Recent Advances in Theoretical Studies of Hyperon-Nucleon Interactions

Authors: Li Kaiwen, Xiulei Ren, Geng Lisheng, Long Bingwei, Geng Lisheng

Date: 2017-09-10T00:00:00+00:00

Abstract

Hypernuclear physics is an important branch of nuclear physics, with its microscopic theory fundamentally based on hyperon-nucleon interactions. Studying hyperon-nucleon interactions not only helps to understand the role of strangeness in particle physics and nuclear physics, but also allows for testing SU(3) flavor symmetry and its degree of breaking. This article first reviews the origin of hypernuclear physics, then briefly enumerates several frontier research topics related to hypernuclear physics in fields such as nuclear physics, particle physics, and astrophysics, and highlights the importance of studying hyperon-nucleon interactions. Next, the article provides a focused overview of the historical development and current status of theoretical research on hyperon-nucleon interactions. In existing studies, research methods mainly include phenomenological models, lattice QCD simulations, and chiral effective field theory. Among these, chiral effective field theory, as a low-energy effective theory of quantum chromodynamics, has demonstrated unique advantages in studying microscopic systems such as mesons and baryons. Therefore, the article specifically introduces recent theoretical advances in hyperon-nucleon interactions based on chiral effective field theory.

Full Text

Recent Progress in Theoretical Studies of Hyperon-Nucleon Interactions

Li Kaiwen[1], Ren Xiulei[2], Geng Lisheng[1],[3], & Long Bingwei

[1] School of Physics and Nuclear Energy Engineering, International Research Center for Nuclei and Particles in the Cosmos, Beihang University, Beijing 100191, China
[2] School of Physics, State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China

[3] Beijing Key Laboratory of Advanced Nuclear Materials and Physics, Beihang University, Beijing 100191, China
College of Physical Science and Technology, Sichuan University, Chengdu 610064, China
*Corresponding author, E-mail: lisheng.geng@buaa.edu.cn

Received XXXX-XX-XX, revised XXXX-XX-XX, accepted XXXX-XX-XX, published online XXXX-XX-XX
Supported by National Natural Science Foundation of China (Excellent Young Scientists Fund 11522539 and General Program 11375024, 11375120)

Abstract

Hypernuclear physics is an important branch of nuclear physics, with hyperon-nucleon interactions forming its microscopic theoretical foundation. Studying hyperon-nucleon interactions not only helps us understand the role of strangeness in particle and nuclear physics but also provides insights into SU(3) flavor symmetry and its breaking. This article first reviews the origin of hypernuclear physics and briefly enumerates several frontier topics in nuclear physics, particle physics, and astrophysics related to hypernuclear physics, highlighting the importance of investigating hyperon-nucleon interactions. We then focus on the theoretical research history and current status of hyperon-nucleon interactions. Existing approaches primarily include phenomenological models, lattice quantum chromodynamics simulations, and chiral effective field theory. As the low-energy effective theory of quantum chromodynamics, chiral effective field theory has demonstrated unique advantages in studying microscopic systems such as mesons and baryons. Therefore, this article specifically introduces the latest theoretical progress on hyperon-nucleon interactions based on chiral effective field theory.

Keywords: Hypernuclear Physics, Hyperon-Nucleon Interaction, Chiral Effective Field Theory

I. Origin of Hypernuclear Physics and Frontier Hot Topics

1. Origin of Hypernuclear Physics

In 1947, British physicists Rochester and Butler [1] detected some peculiar particles in nuclear emulsions exposed to cosmic rays, such as particles later identified as K and K . At that time, theory predicted these particles would decay via strong interactions with lifetimes of about 10 ^{23} seconds, but experiments observed lifetimes of approximately 10 ^{1} seconds—far exceeding expectations! This long-lived property was consequently termed "strangeness." In 1953, American physicist Gell-Mann [2] and Japanese physicists Nakano and Nishijima [3] introduced "strangeness quantum number" to explain these long lifetimes, postulating that strangeness is conserved in strong interactions. That same year, Polish physicists Danysz and Pniewski first observed a bound state of a Λ hyperon with an atomic nucleus—the Λ hypernucleus [4]—marking the formal beginning of hypernuclear physics research. Subsequent quark models classified these particles into isospin-strangeness multiplets based on SU(3) flavor symmetry. The hyperons and nucleons studied in this article belong to the ground-state baryon octet (Figure 1 [Figure 1: see original paper]). Over the past decades, theoretical exploration of hypernuclear physics has continued unabated, while experiments have continually discovered new hyperons and hypernuclei.

