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Light hypernuclei —a testbed for charge symmetry breaking

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Summary. — Charge symmetry can be considered as an approximate symmetry in nuclear structure and interactions. It is broken in quantum chromodynamics by the up and down quark mass difference and electromagnetic interactions on the level of 10^{-3}. In Λ hypernuclei, charge symmetry breaking (CSB) manifests itself in a charge dependence of Λ separation energies. At the Mainz Microtron MAMI, the novel method of high-resolution spectroscopy of decay-pions in strangeness electro-production was established to measure Λ separation energies. A sizable CSB effect was reaffirmed for the $A = 4$ mirror pair and until recently, it could not be reproduced in any *ab initio* 4-body calculation. The full understanding of this large and spin-dependent effect remains one of the unresolved issues of hypernuclear physics.

1. – Charge symmetry breaking: from quarks to nuclei

Symmetries in physics correspond to conservation laws and are useful to understand complex many-body systems and interactions between their building blocks. Consequently, the observation of symmetry breaking can indicate a new mechanism or an unexpected scenario that was not considered before. Isospin symmetry and the closely related charge symmetry can be considered as approximate symmetries and play a key role in the description of nuclear structure and nuclear reactions.

Isospin, formerly termed isotopic or isobaric spin, is defined in analogy to spin. The concept was first used by Heisenberg in 1932 [1] to describe protons and neutrons as two, nearly identical, fundamental parts of nuclei (“Fundamentalbestandteile”) and the terms were introduced by Wigner in 1937 [2]. Formally, in isospin space, charge independence of the nuclear interaction implies that the nuclear Hamiltonian $\mathcal{H}$ commutes with the third component of the isospin operator, $[\mathcal{H}, I_3] = 0$, that is associated to the positive charge, $Q/e = I_3 + A/2$, and that it commutes with the squared isospin operator, $\left[\mathcal{H}, I^2\right] = 0$. Isospin flips can be achieved through the operators $I_\pm = {}^1\!/_2\ (I_1 \pm iI_2)$. These flips are rotations in effect. The charge symmetry operation, $P_{cs} = \exp(i\pi I_2)$, is that of an isospin rotation by 180° about the I_2 axis. Charge symmetry can be expressed by the commutator $[\mathcal{H}, P_{cs}]$ and obviously is a weaker condition than charge independence.

The wave function of a nucleus can be written as a product of the spatial wave function, the spin wave function, and the isospin wave function. Assuming isospin independence, the wave function does not change if one replaces a neutron by a proton and vice versa. A breaking of isospin independence of the strong NN interaction (N = n or p) implies that, in the isospin $I = 1$ state, the proton–proton ($I_3 = +1$), neutron–proton ($I_3 = 0$), or neutron–neutron ($I_3 = -1$) interactions differ, after electromagnetic effects have been removed. In contrast, charge symmetry breaking (CSB) in the NN interaction relates to a difference between proton–proton and neutron–neutron interactions only.

In quantum chromodynamics (QCD), with quarks and gluons as the relevant degrees of freedom, the charge symmetry operator changes d into u quarks and vice versa. In the quark-based definition, CSB is due to the difference between u and d quarks, namely (1) their mass difference $\Delta m_{\mathrm{du}} = m_{\mathrm{d}} - m_{\mathrm{u}} \sim$ few MeV/c^2 and (2) quark–quark electromagnetic energy differences resulting from their different electric charges and magnetic moments [3]. The level of CSB is ultimately determined by the strengths of the different Yukawa couplings and by the vacuum expectation value of the Higgs field.

2. – CSB in the $A = 1$ isospin doublet: why the sun is still shining

In nuclear physics, the charge symmetry of nuclear two-body interactions can be studied by comparing masses, binding energies, and level schemes of mirror nuclei, characterized by the same mass number A, but with interchanged proton and neutron states. A clear indication of the presence of charge symmetry is the near equality of these properties in mirror nuclei such as ^{23}Na–^{23}Mg ($Z_1 = 11, N_1 = 12$ and $Z_2 = 12, N_2 = 11$). In nuclei, charge symmetry holds on the level of 10^{-3} [4].

