Chapter 2 Experimental Setup

2.1 Overview

Jefferson Lab is located approximately twenty miles up the James River in Newport News, Virginia. The facility consists of, among other things, an electron accelerator and three experimental halls, which are ingeniously named A, B, and C. Hall A contains two high resolution spectrometers used to detect particles scattered by a fixed target. Electrons can be delivered to all three halls simultaneously. They are initially accelerated to 45 MeV at the injector site (Figure 2.1). From there they pass through a linac where they acquire another 400 MeV. Next, they travel through a 180° turn in the recirculation arc and accelerate an additional 400 MeV as they pass down a second linac. The electrons can now be delivered to any or all of the experimental halls, or they can enter a recirculation arc that returns them to the first linac. If returned, the electrons pick up an additional 800 MeV before going to a Hall or transported for another pass. Up to five passes are allowed for a maximum electron energy of nearly 6 GeV. The 400 MeV acceleration for each linac section is a nominal amount. It can be adjusted to deliver a variety of energies.

Experiment E94-010 (*Measurement of the Neutron (3He) Spin Structure Function at Low* Q^2 *: a connection between the Bjorken and Drell Hearn Gerasimov sum rules.*) was conducted in Hall A. It used beam energies of 0.860, 1.720, 2.591, 3.384, 4.255, and 5.070 GeV at currents ranging from 3μA to 15μA. The electrons were longitudially polarized, and their helicity was flipped at a rate of 30 Hz. The fixed target was a 40 centimeter long glass tube filled to 10 atmospheres of polarized ^{3}He. The two spectrometers were configured with detector packages designed to detect scattered electrons. The experiment ran from September 25 through Christmas Eve of 1998

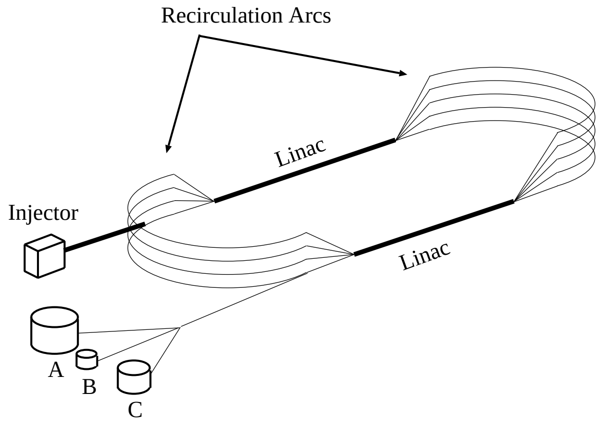

Figure 2.1: Accelerator configuration.

and recorded approximately five and a half billion scattered electron events.

2.2 Polarized Electron Beam

2.2.1 Beam Source

Jefferson Lab's source of polarized electrons is based upon the source used at SLAC [37]. It utilizes a strained GaAs cathode to create highly polarized electrons. The cathode is created by growing layers of various GaAs combinations (Figure 2.2). The top-most layer is pure GaAs. The layer below it is made of $GaAs_{0.72}P_{0.28}$. The shorter lattice spacing of the $GaAs_{0.72}P_{0.28}$ (5.5968 Å) causes the natural spacing of the GaAs (5.6533 Å) to shrink slightly, creating strain [38]. The stain creates a gap in the different sub-levels of the $P_{3/2}$ electrons in the valence band of the GaAs. By tuning a circularly polarized laser to the proper frequency, electrons from the $P_{3/2}$ m= 3/2 state can be excited to the $S_{1/2}$ m= 1/2 level of the conduction band (Figure 2.2). From there the polarized electrons diffuse to the surface and escape into the surrounding vacuum. Because the strain creates a sufficiently wide gap between the $P_{3/2}$ sublevels, electrons from the m=1/2 state will not be excited by the tuned laser. The consequence is the electrons leaving the surface of the cathode are nearly 100% polarized.

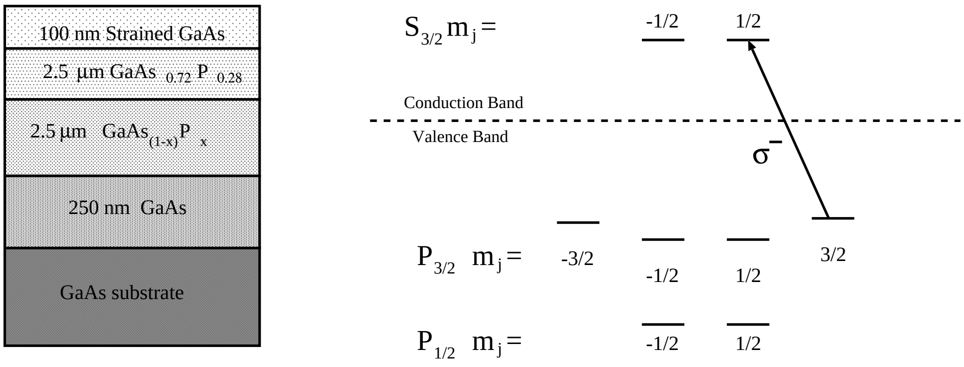

Figure 2.2: The layers of the strained GaAs cathode and the level diagram of the conduction and valence bands.

