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# Charge symmetry breaking in $A = 4$ hypernuclei

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**Abstract.** Charge symmetry breaking in the $A = 4$ hypernuclear system is reviewed. The data on binding energies of the mirror nuclei and hypernuclei are examined. At the Mainz Microtron MAMI the high-resolution spectroscopy of decay-pions in strangeness electro-production is used to extract the $\Lambda$ hyperon ground state binding energy in ${}^4_\Lambda$H. This binding energy is used together with the ${}^4_\Lambda$He ground state binding energy from nuclear emulsion experiments and with energy levels of the $1^+$ excited state for both hypernuclei from $\gamma$-ray spectroscopy to address the charge symmetry breaking in the strong interaction. The binding energy difference of the ground states in the mirror pair is reduced from its long accepted value $\Delta B^4_\Lambda(0^+_{\rm g.s.}) \approx 0.35$ MeV to $\approx 0.24$ MeV. The energy difference of the excited states becomes $\Delta B^4_\Lambda(1^+_{\rm exc}) \approx -0.08$ MeV, for the first time with opposite sign. These values were not reproduced by theoretical calculations with the exception of very recent approaches, although with a large systematic dependence. The full understanding of the charge symmetry breaking in the $A = 4$ hypernuclei still remains one of the open issues of hypernuclear physics.

## 1 Charge symmetry and charge independence breaking

The nuclear interactions have a small charge-dependent component breaking the near symmetry between protons and neutrons in their interactions and their contributions to nuclear properties. However, the concept of charge symmetry is quite useful in describing many facets of nuclear physics, e.g. the observation of nearly identical levels and spin-parity assignments of excited nuclear states in mirror nuclei. The fundamental cause of the charge dependence of nuclear forces, i.e. charge-symmetry breaking (CSB) and charge-independence breaking (CIB), is due to the differences in the up and down quark masses and due to electromagnetic effects.

A very important consequence of CSB is the fact that neutrons are heavier than protons (by only approximately $\Delta M/M \sim 0.1\,\%$) despite the larger electrostatic repulsion of the quarks inside the proton that would make the proton heavier. The decay of free neutrons (allowed by their larger mass) during the primordial nucleosynthesis left a large fraction of protons unbound, now existing mainly in the stars and providing a slow-burning fuel for the universe. The very reverse, protons being heavier than neutrons, would be a disaster for life as we know it.

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Differences between the nucleon forces are experimentally mostly clearly observed in the $a^N_{pp}$ and $a^N_{nn}$ proton–proton and neutron–neutron $^1S_0$ singlet scattering lengths and the value for neutron–proton scattering, when electromagnetic effects have been removed. Recent values for the nuclear parts scattering lengths are

$$\begin{aligned} a^N_{pp} &= -17.3 \pm 0.4\,\text{fm} \\ a^N_{nn} &= -18.8 \pm 0.3\,\text{fm} \\ {}^1\!/_2\,(a^N_{pp} + a^N_{nn}) &= -18.05 \pm 0.5\,\text{fm} \\ a^N_{np} &= -23.77 \pm 0.09\,\text{fm} \end{aligned}$$

following the review of [1]. The $np$ interaction is significantly more attractive than the averaged $nn$ and $pp$ interactions and is a manifestation of CIB. A smaller, but sizable CSB effect is seen in the difference between $a^N_{pp}$ and $a^N_{nn}$ scattering lengths.

In nuclear physics often the meson-exchange theory of nuclear forces is employed. Charged-dependent effects arise through mass splittings and mixing of exchanged vector mesons of different isospin but same spin and parity. CIB in the scattering lengths can be explained quantitatively with the charged and neutral pion mass difference in the one-pion and the two-pion exchange potential [2]. The dominant CSB effect in the scattering lengths can be explained in terms of $\rho^0-\omega$ mixing [3]. Evidence for neutral meson mixing also come from nuclear interactions and cross-section measurements.

## 2 Charge symmetry breaking in the lightest mirror nuclei and hypernuclei

The CSB effect is manifest in the differences between mirror nuclei and mirror hypernuclei. The differences in these heavier systems (compared to the nucleon) are extensions of the neutron–proton difference.

The lightest mirror pair is the $A = 3$ isodoublet ($^3$H,$^3$He). The measured masses of the $A = 3$ pair are $M(^3\text{H}) = 2808.921\,\text{MeV}/c^2$ and $M(^3\text{He}) = 2808.391\,\text{MeV}/c^2$ with negligibly small errors of $\sim 2\,\text{eV}$ [4]. The corresponding nuclear binding energies are $B(^3\text{H}) = 8.482\,\text{MeV}$ and $B(^3\text{He}) = 7.718\,\text{MeV}$, signifying that the neutron richer nucleus $^3$H is more deeply bound. The difference in binding energies is $\Delta B^3 = B(^3\text{He}) - B(^3\text{H}) = -0.764\,\text{MeV}$. The repulsive Coulomb interaction in $^3$He and other electromagnetic contributions need to be removed from the binding energy to determine the strong-interaction CSB. This system is considered best for CSB studies because theoretical studies are well advanced in these few-body cases. The mass and energy values of this mirror pair and of the corresponding $A = 4$ hypernuclei are given in Table 1.

