Ground-state binding energy of ${}^4_\Lambda\text{H}$ from high-resolution decay-pion spectroscopy

A1 Collaboration

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Abstract

A systematic study on the Λ ground state binding energy of hyperhydrogen ${}^4_\Lambda\text{H}$ measured at the Mainz Microtron MAMI is presented. The energy was deduced from the spectroscopy of mono-energetic pions from the two-body decays of hyperfragments, which were produced and stopped in a ${}^9\text{Be}$ target. First data, taken in the year 2012 with a high resolution magnetic spectrometer, demonstrated an almost one order of magnitude higher precision than emul-

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sion data, while being limited by systematic uncertainties. In 2014 an extended measurement campaign was performed with improved control over systematic effects, increasing the yield of hypernuclei and confirming the observation with two independent spectrometers and two targets of different thicknesses. The analysis of these data is in agreement with the previously published value for the ${}^4_{\Lambda}\text{H}$ binding energy as well as with a consistent re-analysis of the 2012 data. When compared to the ${}^4_{\Lambda}\text{He}$ binding energy from emulsion data, a large charge symmetry breaking effect in the $A = 4$ hypernuclear system is confirmed.

Keywords: hypernuclear mass spectroscopy, mesonic weak decay, charge symmetry breaking

1. Introduction

The structure of light Λ -hypernuclei and the precise determination of Λ hyperon binding (separation) energies have been in the focus of many recent experimental and theoretical programs [1]. Existing s -shell hypernuclei include ${}^3_{\Lambda}\text{H}$, which is the least bound, the iso-doublet of ${}^4_{\Lambda}\text{He}$ and ${}^4_{\Lambda}\text{H}$ in their ground and excited states, and the iso-singlet ${}^5_{\Lambda}\text{He}$. The ground state in both $A = 4$ hypernuclei is a singlet, $J^{\pi} = 0^{+}$ spin system, while the first excited state is described by parallel spin orientation of the Λ hyperon and the core nucleus giving rise to a 1^{+} spin system which is excited to energies of the order of 1 MeV.

Charge symmetry of the strong interaction predicts that the Λp and Λn interaction and consequently their contribution to the binding energy of mirror hypernuclei are identical. Charge symmetry breaking (CSB) in the strong interaction occurs because of the mass difference of the fundamental up and down quarks in the hadronic and nuclear systems. In the NN interaction the CSB effect is well understood and was found to be small in the ${}^3\text{He} - {}^3\text{H}$ mirror pair at a level of $\Delta B_{\text{CSB}}^3 \sim 70 \text{ keV}$ [2] after removal of trivial Coulomb energy contributions. In the system of $A = 4$ hypernuclei, however, old emulsion measurements found an exceptionally large difference of $\Delta B_{\Lambda}^4 = 0.35 \pm 0.05 \text{ MeV}$ between the

20 ground state binding energies [3]. From γ -ray spectroscopy it is known, after a very recent new determination of the transition energy in ${}^4_{\Lambda}\text{He}$ [4], that the CSB effect has a large spin-dependence. Calculations have shown that the addition of the Λ hyperon to the ${}^3\text{He}$ core contracts the core slightly, leading to a decreased binding energy in ${}^4_{\Lambda}\text{He}$ [5]. This non-trivial Coulomb effect is in the opposite
 25 direction to the observed ground state binding energy difference and contributes $-\Delta B_C = 0.050 \pm 0.02 \text{ MeV}$ [6]. Additionally, $\Lambda - \Sigma$ coupling can account for charge symmetry breaking. Since the Σ hyperon has isospin 1, while the Λ has isospin zero, the mixing of Σ states in the nuclei depends on the spin-isospin structure of the nuclear core and excited states to which the Λ may be attached.