2.2.2 Møller Polarimeter

Precision measurements of the electron beam polarization were conducted using the Hall A Møller polarimeter [39]. The name "Møller" refers to the scattering of two electrons. For our case, the scattering process was polarized, namely $\vec{e} + \vec{e} \rightarrow e + e$. The scattering cross section depends on the angle at which the two electrons scatter and the polarizations of the beam and target electrons:

$$\sigma \propto 1 + \sum_{i=x,y,z} (A_{ii}(\theta_{CM}) \cdot P_{targ\ i} \cdot P_{beam\ i}), \tag{2.1}$$

where $i = x, y, z$ refer to the the projections of the polarizations, θ_{CM} is the center of mass scattering angle, and $P_{targ(beam)}$ is the polarization of the target (electron beam). If the beam is taken to travel along the z direction and the scattering occurs in the xz-plane, then A_{ii} takes the following form:

$$\begin{aligned} A_{zz} &= -\frac{\sin^2\theta_{CM} \cdot (7+\cos^2\theta_{CM})}{(3+\cos^2\theta_{CM})^2}, && (2.2)\\ A_{xx} &= -\frac{\sin^4\theta_{CM}}{(3+\cos^2\theta_{CM})^2}, && (2.3)\\ A_{yy} &= -A_{xx} && (2.4)\end{aligned}$$

Measurement of the longitudinal component of the electron beam polarization depends on A_{zz}, which has a maximum value of 7/9 for a center of mass scattering angle of 90°. By measuring the number of electrons scattered when the beam is polarized parallel and anti-parallel to its momentum direction, the following asymmetry is formed::

$$A = \frac{N^{\uparrow\downarrow} - N^{\uparrow\uparrow}}{N^{\uparrow\downarrow} + N^{\uparrow\uparrow}} = A_{zz} \cdot P_{targ\ i} \cdot P_{beam\ i}, \tag{2.5}$$

where $N^{\uparrow\downarrow(\uparrow\uparrow)}$ are the counting rates of the scattered electrons when the beam polarization is anti-parallel (parallel) to the target's spin direction. The transverse components, A_{xx} and A_{yy}, can yield a small asymmetry if the target electrons have a spin component in the yz-plane. However, for a center of mass scattering angle of 90°, the value of A_{xx} is 1/9, so this effect is somewhat suppressed.

The Møller polarimeter for Hall A used a 12 μm thick supermendur foil (Fe plated onto a Cu foil) for its target. Due to boundary conditions, the foil is polarized along its length [40]. It was tilted at angles ranging from 20 to 160° with respect to the beam, making the effective target polarization $P_{targ\ z} = P_{foil} \cdot \cos\theta_{target}$. The angle was determined visually by looking at the target with respect to an engraved scale on the target holder and by comparing the counting rates at different angles. The foil was magnetically saturated using two Helmholtz coils, which produce a magnetic field of about 300 G along the beam at the target center. Out of 26 electrons, 2 per atom are polarized in the iron, translating into a polarization of P_{foil}=7.6%.

The Møller spectrometer is comprised of three quadrupole magnets and one dipole magnet followed by two detectors consisting of scintillators and lead glass counters (Figure 2.3). The two spectrometers were set to record events occurring in coincidence with one another. The angular acceptance of the spectrometers ranges from 76° to 104° in the center of mass frame. For incident energies less than 1 GeV the angular acceptance is between 83° and 97°. Taking into account these acceptances, the average value of $< A_{zz} >$ was 0.759 as determined by a Monte-Carlo simulation.

Twenty-six Møller measurements were taken during the E94-010 experiment. Mea-

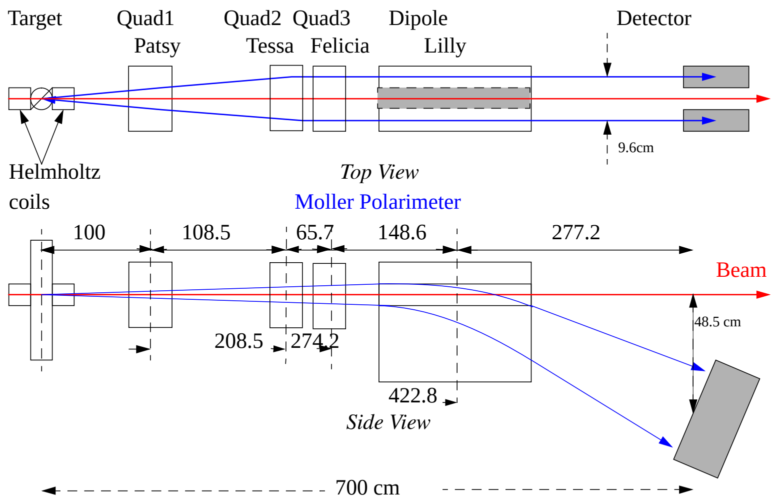

Figure 2.3: Schematic of the Hall A Møller polarimeter.

surements were taken with the target angle at 25 and 155° in order to understand effects due to transverse polarization within the foil and to study the target angle by comparing the counting rates. Several runs of ~30k events were taken at each angle. The background and Møller peak were fitted to obtain $N^{\uparrow\uparrow(\uparrow\downarrow)}$. The fit took into account the Levchuk effect [41]. This effect is due to the fact that the unpolarized Fe atom electrons are contained in the inner atomic shells. They have a higher momentum and momentum spread and therefore broaden the elastic peak compared to the polarized (outer shell) electrons. This systematic effect was taken into account by correcting the apparent beam polarization down by 2% relative. The results with statistical error bars are shown in Figure 2.4. Also given are the polarization results used for each beam energy.

