High resolution hypernuclear spectroscopy at Jefferson Lab, Hall A: The experimental challenge

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Abstract. The E94-107 experiment in Hall A at Jefferson Lab has started a systematic study of 1p-shell hypernuclei. Data have been taken on C-12, Be-9 and O-16 targets. The counting rate for hypernuclear electroproduction decreases dramatically as the scattering angle increases. Therefore, the electron scattering angle has to be as forward as possible to get high virtual photon flux and kaon angle has to be as close as possible to the virtual photon direction to minimize momentum transfer. In order to allow experiments at very forward angle in Hall A, two superconducting septum magnets were added to the High Resolution Spectrometers (HRS). The two magnets bend particles scattered at 6° into each HRS, introducing only a small perturbation on the HRS optics thus preserving the excellent momentum resolution of the HRS. With the new setup a momentum resolution of 10^{-4} FWHM on both HRS arms was obtained. One of the challenges of the experiment at very forward angle is the identification of very small peaks in the missing-energy spectrum; this requires a powerful Particle Identification (PID) system that provides unambiguous kaon selection.

PACS. 29.30.Aj Charged-particles spectrometers: electric and magnetic – 29.40.Ka Čerenkov detectors

1 Introduction

Experiment E94-107 at Jefferson Lab, Hall A, performed high resolution hypernuclear spectroscopy on three 1p-shell target. The experiment faced two main issues [1,2].

The implementation of two septum magnets were needed in order to reach scattering angles as low as 6° up to the maximum momentum of each spectrometer with no degradation in the optical properties.

Moreover, unambiguous kaon identification is needed for hypernuclear spectroscopy esperiments; TOF and Aerogel Čerenkov threshold detectors, constituing the standard PID detectors in Hall A, are not sufficient due to the huge background of pions and protons at very forward angles. For this issue, a RICH detector was built and added to the PID system in the hadron spectrometer.

2 High resolution spectrometer optics

The septum magnets were manufactured by BWTX Technologies under contract with INFN, Sezione di Roma. With the septa in place the target is moved 80 cm upstream from its normal position at the Hall A pivot.

The best direct measurement of the momentum resolution in the $^{12}C(e,e')$ elastic scattering data shown in [4], yielded a FWHM of 2.5×10^{-4}. The difference between the design value and the measured value has been calculated to be due to multiple Coulomb scattering in the path between the carbon target and the spectrometers' wire chambers.

During the Hall A hypernuclear experiment, the HRSs were vacuum coupled to the scattering chamber, dramatically reducing the material between the target and the wire chambers. Furthermore, the measurement was made

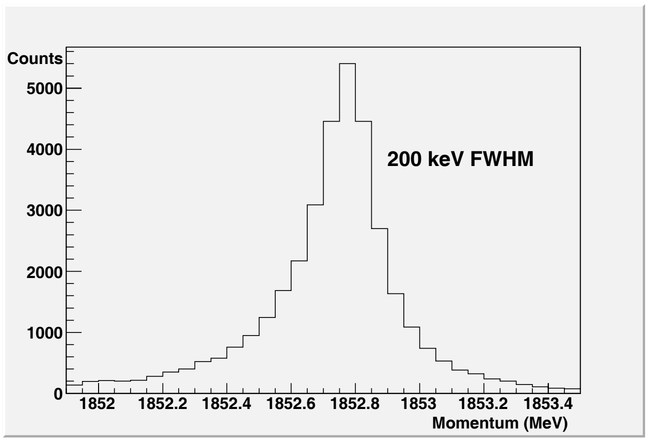

Fig. 1. Momentum resolution obtained with Tantalum target (Left Arm).

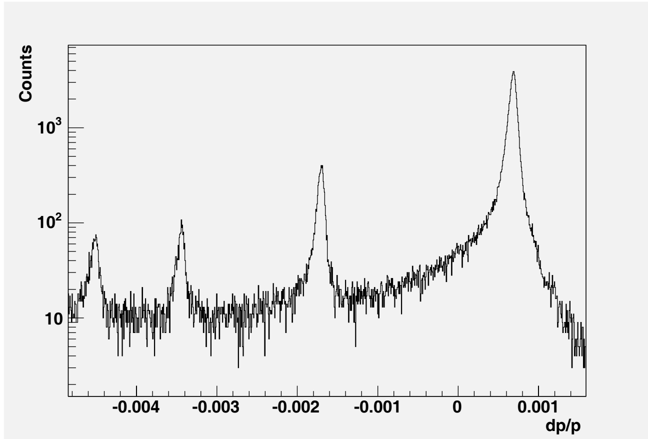

Fig. 2. Reconstruction of momentum elastics peaks on Carbon target. The relative momentum dp/p with respect to the central momentum setting (1852 MeV) of the spectrometer is reported here, an offset calibration and sign inversion would be needed to obtain the carbon excitation energy (reported elsewhere in these proceedings).

at a beam energy of 1852 MeV and a scattering angle of 6°. For the new calibration of the transport matrix, Data were taken not only with two different thicknesses of carbon, 100 mg/cm^2 and 10 mg/cm^2, but also with a 100 mg/cm^2 tantalum target. Due to tantalum's significantly larger mass it has relatively little recoil compared to carbon, making it an excellent choise for calibration.

