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High resolution hypernuclear spectroscopy

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Abstract. Hypernuclear spectroscopy provides fundamental information for understanding the effective Λ-Nucleon interaction. Jefferson Laboratory experiment E94-107 was designed to perform high resolution hypernuclear spectroscopy by electroproduction of strangeness in four 1p-shell nuclei: ^{12}C, ^{9}Be, ^{16}O, and ^{7}Li. The first part of the experiment on ^{12}C and ^{9}Be has been performed in January and April-May 2004 in Hall A at Jefferson Lab. Significant modifications were made to the standard Hall A apparatus for this challenging experiment: two septum magnets and a RICH detector have been added to get reasonable counting rates and excellent particle identification, as required for the experiment. A description of the apparatus and the preliminary analysis results are presented here.

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1 Introduction

The aim of the E94-107 experiment, performed in Hall A at Jefferson Lab, is the first systematic study of 1p shell nuclei ^{12}C, ^{9}Be, ^{16}O, ^{7}Li [2]. A preliminary study was done previously in Hall C using a ^{12}C target [3]. A large effort has been made by the kaon collaboration and Hall A to improve the apparatus for this specific experiment[4]: two septum magnets, the upgrade of aerogel Cherenkov detectors and a new challenging detector, a Ring Imaging CHerenkov (RICH) detector, have been designed, built and successfully used. This paper describes the physics and the needed upgrade of the Hall A apparatus. Data were taken in April - May 2004 on ^{12}C and ^{9}Be. Preliminary results on ^{12}C are presented.

2 Hypernuclear spectroscopy

Hypernuclear physics is an important and exciting part of intermediate energy nuclear physics. The main goal is getting information on the nature of the force between nucleons and strange baryons, i.e. the Λ-N interaction. The nucleus provides a unique laboratory for studying this interaction [1]. A hypernucleus in which a nucleon in a p shell is replaced by a Λ hyperon in the s shell (the Λ particle not being subjected to the Pauli blocking) can be described, by analogy with spectroscopy of light nuclei, in terms of the $|s^4\, p^{(A-5)} * s^{\Lambda}; JT\rangle$ configurations, in which the Λ particle couples to a nuclear state of the parent nucleus with spin and isospin equal to J and T, respectively, creating a doublet of states $J = J^{A-1} \pm 1/2$ (weak coupling model). The Λ-nucleon interaction can be described by the potential:

$$V_{\Lambda N} = V + \Delta + s_\Lambda + s_N + T \tag{1}$$

where:
$V = V(r)$ is the central part
$\Delta = V_\sigma(r) s_\Lambda \cdot s_N$ is the spin-spin term
$s_\Lambda = V_\Lambda(r) s_\Lambda \cdot l_{N\Lambda}$ is the Λ spin orbit term
$s_N = V_N(r)\, s_N \cdot l_{N\Lambda}$ is the N spin orbit term.
$T = V_T(r) S_{12}$ is the tensor part, where $S_{12} = 3(\mathbf{s}_N \cdot \hat{r})(\mathbf{s}_\Lambda \cdot \hat{r}) - \mathbf{s}_N \cdot \mathbf{s}_\Lambda$.

The doublet splitting is essentially determined by Δ, s_Λ, and T; s_N is responsible for the spacing between doublets.

3 Electromagnetic and hadronic probes

Electromagnetic probes provide a very powerful tool for the study of hypernuclear physics. They produce hypernuclei that cannot be generated with hadronic probes and can excite non-substitutional and non-natural parity states [1]. In fact the spectroscopic information that can be obtained from (K^-, π^-), (π^+, K^+) and $(e, e'K^+)$ reactions can be summarized as follows: in the strangeness exchange reaction: $K^- + n \rightarrow \pi^- + \Lambda$ (kaon beam momentum $p_k = 400 - 450$ MeV/c or $p_k = 700 - 800$ MeV/c), the momentum transferred to the target nucleus is small ($q < 100$ MeV/c). Moreover, at these energies, the spin flip transitions for forward pion angles ($\theta_\pi < 10°$) are negligible. Due to the strong absorption of the kaon and pion, the reaction takes place on peripheral nucleons. As

