Charge symmetry breaking in $\Lambda$ hypernuclei: updated HYP 2015 progress report

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Ongoing progress in understanding and evaluating charge symmetry breaking in $\Lambda$ hypernuclei is discussed in connection to recent measurements of the $^{4}_{\Lambda}H(0_{g.s.}^{+})$ binding energy at MAMI [A1 Collaboration: PRL 114 (2015) 232501] and of the $^{4}_{\Lambda}He(1_{\text{exc}}^{+})$ excitation energy at J-PARC [E13 Collaboration: PRL 115 (2015) 222501].

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1. Introduction

Charge symmetry in hadronic physics is broken in QCD by the light $u-d$ quark mass difference and by their QED interactions, both of which contribute significantly to the observed 1.3 MeV $n-p$ mass difference. In nuclear physics, charge symmetry breaking (CSB) results in a difference between the $nn$ and $pp$ scattering lengths, and also contributes about 70 keV out of the Coulomb-dominated 764 keV binding-energy difference in the mirror nuclei $^{3}\text{H}$ and $^{3}\text{He}$, as reviewed in Ref. [1]. It can be explained by $\rho^{0}\omega$ mixing in one-boson exchange models of the $NN$ interaction, or by considering $N\Delta$ intermediate-state mass differences in models limited to pseudoscalar meson exchanges [2]. In practice, introducing two charge dependent contact interaction terms in chiral effective field theory ($\chi$EFT) applications, one is able at next-to-next-to-next-to-leading order (N$^3$LO) to account quantitatively for the charge dependence of the low energy nucleon-nucleon ($NN$) scattering parameters and, thereby, also for the $A=3$ mirror nuclei binding-energy difference [3].

In $\Lambda$ hypernuclei, with scarce and imprecise $\Lambda p$ scattering data and no $\Lambda n$ data, the only clear CSB signal is the large $\Lambda$ separation-energy difference $\Delta B_{A}^{J=0} = 350 \pm 60$ keV in the $A=4$ $0_{g.s.}^{+}$ hypernuclear mirror levels from old emulsion data [4], in contrast to the small difference $\Delta B_{A}^{J=1}$ in the $1_{\text{exc}}^{+}$ states [5], as shown in Fig. 1. Recent measurements [6, 7] at the Mainz Microtron (MAMI) of the $^{4}_{\Lambda}H_{g.s.} \rightarrow ^{4}\text{He} + \pi^{-}$ decay have produced a value of $B_{A}(^{4}_{\Lambda}H_{g.s.}) = 2.157 \pm 0.077$ MeV [7], thereby confirming a substantial CSB $0_{g.s.}^{+}$ splitting $\Delta B_{A}^{J=0} = 233 \pm 92$ keV. This hypernuclear CSB ground state (g.s.) splitting is much larger than the $\approx 70$ keV or so assigned to CSB splitting in the mirror core nuclei $^{3}\text{H}$ and $^{3}\text{He}$.

This updated CSB review, starting with work reported in Ref. [8], demonstrates that the observed CSB splitting of mirror levels in the $A=4\Lambda$ hypernuclei can be reproduced by incorporating $\Lambda-\Sigma^{0}$ mixing [9] within a schematic $\Lambda N \leftrightarrow \Sigma N$ ($\Lambda\Sigma$) coupling potential model for $s$-shell $\Lambda$ hypernuclei [10, 11]. It is further shown, by extending this schematic model to the $p$ shell [12], that smaller and perhaps negative CSB splittings result in mirror $p$-shell $\Lambda$ hypernuclear g.s. [8], in agreement with emulsion data [4]. Finally, new results are presented from application of the Jülich-Bonn leading-order $\chi$EFT $YN$ interaction model [13] in a complete four-body no-core shell model (NCSM) calculation of the $A=4\Lambda$ hypernuclei, again demonstrating that large CSB splittings can be obtained [14,15].
1. $^3\Lambda H - ^4\Lambda He$ level diagram. Ground-state separation energies $B_\Lambda$, loosely termed $\Lambda$ binding energies, are from emulsion data [4], and the $1^+_c$ excitation energies from $\gamma$-ray measurements [5].