The prototype and prime example of mirror nuclei is the neutron–proton isospin pair. The difference in mass between neutrons and protons $\Delta m_{\mathrm{np}} = m_{\mathrm{n}} - m_{\mathrm{p}}$ is only 0.14% of their average mass m_N, comparable in size to the quark mass difference Δm_{du}. Despite the smallness of this fraction, it is the physical source of many major aspects and structures of our world and the universe as we know it [5].

If charge symmetry would be exact in nuclear systems and the proton differed from the neutron only in having a roughly uniformly distributed, positive electric charge, then the proton would be heavier than the neutron because of additional electrostatic repulsion. Modern, sophisticated estimates, for example using electromagnetic interactions in the context of the quark model of hadrons, lead to the same conclusion [6]. The reason for the inverted mass scheme in which the neutron mass is larger than the proton mass, is a second fundamental contribution: strong interaction CSB governed by the underlying quark properties. Because the neutron differs from the proton in containing a d quark in place of a u quark, this contribution tends to make the neutron heavier [5].

Given the precisely known neutron, proton, and electron masses of 939.56563, 938.27231 and 0.51099906 MeV/c^2, respectively, the difference Δm_{np} is about 2.53 times the electron mass. Were the neutron–proton mass difference even slightly less than the electron mass, for example if it were one-third of its actual value, then hydrogen atoms would convert into neutrons and neutrinos by inverse β-decay [5]. In case of a mass difference smaller than the actual one, but not allowing for this decay, the implications for primordial nucleosynthesis would be catastrophic: hydrogen fusion into helium would have been more efficient, leaving less slow-burning hydrogen fuel for main sequence stars including our sun.

By contrast, were the mass difference significantly larger than its actual value, then the synthesis of atomic nuclei beyond hydrogen would be difficult or impossible [5].

Finally, if the mass of the neutron were smaller than the mass of the proton, cosmic nuclear evolution would have proceeded along different paths and produced a fundamentally different universe. Hogan gave examples for nuclear astrophysics in worlds with different levels of strong isospin breaking [7]. In neutron-stable worlds, neutrons move and carry a baryon number relatively freely through radiation and charged-particle plasmas; there is no long-range Coulomb force to inhibit nuclear interactions of neutrons with each other or with other nuclei, at virtually any temperature or density. Since neutrons can be embedded within atoms, there is no atomic-scale limit to the density of stable cold states of matter, so neutron matter tends to settle into metastable systems right up to nuclear density [7]. Hogan shows that the effect of a stable neutron on primordial nucleosynthesis and the nuclear processes in stars would lead to radical differences from our world, such as a predominance of heavy r-process and s-process nuclei and a lack of normal galaxies, stars, and planets.

3. – CSB in non-strange nuclei: a matter of corrections

CSB may be studied by comparing reactions in which a two-particle initial state is converted into a final two-particle state, such as neutron-proton elastic scattering, pion elastic scattering off ^{3}He and ^{3}H, or $n + p \rightarrow d\pi^0$ reactions. However, such processes are contaminated by electromagnetic effects between the interacting particles. These lead to a Coulomb scattering amplitude and to a distortion of the wave function, which violates charge symmetry equalities of cross sections and spin observables. Furthermore, the strong interaction must be evaluated at an energy shifted by the Coulomb barrier, leading to a difference in the effective interaction energy of projectile target interactions. A third complication for testing charge symmetry in nuclear reactions is a mass or Q-value shift. In the $p + {}^3$H and $n + {}^3$He systems, for example, a Coulomb energy shift ΔE exists for $p + {}^3$H, but ^{3}H is more bound that ^{3}He so that the Q-value shift and the ΔE term tend to cancel out.