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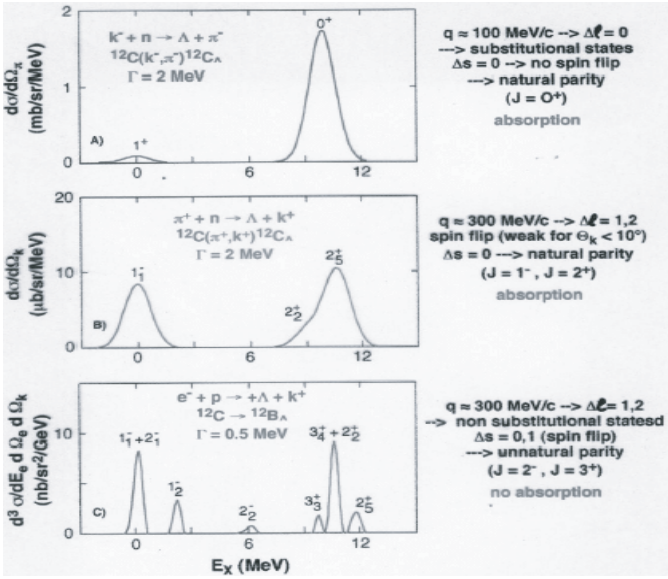

Fig. 1. Strength functions of the hadronic and electromagnetic reaction on ^{12}C

a consequence, $\Delta l = \Delta s = 0$ transitions dominate in this reaction, and substitutional states are predominantly populated. In the associated production $\pi^+ + n \rightarrow K^+ + \Lambda$, the momentum transferred is as high as $q = 350$ MeV/c at the maximum in the elementary cross section ($p_\pi = 1.05$ GeV/c), but the spin flip amplitude, although strong enough to produce an appreciable polarization in the final hypernuclear states, is still weak at $\theta_k < 10°$. As a consequence, $\Delta l = 1$, 2 and $\Delta s = 0$ transitions are favoured. Lower members of the hypernuclear bound states are populated. In the stopped kaon (K_{stop}, π) reaction, the momentum transferred to the nucleus is 250 MeV/c. $\Delta l = 1$, 2 transitions hence dominate, but spin flip is very weak. Because the energy of the incoming kaon is well defined, the energy is determined by the pion detecting system. The energy resolution of the processes described above is typically of the order of 2 MeV.

In the electromagnetic (electro and photo-)production of strangeness: $e +^z A \rightarrow e' + K^+ +^{Z-1} A_\Lambda$, the momentum transfer to the hypernucleus is rather large (q about 350 MeV/c for light nuclei) and decreases steadily with increasing energy of the virtual photon, $E_\gamma = E_e - E_{e'}$. For example for ^{16}O, for forward kaon angles, q decreases from 330 MeV/c at $E_\gamma = 1.2$ GeV to 250 MeV/c at $E_\gamma = 2.5$ GeV. The spin-flip production is strong, both $\Delta l \neq 0$ and $\Delta s \neq 0$ transitions are hence available. Because the $K^+ - \Lambda$ is produced on the proton, the hypernuclei generated are different from those produced by hadronic probes. Figure 1 shows the complementary aspect of the reactions. The advantage of electromagnetic production is evident: spin flip excitation and much better energy resolution. This allows, in principle, the detection of doublet splitting in the $^9Be(e,e'k)^9Li_\Lambda$ [1] (the first 2^+ and 1^+ have mainly L=1 and S=1 and Δ, the spin spin term, provides the main contribution to the doublet splitting), provided good energy resolution (500 keV or less) is attained.

Table 1. Kinematics of the Hall A hypernuclear experiment

E_i (incident electron energy)	4 GeV
ω (virtual photon energy)	~ 2.2 GeV
P_k (Kaon momentum)	1.9 GeV/c
Q^2	0.0789 GeV^2
θ_e (electron scattering angle)	6°
θ_k (kaon scattering angle)	6°

4 JLab, Hall A, and HRS's

The availability of the Thomas Jefferson Laboratory (JLab) beam and of two High Resolution Spectrometers (HRS) in Hall A of this laboratory presents a unique opportunity to perform high resolution hypernuclear spectroscopy by electromagnetic probes. The Continuous Electron Beam Accelerator Facility (CEBAF) at JLab is a 100% duty cycle, high intensity beam accelerator located at Newport News (Virginia, USA). The maximum energy available is 6 GeV with an energy spread of 10^{-4} (4σ). The beam emittance is less than 0.002 μm and the maximum beam current is 200μA. Hall A is equipped with two nearly identical High Resolution Spectrometers (HRS) [9] that can detect particles of momentum up to 3.1 and 4.3 GeV/c with momentum resolution of about 10^{-4} $\Delta p/p$. The angular range of scattered particle central trajectory is $12.5° - 165°$. Vertical Drift Chambers (VDC) are used for tracking, scintillators for triggering, gas and aeroglel threshold detectors and shower counters for Particle IDentification (PID).

5 The experiment

A hypernuclear physics program has been planned in Hall A aiming to perform High Resolution 1p Shell Hypernucear Spectroscopy on ^{7}Li, ^{9}Be, ^{12}C and ^{16}O [2]. Secondary electrons and ejected kaons are detected by the electron and the hadron arms of HRS, respectively. The kinematics is shown in Table 1.The reason for the choice is determined by the small value of the cross section of the electroproduction of hypernuclei dramatically decreasing with increasing scattering angle. So the scattered particles have to be detected at forward angles. Moreover to keep reasonable kaon survival fraction, the kaon momenta have to be fairly high, so high transfer energy is needed. The good momentum resolution of this spectrometer makes it possible to measure the missing energy with a resolution of the order of 500 keV or less (2).