30 The large value of the Λ hyperon binding energy difference and the large difference between ground and excited states of the $A = 4$ mirror pair represent one of the unresolved issues in hypernuclear physics [7, 8]. Many theoretical contemporary attempts based on a variety of hyperon-nucleon interactions were made but failed to reproduce consistently the experimental data [9–12]. Only
 35 very recently, large-scale no-core shell model calculations of ${}^4_{\Lambda}\text{He}$ and ${}^4_{\Lambda}\text{H}$ based on chiral nucleon-nucleon and hyperon-nucleon interactions were capable for the first time of generating sizable charge symmetry breaking in $A = 4$ hypernuclei by including charge-symmetry breaking hyperon-nucleon interactions induced by $\Lambda - \Sigma^0$ mixing [13]. This makes a confirmation of all energy levels in the $A =$
 40 4 system with independent experimental techniques desirable, especially since there is no exact knowledge about the systematic uncertainty for the emulsion data.

2. Decay-pion measurements at MAMI

In 2012, the first high-resolution spectroscopy of pions from decays of stopped
 45 ${}^4_{\Lambda}\text{H}$ hypernuclei was performed by the A1 Collaboration at the Mainz Microtron MAMI, Germany [14]. The MAMI beam with an energy of 1.5 GeV and an intensity of $20 \mu\text{A}$ was incident on a ${}^9\text{Be}$ target foil of $125 \mu\text{m}$ thickness. The process under study was a multi-step strangeness production, nuclear fragmen-

tation, and pionic weak decay reaction:

50 The foil was tilted with respect to the beam direction to minimize the energy straggling of negative pions leaving the target in direction of the spectrometers. These pions were detected alternatively in one of the two spectrometers SpekA and SpekC in coincidence with positive kaons tagged in the KAOS spectrometer. The pion spectrometers were positioned at backward angles to optimize the
55 signal-to-background ratio for pions. The coincidence condition ensured that the observed pions originated from weak decays of hyperons and hypernuclei.

To arrive at predictions for the decay-pion experiments at MAMI a chain of models and Monte Carlo simulations have to be combined to describe the strangeness formation process, the fragmentation mechanism, the pionic decay,
60 and finally the pion detection. Estimates for different hyperfragments are found in Ref. [15]. The fragmentation model predicts that the formation probability of some hyperhelium fragments is of the same order as the one of ${}^4_{\Lambda}\text{H}$. When stopping and two-body pionic decay probabilities are taken into account the ${}^4_{\Lambda}\text{H}$ yield dominates, consistent with the experimental observations.

65 The binding energy of ${}^4_{\Lambda}\text{H}$ was deduced from the mono-energetic decay-pion peak to be $B_{\Lambda} = 2.12 \pm 0.01$ (stat.) ± 0.09 (syst.) MeV with respect to the ${}^3\text{H} + \Lambda$ mass [14]. This value is 0.08 MeV different from emulsion data, for which the most complete compilation found $B_{\Lambda} = 2.04 \pm 0.04$ MeV using only three-body decay modes [3]. A re-analysis of the data collected in 2012 was reported in
70 Ref. [16].

In the year 2014 the experiment at MAMI was continued with improved control of systematic uncertainties, additional background suppression, and higher luminosities. A detailed description of the 2014 experiment can be found in Ref. [15]. Energy-loss fluctuations of pions in the scattering chamber windows
75 have been eliminated by directly coupling the spectrometers to the chamber. Two tungsten alloy collimators were placed behind the target to reduce the

Figure 1: Coincidence time spectra between KAOS spectrometer and SpekA (top) and SpekC (bottom) after flight path corrections for K^+ and π^- . The time gates for selecting accidental coincidences are shown by the blue areas. The light shaded events consisting predominantly of the K^+ and e^- peaks were rejected by gas Čerenkov cuts. The fits to the spectra are composed of Gaussian peaks restricted to the K^+ and π^- regions on top of flat background distributions. The peaks were resolved with $\text{FWHM} \approx 1.4$ ns resolution.

background from quasi-free produced Σ^- in-flight decays. The typical beam intensity was increased to $50 \mu\text{A}$. In order to check systematic momentum uncertainties the acceptance of both pion spectrometers covered the ${}^4\text{H}$ decay-
80 momentum region simultaneously.