In bound systems, a suitable low-energy CSB observable is the binding energy. The difference in total binding energies for the ^{3}He–^{3}H isospin mirror pair is of the order of 760 keV, dominated by electromagnetic effects due to the electrostatic repulsion of the finite-sized protons in ^{3}He. The nucleus with less protons, ^{3}H, is more bound by ~ 650 keV. Another 35 keV are caused by electromagnetic effects neglected in the static Coulomb approximation and 14 keV are due to the n–p mass difference in the kinetic energy [8]. The $\Delta B_{\text{CSB}} \approx 70$ keV discrepancy between the measured and the corrected binding energy differences in ^{3}He–^{3}H is a clear manifestation of CSB of the nuclear interaction.

Models of CSB in the NN interaction could be based upon $\rho - \omega$ mixing, nucleon mass splitting, or phenomenology. These models can predict the strong interaction CSB contribution to the ^{3}He–^{3}H binding energy difference rather accurately [8]. In addition to such nuclear interaction calculations, recent lattice QCD plus quantum electrodynamics computations could nicely reproduce the extracted CSB pattern in the lowest-mass non-strange as well as in the strange baryon spectrum [6].

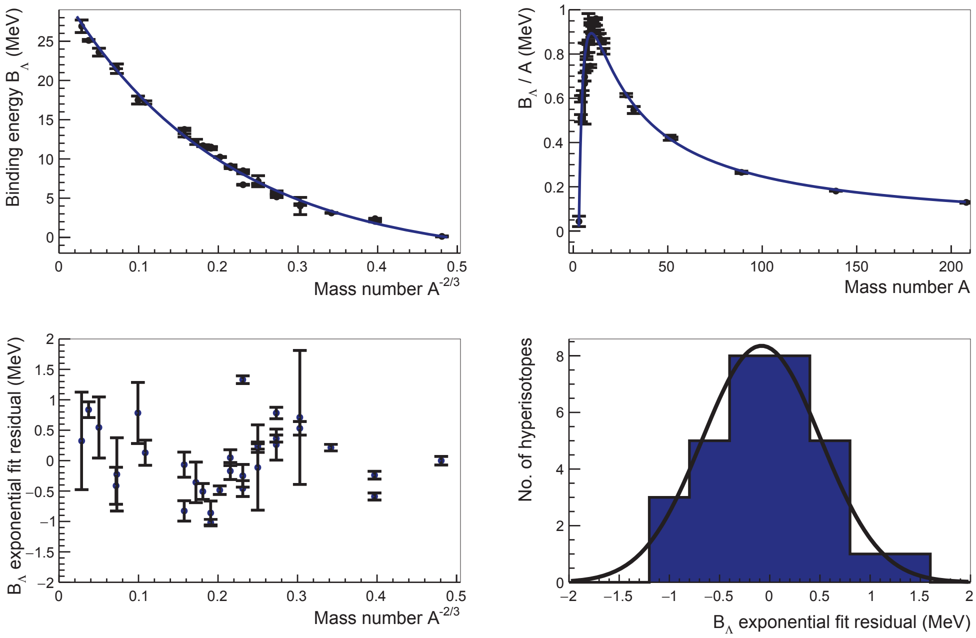

Fig. 1. – Top: Binding energy values of 30 known hypernuclei as a function as a function of $A' \equiv A^{-2/3}$ and the Λ binding energy per nucleon as a function of mass number A. The blue line is a parametrization according to an exponential decrease of B_Λ with A'. Bottom: Residuals between the data and the parametrization and their distribution. In general, most B_Λ values agree within their experimental uncertainties with the parametrization.

