Status Report on Activities in Hall A - 2001

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1 The Facilities

1.1 Optics Commissioning (Contributed by N. Liyanage)

1.1.1 Spectrometer optics

The spectrometer optics data taken in December 99 showed that the excitation history of Q2 and Q3 magnets had a noticeable effect on optics. The most affected matrix elements were \(\langle y|y\rangle\) and \(\langle \delta|\theta\rangle\). This affected the transverse position and momentum resolution. The reconstruction of the horizontal and vertical angles was found to be insensitive to these effects. As a result of the hysteresis effects on the spectrometer optics a new magnet cycling procedure was introduced for Q2 and Q3 magnets. Use of this cycling procedure ensures that the spectrometer optics properties are unchanged at a given momentum.

A complete calibration data set was obtained using the new cycling procedure. The analysis of this data set was completed this year and databases were obtained to cover the full momentum range of both high resolution spectrometers. These databases should cover the requirements of all future Hall A experiments that do not use the septum magnets. Future experiments need only take a minimal optics calibration data set to check the existing databases and to obtain the detector offsets.

1.1.2 Absolute momentum determination

The constant \(\Gamma\) for a spectrometer relates the central momentum measured by the spectrometer \((P_0)\) to the central magnetic field \((B_0)\). The spectrometer constants of the HRS pair were known only to about \(2 \times 10^{-3}\). The precision beam energy measurements using EP and Arc have made it possible to measure the spectrometer constants much more accurately. Data necessary for the calculation of \(\Gamma\) were collected between 07/99 and 11/00 accompanied by beam energy measurements [1].

We used two methods to calculate \(\Gamma\). Both methods involved scattering electrons from a thin \(^{12}\)C target. The energy loss inside such a thin target is negligible compared to the measured energies. Furthermore, due to the relatively high mass of the \(^{12}\)C nucleus, target recoil energy is negligible. As a result, these measurements were rather insensitive to spectrometer angle measurements.

The two methods used were:

1. The direct method, where we measured elastic scattered electrons from \(^{12}\)C accompanied by a beam energy measurement to directly calculate \(\Gamma\) for that spectrometer,

2. The indirect method, where we measured the missing energy of the \(lp_{1/2}\) state in \(^{12}\)C\((e,e'p)\) coincidence data. We then used this information with
the already measured spectrometer constant of one spectrometer to derive \( \Gamma \) for the other spectrometer.

These measurements allowed the calculation of spectrometer constants over the full momentum range of the HRS pair with an accuracy of \( 5 \times 10^{-4} \). \( ^{12}C(e,e'p) \) data accumulated over 15 months show that these constants are stable at this level.

### 1.1.3 Scattering angle determination

The scattering angle between the incident electron and the scattered particle is calculated by combining \( \phi_{tg} \) and \( \theta_{tg} \) (measured relative to the central ray of the spectrometer) and the spectrometer central angle \( \theta_0 \) between the beam line and the spectrometer nominal central ray. Thus, the accuracy of the scattering angle determination depends on the accuracy of \( \phi_{tg} \) and \( \theta_{tg} \) relative to the nominal central ray of the spectrometer. The accuracy of \( \phi_{tg} \) and \( \theta_{tg} \) with respect to the central sieve-slit hole is better than 0.2 mrad. However, the accuracy of the central sieve-slit hole angle with respect to the spectrometer nominal central ray remains at the 0.6 mrad level due to limitations in the surveys required to determine this angle:

- target position
- spectrometer central angle
- displacement of the spectrometer nominal central ray from the hall center
- position of the sieve-slit center with respect to the nominal central ray
- position of the beam position monitors with respect to the ideal beam line.

However, once the central sieve-slit hole angles are calibrated relative to the nominal central ray, this uncertainty is expected to remain a constant systematic offset to the scattering angle at the level of stability of the nominal central ray as determined by the magnetic objects of the spectrometer. A series of kinematically over-determined \( H(e,e'p) \) measurements combined with precision beam energy measurements has been used to determine such a constant offset in the scattering angle [2]. A first set of such measurements has indicated that it is possible to correct constant offsets to achieve a 0.2 mrad accuracy in the measured scattering angles. A series of such measurements has been performed over the past year to test the stability of the corrections obtained using this method. The analysis of the data will indicate the scattering angle precision achievable over an extended period of time for the Hall A HRS pair.
1.2 Spectrometers (Contributed by J.J. LeRose)

1.2.1 Septum Magnets

The septum magnet project continues to be plagued by delays in manufacturing. As of this writing the manufacturer, Babcock and Wilcox X-Technologies (BWXT) of Lynchburg (Virginia), anticipates delivery of the first magnet to JLab in late April or early May of 2002. Implications for the experimental schedule are still being evaluated.

1.2.2 Spectrometer News and Information

Maximum momentum for the Right Arm is 3.169 GeV/c. This was established in April '01 with administrative limits in place.

Maximum momentum for the Left Arm is: 4.3 GeV/c. This was established after some work on the quadrupole power supplies in October '01. Performance at 4.13 GeV/c will be evaluated by EO0-102 which will take data during October and November '01.

Hall A survey reports, including spectrometer pointing, are now being posted on the world wide web. (see:

http://hallaweb.jlab.org/news/minutes/Survey_Reports/Survey_Reports.html)

1.2.3 Spectrometer Optics Mailing List

In order to promote cooperation between various experiments and experimenters working on spectrometer optics questions, a subscribeable e-mail mailing list has been formed for discussions involving spectrometer optics. (halla_hrs_optics@jlab.org) To subscribe send an e-mail to majordomo@jlab.org. The first and only line in that message should be “subscribe halla_hrs_optics” (without the quotes).

1.2.4 Spectrometer Optics Technical Notes

During the past year two JLab technical notes on spectrometer studies have been submitted. One, JLab-TN-01-025, by Paul Ulmer [6], deals with acceptance studies via white spectrum scans. The other, JLab-TN-01-052, by Lubomir Pentchev [65], deals with quadrupole misalignment studies.

1.2.5 Spectrometer Optics Models

Spectrometer models have not changed over the last year. References for forward and reverse transfer functions can be found at

These functions are being used in various Monte-Carlo routines to simulate spectrometer performance.

For acceptance cuts R-functions are now available, see:

http://www.jlab.org/~lerose/r-functions/r-function.html

for a more detailed discussion. These R-functions are based on the transfer functions referenced above and provide a convenient way to make software cuts that optimally use most of the acceptance of the spectrometers. A cut of $R > 0$ includes all trajectories that would have fallen inside the acceptance of the "model" spectrometer. Since the model is not perfect, and never will be, a cut of $R > 0.001$, for example, would include all trajectories at least 1 mrad inside the solid angle acceptance for any given $y_0$ and $\delta$. 
1.3 Simulations (Contributed by P.E. Ulmer)

Hall A Monte Carlo Simulator: MCEEP

Considerable progress has been made in the past few years on the Hall A Monte Carlo program, MCEEP [3]. The program has now reached the sophistication required to make detailed comparisons of theory with experiment.

The magnetic and aperture models for the Hall A high resolution spectrometers were incorporated [4]. Based on this spectrometer model a set of “R-functions” [5] was developed. Through these functions, a multi-dimensional contour in the space of the variables is traced back to the target, and defined at some specified distance from a pre-defined boundary. All events outside this contour can be rejected thus cutting out the poorly understood acceptance edges in a more efficient manner than with ordinary “rectangular” cuts.

As a test of the aperture/magnetic model of the spectrometers, a series of “white” spectra was scanned in overlapping steps across the focal plane of each spectrometer [6]. This was done by making small variations of the magnetic fields and acquiring (prescaled) single-arm data for each spectrometer. An iterative procedure was used to determine the shape of the cross section as well as the relative spectrometer acceptance as a function of the dispersion, δ. This relative acceptance was compared to the simulated phase space. Both data and simulation were obtained using the $R$-function cutting method. The results (after applying overall vertical scale factors) are shown in Fig. 1. Within the vertical bars, defined by $\delta = \pm 3.5\%$, the agreement is essentially perfect. Although these results are encouraging, this method of cutting still results in significant data loss. It would therefore be desirable to improve the spectrometer model to allow looser cuts. An alternate, COSY [7] based, Hall A spectrometer model which was recently incorporated into the Hall C simulation program ("sinc") is currently being ported into MCEEP.

Radiative effects, both internal and external, were added as well as effects of ionization energy loss and multiple scattering. This allows for accounting of the scattering chamber and spectrometer windows as well as the target material and walls, based on realistic Hall A cryogenic target models and including beam rastering effects and effects of spectrometer mispointing and beam centroid offsets/ resolution smearing. However, the energy loss calculation was recently found to have significant discrepancies [8] with respect to GEANT [9] as reflected by the average value integrated from zero to the endpoint. This discrepancy results in an underestimate of the missing mass resolution, for example, and needs to be investigated further. One solution, which avoids a debugging of the existing MCEEP energy loss routines, would be to incorporate the relevant subroutines from GEANT into MCEEP. Though several users have expressed interest in this possibility, no effort has yet been applied in this direction.

A comparison between data and MCEEP was made for $^2\text{H}(e,e'p)n$ (the data were taken as part of experiment E94-004). The simulation includes all the above
mentioned effects and also uses the same $R$-function cuts as for the white spectrum scans. The coordinates traced back to the target are shown in Fig. 2. As can be seen, the agreement is quite reasonable.

To deal with the multitude of recoil polarization experiments in Hall A, ejectile spin precession, based on output of COSY [7], was added to MCEEP. In conjunction with this, various additional polarization weighted histograms have been added.

Numerous theoretical models have been added including elastic scattering form factors for the nucleon and a variety of nuclei, various $(e,e'p)$ spectral functions, and interpolators for state-of-the-art theories for $(e,e'p)$ reactions from the deuteron and $^4$He.

This program along with documentation can be downloaded from the Web [10]. MCEEP is currently supported under the Linux (g77, Absoft f77), Sun, HP, OSF1 (Alpha) and the DEC-Ultrix operating systems.

Figure 1: The relative spectrometer acceptance as a function of $\delta$ extracted from data compared to the MCEEP simulation. The top panel is for the electron (left) arm, the bottom for the proton (right) arm. Within the vertical lines at $\delta = \pm 0.035$ the agreement is essentially perfect. The differing slopes of the spectrum shown for the electron (left) arm compared to that of the proton (right) arm is due to a difference in spectrometer angles, and consequently the target viewing angles, at which the two spectra were acquired.
Figure 2: Target coordinates for the electron="left" (top panel) and hadron="right" (bottom panel) spectrometers. The data are for $^2H(e,e'p)n$ at $p_r = 0$ and were obtained during experiment E94-004. The solid histograms are for the data and the dashed for MCEED. An overall normalization factor was applied to each curve to give the same integral for data and MCEED.
1.4 Møller Polarimeter (Contributed by E. Chudakov)

The Hall A beam line is equipped with a Møller polarimeter, whose purpose is to measure the polarization of the electron beam delivered to the hall. During the period from Oct. 1, 2000 to Sept. 30, 2001, 18 measurements of the beam polarization have been made, including a spin-dance measurement in September, 2001. The systematic error of each measurement is estimated to be about 3% relative, while the statistical error is about 0.3%.

