Observation of $^4_3\text{H}$ hyperhydrogen by decay-pion spectroscopy in electron scattering

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Abstract

At the Mainz Microtron MAMI, the first high-resolution pion spectroscopy from decays of strange systems was performed by electron scattering off a $^9$Be target in order to study the ground-state masses of $\Lambda$-hypernuclei. Positively charged kaons were detected by a short-orbit spectrometer with a broad momentum acceptance at zero degree forward angles with respect to the beam, efficiently tagging the production of strangeness in the target nucleus. In coincidence, negatively charged decay-pions were detected by two independent high-resolution spectrometers. About $10^3$ pionic weak decays of hyperfragments and hyperons were observed. The pion momentum distribution shows a monochromatic peak at $p_\pi \approx 133$ MeV/c, corresponding to the unique signature for the two-body decay of hyperhydrogen $^4_\Lambda$H $\rightarrow ^4$He $+$ $\pi^-$, stopped inside the target. Its binding energy was determined to be $B_\Lambda = 2.12 \pm 0.01$ (stat.) $\pm 0.09$ (syst.) MeV with respect to the $^3$H $+$ $\Lambda$ mass.

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I. INTRODUCTION

A very interesting phenomenon in nuclear physics is the existence of nuclei containing hyperons. When a hyperon \( (Y = \Lambda \text{ or } \Sigma) \) replaces one of the nucleons \( (N = n \text{ or } p) \) in the nucleus, a bound system can be formed by the hyperon and the core of the remaining nucleons. The \(^4\Lambda\!H\) nucleus is a heavy isotope of the element hydrogen, in which a \( \Lambda \) hyperon is bound to a tritium core. It was found in early helium bubble chamber [1] and nuclear emulsion experiments [2–5]. In a ground-state, a \( \Lambda \) hypernucleus decays to a non-strange nucleus through mesonic (MWD) or non-mesonic (NMWD) weak decay modes. By detecting the decay of hypernuclei and measuring the momenta of the decay products, the binding energies of the \( \Lambda \) hyperon, i.e. the \( \Lambda \) separation energy, for a larger number of \( s\)- and \( p\)-shell hypernuclei were reported in the 1960s and 1970s.

Precise determination of the binding energies of hypernuclei can be used to test the \( YN \) interactions in many-body systems. Contrary to the non-strange sector, where a large data base is used to successfully model the \( NN \) forces, the available data on \( YN \) scattering is not sufficient to determine realistic interactions among hyperons and nucleons. Various hypernuclear structure theories exist in which the binding energies of light hypernuclei are calculated, most recent approaches include cluster models and \textit{ab initio} calculations with the interactions constructed either in the meson-exchange picture or within chiral effective field theory [6–11].

Charge independence requires the interaction to be identical for the neutron and proton, whereas charge symmetry requires the \( nn \) interaction to be identical to the \( pp \) interaction. Charge symmetry breaking (CSB) in the strong interaction occurs because of the mass differences of the quarks in hadronic and nuclear systems. It is manifest in the differences between the level schemes of isospin multiplets. CSB is found to be small at a level of \( \sim 0.07 \text{ MeV} \) for \( NN \) interactions and is predicted by all the current baryon-baryon interaction models to be only \( \sim 0.05 \text{ MeV} \) for the \( \Lambda N \) interaction without the introduction of artificial effects. The mass \( A = 4 \) hypernuclei, \(^4\Lambda\!H\) and \(^4\Lambda\!He\), are members of an isospin \( T = 1/2 \) doublet and charge symmetry would predict that their \( \Lambda \) binding energies should be almost equal after correcting for the Coulomb energy difference, calculated to be less than \( 0.05 \text{ MeV} \) [12]. However, their difference was measured to be \( \Delta B_\Lambda = B_\Lambda(^4\Lambda\!He) - B_\Lambda(^4\Lambda\!H) = 2.39 \pm 0.03 \text{ MeV} - 2.04 \pm 0.04 \text{ MeV} = 0.35 \pm 0.06 \text{ MeV} \),
substantially larger than expected.