5.1 The upgrade

Relevant and challenging modifications of the standard Hall A apparatus were needed [4]. In fact : 1) the normal HRS minimum scattering angle is too large (12.5 °). 2) the states one would like to identify are very close together, requiring the best possible missing mass resolution

Table 2. Contributions to the energy resolution (all resolutions in FWHM)

Source			Resolution	
Beam	$6 \cdot 10^{-5}$	$\rightarrow$	240	keV
electron momentum	$1.0 \cdot 10^{-4}$	$\rightarrow$	180	keV
kaon momentum	$1.0 \cdot 10^{-4}$	$\rightarrow$	190	keV
kaon straggling			40	keV
Total			350	keV

(a few hundred keV). 3) Very high π and p backgrounds are present at forward angles, implying that unambiguous kaon identification is challenging. To overcome these difficulties two septum magnets were added enabling the detection of particles scattered at 6 ° and a proximity focusing freon/CsI RICH detector was built to allow unambiguous kaon identification.

5.1.1 Septum magnets

Two septum magnets (two very short dipoles) were added to HRS's. The two magnets bend particles scattered at angles of 6 ° in order to make their trajectories overlap the trajectories detectable by HRS. This overlapping can be achieved by moving the target upstream.

Table 2 reports the energy resolution that is expected in this experiment and the terms that contribute to it. It has been proved that the addition of the septum preserves HRS optic properties. The septa, because of their short length and the small bending angle, can be treated as a small perturbation to the optical properties of HRS. The magnets have been designed, built and successfully used for this experiment as well as for other important experiments in Hall A [7]. These devices have been extensively described elsewere [5,6].

5.1.2 Particle identification

Two aerogel Cherenkov detectors (n=1.015 and n=1.055) have been used for hadron identification ([8]–[11]) within the momentum acceptance of this experiment. In the first aerogel detector with n=1.015 only pions exceed the threshold for the Cherenkov effect. It is used as a veto: only the events below a desired pulse height are selected. In the other aerogel (n=1.055) both pions and kaons exceed threshold, but not protons. Therefore the combination of the two detectors selects kaons. Neverthless, single rates of hundreds of kHz as well as coincidence rates around 100 Hz are expected, while the signal varies from 10^{-2} Hz to 10^{-4}Hz. It has been shown that, in this condition the standard HRS' s Particle IDentification (PID) system is not sufficient for an unambiguous kaon identification [12]. A more powerful system is needed.

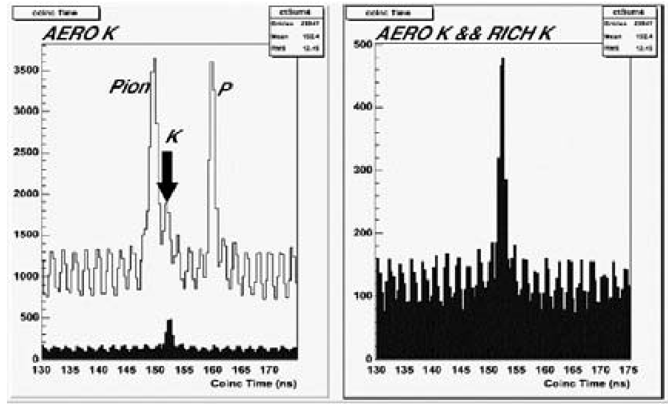

Fig. 2. Kaon selection on Time of Coincidence Spectrum. The three peaks corresonds to real coincidences of (e,π), (e,k), (e,p) with and without RICH. The contamination is clearly reduced to a negligible term

5.1.3 The RICH

For the RICH a proximity focusing geometry (no mirrors involved) was chosen, with a CsI photocathode and liquid perfluoroexane radiator [12]. The detector as well the thin film evaporation system and Quantum Efficiency measuring system has been designed and built in Rome by the INFN group [13], the freon purification system at Jefferson Lab. The detector is similar to the one that will be used at the LHC ALICE experiment at CERN [15]). The RICH, extensively described elsewere [12,14] has worked successfully during the experiment, providing a big improvement in the particle identification. In Fig. 2 the Time Of Coincidence (TOC) of the two arms (electron vs hadron) is reported. The figure shows how the RICH cleans up protons and pions. After the kaon selection on the two aerogel threshold detectors a significant number of pions is still present. The RICH has proven to be crucial for kaon identification. A pion rejection factor of about 1000 has been obtained (only with RICH). A number of p.e. equal to 13 has been measured for pions. The angular resolution, the key parameter for the detector performance is $\simeq 5$ mrad, corresponding to a separation between π and k of $\simeq 6\,\sigma$. This result, agrees with expectations [4] based on Monte Carlo simulations. One should note that the RICH analysis is not optimized yet.