There have been several studies to calculate CSB effects from Coulomb interaction for $A = 3$ [7–9]. A perturbative estimate of the Coulomb contribution can be made from nuclear form factors measured in electron scattering. Reported results include contributions of $\Delta B^3_C = -0.69\,\text{MeV}$ due to the static Coulomb effect, $\Delta B^3_{\text{size}} = +0.04\,\text{MeV}$ due to the finite size effect, and $\Delta B^3_{\text{other}} = -0.04\,\text{MeV}$ from other electromagnetic effects such as the magnetic interaction. Bodmer and Usmani performed a variational calculation and obtained $\Delta B^3_C = -0.67 \pm 0.01\,\text{MeV}$ [10]. In summary, the electromagnetic interaction contributes approximately $\Delta B^3_{\text{em}} = -0.69\,\text{MeV}$ to the binding energy difference. The remaining difference of only $\Delta B^3_{\text{CSB}} = -0.07\,\text{MeV}$ of the original $\sim 0.7\,\text{MeV}$ is attributed to the CSB contribution from the strong interaction.

Brandenburg and Wu et al. estimated the CSB effect with $\pi^0 - \eta$ and $\rho^0 - \omega$ mixing [11, 12] calculating an additional contribution to the binding energy difference of $\Delta B^3_{\text{CSB}} = -0.07\,\text{MeV}$. Adding this contribution to the electromagnetic effects the binding energy difference between $^3$H and $^3$He can

Table 1: Known nuclear masses ($M$ in MeV/$c^2$) and nuclear binding energies ($B$ in MeV) in the system of $A = 4$ mirror hypernuclei from nuclear emulsion measurements [5] including the nuclear core masses from the tabulated mass excess values [4] and the $\Lambda$ hyperon mass from the Particle Data Group compilation [6]. No electron masses or binding energies were included and differences $\Delta M$ and $\Delta B$ were calculated by subtracting the H value from the He value, respectively. Note the neutron–proton mass difference of 1.293 MeV/$c^2$ contributing to the mass differences of the isospin pairs.

| | | | |
|---|---|---|---|
| $M(^3\mathrm{H}) =$ | 2808.921 | $B(^3\mathrm{H}) =$ | 8.482 |
| $M(^3\mathrm{He}) =$ | 2808.391 | $B(^3\mathrm{He}) =$ | 7.718 |
| $\Delta M^3 =$ | −0.530 | $\Delta B^3 =$ | −0.764 |
| $M(^4_\Lambda\mathrm{H}) =$ | 3922.56 | $B_\Lambda(^4_\Lambda\mathrm{H}) =$ | 2.04 |
| $M(^4_\Lambda\mathrm{He}) =$ | 3921.68 | $B_\Lambda(^4_\Lambda\mathrm{He}) =$ | 2.39 |
| $\Delta M^4_\Lambda =$ | −0.88 | $\Delta B^4_\Lambda =$ | 0.35 |
| $M(^3\mathrm{H} +^3\mathrm{He} + \Lambda) =$ | 6732.99 | | |
| $M(^4_\Lambda\mathrm{H}+^3\mathrm{He}) =$ | 6730.95 | | |
| $M(^3\mathrm{H}+^4_\Lambda\mathrm{He}) =$ | 6730.60 | | |

be fully explained. Thus, the mechanisms and the effect of CSB in the $NN$ interaction is understood in light nuclei on the keV level.

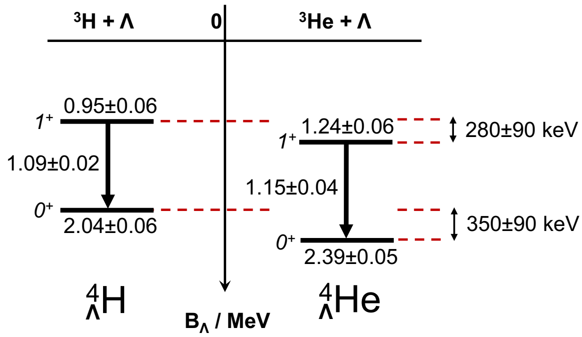
If the $A = 3$ system is expanded with a bound $\Lambda$ hyperon to the ($^4_\Lambda$H,$^4_\Lambda$He) mirror pair of hypernuclei, information on the CSB in the $\Lambda N$ interaction can be extracted. Charge symmetry predicts that the $\Lambda p$ and $\Lambda n$ interactions and consequently their contributions to the binding energies of mirror hypernuclei would be identical. Since the $\Lambda$ binding (or separation) energy is defined by subtracting the binding energy of the core $B_\Lambda(^4_\Lambda\mathrm{He}) = B(^4_\Lambda\mathrm{He}) - B(^3\mathrm{He})$, where $B$ is the total binding energy, the repulsive Coulomb energy in $^3$He and $^4_\Lambda$He cancels to first order.