Several new supermendur target foils have been manufactured and studied. The target foil magnetization measurements are in progress in order to understand better the foil polarization and thereby reduce the systematic error.

1.5 The Compton polarimeter (Contributed by F. Marie)

1.5.1 Introduction

This Compton polarimeter status report deals with the final results of the electron beam polarization measurements during N-Δ (May-July 2000) and $C_{E_{1}}^{0}$ (November-December 2000) experiments. We present here the major analysis improvement leading to the unprecedented level of uncertainty of 1.4% relative of the beam polarization, as developed by Stephanie Escoffier who defended her PhD thesis on October 19, 2001.

We also report on the data taking during $A_{1}^{h}$ and $g_{2}^{h}$ experiments in summer 2001 and will present very preliminary results.

1.5.2 Major Analysis Improvement: Photon Calorimeter Response Function

![Graph showing response function of photon calorimeter](image)

Figure 3: The response function of the central crystal of the photon calorimeter for a 200 MeV incident photon. The experimental ADC distribution is shown, along with a fitted function for the response.
One of the major improvements of the Compton polarimeter data analysis since the HAPPEX measurements is the determination of the response function of the central crystal. For coincidence runs, this response function is determined using the electron detector where each strip (650 μm) defines a narrow energy band (∼ 5 MeV). For a given scattered electron energy (i.e. scattered photon energy) the central crystal ADC spectrum is fitted (see Fig. 3) with a function which reproduces the asymmetrical behavior of the deposited energy distribution and the low energy tail. The response function allows thus to determine without ambiguity the probability that a photon of a given energy is detected in the calorimeter.

For all the runs taken in “photon only” acquisition mode, the ADC spectrum is fitted with the theoretical Compton cross section convoluted with the response function calculated as described above from coincidence runs. Possible gain fluctuations can be thus taken into account (see Fig. 4)

![Figure 4: Response of the photon calorimeter in “ photon only” acquisition mode. The fitted line is a convolution of the theoretical Compton cross section and the calorimeter-crystal response function.](image)

1.5.3 Results and Error Budget (for N-Δ and $G_E^p$ periods)

Polarization measurements were performed 330 times during the N-Δ experiment, and 110 times during the $G_E^p$ experiment. The results are plotted in Figs. 5 and 6. A 1% relative error, corresponding to common systematic uncertainty, must be added to all these points.

The typical relative uncertainty for a run of 40 minutes is 0.8% statistical and 1.1% systematic, giving a total uncertainty of 1.4%. The contributions of the different sources of errors are presented in Table 1.

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<table>
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<tr>
<th>Error source</th>
<th>typical relative uncertainty (%)</th>
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<tbody>
<tr>
<td><strong>Experimental asymmetry</strong></td>
<td></td>
</tr>
<tr>
<td>Statistical (40 minutes)</td>
<td>0.80</td>
</tr>
<tr>
<td>Positions and angles</td>
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<tr>
<td>Events selection</td>
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</tr>
<tr>
<td>Background asymmetry</td>
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</tr>
<tr>
<td>Dead time</td>
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</tr>
<tr>
<td><strong>Laser beam</strong></td>
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<tr>
<td>Polarization $P_\gamma$</td>
<td>0.45</td>
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<tr>
<td><strong>Analyzing power</strong></td>
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</tr>
<tr>
<td>Modelisation</td>
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<tr>
<td>Energy Calibration</td>
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<td>Radiative corrections</td>
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<td>total systematics</td>
<td>1.10</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>1.40</td>
</tr>
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Table 1: Error budget of Compton polarimeter measurements during the $N$-$\Delta$ and $G_E^p$ experiments.

1.5.4 Electron Detector: Preliminary Results

We have performed a preliminary analysis of the electron detector data during the $G_E^p$ experiment. This second method offers a complementary way of measuring the beam polarization, as most of the systematics are different from the photon detector method (energy calibration, resolution, false asymmetry due to vertical displacement of the electron beam, ...). This method relies on the fit of the theoretical asymmetry with the experimental asymmetries calculated for each strip of the electron detector (see Fig. 7). From the statistical point of view, we found the two methods compatible (see Fig. 8).

1.5.5 Determination of $P_e^+/P_e^-$ Helicity Difference

For the first time it has been possible to measure the polarization difference between the two helicity states of the beam: $\Delta h = \frac{P_e^+ + P_e^-}{2}$, using polarization reversal of the photon polarization and energy dependence of the Compton asymmetry. During $N$-$\Delta$ and $G_E^p$ experiments this quantity has been found to be compatible with zero at the level of 0.3%.
1.5.6 Data-taking During the $A_1^n$ and $g_2^n$ Experiments

In the summer of 2001, the Compton polarimeter ran during the $A_1^n$ and $g_2^n$ experiments. About 100 runs and 10 runs have been acquired during $A_1^n$ and $g_2^n$, respectively. The analysis of these data with the electron detector is still in progress, and will be completed and implemented on-line during early 2002.
Figure 6: Results of beam polarization measurements performed using the Compton polarimeter during the $G_E^p$ experiment. The displayed error bars include statistical and run-by-run uncorrelated uncertainties. The dashed lines represent spot moves at the electron source. Preliminary results from the Moller Polarimeter measurements (with statistical error bars only) have been included for comparison.

Figure 7: Fit of the experimental asymmetry, calculated strip by strip with the electron detector.

Figure 8: Comparison of beam polarization measurements done with the electron detector (black dots) and with the photon detector (white squares).
1.6 The BigBite Spectrometer (Contributed by D. W. Higinbotham)

Update on the Construction of the BigBite Spectrometer

(for the BigBite Working Group)

During the past year, two experiments which will use the BigBite spectrometer were approved by the Jefferson Lab program advisory committee. One is an experiment to study the internal small-distance structure of nuclei via the triple coincidence (e,e'p+N) reaction and the other is a precision measurement of electroproduction of $\pi^0$ near threshold to test chiral QCD dynamics. Jefferson Lab and the collaborators of these two experiments have joined together to build the BigBite spectrometer.

The BigBite spectrometer will have a solid angle acceptance of 96 msr with a vertical acceptance of $\pm 300$ mrad and a horizontal acceptance of $\pm 80$ mrad. The maximum magnetic field strength is 1.2 T, though the nominal working field is 0.92 T due to the large stray magnetic fields which occur as the magnet nears saturation. The spectrometer will also have an extended target capacity of $\pm 10$ cm at 90°.

There are presently two different detector packages being built for BigBite. One is a low-resolution scintillator system, which will use an auxiliary scintillator plane and the segmented trigger planes for particle tracking. This pair of scintillator planes will provide approx. 5% momentum resolution at 300 MeV/c with approx. 10 mrad angular resolution. Since the auxiliary plane will only have one-sided read-out, in this configuration the spectrometer will not be able to determine the reaction vertex. The second detector package will use the same trigger plane along with two multi-proportional wire chambers. The wire-chamber planes are still being designed, but the plan for the chambers is to provide approx. 1% momentum resolution, approx. 3 mrad angular resolution in theta and phi, and 3 mm y-target resolution.

Many groups have already committed to building various parts of the BigBite spectrometer. Eli Piaetzky and the Tel Aviv group have committed to build the auxiliary scintillator plane. John Annand and the Glasgow group have committed to build the trigger plane for the BigBite spectrometer. This plane will be made up of 3 mm and 30 mm scintillating layers to provide dE/E particle identification and will have a timing resolution better than 0.5 ns. Richard Lindgren and the University of Virginia have committed to build a new scattering chamber to be used with the BigBite spectrometer. The new chamber, which will have a higher opening, is needed due to the large out of plane acceptance of the BigBite spectrometer. Nilanga Liyanage and the University of Virginia have committed to build the wire chambers for the BigBite spectrometer. Eric Voutier and the ISN Grenoble group along with William Bertozzi and the M.I.T. Nuclear Interaction Group have both already contributed manpower to the project.
The BigBite magnet is already in the Hall and its power supply has been tested. The auxiliary plane will be shipped to Jefferson Lab early next year and the Tel Aviv group plans to travel to Jefferson Lab in February 2002 to rebuild and test the plane on-site. The Glasgow group is also working towards delivering the trigger plane to Jefferson Lab next year. It is the intention of the group to be ready to test the BigBite spectrometer with the scintillator planes in late 2002 and to run our first physics experiment in 2003. The University of Virginia group is presently seeking DOE/NSF funding to build the wire chambers and the scattering chamber.
Figure 9: Shown is a very preliminary view of how the BigBite spectrometer will be configured for the $^{12}$C$(e,e'pX)$ triple coincidence experiment. This experiment does not require precise momentum information, so scintillator planes will be used instead of wire chambers for particle tracking.
1.7 The Cryogenic Target (contributed by J.-P. Chen)

The Hall A cryotarget system\cite{11} consists of 3 loops: loop 1 is usually for gaseous helium (either $^3$He or $^4$He), loop 2 liquid hydrogen and loop 3 liquid deuterium. The nominal operation conditions are summarized in Table 1.

<table>
<thead>
<tr>
<th>Target</th>
<th>T [K]</th>
<th>p [psi]</th>
<th>$\rho$ [g/cm$^3$]</th>
<th>length [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LH$_2$</td>
<td>19</td>
<td>25</td>
<td>0.0723</td>
<td>15, 4</td>
</tr>
<tr>
<td>LD$_2$</td>
<td>22</td>
<td>22</td>
<td>0.167</td>
<td>15, 4</td>
</tr>
<tr>
<td>$^3$He</td>
<td>6</td>
<td>200</td>
<td>0.081</td>
<td>10</td>
</tr>
<tr>
<td>$^4$He</td>
<td>6</td>
<td>220</td>
<td>0.144</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 2: Nominal working temperatures and pressures of the Hall A cryotarget cells. Also listed are the target densities and cell lengths.

All three loops have been successfully used in a number of experiments. In August and September of 2000, the helium target was upgraded: a new heat exchanger with the proper pipe size for helium was installed. Two experiments after the upgrade used the high power $^4$He target. It worked well for both experiments. Total cooling power was enough for 90 $\mu$A of beam current on 10 cm $^4$He with the target operating at 5.8 K and 15 atm. The total heating from beam was about 340 W and the total cooling power (including to cool the heat from the loop pump and heat loss) was close to 500 W. The density fluctuation was small, typically less than 5 percent at the maximum beam current (with the fast raster size of 4 mm by 4 mm and the loop pump speed of 60 Hz).

