High Resolution Spectroscopy of the $^{12}_{\Lambda}$B Hypernucleus Produced by the $(e, e'K^+)$ Reaction

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High-energy, cw electron beams at new accelerator facilities allow electromagnetic production and precision study of hypernuclear structure, and we report here on the first experiment demonstrating the potential of the $(e, e'K^+)$ reaction for hypernuclear spectroscopy. This experiment is also the first to take advantage of the enhanced virtual photon flux available when electrons are scattered at approximately zero degrees. The observed energy resolution was found to be ≈ 900 keV for the $^{12}_{\Lambda}$B spectrum, and is substantially better than any previous hypernuclear experiment using magnetic spectrometers. The positions of the major excitations are found to be in agreement with a theoretical prediction and with a previous binding energy measurement, but additional structure is also observed in the core excited region, underlining the future promise of this technique.

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One of the goals of hypernuclear spectroscopy has been to determine an effective Λ-nucleon interaction [1] which is then tested against proposed Λ-nucleon potentials folded into the nuclear many-body problem. A variety of spectroscopic data, particularly data sensitive to spin dependent interactions, is needed to determine the parameters [2] of the effective potential. Such studies improve the theoretical treatment of the hadronic many-body system containing strange constituents, and provide knowledge of the Λ-nucleon interaction.

Although electroproduction is a high momentum transfer reaction similar to (π^+, K^+), it differs from previous experiments using mesonic reactions in that it has a large spin-flip component, producing states of unnatural parity. In addition, electromagnetic production induces (Λ, proton-hole) states [as opposed to (Λ, neutron-hole) states] in the target nucleus, thus producing hypernuclei charge symmetric to those previously studied, and extending the hypernuclear data base to neutron rich species [3]. The primary advantage, however, of electroproduction is the precision of the resulting spectroscopy, resulting, in part, from the excellent phase space available with the new, cw electron beams. We also remark that the lower electroproduction cross sections can be compensated by increased beam intensity, provided the accidental rate of the required coincidence experiments can be accommodated.

Spin splittings of hypernuclear states are predicted [2] to be generally less than 100 keV, and well below the resolution of any magnetic spectrograph. However, in most cases, it is sufficient to resolve the level structure of the residual core states on which the hypernuclear structure is built. In part, this is because the $(e, e'K^+)$ reaction selectively populates unnatural parity states, generally coupling to only one of the two possible spin structures which is then added to each nuclear core level. There also is a unique angular dependence, albeit over the small angular range which is experimentally accessible, and a cross section dependence on incident photon energy [4] that can potentially help isolate the excitations.

Previously, 1.5 MeV full width at half maximum (FWHM) was the best hypernuclear resolution (excluding emulsion experiments) in a reaction spectrum [5], but this resolution was insufficient to resolve the fine structure of the excitations. All other counter experiments obtained resolutions ≥ 2 MeV (FWHM). For comparison, the technique described here has a resolution substantially better than in any previous reaction spectroscopy, and will be improved by a factor of 3–4 in resolution and ≈ 60 in rate in future experiments [6].

The hypernucleus, ${}^{12}_{\Lambda}$C, charge symmetric to the one chosen for this first study, ${}^{12}_{\Lambda}$B, has been previously investigated in several mesonic reactions [5], and a series of gamma-transition experiments have recently measured the position and spin splitting of several levels in light hypernuclei [7]. For example, the spin splitting of the $(5/2^+, 3/2^+)$ doublet in ${}^{9}_{\Lambda}$Be was found to be $\approx$ 31 keV. Although these small spin splittings can be observed using gamma spectroscopy, reaction spectra are equally important because they provide the complete spectrum of excitations with a strength that not only gives the spectroscopic factor, but the transition matrix. Indeed, the latter can be directly interpreted in the mean-field approximation, which models the reaction as proceeding by coupling of an incident particle (in this case a photon) to an identifiable nucleon in the nucleus, with the subsequent production of a Λ within the nuclear medium. While various elementary photokaon operators predict essentially the same distorted wave impulse approximation (DWIA) production rates, propagator renormalization within the medium could be significant [8], requiring a modification of the single-particle picture of the reaction [9]. However, if the independent particle model remains valid, it may then be possible to extract the Λ single-particle wave function [10] within the nuclear medium.