The systematic uncertainties are listed in Table 2.1. Polarization of the target is given by $P_{target} = P_{foil} \cdot \cos\theta_{foil}$. The angle θ_{foil} is known to $\pm 0.4°$ which contributes

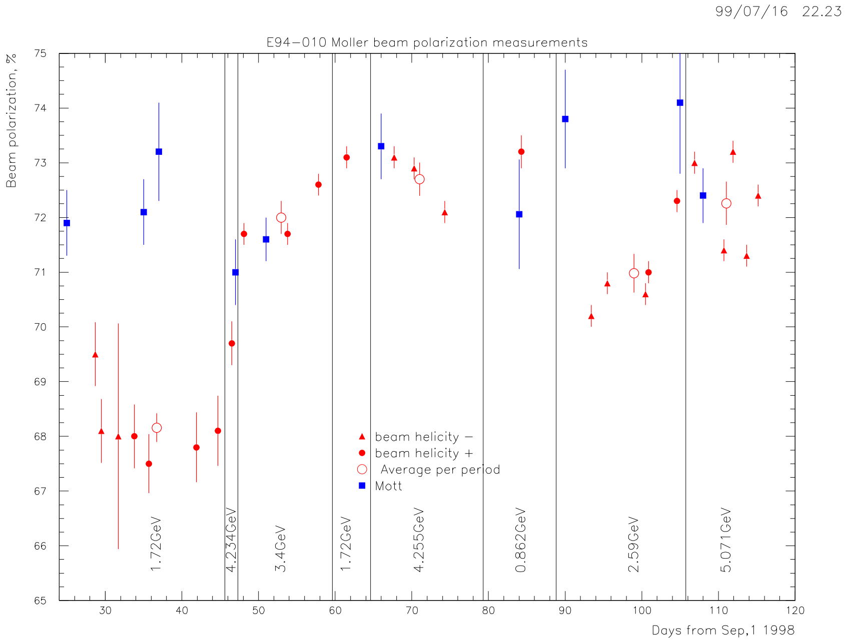

Figure 2.4: Results of the Mott and Møller measurements.

0.3% to the uncertainty of P_{target}. The polarization of the target foil is given by

$$P_{foil} = B_{foil}\frac{g'-1}{2\pi g'}\frac{1}{N_e\mu_e}, \tag{2.6}$$

where g' is a spin-orbital correction for supermendur and is equal to 1.900$\pm$0.005 [39] (this uncertainty contributes negligibly to the uncertainty in P_{foil}), N_e is the number of electrons per unit volume, and B_{foil} is the field within the foil. B_{foil} is given by $\Phi \cdot$ width $\cdot$ thickness, where Φ is the applied magnetic flux and was determined by varying the external field and measuring the induced EMF in a coil wound around the foil. From systematic studies, maximum deviations in Φ of $\pm$1.5% were observed. The foil thickness is uniform to within $\pm$1.0%. Taking this and the flux into account, a $\pm$2.0% uncertainty is placed on P_{foil}. Background counts make up about 50% of the data but contribute an uncertainty of less than 1% after subtraction. The deadtime

Source	**Uncertainty** [%]
$< A_{zz} >$	0.3
P_{foil}	2.0
θ_{foil}	0.5
Background	<1
Deadtime	<2
Transverse Polarization	0.2
Other fluctuations	1.0
Total	**3.2**

Table 2.1: Systematic uncertainties on P_{beam}.

correction contributed an uncertainty of ~2%. Having taken data at two complementary angles, the uncertainty in the observed asymmetry due to transverse components of polarization was extracted and found to be ±0.2%. The total uncertainty from the beam polarization is taken to be $\pm 0.5\%_{stat} \pm 3.2\%_{syst}$.

2.2.3 Beam Current Monitors

The accumulated electron beam charge that the target sees was recorded using two Beam Current Monitors (BCMs). A BCM is a resonance cavity tuned to the frequency of the electron beam: 1497 MHz. When the beam passes through the cavity it excites the TM_{010} mode. A large wire loop inside the cavity detects the changing magnetic field (Figure 2.5). The amplitude 1497 MHz signal produced by this loop is proportional to the beam's current.

The BCM signal was recorded in two ways. The first method converts the output amplitude into a DC voltage proportional to the original amplitude. This voltage is recorded every 4, 10, and 50 seconds by a VME crate. The second method converts the DC voltage signal into a sine wave whose frequency is proportional to the DC voltage. This sine wave is continuously recorded by a scaler counter.

