (blue) line when they are combined with N$^3$LO 3NF composed of $\pi\pi$-exchange-contact, purely contact, and $2\pi$-exchange-contact terms supplemented with long-range terms: $2\pi$-exchange, $2\pi-1\pi$-exchange, and ring, for two cut-off values used in Lippmann-Schwinger and spectral function regularization. The nd data (full circles) are from [8].

alone or combined with standard 3N forces, provide practically the same SST and QFS cross sections. Also, the chiral N$^3$LO 3NF is no exception and cannot explain the discrepancy with the data found for the SST configuration [10] (Fig.3). At low energies the cross sections in the SST and QFS configurations are dominated by the S-waves. For the SST configuration the largest contribution to the cross section comes from the $^3S_1$ partial wave while for neutron-neutron (nn) QFS the $^1S_0$ partial wave dominates. Neglecting rescatterings the QFS configuration resembles free NN scattering. For free, low-energy neutron-proton (np) scattering one expects contributions from $^1S_0$ np and $^3S_1$ force components. For free nn scattering only the $^1S_0$ nn channel is allowed. That implies that QFS nn would be a powerful tool to study the nn interaction. The measurement of QFS np cross sections have shown good agreement of data with theory [11], confirming thus good knowledge of the np force. For nn QFS it was found that theory underestimates the data by $\approx 20\%$ [11]. The large stability of the QFS cross sections to the underlying dynamics, implies that the present day $^1S_0$ nn interaction is probably incorrect. Modifications of the $^1S_0$ nn CD Bonn force component by multiplying its matrix elements by a factor $\lambda$ leads to large changes of the nn QFS cross sections, leaving the np ones practically unchanged [12–14]. To remove the discrepancy found in experiment for nn QFS one needs $\lambda \approx 1.08$.

4 Summary

The chiral N$^3$LO 3NF is not able to explain the low-energy $A_y$ puzzle. It also does not resolve the discrepancies found for cross sections in the nn QFS and SST configurations of the low-energy nd breakup.
Figure 3. (color online) The cross section \( d^5\sigma/d\Omega_1 d\Omega_2 dS \) as a function of the arc-length \( S \) in the \( E_{\text{lab}} = 13 \) MeV \( nd \) breakup reaction for the SST and QFSnn configurations. The light shaded (red) and dark shaded (blue) bands show predictions of N\(^3\)LO chiral NN potentials alone and combined with N\(^3\)LO 3NF (without short-range 2\(\pi\)-exchange-contact term) for five different cut-offs, respectively. The solid (orange) line is a prediction obtained with the CD Bonn potential. The nd data for SST configuration (full circles) are from [8].

References