4. – Binding energies of Λ hypernuclei: setting the stage

The strong and undesired Coulomb effects can be eliminated in first order if the beam and/or target particle is neutral. Furthermore, to assess the isospin dependence in the strong interaction, it is desirable to use isospin singlets. Therefore, Λ hyperons, baryons without charge and isospin, are ideal probes to test CSB in nuclei. When a Λ hyperon replaces one of the nucleons in the nucleus, a bound system can be formed by the hyperon and the core of the remaining nucleons, which is a Λ hypernucleus. The total binding energy $B_E({}^{A}_{\Lambda}\mathrm{X})$ of an hypernucleus ${}^{A}_{\Lambda}\mathrm{X}$ is given by the often precisely known binding energy of the nuclear core $B_E({}^{A-1}\mathrm{X})$ and the Λ separation energy B_Λ, that is measured in hypernuclear experiments: ${}^{A}_{\Lambda}\mathrm{X} = B_E({}^{A-1}\mathrm{X}) + B_\Lambda$. The electromagnetic mass shifts observed in non-strange mirror nuclei do not affect the Λ binding energy directly, so that this observable provides unique information on CSB.

In a ground-state, a hypernucleus decays to a non-strange nucleus through mesonic or non-mesonic weak decay modes. By detecting the decay of hypernuclei and measuring the momenta of the decay products, the binding energies of the Λ hyperon for a number of s- and p-shell hypernuclei were reported in the 1960s and 1970s. Presently, only a few tens of B_Λ values for mostly light hypernuclei have been experimentally established [9]. The binding energy data for light hypernuclei can be understood in terms of two-body ΛN interactions. In general, the measured values follow a trend with hypernuclear mass, which has been described satisfactorily by a variety of semi-empirical formulae, *e.g.* by using a generalized Bethe-Weizsäcker mass formula [10]. The variation of the binding energies of the Λ hyperon with $A' \equiv A^{-2/3}$ has been studied by various authors and is motivated by calculations using the nuclear potential well for Λ hyperons. Figure 1 shows 30 known B_Λ values from ${}^{3}_{\Lambda}$H to ${}^{32}_{\Lambda}$S together with a simple parametrization based on an exponential dependence on A': $B_\Lambda(A) = B_0 - B_A \exp(-A'/A'_0)$. The three parameters B_0, B_A and A'_0 were fitted to the data. It can be seen that most Λ binding energies agree within their experimental uncertainties with the parametrization. However, it is obvious that a level of precision comparable to non-strange nuclear data is lacking. At $A = 4$, corresponding to $A^{-2/3} \approx 0.39$, a significant deviation is visible, which will be discussed in the next section.

5. – CSB in the $A = 4$ hypernuclear isospin doublet: clear evidence

Charge symmetry requires the binding of the Λ hyperon with protons to be identical to the binding with neutrons. Therefore, the binding energy B_Λ of hyperons to the cores of mirror nuclei should be identical. The experimental evidence for CSB in the $A = 4$ system relies on the comparison of ground state and first excited state binding energy differences between the two hypernuclei of the isospin doublet. When adding the Λ hyperon to the ^{3}He–^{3}H mirror pair, the Λ binding energy difference is about five times larger than in the core: from emulsion studies, the values $B_\Lambda({}^{4}_{\Lambda}\mathrm{H}) = 2.04 \pm 0.04\,\mathrm{MeV}$ and $B_\Lambda({}^{4}_{\Lambda}\mathrm{He}) = 2.39 \pm 0.03\,\mathrm{MeV}$ were known for more than four decades [11].

This observation is quite remarkable, considering the weaker ΛN interaction as compared to the n–n or p–p interactions. Interestingly, the binding to the charged nucleon is stronger than to the uncharged nucleon, while the n–n interaction is more attractive than the p–p one. Therefore, the mirror pair of hypernuclei ${}^{4}_{\Lambda}$He–${}^{4}_{\Lambda}$H is the most interesting source of information about the CSB in ΛN interactions.

Several questions need to be answered in this situation. (1) Are there higher-order electromagnetic corrections even for an uncharged, isospin-scalar probe to be considered? (2) What is the experimental evidence for the difference in B_Λ values of this hypernuclear mirror pair? (3) And finally, what is the source of such a strong violation of charge symmetry?