The second experiment that used the helium target also used liquid hydrogen and liquid deuterium targets. Target changes were frequent. Target changes from helium to LH$_2$/LD$_2$ and vice versa took 10-15 hours due to the change in cooling line. The helium target used 5 K coolant and the LH$_2$/LD$_2$ targets used 15 K coolant.

The main problem encountered during this period (October 2000 to May 2001) was with target motion. Measurement devices were installed outside the scattering chamber alongside the lifting mechanism, which helped to identify misalignment quickly. However, the problem reoccurred a couple of times.

The cryotarget system was taken back to the target lab while experiments using other targets were running (polarized $^3$He for the summer of 2001 and waterfall target for October to December 2001). It will be reinstalled in January with minimal improvement to be used for two more experiments in early 2002. The first experiment, Real Compton Scattering (RCS), will use two loops. One liquid hydrogen loop with two 15 cm cells, one with a radiator in front of the cell and one without radiator. Another loop with two 15 cm cells will be empty for background study and also serve as a spare for the liquid hydrogen loop. The second experiment, $G_E^p/G_M^p$ with super-Rosenbluth separation, will need only the liquid hydrogen loop with 4 cm cells. To minimize the chance of lifting mechanism
failure, the BeO target, which is needed for checking beam position, will be moved closer to the cryotargets.

An upgrade was planned when the cryotarget will be available for long maintenance. The motion system will be changed to be more robust with one lifter (instead of three as it is now). Pressure readouts will be changed from Sensor Tech units to regular ADCs with proper calibrations. Cells will be changed to machined cells instead of the 'beer' can type (except when experiments need the 'beer' can type, such as the real photon experiments, which can not tolerate the small diameter of the machined cells).

Some experiments require a helium target with increased target length, more cooling power, and less material in the path of the scattered particles. R & D efforts have been going on in new cell design and to increase the cooling power. The Cal-State-LA group made prototypes of new cells 12, 15 and 20 cm long with a race-track shape, which should satisfy the need of the planned high power helium target experiments. The prototype cells were tested to about 450 psi (twice the designed operating condition). Design work is underway to incorporate the new cells into the existing loop.

To increase the cooling power (by up to a factor of two), there are two issues. The first is the total 4 K cooling power available for target cooling from ESR. It depends on the usage of the three halls’ magnets and Hall C’s cryotarget. Reducing the cooling line power leakage (especially in the Hall A magnet lines) would help to make more cooling power available. The second issue is the return line pressure which limits the total cooling power be used for cooling the helium target. Since the two major users of the 4 K cooling power, the Hall A magnets and the Hall A high power helium target, are sharing the same return line, it puts a severe limit to the total cooling power available for cooling the helium target. A possible solution was proposed and discussed at a recent meeting among Hall A, Hall B, Hall C, JLab cryo group and JLab cryotarget group. The proposal calls for a re-distribution of the return lines. In particular, the Hall A magnets cooling and the helium cryotarget cooling will not share a same return line. The solution is being evaluated by the cryo group to make sure it has no adverse effects.

The schedule of the cryotarget upgrade plan and the high power helium target upgrade plan will depend on the experimental schedule which is currently uncertain due to the delay in the Septum magnet delivery schedule.
1.8 The Polarized $^3$He Target (contributed by J.-P. Chen)

The Hall A polarized $^3$He target [12] was built in 1998 and was successfully used for experiments E94-010[13,14] and E95-001[15] in 1998-1999. After this first round of experiments, the target was moved back to the target lab in the EEL building and was upgraded and improved for the next round of experiments. It was then used successfully for E99-117[16] and E97103[17] this summer.

The polarized $^3$He target uses optically pumped Rubidium vapor to polarize $^3$He nuclei via spin exchange. Two kinds of polarimetries, NMR and EPR (Electron-Paramagnetic-Resonance), are used to measure the polarization of the target. They can be checked with a known physics asymmetry, such as the elastic $^3$He asymmetry.

During the first round of experiments, the average target polarization in beam (10-15 $\mu$A) was $\sim 35\%$. Eight target cells were used. Four of them ruptured, probably due to beam radiation damage. With experience learned over the course of running, we tried to improve the running conditions by making sure the fast raster is always on, the beam current is always ramped up, and the cell density (pressure) does not exceed 10 atm. There were no cell ruptures in the last period of running with the improved running conditions. The target polarization was monitored with NMR using Adiabatic Fast Passage (AFP). NMR AFP measurements on water and EPR measurements were used calibrate the $^3$He NMR signal. The target analysis from the first round of experiments was summarized in last year’s status report and also reported in the students’ theses[14]. The two methods of polarization measurements agree with each other very well. The final error on the polarization measurement is less than 4%. The polarization measurements were independently checked by measuring the elastic scattering asymmetry. The ratio of the measured asymmetry to the world data gives a measure of the product of the beam polarization and the target polarization. The deduced target polarization is in excellent agreement with the NMR water and EPR results.

After the first round of experiments, extensive tests were done, mostly by two PhD students K. Kramer and X. Zheng, in the target lab to better understand the system and to improve the target performance. Tests were performed to study the flux distribution, the temperature distribution, the polarization gradients, the field stabilities, various de-polarization effects and noises for NMR water calibrations. Extensive studies were performed to understand the relatively new EPR system to make it reliable. Improvements were made in the EPR optical system so that EPR measurements could be performed remotely from the counting house during experiments (as opposed to the situation during the first round of experiments when EPR measurements could only be performed with an access to the hall). Both NMR and EPR were used successfully and reliably to measure the target polarization during E99-117 and E97-103. Online results are available. Offline analysis is underway.

The eight 30W diode lasers (six for pumping in longitudinal and transverse
directions and two spares) with the Rb wavelength (795 nm) used in the first round of experiments were made by Opto-power. At the time it was the only company which produced the high power 795 nm diode lasers. The company stopped production of the high power 795 nm diode lasers shortly after our first round of experiments. Luckily another company, Coherent Lasers, started the production of high power 795 nm diode lasers. We switched smoothly to the new lasers, which turned out to perform better (more reliable with longer life time). Seven new lasers (six plus one spare) were used for E99-117 and E97-103 running. All lasers survived to the end of the experiments. Most of the lasers have only a small power degradation (down to 28 W), and can be used again for testing and for future experiments.

The target cells were initially all made by the Princeton group (G. Cates). The group moved to University of Virginia last year and continued to produce good cells for the second round of experiments. In the mean time, a second group at William and Mary (T. Averett) started to produce good cells after a learning period. The two groups produced 15 good cells (life time > 30 hours) for the two experiments (E99-117 and E97-103).

With the target lab fully functioning, most of the cells were extensively tested. The best four cells were used in the two experiments. They all have very good life time (above 40 hours for the two 25 cm cells and above 60 hours for the two 40 cm cells) and reached excellent polarization (about 50% without beam and about 40% with 10-15 µA beam). Each of the four cells were used in beam for 3 to 4 weeks. They were replaced after 3 weeks when there was a long maintenance period. Only one cell ruptured, one day before the scheduled replacing time, during the two experiments.

Mechanical modifications were made to accommodate the kinematics requirements for the two experiments as well as to add new features and improvements. The Helmholtz coil mount was re-designed to provide rotation capability. A new motion subsystem with improved target ladder subsystem was manufactured. The reference cell mount and coupling were re-designed. A new RTD mount and wire harness were used for reliable monitoring of the target temperature. Other improvements include easier target alignment and the addition of online monitoring of the laser profile.

The target control system went through a transition. The EPICS control software developed by the polarized 3He collaboration for the last round of experiments was taken over by the JLab EPICS group. New improvements were developed by the EPICS group with help from the polarized 3He collaboration. The EPICS system reads all the RTDs. Added features include the new motion system control, new laser system control, oven control and read-backs for pressure and flow. Also a two way communication was established between EPICS and LabView, which was used for the target polarimetry.

After the successful operation for E99-117 and E97-103, the polarized 3He target was moved back to the target lab. It has been set back up. Further tests
and improvements are just getting underway for the next experiment, E97-117[18],
measurement of the small angle GDH sum rule, which is expected for the fall of
2002.
1.9 Update on Electronics Dead Time (Contributed by R. Michaels)

Robert Michaels, Bodo Reitz, James Proffitt

This is an update on electronics dead time (EDT) measurements which were first reported on in the Year 2000 Annual Report. Some experiments run with rates of several hundred kHz in the scintillators, and therefore one should expect dead times of a few percent. In the past year the two goals have been: 1) to reduce the EDT by reconfiguration of the trigger hardware; and 2) to improve the accuracy and reliability of the EDT measurement.

To reduce the EDT, we tried two things: 1) to avoid using the Memory Lookup Unit (MLU) which may introduce a bottleneck when strobed. The results are discussed below. 2) to reduce the width of the discriminator outputs, but this latter attempt did not work well because reducing the discriminator widths from 100 ns to 40 ns causes too much “after-pulsing”, which are secondary pulses at the trigger supervisor that result from the PMT signals ringing and crossing threshold multiple times. After-pulsing is dangerous if not corrected, since it distorts the DAQ dead time computed from scalers. With standard thresholds and high voltages, the probability of after-pulsing is ≈ 8% for a singles trigger if one uses a 40 ns discriminator output width and this reduces to ≈ 0.1% with 100 ns pulses since most ringing occurs before 100 ns. (Note, these numbers are not known precisely.) One can eliminate after-pulses by increasing the threshold or lowering HV, but this is considered an undesirable reduction in efficiency. Instead, our approach is to leave the widths 100 ns and to put the trigger into a multi-hit TDC to try to measure the probability of after-pulsing.

In Jan 2001 we started running our main trigger without the MLU. Instead, the trigger is formed from an overlap of the scintillator planes S1 and S2 after first requiring 2 PMTs on either end of a paddle in each plane to fire above a discriminator level. Thus, the trigger requires 4 PMTs and no particular angle through the detector stack. One may suffer more background, depending on running conditions, but there is some evidence that this has also reduced the EDT. Comparing to the EDT measurements from Mark Jones' Oct 2000 report (see www.jlab.org/~jones/e97111/report_on_deadtime.ps.gz), Lingyan Zhu's analysis of data from Spring 2001 shows a reduction in the EDT when parameterized as the MLU strobe rate in order to compare to running with an MLU. The MLU strobe rate should not be a relevant parameter anymore, and comparisons between different running periods is fraught with difficulties, but nevertheless there did appear to be a reduction in EDT by at least a factor of two. The preliminary analysis of E00-102 data from Oct 2001 suggests that the EDT is ≈ 100ns × R_{trig} where R_{trig} is the trigger rate, which is now the relevant parameter. Since the trigger rate is usually less than the strobe rate (typically by a factor of 2), we believe we have reduced the EDT by this factor. If the backgrounds are also not bad, then avoiding the MLU is worthwhile. During E00-102, a high rate experiment

28
with the new trigger setup, the pattern of scintillator paddle hits looks like the old “S-Ray” pattern of the MLU trigger; therefore, the background is similar.

