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Three-nucleon reactions with chiral dynamics*

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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.

1 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^3LO) 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^3LO 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.

2 A_y puzzle and the N^3LO 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^3LO in chiral expansion [1, 2]. In the following, results of 3N Faddeev calculations [3, 4] based on five versions of chiral N^3LO potentials, which use different cut-off's 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

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six topologies contribute to the 3NF: 2π-exchange, $2\pi - 1\pi$-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^{3}LO 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^{3}LO 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^{2}LO) 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_j NN force components and to a poor description, especially for $^3P_2$, of the experimental phase-shifts by the NLO and N^{2}LO chiral potentials [1]. Only with the N^{3}LO 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.

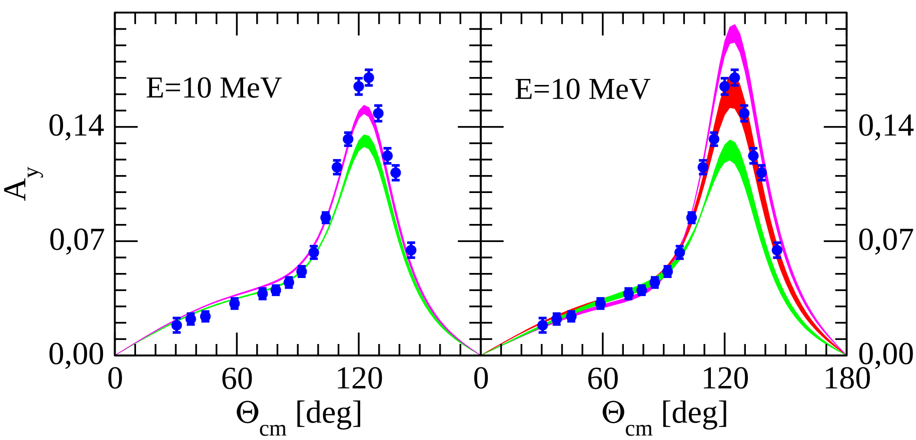

Figure 1. (color online) The neutron analyzing power A_y in elastic nd scattering. In the left column the light shaded (green) and dark shaded (magenta) bands show predictions of realistic NN potentials (AV18, CD Bonn, Nijm1 and Nijm2) alone or combined with TM 3NF, respectively. In the right column the magenta (upper), red (middle) and green (low) bands show predictions of NLO, N^{2}LO, and N^{3}LO chiral NN potentials, respectively. The nd data (full circles) are from [8].

The chiral N^{3}LO 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^{4}LO chiral 3NF [9] or/and using NN forces with corrected low-energy ^3P_j 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,

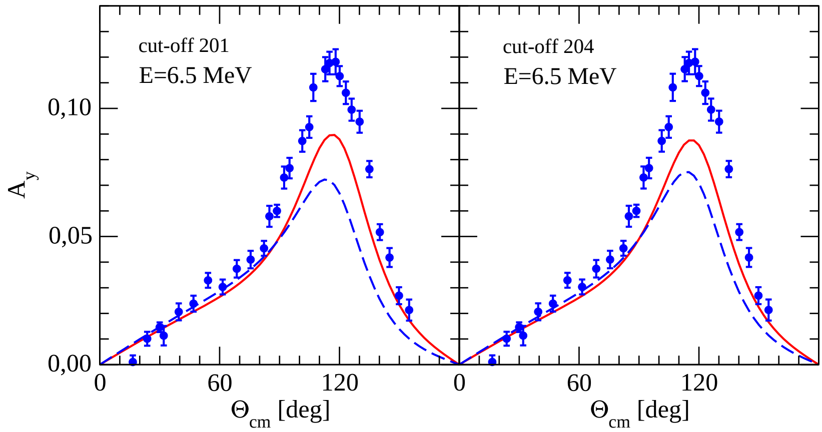

Figure 2. (color online) The neutron analyzing power A_y in elastic nd scattering. In the left and right column the solid (red) line shows predictions of N^{3}LO chiral NN potentials alone and the dashed (blue) line when they are combined with N^{3}LO 3NF composed of 1π-exchange-contact, purely contact, and 2π-exchange-contact terms supplemented with long-range terms: 2π-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 λ 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.

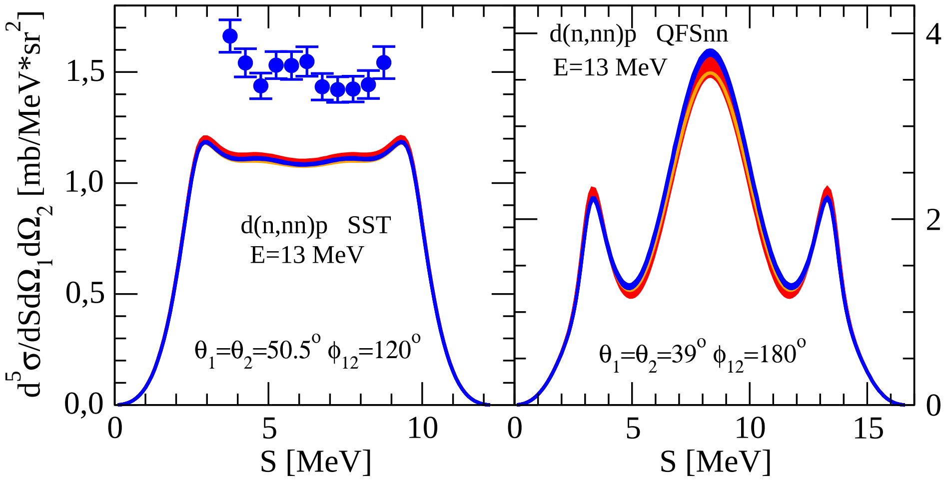

Figure 3. (color online) The cross section $d^5\sigma/d\Omega_1 d\Omega_2 dS$ as a function of the arc-length S in the E_n^{lab} = 13 MeV nd breakup reaction for the SST and QFSnn configurations. The light shaded (red) and dark shaded (blue) bands show predictions of N^{3}LO chiral NN potentials alone and combined with N^{3}LO 3NF (without short-range 2π-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].

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