Observation of the $^{7}_{\Lambda}$He Hypernucleus by the $(e, e'K^+)$ Reaction

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An experiment with a newly developed high-resolution kaon spectrometer and a scattered electron spectrometer with a novel configuration was performed in Hall C at Jefferson Lab. The ground state of a neutron-rich hypernucleus, $^{7}_{\Lambda}$He, was observed for the first time with the $(e, e'K^+)$ reaction with an energy resolution of ~0.6 MeV. This resolution is the best reported to date for hypernuclear reaction spectroscopy. The $^{7}_{\Lambda}$He binding energy supplies the last missing information of the $A = 7$, $T = 1$ hypernuclear isotriplet, providing a new input for the charge symmetry breaking effect of the ΛN potential.

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Our world consists of electrons and nucleons (protons and neutrons), which are composed of up and down valence quarks. In a hyperon, one of these original quarks is replaced by a strange quark. A hypernucleus contains a hyperon implanted as an impurity within the nuclear medium. The lightest hyperon is the Λ particle (up + down + strange, isospin 0). Precise information about the mass and excitation energies of hypernuclei allows one to infer the underlying hyperon-nucleon (YN) interaction, which is relevant to the discussion of high density nuclear matter such as neutron stars. Precise nucleon-nucleon potentials have been derived from the rich data set of nucleon scattering experiments as well as from the masses and excitation energies of nuclei. In contrast, YN scattering experiments are technically difficult and data is very limited. Therefore, hypernuclear spectroscopy is a more realistic method to study the YN interaction.

The study of hypernuclei seeks to extend our knowledge of the nuclear force and baryon-baryon forces in general. While the strange quark is heavier than up and down quarks, it is light enough to be treated in the framework of $SU(3)_{flavor}$ symmetry, a natural extension of isospin symmetry for nucleons. An understanding of baryon-baryon forces based on $SU(3)_{flavor}$ symmetry is important to bridge the gap between phenomenologically well studied nuclear force models and the underlying degrees of freedom of the strong interaction as described by QCD.

Since a single Λ inside a nucleus is not subject to the Pauli exclusion principle, it can occupy any accessible shell, including the deeply bound s shell in the heaviest nuclei. The Λ decays with a relatively long lifetime, even in a nucleus (~ 200 ps) [1,2], and thus the widths of hypernuclear energy levels are typically less than a few 100 keV. This fact makes the spectroscopic study of these systems possible. The Λ can also probe the interior structure of the host nucleus. Furthermore, one can search for possible modifications of the composition and structure of deeply bound baryons [3,4].

After the first observation of a Λ hypernucleus more than a half century ago with an emulsion [5], meson beams such as K^- and π^+ have been widely used to obtain spectroscopic information via missing mass analysis in the ${}^{A}Z(K^-, \pi^-){}^{A}_{\Lambda}Z$ and ${}^{A}Z(\pi^+, K^+){}^{A}_{\Lambda}Z$ reactions. In both of these reactions, Λ hyperons are produced off neutrons, which precludes the use of the elementary reaction channel for an accurate mass calibration. Together with the inherently limited quality of these secondary meson beams, the accuracy of absolute mass determinations has been limited to a resolution of no better than 1.5 MeV.

The ${}^{A}Z(e, e'K^+){}^{A}_{\Lambda}(Z-1)$ reaction produces strangeness by $s-\bar{s}$ pair-production, similar to the (π^+, K^+) reaction. An interesting feature of the $(e, e'K^+)$ reaction is that it converts a proton to a Λ, enabling us to calibrate the absolute missing mass scale by using the $p(e, e'K^+)\Lambda$, Σ^0 reactions with the well known masses of the Λ and Σ^0 hyperons. Furthermore, the $(e, e'K^+)$ reaction can produce new species of hypernuclei, and thus the charge dependence of hypernuclei can be studied by comparing $(e, e'K^+)$ hypernuclear spectroscopy to already known isomultiplet partners. As well as the above unique features, $(e, e'K^+)$ hypernuclear reaction spectroscopy has the potential for good (sub-MeV) energy resolution due to the availability of primary electron beams with a lower energy spread than that available for secondary meson beams.