Calibration of the BCMs was conducted in two ways. Relative changes were measured by using a second excitation loop located within the BCM. A current source

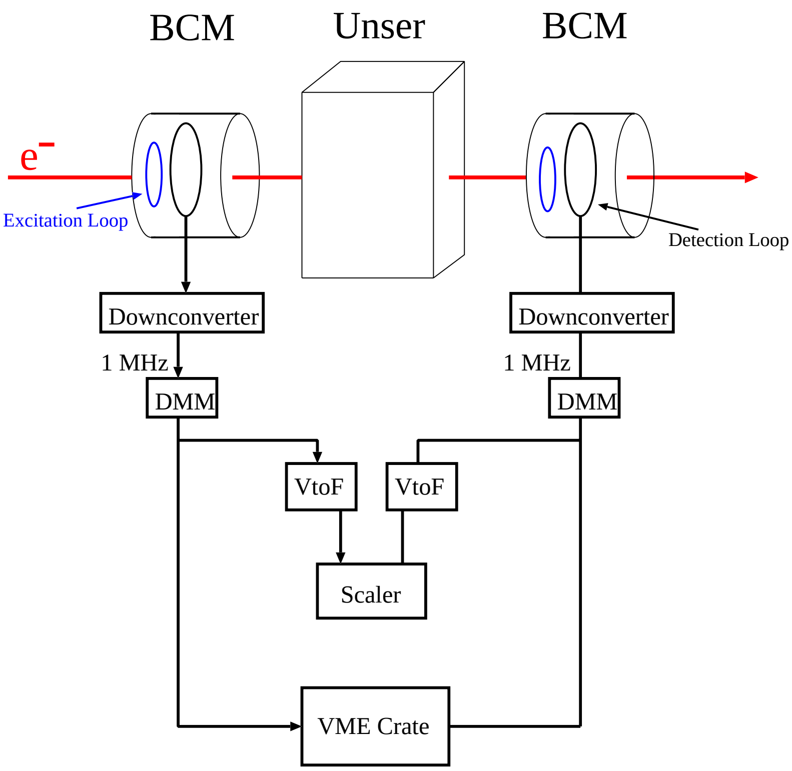

Figure 2.5: Schematic of the beam monitoring device.

sends a 1497 MHz signal into the excitation loop. By measuring the response of the detection loop, relative changes were recorded. Absolute calibration is conducted using an Unser device [42]. The device sits between two BCMs, see Figure 2.5, and uses two identical toroidal cores. Opposite currents are passed trough the cores by an external modulation source. A common sensing wire that is wound around both coils detects a zero voltage when there is no beam current passing through the center of the toroids. However, when a DC current is present it creates an asymmetry in the amount of flux within the cores, and a signal can then be recorded with a common sensing wire. By using a wire that is located along the beam path and a high-precision current source, the electron beam can be simulated, and the Unser calibrated. Once the Unser is calibrated the beam is turned on and the BCMs are calibrated using the Unser. Using this method a calibration value was calculated to convert the scaler response of the BCMs to the amount of charge incident upon the target. This number had an uncertainty on the order of $\pm 1\%$ coming primarily from the non-linearity in the BCM response.

2.2.4 Beam Position Monitors

The beam position at the target was monitored using Hall A's beam position monitors (BPMs). They consisted of four antennae situated around the beam in a diamond pattern. The antennae pick up the signal from the fundamental frequency of the beam (1497 MHz). The strength of the signal in a particular antenna is inversely proportional to the distance between the beam and that particular antenna. By combining the signals from all four antennae, the beam location is reconstructed. At a current of 10 μA (typical for this experiment) the beam position was resolved to ± 20 μm. The two BPMs used to determine the location of the beam on the target were located 1.3 and 7.5 meters upstream of the target platform (Figure 2.6).

Fast Raster

A fast raster located 23 meters upstream of the target steers the beam to create a profile of a 3mm diameter disk on the target. By knowing the current pattern of the magnets in the raster and by recording the position of the beam using the BPMs, the position of the beam is steered and determined to ± 0.1 mm in the beam's y-direction and $\pm$ 0.3 mm in the beam's x-direction. Overall location of the beam was kept to within ± 0.5 mm of the target center.

2.2.5 Beam Energy

For the E94-010 experiment, three independent methods were used to measure the energy of the incident electrons [43]: by measuring the electron trajectory in a B-field (Arc Energy), by electron-proton scattering, and by electron-^{3}He elastic scattering.

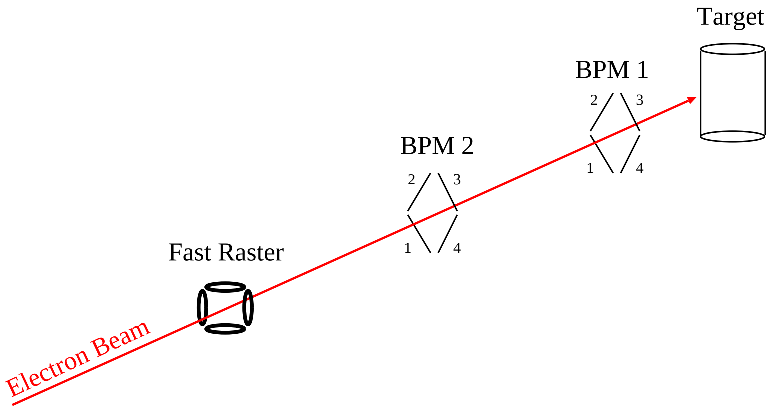

Figure 2.6: Relative positions of the BPMs and Fast Raster.

