Abstract: The first systematic study of 1p-shell and medium-heavy hypernuclei by electroproduction of strangeness has started at Jefferson Laboratory with the experiments E89-009, E94-107, E01-011, E05-115. The main results obtained in Hall A and future prospects of the investigation of hypernuclei at Jefferson Laboratory regarding the study of the angular dependence of electroproduction of strangeness and the possibility of performing the spectroscopy of $^{208}\Lambda Tl$ are reported here.

1 Introduction

The physics of hypernuclei is an important branch of contemporary nuclear physics. Indeed, due to the low intensities of the available $\Lambda$ beams, only very limited information about $\Lambda - N$ interaction can be extracted by means of $\Lambda - p$ low energy scattering, therefore the hypernuclei provide a unique laboratory for studying the $Y - N$ force. Many progresses have been done in the last years in the physics of hypernuclei and few facilities in the world are planning new challenging experiments in this field [1].

In principle, information derived from hypernuclear structures have important implications in the study of the core of neutron stars, providing constraints to the equation of state [2, 3].

In the case of production of hypernuclei by electromagnetic probes [4] the parameters of the in medium effective $\Lambda - N$ potential could be determined from the structure of the missing mass spectra of the $^{A}Z(e, e'K^+)_{\Lambda}(Z - 1)$ reactions. Therefore, those experiments are complementary to the investigations using hadronic probes [5] which produce mirror hypernuclei, hence the Charge Symmetry Breaking (CBS) term of the $\Lambda - N$ interaction could be accessed. In addition, experiments using electromagnetic and hadronic probes are complementary to the successful studies performed by $\gamma$-ray spectroscopy [6] since some energy levels can not be determined by $\gamma$-ray decays.

Theoretical predictions reported here of the electroproduction of hypernuclei are obtained in the

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framework of the Distorted Wave Impulse Approximation (DWIA) [7] using the Saclay-Lyon (SLA) model [8] for the elementary process.

2 Electroproduction of Strangeness at Jefferson Laboratory

The beam and the spectrometers available at Jefferson Laboratory (JLab) are well suited for studying electroproduction of strangeness. Last decade both Hall A and Hall C started the studies of electroproduction spectra of hypernuclei with sub-MeV resolution [9, 10]. To some extent, the systematical study of hypernucleus spectra can provide information also on the elementary process of electroproduction of strangeness. This possibility is evident in the peculiar case of using a waterfall target [11]. The elementary amplitude for kaon electroproduction on the proton can be probed by studying the hypernucleus-production cross sections for various excited states in DWIA as they are sensitive to the specific kinematical region at very small kaon angles. This kinematical region is not well understood either from the experimental nor the theoretical side as is shown in Fig. 1. Direct measurement of the elementary cross section is problematic and the lack of data do not allow thoroughly testing models for zero kaon angles. This results in a wide range of model predictions as seen in Fig. 1.

In Fig. 1 predictions from the isobar and Regge-plus-resonance models are compared with data for photoproduction (CLAS [12], LEPS [13], SAPHIR [14]), and electroproduction (E94-107 [15] and Brown72 [16]). For \( \theta_K < 30^\circ \) dynamics of the models is not well determined yet. In general, the models group into three different variants. The isobar model with hadronic form factors (H2 [17]) is strongly suppressed at zero \( \theta_K \) which is ruled out by a comparison of the hypernucleus cross sections as predicted by H2 with experimental data [18, 19]. On the other hand, the isobar model without the form factors (SLA [8]) is consistent with the hypernucleus cross sections [18, 19] and

\[
p(\gamma, K^+)\Lambda
\]

\[W = 2.24 \text{ GeV}\]

\[d\sigma/d\Omega \quad [\mu b/sr]\]

\[\theta_K^{c.m.} \quad [\text{deg}]\]

Figure 1: Cross section of photoproduction of strangeness as function of the \( K^+ \) scattering angle. See the text for details.
also with the measurement of the elementary electroproduction cross section in Hall A \[15\] and the older measurement published in \[16\] (Brown72 in Fig. 1). The hybrid models based on the Regge and isobar formalisms, the old version RPR-2007 \[20\] and our recent fit RPR, predict a flat angular dependence below 30° which is quite consistent with the photoproduction data, see Fig. 1.

