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Nuclear Physics A 957 (2017) 347–378

NUCLEAR PHYSICS A

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Density-dependent effective baryon–baryon interaction from chiral three-baryon forces

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Received 14 July 2016; received in revised form 23 September 2016; accepted 25 September 2016

Available online 28 September 2016

Abstract

A density-dependent effective potential for the baryon–baryon interaction in the presence of the (hyper)nuclear medium is constructed, based on the leading (irreducible) three-baryon forces derived within SU(3) chiral effective field theory. We evaluate the contributions from three classes: contact terms, one-pion exchange and two-pion exchange. In the strangeness-zero sector we recover the known result for the in-medium nucleon–nucleon interaction. Explicit expressions for the ΛN in-medium potential in (asymmetric) nuclear matter are presented. Our results are suitable for implementation into calculations of (hyper)nuclear matter. In order to estimate the low-energy constants of the leading three-baryon forces we introduce the decuplet baryons as explicit degrees of freedom and construct the relevant terms in the minimal non-relativistic Lagrangian. With these, the constants are estimated through decuplet saturation. Utilizing this approximation we provide numerical results for the effect of the three-body force in symmetric nuclear matter and pure neutron matter on the ΛN interaction. A moderate repulsion that increases with density is found in comparison to the free ΛN interaction.

Keywords: Chiral effective field theory; Three-baryon forces; Hyperons; Nuclear matter

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http://dx.doi.org/10.1016/j.nuclphysa.2016.09.010
0375-9474/

1. Introduction

Three-body forces (3BFs) are an indispensable ingredient of any modern calculation of few-nucleon systems. Specifically, for the three- and four-nucleon systems where rigorous computations can be performed based on the Faddeev or Faddeev–Yakubovsky equations there is clear evidence that agreement with experimental data cannot be achieved if one resorts to nucleon–nucleon (NN) forces alone. Three-nucleon forces are required to reproduce correctly the binding energies in the few-nucleon sector but also for scattering observables such as the proton–deuteron differential cross section at incident proton energies around 100–200 MeV. For a recent review on these topics see, for example, [1]. Accordingly, one expects that such three-body forces are also important for heavier nuclei as well as for the properties of nuclear matter. Indeed, in the latter case standard calculations based on two-body interactions and utilizing the Bethe–Goldstone equation are unable to describe the saturation point correctly, i.e., to obtain the empirical energy per nucleon of $E/A = -16$ MeV at the saturation density $\rho_0 = 0.17\ \mathrm{fm}^{-3}$. Three-nucleon forces are considered as an essential mechanism that could resolve this problem [2–5].

Likewise, three-body forces are expected also to play an important role in strangeness nuclear physics, in particular the Lambda-nucleon–nucleon (ΛNN) interaction, see for example Refs. [6–11]. It has been argued in the context of (exotic) neutron star matter that strongly repulsive 3BFs are needed in order to explain the recent observation of two-solar-mass neutron stars, i.e., to resolve the so-called hyperon puzzle [12–18]. For example, a phenomenological ΛNN three-body force has been introduced in Ref. [17], with a repulsive coupling strength chosen large enough just so that the Λ is prevented from appearing in dense matter and the equation-of-state remains sufficiently stiff to support a $2\,M_\odot$ neutron star. The situation is less clear when it comes to light hypernuclei such as the hypertriton ${}^{3}_{\Lambda}\mathrm{H}$, or ${}^{4}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{He}$, owing to the fact that the two-body interaction in the relevant ΛN and ΣN systems is not well determined from the scarce experimental data presently available.

Utilizing realistic models of the three-baryon force directly in many-body calculations or in the Brueckner–Bethe–Goldstone approach (e.g., via the Bethe–Faddeev equations [19]) is a very challenging technical task. Therefore, it has become customary to follow an alternative and simpler approach that consists in employing a density-dependent two-body interaction derived from the underlying three-body forces. For the nucleonic sector such a density-dependent in-medium NN interaction, generated at one-loop order by the leading chiral three-nucleon force, has been constructed in Ref. [20]. It has been shown in subsequent studies [21,22] and by several other calculations in the literature [23–28] that this approximate treatment of three-body forces works very well.

In the present work we investigate the effect of the ΛNN three-body force on the ΛN interaction in the presence of a nuclear medium. We start from the leading (irreducible) 3BFs, cf. Fig. 1, which have been derived recently [29] within SU(3) chiral effective field theory (χEFT), a systematic approach that exploits the symmetries of the underlying QCD. Among other advantages, this approach ensures that the three-body forces are constructed consistently with the corresponding two-baryon interactions (e.g. ΛN, ΣN) [30,31]. In our derivation we follow closely the work of Ref. [20] and extend those calculations to sectors with non-zero strangeness. As a result one obtains a density-dependent effective baryon–baryon interaction which facilitates the inclusion of effects from 3BFs into many-body calculations.

The irreducible chiral 3BFs appear formally at next-to-next-to-leading order (NNLO). However, in the nucleonic sector one has observed that some of the corresponding low-energy constants (LECs) are much larger than expected from the hierarchy of nuclear forces. This feature has