We report here the first clear observation of the ground state of ${}^{7}_{\Lambda}$He through the ^{7}Li$(e, e'K^+){}^{7}_{\Lambda}$He reaction. Although ${}^{7}_{\Lambda}$He has been observed in emulsion experiments [6], only a total of 11 events are known; furthermore, the measured masses for these events are spread out widely, which led to speculation that long-lived isomeric states [7–9] were observed together with the ground state. Therefore, no ground state mass has been quoted in the literature.

${}^{7}_{\Lambda}$He is the missing member of the $A = 7$, $T = 1$ isospin triplet, the other two being ${}^{7}_{\Lambda}$Li* and ${}^{7}_{\Lambda}$Be. The three core nuclei ^{6}He, ^{6}Li*, and ^{6}Be have in common an α core surrounded by a halo nucleon pair, nn, pn, and pp, respectively. Likewise, the bound Λ wave function is predicted to reach far beyond the α core and thus have a significant overlap with the halo nucleon pair [10]. In particular, ${}^{7}_{\Lambda}$He plays a key role in the study of the halo structure of neutron-rich hypernuclei since it has a core of the lightest bound neutron-halo nucleus ^{6}He.

As suggested by Hiyama *et al.*, this isotriplet is the perfect testing ground to study the charge symmetry breaking (CSB) effect in the ΛN potential. The binding energies of the isotriplet were recently computed using a four-body cluster model with the CSB effect [10]. A ΛN CSB potential was phenomenologically introduced to explain the binding energy difference of the $A = 4$ isodoublet ($T = 1/2$) hypernuclei ${}^{4}_{\Lambda}$H and ${}^{4}_{\Lambda}$He. The difference $B_\Lambda({}^{4}_{\Lambda}\text{He}) - B_\Lambda({}^{4}_{\Lambda}\text{H}) = +0.35 \pm 0.06$ MeV is unexpectedly large, even after corrections due to the Coulomb interaction.

The experimental challenge of $(e, e'K^+)$ hypernuclear reaction spectroscopy originates from the small hypernuclear production cross section and high backgrounds. The cross section of the $(e, e'K^+)$ reaction is ≤ 100 nb/sr, which is 2–3 orders of magnitude smaller than that of hadronic production. Furthermore, the $(e, e'K^+)$ reaction requires two spectrometers for a coincidence between scattered electrons and kaons. These experimental difficulties result in lower hypernuclear yields and poorer signal-to-noise ratios than meson reactions.

The pilot experiment E89-009 [hypernuclear spectrometer system (HNSS)], performed at Jefferson Lab (JLab) in 2000, demonstrated the principle of $(e, e'K^+)$ hypernuclear spectroscopy [11,12]. The experiment showed that ^{12}C$(e, e'K^+){}^{12}_{\Lambda}$B spectroscopy with sub-MeV resolution is possible with the high quality electron beam at JLab, but it also showed that improvements were possible to fully exploit the potential of hypernuclear study by electroproduction. The 10^{-3} momentum resolution and small solid angle of the kaon spectrometer [short orbit spectrometer (SOS)] limited the resolution and hypernuclear yield. In E89-009, zero-degree electrons were measured to maximize the virtual photon yield, but this also reduced the signal-to-noise ratio, thus limiting the beam current and target thickness that could be used.

The natural extension to the E89-009 experiment is the E01-011 experiment [high-resolution kaon spectrometer (HKS)] performed in JLab's Hall C in 2005 [13] from which the spectrum discussed here was obtained. In the E01-011 experiment, a HKS ($\Delta p/p \sim 2 \times 10^{-4}$) was constructed and an existing electron spectrometer was optimized to improve the resolution and hypernuclear yield over the E89-009 experiment. The improvements allowed the system to handle 180 times higher luminosity (4.5 times thicker target and 40 times more intense electron beam) with a 100 times smaller electron background rate in the electron spectrometer.