The new EDT measurement (EDTM) system was engineered and constructed by James Proffitt of the Jefferson Lab Electronics Group. It was installed on the spectrometers by Bodo Reitz in April 2001. The principle behind the measurement is as follows: we send a well-defined, recognizable pulse into the frontend of the trigger and see if it makes it through to the trigger supervisor, which is the point at which the DAQ is triggered. Also, if the DAQ is alive, the trigger supervisor will accept this pulser trigger and it will show up in the datastream as a tagged event. The fraction of such events that get lost is the dead time correction. Note, one can measure both the electronics and the DAQ dead time separately this way.

The EDTM system sends a pulser signal which looks like a scintillator pulse through the path of four PMT required to make a trigger (left and right on one paddle in S1 and S2). The two spectrometers are simultaneously pulsed, when run in coincidence mode, and this also provides a check of the timing of the trigger. The pulser signals are added to the PMTs signals using an active circuit which preserves the time resolution and low-noise of the apparatus. Each paddle has its dead time measured in turn, i.e. we first pulse paddle 1, then paddle 2, etc up to 6. The pulser is sent to a TDC as a flag, and also the “and” of the pulser and trigger is sent to scalers to measure losses up to this point. The main difference to last year’s one-paddle pulser setup is that now the dead time can be measured differentially across the focal plane. The rate of pulsing an individual paddle is \(\approx 1 \text{ Hz}\) and can be made proportional to the beam current, though at present we only use fixed rates.

To obtain the total dead time of the system (TDT), which to first order is the sum of the computer DAQ dead time (CDT) and the EDT, one observes how many pulses are in the TDC. This is essentially Mark’s and Lingyan’s analysis, see Mark’s report for definitions. In the data, in addition to a loss we see a tail and secondary narrow peaks in TDCs (e.g. the EDT flag) which is presumably caused by pileup in the gate retiming circuit and in the stops. One can extract the EDT by subtracting the CDT calculated in the usual way from the TDT, with some small corrections to avoid double counting and to correct for the fact that the EDTM pulser is not random. One curious result is that at present the scaler measurement of EDT is zero. Probably this is because the nature of the EDT is a pileup condition, not a loss. However, the EDT measured from event analysis using the TDCs is not zero. A code to analyze these data will be made publicly available.
1.10 Hall A Analysis Software (Contributed by J.-O. Hansen)

1.10.1 The Hall A Object-Oriented Analyzer

Progress on the new C++/ROOT-based object-oriented Hall A data analysis software has been steady over the last year. In March 2001, version 0.55 was released which included the first full implementation of the “standard analyzer” algorithm [19]. This version also defined the essential elements of the detector interface and thus allowed collaborators to begin writing prototype detector classes for the project. In particular, the RCS collaboration has developed several such classes for the RCS calorimeter.

In October, version 0.60 was finalized. This release included a large number of important new features:

- Full sets of detector and spectrometer classes, e.g. left and right HRS spectrometers, and scintillator, Cherenkov, shower counter, and wire chamber detectors.
- Support for on-the-fly definition of 1-d histograms.
- ASCII database files with basic support for time dependence.
- Support for fixed- and variable-size arrays of global variables and for global variables of types other than double.
- Support for analysis of scalers.
- Clean-up of the file/tree output routines (*THaEvent*).
- Support for the Sun/Solaris platform.

The protocol for detector initialization was changed significantly for this version in order to support time-dependent database information properly. The time/date of the run being analyzed is now passed to the initialization routines, and it is now possible to re-initialize a detector, for instance to load new calibration constants in case several runs are analyzed sequentially. This implies, however, that detector classes written for version 0.55 require some (minor) modifications to work with 0.60. The interface for detector classes should now be very close to final, and so detector classes written for this version can be expected to work with future releases without significant changes, at least until version 1.00.

The tracking code in version 0.60 is still rather primitive, but better code has already been written and will be included in the next version of the analyzer, expected in December 2001. The VDC code in 0.55 and 0.60 ignores drift time information and uses only wire numbers to calculate track positions and angles. In addition, no target reconstruction is performed. A prototype high-precision wire chamber class, which fits drift times and can handle multiple tracks, was developed in the summer of 2001 in collaboration with a summer intern [20].
Figure 10: Preliminary results obtained with the high-precision VDC tracking code. Shown are the reconstructed focal-plane TRANSPORT coordinates, $x_T$, $y_T$, $\theta_T$, and $\phi_T$. The $x_T$-$y_T$ plane is tilted by about 45° with respect to the actual focal plane, which, in the HRS, lies roughly parallel to the VDC. Blue histograms are results from the C++ analyzer, and red histograms were obtained with ESPACE (from [20]).

Initial results are very similar to those obtained with ESPACE (see Fig. 10). This code is currently being extensively tested.

The next versions of the C++ analyzer can be expected to include:

- **0.65**: High-precision C++ class. Source in CVS.

- **0.70**: Target reconstruction. Several standard Physics classes. More sophisticated standard detector classes (e.g. timewalk corrections, PID). Support for autoconf.

- **0.80**: Full-featured output module, allowing dynamic (on-the-fly) definition of histograms, ntuples, and tree variables. Full support for dynamic cuts/tests.

- **0.90**: Full database interface. SQL database.

Most of this work should be finished by the end of the Spring 2002 shutdown, i.e. by May 2002. A version usable for analysis, i.e. including the main features of 0.70, should already be available by the end of 2001.

Up-to-date information about this project can be found on the Web [20]. Manpower is tight and volunteers are very welcome to join, especially those with a good background in C++ programming.
1.10.2 ESPACE

Over the last year, the main improvements of our current analysis software, ESPACE, were the integration of code for the new burst-mode beam position monitors (BPMs), additional BPM and raster analysis code, and a few useful additions to the ntuple routines.

Since October 2000, three new versions of ESPACE have been released:

- In version 2.9.0 (18 Jan 2001), support for burst mode BPMs was added. The BPM readout mode is automatically selected based on the run date: Runs after 01 Dec 1999 are assumed to have burst mode BPM data. Michael Kuss contributed this code.

- Version 2.9.1 (24 Jan 2001) contains mostly corrections of a number of problems discovered in 2.9.0. DAQ synchronization checks and linking with CERNLIB 2000 on Linux now work correctly, and a compilation problem with beta_calc on Alpha was fixed.

- With version 2.9.2 (17 Jul 2001), the default format of output HBOOK files and ntuples was changed. ESPACE now creates column-wise instead of row-wise ntuples, which can be analyzed with PAW much more efficiently. The default record size of HBOOK files was increased from 1024 to 4096, the RZ allocation quota was increased to 65000 records, and the files are written in the “new” RZ format, which, unlike the “old” format, does not have a limit of 64k on the maximum number of records. As a result, the maximum size of output files is now 1 Gb, up from the previous limit of 125 Mb.

Several improvements were made to the way ntuples are written. In particular, dots in variable names are automatically replaced with underscores, and several bookkeeping fields are included in the output, without which analysis of array data would be rather difficult. Detailed documentation can be found in the ESPACE mailing list archive on the Web [21].

Finally, Bodo Reitz’s improvements of the BPM and raster routines (additional methods to fit amplitudes and phases) were added.

Several projects, such as support for the new “left/right” spectrometer naming conventions and inclusion of Jeff Templon’s extensive corrections of poor and potentially incorrect FORTRAN constructs, are in progress but delayed because of work on the new object-oriented analysis software (see previous section). The roadmap for future ESPACE development is roughly as follows:

- 2.9.3: Code clean-up. Improved error reporting.
- 2.10: Support for left/right spectrometer names and second aerogel.
- 2.11: Improved database support.
The timescale for this development is undetermined and depends entirely on available manpower. As with the C++ project, volunteers are welcome.
1.11 The Hall A RICH Detector (Contributed by F. Garibaldi)

for the Hall A RICH Collaboration.

1.11.1 Introduction

JLab experiment E94-107, “High Resolution Hypernuclear Spectroscopy” has been tentatively scheduled for next fall [22]. In order to perform hypernuclear spectroscopy in Hall A, however, two experimental difficulties have to be overcome [22–25].

- The present minimum scattering angle for the HRS is 12.5°. The addition of two septum magnets is needed in order to reach scattering angles as low as 6°.
- Due to the high background from protons and pions, the present HRS PID detector package is not sufficient to cleanly identify kaons.

1.11.2 Limits of the Present PID Setup

The expected signal and accidental rates are shown in Table 3. Since this hypernuclear spectroscopy experiment would detect energy levels by looking for peaks in the \((e,e'K)\) missing mass spectrum, the contamination of pions and protons in the kaon signal plays an important role. In order to minimize the contamination an effective particle identification system has been designed, built and tested. Central to that system is a RICH detector with a proximity focusing geometry, a freon radiator and a CsI photo converter. The detector has been successfully tested at CERN (November 2000) and is going to be commissioned during the E00-102 experiment. Two aerogel Cherenkov detectors with different index of refraction will be used to reduce on-line the proton and pion contamination [26–29].

The superior PID performance of this RICH detector is outlined in Fig. 11 where they are compared with two PID systems based on a Time Of Flight (TOF) measurement and on the use of two aerogel Cherenkov detectors. Figure 12 shows the expected \(9Be(e,e'K^+)\)\(^{9}\)\(Li\) and \(^{12}C(e,e'K^+)\)\(^{12}\)\(B\) spectra obtained with the TOF measurement and the use of two aerogel Cherenkov detectors. On the right hand side the combination of all three PID detectors is shown.

1.11.3 The RICH Detector

The RICH for Hall A is conceptually identical to one module of the ALICE-HMPID RICH[25], which is presently installed at the STAR RHIC experiment. The RICH has a proximity focusing geometry (no mirrors involved) which makes the detector compact (total thickness less than 50 cm), relatively thin (18% \(X_0\)) and inexpensive.
Figure 11: Contamination of $\pi$ and $p$ on the Kaon signal in experiment E94-107 with three PID systems. The rates are from Table 3.

