On the Binding Energies of Λ-Hyperons in Hyperhydrogen

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DOI: http://dx.doi.org/10.3204/DESY-PROC-2014-04/12

The study of the binding energies of the Λ-hyperon in the lightest hypernuclei can reveal details of the strong nucleon-hyperon interaction. The binding energy of the Λ-hyperon, B_Λ, is defined as the Λ-hyperon separation energy from the non-strange core: $B_\Lambda = (M_{core} + M_\Lambda - M_Y)c^2$ where M_Y, M_{core} and M_Λ are the masses of the hypernucleus, its core and the Λ-hyperon respectively.

For many decades visual detectors like nuclear emulsions, with spatial resolutions better than one micrometer to track production and decay, and helium bubble chambers were employed. The masses of hypernuclei $A < 14$ were determined by analyzing the kinetic energies of decay products from the weak pionic decays. No bound states of Λp or Λn were found. The lightest systems are the s-shell ($A \leq 5$) hyperhydrogen and hyperhelium isotopes. The statistical error for the binding energies in light hypernuclei with the emulsion method ranges from 0.02 MeV for ${}^{5}_{\Lambda}$He to more than 0.7 MeV for ${}^{8}_{\Lambda}$He [1–3]. In one of these compilations a possible systematic error of 0.15 MeV [3] is quoted. In a later work by D.H. Davis systematic errors of the order of 0.04 MeV are given [4].

This era was followed by spectroscopic measurements at secondary, mesonic beams achieving energy resolutions of the order of $\Delta B_\Lambda \sim 1.5$ MeV (FWHM) [5]. Only recently energy resolutions of ~ 0.5 MeV (FWHM) have been achieved in the $(e, e'K^+)$ reaction using a dedicated kaon spectrometer at Jefferson Lab. The best reaction spectroscopy data in terms of resolution was reported for ${}^{12}_{\Lambda}$B [6] and ${}^{7}_{\Lambda}$He [7]. During the last three years the new method of decay-pion spectroscopy was pioneered at the Mainz Microtron MAMI, that has the potential to achieve mass measurements of several light hypernuclei with a precision comparable or better than with the emulsion technique.

${}^{3}_{\Lambda}$H decay mode	N	B_Λ (MeV)	Ref.
${}^{3}_{\Lambda}\text{H} \to \pi^- + {}^{1}\text{H} + {}^{2}\text{H}$	24	$+0.23 \pm 0.11$	[1]
${}^{3}_{\Lambda}\text{H} \to \pi^- + {}^{3}\text{He}$	58	$+0.06 \pm 0.11$	[1]
both modes	82	$+0.15 \pm 0.08$	[1]
${}^{3}_{\Lambda}\text{H} \to \pi^- + {}^{1}\text{H} + {}^{2}\text{H}$	16	-0.11 ± 0.13	[2]
${}^{3}_{\Lambda}\text{H} \to \pi^- + {}^{3}\text{He}$	86	$+0.05 \pm 0.08$	[2]
both modes	102	$+0.01 \pm 0.07$	[2]
${}^{3}_{\Lambda}\text{H} \to \pi^- + {}^{1}\text{H} + {}^{2}\text{H}$	6	$+0.33 \pm 0.21$	[3]
${}^{3}_{\Lambda}\text{H} \to \pi^- + {}^{3}\text{He}$	26	$+0.13 \pm 0.15$	[3]
both modes	32	$+0.20 \pm 0.12$	[3]
mean (both modes)	204	$+0.13 \pm 0.05$	[1]

Table 1: Binding energies of ${}^{3}_{\Lambda}$H from emulsion experiments as compiled by Refs. [1–3]. The number of uniquely identified events, N, for determining B_Λ is given for two decay modes. The mean value was evaluated in Ref. [1] using both modes.

The lightest strange nuclear system is the hypertriton ${}^{3}_{\Lambda}$H, found to be just bound. Available data on ${}^{3}_{\Lambda}$H is summarized in Table 1. From the Table it is seen that the number of uniquely identified events for determining B_Λ was in total of the order $\sim$ 200 from different decay modes, analyzed and compiled in three different works. The mean value was evaluated in Ref. [1] using both decay modes to be (0.13 ± 0.05) MeV. The distribution of binding energies of ${}^{3}_{\Lambda}$H determined from pionic two-body and three-body decays is shown in Fig. 1. The FWHM of the distribution of binding energies is 2.1 MeV corresponding to a width $\sigma = 0.89$ MeV if the distribution were Gaussian, which would allow for a determination of its mean value with a statistical uncertainty of $\Delta B_\Lambda = 0.89\,\text{MeV}/\sqrt{204} = 0.06$ MeV. The published B_Λ values are shown in Fig. 2. From the data one can deduce that the mean B_Λ value of the 176 events of the two-body mode is 0.07 MeV and of the 46 events of the three-body mode is 0.13 MeV. The B_Λ values evaluated by Ref. [2] and by Ref. [1] differ by (0.14 ± 0.11) MeV.