However, the presence of the bound $\Lambda$ hyperon tends to compress the core nucleus. For $^4_\Lambda$He this compression increases the Coulomb repulsion and lowers the binding energy. It is expected that the change in $B_\Lambda$ is not more than 10 % of the total Coulomb energy [13]. To leading order in the Coulomb interaction the difference in binding energies is $\Delta E_C = -\Delta B_C = 0.05 \pm 0.02$ MeV and $0.025 \pm 0.015$ MeV for the ground and excited states, where $\Delta E_C = E_C(^4_\Lambda\mathrm{He}) - E_C(^3\mathrm{He})$ is the difference between the Coulomb energies of $^4_\Lambda$He and $^3$He [10].

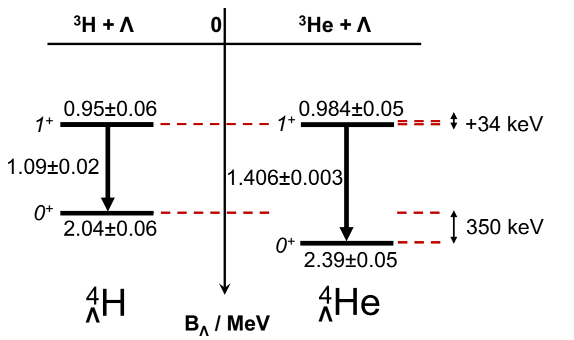
The corresponding differences of $B_\Lambda$ between $^4_\Lambda$He and $^4_\Lambda$H to be attributed to CSB effects were then found by Bodmer and Usmani to be $\Delta B^{\mathrm{CSB}}_\Lambda = \Delta B^{\mathrm{exp}}_\Lambda - \Delta B_C = (0.35 \pm 0.06)$ MeV + $(0.05 \pm 0.02)$ MeV $= 0.40 \pm 0.06$ MeV for the ground state and $\Delta B^{\mathrm{CSB}}_\Lambda = (0.24 \pm 0.06)$ MeV + $(0.025 \pm 0.015)$ MeV $= 0.27 \pm 0.06$ MeV. From these values a phenomenological CSB potential was derived which is effectively spin independent.

## Recent experimental and theoretical developments

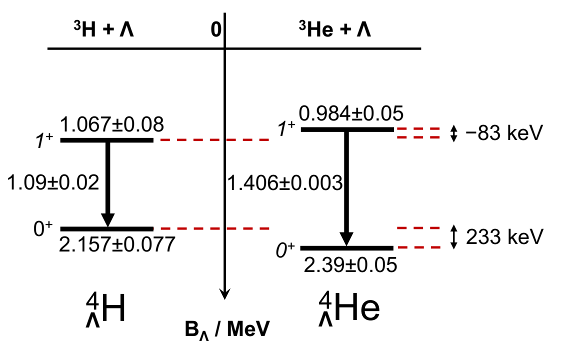
In 2015 measurements with HPGe detectors on $^4_\Lambda$He hypernuclei produced by $(K^-, \pi^-)$ reactions on a helium target at the Hadron Experimental Facility of J-PARC found that the transition energy from the exited $1^+$ state to the $0^+$ ground state is $1.406 \pm 0.002$ (stat.) $\pm 0.002$ (syst.) MeV [17], falsifying




(a) Knowledge before 2015




(b) Knowledge in 2015




(c) Knowledge after 2015

Figure 1: Advancement of the knowledge on the level diagrams of the ${}^{4}_{\Lambda}$H and ${}^{4}_{\Lambda}$He mirror hypernuclei. CSB splittings are shown to the right of the ${}^{4}_{\Lambda}$He levels, $\gamma$-ray transitions are shown by arrows, with $\gamma$-ray energies to the left. Diagram (a) shows binding energies, $B_{\Lambda}$, for the ground states from nuclear emulsion measurements [5] in the 1960s and 1970s and for the excited states from low-resolution, low-efficiency NaI detector measurements of $\gamma$-ray transitions in the 1970s [14–16]. Diagram (b) includes the ${}^{4}_{\Lambda}$He transition energy re-measured recently at J-PARC [17], falsifying the earlier values. Finally, diagram (c) uses the ${}^{4}_{\Lambda}$H ground state binding energy recently re-measured at MAMI [18].

earlier results from low-resolution, low-efficiency NaI detector measurements in the 1970s [14]. The excitation energy of ${}^{4}_{\Lambda}$H was known to be only 1.09 ± 0.02 MeV [14–16]. The use of emulsion data for the ground state binding energies lead to a binding energy difference of $\Delta B^{4}_{\Lambda}(1^{+}_{\text{exc}}) \approx 0.03 \pm 0.05$ MeV for the excited states. In summary, the breaking of the charge symmetry in $A = 4$ hypernuclei was found to be large and differing between the $0^{+}$ ground state and the $1^{+}$ excited state.