Fig. 1 shows the measured coincidence time distributions after identification of kaons in the KAOS spectrometer for the 2014 data set. Measured times were corrected for the nominal flight time from target to time-of-flight detectors in the spectrometers by $t_{\text{corr}} = Lm/pc$, where the reconstructed flight path L and the
85 reconstructed momentum p for kaons in KAOS and pions in SpekA or SpekC with

the known masses m were used. The peaks for different particle combinations are closer in time in SpekC compared to SpekA because of the shorter flight paths in SpekC. The narrow K^+ and π^- coincidence peaks are signatures for the pionic weak decay of quasi-free produced hyperons and of hyperfragments. The FWHM ≈ 1.4 ns is a factor of 2 better than in the 2012 data set as a result of extensive calibrations of the time-of-flight detectors. Other peaks appear broadened because of the time correction. The K^+ and μ^- coincidence peaks are coming from $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$ decays near the target. Details on the improvements can be found in Ref. [17].

Figure 2: Pion momentum distributions in the region of interest taken with SpekA (left) and SpekC (right) using 123 μm (top) and 253 μm (bottom) thick ^9Be target foils from the 2014 data sets. The fits are composed of Gaussian resolution functions on top of flat background functions. The blue areas are accidental background events evaluated from the coincidence time side bands.

The four panels of Fig. 2 display the pion momentum distributions in SpekA and SpekC for the two ^9Be targets of different thicknesses. These data consistently showed mono-energetic lines from pionic $^4_\Lambda\text{H}$ decays near $p_\pi \approx 133$ MeV/c in both spectrometers. The combined significance level for the signals is $S_L = 5.1$ as determined by the profile likelihood method, confirming the observation in-

100 dependently from the 2012 data set.

3. Determination of the decay-pion momenta

The absolute momentum was referenced to the momentum of electrons with energies of 195 and 210 MeV scattered off a $6\text{ }\mu\text{m}$ thick ^{181}Ta target, details are found in Ref. [17]. The typical MAMI beam energy spread was 13 keV with an
105 energy variation of typical $\sigma_E < \pm 10\text{ keV}$ that can be reduced to $\sigma_E < \pm 1\text{ keV}$ using a stabilization system inside the racetrack microtron. The absolute energy of the extracted beam was known with an accuracy of $\delta E_{\text{beam}} \approx \pm 160\text{ keV}$. The peaks of elastic scattered electrons had widths of order $50\text{ keV}/c$ (FWHM). The precision of the calibration was $\delta p_{\text{calib}} \approx \pm 10\text{ keV}/c$ including uncertainties in
110 the fitting procedure and statistical errors. For SpekC the relative momentum of the elastic scattering peak was not the same as for the observed decay-pion peak, so an additional error $\delta p_{\text{calib}}(\text{SpekC}) \approx \pm 30\text{ keV}/c$ was assigned to uncertainties in the transfer matrix. All errors were propagated to the decay-pion momentum by scaling with the absolute momentum of the peaks.

115 The momentum calibration of the spectrometers was consistently performed for the 2012 and 2014 data sets by scaling the momentum spectra linear with a factor determined from the analysis of the elastic scattering data. The calibration lead to a shift of the order of 1×10^{-3} when compared to the online momentum spectra.

120 The fraction of ^4H fragments that stop inside the target was evaluated in the model to be 36 % for the $125\text{ }\mu\text{m}$ thick foil and to be 50 % for the $250\text{ }\mu\text{m}$ thick foil. The contribution of in-flight decays to the width, position, and shape of the mono-energetic decay-pion peak was predicted to be negligible. The decay of the hyperfragments was simulated with a Monte Carlo code to determine
125 the energy-loss and the multiple scattering of the pions inside the target. The simulated pion momentum distribution for a thin target of $125\text{ }\mu\text{m}$ thickness is shown in Fig 3. A response function to closely describe the peak shape was found including a Gaussian distribution for the resolution and a Landau distri-