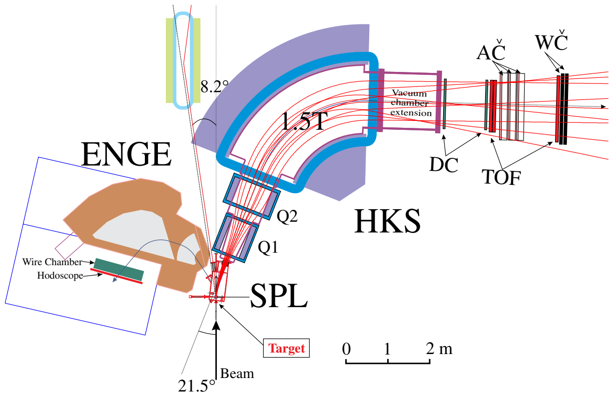

FIG. 1 (color online). Schematic figure of the E01-011 experimental setup. A newly constructed HKS and an ENGE-type split-pole spectrometer that was also used in E89-009 were used as the kaon and scattered electron spectrometers. The HKS detector package consists of drift chambers (DC), time-of-flight counters (TOF), aerogel Čerenkov (AČ) and water Čerenkov (WČ) counters. The ENGE was vertically tilted to suppress background originating from bremsstrahlung and Møller scattering.

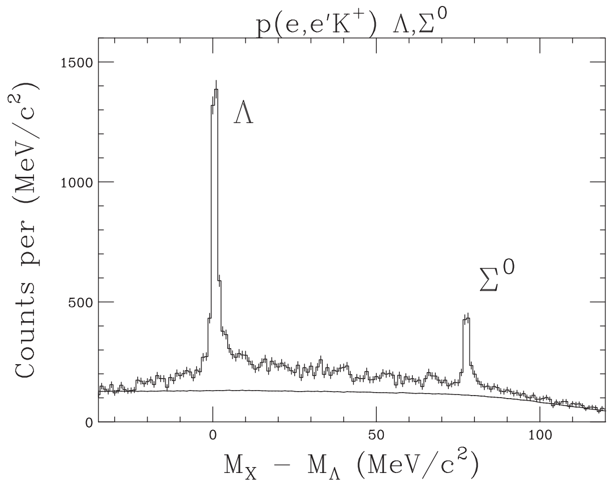

FIG. 2. Missing mass spectrum of the $p(e, e'K^+)\Lambda/\Sigma^0$ reaction. The mass of the Λ particle was subtracted. The Λ, Σ^0 peaks were used to calibrate the absolute missing mass scale. The line shows the accidental background estimated by the mixed events analysis method.

Figure 1 shows a layout of the experimental setup. The target was placed in a dipole splitter magnet (SPL) that separated the oppositely charged particles at small forward angles. The K^+'s were measured by the HKS, which has a central momentum of $P_K = 1.2$ GeV/c and a 16 msr solid angle when used with the SPL magnet. The scattered electrons (central momentum $P_{e'} = 0.35$ GeV/c) were measured by the ENGE-type split-pole spectrometer that was vertically tilted by 8 degrees from the dispersion plane and shifted vertically by an amount to suppress electron backgrounds originating from bremsstrahlung and Møller scattering that have very sharp forward distributions (tilt method). The electron beam energy was set at $E_e = 1.851$ GeV, giving a virtual photon energy of about 1.5 GeV ($\simeq E_e - cP_{e'}$). The typical beam current for the lithium target was 25 μA. Details of the design of the experiment will be explained elsewhere [14]. Since the beam energy from the continuous electron beam accelerator facility at JLab was known with an accuracy of $1 \times 10^{-4} \sim 180$ keV, measurements of the momentum vectors of K^+ and e' at the target were sufficient to obtain the missing mass of the hypernuclei. The positions and angles of the scattered kaons and electrons were measured at the focal planes of the HKS and ENGE spectrometers. These focal plane quantities were converted to target momentum vectors using backward transfer matrices of the spectrometers. The initial transfer matrices were generated by using a GEANT4 Monte Carlo simulation with three-dimensional magnetic field maps obtained by field measurements and finite element calculations by Opera-3D (TOSCA). The backward transfer matrices were obtained from these initial transfer matrices and tuned using calibration data such as the sieve slit data that constrains the angular parts of the matrices and the Λ and Σ^0 peaks from the $p(e, e'K^+)\Lambda$, Σ^0 reaction with protons in a CH_2 target, constraining the momentum parts of the matrices.

