Recent results on High Resolution Hypernuclear Spectroscopy by Electroproduction at Jefferson Lab, Hall A

F. Garibaldi^{a *}, H. Breuer^b, P. Brindza^c, P. Bydzovski^d, G. Chang^e, E. Cisbani^a, S. Colilli^a, F. Cusanno^e, R. De Leo^f, G. De Cataldo^f, K. De Jager^c, R. Feuerbach^c, E. Folts^c, R. Fratoni^a, S. Frullani^a, F. Giuliani^a, M. Gricia^a, D. Higinbotham^c, M. Iodice^g, B. Kross^c, L. Lagamba^f, J.J. Le Rose^c, M. Lucentini^a, P. Markowitz^h, S. Marrone^f, R. Michaels^c, E. Nappi^f, Y. Qiang^c, B. Reitz^c, F. Santavenere^a, J. Segal^c, M. Sotona^d, G.M. Urciuoli^e, P. Veneroni^a, B. Wojtsekhowski^c, C. Zorn^c

^aINFN Roma1, gr. collegato Sanita' and ISS, Viale Regine Elena 299, 00161 - Rome, Italy

^bUniversity of Maryland

^cJefferson Lab

^dNuclear Physics Institute, Rez near Prague, Czech Republic.

^eINFN Roma1

^fINFN Bari

^gINFN Roma3

^hUniversity of Florida

The first “systematic” study of 1 p shell hypernuclei with electromagnetic probes has started in Hall A at Jefferson Lab [?]. The aim is to perform hypernuclear high resolution spectroscopy by the electroproduction of strangeness on four 1p-shell targets: ^{12}C , ^9Be , ^{16}O , ^7Li . The first part of the experiment on ^{12}C and ^9Be has been performed in 2004, the second part (^{16}O and ^7Li) is scheduled for June 2005. To overcome the major experimental difficulties, namely the low counting rate and the challenging Particle IDentification (PID), two septum magnets and a Ring Imaging CHerenkov (RICH) detector had to be added to the existing apparatus. After underlining the particular role the electroproduction reaction plays in hypernuclear physics we describe the challenging modifications of the Hall A apparatus. Preliminary results on ^{12}C and ^9Be are presented.

1. Introduction

The Lambda hypernucleus, a nuclear system with strangeness $S=-1$ in which the Lambda hyperon replaces one of the nucleons, is a long-living baryon system and provides a vari-

*Corresponding author

ety of phenomena. The strange quark is an impurity in the system and the study of its propagation can reveal configurations or states not seen in other ways. The study also gives interesting important insight into the structure of ordinary nuclear matter. The hyperon is not excluded from the filled nucleon orbitals by the Pauli principle and can penetrate deep inside the nucleus. Moreover the high resolution spectroscopic study of light hypernuclei allows access to important information on the nature of the force between nucleons and strange baryons, i.e. the $\Lambda - N$ interaction. The nucleus provides a unique laboratory for this study. From low-energy $\Lambda - p$ scattering studies we obtained information about the s-state $\Lambda - N$ interaction, but the non-central part of the $\Lambda - N$ force is not well established. Especially useful information comes from the spin dependent part of the interaction[?]. Hypernuclear experimental studies up to now have been carried out essentially by hadron-induced reactions with limited energy resolution (1.5 MeV at the best). Moreover the spin flip transition excitation was weak so doublets have not been detected. In the electromagnetic case, the spin flip transitions are strong, so doublet splitting detection is possible in principle because both members are populated. The disadvantage of smaller electromagnetic cross sections is partially compensated by the high current, continuous beam available at JLab[?]. The feasibility of these experiments has been recently demonstrated by the Hall C E-89-009 experiment [?]. The aim of the Hall A experimental program is the first “complete” study in 1p shell nuclei: ${}^7\text{Li}$, ${}^9\text{Be}$, ${}^{12}\text{C}$, ${}^{16}\text{O}$ [?]. A missing mass resolution as good as 350 keV - 400 keV (FWHM) can be attained, with beam energy stability of 2.5×10^{-5} (σ_E/E) and the High Resolution Spectrometers (HRS) momentum resolution, $\Delta p/p \simeq 10^{-4}$ (FWHM)[?]. In the following, after presenting the physics information that can be extracted from the experiment, we describe the experimental difficulties and the challenging modifications made to the Hall A apparatus. Then preliminary results on ${}^{12}\text{C}$ and ${}^9\text{Be}$ will be presented.