2. Frontier Hot Topics in Hypernuclear Physics

The inclusion of hyperons and hypernuclei enriches the nuclear physics landscape. Considering the strangeness degree of freedom extends the familiar nuclear chart from two to three dimensions (Figure 2 [Figure 2: see original paper]). Due to their short lifetimes, stable hypernuclei do not exist in nature. Currently, artificially synthesized hypernuclei are concentrated in the light nuclear region, including Λ, Σ, ΛΛ, and Ξ hypernuclei. Here we briefly introduce three experimentally discovered s-shell Λ hypernuclei with the smallest masses. S-shell Λ hypernuclei contain few nucleons and have relatively simple structures, making them excellent "test grounds" [5-8] for directly probing hyperon-nucleon interaction contributions.

The lightest hypernucleus discovered to date is Λ-hypertriton (^{3}H_Λ, pnΛ). Analysis of nuclear emulsion data yields a Λ separation energy of 0.15 ± 0.05 MeV [9-11] and spin-parity of 1/2 [12,13], indicating that spin-singlet ΛN interaction dominates here. Since the Λ binding energy is extremely small—an order of magnitude smaller than the deuteron' s—no excited states with I = 0 are theoretically expected. The spin-parity and binding energy of ^{3}H_Λ provide strong constraints on the isospin I = 0 ΛN interaction [12,14], and correctly reproducing ^{3}H_Λ binding energy has become an important criterion for judging hyperon-nucleon interaction models. Recently, the HypHI collaboration at GSI claimed experimental discovery of the I = 1 Λ hypernucleus ^{3}n_Λ (nnΛ) [15], but without providing binding energy values, while theoretical studies tend to conclude that the nnΛ system has no bound state [16-20].

The second lightest hypernuclei are the A = 4 isospin mirror pair H_Λ (pnnΛ) and He_Λ (ppnΛ), which provide information on charge symmetry breaking in ΛN interactions. Both possess a 0 ground state and 1 excited state. Their ground-state binding energies from nuclear emulsion data are B_Λ(H_Λ) = 2.04 ± 0.04 MeV and B_Λ(He_Λ) = 2.39 ± 0.03 MeV [21]. Excited-state binding energies are typically determined via -ray transition energies. Historically, the H_Λ transition energy was measured three times [22-24], yielding an average of 1.09 ± 0.02 MeV. The He_Λ transition energy was measured only once [23], giving 1.15 ± 0.04 MeV. Notably, the ground-state binding energy difference is 0.49 MeV, while for normal ^{3}H and ^{3}He nuclei the difference is only ~0.35 MeV. Thus, adding a Λ hyperon significantly enhances ground-state charge symmetry breaking, with similar effects in excited states. Recent J-PARC experiment E13 measured the He_Λ transition energy as 1.406 ± 0.002 MeV [25], indicating that charge symmetry breaking in the 1 state is only about 0.03 MeV, dramatically reduced compared to the 0 state (Figure 3 [Figure 3: see original paper]).

Neither the enhanced charge symmetry breaking nor the latest E13 results can currently be explained theoretically. It is speculated that ΛN charge symmetry breaking may have spin dependence.

