IL NUOVO CIMENTO **42 C** (2019) 91
DOI 10.1393/ncc/i2019-19091-0

Colloquia: EuNPC 2018

Charge Symmetry Breaking in strange nuclei

E. Botta([1])([2])

([1]) *INFN, Sezione di Torino - Torino, Italy*
([2]) *Dipartimento di Fisica, Università di Torino - Torino, Italy*

received 5 February 2019

Summary. — Charge symmetry breaking in Λ-hypernuclei manifests in a difference between the Λ separation energies in mirror hypernuclei. For the $s-$shell this difference appears to be sizeable, while for $p-$shell experimental results suggest a much weaker effect. In this paper an updated experimental review is given.

1. – Introduction

Charge Symmetry is the invariance under a rotation of 180° around the y axis in isospin space; its violation is known as charge symmetry breaking (CSB).

CSB in the strong Nucleon-Nucleon (NN) interaction refers to a difference between proton-proton (I_3=+1) and neutron-neutron (I_3=-1) interactions and manifests in the differences between mirror nuclei ((N,Z) = (Z+1, Z) and (Z, Z+1)) binding energies: the ground state binding energy difference in the $A = 3$ system, ΔB = B(^{3}H) - B(^{3}He) is the paradigm of CSB effect in nuclei and its value, ∼71 keV, gives the scale of the violation. The present understanding is that, on a fundamental level, the isospin dependence of the nuclear forces is due to a difference between the u and d quark masses and to electromagnetic interactions among quarks. As a consequence, on the hadronic level, the main causes of CSB are mass differences between hadrons of the same isospin multiplet, meson mixing and irreducible meson-photon exchanges (see Ref. [1] for a complete review).

CSB in the strong Hyperon-Nucleon (YN) interaction refers to a difference between proton-Λ (I_3=+1/2) and neutron-Λ (I_3=-1/2) interactions and shows in the differences between mirror hypernuclei Λ separation energies. It is predicted by all the current baryon-baryon interaction based model to be ∼ 50 keV and to obtain higher values it is necessary to resort to more complex mechanisms like the $\Lambda - \Sigma$ mixing process. It is worth to remind that the Λ separation energy in a Λ hypernucleus is defined as:

$$B_\Lambda = [M(\Lambda) + M(^{A-1}Z) - M(^A_\Lambda Z)]\ c^2 \tag{1}$$

where $M(\Lambda)$ is the mass of the Λ-hyperon, $M(^{A-1}Z)$ the mass of the core nucleus in its ground state and $M(^A_\Lambda Z)$ the mass of the hypernucleus. The asymmetry in mirror hypernuclei Λ separation energies is, in turn, given by:

$$\Delta B_\Lambda(A) = B_\Lambda(^A_\Lambda Z) - B_\Lambda(^A_\Lambda(Z-1)). \tag{2}$$

In the following a review is given of the results on the asymmetry of the separation energies in mirror Λ hypernuclei with $s-$ and $p-$shell core. The survey presented here contains the most up-to-date results as for 2018.

2. – CSB effects in $s-$ and $p-$shell Λ-hypernuclei

To investigate the presence of CSB effects, the accuracy of the measured B_Λ's of isotopic mirror Λ-hypernuclei pairs is of paramount importance.

At accelerator machines, Λ-hypernuclei have been produced in the '60s by the interaction of K^-, both stopped and in flight, with the heavy components of photographic emulsions (Ag, Br) or with the He filling of bubble chambers detectors. By recognizing and measuring the energy of the charged disintegration products, the visualizing techniques permitted to determine accurately B_Λ's for hypernuclei in the $3 \leq \mathrm{A} \leq 15$ range. In particular, they allowed for the detection of all states of an isospin multiplet at the same time, potentially with a common systematic error for all B_Λ's values. The energy scale calibration could be obtained by the Λ hyperon mass through the invariant mass evaluation of the weak decay $\Lambda \to p + \pi^-$; it could be extended to the mesonic decay of hypernuclei, provided that the outgoing daugther nucleus was uniquely identified, condition which is more and more difficult to satisfy when increasing the hypernucleus mass number A. Also the statistics of the data sample of the various $s-$ and $p-$shell hypernuclei produced in these experiments was rather different, ranging from few events to hundreds of events.

From the '70s, Λ-hypernuclei have been produced at accelerators by means of dedicated reactions on single nucleons of the target nucleus:

$$K^- + n \to \Lambda + \pi^- \tag{3}$$
$$\pi^+ + n \to \Lambda + K^+ \tag{4}$$
$$e + p \to e' + \Lambda + K^+ \tag{5}$$

where (3) is a *strangeness exchange reaction*, (4) is an *associate strangeness production reaction* and (5) corresponds to a *photoproduction reaction* with a virtual (quasi-real) photon: $\gamma_{virtual} + p \to \Lambda + K^+$. Counter experiments techniques have been used and the B_Λ values have been obtained from the missing mass of the nuclear reactions evaluated from the measured momentum of the outgoing charged particles. High statistics data samples have been collected.