2. CSB from $\Lambda - \Sigma^0$ mixing

Pion emission or absorption by a $\Lambda$ hyperon is forbidden by isospin, hence there is no one-pion exchange (OPE) contribution to the $\Lambda N$ charge symmetric (CS) strong interaction. However, as pointed out by Dalitz and von Hippel [9] the SU(3) octet $\Lambda_{I=0}$ and $\Sigma_{I=1}^0$ hyperons are admixed in the physical $\Lambda$ hyperon, thereby generating a direct $\Lambda N$ CSB potential $V_{CSB}$ with a long-range OPE component that contributes substantially to the $0^+_{g.s.}$ splitting $\Delta B_{\Lambda=0}^{OPE}$. With updated coupling constants, their $0^+_{g.s.}$ purely central wavefunction yields $\Delta B_{\Lambda=0}^{OPE} \approx 95$ keV. This is confirmed in our recent calculations in which tensor contributions add roughly another 100 keV [15]. Shorter-range CSB meson-mixing contributions apparently are considerably smaller [16].

The $\Lambda - \Sigma^0$ mixing mechanism gives rise also to a variety of (e.g. $\rho$) meson exchanges other than OPE. In baryon-baryon models that include explicitly a CS strong-interaction $\Lambda\Sigma$ coupling, the direct $\Lambda N$ matrix element of $V_{CSB}$ is related to a suitably chosen strong-interaction isospin $I_{NY} = 1/2$ matrix element $\langle N\Sigma|V_{CS}|N\Lambda \rangle$ by

$$\langle N\Lambda|V_{CSB}|N\Lambda \rangle = -0.0297 \tau_{N\Sigma} \frac{1}{\sqrt{3}} \langle N\Sigma|V_{CS}|N\Lambda \rangle,$$

(1)

where the isospin Clebsch-Gordan coefficient $1/\sqrt{3}$ accounts for the $N\Sigma^0$ amplitude in the $I_{NY} = 1/2$ $N\Sigma$ state, and the space-spin structure of this $N\Sigma$ state is taken identical with that of the $N\Lambda$ state sandwiching $V_{CSB}$. The $\approx 3\%$ CSB scale factor $-0.0297$ in (1) follows from the matrix element of the $\Lambda - \Sigma^0$ mass mixing operator $\delta M$,

$$-2 \frac{\langle \Sigma^0|\delta M|\Lambda \rangle}{M_{\Sigma^0} - M_\Lambda} = -0.0297,$$

(2)

by using for $\delta M$ one of the SU(3) mass formulae [9,17]

$$\langle \Sigma^0|\delta M|\Lambda \rangle = \frac{1}{\sqrt{3}}(M_{\Sigma^0} - M_{\Sigma^+} + M_{\rho} - M_n) = 1.14 \pm 0.05 \text{ MeV}.\quad (3)$$

Lattice QCD calculations yield so far only half of this value for the mass-mixing matrix element [18]. The reason apparently is the omission of QED from these calculations.
Since the CS strong-interaction $\Lambda\Sigma$ coupling, according to Eq. (1), is the chief provider of the CSB $\Lambda N$ matrix element, it is natural to ask how strong the $\Lambda\Sigma$ coupling is in realistic microscopic $YN$ interaction models. In Fig. 2 we show results of NCSM calculations of $^4\Lambda\text{He}(0^+_\text{g.s.},1^+_{\text{exc}})$ states [19, 20] as a function of $N_{\text{max}}$, using LO $\chi$EFT $YN$ interactions with cutoff 600 MeV [13], including (left) or excluding (right) $\Lambda\Sigma$ coupling. This also occurs in the Nijmegen NSC97 models [21] as demonstrated in the next section. With $\Lambda\Sigma$ matrix elements of order 10 MeV, the 3% CSB scale factor (2) suggests CSB splittings of order 300 keV, in agreement with the observed $0^+_\text{g.s.}$ CSB splitting, see Fig. 1.