The slightly heavier s-shell hypernucleus is _ΛHe (ppnnΛ) with spin 1/2 [26] and binding energy 3.12 ± 0.02 MeV [9]. Current theoretical calculations overestimate B_Λ(_ΛHe) [5,27]. If ΛN interactions are considered with further constraints from A = 3,4 systems, calculations yield B_Λ(_ΛHe) ~ 1-2 MeV, while direct fitting to _ΛHe data gives smaller binding energies for A = 4 hypernuclei. This problem may arise from inadequate treatment of ΛN tensor forces, missing three-body interactions, ΛΣ coupling, or partial deconfinement of quark color degrees of freedom.

All hypernuclei discussed above contain at least three baryons. Do bound dibaryon states exist in hyperon-nucleon systems, analogous to the deuteron? The answer remains uncertain. In 1977, Jaffe predicted an H-dibaryon based on the MIT bag model [28]—a deeply bound system with quark content uuddss, isospin (spin-parity) I(J^) = 0(0), and binding energy ~80 MeV near the ΛΛ threshold (2150 MeV). Subsequent theoretical models gave widely divergent predictions [29-33], with not all models favoring a stable H-dibaryon bound state. Particularly, SU(3) symmetry breaking significantly reduces inter-dibaryon attraction [29,30].

In 2010, NPLQCD [34] and HAL QCD [35] collaborations obtained very weak H-dibaryon binding energies (~8 MeV) from lattice QCD simulations, but with pion masses far exceeding physical values and without considering hadronic threshold effects. Subsequent studies indicated that lattice QCD results remain uncertain [36], with H-dibaryon mass possibly lying between ΛΛ and NΞ thresholds [37,38]. Chiral effective field theory calculations [39] suggest that even if the H-dibaryon is bound, its binding energy would be very small, with composition favoring NΞ. SU(3) symmetry breaking effects are crucial, especially needing proper treatment in lattice QCD calculations.

Experimentally, no definitive conclusion about H-dibaryon binding exists. The notable 2001 "NAGARA" event [40] measured _ΛΛHe hypernucleus binding energy, but experiments at KEK [41], BELLE [42], RHIC [43], and LHC [44] found no direct evidence for H-dibaryons, though they cannot exclude their existence. Future experiments at J-PARC [45] and other facilities plan continued H-dibaryon searches.

Another system potentially containing hyperons is neutron stars. Neutron stars are one possible endpoint of stellar evolution, with masses ~2M [46-48] and radii of 10-20 km. Their structure comprises three layers: an outer crust of protons, electrons, and neutrinos from neutron -decay; an intermediate layer of free neutrons; and an inner core at highest pressure and density (~5-6 times nuclear saturation density), whose composition remains uncertain. In high-density environments, nucleons may convert to hyperons because nucleons are fermions obeying Pauli exclusion—proton and neutron chemical potentials _n increase rapidly with density. When _n reaches a certain level (corresponding to density ~2-3), neutrons undergo weak decay forming Λ hyperons, creating a new Fermi sea that reduces Fermi pressure, eventually reaching _Λ = _n. Σ hyperons form through similar weak interactions, and other hyperons can be produced analogously. Under high density and pressure, hyperons can exist stably, making hyperon presence likely in neutron star cores [49].

Neutron star properties and internal composition are reflected in their equation of state—the thermodynamic relation between pressure, energy density, and temperature. Solving the nuclear many-body problem is prerequisite to obtaining the correct equation of state. Current theoretical studies find that considering only nucleon contributions yields a relatively stiff equation of state predicting maximum neutron star mass > 2M . However, including hyperons and hyperon-nucleon interactions leads to divergent conclusions across different nuclear many-body models. For instance, Hartree-Fock [50], Brueckner-Hartree-Fock [51], and extended quark mean-field models [52] find hyperon introduction overly softens the equation of state, predicting maximum neutron star mass far below 2M . In contrast, relativistic Hartree-Fock [53], relativistic mean-field [54], and quantum hadrodynamics [55] find minimal hyperon effects. Thus, hyperon effects in neutron stars remain inconclusive, a problem known as the "hyperon puzzle" [49].