2. Hypernuclei

In the Lambda hypernucleus the Λ is weakly coupled to the nuclear core, and the shell model can be used to describe this system. In this model the Λ resides in the 1s shell in the hypernuclear ground state. Excited states are obtained by promoting a Λ to higher orbits or coupling a Λ in the ground state to an excited nuclear core. The shell model is a precise and predictive tool used to describe nuclear spectra. Based on the experimental knowledge of some light hypernuclei, scattering data of hyperons from nucleons, and flavor SU(3) symmetry, an effective ΛN interaction for the shell model can be constructed [?][?]. Consider 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 Pauli blocking). This system can be described, by analogy with the 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 equal to J^{A-1} , 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 $V_{\Lambda N} = V + \Delta + s_\Lambda + s_N + T$, 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 $S_{12} = 3(\vec{s}_N \cdot \hat{r})(\vec{s}_\Lambda \cdot \hat{r}) - \vec{s}_N \cdot \vec{s}_\Lambda$. The potential is particularly sensitive to the spin dependent part of the interaction [?].

Figure 1. Be missing mass spectrum with three different missing mass resolution

2.1. Electromagnetic versus hadronic probes

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: $K^- + n \rightarrow \pi^- + \Lambda$, the momentum transferred to the target nucleus is small ($q < 100$ MeV/c). The spin flip transitions for forward pion angles ($\theta_\pi < 10^\circ$) are negligible. Due to the strong absorption of the kaon and pion, the reaction takes place on peripheral nucleons. As consequence, in this reaction, $\Delta l = \Delta s = 0$ transitions dominate and substitutional states are predominantly populated. In the stopped kaon (K_{stop}, π) reaction, the momentum transferred to the nucleus is 250 MeV/c, hence the $\Delta l = 1, 2$ transitions dominate, but spin flip is very weak. In the strangeness associated production $\pi^+ + n \rightarrow K^+ + \Lambda$, the momentum transferred is as high as $q = 350$ MeV/c, but the spin flip amplitude is still weak at $\theta_k < 10^\circ$. As a consequence, $\Delta l = 1, 2$ and $\Delta s = 0$ transitions are favoured. The energy resolution of the processes described above is typically of the order of 2 MeV.

In the electromagnetic production of strangeness: $e + p \rightarrow e' + K^+ + \Lambda$, the momentum transfer to the hypernucleus is rather large (q about 350 MeV/c for light nuclei). The spin-flip production is strong so both $\Delta l \neq 0$ and $\Delta s \neq 0$ transitions are available. Because the production of the $K^+ - \Lambda$ pair goes on the proton, the hypernuclei generated are different from those produced by hadronic probes. The reactions are complementary: different hypernuclei and different states are generated, and different energy resolutions are obtained[?]. The experimental advantage of the electromagnetic probe is evident: much better energy resolution. Improving the missing mass resolution has obvious advantages. Two, three or four peaks have been found for ^{12}C , as the resolution improves from 4 to 2 MeV, and to 1.5 MeV in the hadronic case[?]. For the electromagnetic probe it has been shown that doublet splitting can be detected in principle, if the energy resolution is about 500 keV or better, in the case of $^9\text{Li}_\Lambda$ (see Fig.??[?]).

3. The experiment

The experiment took place in Jefferson Lab Hall A. The HRS spectrometers were used to detect the electrons and kaons. To get reasonable counting rates we have to consider the following. The electron scattering angle has to be small to get a high virtual photon flux and the kaon angle has to be close to the virtual photon direction to minimize the momentum transfer. The momentum transfer to the hypernucleus in electroproduction is rather large and decreases steadily with increasing energy of the virtual photon so high energies are preferable. Since cross sections depend strongly on Q^2 , the measurements have to be made at low Q^2 . To keep a reasonable kaon survival fraction the kaon momenta

have to be fairly high. Scattering angles of 6° for both for electron and kaons, an incident energy of 3.77 GeV, a photon energy of 2.2 GeV, a scattered electron momentum of 1.86 GeV/c, a kaon momentum of 1.96 GeV/c, and $Q^2 = 0.079 \text{ (GeV/c)}^2$ have been used. The expected counting rates for the two nuclei are reported in Table ?? . The C4 model [?] of the elementary process is used in the calculation. The electron-nucleus luminosity,

Background	(Hz)	$^{12}\text{C}(e, e'K)^{12}\text{B}_\Lambda$			$^9\text{Be}(e, e'K)^9\text{Li}_\Lambda$		
		E	J	counts	E	J	counts
		(MeV)		(h^{-1})	(MeV)		(h^{-1})
(e,e')	$1.5 \cdot 10^5$	0	1^-	5.9	0	$3/2^+$	1.78
(e, π)	$2.0 \cdot 10^5$	0.03	2^-	34.6	0.69	$5/2^+$	9.7
(e,K)	$3.6 \cdot 10^3$	2.54	1^-	14.9	1.42	$1/2^+$	1.95
(e,p)	$1.8 \cdot 10^5$	5.46	2^-	4.5	1.71	$3/2^+$	2.8
(e,e' π)	$\sim 1.0 \cdot 10^2$	6.04	1^-	1.0	2.43	$5/2^+$	1.07
(e,e'K) (QF)	$\sim 0.1 \cdot 10^1$	10.03	3^+	5.8	2.78	$7/2^+$	3.04
(e,e'p)	$\sim 5.0 \cdot 10^1$	10.63	3^+	27.1			