Figure 12: Spectrum obtained by different PID systems (with or without RICH).
<table>
<thead>
<tr>
<th>Process</th>
<th>Rate (Hz)</th>
<th>Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>(e,e')K</td>
<td>$10^{-1} : 10^{-2}$</td>
<td></td>
</tr>
<tr>
<td>Accidentals (e,e')pi</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Accidentals (e,e')p</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Accidentals (e,e')K</td>
<td>0.1</td>
<td></td>
</tr>
</tbody>
</table>

Table 3: The expected rates for the E94-107 experiment in the excitation energy region corresponding to the oxygen hypernucleus. The coincidence resolving time is 4 ns.

Figure 13 shows the working principle of the adopted solution. The Cherenkov effect takes place in the liquid freon when a charged particle crosses it. The liquid radiator, 1.5 cm thick, is housed in a vessel made of NEOCERAM\(^1\) on all sides but the exit window which is made of pure quartz, 0.5 cm thick. The use of a liquid radiator has been imposed by the momentum range (around 2 GeV/c) of the particles to be identified. The Cherenkov photons, emitted along a conic surface, are refracted by the freon-quartz-methane interfaces and strike a pad plane after traveling a proximity gap of 10 cm filled with methane.

The pad plane is covered by a thin substrate of CsI which acts as photon converter. The emitted photo-electron is accelerated by an electrostatic field (2000 V/2 mm) between the pad plane and an anode wire plane in front of the pads, forming a MWPC (Multi Wire Proportional Chamber). While the anode wires collect the electron avalanche, the counterpart ions are collected by clusters of pads, each of which is connected to the input channel of a multiplexed sample and hold electronics, housed on the back of the pad plane. At the end of this process, the clusters of pads hit by the photons should be scattered on a ring (ellipse) while one cluster coming from the charged particle track should be located in the central region of the ring. A drift electrode operated at 300 V and located close to the quartz window, prevents electrons produced by ionization of the counting gas by charged particles in the proximity gap from reaching the MWPC. Table 4 presents a detailed list of the RICH components.

**The Radiator**

A freon recirculating system provides a pure and stable liquid radiator; filtering and refilling stages keep the high solubility and volatility of the freon itself under control. The transparency of this radiator is very low for wavelengths below 160 nm and therefore cuts out those photons. The purity of the freon, one of the important parameters to control, is monitored continuously, details of this monitoring system will be described elsewhere\(^{[30]}\).

\(^{1}\)NEOCERAM is a glass-ceramic material with mechanical and thermal properties almost identical to quartz.
The $C_6F_{14}$ radiator vessel represents a critical part in the detector design. The rather high perfluorohexane and silica glass densities, 1.68 g/cm$^3$ and 2.1 g/cm$^3$ respectively, and the need to avoid pollution from the material in contact with the liquid radiator that would affect the transparency in the 160 – 220 nm band, required careful investigation and optimization.

The liquid radiator container consists of a tray made of NEOCERAM closed by a UV-grade fused silica plate. Their thickness and size have been carefully optimized by investigating the best compromise between the detector total radiation length and the perfluorohexane hydrostatic pressure. In the current geometry the quartz window is 5 mm thick, while the NEOCERAM base plate is 4 mm thick. Moreover the radiator thickness is chosen to be 15 mm for an optimal Cherenkov angle resolution and a high number of Cherenkov photons. NEOCERAM is a glass-ceramic material, thermally compatible with the fused silica (thermal coefficient $0.5 \cdot 10^{-6} \text{K}^{-1}$). The vessel elements are glued together with Araldite AW106. The liquid radiator inlet and outlet are obtained by inserting two stainless steel pipes on the opposite edges of the NEOCERAM tray, the outlet always being at the highest location. To withstand the hydrostatic pressure, cylindrical spacers are glued to the NEOCERAM bottom plate on one side and the quartz window on the other side.
Table 4: Detailed list of the RICH components.

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>RICH size</td>
<td>$50 \times 210 \times 50$ cm$^3$</td>
</tr>
<tr>
<td>Optics</td>
<td>proximity focusing</td>
</tr>
<tr>
<td>Radiator</td>
<td>15 mm of liquid freon ($C_6F_{14}$) $n = 1.28$</td>
</tr>
<tr>
<td>Quartz window</td>
<td>5 mm, $n = 1.56$</td>
</tr>
<tr>
<td>Position detector</td>
<td>MWPC, with one cathode of pads, size: $1920 \times 400$ mm$^2$, anode wire pitch: 4.2 mm, anode-cathode gap: 2 mm, amplification gas: CH$_4$ at STP, operating voltage: 2 kV</td>
</tr>
<tr>
<td>Pad surface</td>
<td>3 pad planes, $630 \times 400$ mm$^2$ each; 11520 pads, 8 x 8.4 mm each</td>
</tr>
<tr>
<td>Photon converter</td>
<td>300 nm of CsI coating the pad surface</td>
</tr>
<tr>
<td>Electronics</td>
<td>analog, charge sensitive sample and hold, 11520 channels</td>
</tr>
<tr>
<td></td>
<td>multiplexed in 48 ADCs</td>
</tr>
</tbody>
</table>

Table 5: Mass composition of the HMPID module

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness(mm)</th>
<th>$X/X_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Honeycomb back panel</td>
<td>50</td>
<td>0.02</td>
</tr>
<tr>
<td>Neoceram plate</td>
<td>4</td>
<td>0.03</td>
</tr>
<tr>
<td>Quartz window</td>
<td>5</td>
<td>0.04</td>
</tr>
<tr>
<td>$C_6F_{14}$</td>
<td>10</td>
<td>0.05</td>
</tr>
<tr>
<td>Photocathode plane and electronics</td>
<td>1</td>
<td>0.02</td>
</tr>
</tbody>
</table>

The radiator vessel and the contained fluid dominate the bulk of the detector material, estimated to be 16% $X_0$ (see Table 5).

Before the construction of the radiator, strains and deflections of the vessel elements have been measured by strain gauges during tests on a prototype in several hydrostatic conditions.

The Gas System

The RICH detector has to be operated with pure methane to achieve the designed performances. A gas control system has been built, which controls the gas flow, and measures the purity of the gas. Main purpose of this system is to avoid any contamination with oxygen or moisture, that could eventually damage the CsI photocathode. Detailed description of the system will be described elsewhere [31].

The Photon Detector Subsystem

The photon detector is made of a MWPC, with one cathode plane replaced by a pad plane which allows the 2-dim localization of the photon hit.
The CsI is evaporated onto the pad surface by the technique developed successfully by the ALICE-R&D26 group [25]: the prepolished pad plane – a printed circuit with 3 layers of metals (nickel, copper and gold) glued on the vetronite substrate – is housed in a vacuum chamber (10⁻⁷ torr) and heated to 50°C. At a distance of about 1 m from the pad plane four DC heated tungsten crucibles containing a measured amount of CsI powder are placed. When the crucibles’ temperature reaches ~ 500 °C all the CsI powder evaporates and a layer grows at the pad surface at a speed of about 2 nm/s; thus producing the desired CsI layer of 300 nm in about 150 s.

The obtained photocathode plane is maintained in the vacuum chamber at 50°C for one day of post-treatment[25] which has been shown to be useful for an enhancement of the photon-conversion quantum efficiency (QE).

Since H₂O vapor reduces the performance of the CsI photon conversion, the photocathode must not be exposed to air. For this reason, the assembly of the pad planes in the RICH structure is done in argon atmosphere inside a large-volume glove box.

The whole evaporation and assembly system (gloves box) was built and tested in Rome and then installed at JLab [32]. In order to verify the quality of the evaporation and its uniformity on the large pad surface an on-line QE measuring system [33] has been built and successfully used. The results of such a measurement are compatible with the results of the CERN measurements.

Readout Electronics

The present set up of the front-end (FEE) and Readout (RO) electronics on the RICH detector is as follows: the FEE is arranged in 24 rows, each consisting of 30 daisy-chained GASSIPLEX chips for a total of 11520 input channels, 480 per row. The charge content of these multiplexed analogue channels is converted by a 10 bit ADC when an experiment trigger is issued. The readout electronics consists of two CAEN VME modules: the V551 Sequencer and V550 CRAMS two channels FADC. When a trigger is asserted, the Sequencer provides at the same time the clock pulse to all the FEE rows and the related convert pulses, phase shifted, to the ADC modules V550. Each ADC channel is connected to a GASSIPLEX row of 480 input channels. The synchronised clock-convert pulses allow each analogue channel to be correctly converted and stored. The V550 CRAMS module is equipped with a zero-suppression circuit which prevents ADC values under a certain threshold, channel based, to be stored in the 2 K x 32 bit memory locations. By means of a phase-correction module, the clock readout and convert frequency has been successfully pushed and tested up to 2.5 MHz. This ensures a time duration of 197 μs to readout 480 channels including CLEAR and T/H control signals.

In order to evaluate the maximum trigger rate for the RICH, a simplified model of the system can be investigated. It consists of 480 FEE channels, 2.5 MHz RO
clock frequency, and a readout time of 1.1 µs per ADC value on the VME bus. Furthermore, the dead time of the RICH DAQ system has to be below 20%. According the previous figures and assuming 100 ADC values above threshold per event (1 ~ of the 11520 RICH channels), the maximum trigger rate for RICH detector is about 700 Hz.

In order to increase this rate to about 2 kHz, there are two solutions, which both could be implemented. The first one is based on the FEE row length division by two, to get for the entire RICH 48 rows × 240 daisy-chained channels each. To readout these 48 FEE rows, two VME crates fully equipped with 12 V550 modules each are requested. This solution will double the rate capability up to 1.4 kHz. The second solution is based on the ADC buffering in the CRAMS memory and the ”block mover” useful when at least ten or more ADC values have to be transferred from the ADC memories via the Link 2 in the VME CPU RAM memory. Although the second solution has to be better investigated and tested, in principle for a row of 480 FEE channels, four subsequent events can be stored in the ADC buffer memory and readout after 4 events. The association between ADC value and event number is ensured by the relevant address of each ADC value: the first event will have the addresses in the range 1-480, the second in the range 481-961 and so on up to 2000. In this way a sort of trigger pre-scaler with a factor 4 can be implemented and the link 2 will be activated one time out of four reducing the total readout time. In this case the 700 Hz of trigger rate can be pushed up to about 900 Hz. Combining these two solution, a 1.8 kHz trigger rate could be reached with a 20% dead time of the RICH DAQ system.

1.11.4 Expected Performance

In order to tune the various elements of the RICH, the analytical estimation of the angle resolution of ALICE-HMPID[25] has been revised and adapted and a new Monte Carlo program based on GEANT3 has been developed.

The single photon angular resolution (σθ) is expected to be affected mainly by the chromatic aberrations of both the freon radiator and the quartz window, the uncertainty of the emission point in the radiator, and the resolution of the position detector (for details see [29]).

The Monte Carlo simulates a realistic Hall A hadron arm phase space, realistic optical characteristics and CsI QE, while the pad digitization is based on a gaussian charge production in the MWPC which produces clusters of pads.