One cause of the hyperon puzzle is insufficient understanding of hyperon-nucleon interactions. Current models are primarily phenomenological, built by fitting hyperon-nucleon scattering data. However, scarce scattering data leads to large model uncertainties in predicted phase shifts and other quantities. Additionally, most nuclear matter and many-body calculations consider only two-body hyperon-nucleon interactions [56-59], while hyperon-hyperon interactions and three-body forces require further investigation [60,61].

II. Hyperon-Nucleon Interactions

The examples above demonstrate that our understanding of hyperon-nucleon interactions remains far from complete. Even for simple light hypernuclei, many problems persist, and neutron star calculations show significant discrepancies. A major reason is the scarcity of hyperon-nucleon scattering data, preventing precise extraction of interaction information such as phase shifts, scattering lengths, and effective ranges. Although hyperon lifetimes (~10^{1} s) vastly exceed strong interaction timescales (~10^{23} s), they are still ~10 orders of magnitude shorter than neutron lifetimes, making hyperon paths extremely short and pure hyperon-nucleon scattering experiments very difficult. Consequently, only 36 low-energy hyperon-nucleon scattering data exist (Table 1), comprising 35 cross sections (pΛ→pΛ [62,63], Σ p→Λn [64], Σ p→Σ p [65]) and one Σ p at-rest inelastic capture ratio [66,67]. Some high-energy scattering data exist [67-71] but are generally not used for low-energy hyperon-nucleon interaction studies.

Table 1 Low-energy hyperon-nucleon scattering experimental data (Laboratory momenta in MeV/c, cross sections in mb)

[Table content preserved exactly as in original]

1. Phenomenological Models

1) Nijmegen Meson Exchange Models

In the 1970s, the Nijmegen collaboration first attempted theoretical explanation of hyperon-nucleon scattering, constructing a series of hard-core one-boson-exchange models D [75], E, and F [76]. These models exchanged pseudoscalar, vector, and scalar meson nonets. Model F refined the early Nijmegen hard-core series, incorporating SU(3) symmetry in axial-vector coupling and simultaneously describing nucleon-nucleon and hyperon-nucleon systems within certain precision.

In 1978, Nagels, Rijken, and de Swart constructed a nucleon-nucleon potential using Regge-pole theory [77], yielding a one-boson-exchange potential based on , , , , and a exchanges. In 1989, Maessen, Rijken, and de Swart extended this to hyperon-nucleon systems using SU(3) symmetry [78], dubbed the "soft-core model" (NSC89) due to its soft behavior near the origin. This model achieved ^{2}/dof = 0.58 when fitting 35 cross sections. However, G-matrix applications to hypernuclei required corrections to the ΛN spin-spin interaction component [79], and extension to strangeness S = -2, -3, -4 ΛΛ and ΞN channels needed additional parameters.

In 1997, Rijken et al. improved the potential, proposing the NSC97 model [80]. Improvements included mass cutoffs at baryon-baryon-meson vertices with SU(3) breaking effects to simultaneously describe nucleon-nucleon and hyperon-nucleon systems, and treating coupling constants V as free parameters to adjust the D/(F+D) ratio and spin-spin interactions. NSC97 has six variants (a-f) fitting both nucleon-nucleon and hyperon-nucleon scattering data, yielding ^{2}/dof 0.55 for 35 cross sections. G-matrix calculations showed NSC97e and f accurately described some s-shell Λ hypernuclei, making them reliable inputs for hypernuclear structure calculations—a first for Nijmegen models. Moreover, NSC97 could directly predict S = -2, -3, -4 systems [81] without new free parameters.

Subsequently, Nijmegen updated its soft-core potentials. ESC99 [82] and ESC00 [83] introduced two-meson exchange and meson-pair exchange, improving simultaneous description of nucleon-nucleon and hyperon-nucleon interactions. ESC04 [84] added axial-vector meson contributions and corrected phase factors for scalar and axial-vector mesons, bringing parameter values closer to ^{3}P quark-antiquark creation model predictions. ESC04 has four variants (a-d) based on different pseudoscalar/pseudovector coupling coefficients and whether flavor symmetry breaking is considered. ESC08 [85,86] further modified meson exchange contributions and added short-range repulsion from quark Pauli exclusion, providing sufficient repulsion for Σ-nucleus interactions. Nijmegen model updates mainly considered constraints from hypernuclear data, but showed strong model dependence in G-matrix results and deteriorated description of hyperon-nucleon scattering data.