At the Mainz Microtron MAMI the high-resolution spectroscopy of decay-pions in strangeness electro-production is used to extract the Λ hyperon ground state binding energy in ${}^{4}_{\Lambda}$H [19]. A very important result was the confirmation of the $B_{\Lambda}$ value for ${}^{4}_{\Lambda}$H independently from the experimental technique. Recently an updated value of $B_{\Lambda} = 2.157 \pm 0.005$ (stat.) ± 0.077 (syst.) MeV has been published [18] including a detailed error and bias analysis.

This binding energy can be used together with the ${}^{4}_{\Lambda}$He ground state binding energy from nuclear emulsion experiments and with energy levels of the $1^{+}$ excited state for both hypernuclei from $\gamma$-ray spectroscopy to arrive at the latest level diagrams and CSB splittings of the ${}^{4}_{\Lambda}$H and ${}^{4}_{\Lambda}$He mirror hypernuclei. Fig. 1 shows the advancement of the knowledge during the last years.

The updated ground state binding energy difference $\Delta B^{4}_{\Lambda}(0^{+}_{\text{g.s.}}) = B_{\Lambda}({}^{4}_{\Lambda}\text{He}(0^{+}_{\text{g.s.}})) - B_{\Lambda}({}^{4}_{\Lambda}\text{H}(0^{+}_{\text{g.s.}})) = 233 \pm 92$ keV is smaller as measured by the emulsion technique but still supports a sizable CSB effect in the $\Lambda N$ interaction. The binding energy difference between the excited states of $\Delta B^{4}_{\Lambda}(1^{+}_{\text{exc}}) = B_{\Lambda}({}^{4}_{\Lambda}\text{He}(1^{+}_{\text{exc}})) - B_{\Lambda}({}^{4}_{\Lambda}\text{H}(1^{+}_{\text{exc}})) = -83 \pm 94$ keV is negative.

These values were not reproduced by theoretical calculations [20, 21] with the exception of very recent approaches [22, 23]. In these approaches a $\Lambda - \Sigma^{0}$ mixing CSB mechanism due to Dalitz and von Hippel [13] reproduces the large value of $\Delta B_{\Lambda}$ in the ground state and an opposite sign difference in the first excited state, although with large systematic dependence. In this model the isospin zero singlet Λ hyperon mixes electromagnetically with the $\Delta M_{\Lambda\Sigma} \sim 80\,\text{MeV}/c^{2}$ more massive isospin triplet Σ hyperon. The effect of admixture breaks charge symmetry and leads to a binding energy difference in mirror hypernuclei.

## Conclusion and outlook

The updated results for the ${}^{4}_{\Lambda}$H binding energy measured at MAMI lead to a difference of $\Delta B^{4}_{\Lambda}(0^{+}_{\text{g.s.}}) \approx 0.233 \pm 0.09$ MeV between the binding energies for the ground states in the $A = 4$ system when combined with emulsion data. The data suggest a negative binding energy difference between the excited states of $\Delta B^{4}_{\Lambda}(1^{+}_{\text{exc}}) = -0.083 \pm 0.09$ MeV when combined with the known excitation energies supporting a large spin-dependent CSB effect. At J-PARC a precise measurement of the $\gamma$-transition energy of ${}^{4}_{\Lambda}$H is planned [24] to confirm the earlier results from the 1970s.

In the mirror pair (${}^{4}_{\Lambda}$He,${}^{4}_{\Lambda}$H) CSB effects appear to be considerably stronger than in any other nuclei or heavier hypernuclei. From the theoretical studies of CSB in $A = 4$ hypernuclei it can be concluded that $\Lambda N - \Sigma N$ coupling and 3-body forces in the hyperon–nucleon interaction are essential ingredients to the $\Lambda N$ interaction. This also means that the interactions of Λ hyperons in symmetric nuclear matter and neutron rich nuclei would be largely different. At Jefferson Lab a series of measurements on the isospin dependence of the $\Lambda N$ interaction was proposed and approved [25] to address this issue. The outcome of those and all other ongoing or planned hypernuclear physics endeavors will be a key to understand CSB in light hypernuclei.

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