The Arc Energy method used the principal that an electron in a magnetic field moves in a circular pattern, the radius of which depends on the strength of the magnetic field and the electron's energy. Before electrons enter Hall A, they pass through a 34.3° bend: see Figure 2.7. The energy of these electrons is determined by the following relation: $E = c\frac{\int B_\perp \cdot dl}{\theta_{||}}$, where $B_\perp$ is the magnetic field perpendicular to the electron motion, dl is the path length of the electron, and $\theta_{||}$ is the angle by which the electrons are deflected. Precise knowledge of the beam's entrance to and exit from the bend is given using two sets of superharps. A superharp is a set of three wires that are spaced evenly apart. The superharp is moved across the beam path. When the beam strikes a wire, a current is generated and the beam's position is recorded. This information, along with the knowledge of the magnetic field, allowed for the determination of the electron's energy to a precision of $\Delta p/p$ to $\pm 2\times 10^{-4}$.

A second method used for the energy determination involved the scattering of an incident electron by a proton: p(e,e′p). The carbon target (CH_2) and detectors for this measurement were located 21.7 meters upstream of the target. For elastic scattering, the angles of the scattered electron and proton determine the energy of the incident electron:

$$E = M_p(\cot\frac{\theta_e}{2} \cdot \cot\theta_p - 1). \qquad (2.7)$$

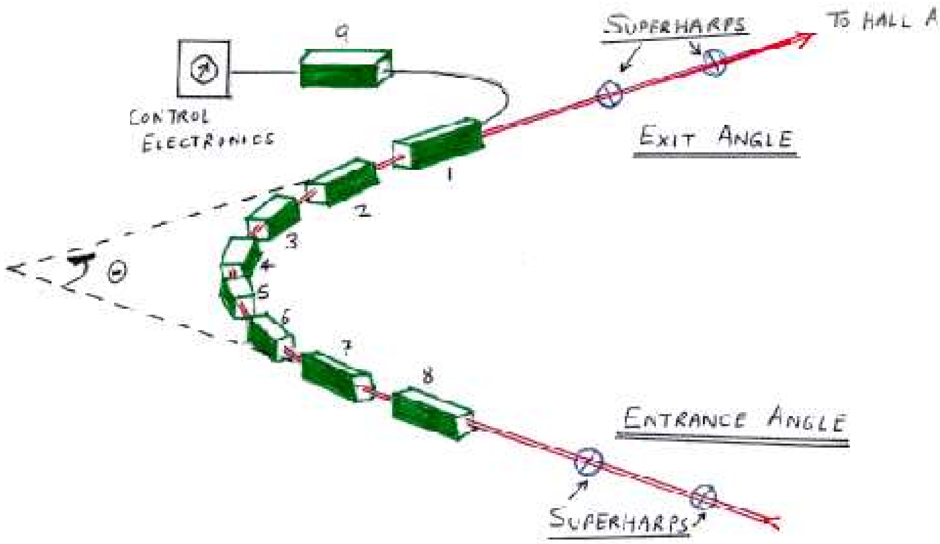

Figure 2.7: The Arc Energy device for Hall A.

Here $\theta_{p(e)}$ is the proton (electron) scattering angle and M_p is the proton mass.

The eP measuring device, as it's known in Hall A, consists of Cerenkov chambers, scintillators, silicon microstrips, and a CH_2 target, see Figure 2.8. An electron entering the eP device is scattered by a proton and then triggers a scintillator. The scattered proton is detected first with a microstrip (a plate of silicon that gives precise knowledge of the location of a particle passing through it) and then a set of scintillators. The scattered electron passes through a microstrip, then a scintillator, and then through a Cerenkov chamber. The Cerenkov light is detected by a phototube. Coincidence signals from the electron and proton scintillators define an event. Knowledge of the beam position and information from the microstrips allows for a calculation of the electron and proton scattering angles, from which the electron's incident energy can be calculated. The eP device has an energy resolution of $\Delta p/p = 1\times10^{-4}$.

A third method used to measure the incident electron's energy comes from elastic

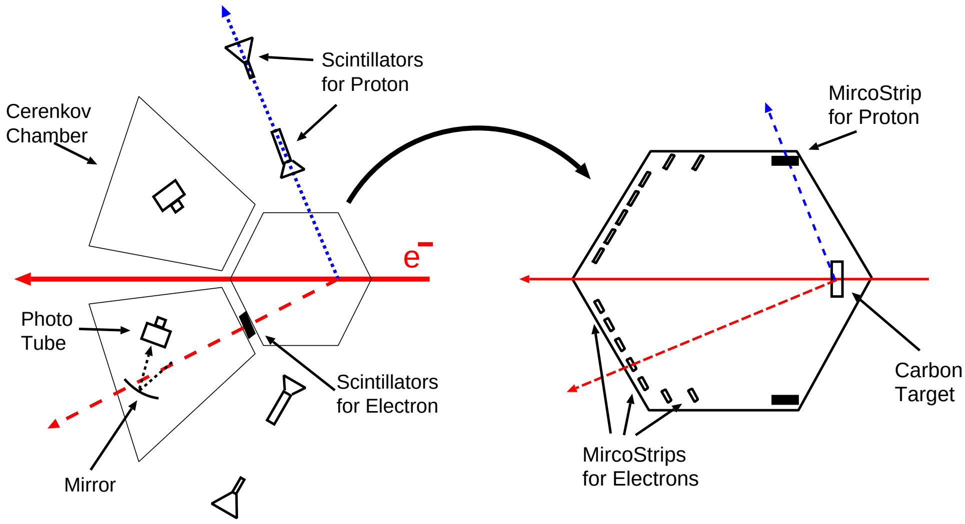

Figure 2.8: Schematic for the eP measuring device.