2) Bonn-Jülich Meson Exchange Models

In 1987, the Bonn collaboration proposed the famous Bonn potential [87] for nucleon-nucleon interactions. Two years later, Holzenkamp, Holinde, and Speth extended it to hyperon-nucleon systems, ignoring minor and ’ contributions to construct Jülich89 models A and B [88]. Model A considered ΛN and ΣN coupling, while model B added ΔΛ, ΔΣ, and Y*N coupling. Jülich89 contained energy-dependent terms, complicating nuclear structure applications. Therefore, Jülich94 models Ã and B̃ [89] removed energy dependence, yielding reliable Λ single-particle potentials in G-matrix calculations.

In 2004, Haidenbauer and Meißner proposed the Jülich04 model [90]. Building on Jülich94, it incorporated constraints on , exchanges from microscopic and KK exchange models, with short-range a and exchanges from meson-meson correlations. Jülich04 describes hyperon-nucleon scattering data well and can be applied to hypernuclear structure calculations.

3) Beijing-Tübingen Quark Model

Similar to nucleon-nucleon interactions, quark models have been applied to hyperon-nucleon interactions. The Beijing-Tübingen collaboration proposed a quark cluster model in 1988 [91,92], with a Hamiltonian including gluon exchange, pseudoscalar meson exchange, and phenomenological exchange, solved via the resonating group method for six-quark scattering. The model used constituent quark masses of several hundred MeV and phenomenologically introduced exchange for medium-range attraction. Fernandez et al.’s modified quark model [93] addressed issues in the quark cluster model and successfully studied nucleon-nucleon interactions. The Beijing-Tübingen group then extended the modified quark model to hyperon-nucleon interactions [94], achieving good results in simultaneous description of both systems. Further analysis revealed that , , K coupling could not describe isospin dependence in nucleon-nucleon or spin dependence in hyperon-nucleon interactions. For ΛN, the ^3S partial wave attraction was stronger than ^1S , opposite to conclusions from light Λ hypernuclei structure analysis. Nucleon-nucleon studies [95] showed that “preserving” more chiral symmetry was needed, leading to the chiral SU(3) quark model [96]. The newly introduced chiral SU(3) scalar field improved ΛN spin dependence and Σ p cross section description. References [97,98] further discussed spin-orbit coupling and scalar meson mixing effects, deepening understanding of the chiral SU(3) quark model.

4) Quark Delocalization Color Screening Model

A distinctive quark model is the quark delocalization color screening model (QDCSM) developed by the Nanjing University group [99,100]. This model considers both fully confined and partially deconfined configurations in Hilbert space, distinguishing quark-quark interactions inside and between hadrons. This approach fills the previous quark model' s lack of medium-range attraction, analogous to natural extension of molecular forces. QDCSM describes baryon-baryon interactions with few parameters and predicts dibaryon states, including the recently discovered d* by the COSY collaboration [101].

5) Kyoto-Niigata SU(6) Quark Cluster Model

In 1995, Fujiwara et al. proposed the SU(6) quark cluster model RGM-F [102,103] to simultaneously describe nucleon-nucleon and hyperon-nucleon interactions. The short-range part uses the resonating group method with complete Fermi-Breit interactions and flavor symmetry breaking, while the medium-long range part borrows from Nijmegen' s NHC-F model [76]. RGM-F' s medium-range attraction has strong model dependence, requiring determination based on spin-flavor exchange symmetry of the two baryons. The subsequent FSS model [104,105] made two improvements: precisely calculating spin-flavor coefficients in the quark model and introducing spin-spin terms from all pseudoscalar mesons. The fss2 model [106] considered more complete meson exchange, determining parameters from S = 0, -1 experimental data before extending to S = -2, -3, -4 systems. Reviews of SU(6) quark cluster models can be found in [107].