Figure 3: Simulated pion momentum distribution for a $125\mu\text{m}$ thick ^9Be target and the spectrometer geometry of the 2014 data set. Due to the energy-loss and the multiple scattering of the pions inside the target the peak shape is asymmetric and the width of the peak differs for the two pion spectrometers SpekA and SpekC.

bution for the energy-loss, see Ref. [17]. However, due to the low count number
of observed $^4_\Lambda\text{H}$ a simple Gaussian fit to the peak proved to be more robust
to determine the most probable momentum in the data than more complex
fits. The mean energy-loss was $\Delta E \sim 20\text{ keV}$ for the $125\mu\text{m}$ thick target and
 $\Delta E \sim 40 - 50\text{ keV}$ for the $250\mu\text{m}$ thick target. The systematic bias of the
Gaussian mean value from the most probable momentum was $\Delta p \sim 12\text{ keV}/c$.
In comparison, the energy-loss for the 2012 data set was $\Delta E \gg 100\text{ keV}$ due to
the use of two vacuum window foils made of $125\mu\text{m}$ Kapton each.

In Table 1 the corrections added to the measured decay-pion momentum and
the systematic errors are tabulated. In contrast to 2012, the magnetic fields of
the spectrometers were monitored continuously throughout the 2014 beam-time
by NMR probes every 5 minutes. As a result, variations of the magnetic fields
of the spectrometers which previously contributed $40\text{ keV}/c$ to the momentum
error have been reduced to $\delta p_{\text{stabil}} < 5\text{ keV}/c$.

The two-body pionic decay momenta of $^4_\Lambda\text{H}$ hyperfragments measured with
the two spectrometers SpekA and SpekC for the two different target thicknesses
in the two beam-times in 2012 and 2014 are presented in Table 2. The values

Table 1: Compilation of corrections added to the measured decay-pion momentum and systematic errors in the decay-pion measurement and the spectrometer calibration. The total systematic error was determined by adding the individual contributions in quadrature.

Correction or error type	SpekA	SpekC
	keV/c	keV/c
momentum-loss in 125 μm ^9Be	+ 36	+ 26
momentum-loss in 250 μm ^9Be	+ 76	+ 57
fit bias for peak from 125 μm ^9Be	+ 11	+ 12
fit bias for peak from 250 μm ^9Be	+ 11	+ 12
beam energy uncertainty in calibration	± 101	± 109
transfer matrix uncertainty	—	± 20
precision in calibration	± 6	± 7
magnetic field instability	$< \pm 5$	
uncertainty of corrections	$< \pm 5$	
total systematic uncertainty	± 101	± 111

were extracted with binned and un-binned maximum likelihood fits and have been corrected for energy-loss in the targets and for the systematic fit bias when using a Gaussian distribution for the peak shape in the response function. The table also includes the extracted FWHM of the decay-pion peaks. As predicted, the FWHM of $\sim 80 - 90$ keV/c observed in the 2014 data was distinctly smaller than the FWHM $\sim 130 - 140$ keV/c observed in the 2012 data.

4. Extraction of Λ binding energy of $^4_\Lambda\text{H}$

The binding energy B_Λ of the Λ hyperon in the ground state of $^4_\Lambda\text{H}$ was deduced from the decay pion momentum p_π by

$$-B_\Lambda = \sqrt{M^2(^4\text{He})c^4 + p_\pi^2c^2} + \sqrt{M_\pi^2c^4 + p_\pi^2c^2} - M(^3\text{H})c^2 - M_\Lambda c^2$$

where the masses $M(^3\text{H}) = 2808.921$ MeV/c², $M(^4\text{He}) = 3727.379$ MeV/c², $M_\pi = 139.570$ MeV/c², and $M_\Lambda = 1115.683$ MeV/c² were used.