Figure 14 shows the angular distributions of the Cherenkov ring for π, K and p for a freon thickness of 14 mm. The bottom histogram (the most realistic) shows that the angle resolution for the whole ring coming out from the Monte Carlo and the applied reconstruction algorithm is 4.1 mrad for π’s.

The Monte Carlo shows that one gets a satisfactorily small π+p contamination on the kaon sample between 0.5 and 0.005 depending on which hypernuclear energy level produces the K. These values are 6 orders of magnitude less than the present
Figure 14: Angular distributions of Cherenkov rings for protons ($\theta_{\text{cher}} \sim 0.55 \, \text{rad}$), kaons ($\theta_{\text{cher}} \sim 0.65 \, \text{rad}$) and pions ($\theta_{\text{cher}} \sim 0.68 \, \text{rad}$) with equal populations. Top plot: GEANT3 generated angle (it takes into account the radiator chromaticity only); center plot: reconstructed angle with zero size pad (no position detector uncertainty); bottom plot: realistic reconstructed angle (real pad size).
Hall A kaon ID contamination.

1.11.5 Tests at CERN

The Hall A RICH detector was tested at CERN in November 2000 in the T7 PS test beam experimental area (see Fig. 15). Mechanical problems (anode wires closer to the photocathode than the designed value (2 mm)) required using an Ar/Methane (76/24) gas mixture with the proportional chamber high voltage set at 1500 V. The data acquisition system, as well as the recirculating freon system, were provided by the CERN group.

Figure 15: Photographs: the RICH in T7 Hall PS beam at CERN (top), the evaporator and one photocathode (left), and the RICH in the Hall A detector hut (right).

The RICH was exposed to a 7 GeV/c pion beam with a small area (3x3 cm²) scintillator trigger, making it possible to investigate different zones on the photocathodes. Only two out of the three photocathodes were tested. One was
evaporated with CsI in the ISS/INFN laboratory in Rome and then shipped to CERN in a controlled dry atmosphere of Argon. The other photocathode was evaporated just before the tests at CERN by the ALICE group. Both photocathodes performances were satisfactory with no significant differences found between them.

A summary of the results obtained is shown in Fig. 16. In the top–left panel the distribution of the number of “resolved clusters” as counted in the fiducial zone where rings are expected, is reported. The number of “resolved clusters” is the number of detected photoelectrons (see [25]). The average value obtained was 12.4 as reported in the figure. In the top–right panel the Cherenkov angle for 7 GeV/c pions, as measured for each event averaging over all the clusters, is reported. An angular resolution of about 3.7 mrad was observed in good agreement with the Monte Carlo predictions. The bottom–left panel shows a hit map, weighted by the ADC value, of many events overlapped. A ring is clearly visible with a very low level of background. The last panel shows a ring for a single event.

The detector performance was very satisfactory – indeed it is possible to compare the obtained results with expected Methane 2100 V chamber condition performance. At this point the evaporation technique is considered to be under control.

1.11.6 Tests at JLab

During JLab experiment E98-108 “Electroproduction of Kaons” the RICH detector was installed in the detector stack of the left HRS. It was equipped with a prototype radiator, covering only one third of the length of the detector. Additionally only two out of three cathodes were fully equipped with front-end electronics. The DAQ of the RICH detector could be operated in two different modes: in the so-called “stand-alone mode” the DAQ was totally independent from the HRS DAQ system. Because the systems were not synchronized in this mode, no tracking information was available for the analysis of the RICH data. In the second mode, the RICH readout was integrated into the HRS DAQ system, raw data from both systems were written to the same raw data file. The full tracking and PID information from the standard HRS detectors and the PID information from the RICH detector were combined. It was possible to change between these two modes remotely. In this mode, the readout of the RICH front-end electronics was started by the HRS trigger supervisor accepted event. Because of the synchronization of the two spectrometers for a coincidence between the left and the right HRS, this accepted trigger comes at least 550 ns after a particle crosses the detector stack. The mechanical problems already mentioned in section 1.11.5 required operation of the MWPC at high voltages below 1420 V with an Ar/Methane mixture, even below the voltage applied at CERN.

After fixing the mechanical problems by modifying the mechanical support frames for the MWPC, the RICH detector was installed in the EEL building to
perform test runs with cosmic radiation. Therefore it was installed upside down, so that cosmic radiation could produce Cherenkov light radiating the photocathode. For the Freon system to be working, the detector must not be installed horizontally, instead it was put at an angle of 12.5° out of plane. For the cosmic tests all three evaporated photocathodes and a complete set of FEE including 12 C-RAM ADC modules were used. Also the final radiator covering the full detector area was installed.

The RICH was operated with pure methane. For standard operations a high voltage of 2100 V was applied. After a few weeks of operation in these conditions a group of at least three wires was not able to stand this high voltage anymore, affecting some neighboring wires as well. After disconnecting 16 wires from the high voltage, the remaining part of the MWPC was operational again at the designed high voltage.

A set of four scintillators served as trigger detectors mounted above and below
the RICH detector. A coincidence between one upper and one lower scintillator started the RICH readout. To get reasonable counting rates, rather big scintillators were chosen. The pair with the highest counting rate (0.05 Hz) covered an area of 15 x 15 cm² and had an angular acceptance from -11° to 4° with respect to the axis perpendicular to the radiator. These numbers have to be compared to the expected diameter of the rings (16 cm) and the angular acceptance of the RICH itself, which is below 13°. So the scintillators did not provide sufficient tracking information. To suppress particles with low energy, 55 cm of lead blocks were placed between the trigger scintillators. In the first measurements, the operational parameters for the high voltage, timing, and delays were optimized. A high voltage of 2100 V turned out to be sufficient. The optimal value for the delay between the trigger signal from the scintillators and the start of the readout-cycle (“track and hold”) of the front-end electronics was found to be between 300 and 350 ns. Although this is smaller than the design value of 600-700 ns, this result is consistent with the experience from the RICH detector at BNL/STAR, using the same kind of electronics.

![Graphs showing results of RICH tests](image)

**Figure 17:** Results of the RICH tests carried out in August 2001 at JLab using cosmic radiation. The plots include the statistics of one setting with 2500 triggers. See text for details.

In Fig. 17 the results of one cosmic run are presented. Because no external tracking information was available in this setup, the data was analyzed the following way: in the area of the detector covered by the scintillators, the cluster with largest signal was identified as the MIP. All clusters within a circle of 40 cm diameter around this cluster were treated as clusters produced by Cherenkov light. Because of the asymmetric acceptance of the scintillators, the rings are in fact ellipses with the MIP in one focus. Due to the lack of tracking information,
there is a probability of a wrong assignment of the MIP, which leads to a relatively high background compared to the CERN results. Along with the relatively large angles, this explains why the number of photo-electrons per ring is smaller than at CERN. It was also noticed that the detector response was not completely homogeneous over its area. This effect will be addressed during the next phase of commissioning, which takes place during JLab experiment E00-102 and will be described later.

The readout speed of the system is limited by the fact that groups of 480 pads are read out sequentially by one ADC. The frequency of the sequencer was 666 kHz, leading to a deadtime of 720 μs. (One has to add the time for the data transfer from the ADC to the readout CPU via the VME–bus, which takes 1 μs per ADC value above threshold).

The RICH detector was again installed in the detector stack of the left HRS at the beginning of October, 2001. Compared to the two setups described above, the following changes were made:

- The frequency of the sequencer was increased to 2000 Hz, using an additional NIM module provided by collaborators from Bari.

- The firmware of the CRAMS was changed to allow data transfers via the VME bus in block transfer mode.

- Due to increased HV problems another group of 8 wires was disconnected.

- The readout of the RICH front-end electronics is started with each left arm raw trigger; if the trigger is not accepted by the trigger supervisor of the HRS after 1 μs, a fast clear (FCL) is applied (duration 600 ns). During the standard settings of E00-102 the raw trigger rate is about 200 kHz, whereas the accepted trigger rate is below 2 kHz.

A few test runs during the beginning of E00–102 have already been performed (in stand alone mode), confirming the choice of operational parameters obtained in the cosmic tests. Detailed studies will follow after the end of E00-102.

After these tests, the RICH detector will be opened again to repair the wires currently disconnected and to install new photocathodes.

1.11.7 Conclusion

The kaon ID project for Hall A (Hall A RICH collaboration (INFN Rome-Sanita’ and Bari, Jefferson Lab, University of Maryland, Florida International University, Tohoku)) started in the summer of 1998. Design work began in December of the same year. This RICH as well as the evaporator system was built in Rome. The detector was successfully tested at CERN in November, 2000. The gas and freon system was built at Jefferson Lab. The DAQ implementation and integration in

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the Hall A DAQ system as well as the slow control system has been done at Jefferson Lab. The QE on-line measurement was built by University of Maryland collaborators. The detector is presently installed in the left arm in Hall A for commissioning and it is almost ready for the experiment. The performances achieved so far are as good as expected. We would like to acknowledge the invaluable contribution of A. Braem and E. Schyns for the CsI evaporation, M. Davenport for the freon circuit during the tests, F. Piuz, A. Di Mauro, P. Martinengo for the availability of the CERN facilities, for the readout during the CERN tests and for helping in data analysis, F. Tessarotto and S. Della Torre, for many useful discussions in the design phase and for having provided the photocathode transport device.
2 Summaries of Experimental Activities

2.1 E89-044

Selected Studies of the $^3$He Nucleus through Electrodisintegration at High
Momentum Transfer

D. W. Higinbotham for the Hall A and E89-044 Collaborations

The E89-044 collaboration completed its measurements of $^3He(e, e'p)$ in March
2000 after receiving nearly three months of beam time. In perpendicular kinematics,
with a constant momentum transfer of 1.5 GeV/c and a constant energy transfer
of 0.837 GeV, cross sections were measured at missing momentum-values of 0,
150, 300, 425, 550, 750, and 1000 MeV/c. The $R_{L+TT}$, $R_T$, and $R_{LT}$ response
functions will be extracted for missing momenta of 0, 150, 300, 425, and 550
MeV/c. In parallel kinematics, where the proton is emitted in the direction of the
momentum transfer vector, the $Q^2$ dependence from 0.8 to 4.1 (GeV/c)$^2$ will be
determined by performing longitudinal/transverse separations. These measurements
were performed for -300, 0, 300 MeV/c missing momentum and for momentum
transfers 1.0, 1.9 and 3.0 GeV/c. In addition, the experiment measured the cross
section in the continuum region to study correlated nucleon pairs.