The E94-107 data reported in Fig. 1 were measured at JLab’s Hall A using 3.777 GeV electron beam with central values of \( W = 2.2 \ GeV \) and \( Q^2 = 0.07 \ (GeV/c)^2 \) \[18\] which are very similar to those for Brown72 data, \( W = 2.17 \ GeV \) and \( Q^2 = 0.18 \ (GeV/c)^2 \) \[16\]. The measured cross sections for electroproduction are higher than for photoproduction, hence it is possible that, although at a low \( Q^2 \), longitudinal and interference response functions could strongly contribute to the cross section.

Precise measurements of the energy and angular dependence of the cross sections in the kaon electroproduction on the proton in the very small kaon-angle region, e.g. using liquid-\( H_2 \) or waterfall target, would help in determining the forward angle dynamics of the process.

2.1 Experimental Equipment in Hall A

The CEBAF accelerator at JLab delivers very high intensity continuous electron beam to its experimental halls. This condition is a mandatory requirement for electroproduction of strangeness due to its small cross section. In addition, the very good energy spread and the precise determination of the absolute central energy of the CEBAF beam allow high-quality spectroscopy of hypernuclei.

In Hall A, the detector \[21\] is based on the two-arm High-Resolution-Spectrometer (HRS) having a momentum resolution of \( 10^{-4} \) which is sufficient for obtaining energy resolution of few hundreds of keV in missing mass spectroscopy. In order to increase the counting rates, scattering reactions at low \( Q^2 \) have to be performed, hence the electron scattering angle has to be as small as possible and the kaon direction must be close to the direction of the virtual photon. These conditions mean that small scattering angles correspond to larger counting rates. Since the standard setup of HRS has a minimal angle to the beam axes of 12.5°, two superconducting septum magnets \[22\] were added to the experimental setup in order to allow electron scattering angle and kaon angle as small as 6°, corresponding to \( Q^2 = 0.08 \ (GeV/c)^2 \) in the kinematics adopted for E94-107 \[18\]. At such forward angle the background of \( \pi^+ \) and \( p \) in the \( K^+ \) arm is huge, requiring an excellent particle identification (PID). For this purpose the standard PID of HRS in the hadron arm was improved adding a RICH detector \[23\].

2.2 Electroproduction of Hypernuclei in Hall A

Experiment E94-107 used \( ^{12}C \) and \( ^9Be \) solid targets and a waterfall target in order to study respectively the \( ^{12}C(e, e'K^+)^{12}B \), the \( ^9Be(e, e'K^+)^{9}Li \), and the \( ^{16}O(e, e'K^+)^{16}N \) reactions. Detailed analysis of the \( ^{12}B \) excitation energy spectrum and \( ^{16}N \) binding energy spectrum are found respectively in \[18\] and \[19\]. The analysis of \( ^{9}Li \) energy spectrum is not yet finalized: with respect to what reported in \[24\] a fine correction for radiative effects has been performed, Fig. 2 shows the effect of this correction. The Monte Carlo code SIMC \[25\] has been used for this purpose: once the simulated data fit well the experimental data, then the radiative effects in SIMC are turned off and the ratios between simulated data with no radiative effects and simulated data including radiative effects are the bin-by-bin correction factors for the experimental points.

Fig. 3 shows a preliminary \( ^{9}Li \) excitation energy spectrum corrected for the radiative effects. Since the DWIA calculations predict five states, a five-peak gaussian fit (thick black curve) is performed on the data points, with the only constraint of having the same width for the five peaks. The
Figure 2: Correction of radiative effects on preliminary $^9\Lambda Li$ excitation energy spectrum. The black points are the experimental data, the gray curve represents simulated data including radiative effects, the histogram represents simulated data with no radiative effects. See text for details.

resulting width for the five peaks is 570 keV (FWHM), then the histogram of the predicted values is obtained assuming the same width for the theoretical expectations (thin line).