Table 1

Expected single and random coincidence rates compared to the $^{12}\text{C}(e, e'K)^{12}\text{B}_\Lambda$ and $^9\text{Be}(e, e'K)^9\text{Li}_\Lambda$ events.

obtained with a constant beam current of 100 μA and target thickness of 100 mg/cm^2 , ranges from 2.4×10^{36} to $5.4 \times 10^{36} \text{ cm}^{-2}\text{s}^{-1}$. The single and accidental coincidence counting rates are about constant for all the investigated nuclei and the numbers reported in Table ?? represent upper limits for our conditions.

3.1. Experimental challenges

3.1.1. Forward angle. Septum magnets

In order to allow experiments at very forward angles, smaller than the actual HRS minimum angle (12.5°), two septum magnets were added to the HRS's . The two magnets bend particles scattered at angles as small as 6° in order to make their trajectories overlap with trajectories detectable by the HRS's. This overlapping as well as the room for the septum magnets has been achieved by moving the target upstream. The chosen target shift makes the new HRS angular acceptance $\sim 4.5\text{msr}$ and the maximum field ~ 3.3 Tesla. The septum magnetic length is 84 cm. This new spectrometer configuration provides a general purpose device that extends the HRS features at small scattering angles[?] while meeting the HRS optical performances.

3.1.2. The challenge of Particle IDentification

As previously mentioned a very powerful PID system is mandatory for this experiment. In the electron arm Cherenkov counters were expected to give pion rejection ratios up to 10^3 . The dominant background (knock-on electrons) can be reduced another 2 orders of magnitude by the lead glass shower counters, giving a total pion rejection ratio $\geq 10^5$. In the hadron arm two aerogel Cherenkov counters with $n = 1.015$ and $n = 1.055$ have been used. Fig.?? shows the velocity β vs the momentum of pions, kaons and protons. With

Figure 2. PID with Threshold aerogel Cherenkov counters.

the choice of $n = 1.05$ it is possible to separate kaons (above threshold) from protons (below threshold) in the range 1.6 - 3.0 GeV/c. Using $n = 1.01$ allows the separation between pions and kaons so that with the combination of the two, kaons can be identified. Nevertheless, it has been shown that TOF and threshold Cherenkov counters are not sufficient for the unambiguous kaon identification needed to obtain "background free" missing mass spectra.

4. Improving the PID: RICH detector

Simulations performed to understand how to improve the kaon identification capability showed that a Ring Imaging Cherenkov (RICH) detector would provide the added PID capability. Fig.?? shows the advantage of using the RICH. It can be clearly seen, in the case of ${}^9\text{Be}_\Lambda$ how the low signal to noise ratio makes the spectroscopic measurements particularly hard. A clear assignment can be only given to the second component of the first doublet, losing any (important) information on the position of the first component. It should be realized that a standard PID system capable of rejecting pions and protons only at a 95% level is probably not enough to extract outstanding physics information. The choice was a proximity focusing CsI/freon gaseous detector. The RICH discriminates particles by differentiating between different values of Cherenkov emission angle. The Cherenkov radiation, emitted in a transparent medium (the radiator) whose refractive index is appropriate for the range of particle momentum being specifically studied, is transmitted through an optical elements, which could be either focusing with a spherical or parabolic

Figure 3. ^{12}C and ^9Be with and without RICH

mirror or not focusing (proximity focusing), onto a photon detector that converts photons into photoelectrons with high spatial and time resolution (Fig.??-left). In our case the proximity focused geometry was chosen. The Cherenkov photons, emitted along a conic surface in the radiator (C_6F_{14} with $n=1.29$), chosen because of the momentum of the particles to be identified ($2 \text{ GeV}/c$) are refracted by the freon-quarz methane interfaces and strike a pad plane after traveling through a proximity gap of 10 cm filled with methane. A dedicated evaporation facility, with on-line Quantum Efficiency (QE) measurement capability was built for this [?].

4.1. Detector performances

In Fig.?? the Time of Coincidence (TOC) spectra between the electron and the hadron arm are shown. The top left spectrum is obtained without any PID selection. Kaons are not visible. In the top right plot the aerogel kaon selection is applied showing that kaons are barely visible. When the RICH selection is applied (bottom right plot) only the kaon contribution survives. In Fig.?? the good RICH performance is shown: a separation of pions from kaons at level of 6 sigma has been attained to be compared with MonteCarlo caluclations (Fig.??-right). The role of the detector in cleaning up the pion and protons is evident. A rejection factor of 1000 for pions has been measured [?]. It should be considered that the RICH analysis has not been fully optimized yet.