Figure 4: Λ binding energies of ${}^4_\Lambda\text{H}$ from decay-pion measurements using spectrometers, pioneered by Tamura [18], or using the nuclear emulsion technique as published by Gajewski [19], Bohm [20], Jurić [3], and Raymund [21]. The binding energy value for Ref. [18] was calculated from the observed momentum. Errors on the emulsion data are statistical only. The mean value of all emulsion data as compiled by Ref. [3] includes only three-body decays (full circles) and is represented by the error band. The uncertainties on the MAMI value are statistical (inner) and total (outer), where the total error is the sum of the statistical one and the systematic one in quadrature. The MAMI 2012 data set has an additional error (middle) of $\delta B_\Lambda \sim 30$ keV due to the instability of the magnetic field.

The binding energy of ${}^4_{\Lambda}\text{H}$ hypernuclei measured at MAMI are compiled in Table 3. For comparison, the table lists also the luminosities for the different data sets, the number of identified pionic weak decays N_{K^+, π^-} , and the yield of ${}^4_{\Lambda}\text{H}$ events $N_{\Lambda\text{H}}$. The value of N_{K^+, π^-} was evaluated from the number of events in the coincidence time spectra shown in Fig. 1 by subtracting the background from the K^+ and π^- peaks. The value of $N_{\Lambda\text{H}}$ was evaluated in a similar way from the spectra shown in Fig. 2. The numbers include systematic uncertainties due to the choice of the kaon selection criterion as discussed in Section 5.

A presentation of the binding energies from decay-pionic measurements is found in Fig. 4. The ${}^4_{\Lambda}\text{H}$ binding energies determined in the 2014 data set have reduced statistical and systematic uncertainties as compared to the 2012 data set. The four ${}^4_{\Lambda}\text{H}$ binding energy values from the 2014 data sets can be combined by weighing with the number of observed ${}^4_{\Lambda}\text{H}$ events:

$$B_{\Lambda}(\text{MAMI 2014}) = 2.154 \pm 0.006 \text{ (stat.)} \pm 0.077 \text{ (syst.) MeV} \quad (\text{binned fit})$$

$$B_{\Lambda}(\text{MAMI 2014}) = 2.157 \pm 0.005 \text{ (stat.)} \pm 0.077 \text{ (syst.) MeV} \quad (\text{un-binned fit}).$$

This binding energy is consistent with the value of

$$B_{\Lambda}(\text{MAMI 2012}) = 2.117 \pm 0.012 \text{ (stat.)} \pm 0.029 \text{ (stabil.)} \pm 0.081 \text{ (calib.) MeV}$$

from the re-analysed 2012 data set. A combined momentum calibration for all five data sets was performed to minimize the systematic error in the momentum scale of the spectrometers. As a consequence the remaining systematic errors are correlated, while the uncertainty of the magnetic field instability contributing to the 2012 data set is independent from the calibration. The largest systematic error originates from the uncertainty in the MAMI beam energy affecting the absolute momentum calibration of the spectrometers by $\delta p_{\text{calib}} \sim \pm 100 \text{ keV}/c$, the sum of all other systematic errors contributes one order of magnitude less.

5. Study of systematic effects

Uncertainties in the extracted decay-pion peak position were studied by systematically varying the data cuts on kaon selection, kaon vertical angle, kaon

horizontal angle, kaon minimum momentum, kaon maximum momentum, coincidence time gate, and pion vertex position. The largest effect was found when changing the kaon selection criterion, X_κ , as shown in Fig. 5. Smaller values of X_κ represent tighter cuts that reject more particles, causing a loss in ${}^4\text{H}$ counts, whereas higher values lead to additional background. The observed variations were of the order of $\delta p_{\text{cuts}} \sim \pm 10 \text{ keV}/c$ and were almost completely covered by the evaluated fit uncertainties. Other cut conditions led to variations of $\delta p_{\text{cuts}} < \pm 5 \text{ keV}/c$. Therefore, no additional error by systematic shifts has been assumed for the combined value.