The cross section for electroproduction can be written in a very intuitive form by separating out a factor, Γ, which multiplies the off-shell (virtual) photoproduction cross sections. This factor may be interpreted as the virtual photon flux produced by (e, e') scattering [11–14].

$$\frac{\partial^3\sigma}{\partial E'_e \partial\Omega'_e \partial\Omega_k} = \Gamma\left[\begin{array}{c} \frac{\partial\sigma_T}{\partial\Omega_k} + \epsilon\frac{\partial\sigma_L}{\partial\Omega_k} + \epsilon\cos(2\phi)\frac{\partial\sigma_P}{\partial\Omega_k} \\ +\cos(\phi_k)\sqrt{2\epsilon(1+\epsilon)}\frac{\partial\sigma_I}{\partial\Omega_k} \end{array}\right]. \quad (1)$$

The label of each of the above cross section expressions (T, L, P, and I) represents transverse, longitudinal, polarization, and interference terms. At very forward angles, in this case $\approx 0°$, the virtual photons are almost on the mass shell, the polarization parameter, ϵ, $\approx$ 0, and the only nonvanishing cross section term is $(\partial\sigma_T)/(\partial\Omega_k)$. Thus, at very forward angles, the reaction can be approximated by the real photoproduction cross section multiplied by a flux factor giving the number of incident photons.

The virtual photon flux factor, Γ, has the feature that it is very forward peaked so that, for 2 GeV electron energies, $\geq 50\%$ of the total flux is captured between scattering angles of 0 and 10 mrad [12–14]. Therefore if the electron spectrometer is placed at zero degrees, it needs only a small angular acceptance to assure that almost all the scattered electrons are transported to the focal plane, and that aberrations in the transport optics of the spectrometer system are small and easily corrected. On the other hand, zero-degree-electroproduction uses essentially transverse photons, and results in very high electron rates due to bremsstrahlung in the target [14].

It is important to use both low incident and scattered electron energies. While the virtual flux for a fixed photon energy, $\omega = E_e - E_{e'}$, increases with beam energy, so does the resolution and background. Particularly troublesome are the production of quasifree Σ, and hyperon and strange meson resonances which are associated with coincident K^+ in the momentum and angle ranges of interest. However, if the incident beam energy is ≤ 2 GeV$/c$, this background is not important.

The electron beam at Jlab is ≈ 60 μm in diameter with a momentum spread of $\Delta p/p \approx 10^{-5}$. At a beam energy of 2 GeV, this introduces negligible error in the missing mass resolution. However, beam stability is a much more important issue, i.e., the requirement that, whatever the beam momentum, it must be stable and reproducible for days (weeks) during the course of an experimental run. In the experiment reported here, beam stability was accomplished to $\approx 10^{-4}$ by implementing a feedback lock to the accelerator controls based on momentum measurements of the beam in the arcs of the accelerator.

The layout of the HNSS (E89-009) experiment is shown in Fig. 1. An electron beam of primary energy, approximately 1.8 GeV and 1 μA current, strikes a very thin target (20 mg/cm^2) placed just before a small zero-degree dipole magnet. This magnet splits the scattered particles at approximately 0°; the e^- of about 300 MeV$/c$ into a split-pole spectrometer [15], ENGE, and the K^+ of about 1.2 GeV$/c$ into the short-orbit spectrometer (SOS), fixed to the Hall C pivot at the Jefferson Laboratory. A

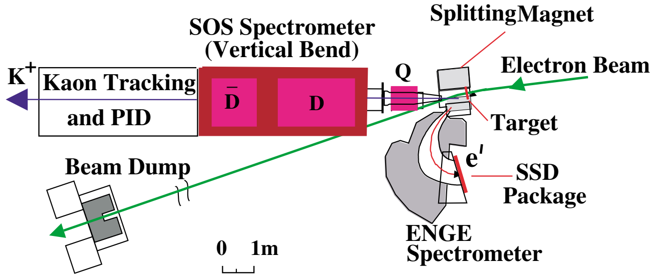

FIG. 1 (color online). The experimental plan view showing both the kaon spectrometer (SOS) and the electron spectrometer (ENGE). The SOS is a $QD\bar{D}$ spectrometer with Q an entrance quadrupole, and $D\bar{D}$ two dipoles bending in opposite directions, providing large momentum acceptance but reducing dispersion.

momentum of 300 MeV/c is optimal for the ENGE spectrometer, and photon energies of about 1500 MeV maximize the photoproduction of kaons from protons. A specially designed silicon strip detector (SSD) was used at the focal plane of the ENGE spectrometer [16].

The resolution for the experimental arrangement was expected to be 600–1000 keV, and was completely dominated by the SOS spectrometer. However, the SOS was a short-orbit magnet (important as the decay length for a 1.2 GeV/c kaon was about 9 m), was already mounted and tested at the Hall C pivot, and had the sophisticated particle identification package (PID) [17] required to identify kaons within the large background of pions and positrons. Therefore, for the first $(e, e'K^+)$ experiment, the SOS was chosen as the kaon spectrometer.