For the determination of the new optics matrix elements, only tantalum elastic data were used; eight different momentum settings were combined in order to cover the momentum acceptance of the spectrometers. Fig. 1 shows the reconstruction of momentum (Hadron Spectrometer) at the end of the optimization procedure for the central momentum setting. Once the matrix elements were optimized, using a dedicated C++ code [5], the separation of carbon excitation levels were used to check the quality of the matrix elements (Fig. 2). The resolution of all peaks are in agreement with 10^{-4} FWHM resolution. During all of these measurements, the Jefferson Lab accelerator division took great care to maintain both the beam energy spread and the absolute beam energy stability to a FWHM of much better than obtained momentum resolution of 1×10^{-4}, demonstrating the achievement of the designed momentum resolution of the two spectrometers.

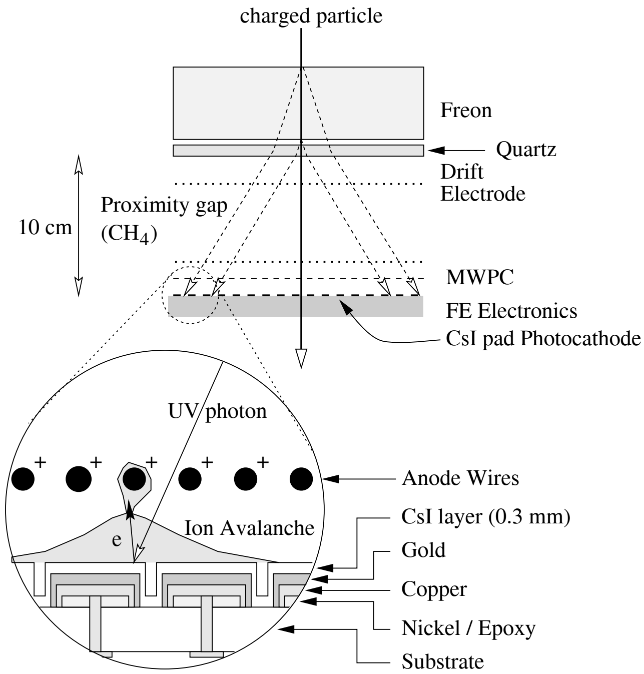

Fig. 3. Sketch of the proximity focusing RICH at JLab and its working principle.

3 RICH detector

The design of the RICH for Hall A has been based on the ALICE-HMPID (High Momentum Particle Identification) RICH [3]. The RICH discriminates particles by differentiating between different values of Čerenkov emission angle. The Čerenkov 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 element, which could be either focusing with a spherical or parabolic mirror or not focusing (proximity focusing), onto a photon detector that converts photons into photoelectrons with high spatial and time resolution (Fig. 3). In our case the proximity focused geometry was chosen because a focusing RICH would not match the space available in the Hall A detector package. The Čerenkov 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 GeV) are refracted by the freon-quartz methane interfaces and strike a pad plane after traveling through a 100 mm proximity gap filled with methane. The JLab RICH hardware is extensively described elsewhere [6–8].

The RICH particle identification algorithm can be essentially summarized in the following items:

– Locate clusters and charged particles (Minimum Ionizing Particle, MIP)
– Cluster resolution
– Single-photon Čerenkov angle calculation
– Particle hypothesis based on a χ^2 test
– Average Čerenkov angle calculation for single particle in combination with the χ^2 test to identify the particle.

3.1 Cluster and MIP location

The first step of the RICH analysis is the identification of the clusters in the pad plane. A cluster is defined as a group of contiguous pads firing in the cathode plane. A cluster is made by only one pad if all the contiguous pads have no signal. In this first step, it is assumed that, without any noise, each cluster but one corresponds to a Čerenkov photon. The exception is the cluster that is generated by the charged particle itself. This cluster, the MIP, usually is the largest and has the biggest charge, since it corresponds to an average signal of nearly 20 photoelectrons.

The positions of the points where the photons and the paricle hit the pad plane are identified by the center of gravity of the charges making up the clusters. The MIP is identified calculating the interception point between the particle track and the RICH pad plane. The maximum charge cluster inside a defined radius R around this point is assumed to be the MIP. The value of R is a free parameter in the RICH database. An option in the RICH database allows identification of the MIP directly from the particle track. This option is applied only when the MIP hits the RICH in a insensitive zone.