For the description of the $A = 4$ system the effects of $\Lambda N - \Sigma N$ coupling and three-body $\Lambda NN$ interactions are of key importance and in some models phenomenological CSB components in the $\Lambda N$ interaction are the source of the binding energy difference \cite{9}. The models should also be able to reproduce consistently the CSB effects for the $T = 1$ triplet $^7\Lambda\text{He}$, $^7\Lambda\text{Li}^*$, $^7\Lambda\text{Be}$ and other $T = 1/2$ mirror pairs such as $^{10}\Lambda\text{Be}$, $^{10}\Lambda\text{B}$ and $^{12}\Lambda\text{B}$, $^{12}\Lambda\text{C}$. A coherent theoretical description based on realistic $YN$ interactions or phenomenological $\Lambda N$ CSB interactions is not yet found. Therefore, the precise level and the origin of CSB in the $\Lambda N$ interactions are important issues related to our understanding of the fundamental baryon-baryon interactions.

This Letter presents the first result of the measurement of a hypernuclear ground-state mass from pionic decay spectroscopy in electron scattering. It was demonstrated that the use of high-resolution spectrometers at a high intensity electron beam provides a novel technique to study light hypernuclei.

II. MEASUREMENT TECHNIQUE

In reaction spectroscopy, ground- and excited hypernuclear states can be identified by a missing mass analysis of the incident beam and the associated reaction meson. Since these reactions require stable target nuclei, hypernuclei accessible by these reactions are limited. The direct reaction spectroscopy of $^4\Lambda\text{H}$ is not possible using charged meson beams in the established $(\pi^+, K^+)$ and $(K^-, \pi^-)$ reactions. The first observation of $^4\Lambda\text{H}$ bound states in missing mass spectroscopy using the $(e, e'K^+)$ reaction was reported a decade ago \cite{13}. This pioneering experiment reached an experimental mass resolution of 4 MeV/$c^2$. In the following years precision measurements of $\Lambda$ binding energies of a few light hypernuclei were conducted at Jefferson Lab, one recent example being the spectroscopy of $^7\Lambda\text{He}$ with a binding energy resolution of $\sim 0.6$ MeV \cite{14}.

In 2007 the usage of magnetic spectrometers to measure the momenta of pions from two-body decays of light hypernuclei fragmented from the excited states of initially electro-produced hypernuclei was proposed for Jefferson Lab \cite{15}. With large momentum transfer, an electro-produced hypernucleus can have excitation energies above the lowest particle emission threshold and then loose excitation energy through fragmentation, i.e. nucleon or
cluster emission. This is a very fast process that can lead to particle-stable hypernuclei in a large range of mass and atomic numbers, including hyperisotopes which are not accessible in missing-mass experiments. MWD takes place at the ground-state of these hypernuclei. The pion momenta from two-body MWD of the lightest systems \( A \leq 9 \) stopped at rest are \( p_{\pi} \sim 96 - 138 \text{ MeV}/c \). The mass of a hypernucleus can be obtained from a measurement of \( p_{\pi} \). Kaons can be tagged to suppress the background from non-strange processes.

III. EXPERIMENT

The experiment was carried out by the A1 Collaboration at the spectrometer facility (see Refs. [16, 17] for a detailed description of the spectrometers) at the Mainz Microtron MAMI-C, in Germany, with a 1.508 GeV electron beam incident on a 125 µm thick and 54° tilted \(^9\text{Be} \) target foil with a beam current of 20 µA. The layout of the experimental setup and the detectors inside the spectrometers can be found in Ref. [18]. The luminosity corrected for the data acquisition dead-time was \( \int \mathcal{L} dt \sim 235 \text{ fb}^{-1} \), integrated over a period of \( \sim 150 \) h during the year of 2012.

Pions were detected with two high-resolution spectrometers (SpekA and SpekC) with quadrupole-sextupole-dipole-dipole configuration and a \( \Omega_{\pi}^{\text{lab}} = 28 \) msr solid angle acceptance each, in which vertical drift chambers (VDCs) were used for tracking, scintillation detectors for triggering and timing, and gas Čerenkov detectors for discrimination between electrons and pions. The VDCs are capable of measuring a particle track with effective position and angle resolutions of \( \sigma_x = 180 \mu \text{m} \) and \( \sigma_\theta = 1.0 \text{ mrad} \). The spectrometers achieve a relative momentum resolution of \( \delta p/p \sim 10^{-4} \) and were operated at central momenta of 115 and 125 MeV/c with momentum acceptances of \( \Delta p/p = 20\% \) (SpekA) and 25\% (SpekC). The survival probabilities of pions at these momenta are \( \epsilon_{\pi} \sim 0.3 \).