With regard to (1), there exist calculations of Coulomb energy effects for a bound neutral particle, namely the compression of the hypernucleus as compared to the non-strange core which introduces additional electrostatic repulsion of the protons in the ${}^{4}_{\Lambda}$He core. However, this correction works in the opposite direction to the observed binding energy difference and is of order $< 50\,\mathrm{keV}$ [12].

A comparison of the published binding energy values of ${}^{4}_{\Lambda}$H is shown in Fig. 2, in which the emulsion value [11] is confronted with the more recent decay-pion spectroscopy data [13,14]. The FWHM of the binding energy distributions, corresponding to the energy resolutions for single events of the two different techniques, is about 1.5 and 0.2 MeV, respectively. The emulsion values could be reaffirmed with an order of magnitude higher precision. For ${}^{4}_{\Lambda}$He, no independent B_Λ measurement using magnetic spectrometers exists so far.

Different hypernuclear structure theories exist in which the binding energies of light hypernuclei are calculated, most recent approaches include cluster models and *ab initio* calculations with the interactions constructed either in the meson-exchange picture or within chiral effective field theory. Bodmer and Usmani [12] obtained a phenomenological CSB potential that is effectively spin independent. An examination of meson-exchange CSB models showed that these are consistent with the phenomenological CSB potential

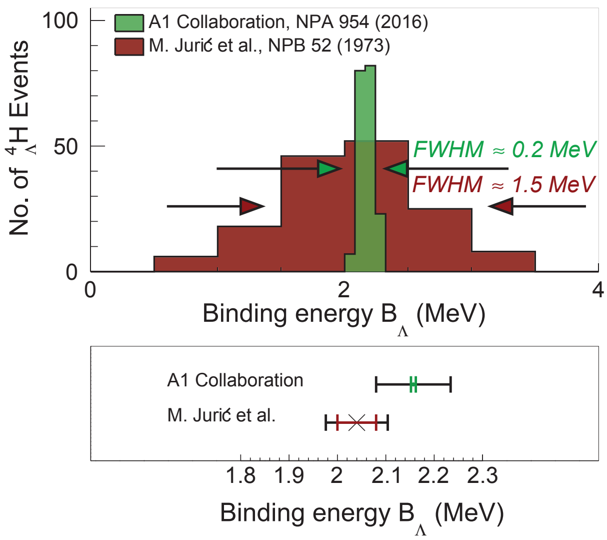

Fig. 2. – Top: Distribution of ${}^{4}_{\Lambda}$H binding energy values for the two most precise determinations, the decay-pion spectroscopy [13, 14] and the emulsion technique [11]. The FWHM of the distributions are indicated corresponding to the experimental resolutions. Bottom: Mean values of the two binding energy determinations with separated statistical and total errors, where the latter include systematic errors added in quadrature.

for the triplet, but not for the singlet case. However, by combining the precise γ-ray spectroscopy data on ${}^{4}_{\Lambda}$He from the E13 experiment at J-PARC [15] with the known ground-state binding energies, it was found that the CSB effect is large in the 0^+ ground state but is apparently vanishingly small in the 1^+ excited state, demonstrating that the ΛN CSB interaction has a strong spin dependence. Hiyama and coworkers also introduced a phenomenological CSB potential [16, 17]. For many decades the hypernuclear isospin doublet ${}^{4}_{\Lambda}$He–${}^{4}_{\Lambda}$H represented a real challenge for modern hyperon–nucleon interaction calculations [18]. Modern efforts to understand the observed CSB in the $A = 4$ system address the isospin mixing of hyperon states leading to one pion exchanges, which could be the dominant CSB source [19, 20]. Using a schematic strong-interaction $\Lambda N \leftrightarrow \Sigma N$ coupling model, the evaluation of CSB could be extended to explain p-shell binding energy differences for the $A = 7 - 10$ mirror hypernuclei.