3. CSB in $s$-shell hypernuclei

Akaishi et al. [10] derived $G$-matrix $YN$ effective interactions from NSC97 models [21]. These have been employed in Ref. [8] to calculate CSB contributions using Eq. (1) in which a spin-dependent central CS form is assumed for the $\Lambda\Sigma$ $0s_N0s_Y$ effective interaction $V_{\Lambda\Sigma}$,

\[
V_{\Lambda\Sigma} = (\bar{V}_{\Lambda\Sigma} + \Delta_{0s} s_N \cdot s_Y) \sqrt{4/3} t_N \cdot \bar{t}_{\Lambda\Sigma},
\]

and where $\bar{t}_{\Lambda\Sigma}$ converts a $\Lambda$ to $\Sigma$ in isospace. The $s$-shell $0s_N0s_Y$ matrix elements $\bar{V}_{\Lambda\Sigma}^{0s}$ and $\Delta_{0s}$ are listed in Table I, adapted from Ref. [8], for two such $G$-matrix models denoted $(\Lambda\Sigma)_{e,f}$. The $A=4$ matrix elements $v(J^\pi)$, in terms of these two-body matrix elements, are

\[
v(0^+_{\text{g.s.}}) = \bar{V}_{\Lambda\Sigma}^{0s} + \frac{3}{4} \Delta_{0s}^{0s}, \quad v(1^+_{\text{exc}}) = \bar{V}_{\Lambda\Sigma}^{0s} - \frac{1}{4} \Delta_{0s}^{0s},
\]

from which the downward energy shifts $\delta E_1(J^\pi)$ defined by $\delta E_1(J^\pi) = v^2(J^\pi)/(80 \text{ MeV})$ are readily evaluated, with their difference $E_x^{\Lambda\Sigma}$ listed in the table. Furthermore, by comparing
this partial excitation-energy contribution to the listed values of the total $E_x(0^+_{g.s.} - 1^+_{exc})$ from Refs. [10, 11, 22] we demonstrate a sizable $\sim 50\%$ contribution of $\Lambda\Sigma$ coupling to the observed excitation energy $E_x(0^+_{g.s.} - 1^+_{exc}) \approx 1.25$ MeV deduced from the $\gamma$-ray transition energies marked in Fig. 1. Recall also the sizable $\Lambda\Sigma$ contribution to the induced CSB generates a value of $\Delta B_\Lambda(J^\pi)$ of $0.0343$ $v(J^\pi)$ in the schematic model [8]. Listed values are in MeV.

Listed in the last four columns of Table I are $A=4$ CSB splittings $\Delta B_\Lambda(J^\pi)$, calculated for NSC97 $YN$ models in Refs. [22, 23] and for the schematic $\Lambda\Sigma$ coupling model in Ref. [8]. The listed CSB splittings include a residual ($V_{CSB}=0$) splitting of size $\sim 20$ keV consisting of a small positive contribution from the $\Sigma^\pm$ mass difference and a small negative contribution from the slightly increased Coulomb repulsion in $^4$He with respect to that in its $^3$He core. The $1^+_{exc}$ CSB splittings listed in the table come out universally small in these models owing to the specific spin dependence of $V_{\Lambda\Sigma}$. The values of $\Delta B_\Lambda(0^+_{g.s.})$ listed in Table I are smaller than 100 keV upon using NSC97 models, thereby leaving the $A=4$ CSB puzzle unresolved, while being larger than 200 keV in the schematic $\Lambda\Sigma$ model and therefore getting considerably closer to the experimentally reported $0^+_{g.s.}$ CSB splitting. A direct comparison between the NSC97 models and the schematic $\Lambda\Sigma$ model is not straightforward because the $\Lambda\Sigma$ coupling in NSC97 models is dominated by tensor components, whereas no tensor components appear in the schematic $\Lambda\Sigma$ model.