There are presently three doctoral candidates working on the analysis of the
data. Fatiha Benmokhtar of Rutgers University is working on the analysis of the
continuum data, Emilie Penel-Nottaris of ISN Grenoble is working on the analysis
of the two-body break-up channel in parallel kinematics, and Marat Rvachev of
M.I.T. is working on the analysis of the two-body break-up channel in perpen-
dicular kinematics. The analysis of Marat is nearing completion and he should
be extracting the final response functions for the perpendicular kinematics in the
near future. Emilie’s analysis is at the stage where preliminary cross sections
for the parallel kinematics are now becoming available, and Fatiha, who recently
passed her doctoral qualifying exams, is now working full time on her analysis of
the continuum data.

The preliminary cross section results of Marat, shown in Fig. 2.1 have gener-
ated considerable theoretical interest. The curves show the most recent calcula-
tions of Jean-Marc Laget. The agreement of the theory to missing momentum of
750 MeV/c is striking. There is as yet no clear indication as to what is causing the
cross section at the largest missing momentum to be much greater than predicted.
Jose Udias is also working on theoretical calculations. He has already provided
the collaboration with a rough $A_{TL}$ calculation and is now working on making a
full calculation of the cross sections and $A_{TL}$ using a realistic potential. Rocco
Schiavilla and Sabine Jeschonnek are also planning to provide calculations for the
collaboration.

\footnote{http://hallweb.jlab.org/physics/experiments/E89-044/collaboration.ps}
Figure 18: Preliminary cross section results for the reaction $^3$He$(e,e'p)d$ as a function of missing momentum, with a beam energy of 4807 MeV and a fixed $q$ of 1.5 GeV/c and $\omega$ of 837 MeV. The curves show also the latest calculations of Jean-Marc Laget. The enhancement in the cross section near 300 MeV/c, continuing to larger missing momentum, is predominantly due to final state interactions. There is no clear indication from theory what causes the enhancement of the cross section near 1000 MeV/c.
2.2 E91-011

Investigation of the $N \rightarrow \Delta$ Transition via Polarization Observables in Hall A


Recoil polarization observables can provide new insight into properties of nucleon resonances and the reaction mechanisms for electroproduction of mesons by providing access to interference between small amplitudes and dominant amplitudes. The dominant amplitude for pion electroproduction at the $\Delta$ resonance is the $M_{1+}$ multipole, but there is much current interest in the smaller $S_{1+}$ amplitude that arises from configuration mixing within the quark core [34], often described as quadrupole deformation, or from meson and gluon exchange currents between quarks [35], or coupling to the pion cloud outside the quark core [36,37]. Observables which depend on real parts of interference products are sensitive to these quadrupole amplitudes, but reliable interpretation of such data requires understanding background contributions from non-resonant production mechanisms and from underlying non-dominant resonances. Sensitivity to background amplitudes is provided by observables which depend on the imaginary parts of similar interference products. Experiment E91-011 was designed to measure both types of observables for the $p(\bar{e}, e'\bar{p})\pi^0$ reaction using the focal-plane polarimeter.

The experiment ran between May 19 and August 1, 2000 and obtained recoil polarization data covering a large fraction of the angular distribution for $(W,Q^2)$ centered on $(1.232 \text{ GeV}, 1.0 \text{ (GeV/c)}^2)$. A brief summary of experimental conditions can be found in the status report for year 2000.

The cross section analysis is using a generalization of the $R$-function method. Two-dimensional plots of pairs of the basic target variables, $\{\theta, \phi, y, \delta\}$, for each arm are used to define 12 polygons that delimit the experimental phase space acceptance. Polygons based on singles events represent the intrinsic instrumental acceptance while smaller polygons based upon coincidence events for a particular reaction and kinematics reduce background. For each event the quantity $R$ is defined by the cartesian distance to the nearest border, with each polygon scaled to a common area. Events with $R = 0$ lie on one of the borders, events with negative $R$ are outside the acceptable region, while events with positive $R$ are inside. Therefore, we select events with $R > R_{\text{cut}}$ that are comfortably within the acceptance. The appropriate value of $R_{\text{cut}}$ is determined by looking for a plateau in the ratio between experimental and simulated yields for fixed luminosity where both experimental and simulated events are analyzed with the same acceptance function. The simulations were performed using MCEEP [3,10] with an event generator based upon the MAID model [38]. Acceptance functions based upon either coincidences or singles provide virtually identical ratios between experimental and
simulated yields on their respective plateaus and both provide excellent simulations of the distribution of the basic target variables. Figure 19 demonstrates that with \( R > 0.06 \) the simulation also reproduces the distributions of \( W, Q^2 \), and missing mass for parallel kinematics; comparable results are obtained for all settings.

Preliminary data for the azimuthal distribution of recoil polarization components for one bin of polar angle are compared in Fig. 20 with calculations based on the MAID [38] and SAID [39] models. Both models provide fairly good descriptions of these data, but the differences increase with \( \theta_{cm} \). These data were obtained by the standard Fourier analysis method. Although we studied the false asymmetry, corrections to the helicity-independent polarizations have not yet been applied to these data. Response functions can be extracted by fitting the azimuthal distributions, but we are presently testing an alternative procedure that uses the maximum likelihood method to extract response functions directly without need for binning with respect to \( \phi \). This method permits several overlapping settings to be analyzed simultaneously, takes better advantage of the experimental acceptance, and applies corrections for spin precession on an event-by-event basis rather than averaging over the acceptance.
Figure 19: Comparison between experimental (blue) and simulated (red) kinematical distributions for the $\theta_{cm} = 0^\circ$ setting of the $p(e,e'p)\pi^0$ reaction from E91-011. An $R$-function cut has been used to define the acceptance for coincidence events.
\[ \theta_{\text{cm}} = 11 - 33^\circ \]

Figure 20: Preliminary E91-011 data for the azimuthal distribution of recoil polarization components in the \( p(e,e'p)\pi^0 \) reaction. Data are shown for one sample bin: \( W = 1.232 \pm 0.25 \text{ GeV}, \ Q^2 = 1.0 \pm 0.1 \text{ (GeV/c)}^2, \) and \( \theta_{\text{Ncm}} = 22^\circ \pm 11^\circ. \) The data are compared with calculations based on the MAID (solid) and SAID (dashed) models. Black circles and red squares come from the \( \theta_{\text{Ncm}} = 0^\circ \) and \( 25^\circ \) settings, respectively.
2.3 E93-049

Polarization Transfer in the Reaction \(^4\text{He}(e',e'p)\) \(^3\text{H}\) in the Quasi-elastic Scattering Region


2.3.1 Introduction

Whether nucleons undergo considerable change of their internal structure when bound in the nuclear medium is a long standing issue in nuclear physics. Polarization transfer in quasi-elastic nucleon knockout is sensitive to the properties of the nucleon in the nuclear medium, including possible modification of the nucleon form factor and/or spinor. Experiment E93-049 measured the polarization transfer coefficients over the range of \(Q^2\) from 0.5 to 2.6 (GeV/c)^2, and as a function of missing momentum in the range 0 to 240 MeV/c, in order to determine the electric to magnetic form factor ratio for protons bound in the \(^4\text{He}\) nucleus. \(^4\text{He}\) was selected for this study since its relative simplicity allows for realistic microscopic calculations and since its high density enhances possible medium effects. Also, a variety of calculations indicate polarization observables for the \(^4\text{He}(e',e'p)\) \(^3\text{H}\) reaction have minimal influence from final state interactions (FSI) and meson exchange currents (MEC). It is precisely these effects (especially FSI) that have so far prevented a clean determination of nucleon medium modifications from unpolarized response functions in \((e,e'p)\) experiments.

A recent calculation by D.H. Lu et al. [40], suggests a measurable deviation from the free space ratio over the \(Q^2\) range of this experiment. The calculation is consistent with present constraints on possible medium modifications for both the electric form factor (from the Coulomb Sum Rule, with \(Q^2 < 0.5\) (GeV/c)^2), and the magnetic form factor (from a y-scaling analysis for \(Q^2 > 1\) (GeV/c)^2). The calculation seems to predict too large an effect for the magnetic form factor at higher \(Q^2\); however, it has been suggested that in order to interpolate smoothly between confined and deconfined phases, the bag constant might decrease as the baryon density increases. Such an effect would reduce the \(Q^2\)-dependence of the medium modification of the magnetic form factor, while still having a measurable effect in the ratio of \(G_E/G_M\). Similar measurable effects have been calculated in the model of Frank et al. [41].

For free electron-nucleon scattering, the ratio of the electric to magnetic Sachs form factors, \(G_E\) and \(G_M\), is given by [42]:

\[
\frac{G_E}{G_M} = \frac{P_x'}{P_z'} \cdot \frac{E_x + E_{x'}}{2m_p} \tan(\theta_e/2),
\]  

(1)

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where $P'_x$ and $P'_y$ are the transverse and longitudinal transferred polarizations [43]. The beam energy is $E_e$, the energy (angle) of the scattered electron is $E_{e'}$ ($\theta_e$) and $m_p$ is the proton mass. The relation in Eq. (1) was recently used to extract $G_E/G_M$ for the proton [44]. For quasielastic nucleon knockout of a bound proton this relation is only approximately correct, but polarization transfer remains sensitive to the properties of the nucleon in the nuclear medium; although proper interpretation of the results requires accounting for such effects as FSI and MEC, their effects on polarization transfer are, as mentioned, expected to be small.

2.3.2 Experiment Status

Data taking for this experiment was completed in May 2000. The experiment used beam currents of 40 $\mu$A for the lower $Q^2$ values and up to 70 $\mu$A for the highest $Q^2$ value, combined with beam polarizations of 66% for the lowest $Q^2$ value and $\approx 77\%$ for the other $Q^2$ values. The beam helicity was flipped pseudorandomly to reduce systematic uncertainties of the extracted polarization transfer observables. The proton spectrometer was equipped with a focal plane polarimeter (FPP). Polarized protons lead to azimuthal asymmetries after scattering in the carbon analyzer of the FPP. These distributions, in combination with information on the beam helicity, were analyzed by means of a maximum likelihood method to obtain the induced and transferred polarization components.

As the experiment was designed to detect differences between the in-medium polarizations compared to the free values, both $^4$He and $^1$H targets were employed (due to beam time constraints, at $Q^2 = 2.6$ (GeV/c)$^2$ only $^4$He data was acquired). The statistical precision for the polarization double ratio is roughly 5%, 4%, 4% and 12% at $Q^2$ of 0.5, 1.0, 1.6, and 2.6 (GeV/c)$^2$ respectively. Systematic errors are expected to be significantly less than the statistical errors.

2.3.3 Results

Our results, binned versus missing momentum, are shown in Fig. 21 for $Q^2$ of 1.0 (GeV/c)$^2$ along with theoretical results in terms of the polarization double ratio

$$R^{\text{Exp}} = \frac{(P'_x/P'_y)_{^4\text{He}}}{(P'_x/P'_y)_{^1\text{H}}}.$$  

(2)

Negative values of missing momentum correspond to the recoiling nucleus having a momentum component antiparallel to the direction of the three-momentum transfer.

