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Baryon–baryon interactions from chiral effective field theory

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Abstract

Results from an ongoing study of baryon–baryon systems with strangeness $S = -1$ and -2 within chiral effective field theory are reported. The investigations are based on the scheme proposed by Weinberg which has been applied rather successfully to the nucleon–nucleon interaction in the past. Results for the hyperon–nucleon and hyperon–hyperon interactions obtained to leading order are reviewed. Specifically, the issue of extrapolating the binding energy of the H-dibaryon, extracted from recent lattice QCD simulations, to the physical point is addressed. Furthermore, first results for the hyperon–nucleon interaction at next-to-leading order are presented and discussed.

Keywords: Hyperon–nucleon interaction; Hyperon–hyperon interaction; Lattice QCD; Effective field theory

1. Introduction

Chiral effective field theory (EFT) as proposed in the pioneering works of Weinberg [1,2] is a powerful tool for the derivation of nuclear forces. In this scheme there is an underlying power counting which allows to improve calculations systematically by going to higher orders in a perturbative expansion. In addition, it is possible to derive two- and corresponding three-nucleon forces as well as external current operators in a consistent way. Over the last decade or so it has been demonstrated that the nucleon–nucleon (NN) interaction can be described to a high precision within the chiral EFT approach [3,4]. Following the original suggestion of Weinberg, in these works the power counting is applied to the NN potential rather than to the reaction

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amplitude. The latter is then obtained from solving a regularized Lippmann–Schwinger equation for the derived interaction potential. The NN potential contains pion-exchanges and a series of contact interactions with an increasing number of derivatives to parameterize the shorter ranged part of the NN force. For reviews we refer the reader to Refs. [5–7].

In the present contribution I focus on recent investigations by the groups in Bonn–Jülich and Munich on the baryon–baryon interaction involving strange baryons, performed within chiral EFT [8–12]. In these works the same scheme as applied in Ref. [4] to the NN interaction is adopted. First I discuss the application to the strangeness $S = -1$ sector (ΛN, ΣN). Here the extension of our study [8] to next-to-leading order (NLO) is in progress [12] and a first glimpse on the (still preliminary) achieved results for the ΛN and ΣN interactions will be given. Then I report results of a study on the strangeness $S = -2$ sector, i.e. for the $\Lambda\Lambda$, $\Sigma\Sigma$, and cascade–nucleon (ΞN) interactions. Predictions obtained at leading order (LO) [9] are reviewed and implications for the H-dibaryon are discussed, based on our framework, in the light of recent lattice QCD calculations where evidence for the existence of such a state was found.

At LO in the power counting, as considered in the aforementioned investigations [8–10], the baryon–baryon potentials involving strange baryons consist of four-baryon contact terms without derivatives and of one-pseudoscalar-meson exchanges, analogous to the NN potential of [4]. The potentials are derived using constraints from SU(3) flavor symmetry. At NLO one gets contributions from two-pseudoscalar-meson exchange diagrams and from four-baryon contact terms with two derivatives [4].

The paper is structured as follows: In Section 2 a short overview of the chiral EFT approach is provided. In Section 3 results for the ΛN and ΣN interactions obtained to NLO are presented. In Section 4 results for the $S = -2$ ($\Lambda\Lambda$, ΞN $\Sigma\Sigma$) systems are briefly reviewed and connection is made with lattice QCD results for the H-dibaryon case. The paper ends with a short summary.

2. Formalism

The derivation of the chiral baryon–baryon potentials for the strangeness sector at LO using the Weinberg power counting is outlined in Refs. [8,10,14]. Details for the NLO case will be presented in a forthcoming paper [12], see also [11,13]. The LO potential consists of four-baryon contact terms without derivatives and of one-pseudoscalar-meson exchanges while at NLO contact terms with two derivatives arise, together with contributions from (irreducible) two-pseudoscalar-meson exchanges.

The spin and momentum structure of the potentials resulting from the contact terms to LO is given by

$$V^{(0)}_{BB\to BB} = C_{S;BB\to BB} + C_{T;BB\to BB}(\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2) \tag{1}$$

in the notation of [4] where the $C_{i;BB\to BB}$'s are so-called low-energy coefficients (LECs) that need to be determined by a fit to data. Due to the imposed $\mathrm{SU(3)_f}$ constraints there are only five independent LECs for the NN and the YN sectors together, as described in Ref. [8] where also the relations between the various $C_{i;BB\to BB}$'s are given. A sixth LEC is, however, present in the strangeness $S = -2$ channels with isospin $I = 0$.

In next-to-leading order one gets the following spin and momentum structure:

$$\begin{aligned} V^{(2)}_{BB\to BB} = {} & C_1\mathbf{q}^2 + C_2\mathbf{k}^2 + \big(C_3\mathbf{q}^2 + C_4\mathbf{k}^2\big)(\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2) + \frac{i}{2}C_5(\boldsymbol{\sigma}_1 + \boldsymbol{\sigma}_2)\cdot(\mathbf{q}\times\mathbf{k}) \\ & + C_6(\mathbf{q}\cdot\boldsymbol{\sigma}_1)(\mathbf{q}\cdot\boldsymbol{\sigma}_2) + C_7(\mathbf{k}\cdot\boldsymbol{\sigma}_1)(\mathbf{k}\cdot\boldsymbol{\sigma}_2) + \frac{i}{2}C_8(\boldsymbol{\sigma}_1 - \boldsymbol{\sigma}_2)\cdot(\mathbf{q}\times\mathbf{k}). \end{aligned} \tag{2}$$