Figure 3: Five-peak gaussian fit on preliminary $^9\Lambda Li$ excitation energy spectrum corrected for radiative effects. Data points are reported with their statistical errors, the black-filled histogram represents the systematical errors, the thin-black-line histogram represents the expectations from the theoretical model [7], the thick black curve is a fit of the experimental data as explained in the text.
Fig. 4 shows the same data as in Fig. 3 but a different fit is calculated. Indeed in this case the five-peak gaussian fit is constrained by the model: the separation and the relative amplitude of the individual levels composing the first and the third peak (doublets) are fixed according to the theoretical expectations. In other words, this fit corresponds to a three-peak fit where the internal structure of the complex peaks is determined by the theory. As well as for Fig. 3, the width of the five peaks is constrained to be a single value, resulting here in 760 keV (FWHM).

According to this preliminary analysis, the position of the peaks and the amplitude of the first doublet are in good agreement with the model, the amplitude of the excited states are instead underestimated by the theoretical predictions. However, the analysis of the data is still ongoing.

Figure 4: Same as Fig. 3 in case of constraining the fit according to the theoretical model. See text for details. For the theoretical histogram the width of 760 keV (FWHM) was used contrary to 570 keV in Fig. 3.

3 Future Prospects

For further studies of electroproduction of strangeness at JLab, a Letter of Intent (LoI 12-003) has been submitted to the Physics Advisory Committee (PAC39) and a new proposal is planned for the 12 GeV era at JLab. The future experiments will be performed in one experimental Hall only and the collaboration joining the previously independent Hall A and Hall C groups is studying the most favorable setup.

One scenario is the installation of the High-resolution Kaon Spectrometer (HKS) in Hall A as $K^+$ arm. With the addition of two new septum magnets a setup similar to what used for E94-107 could be realized with the advantage of larger acceptance and smaller fraction of decayed $K^+$ in the spectrometer, which mean larger counting rates. With respect to E94-107, the kinematics should be adjusted in order to fit the new CEBAF specifications and the angular and momentum acceptance of HKS. The design of two new septum magnets and the definition of the optimal setup is under
an investigation and a proposal will be submitted accordingly, including also the study of the angular
dependence of the elementary electroproduction of strangeness which would add data points in the
unexplored region of Fig. 1. This study was already approved and tentatively scheduled (experiment E07-012) but it did not run in the 6-GeV era of JLab due to the incoming shutdown of the
accelerator for the upgrade.

In the case of using a waterfall target, a simultaneous study of the angular dependence of the elec-
}troproduction of $^{16}_ΛN$ and elementary production could be performed. In addition, at very forward
angles the ratio of the hypernuclear (calculated in DWIA) and elementary cross sections at the
same kinematics should be almost independent of the used elementary amplitude, therefore the
ratio contains direct information on the target and hypernuclear structure, production mechanisms
and, possibly on the modification of the dynamics of the $p(e,e'K^+)$ process in the nuclear environ-
ment.

The future experiments might have sufficiently high counting rates to allow the study of medium-

![Figure 5: Expected excitation energy spectrum for $^{208}_ΛTl$, calculations performed by M. Sotona for the E94-107 kinematics.](image)

heavy or even as heavy hypernuclei as what could be produced on thin $^{208}Pb$ target. Very pre-
liminary estimations of the counting rates of $^{208}_ΛTl$ energy spectrum assuming a realistic setup in
Hall A have been performed, based on the cross section reported in Fig. 5. The calculations show
that energy spectrum with statistics comparable to what is reported for example in [18] might be
obtained in few weeks.

4 Conclusions

The systematic study of hypernuclear spectroscopy by electroproduction of strangeness performed
at Jefferson Laboratory has been very successful and has provided important elements for a better
understanding of the baryon-baryon interactions and production mechanism in strangeness physics. The planned study of angular dependence of the elementary electroproduction of strangeness in the very forward angular region is still not performed and it will be proposed again for the 12-GeV era. Furthermore, the possibility of investigating the structure of $^{208}$Tl is under evaluation.

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