6. – Higher mass hypernuclear isospin multiplets: in search of symmetry lost

For higher mass numbers A, not only do the theoretical calculations become less precise [20], the experimental data base also becomes inconclusive [22]. One of the problems is rooted in the fact that the different species of hypernuclei in an isospin multiplet have necessarily been measured in different types of spectrometer experiments with different systematic uncertainties. Experimental evidence of CSB in the mass $A = 7$, 8, and 9 isospin multiplets could potentially be hidden by systematic uncertainties. Only with the emulsion technique, hyperfragments of the same isospin multiplet, emitted from Ag or Br nuclei, have been detected in the past. However, the few available data from emulsion studies [23] show discrepancies on the order of 0.4 to 0.8 MeV with the (π^+, K^+)

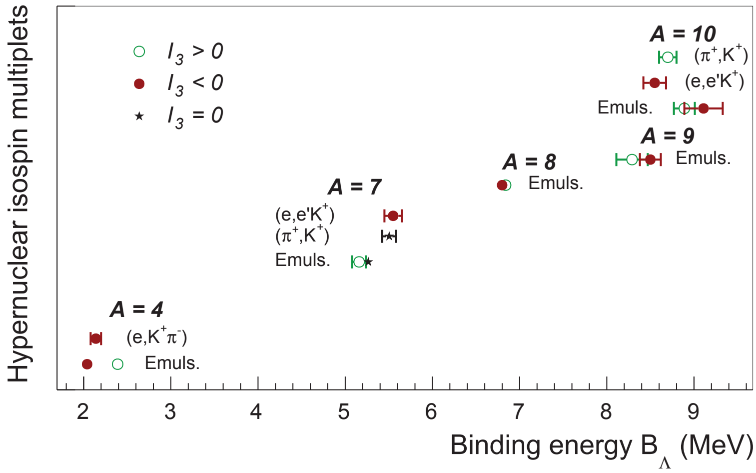

Fig. 3. – Λ binding energies for the hypernuclear isospin multiplets of the lightest known hypernuclei up to mass numbers $A = 10$. The experimental technique (emulsion, electro-production, or meson-production) is indicated and the isospin 3-component can be identified by the marker type. Recent values based on FINUDA data are not included and will be discussed in [21].

reaction data obtained at the SKS-KEK experiment [24]. One example of an apparently false binding energy difference is the $A = 12$ system, in which an unreported systematic error of 0.6 MeV was recently anticipated [24, 9, 25]. The shift affects all reported hypernuclear binding energies from (π^+, K^+) measurements calibrated with ${}^{12}_{\Lambda}$C. Figure 3 shows Λ binding energies for the hypernuclear isospin multiplets of the lightest known hypernuclei up to mass numbers $A = 10$ from emulsion, electro-production, and meson-production experiments. Recent values based on FINUDA data will be discussed in [21]. As it can be deduced from the data, the situation concerning CSB in the p-shell isospin multiplets is not conclusive. The competition between electromagnetic and mass isospin breaking effects is not resolvable given our current accuracy of hypernuclear binding energy data.

7. – Summary

CSB is considerably stronger in hyper- than in non-strange nuclei. A sizable effect in the mass number $A = 4$ isospin doublet has been known since decades and was recently confirmed by high-precision experiments. It seems that the CSB in light hypernuclei is strongly spin-dependent and possibly changing sign between the $A = 4$ ground and excited states.

Large experimental, especially systematic, uncertainties and limitations in the experimental approaches disguise a possible CSB effect in the higher mass isospin multiplets. An improved database is needed to study the A dependence of hypernuclear CSB effects.

Modern theoretical descriptions of large CSB effects in s-shell hypernuclei are based on an effective $\pi\Lambda\Lambda$ coupling in LO χEFT interactions. For p-shell hypernuclei, the extension of these calculations are needed.

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