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Faddeev–Yakubovsky calculations for $A = 4$ hypernuclear systems ☆

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Abstract

We present results for the Λ separation energies of the four-body hypernuclei ${}^4_\Lambda$He and ${}^4_\Lambda$H based on solutions of the Yakubovsky equations for these systems. Our results show that none of the Nijmegen soft-core models or the Jülich $\tilde{\text{A}}$ model correctly binds all four-body hypernuclei states simultaneously. We discuss the possibilities to constrain hyperon–nucleon interactions using the charge-dependence of the four-body Λ separation energies.

1. Introduction

The properties of the Λ nucleon (ΛN) interactions are to a large extent unknown. In contrast to the two-nucleon (NN) system, where the world NN database comprises several thousand data, there are only 35 data for ΛN and ΣN scattering available [1].

Because of this situation, one has to constrain the hyperon–nucleon (YN) interaction using the known binding energies of hypernuclei. The three- and four-body nuclei are especially important, because reliable methods exist to solve the Schrödinger equation for these systems. The results for ${}^3_\Lambda$H have already shown that only some YN interaction models can describe its binding energy [2]. But the very small binding energy of ${}^3_\Lambda$H leads to rather large uncertainties in the experimental value. Moreover, only one spin and isospin

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state is bound for ${}^{3}_{\Lambda}$H, so that it can only provide limited information on the spin and isospin dependence of the YN interaction. On the other hand, ${}^{4}_{\Lambda}$H and ${}^{4}_{\Lambda}$He are found in two spin states, the $J = 0^+$ ground and $J = 1^+$ excited states, and their binding energies are accurately known experimentally making them very interesting to study YN forces.

YN forces are not only an extension of ordinary nuclear forces, but offer a wide variety of new phenomena and insights into the nuclear interactions. One of these phenomena is the strong conversion of the ΛN system to a ΣN system. The Σ particle differs in mass only by 80 MeV from the Λ particle. Due to isospin conservation, 1π exchange is suppressed in the ΛN system. Therefore, the 2π exchange with intermediate Σ accounts for the longest range part of the interaction. Moreover, the conversion process takes place in s-waves. Therefore, it is by far more important than a conversion of nucleons in Δ particles in ordinary nuclear physics. Because the YN interaction is generally weaker than the NN interaction, hypernuclei have a core–hyperon structure. For some isospins and spins of the core nucleus, isospin conservation leads to a suppression of the conversion process in the nuclear medium [3,4], which induces a strong medium dependence in effective ΛN interactions, where the Σ has been integrated out. This effect has been observed [2,5,6] in several three- and four-body calculations and even used to alter the YN interaction in the medium [7]. Taking explicit Σ into account is mandatory in few-nucleon systems, if one wants to learn about the free interaction from such studies.

Several one-meson exchange models of the YN interaction have been developed. The efforts of the Nijmegen group culminated in the SC89 [8] and SC97 [9,10] models. Because the parameters in these one-meson exchange models cannot be fixed by the scarce YN scattering data, it is assumed that flavor SU(3) symmetry applies to the coupling constants of the baryon–baryon–meson vertices. Their model includes charge-symmetry breaking (CSB) terms, not only due to the mass differences of the mesons, but also due to Λ–Σ^0 mixing. The Nijmegen SC97a-f models are a series of interactions with different spin dependences, which is reflected in a range of predictions of the singlet and triplet ΛN scattering lengths.

Another model, also based on one-meson exchange, has been developed by the Jülich group [11]. Based on the full Bonn interaction [12] for the NN system, they extended the interaction to the YN system applying SU(6) spin-flavor symmetry to the coupling constants. CSB is induced only by the mass differences of the mesons. Because the Bonn–Jülich models generally take the full Dirac structure of the baryons into account, the resulting interactions are strongly non-local. The scalar mesons are seen as effective parameterization of correlated two-meson exchanges. In contrast to the Nijmegen interactions, the couplings are not related by flavor symmetry and taken as free parameters of the models. In this work, we only employ the Jülich $\tilde{\mathrm{A}}$ interaction of this series. It is energy independent and therefore suitable for few-body calculations.

Here we discuss in more detail a recent study of the binding energies of the four-body hypernuclei based on full YN interaction models [13]. It is based on Yakubovsky equations (YEs). Therefore, we start with a discussion of their numerical implementation in Section 2. In Section 3, we present our results. Conclusions and an outlook are given in Section 4.