6 Results

The missing energy spectra for $^{12}C(e,e'K^+)^{12}B_\Lambda$ and $^9Be(e,e'K^+)^9Li_\Lambda$ have been extracted from the data. We report here only the ^{12}C data because the analysis of ^9Be is still too preliminary. The physics information that can be extracted from the spectra strongly depends on the energy resolution, determined by the beam energy spread (σ_E/E) and by the spectrometer momentum resolution, and on the PID. The beam energy stability was not as good as expected ($\sigma_E/E = 2.5 \times 10^{-5}$) during part of data taking in April. It was was significantly improved in

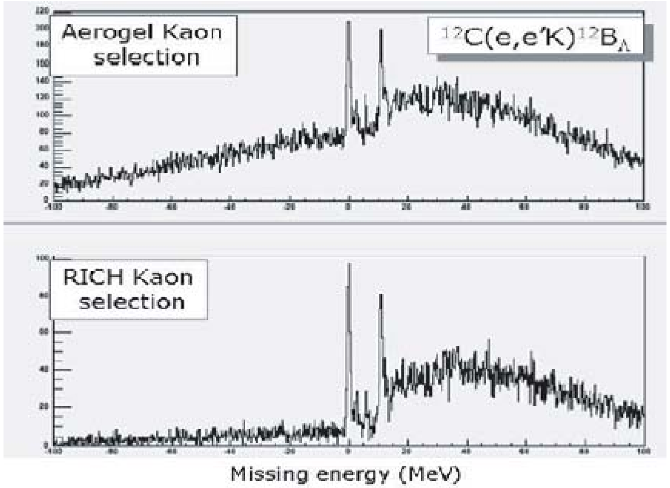

Fig. 3. C12 missing energy spectrum with and without RICH

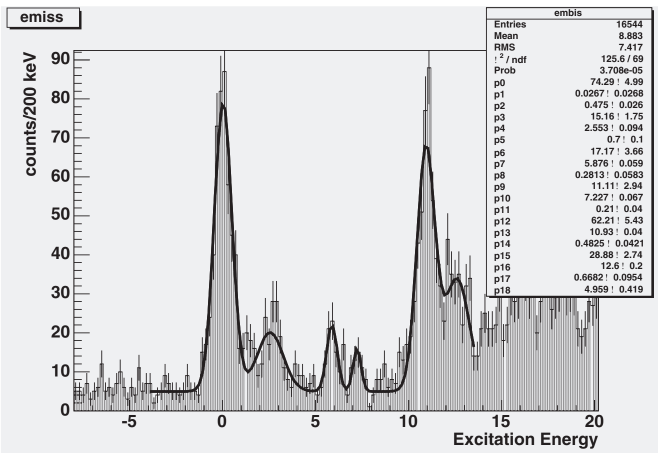

Fig. 4. Missing mass spectrum of ^{12}C

May ($^9Be(e,e'K^+)^9Li_\Lambda$). One should note also that the optimization of the optics database is not completed yet. In fact the analysis has shown that careful cuts on momentum acceptance of the spectrometer have to be applied in order to improve the missing energy resolution. The main results of the analysis are shown in Figs. 3- 4. Figure 4 shows the $^{12}C(e,e'K^+)^{12}B_\Lambda$ missing mass spectrum with and without RICH cuts. The crucial role of the RICH in cleaning the background is evident. Figure 4 shows that the first large peak and the other peak at $\sim$ 10 MeV are clearly visible, corresponding to the substitution of a p shell proton with a Λ in a s state and p state, respectively. In between two levels at $\sim$ 2.4 MeV and $\sim$6 Mev are also evident. The energy resolution is 1 MeV, Further work is needed to attain a missing energy resolution of the order of $\sim$ 500 keV or less. The optics database optimization is not yet completed. Moreover the optimization of event selection for the beam energy stability as well as the acceptance cuts requires further work too. The analysis is still very preliminary.

7 Conclusions

The first systematic study of 1p shell hypernuclei with electromagnetic probe has started in Hall A at Jab. Important information on Λ-N interaction will be extracted from the good-quality ^{12}C and ^9Be data. The new experimental devices (septum magnets and RICH detector) have performed very well. The RICH detector allowed excellent kaon identification and clean kaon signal over a large pion and proton background. The energy resolution is the best obtained so far for hypernuclear production experiments. New data taking on ^{16}O and ^9Be has been scheduled for June 2005.

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