scattering by ^{3}He. The incident energy is given by

$$E = E'(1 + \frac{2E}{M_{^3He}} \sin^2 \frac{\theta}{2}), \tag{2.8}$$

where E is the incident energy and E is the energy of the scattered electron. By knowing the strength of the dipole field (γB [MeV]) and the spectrometer dispersion coefficients (d [m^{-1}]), one can determine the energy of the scattered electron. The equation $E = \gamma B[1 + \sum_{i=1}^{2} d_i x^i_{fp}]$ relates these quantities and the focal plane position (x_{fp} [m]) to the scattered energy (E). This measurement is limited by the uncertainty in the dispersion coefficients. Energy measurement made using this technique had an uncertainty of $\pm 3 \times 10^{-3}$.

Results for the three methods are shown in Table 2.2.

2.3 The Hall A Spectrometers

The detection of scattered electrons was conducted using Hall A's two high resolution spectrometers: the HRSH (High Resolution Spectrometer Hadron) and the HRSE

Nominal [GeV]	Arc [GeV]	eP [GeV]	Elastic [GeV]
0.860	-	-	0.8595
1.720	-	1.7179	1.715
2.500	2.5811	-	-
3.385	3.3850	3.3818	-
4.225	4.2362	4.2386	-
5.071	5.0555	-	-

Table 2.2: Energy measurements.

(High Resolution Spectrometer Electron). Each arm is approximately 26 meters long and 25 meters high, and both can be positioned at any angle between 12.5 and 165° relative to the beam line, see Figure 2.9. The scattered electrons first pass through a collimator ($\sim$ 121mm$\times$63mm). The collimator was used to reduce the number of electrons entering the spectrometer originating from the target windows. The electrons then pass through four magnets. The first two are quadrupoles which focus the electrons in the vertical and transverse planes. The third magnet is a dipole which deflects the electrons 45° towards the ceiling. It has a central momentum range from 0.3 to 4 GeV/c with a momentum acceptance per setting of $\Delta p = 0.1$ and a resolution of $\Delta p/p \cong 10^{-4}$. The final quadrupole magnet de-focuses the electrons in the transverse direction. Next, the electrons enter the detector package (Figure 2.10) consisting of two planes of vertical drift chambers, a plane of scintillators, a gas Čerenkov detector, a second plane of scintillators, a lead glass pre-shower (HRSE arm only), and finally a lead glass shower counter.

2.3.1 Scintillators and Triggering

The two scintillator planes (S1 and S2) were responsible for triggering on electron candidates. Each plane consists of six scintillator paddles which overlap by 0.5 cm each (Figure 2.10). The active area of S1 is approximately 170cm $\times$ 35cm, and the active area of S2 is about 220cm $\times$ 54cm. There is a single photo-multiplier (PM)

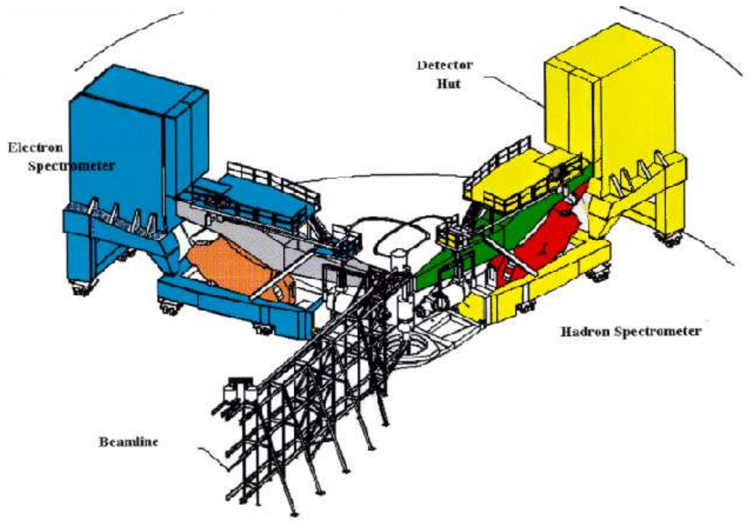

Figure 2.9: Hall A.

located at each end of a paddle. The PM signal is read out by an Analog-Digital Converter (ADC) and a Time-Digital Converter (TDC).

A signal in the two scintillators is considered a candidate when the following three conditions are satisfied. Both photo-multipliers on a paddle receive a signal. The signal from S1 and S2 are in coincidence. And the paddle on S2 corresponds to the paddle on S1 with some angular acceptance ($\pm$ 1 paddle on S1 and S2). A second type of event was also recorded when two of the three detectors, S1, S2, or Čerenkov (Section 2.3.3), fire. Most of these second type of events were junk. They were used to study the efficiency of the detectors.