Results of recent four-body NCSM calculations of the $A=4$ hypernuclei [14, 15], using the Bonn-Jülich LO $\chi$EFT SU(3)-based $YN$ interaction model [13] with cutoff momentum in the range $\Lambda=550$–700 MeV, are shown in Fig. 3. In line with the schematic model, the $\Lambda\Sigma$ coupling potential in this $\chi$EFT model is dominated by a central-interaction contact term. Plotted on the left-hand side (l.h.s.) are the calculated $0^+_{g.s.} \rightarrow 1^+_{exc}$ excitation energies $E_x$, for which the CS $\Lambda\Sigma$ coupling potential according to Fig. 2 is so crucial. With $\Lambda$ between 600 and 650 MeV, one is close to reproducing the $\gamma$-ray measured values of $E_x$. In fact for $\Lambda=600$ MeV the induced CSB generates a value of $\Delta B_\Lambda^{calc}(0^+_{g.s.}) - \Delta B_\Lambda^{calc}(1^+_{exc}) = 330 \pm 40$ keV, in excellent agreement with the measured value of $E_x(^4$He$) - E_x(^3$H$) \approx 320 \pm 20$ keV, see Fig. 1. Other models underestimate this measured value of $\Delta E_x$, with $\approx 210$ keV in the schematic $\Lambda\Sigma$ model and at most $\approx 110$ keV in the NSC97 model. Plotted on the right-hand side of Fig. 3 are the separate CSB splittings $\Delta B_\Lambda(J^\pi)$, demonstrating for the first time that the observed CSB splitting of the $0^+_{g.s.}$ mirror levels can be reproduced using realistic theoretical interaction models, although with appreciable momentum cutoff dependence. We note that the central value of $\Delta B_\Lambda^{exp}(0^+_{g.s.})=233\pm92$ keV, as derived from the recent measurement of $B_\Lambda(^3$H$)$ at MAMI [7], is comfortably reproduced for $\Lambda=650$ MeV.
Fig. 3. Cutoff momentum dependence of excitation energies $E_x(0^+_g.s. \rightarrow 1^+_{exc})$ (left) and of CSB splittings $\Delta B_A(J^p)$ (right) in NCSM calculations [14, 15] of the $A=4$ hypernuclei, using LO $\chi$EFT $YN$ interactions [13]. Values of $E_x$ from $\gamma$-ray measurements [5] are marked by dotted horizontal lines.

4. CSB in $p$-shell hypernuclei

Recent work by Hiyama et al. has failed to explain CSB splittings in $p$-shell mirror hypernuclei [24–26], apparently for disregarding the underlying CS $\Lambda\Sigma$ coupling potential. In the approach reviewed here, one extends the NSC97e model $0sN0s_Y$ effective interactions by providing $<\Lambda\Sigma>$ $0pN0s_Y$ central-interaction matrix elements which are consistent with the role $\Lambda\Sigma$ coupling plays in a shell-model reproduction of hypernuclear $\gamma$-ray transition energies by Millener [27]. The $p$-shell $0pN0s_Y$ matrix elements (given in the caption to Table II) are smaller by roughly a factor of two from the $s$-shell $0sN0s_Y$ matrix elements in Table I, reflecting the reduced weight which the major relative s-wave matrix elements of $V_{NY}$ assume in the $p$ shell. This suggests that $\Sigma$ admixtures, which are quadratic in these matrix elements, are weaker roughly by a factor of four with respect to the $s$-shell calculation, and also that CSB contributions in the $p$ shell are weaker with respect to those in the $A=4$ hypernuclei, although only by a factor of two. To evaluate these CSB contributions, the single-nucleon expression (1) is extended by summing over the $p$-shell nucleons:

$$V_{CSB} = -0.0297 \frac{1}{\sqrt{3}} \sum_j (V_{\Lambda\Sigma}^{0p} + \Delta_{\Lambda\Sigma}^{0p} \vec{s}_j \cdot \vec{s}_Y) \tau_{jz}. \quad (6)$$