Figure 5: Extracted decay pion momentum p_π when changing the kaon selection cut X_κ . The momentum was determined by fitting the 2014 data sets for SpekA (left) and SpekC (right) with the $125 \mu\text{m}$ (top) and $250 \mu\text{m}$ (bottom) thick ${}^9\text{Be}$ target. Cuts used for the final decay-pion momentum determination are indicated in blue. The uncertainty of the fit for these cuts is represented by the dashed lines.

Similar studies were performed for the extracted ${}^4\text{H}$ yield. The kaon cut conditions for each spectrometer were chosen so that the corresponding yield reached saturation and, therefore, had the best signal-to-background ratio. The variations in the yield of $\delta N_{\text{cuts}} \sim \pm 1\text{--}2$ events at the plateau value were well within the statistical uncertainties.

6. Conclusions

The Λ separation energy of ${}^4_\Lambda\text{H}$ has been measured for the second time by high-precision decay-pion spectroscopy at MAMI. The pions were observed in two independent spectrometers using two targets of different thicknesses, confirming the previous results in a consistent analysis of both experiments. Moreover, the results proved to be consistent after further calibration of the absolute momentum as well as in systematic studies of the used cut conditions.

When compared to the ${}^4_\Lambda\text{He}$ binding energy measured with the emulsion technique and adding the information from γ -ray spectroscopy the MAMI data of ${}^4_\Lambda\text{H}$ lead to the level schemes of ${}^4_\Lambda\text{H}$ and ${}^4_\Lambda\text{He}$ as shown in Fig. 6. Here, the systematic error estimate of 40 keV from Ref. [22] for the emulsion value was used. While the ground state binding energy difference of $\Delta B_\Lambda(0^+_{\text{g.s.}}) = B_\Lambda({}^4_\Lambda\text{He}(0^+_{\text{g.s.}})) - B_\Lambda({}^4_\Lambda\text{H}(0^+_{\text{g.s.}})) = 233 \pm 92$ keV is smaller as measured by the emulsion technique it still supports a sizable CSB effect in the ΛN interaction. Furthermore, it suggests a negative binding energy difference between the excited states of $\Delta B_\Lambda(1^+_{\text{exc}}) = B_\Lambda({}^4_\Lambda\text{He}(1^+_{\text{exc}})) - B_\Lambda({}^4_\Lambda\text{H}(1^+_{\text{exc}})) = -83 \pm 94$ keV.

Most calculations performed so far resulted in much smaller binding energy differences than observed. Gazda and Gal have recently reported on *ab initio* no-core shell model calculations of the mirror pair using the charge-symmetric Bonn-Jülich leading-order chiral effective field theory hyperon-nucleon potentials plus a charge symmetry breaking $\Lambda - \Sigma^0$ mixing vertex [13]. These calculations predict a large CSB ground state splitting and a CSB splitting of opposite sign for the excited states.

During the last years the MAMI accelerator was the only place worldwide where a precise and intense continuous electron beam was available for hypernuclear physics. While the total error of the MAMI binding energy data is of the same order than that of the compiled results from the emulsion technique, it is currently dominated by the systematic uncertainty of the absolute momentum calibration, which can be improved further. Current developments at MAMI are aiming at a higher accuracy of the calibration, which could reduce the error

Figure 6: Level schemes of the mirror hypernuclei ${}^4_{\Lambda}\text{H}$ and ${}^4_{\Lambda}\text{He}$ in terms of Λ binding energy. For the ground state binding energy of ${}^4_{\Lambda}\text{H}$ the MAMI data were used, for that of ${}^4_{\Lambda}\text{He}$ data from past emulsion experiments [3] with a systematic error estimate of 40 keV [22]. The B_{Λ} values for the excited states were obtained from the $1_{\text{exc}}^{+} \rightarrow 0_{\text{g.s.}}^{+}$ γ -ray transition energies [4].

on the binding energy by a factor of four.

Together with prospects for a precise measurement of the γ transition energy of ${}^4_{\Lambda}\text{H}$ at J-PARC [23], the ${}^4_{\Lambda}\text{H}$ level scheme could become the most accurate among hypernuclei and provide further guidance for theory and for investigating the origin of CSB in the ΛN interaction.