Two targets, (i) 22 mg/cm^2 ^{nat}C and (ii) 19 mg/cm^2 ^{7}Li, were investigated, and a calibration target, an 8.8 mg/cm^2 CH$_x$ foil, was used to observe Λ and Σ production from hydrogen. Only the analysis of the C and CH$_x$ data is reported here. The reaction of interest, $(e, e'K^+)$, resulted in the production of a $^{12}_{\Lambda}$B hypernucleus when a C nucleus was targeted. Beam intensities were tuned to produce an acceptable signal to accidental ratio, which for the C target was approximately 0.6 μA, giving an experimental luminosity of approximately 4×10^{33} cm^{-2} s^{-1}. The total usable virtual flux was 1.5×10^9 photons/s. To satisfy conflicting beam requirements when simultaneously operating several experiments in the different Halls, data had to be acquired at two different beam energies, 1721 and 1864 MeV. However, within statistics, there are no differences in the resulting $^{12}_{\Lambda}$B spectra.

Because of the high electron rates, the event trigger was the identification of a kaon in the SOS arm. The coincidence of this kaon with an electron in the ENGE spectrometer was made in the off-line analysis. A large flux of positrons from Dalitz pairs was observed in coincidence with two electrons, $A(e, e'[e^+e^-])A$, because the SOS angular acceptance extended to 0°. Positrons in the SOS were easily identified and removed by the shower counter PID, but were used here to confirm the experimental resolution. The resolution of the energy peak of the Dalitz spectrum, obtained by subtracting the sum of the measured energies of all detected particles from the beam energy, was ≈ 900 keV FWHM. As the resolution of the ENGE spectrometer was small, ≈ 250 keV FWHM, the expected hypernuclear resolution is approximately given by this measurement.

The calibration spectrum obtained from the CH$_x$ target with the accidental background, as taken with the 1864 MeV beam, is shown in Fig. 2. The Λ and Σ peaks are evident, as well as an enhanced region underlying the peaks. This enhancement is due to $(e, e'K^+)$ reactions on C in this target, and the threshold for $^{12}_{\Lambda}$B production lies about 37.4 MeV below the Λ peak. The missing mass resolution in this spectrum, 3.5 MeV (FWHM), is dominated by the kinematics due to the Λ recoil, and cannot be corrected because of the intrinsic angular resolution (13 mrad FWHM) of the SOS spectrometer. This kinematic effect falls rapidly with target mass so that for the C target the contribution is small.

Although the Λ and Σ peaks were used to calibrate the focal plane of the ENGE spectrometer, the known Λ photoproduction cross section could not be used for cross section normalization because the beam changed the hydrogen to carbon ratio of the CH$_x$ target. The absolute value and shape of the accidental coincidence background was obtained by averaging over eight out-of-time peaks.

The ^{12}C$(e, e'K^+)^{12}_{\Lambda}$B spectrum with the averaged accidental background is shown in Fig. 3. Clearly evident

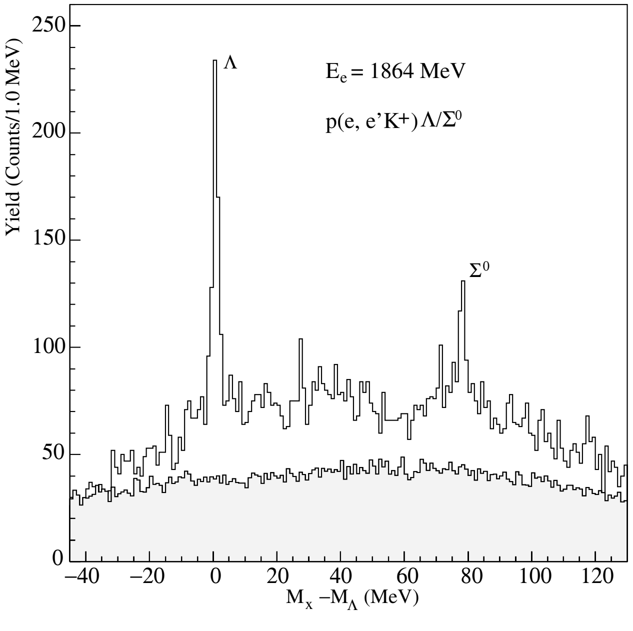

FIG. 2. The missing mass spectrum obtained from a CH$_x$ target at an incident electron energy of 1864 MeV. The solid histogram is the accidental background.

are the ${}^{12}_{\Lambda}$B hypernuclear excitations where the reaction replaced a proton by a Λ in the s and p shells. The ground state (gs) doublet, $(1^-; 2^-)$, as well as the p-shell excitations are unresolved. The gs doublet contains approximately 165 counts above background, obtained in approximately 440 beam hours. There is also strength in the bound-state region between these excitations.