Results of applying the present $<\Lambda\Sigma>$ coupling model to several pairs of g.s. levels in $p$-shell hypernuclear isomultiplets are given in Table II, extended from Ref. [8]. All pairs except for $A=7$ are mirror hypernuclei identified in emulsion [4] where binding energy systematic uncertainties are largely canceled out in forming the listed $\Delta B_A^{exp}$ values. For $A=7$ we calculated (i) $\Delta B_A$($^7$Be$^-$ $^7$Li$^+$), comparing it to $\Delta B_A$ obtained from g.s. emulsion data, as well as (ii) $\Delta B_A$($^7$Li$^+$ $^7$He$^-$), comparing it to $\Delta B_A$ obtained from FINUDA $\pi^-$-decay data.
for \(^7\)Li\(g.s.\) \([29]\) and from very recent JLab electroproduction data for \(^7\)He \([30]\). The Jlab and FINUDA measurements allow comparison since by using magnetic spectrometers it becomes possible to make absolute energy calibrations relative to precise values of free-space known masses. Note that the value reported by FINUDA for \(B_A(\overline{A}Li\_g.s.)\), 5.85±0.17 MeV, differs from the emulsion value of 5.58±0.05 MeV (including systematic errors too, see \([31]\)). To obtain \(B_A(\overline{A}Li\_^*\) from \(B_A(\overline{A}Li\_g.s.)\) we made use of the observation of the 3.88 MeV \(\gamma\)-ray transition \(^7\)Li\(^*\) → \(\gamma+\overline{A}\)Li \([32]\). Note that the \(^6\)Li core state of \(^7\)Li\(^*\) is the 0\(^+\) \(T=1\) at 3.56 MeV, whereas the core state of \(\overline{A}\)Li\(_{g.s.}\) is the 1\(^+\) \(T=0\) g.s. Recent \(B_A\) values from JLab electroproduction experiments at JLab for \(^7\)Li \([33]\) and \(^{10}\)Be \([34]\) were not used for lack of similar data on their mirror partners.

Table II. CSB contributions to \(\Delta B_{A}^{\text{calc}}(g.s.)\) values in \(p\)-shell hypernuclear isomultiplets, using the \((\Lambda\Sigma)_c\) coupling model with matrix elements \(\hat{V}_{\Lambda\Sigma}^{op}\) = 1.45 and \(\Delta_{\Lambda\Sigma}^{op}\) = 3.04 MeV in Eq. (6); see text. The \(s\)-shell contributions to \(\Delta B_A(0^+_{g.s.})\) from Table I are also listed for comparison. Listed values of \(\Delta B^{\text{exp}}_A\) are based on g.s. emulsion data except for \(\Delta B^{\text{exp}}_A(\overline{A}\)Li\(^*-7\)He\), see text.

| \(A\) | \(\Lambda\) | \(Z\) | \(\Lambda\) | \(Z\) | \(I^J\) | \(P_{\Sigma}\) | \(\Delta T_{YN}\) | \(\Delta V_{C}\) | \(\langle V_{CSB}\rangle\) | \(\Delta B^{\text{calc}}_A\) | \(\Delta B^{\text{exp}}_A\) |
|------|------|------|------|------|------|--------|-----------|-----------|-------------|-------------|-------------|
| \(^4\)He \(-\Lambda\)H | \(1^-\) | 0 \(^+\) | 0.72 | 39 | -45 | 232 | 226 | +350±60 |
| \(^7\)Be \(-\Lambda\)\(^7\)Li \(+\) | 1 | 0.12 | 3 | -70 \([24]\) | 50 | -17 | -100±90 |
| \(^7\)Li \(+\) \(-\Lambda\)\(^7\)He | 1 | 0.12 | 2 | -80 \([24]\) | 50 | -28 | -20±230 |
| \(^8\)Be \(-\Lambda\)\(^8\)Li | 1 | -0.20 | 11 | -81 \([28]\) | 119 | +49 | +40±60 |
| \(^9\)B \(-\Lambda\)\(^9\)Li | 1 | 0.23 | 10 | -145 | 81 | -54 | -210±220 |
| \(^{10}\)Be \(-\Lambda\)\(^{10}\)Be | 0.053 | 1 | -0.156 | 17 | -136 | -220±250 |
between s-shell to p-shell $\Lambda\Sigma$ matrix elements.

Comparing $\Delta B_{\Lambda}^{\text{calc}}$ with $\Delta B_{\Lambda}^{\exp}$ in Table II, we note the reasonable agreement reached between the $\langle\Lambda\Sigma\rangle_{e}$ coupling model calculation and experiment for all five pairs of $p$-shell hypernuclei, $A = 7 - 10$, listed here. Extrapolating to heavier hypernuclei, one might naively expect negative values of $\Delta B_{\Lambda}^{\text{calc}}$. However, this rests on the assumption that the negative $\Delta V_{\chi}$ contribution remains as large upon increasing $A$ as it is in the beginning of the $p$ shell, which need not be the case. As nuclear cores beyond $A = 9$ become more tightly bound, the $\Lambda$ hyperon is unlikely to compress these nuclear cores as much as it does in lighter hypernuclei, so that the additional Coulomb repulsion in $^{12}_{12}$C, for example, over that in $^{12}_{12}$B, while still negative, may not be sufficiently large to offset the attractive CSB contribution to $B_{\Lambda}(^{12}_{12}C) - B_{\Lambda}(^{12}_{12}B)$. Hence, one expects that $|\Delta B_{\Lambda}(A = 12)| \lesssim 50$ keV, in agreement with the recent discussion of measured $B_{\Lambda}$ systematics [31]. In making this argument one relies on the expectation, based on SU(4) supermultiplet fragmentation patterns in the $p$ shell, that $\langle V_{\text{CSB}} \rangle$ does not exceed $\sim 100$ keV.