The tagging of kaons was performed by the KAOS spectrometer. It was positioned at zero degrees with respect to the electron beam direction. The central momentum was 924 MeV/c, covering a momentum range of \( \Delta p/p = 50\% \) with a solid angle acceptance of \( \Omega_{K}^{\text{lab}} = 16 \) msr. The detector system includes segmented scintillator walls for tracking, energy-loss determination and timing. Two aerogel Čerenkov detectors were used for pion rejection with a combined 94\% efficiency when keeping the kaon rejection lower than 1\%. The kaon survival probability was \( \epsilon_K \approx 0.40 \) for a flight-path of 6.45 m. The time-of-flight (TOF) was
FIG. 1. (color online). Coincidence time spectrum for $K^+$ in the KAOS spectrometer and $\pi^-$ or $\mu^-$ in SpekC, after correcting for the reconstructed flight path lengths of $K^+$ and $\pi^-$ through the spectrometers. The time gates for selecting true (2.5 ns width) and accidental coincidences (45 ns width) are indicated by different colors. The solid line represents a fit to the spectrum with two Gaussian shaped peaks each on top of a linear background distribution. The peaks were resolved with $\sigma_t \sim 1.4$ ns resolution.

measured inside the spectrometer with a resolution of $\sigma_t \approx 180$ ps along flight-paths of $1 - 1.5$ m. The experimental challenge in this experiment was originated by the positrons from pair production with large cross-sections near zero degrees. The resulting high flux of background positrons in the spectrometer was reduced by several orders of magnitude by using a lead absorber with its thickness up to $t = 25 X_0$ radiation lengths. The detection loss for the kaons in this absorber amounted to $\eta_{\text{Lead}} \sim 70\%$.

IV. DATA ANALYSIS

The pion momentum, its direction and the reaction vertex were reconstructed from the focal plane coordinates using the well-known backward transfer matrices describing the
spectrometer optics. The momenta of the outgoing pions were corrected for energy-loss inside the target, a few cm thick of air, and two vacuum window foils 120 µm thick each. Kaons were identified by their specific energy-loss \( \frac{dE}{dx} \) and velocity \( \beta \) from TOF.

Fig. 1 shows the coincidence time between \( K^+ \) in the KAOS spectrometer and \( \pi^- \) or \( \mu^- \) in SpekC. The prominent peak at zero time is attributed to about \( 10^3 \) events from MWD of strange systems, while the peak of muons is originated by the decay events of pions. True coincidence events were selected from a time gate width of 2.5 ns. Accidental coincidence events were used to extract background height and shape in the momentum distribution.

The top panel of Fig. 2 shows the distribution of available data on the \( \Lambda \) hyperon binding energy in \( ^4_\Lambda H \) from emulsion experiments [2–4], where the compilation in Ref. [4] includes re-analysed events from Refs. [2] and [3]. The width of this distribution from \( B_\Lambda > 0.5 \) MeV to \( B_\Lambda < 3.5 \) MeV defines a region of interest corresponding to the momenta of two-body decay pions for stopped hyperhydrogen \(^4_\Lambda H\): \( 131 \) MeV/c < \( p_\pi < 135 \) MeV/c.

The bottom panel of Fig. 2 shows the pion momentum distribution in SpekC for the events selected within the true coincidence time gate. The distribution above the accidental background is attributed to MWD events. The distribution outside of the region of interest was fitted with a single scale factor to a template function \( bg \) which was determined by a Monte Carlo simulation including angular and energy dependencies of kaon production in electron scattering off \(^9\)Be. In the simulation, the elementary cross-sections for \( p(\gamma,K^+)_\Lambda \), \( p(\gamma,K^+_+)\Sigma^0 \), and \( n(\gamma,K^+)_\Sigma^- \) were taken from the K-Maid model [19, 20] which describes available kaon photoproduction data. The Fermi-motion effects which modify the elementary cross-sections for the Be target were calculated in the incoherent impulse approximation. Inside the momentum and angular acceptances this background is dominated by \( \Sigma^- \) hyperon decays and the momentum dependence is practically flat.

A localized excess of events over this background was observed inside the region of interest near to \( p_\pi \approx 133 \) MeV/c that is a unique signature for \(^4_\Lambda H \rightarrow ^4\text{He} + \pi^-\).