Figure 2 shows the missing mass spectrum from scattering off a CH_2 target with clear peaks corresponding to Λ and Σ^0 hyperon production off of protons and an underlying background from quasifree hyperon production on carbon and accidental coincidences between e''s and K^+'s. The background shape from the quasifree hyperon production on carbon was measured by using a ^{12}C target, and the accidental background shape was obtained by randomly selecting uncorrelated e''s and K^+'s (mixed events analysis). These events were sampled from real data with an off-time gate in the coincidence timing of e' and K^+. Therefore, it is ensured that the mixed events and the background have the same momentum distributions. The background shape of the CH_2 target data was almost completely described by the above contributions, and thus we can conclude that the mixed event analysis technique can be safely applied to estimate the accidental background shapes in our analysis.

The Λ and Σ^0 peak positions were used for missing mass calibration and the backward transfer matrix tunes. The tuned and calibrated matrices gave the peak positions in Table I. The missing mass scale was calibrated for these hyperons within a 100 keV uncertainty. The widths of hyperon peaks are worse than the expected sub-MeV resolution for hypernuclei because hyperons are much lighter

TABLE I. Λ and Σ^0 masses: M_Y (PDG values [15]) and M_X fitted values of E01-011 data. The unit of values is MeV/c^2.

Hyperon	M_Y	$M_X - M_Y$	Width (FWHM)
Λ	1115.683	0.09 ± 0.02	1.94 ± 0.45
Σ^0	1192.642	0.05 ± 0.03	1.87 ± 0.56

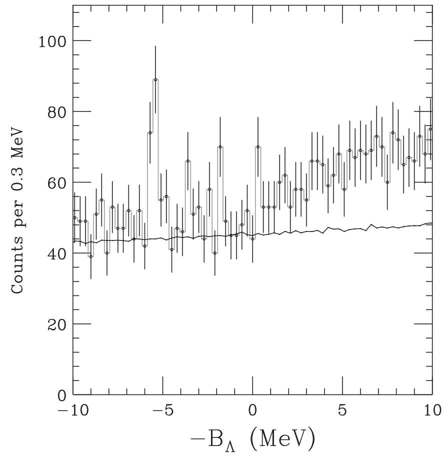

FIG. 3. Binding energy spectrum obtained by the ^{7}Li$(e, e'K^+)^7_\Lambda$He reaction. The line shows the accidental background estimated by the mixed events analysis method. The events in the unbound region $(-B_\Lambda > 0)$ originate from quasi-free Λ production.

than hypernuclei and kinematic broadening because the finite angular resolution of spectrometers contributed more significantly to the energy resolution.

In the E01-011 experiment, a natural Li target of 189 mg/cm^2 (^{7}Li abundance 92.4%) was used as a target. The measured missing mass was converted to binding energy using

$$-B_\Lambda = M(^7_\Lambda\text{He}) - [M_\Lambda + M(^6\text{He})]$$

and plotted in Fig. 3. A ^{6}He mass of 5605.537 MeV$/c^2$ was obtained from the reported mass excess [16]. The accidental coincidence events in Fig. 3 were estimated by using the mixed events technique. After subtraction of the accidental background and correction of the spectrometers' acceptances and detector efficiencies, the number of counts was converted to the differential cross section averaged over the acceptance of the HKS ($1.05 < P_K < 1.35$ GeV$/c$, $1° < \theta_K < 13°$). Since the virtual photon is almost real ($Q^2 \sim 0.01$ GeV$^2/c^2$, $W \sim 1.9$ GeV), the $(e, e'K^+)$ differential cross section was converted to the differential cross section for virtual photons using the virtual photon flux (Γ) as

$$\frac{d\sigma}{d\Omega_K} = \frac{1}{\Gamma}\frac{d\sigma}{dE_{e'}d\Omega_{e'}d\Omega_K}.$$