5. Preliminary results

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); by the spectrometer

Figure 4. left: RICH scheme and event display, right: Simulated performances

Figure 5. The role of the RICH for Kaon identification: many pions and protons are still present if RICH cuts are not applied

Figure 6. RICH performances. On the left side the number of photoelectrons for pions and protons is shown. On the right side the distribution of Cherenkov angle reconstruction is reported, showing a resolution of 5 mr

momentum resolution, and by the capability of reducing background with PID. Data were taken for both ^{12}C and $^9\text{Be}(e, e'K^+)$ reactions. The analysis is still in a preliminary stage. First of all the optimization of the optics database is not completed yet. Moreover the analysis has shown that cuts on the momentum acceptance of the spectrometer have to be applied in order to improve the missing energy resolution. Fig.?? shows the missing mass spectrum with and without RICH. The crucial role of the detector in cleaning the background is evident. Fig.?? shows the preliminary physics analysis of the missing energy spectra of the $^{12}\text{C}(e, e'K^+)^{12}\text{B}_\Lambda$ (left plot) and $^9\text{Be}(e, e'K^+)^9\text{Li}_\Lambda$ reactions (right plot).

The first large peak, in the left plot, and another peak at ~ 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 ~ 2.4 MeV and ~ 6 MeV are also evident. The background is evaluated by fitting the ‘not-physical’ region (negative region of the missing energy spectrum). The resulting values of the Signal to Noise Ratio (SNR) for the two identified core-excited-state peaks are 7.5 at 2.6 MeV and 6.5 at 5.4 MeV.

Two theoretical curves have been superimposed on both spectra, differing in the model used for the elementary $K^+ - \Lambda$ production on protons. The hypernuclear wave function is the same for the two curves as computed by M. Sotona. The solid line uses the model of Bennhold-Mart(K-MAID)??, the dashed line the one by Saghai Saclay-Lyon (SLA)???. Both curves have been normalized to the first (ground state) experimental peak. In the $^{12}\text{C}(e, e'K^+)^{12}\text{B}_\Lambda$ reaction, the relative intensities (with respect to the ground state) of the first excited peak at 2.6 MeV and of the strongly populated $p - \Lambda$ state at 11 MeV seem to be better reproduced by the MAID model than the SLA one. Another peak at 6 – 7 MeV is underestimated by both models. Of course, for any conclusion one has to wait for the final results of the analysis.

In the reaction $^9\text{Be}(e, e'K^+)^9\text{Li}_\Lambda$ the relative strength of the doublets is different from

Figure 7. ${}^9\text{Li}_\Lambda$ missing energy spectrum with and without the RICH selection.

Figure 8. Left: ${}^{12}\text{B}_\Lambda$ missing energy spectrum, the solid and dashed lines represent the theoretical data (see text). Right: ${}^9\text{Be}_\Lambda$ missing energy spectrum, the solid and dashed lines represent the theoretical data (see text).

theoretical prediction. At the present stage of the analysis is not possible to select the “best” model. In fact the analysis and the interpretation of the measured missing mass spectra is still at a preliminary stage and not ready for final conclusions. Improvements in the energy resolution as well as statistics is crucial.

A first evaluation of the cross section has been extracted from the carbon data. Considering the ground state of the $^{12}\text{C}(e, e'K^+)^{12}\text{B}_\Lambda$, the cross section is $\sigma_{g.s.}(^{12}\text{B}_\Lambda) = 5.0 \pm 0.2 \text{ (stat)} \pm 1.0 \text{ (syst)} \frac{\text{nb}}{(\text{msr})^2 \text{GeV}}$, to be compared with a prediction of $[?], \sigma_{g.s.} \sim 5.4 \frac{\text{nb}}{(\text{msr})^2 \text{GeV}}$.

6. Conclusion

The first ‘systematic’ study of $1p$ shell hypernuclei with an electromagnetic probe has begun. The experiment E94-107 in Hall A at Jefferson Lab, designed to perform hypernuclear spectroscopy of light hypernuclei, took data on ^{12}C and ^9Be targets. The new experimental devices (septum magnets and RICH detector) have proven to be very effective. The RICH detector provided excellent kaon identification and a clean kaon signal over large pion and proton backgrounds. The analysis is still at a preliminary stage. Further work is needed to attain a missing energy resolution of the order of $\sim 500 \text{ keV}$ 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. The RICH analysis can be further improved. Finally, we will take data not only on new targets (^{16}O) and on the ^9Be and ^{12}C , during the June 2005 run.

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