In the pion momentum distribution of SpekA no localized excesses of counts over the background expectation of quasi-free hyperon decays were found. The region of interest for \(^4_\Lambda H\) was not inside the acceptance of SpekA.
FIG. 2. (color online). Pion momentum distribution in SpekC for true coincidences (green) and scaled accidental coincidences (blue). A monochromatic peak at $p_\pi \approx 133$ MeV/c was observed which is a unique signature for the two-body decay of stopped hyperhydrogen $^4\Lambda H \rightarrow {}^4\text{He} + \pi^-$. The top panel shows on the corresponding binding energy scale the distribution of data on the $\Lambda$ hyperon binding energy in $^4\Lambda H$ from emulsion experiments [2–4]. Arrows indicate the region of interest in the momentum spectrum.

V. RESULT AND DISCUSSION

Fig. 3 shows the pion momentum distribution in SpekC in the region of interest. The spectrum was fitted by a function that is composed of a signal $s$ that is formed by a Landau distribution representing the known energy loss convoluted with a Gaussian resolution function on top of the known background $b_g$, minimizing the negative logarithm of the likelihood.
FIG. 3. (color online). Pion momentum distribution in SpekC in the region of interest with a fit composed of a Gaussian resolution function convoluted with a Landau distribution representing the energy loss on top of the background function. The observed signal shape and width are consistent with the simulation.

\[ \Delta E \sim 0.140 \pm 0.005 \text{MeV} \]

The width of the peak was predicted to be \( \text{fwhm} \sim 0.2 \text{MeV/c} \) which is consistent with the observed width of \( \text{fwhm} \sim 0.19 \pm 0.05 \text{MeV/c} \). The largest contribution to the width was from multiple scattering of the pions inside the target and at the two vacuum window foils. Uncertainties in the backward transfer matrix contribute less.

Systematic differences due to the fitting procedure were estimated by using different probability distribution functions to describe the peak shape, different fit methods (unbinned and binned) and minimizers, different fit regions, and different parameterizations of the background. The most probable momentum for the decay pion peak was within \( \delta p < 10 \text{keV/c} \) for all cases.
The peak position, $p_\pi = 132.92$ MeV/c, of the signal was converted to $\Lambda$ hyperon binding energy, $B_\Lambda$, using

$$\begin{align*}
M(4^\Lambda H) &= \sqrt{M^2(4^{\text{He}}) + p_\pi^2} + \sqrt{M^2_\pi + p_\pi^2} \quad \text{and} \\
B_\Lambda &= M(3^\Lambda) + M_\Lambda - M(4^\Lambda H) \quad \text{with } c = 1,
\end{align*}$$

where the known nuclear masses, $M(3^\Lambda) = 2808.921$ MeV and $M(4^{\text{He}}) = 3727.379$ MeV, were obtained from tabulated mass excess values [22] and the charged pion mass $M_\pi = 139.570$ MeV and $\Lambda$ hyperon mass $M_\Lambda = 1115.683$ MeV from the latest PDG (Particle Data Group) publication [23].

The calibration of the momentum spectra has been performed with a 195.17 MeV electron beam using the $^{181}\text{Ta}(e, e')$ elastic scattering as well as the inelastic spectrum of the $^{12}\text{C}(e, e')$ reaction to check the linearity of the momentum scale. The momentum was referenced against the beam energy. The beam energy was measured with an absolute accuracy of $\delta E_{\text{beam}} = \pm 0.16$ MeV by exact determination of the beam position on the accelerator axis and in a higher return path. The uncertainty on the beam energy translates into a calibration uncertainty of $\delta p_{\text{calib.}} = \pm 0.11$ MeV/c. This is the dominant source of systematic uncertainty in the binding energy. The peak width for the scattered electron momentum was fwhm = 0.12 − 0.13 MeV/c. Uncertainties in the spectrometer angle were insignificant. The backward transfer matrices were checked using the sieve slit data. The stability of the magnetic field in the spectrometers, checked with regular Hall probe and NMR probe measurements, showed relative variations of the order $10^{-4}$ that translate into a systematic uncertainty, $\delta p_{\text{stabil.}} = \pm 0.04$ MeV/c, in the momentum. A total systematic uncertainty of 0.09 MeV for the binding energy was obtained using the kinematical relation $d B_\Lambda / c \approx -0.725 \, dp_\pi$ for $4^\Lambda H$.