The virtual photon flux integrated over the ENGE acceptance ($0.24 < P_{e'} < 0.44$ GeV$/c$, $\Delta\Omega_{e'} = 5.6$ msr) was 4.8×10^{-6} virtual photons per electron.

Figure 4 shows the $^7_\Lambda$He spectra measured by the emulsion experiment (top) [6] and by JLab E01-011 (bottom). The E01-011 spectrum shows a clear peak that corresponds to the $^7_\Lambda$He ground state $(1/2^+)$.

The number of events in the peak (S for $-6.15 < -B_\Lambda < -4.65$ MeV) and the number of background events under the peak (N) were counted in the raw spectrum (Fig. 3) to obtain the peak significance:

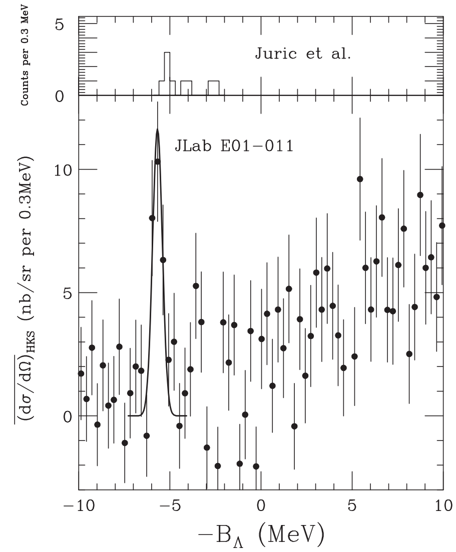

FIG. 4. Binding energy spectra of $^7_\Lambda$He measured by the emulsion experiment [6] (top) and the JLab E01-011 (HKS) experiment after background subtraction and acceptance corrections (bottom).

$$S/\sqrt{S+N} = 97/\sqrt{316} = 5.5,$$

which is consistent with the statistical error of the cross section obtained from the fit of the acceptance corrected spectrum to be shown. Different choices for the background in the region of the peak result in lower peak significance. However, the peak retains a high likelihood of being real and its existence is quite solid.

There exists some structure between the ground state and the threshold ($B_\Lambda = 0$), but the statistics are not enough to discuss in detail. The systematic error of the binding energy due to the tuning processes of the transfer matrices was estimated by applying the analysis procedures to dummy data generated by a full Monte Carlo simulation with arbitrarily chosen hypernuclear masses and various signal-to-noise ratios (S/N). The simulated data were analyzed using the same software as the real data, and the arbitrarily chosen hypernuclear masses were hidden from the analysis group. The difference between the inputs to the simulation and the analysis results were treated as the systematic error due to the matrix tuning processes. The estimated systematic error depends on S/N. For major peaks ($S/N > 0.3$), the error was less than 100 keV, but, for poor S/N peaks ($S/N < 0.3$), the error is as large as 400 keV. Other sources of systematic error on the binding energy are uncertainties in the kinematic parameters such as the absolute electron beam energy and the central momenta of the K^+ and e'. These contributions were studied carefully and estimated to be less than 150 keV. The systematic errors on the cross section were estimated with the same method and combined with the beam current uncertainty.

The ground state peak of $^7_\Lambda$He was fitted with a Gaussian. The binding energy and virtual photon cross section obtained were

TABLE II. Binding energies of the $A = 7$, $T = 1$ isotriplet Λ hypernuclei. The E01-011 errors are statistical and systematic.