3.2 Cluster resolving

In the second step of the analysis the clusters are "resolved". This means that sometimes two or more photons have signals that partially overlap. The result in the pad plane is one single cluster. Usually a cluster created by more photons can be identified because it has a charge distribution with several relative maxima. The number of the maxima is equal to the number of the original photons. There are different methods to resolve clusters. The resolving method used in our RICH code assigns to each elementary cluster, that makes up a not resolved one, a charge proportional to the charge of the corresponding relative maximum. Other more complex and time-consuming methods will not improve our results due to the low cluster density in the pad plane and the consequent low number of overlapping clusters, that is $\sim 10\%$.

3.3 Single-photon Čerenkov angle calculation

Knowing the relative position of the clusters (including the MIP) in the RICH pad plane and the direction of the particle track with respect to the normal to the RICH, it is possible to calculate, for each cluster, the Čerenkov emission angle of the corresponding photon. The algorithm, based on a geometrical backtracking, is described elsewhere [3]. The photon signals giving a reconstructed angle not compatible with possible values with respect to the charged particles crossing the RICH are considered noise and not included in the particle hypothesis.

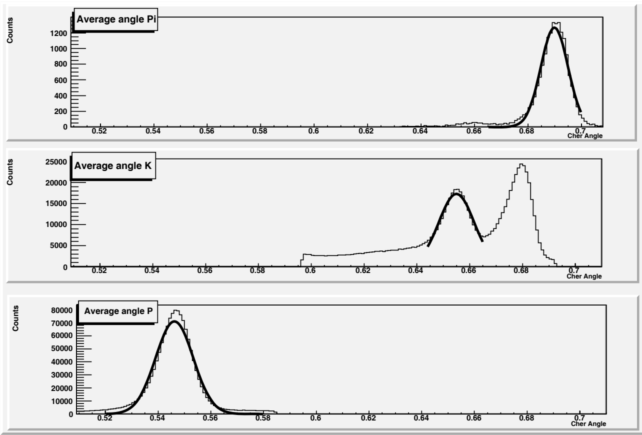

Fig. 4. Performance of average Čerenkov angle reconstruction, for the three particle hypotheses. Up: Pion hypothesis, angle resolution is 5.0 mrad. Central: Kaon hypothesis, the second peak at higher angle reveals the pion contamination surviving the kaon selection of threshold-Cherenkov detectors. Angle resolution is 5.5 mrad. Down: Proton hypothesis, angle resolution is 8.5 mrad.

3.4 Particle hypothesis based on the χ^2 test

The standard method calculates, for each event, the averages of the single Čerenkov photon angles inside three "fiducial zones", one for each particle hypotesis (proton, kaon or pion) (Fig. 4). Since the single-photon angles are gaussian distributed, the sum:

$$\sum_i \frac{(\theta_i - \theta_{p/k/\pi})^2}{\sigma^2} \tag{1}$$

where

- θ_i is the single photon Čerenkov angle
- $\theta_{p/k/\pi}$ are the expected Čerenkov angles for the three particles,
- σ is the standard deviation of the single photon distribution,

is expected to follow the χ^2 distribution. Using equation (1) the whole single-photon distribution is analyzed, not only its mean as is the case with a method simply employing the mean Čerenkov angle. For the same reason, the sum 1 is extended to the OR of the three fiducial zones, just not to loose any piece of information "a priori" and to try to select the most likelihood hypothesis on the particle to identify.

Equation (1) provides three χ^2 values, one for each hypothesis on the type of particle. It is then possible to evaluate which hypothesis for the particle is acceptable. If all of the three χ^2 values correspond to a very small probability, an iterative procedure is performed to exclude up to n photons from the sum (1) until at least one of the three χ^2 values correspond to a probability larger than ϵ, where n and ϵ were set to 3 and 0.01 respectively for the analysis of the E94-107 experiment.

3.5 Average Čerenkov angle calculation combined with the χ^2 test

The three χ^2 values of (1) could be affected by clusters generated by noise which could leave none of them with a reasonable confidence level. A 95% confidence level was used in our analysis. Therefore a combination of the Average Čerenkov angle and the χ^2 calculation is used to completely identify the particle.

3.6 Conclusion

New experimental devices in Hall A at Jefferson Lab, two superconducting septum magnets and a proximity focusing RICH detector, have proven to be very effective for high-resolution hypernuclear spectroscopy. The RICH detector provided excellent kaon identification and a clean kaon signal over a huge background of pions and protons. A pion rejection factor of 1000 has been achieved [6]. Forward angle, 6°, experiments reaching the design momentum resolution of 1×10^{-4} can be performed using the septum magnets. This excellent momentum resolution is obtained using new matrix elements of the optics database, determined using a dedicated tantalum target during the commissioning of the second part of experiment E94-107 at Jefferson Lab.

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