It can be noticed that reactions (3), (4), (5) produce only one state of a isotopic mirror Λ-hypernuclei pair, so that results of different experiments have to be used to evaluate $\Delta B_\Lambda(A)$ and, thus, the absolute energy scale calibration is even more mandatory.

Experiments exploiting reaction (5) have been performed at JLab by the Hall A and Hall C Collaborations; the absolute energy scale has been obtained by the elementary reaction $p(e, e'K^+)\Lambda, \Sigma^0$ on CH_2 target. Very recently, at MaMi-C, the A1 Collaboration used reaction (5) to produce $^4_\Lambda$H; the calibration was done with the elastic e scattering

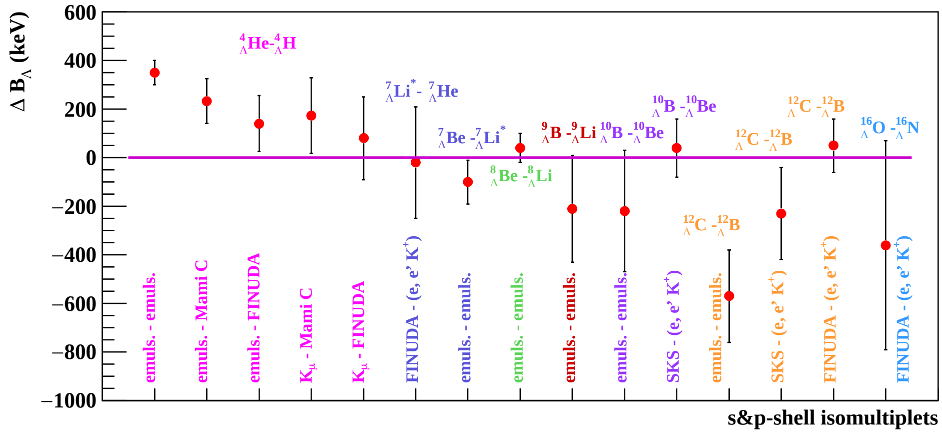

Fig. 1. – Synopsis of the available values of ΔB_Λ(A) to measure CSB effects in $s-$ and $p-$shell Λ-hypernuclei.

at fixed angle by a ^{181}Ta target. On the other hand, elementary reactions cannot be used for energy calibration in experiments working with reactions (3) and (4), since no neutron target is available. A recent experiment exploting reaction (3) has been made at INFN-LNF by the FINUDA Collaboration by stopping into thin targets the low energy kaons coming from the ϕ meson decay: $\phi \to K^+K^-$ ($\sim$ 49%). The absolute scale calibration has been obtained through the monochromatic charged particles produced in the decay reactions: $K^+ \to \pi^+\pi^0$ and $K^+ \to \mu^+\nu_\mu$. Several experiments have been done at KEK with the SKS spectrometer by using reaction (4). For these experiments no direct calibration was available and the B$_\Lambda$ value of $^{12}_{\Lambda}$C measured by emulsions has been taken as reference. This value, unfortunately, turned out to be unaccurate so that many authors from both JLab and FINUDA Collaborations suggested a correction to be applied to all KEK results. Full details on CSB effects in $s-$ and $p-$shell Λ-hypernuclei and on their evaluation can be found in [2] and [3].

Figure 1 shows the $\Delta B_\Lambda(A)$ values measured so far for the $s-$shell hypernuclei isotopic pair $^{4}_{\Lambda}$He/$^{4}_{\Lambda}$H and for the $p-$shell hypernuclei isotopic pairs $^{7}_{\Lambda}$Li*/$^{7}_{\Lambda}$He, $^{7}_{\Lambda}$Be/$^{7}_{\Lambda}$Li*, $^{8}_{\Lambda}$Be/$^{8}_{\Lambda}$Li, $^{9}_{\Lambda}$B/$^{9}_{\Lambda}$Li (not discussed here), $^{10}_{\Lambda}$B/$^{10}_{\Lambda}$Be, $^{12}_{\Lambda}$C/$^{12}_{\Lambda}$B and $^{16}_{\Lambda}$O/$^{16}_{\Lambda}$N. In the plot, different colors indicate different isotope pairs; multiple measurements of the same ΔB_Λ(A) performed by different experiments are listed, when available, in chronological order. Indications are also given about the experiments who measured the B$_\Lambda$ values; for $^{4}_{\Lambda}$He/$^{4}_{\Lambda}$H, K_μ indicates an older determination of B$_\Lambda$(^{4}He) obtained at KEK by a counter experiment with the (K^-, π^-) reaction on a ^{4}He target. The full listing of B$_\Lambda$'s can be found in [2] and [3].