Some implications of the state dependence of CSB splittings, e.g. the large difference between the calculated $\Delta B_{\Lambda}(^{0+}_{g.s.})$ and $\Delta B_{\Lambda}(^{1+}_{\text{g.s.}})$ in the s shell, are worth noting also in the $p$ shell, the most spectacular one concerns the $^{10}_{8}$B g.s. doublet splitting. Adding the $\langle\Lambda\Sigma\rangle_{e}$ coupling model CSB contribution of $\approx -27$ keV to the $\approx 110$ keV CS $^{1}_{g.s.} \rightarrow 2_{exc}^{-} g.s.$ doublet excitation energy calculated in this model [27] helps bring it down well below 100 keV, which is the upper limit placed on it from past searches for a $2_{exc}^{-} \rightarrow 1_{g.s.}^{-}$ $\gamma$-ray transition [35, 36].

5. Summary and outlook

The recent J-PARC observation of a 1.41 MeV $^{4}_{4}$He($^{+}_{1\text{exc}} \rightarrow 0^{+}_{g.s.}$) $\gamma$-ray transition [5], and the recent MAMI determination of $B_{\Lambda}(^{4}_{4}H)$ to better than 100 keV [6, 7], arouse renewed interest in the sizable CSB confirmed thereby in the $A=4$ mirror hypernuclei. It was shown in the present updated report how a relatively large $\Delta B_{\Lambda}(^{0+}_{g.s.})$ CSB contribution of order 250 keV arises in $\Lambda\Sigma$ coupling models based on Akaishi’s G-matrix effective s-shell central interactions approach [10, 11], well within the uncertainty of the value 233±92 keV deduced from the recent MAMI measurement [7]. It was also argued that the reason for the $YNNN$ coupled-channel calculations using NSC97 models to fall considerably behind, with 100 keV at most, is that their $\Lambda\Sigma$ coupling is dominated by a strong tensor term. In this sense, the observed large value of $\Delta B_{\Lambda}(^{0+}_{g.s.})$ places a powerful constraint on the strong-interaction $YN$ dynamics. Recent results of ab-initio four-body calculations [14, 15] using $\chi$EFT $YN$ interactions in LO exhibit sizable CSB $0^{+}_{g.s.}$ splittings in rough agreement with experiment. In future work one should apply the CSB generating equation (1) in four-body calculations of the $A=4$ mirror hypernuclei using the available NLO $\chi$EFT version [37, 38], and also to readjust the $\Lambda\Sigma$ contact terms in NLO by imposing the most accurate CSB datum as a further constraint.

Finally, an extension of the schematic $\Lambda\Sigma$ coupling model to the $p$ shell was shown to reproduce successfully the main CSB features indicated by mirror-hypernuclei binding energies there [8]. More theoretical work in this mass range, and beyond, is needed to understand further and better the salient features of $\Lambda\Sigma$ dynamics [39]. On the experimental side, the recently approved J-PARC E63 experiment is scheduled to remeasure the $^{4}_{4}H(1_{\text{exc}}^{+} \rightarrow 0^{+}_{g.s.})$ $\gamma$-ray transition [40] and, perhaps in addition to the standard ($\pi^{+}, K^{+}$) reaction, to also use the recently proposed ($\pi^{-}, K^{0}$) reaction [41] in order to study simultaneously several members of given $\Lambda$ hypernuclear isomultiplets, for example reaching both $^{12}_{12}$B and $^{12}_{12}$C on a carbon target.
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