The observed spectrum is similar to that predicted by Motoba *et al.* [18,19] and by Millener [20]. Reference [19] calculates the excitation strengths in DWIA for the photoproduction process of a kaon at an angle of 3° by a 1.3 GeV photon. The curve in Fig. 3 is generated by superimposing Gaussian peaks, having a FWHM of 900 keV below and 5 MeV above 15 MeV excitation energy, on a polynomial fit to the averaged accidental background. The strength of the peaks is taken from Ref. [19] and their positions from [20], as this latter spectrum was obtained from an effective p shell Λ-nucleus interaction previously matched to (π^+, K^+) data. The curve in the figure is directly overlayed on (not fitted to) the data.

The binding energy scale is determined from the position of the Λ and Σ peaks in the calibration spectrum. The ${}^{12}_{\Lambda}$B binding energy is found to be 11.4 ± 0.5 MeV and is in agreement with the accepted value [21] obtained from a measurement using emulsion, 11.37 MeV.

The differential cross section can be calculated as if it were photoproduction, by assuming the virtual photons are massless. This averages the elementary (γ, K) reaction at 1500 MeV over the ≈ 100 MeV spread of virtual gamma energies. The weighted average of the cross section measurements at the two incident beam energies is $140 \pm 17(\text{stat}) \pm 18(\text{sys})$ nb/ns. This value is consistent with the individual values of the separate energy measurements, and also the theoretical prediction [19], 152 nb/sr, for the ground state doublet. To confirm our cross section normalization, the quasifree component of the experimental spectrum was extracted, and the yield corrected for acceptance and momentum transfer [22]. We obtained 4.2 interacting protons, in agreement with previous measurements [23,24].

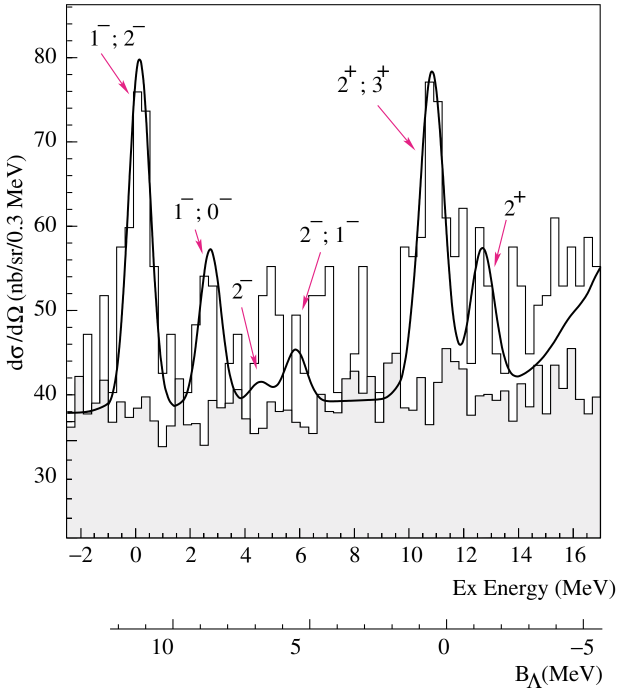

FIG. 3 (color online). The summed ${}^{12}_{\Lambda}$B missing mass spectrum for both energies. The solid histogram is the measured accidental background, and the curve is a theoretical calculation, spread by 900 keV and overlayed on, not fit to, the data.

In summary, the first $(e, e'K^+)$ experiment has successfully observed the electroproduction of ${}^{12}_{\Lambda}$B, illustrating that excellent resolution and reasonable counting rates are possible. The missing mass resolution, ≈ 900 keV, is consistent with the expected value, and is a factor of 1.6 better than existing measurements.

The positions and strengths of the gs and strongest p-shell excitations are consistent with a previously extracted Λ-nucleus effective interaction when inserted in a DWIA calculation with a phenomenological parametrization of the elementary kaon photoproduction amplitude [18]. However, there are differences in the core excited region of the spectrum (2–8 MeV), and perhaps there is structure underlying the two major p-shell excitations (10–13 MeV). It is the overlap of the 2^+ and 3^+ states in the p-shell region [20] which provides the excellent agreement with the data, but these two states are not as degenerate in the calculated spectrum of Ref. [19] which uses a slightly different set of effective parameters, and the resulting agreement for the p shell is then poor. The gs doublet splitting is predicted to be unobservable. This work thus demonstrates sensitivity to the effective interaction and the DWIA transition amplitudes.

The results of the experiment, including rates, backgrounds, and magnetic optics, were used to confirm that a future experiment with a dedicated Kaon spectrometer [6] will provide resolutions of a few hundred keV with rates increased by a factor of 60. We also note that the experiment used a small quantity of target material (10–20 mg/cm^2) so that almost any nuclear isotope can be investigated. The expected precision of the future data will require consistent DWIA and effective interaction calculations.

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