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Table 2: Two-body pionic decay momenta of ${}^4\text{H}$ hyperfragments measured with the two spectrometers SpekA and SpekC in electron scattering off ${}^9\text{Be}$ targets with two different thicknesses x_{target} at the Mainz Microtron MAMI during the two beam-times in 2012 and 2014. The statistical errors were evaluated from the binned and un-binned maximum likelihood fits respectively, the systematic corrections and errors are compiled in Table 1.

Experiment	x_{target} μm	Spectrometer	binned fit		un-binned fit		$\delta p_{\pi}(\text{syst.})$ MeV/c	FWHM keV/c
			p_{π}	$\delta p_{\pi}(\text{stat.})$	p_{π}	$\delta p_{\pi}(\text{stat.})$		
			MeV/c	MeV/c	MeV/c	MeV/c		
MAMI 2012 [14]	125	SpekC	132.922	± 0.016	—	—	$\pm 0.111 \pm 0.040$	143
MAMI 2012 [16]	<i>dto.</i>	<i>dto.</i>	132.923	± 0.016	132.922	± 0.019	$\pm 0.111 \pm 0.040$	129
MAMI 2014	123	SpekA	132.875	± 0.014	132.875	± 0.012	± 0.101	89
MAMI 2014	<i>dto.</i>	SpekC	132.859	± 0.014	132.846	± 0.014	± 0.111	84
MAMI 2014	253	SpekA	132.846	± 0.017	132.851	± 0.011	± 0.101	77
MAMI 2014	<i>dto.</i>	SpekC	132.918	± 0.019	132.920	± 0.014	± 0.111	91

Table 3: Compilation of Λ binding energies of ${}^4\text{H}$ evaluated from the two-body pionic decay momenta presented in Table 2 together with their statistical and systematic errors, the integrated and dead-time corrected luminosities $\int \mathcal{L} dt$, the number of identified pionic weak decays N_{K^+, π^-} , and the hyperfragment yield $N_{\Lambda\text{H}}$. The statistical errors of the yields were evaluated from the count numbers. The combined value for MAMI 2014 was calculated by weighing with the number of observed ${}^4\text{H}$ events.

Experiment	$\int \mathcal{L} dt$ fb^{-1}	x_{target} μm	Spectrometer	N_{K^+, π^-}	$N_{\Lambda\text{H}}^4$	binned fit		un-binned fit		$\delta B_{\Lambda}(\text{syst.})$ MeV
						B_{Λ} MeV	$\delta B_{\Lambda}(\text{stat.})$ MeV	B_{Λ} MeV	$\delta B_{\Lambda}(\text{stat.})$ MeV	
MAMI 2012 [14]	235	125	SpekC	—	—	2.117	± 0.012			$\pm 0.081 \pm 0.029$
MAMI 2012 [16]	<i>dto.</i>	<i>dto.</i>	<i>dto.</i>	1130 ± 33	26 ± 6	2.117	± 0.012	2.117	± 0.014	$\pm 0.081 \pm 0.029$
MAMI 2014	786	123	SpekA	2246 ± 257	26 ± 7	2.151	± 0.010	2.151	± 0.009	± 0.074
MAMI 2014	<i>dto.</i>	<i>dto.</i>	SpekC	3364 ± 416	25 ± 7	2.163	± 0.010	2.172	± 0.011	± 0.081
MAMI 2014	170	253	SpekA	469 ± 65	8.5 ± 4	2.172	± 0.012	2.169	± 0.008	± 0.074
MAMI 2014	<i>dto.</i>	<i>dto.</i>	SpekC	609 ± 72	8.5 ± 4	2.120	± 0.014	2.119	± 0.010	± 0.081
MAMI 2014	1912	—	—	6688 ± 810	68 ± 12	2.154	± 0.006	2.157	± 0.005	± 0.077