2.3.2 Vertical Drift Chambers

The scattered electron's trajectory is a key element in determining its energy and in reconstructing its vertex at the target. Located in front of the other detectors and after the third quadrupole, two vertical drift chambers (VDCs) were used to measure the electron's trajectory [44, 45]. Each VDC is a panel of crisscross wires measuring

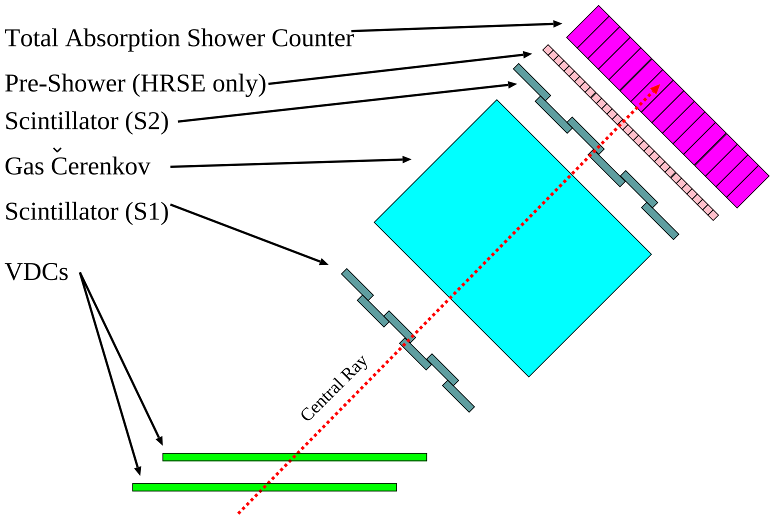

Figure 2.10: Detector package used for the E94-010 experiment.

211.8 cm × 28.8 cm. The panels are parallel to the Hall A floor. The scattered electron passes through the panels at 45° (Figure 2.11).

The wires form two planes: one U and one V. The U and V planes are perpendicular to one another. The VDC wires are enclosed between two Mylar windows. A voltage drop of -4kV was held between the windows and the enclosed wires. The gas between the windows consists of an equal mixture of argon and ethane. Each plane contains 368 wires made of gold-plated tungsten each with a diameter of 20 μm.

When an electron passes through the VDC chamber the gas along its path is ionized. The free electrons then accelerated towards a signal wire. As the electrons approach the wire they gain sufficient kinetic energy to ionized other gas atoms, creating more free electrons. This process continues, creating what is called an avalanche. As the electrons finally collide with the wire, they create a signal which is fed into a TDC and an ADC. The ADC and TDC are used to determine when the greatest number of avalanche electrons are hitting the wire. The time at which the electron passed through the VDC is given by the TDC connected to the scintillators. Knowledge of the drift velocity and the TDC signal from the signal wire yield the distance from the wire at which ionization first occurred. The resolution on the electron's

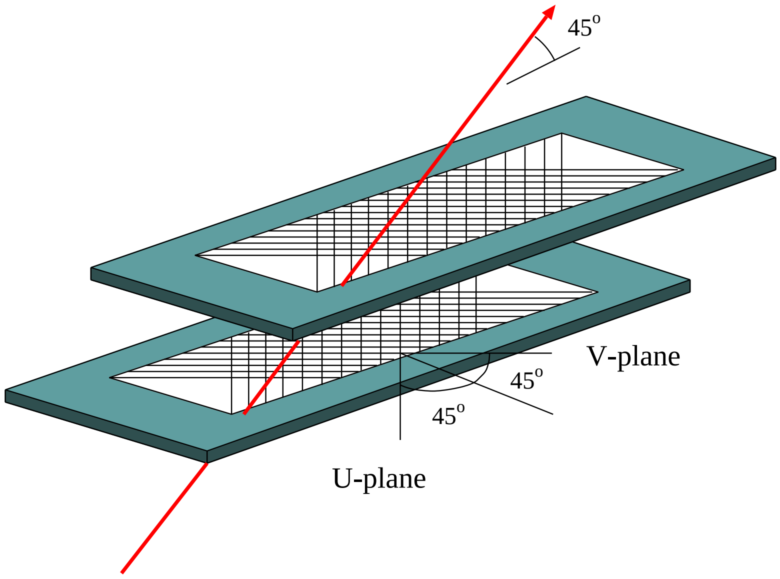

Figure 2.11: Schematic of VDC wire planes. Each plane has 368 signal wires.

position is approximately ± 200 μm.

2.3.3 Gas Čerenkov

A gas Čerenkov was employed in both the HRSE and HRSH in order to discriminate between electrons and pions. Čerenkov counters rely upon the fact that particles moving faster than the speed of light ($\beta > 1/n$), in a particular medium, will emit Čerenkov light [46]. This light is emitted in a cone at an apex angle given by $\theta_c = \cos^{-1}(1/(\beta n))$. By selecting a gas with the correct index of refraction, the term $1/(\beta\text{n})$ will be less than one for electrons (real value for θ_c) and greater than one for pions (imaginary value for θ_c). Therefore, light will be emitted when an electron passes through, but not for a pion.