	$^{7}_{\Lambda}$He (E01-011)	$^{7}_{\Lambda}$Li* [6,17]	$^{7}_{\Lambda}$Be [6]
B_Λ (MeV)	$5.68 \pm 0.03 \pm 0.25$	5.26 ± 0.03	5.16 ± 0.08

$$-B_\Lambda = -5.68 \pm 0.03(\text{stat}) \pm 0.25(\text{syst})\ \text{MeV},$$

$$\overline{\left(\frac{d\sigma}{d\Omega}\right)}_{\text{HKS}} = 26 \pm 5.1(\text{stat}) \pm 9.9(\text{syst})\ \text{nb/sr},$$

with a width of 0.63 ± 0.12 MeV (FWHM).

The E01-011 experiment successfully observed the $^{7}_{\Lambda}$He ground state with sufficient statistics. The emulsion data show a cluster with a broad tail (top of Fig. 4), and the binding energy was not obtained [6]. It was hypothesized that the cluster corresponded to the ground state and that the broad tail originated from the decay of isomeric states of $^{7}_{\Lambda}$He, but this was not experimentally confirmed [7–9]. The E01-011 data are consistent with the interpretation that the cluster of emulsion data corresponds to the ground state.

The binding energies of the $^{7}_{\Lambda}$Li and $^{7}_{\Lambda}$Be ground states were measured by emulsion [6], but the ground state of $^{7}_{\Lambda}$Li is the $T = 0$ state [$B_\Lambda(^{7}_{\Lambda}\text{Li}, T = 0) = 5.58 \pm 0.03$ MeV] [6]. Therefore, the energy spacing information from the γ-ray measurement, $Ex(T = 1, 1/2^+) = 3.88$ MeV [17] and the excitation energy of ^{6}Li$^*(T = 1) = 3.56$ MeV were used to calculate the binding energy of the $^{7}_{\Lambda}$Li* ($T = 1$) state.

The binding energies of the $A = 7$, $T = 1$ isotriplet hypernuclei, $^{7}_{\Lambda}$He, $^{7}_{\Lambda}$Li*, and $^{7}_{\Lambda}$Be, now experimentally measured, are shown in Table II.

The binding energies of the $A = 7$ hypernuclear isotriplet can provide useful information about the CSB effect of the ΛN potential by comparing to the results of an $\alpha NN\Lambda$ four-body cluster calculation, as has been done with the $A = 4$ ($NNN\Lambda$; $^{4}_{\Lambda}$H, $^{4}_{\Lambda}$He) and $A = 10$ ($\alpha\alpha N\Lambda$; $^{10}_{\Lambda}$Be, $^{10}_{\Lambda}$B) hypernuclei [18,19].

The $(e, e'K^+)$ hypernuclear spectroscopy technique was established at JLab by the present E01-011 experiment in Hall C and an independent experiment (E94-107) performed in Hall A [20,21]. The experimental efforts have continued to improve with the JLab E05-115 experiment [22] and a recently initiated program at the upgraded Mainzer Mikrotron C (MAMI-C), Mainz University [23,24].

As the binding energy difference between $^{4}_{\Lambda}$H and $^{4}_{\Lambda}$He hypernuclei is the starting point of CSB discussions, new measurements with recent experimental techniques are necessary. Binding energy measurements of $^{4}_{\Lambda}$H are planned at both JLab and MAMI-C by using the ^{4}He$(e, e'K^+)^{4}_{\Lambda}$H reaction, and there are plans to use the newly proposed decay π spectroscopy of hyperfragments technique [25] and to do a hypernuclear γ-ray experiment of $^{4}_{\Lambda}$He at Japan Proton Accelerator Research Complex (J-PARC) [4]. More precise data on $^{7}_{\Lambda}$He and $^{10}_{\Lambda}$Be with a better control of the systematic errors from JLab E05-115 and the planned experiments on $A = 4$ hypernuclei will provide definitive experimental information to determine the CSB terms in the ΛN potential.

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