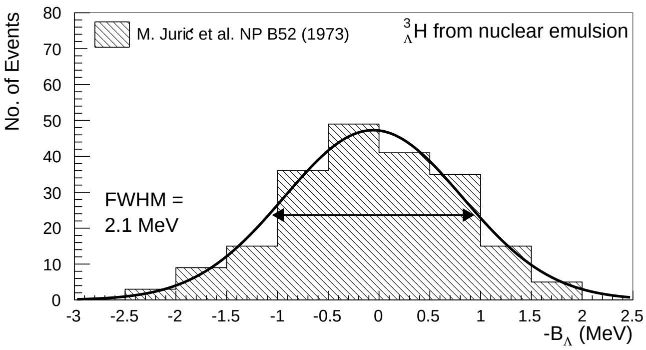

Figure 1: Distribution of binding energies of ${}^{3}_{\Lambda}$H determined from pionic two-body and three-body decays observed in emulsion experiments as compiled in Ref. [1]. A Gaussian function was fitted to the distribution for the illustration of the dispersion of the values with a FWHM of 2.1 MeV. The total number of events was 204 and the mean value was evaluated in Ref. [1] to be $B_\Lambda = 0.13 \pm 0.05$ MeV.

When going from a mass $A = 3$ to a $A = 4$ system the binding energy of the Λ-hyperon increases by about 1 MeV. Table 2 summarizes the B_Λ values for ${}^{4}_{\Lambda}$H. The mean value was evaluated in Ref. [1] using only three-body decay modes to be (2.04 ± 0.04) MeV. In the same publication the B_Λ values for the $\pi^- + {}^1\text{H} + {}^3\text{H}$ decay mode, 2.14 ± 0.07 MeV, and for $\pi^- + {}^2\text{H} + {}^2\text{H}$ mode, 1.92 ± 0.12 MeV, are reported separately. They differ by (0.22 ± 0.14) MeV. The mean B_Λ value of the 760 events of the two-body mode reported by Refs. [2, 3] is 2.28 MeV which would indicate a $\sim$ 0.2 MeV stronger binding. This decay mode is not included because of the larger systematic error in the pion range-energy relation for pion ranges greater than 3 cm [1].

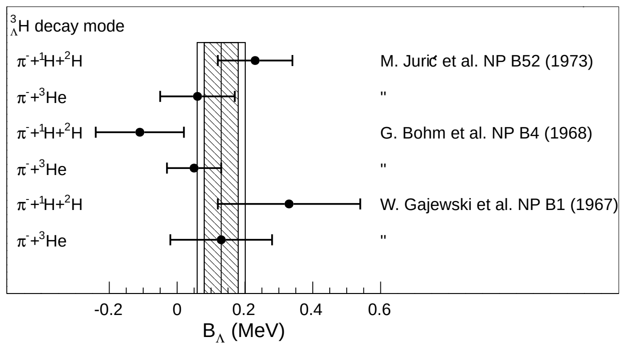

Figure 2: Measurements of the binding energy of ${}^{3}_{\Lambda}$H determined from two-body and three-body pionic decays observed in emulsion experiments [1–3] (with statistical errors only). The mean value was evaluated in Ref. [1] (shaded bands with statistical and total uncertainties).

The mirror pair of hypernuclei $^4_\Lambda$H and $^4_\Lambda$He is especially important because it is used as the main source of information about the charge symmetry breaking (CSB) in the ΛN interaction. Charge symmetric interactions do not distinguish between the nucleon isospin channels Λp and Λn. CSB effects in the strong interaction occurs because of the difference between the masses of the quarks in hadronic and nuclear systems. In mirror hypernuclei the binding energies of the Λ-hyperon could reveal CSB contributions in the strong interaction. The distribution of binding energies of $A = 4$ hypernuclei is shown in Fig. 3. The binding energies for the (0^+) ground states, $B_\Lambda(^4_\Lambda\text{H}) = 2.04 \pm 0.04\,\text{MeV}$ and $B_\Lambda(^4_\Lambda\text{He}) = 2.39 \pm 0.03\,\text{MeV}$ systematically differ, the difference being $\Delta B_\Lambda = 0.35 \pm 0.06\,\text{MeV}$. However, the FWHM of the distributions of binding energies is larger than 1 MeV. The Coulomb correction due to core compression induced by the presence of the Λ-hyperon in the nucleus was calculated to be less than 0.05 MeV [8]. If the mirror pair difference is as large as 0.35 MeV the CSB effect in the ΛN interaction would be much larger than in the NN interaction.