Some comments can be done on the ΔB_Λ(A) values of Figure 1, for each A value starting from the $p-$shell systems and continuing with the $s-$shell.

- A=7 T=1: $^{7}_{\Lambda}$He, $^{7}_{\Lambda}$Li* and $^{7}_{\Lambda}$Be isotriplet, $^{7}_{\Lambda}$Li* being the excited state of $^{7}_{\Lambda}$He formed with the excited ^{6}Li* (0^+, T=1) core. The B$_\Lambda$ difference between the two extreme states T$_3$ = +1, −1 of the isotriplet is −390 ± 170 keV. It is obtained by comparing results from counter and emulsion experiments and −270 ± 170 keV come from the existing difference between the B$_\Lambda$($^{7}_{\Lambda}$Li*) determinations provided by the different techniques. On the other hand, the separate $\Delta B_\Lambda(A)$ are: ${}^{7}_{\Lambda}$Li* - ${}^{7}_{\Lambda}$He = -20±230 keV, from FINUDA and JLab Collaborations, and ${}^{7}_{\Lambda}$Be - ${}^{7}_{\Lambda}$Li* = -100±90 keV, from emulsions. Theoretical predictions indicate ${}^{7}_{\Lambda}$Be - ${}^{7}_{\Lambda}$Li* values varying from -17 keV to 220 keV, see [2] and [3] for full details. With the caution arising from the still large errors it is possible to conclude that no substantial contributions from the CSB effect seem to be present in the A = 7, T = 1 hypernuclear isotriplet.

- A=8, T=1/2: ${}^{8}_{\Lambda}$Be and ${}^{8}_{\Lambda}$Li. Only emulsion measurements are available. A Λ binding energy difference of +40±60 keV is found, to be compared with theoretical predictions of +49 keV and of +160 keV [2, 3]. Also for the A=8, T=1/2 sector, no substantial contributions appear from the CSB effect.

- A=10, T=1/2: ${}^{10}_{\Lambda}$B and ${}^{10}_{\Lambda}$Be. Measurements are available from both emulsion experiments and counter experiments. From emulsion data a Λ binding energy difference of -220±250 keV is found, while from magnetic experiments the difference changes sign and reduces to +40±120 keV. Theoretical predictions indicate a difference of -136 keV [2, 3]. Thus also for the A=10, T=1/2 sector, no substantial contributions seem to originate from the CSB effect.

- A=12, T=1/2: ${}^{12}_{\Lambda}$C and ${}^{12}_{\Lambda}$B. Measurements are available from emulsion experiments and counter experiments. From emulsion data a Λ binding energy difference of -570±190 keV is found. From JLab and revised SKS experiments the difference reduces to -230±190 keV, almost compatible with zero within the errors. Finally, from JLab and FINUDA it changes sign and reduces to +50±110 keV. Theoretical predictions indicate a difference of -136 keV [2, 3].

- A=16, T=1/2: ${}^{16}_{\Lambda}$O and ${}^{16}_{\Lambda}$N. Measurements are available from counter experiments, namely JLab and FINUDA. The Λ binding energy difference is -360±430 keV while no theoretical calculation is available.

- A=4, T=1/2: ${}^{4}_{\Lambda}$He and ${}^{4}_{\Lambda}$H. The A=4 system is the archetype of CSB in Λ-hypernuclei. Emulsion data give $\Delta B_\Lambda(4)$=350±60 keV, much higher than can be explained by simple theoretical calculations, without including the $\Lambda - \Sigma^0$ mixing mechanism (see [2, 3] and references quoted therein). The most recent published value for ${}^{4}_{\Lambda}$H is from MaMi-C A1 Collaboration; when comparing with the ${}^{4}_{\Lambda}$He Λ separation energy from emulsions the asymmetry is reduced to 233±92 keV. If the preliminary result from FINUDA is considered, it drops further to 140±119 keV. On the other hand, if the $B_\Lambda({}^{4}_{\Lambda}\mathrm{He})$ is taken from the above mentioned older KEK experiment, less precise than the emulsions result but with absolute energy scale calibration (K^+ and Σ^+ decay peaks), the asymmetry is 173±126 keV with respect to MaMi-C A1 and 80±155 keV with respect to FINUDA. In the end, for the A=4, T=1/2 sector, indications of substantial contributions from the CSB effect seem to be present but a precise determination of the ${}^{4}_{\Lambda}$He Λ separation energy by an experiment with an absolute energy scale calibration is needed to fix its final value.

To conclude, Λ-hypernuclei do not indicate CSB effects in the Λ-N interaction when the hyperon sticks to a $p-$shell core; CSB contributions appear when an A=3 core is considered, but accurate and precise determination of $B_\Lambda({}^{4}_{\Lambda}\mathrm{He})$ is needed to define the scale of this charge invariance breaking.

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