The Hall A Čerenkov detector [47] (Figure 2.12) is a rectangular tank measuring approximately 2×0.56 m on the entrance window and 1.5 m along the electron path. The tank was filled with 1 atm of CO_2, which has an index of refraction of n=1.00041. Electrons emit Čerenkov light if they have a minimal energy of 0.017 GeV. Pions

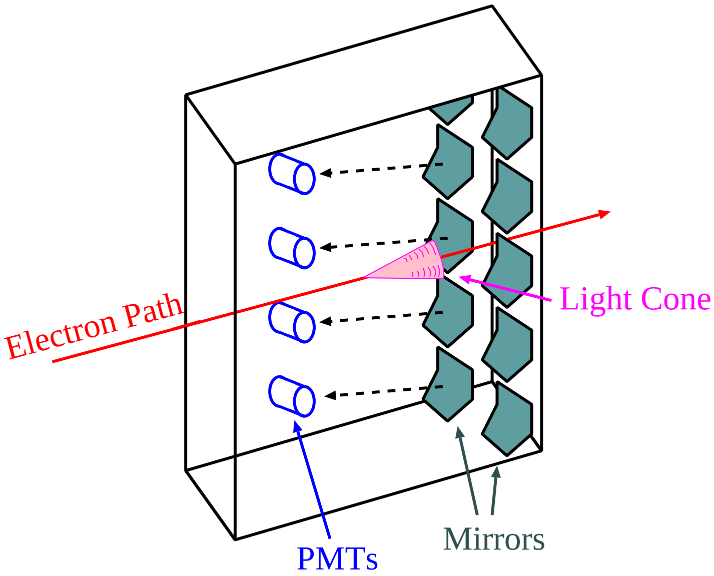

Figure 2.12: The CO_2 gas Čerenkov detector.

require an energy of at least 4.8 GeV to emit Čerenkov light. Since the spectrometers have a maximum momentum acceptance of 4.0 GeV, no pions in principal should be observed in the Čerenkov detector. Light from the passing electrons is collected by ten spherical mirrors located in front of the exit window of the detector. Each mirror reflects the light towards a particular photo-multiplier tube (PMT): see Figure 2.12. The electron detection inefficiency was found to be less than a few parts per thousand throughout the experimental run [48].

2.3.4 Shower Detector

The Hall A shower detector was used in conjunction with the Čerenkov detector to reject pions. When an electron passes through material it emits Bremsstrahlung radiation [44] along its path. This radiation creates secondary particles (γ,e$^-$,e$^+$) which, in turn, create still more particles. The result is a cascade of particles which is eventually converted to light and heat. The total amount of light emitted is proportional to the scattered electron's energy. A properly calibrated shower detector has an energy

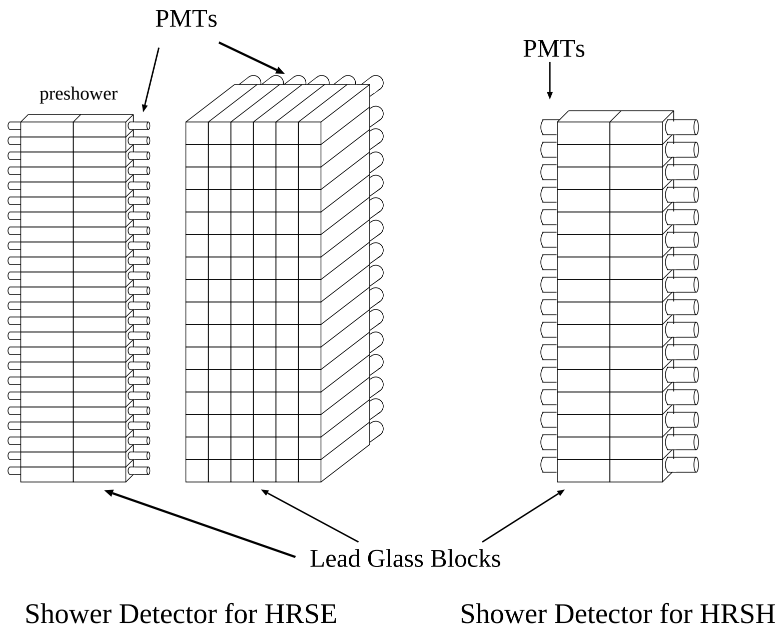

Figure 2.13: The configurations of the HRSE and HRSH shower detectors.

over momentum (E/p) ratio of one for electrons. Pions do not deposit as much energy as electrons and have an E/p ratio less than one; therefore, selection of electron can be based upon an event's E/p ratio.

The HRSE shower detector consists of two layers (Figure 2.13). The first layer, called the pre-shower, is made from 48 (24×2) blocks of TF-1 lead glass. Each block measures 10×10×35 cm. The pre-shower's total number of radiation lengths is 3.65 [49]. Here a radiation length refers to the distance an electron, on average, travels before its energy is reduced by a factor of 1/e. The second layer is made from 96 (16×6) blocks of SF-5 lead glass. The blocks measure 15×15×35 cm each, and the total number of radiation lengths is 15.2 [49]. Attached to the ends of the glass blocks are PMTs to collect the light.

The HRSH shower counter was installed specifically for the E94-010 experiment. It consists of 32 (16×2) SF-5 lead glass blocks (Figure 2.13). The total radiation length is approximately six.