$^4_\Lambda$H decay mode	N	B_Λ (MeV)	Ref.
$^4_\Lambda\text{H} \to \pi^- + {}^1\text{H} + {}^3\text{H}$	56	$+2.14 \pm 0.07$	[1]
$^4_\Lambda\text{H} \to \pi^- + {}^2\text{H} + {}^2\text{H}$	11	$+1.92 \pm 0.12$	[1]
both three-body modes	67	$+2.08 \pm 0.06$	[1]
$^4_\Lambda\text{H} \to \pi^- + {}^1\text{H} + {}^3\text{H}$	63		[2]
$^4_\Lambda\text{H} \to \pi^- + {}^2\text{H} + {}^2\text{H}$	7		[2]
both three-body modes	70	$+2.08 \pm 0.06$	[2]
$^4_\Lambda\text{H} \to \pi^- + {}^4\text{He}$	552	$+2.29 \pm 0.04$	[2]
$^4_\Lambda\text{H} \to \pi^- + {}^1\text{H} + {}^3\text{H}$	21		[3]
$^4_\Lambda\text{H} \to \pi^- + {}^2\text{H} + {}^2\text{H}$	2		[3]
both three-body modes	23	$+1.86 \pm 0.10$	[3]
$^4_\Lambda\text{H} \to \pi^- + {}^4\text{He}$	208	$+2.26 \pm 0.07$	[3]
mean (three-body)	155	$+2.04 \pm 0.04$	[1]

Table 2: Binding energies of $^4_\Lambda$H from emulsion experiments as compiled by Refs. [1–3]. The number of uniquely identified events for determining B_Λ is given for three decay modes. The mean value was evaluated in Ref. [1] using only the three-body modes.

At the Mainz Microtron MAMI the first high-resolution spectroscopy of pions from decays of hypernuclei was performed. The associated strangeness production with the incident electron beam on a thin ^{9}Be target was tagged by the detection of kaons with the spectrometer KAOS. Pions were detected in coincidence with two high-resolution spectrometers. Details on the setup, the experimental conditions, and the identification of pionic weak decays can be found in Refs. [9, 10]. The binding energy of stopped $^4_\Lambda$H was deduced from the two-body decay mode $^4_\Lambda\text{H} \to \pi^- + {}^4\text{He}$ with a 10^{-3} relative momentum resolution [11]. Details on the statistical and systematic error are found in the reference.

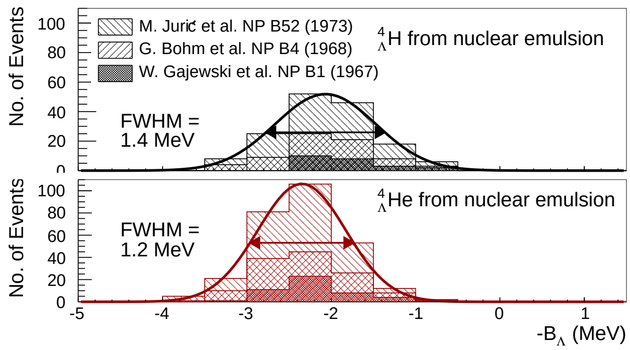

Figure 3: Distribution of binding energies of $^4_\Lambda$H and $^4_\Lambda$He determined from pionic three-body decays observed in emulsion experiments as compiled in Refs. [1–3]. A Gaussian function was fitted to the distribution for the illustration of the dispersion of the values with a FWHM of 1.2–1.4 MeV. The total number of events was 155 resp. 279 and the mean value was evaluated in Ref. [1] to be $B_\Lambda = 2.04 \pm 0.04\,\text{MeV}$ resp. $2.39 \pm 0.03\,\text{MeV}$.

In Fig. 4 the preliminary MAMI result on the binding energy of ${}^{4}_{\Lambda}\mathrm{H}$ is compared to the emulsion experiments [1–3]. Full circles present evaluations from three-body decays, open circles from two-body decays, error bars on the emulsion values are statistical only. The mean values were evaluated in Ref. [1] excluding data from the two-body decay mode, where the shaded bands show statistical and total uncertainties. The error bars on the MAMI value are statistical (inner) and total (outer). The figure also shows the data from the pioneering decay-pion spectroscopy with a stopped K^--beam at KEK [12].

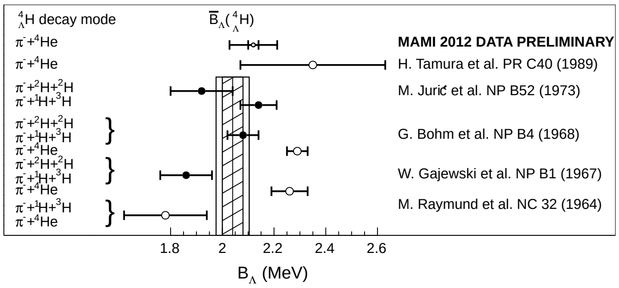

Figure 4: Measurements of the binding energy of ${}^{4}_{\Lambda}\mathrm{H}$ determined from different pionic decays. Details are discussed in the text.

A major effort in hypernuclear physics is to understand the interaction between hyperons and nucleons. Parameters of many employed phenomenological models are fitted to reproduce the binding energies of light hypernuclei. Many theoretical descriptions include ΛNN three-body forces and charge symmetry breaking terms to yield an agreement with available experimental data over a wide range of hypernuclear masses. In the literature the binding energies of the light hyperhydrogen isotopes are often quoted with errors of $0.04 - 0.05\,\mathrm{MeV}$. One should be aware of systematic errors. A cross-check of the experimental values with an independent method with high resolution seems timely and necessary.

This work was supported in part by Deutsche Forschungsgemeinschaft (SFB 1044), by Carl Zeiss Foundation, by European Community Research Infrastructure Integrating Activity HadronPhysics2 (SPHERE).

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