The final result is then

$$B_\Lambda = 2.12 \pm 0.01 \, \text{(stat.)} \pm 0.09 \, \text{(syst.) MeV}$$

with respect to the $3^\Lambda + \Lambda$ mass.

Fig. 4 shows a compilation of the $\Lambda$ binding energy in the isospin doublet $4^\Lambda H$ and $4^\Lambda \text{He}$ evaluated from the pionic decays. The most abundant decay of $4^\Lambda H$ observed in nuclear emulsions is the charged two-body mode $4^\Lambda H \to 4^{\text{He}} + \pi^-$. However, it could not be used to deduce the $4^\Lambda H$ mass since the pion momentum is too high and range is too large for the emulsion technique. Instead, a total of only $\sim 160$ three-body decays compiled from
FIG. 4. (color online). Measured $\Lambda$ binding energies in the isospin doublet $^4\Lambda$H (red) and $^4\Lambda$He (black) evaluated from pionic decays [2–4, 24, 25]. Full circles present values from three-body decays, open circles from two-body decays, errors on the emulsion data are statistical only. The mean values as compiled by Ref. [4] exclude data from the $\pi^-\Lambda^+\text{He}$ decay mode of $^4\Lambda$H and are shown by the vertical bands with statistical and total errors. The uncertainties on the MAMI value are statistical (inner) and total (outer).

Several experiments were used. Ref. [2], [3] and [4] evaluated 21, 63, and 56 events from $^4\Lambda$H $\rightarrow$ $\pi^- + ^1\text{H} + ^3\text{H}$ and only 2, 7, and 11 events from $^4\Lambda$H $\rightarrow$ $\pi^- + ^2\text{H} + ^2\text{H}$, respectively. In Ref. [4] the binding energies of decays from these two decay modes were reported separately as 1.92 ± 0.12 MeV versus 2.14 ± 0.07 MeV. For $^4\Lambda$He a total of 279 events were analyzed. Despite extensive calibrations, additional systematic uncertainties of at least 0.05 MeV in the binding energies should be assumed for emulsion data [26].

The first experiment using a magnetic spectrometer to detect the MWD of $^4\Lambda$H decays was performed in the late 1980s [24]. In this experiment strangeness was exchanged with nuclei by $K^-$ absorption within a thick target so that the momentum resolution was not competitive to the emulsion data in determining the $^4\Lambda$H mass and the spectrometer had a low efficiency below $p_\pi$ $\sim$ 120 MeV/c.

The momentum acceptance of the pion spectrometers covered the monochromatic decay momenta from several hyperisotopes of hyperhydrogen, hyperhelium and hyperlithium,
including very neutron-rich nuclei. A statistical decay model was applied to evaluate the relative yields \[18\]. From the range of kinetic energies of the different hypernuclei the stopping probabilities inside the target could be evaluated using a Monte Carlo simulation: 
\[ P_{\text{stop}} \sim 40\% \text{ for hyperhydrogen isotopes, } 70-80\% \text{ for hyperhelium isotopes and } \sim 90\% \text{ for hyperlithium isotopes.} \]

However, in the combined momentum spectrum above 102 MeV/c no two-body decay peak was observed other than from \( ^4\Lambda H \). One reason is its large total \( \pi^- \) decay width, comparable to the free \( \Lambda \) decay width, \( \Gamma_{\pi^-}/\Gamma_\Lambda = 1.00^{+0.18}_{-0.15} \), and the relative partial decay width of the two-body mode, \( \Gamma_{\pi^-+^4\text{He}}/\Gamma_{\pi^-} = 0.69 \pm 0.02 \ [27] \). These decay widths are larger than for all other known light hyperisotopes.

Detection of the pionic decay of \( ^4\Lambda H \) has been achieved for the first time in electroproduction and for the first time a spectrometer with \( 10^{-4} \) relative momentum resolution was employed in hypernuclear decay spectroscopy. The measured \( \Lambda \) binding energy provides important information on the \( A = 4 \) system, especially helpful for investigating the origin of CSB. The result from this experiment shows the \( \Lambda \) binding energy difference to \( ^4\Lambda \text{He} \) is \( \Delta B_\Lambda = 0.27 \text{ MeV}, \) a 0.08 MeV reduction from emulsion data, but still supporting the CSB effect in the system.

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