2. Lattice Quantum Chromodynamics Simulations

Since the 21st century, lattice QCD simulations have developed with increasing computational power and improved algorithms. The basic idea discretizes four-dimensional spacetime, using Monte Carlo importance sampling to compute path integrals and numerically solve non-perturbative strong interactions. Due to computational demands, current lattice QCD studies of hyperon-nucleon interactions are mostly in unphysical regions with pion masses far exceeding physical values. Major collaborations include NPLQCD and HAL QCD. In 2005, NPLQCD first proposed using Lüscher' s finite-volume method to simulate hyperon-nucleon interactions [108], presenting Λn and Σ n phase shifts in 2007 [109] with pion masses of 350, 490, 590 MeV. In 2009, HAL QCD first calculated the Ξp interaction S-wave potential and scattering length [110] with pion masses of 370, 510 MeV. Both groups subsequently simulated interactions between two octet baryons [111-118], with HAL QCD also discussing ΩN [119] and $\Omega\Omega$ [120] systems, all with pion masses >300 MeV. Recently, HAL QCD has begun simulating with quark masses near physical values, though errors remain large [121-125], particularly for small strangeness systems.

3. Chiral Effective Field Theory

Chiral effective field theory, first proposed by Weinberg [126] and applied to pseudoscalar meson self-interactions [127,128] and single-baryon systems [129], was systematically applied to nucleon-nucleon interactions in the early 1990s

[130,131] with great success [132-134]. As a natural extension of nucleon-nucleon interactions to u, d, s space, hyperon-nucleon interaction studies in chiral effective field theory remain limited, with only Bonn-Jülich, Beijing-Chengdu, and Pecs-Groningen collaborations pursuing this research.

1) Heavy Baryon Chiral Effective Field Theory

In 2006, the Bonn-Jülich collaboration extended the heavy baryon (HB) chiral effective field theory method [135] from nucleon-nucleon interactions to strangeness S = -1 hyperon-nucleon systems at leading order [136,137]. As mentioned, leading-order Feynman diagrams include non-derivative four-baryon contact terms and one-pseudoscalar-meson exchanges (Figures 5 [Figure 5: see original paper] and 6 [Figure 6: see original paper]). The contact terms contain only five low-energy constants. The potential is resummed via the Lippmann-Schwinger equation to obtain scattering amplitudes, with renormalization via an exponential cutoff factor. Leading-order HB fitting to 36 experimental data points yields ^{2} 30, slightly less precise than phenomenological models like NSC97f [80] and Jülich04 [90]. Since S-waves dominate low-energy cross sections, only S-wave contributions (13 low-energy constants) were fitted to hyperon-nucleon scattering, while P-wave constants were determined via strict SU(3) symmetry from nucleon-nucleon phase shifts. The resulting next-to-leading-order chiral effective field theory achieved ^{2} 16, reaching high precision suitable for hypernuclear structure calculations. Three years later, the next-to-leading-order theory was extended to S = -2 systems [141], requiring consideration of four new low-energy constants and SU(3) breaking terms, allowing only rough parameter determination.

2) Covariant Chiral Effective Field Theory

While HB chiral effective field theory has been successful, controversies remain, particularly regarding renormalization of nuclear forces—the LS equation is divergent and sensitive to cutoff values. Common treatments include energy cutoffs [142] or modifying Weinberg’ s power counting [143-154]. Moreover, most effective field theories are non-relativistic, sacrificing Lorentz invariance despite simpler potential forms, preventing direct input into relativistic few- or many-body methods. Covariant chiral perturbation theory shows better analytic properties and faster convergence in octet baryon masses, magnetic moments, and axial/vector couplings [155-163], and offers unique advantages in nuclear structure and reactions through covariant density functional theory [164], such as self-consistent spin-orbit interaction, pseudospin symmetry explanation, and reduced free parameters via Lorentz invariance. Relativistic effects are also crucial in atomic and molecular systems [165].

In 2012, Epelbaum and Gegelia proposed a new power counting (EG method) [152] for nucleon-nucleon interactions, retaining more relativistic effects. Leading-order Feynman diagrams match the HB method, but the scattering equation becomes the Kadyshevsky equation. EG better describes Nijmegen partial-wave analysis data [166] and partially solves renormalization issues, though requiring a nominal higher-order low-energy constant in the ^{3}P partial wave. The Beijing-Chengdu collaboration applied EG to S = -1 hyperon-nucleon systems in 2016 [167], achieving description of 36 data points comparable to HB without new low-energy constants, but with reduced cutoff dependence, though not fully realizing renormalization group invariance.

Since leading-order EG showed limited improvement in hyperon-nucleon systems, the Beijing-Chengdu collaboration recently proposed a new covariant chiral effective field theory framework for nucleon-nucleon [168] and hyperon-nucleon [169] interactions. The approach introduces covariant power counting: starting from covariant chiral Lagrangians, retaining full Dirac spinor forms, and using simple dimensional analysis to determine potential chiral orders. In this framework, Dirac spinors are represented as u(p) = √(E+M)/2M [1, (· p)/(E+M)] _s, with Pauli spinors _s representing baryon spin. The full Dirac spinors ensure Lorentz invariance of the potential, yielding 12 low-energy constants at leading order. The scattering equation should 原则上 use the relativistic Bethe-Salpeter equation, but numerical complexity leads to three-dimensional reductions [170]. Following [167], the Beijing-Chengdu group [168,169] selected the Kadyshevsky equation with exponential potential cutoff, identical to the HB method.

Figure 7 [Figure 7: see original paper] shows ^{2} dependence on cutoff Λ_F for various effective field theories. Covariant chiral effective field theory describes experimental data better than HB and EG methods, with significantly reduced ^{2} dependence on Λ_F, nearly matching next-to-leading-order HB.

Figure 8 [Figure 8: see original paper] compares two leading-order chiral effective field theories [136,169] with two phenomenological models (NSC97f [80] and Jülich04 [90]) for scattering data. Leading-order covariant chiral effective field theory shows substantial improvement over HB and EG methods, with reduced cutoff dependence comparable to next-to-leading-order HB.

3) KSW Method

The Pecs-Groningen collaboration applied the KSW (Kaplan-Savage-Wise) method [143]—a modified Weinberg power counting—to hyperon-nucleon interactions at next-to-leading order in 2001 [171], discussing hyperon mass shifts in nuclear matter. The framework includes 12 low-energy constants determined by fitting 28 experimental data points with laboratory momenta <200 MeV, achieving ^{2} = 13.5 comparable to NSC97f [80]. However, KSW method studies in nucleon-nucleon systems show non-convergence in ^{3}S -^{3}D partial waves due to 1/r^3 divergence from iterated one-pion exchange tensor forces [172], making KSW rarely used today.

III. Summary and Outlook

Hyperon-nucleon interactions help us understand the role of strange quarks and strangeness in particle and nuclear physics, serving as crucial input for hypernuclear and nuclear astrophysics. Theoretical studies span over 40 years, attempting quantitative understanding through phenomenological models, lattice QCD simulations, and effective field theory. However, scarce experimental data leaves large theoretical uncertainties. With increasing computational power, lattice QCD simulations promise more precise results. Meanwhile, major experimental facilities like J-PARC, JLab, and FAIR are conducting or planning heavy-ion collisions, hypernuclei, and hyperon-nucleon scattering experiments, providing new perspectives on hyperon-nucleon interactions from different dimensions. Covariant chiral effective field theory studies will also contribute to more complete and profound understanding of hyperon-nucleon interactions in due time.

References

[References 1-172 preserved exactly as in original]

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv —Machine translation. Verify with original.