The helium polarization ratio is normalized to the hydrogen polarization ratio measured in the identical setting. As a cross check, the hydrogen results were also used to extract the free proton form factor ratio $G_E/G_M$ and found to be in excellent agreement with previous data [44].

55
Figure 21: Measured values of the polarization double ratio $R_{Exp}$ for $^4\text{He} (\vec{e}, \vec{e}' p)^3\text{H}$ at $Q^2 = 1.0 \text{ (GeV/c)}^2$. The theoretical curves represent calculations of PWIA (dotted), relativistic DWIA (dashed), and relativistic DWIA including QMC medium-modified form factors [40] (solid) by Udias et al. [46].

Figure 22 shows a summary of the ratio relative to PWIA averaged over the entire acceptance for all points, along with the result from Mainz [45]. The theoretical predictions are results of our acceptance-averaging of calculations by the Madrid group [46]. The plane-wave impulse approximation (PWIA) calculation is not able to describe the experimental results although it follows a similar trend. The relativistic distorted-wave impulse approximation (RDWIA) calculation gives a smaller value of $R_{Exp}$ but still overpredicts the data. The inclusion of a medium modification of the proton form factor as predicted by Lu et al. [40] in the RDWIA calculation is in excellent agreement with all settings. All calculations shown use the Coulomb gauge, the CC1 current operator as defined in [48], and the MRW optical potential of [49]. The CC2 current operator gives higher values of $R_{Exp}$, worsening agreement with the data. Our results at $Q^2 = 0.5 \text{ (GeV/c)}^2$ closely coincide with the recent results at $Q^2 = 0.4 \text{ (GeV/c)}^2$ of Mainz [45]. These results have sparked considerable theoretical interest and new calculations are being done by Udias, Ryckebusch, Laget, Melnitchouk, and others.

The data analysis is essentially complete. A paper is currently in preparation.

We also want to note that in the course of the analysis, some problems in the FPP alignment routines were discovered, which led to small rotations in the reconstructed position along the $z$ axis ($z_{close}$). The corrected alignment, along with the tighter cuts on $z_{close}$, reduced the instrumental asymmetries. This will be discussed in the thesis of S. Dieterich, which is expected to be completed by the end of 2001.
Figure 22: The ratio $R^{Exp}$ averaged over all missing momenta and normalized to PWIA calculations, again with DWIA and QMC modified form factors from Udias. Also shown is the non-relativistic calculation of Laget [47].

Figure 23: Distance of closest approach, “zclose”, with old (a) and new (b) alignment.
2.4 E93-050

Virtual Compton Scattering

C.E. Hyde-Wright, for the VCS and Hall A Collaborations

In experiment E93-050 we studied the $H(e,e'p)\gamma$ and $H(e,e'p)\pi^0$ reactions, using the Hall A cryotarget and the HRS$^2$ pair to detect the scattered electron and recoil proton in coincidence [50]. To lowest order in $\alpha_{QED}$, the $H(e,e'p)\gamma$ reaction is a coherent superposition of radiation from the incident or scattered electron in elastic $ep$ scattering (Bethe-Heitler–BH) and exclusive production of a photon on the proton, by absorption of a virtual photon (Virtual Compton Scattering–VCS). Experimentally, we separate the exclusive photon final state from $\pi^0$ electroproduction and other channels by reconstructing the missing mass of the unobserved particle(s). Five Ph.D. theses have been completed from this experiment: N. DeGrande (Gent, 2001), S. Jamionin (Clermont-Ferrand, 2000), C. Jutier (ODU - Clermont-Ferrand, 2001), G. Laveissière (Clermont-Ferrand, 2001), and L. Todor (ODU, 2000).

The virtual Compton amplitude includes a coherent sum of all possible intermediate states. In the low energy limit ($s \rightarrow M_p^2$, for arbitrary $Q^2$) the low-energy theorems describe the VCS amplitude as a sum of the Born term (proton bremsstrahlung) plus a set of generalized polarizabilities [51]. The $Q^2$-variation of the generalized polarizabilities measures the spatial variation of the electric and magnetic polarization induced in the proton by external electric and magnetic fields. The VCS cross section can be expanded in powers of $q' \epsilon$ (the final CM photon energy) as follows:

$$d^5 \sigma = d^5 \sigma^{BH+B}$$

$$+ \frac{(2\pi)^5 k'_{lab}}{64 M_{lab}^2} \frac{q'^2}{\sqrt{s}} \left[ v_{LL} \left(P_{LL}(Q^2) - P_{TT}(Q^2) / \epsilon\right) + v_{LT} P_{LT}(Q^2) \right] + O(q'^2)$$

In this expansion, $v_{LL}$ and $v_{LT}$ are kinematic factors independent of $q'$, $d^5 \sigma^{BH+B}$ is the cross section resulting from the coherent superposition of the Bethe-Heitler and Born amplitudes, and structure functions $P_L$ are related to the $q^2$-dependent electric and magnetic polarizabilities $\alpha$ and $\beta$, respectively, as follows:

$$P_{LL} - P_{TT}/\epsilon = \frac{4 M_p}{\alpha_{QED}} G^p_E(Q^2) \alpha(Q^2) + \text{Spin Polarizabilities}$$

$$P_{LT} = -\frac{2 M_p}{\alpha_{QED}} \sqrt{\frac{Q^2}{Q^2}} G^p_E(Q^2) \beta(Q^2) + \text{Spin Polarizabilities}$$

In E93-050, we took data below pion threshold ($M_p^2 < s < (M_p + m_\pi)^2$) at $Q^2 = 1.0$ and 1.9 GeV$^2$. In these measurements, a single electron arm setting spanned the entire region below threshold, and we moved the proton arm to span...
a large range in $\theta_{\gamma\gamma}$. At $Q^2 = 1$, we also measured a resonance excitation scan for nine central values of $s$ from 1.3 GeV$^2$ to 3.6 GeV$^2$, with the coincidence angular kinematics centered on $\theta_{\gamma\gamma} = \pi$.

Below pion threshold, we extract the differential cross section by comparing the integrated yield in a bin with a simulated cross section including the Bethe-Heitler and Born terms[52] and the radiative tail (second photon emission) of the complete VCS process [53]. From the experimental cross sections, we use the expansion of Eq. 3 to extract the polarizability combinations $P_{LL} - P_{TT}/\epsilon$ and $P_{LT}$. We use these initial estimates of the polarizabilities in the simulation cross section to iterate the analysis. The statistical errors from this analysis are shown in Table 6 with the heading ‘LET’. At the present time, the systematic errors are much larger than the statistical errors. The systematic errors result in part from the contribution of higher order terms beyond the Low Energy Theorem of Eq. 3.

B. Pasquini et al. [54] have developed a dispersion theory formalism for the analysis of Virtual Compton Scattering up to the $\Delta$-resonance. In this formalism, the VCS scattering amplitude is predicted from the MAID[38] parameterization of pion electroproduction, plus two low-energy parameters $\Delta\alpha(Q^2)$ and $\Delta\beta(Q^2)$, which are the phenomenological contributions to these two polarizabilities, not otherwise constrained by the dispersion integrals over the pion electroproduction data.

Both below and above pion threshold, the DR formalism provides a rigorous description of the higher order terms beyond the polarizabilities in the VCS amplitude. We have included the DR formalism in our analysis of the VCS data at $Q^2 = 1$ GeV$^2$ from threshold to the $\Delta$ resonance. The statistical precision of this analysis is indicated in Table 6 with the heading ‘DR’. In the next phase of analysis, we will use the DR formalism to analyse the data below pion threshold. Based on our current analysis, we expect the final results for the polarizabilities $P_{LL} - P_{TT}/\epsilon$ and $P_{LT}$, to lie in the ranges: $[2.0, 7.0]$ GeV$^{-2}$ and $[-2.0, -0.5]$ GeV$^{-2}$, respectively, at $Q^2 = 1.0$ GeV$^2$; and in the ranges $[0.2, 0.8]$ GeV$^{-2}$ and $[-0.3, +0.1]$ GeV$^{-2}$, respectively, at $Q^2 = 1.9$ GeV$^2$.

Our resonance data include $\pi^0$ electroproduction. Figure 24 displays the backward $\pi^0$ production from threshold to $W = 2$ GeV at $Q^2 = 1$ GeV$^2$ and

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Table 6: Statistical precision of polarizability analysis of Jefferson Lab E93-050.
\( \cos \theta_{\gamma\pi^0}^{CM} = -0.975 \), where \( \theta_{\gamma\pi^0}^{CM} \) is the angle between the virtual photon and the \( \pi^0 \) in the pion-proton center-of-mass frame. The figure also includes the calculations of the MAID[38] and SAID [39] models, both before and after a re-adjustment of the parameters of these models [55,56].
Figure 24: Separated $\gamma^* p \rightarrow \pi^0 p$ cross sections as a function of $W$ at $Q^2 = 1$ GeV$^2$ and at $\cos \theta^{CM}_{CM} = -0.975$. The dashed black curve (lowest curve for $\sigma_T + \epsilon \sigma_L$ at $W = 1.5$ GeV) represents MAID2000[38]. The dashed blue curve represents the SAID[39] parameterization NF18K. The solid lines are the result of an adjustment of the parameterizations to fit these data. Solid black (lower of the two for $\sigma_T + \epsilon \sigma_L$ at $W = 1.4$ GeV) represents a refit of MAID[55]. Solid blue represents a SAID refit, GF20 [56]. The error bars at the bottom of each figure represent the additional systematic error introduced by the fact that the $Q^2$ dependence of our data within our acceptance does not match the $Q^2$ dependence of the MAID parameterization we used in our simulations to extract the experimental results. Fig. d) displays the reduced $\chi^2$ of the fits to the experimental $\phi$ distributions to extract the results in Figs. a)–c).
2.5 E94-004

In-plane Separations and High Momentum Structure in d(e, e'p)n

M.K. Jones and P.E. Ulmer, Spokespersons, for the E94-004 Collaboration

Experiment E94-004 proposed a systematic study of the d(e, e'p)n reaction for a variety of quasifree kinematics. The three calendar days of beam taken in October of 1999 (about 5% of the 29 days of approved beam time) were used to measure the unseparated cross section only. The cross section was measured at $Q^2 = 0.66$ (GeV/c)$^2$, $x = 0.96$ and for recoil momenta from 0 to 0.55 GeV/c. The electron kinematics were fixed and the recoil momentum range was spanned by varying the proton spectrometer angle and momentum.

The deuteron, as the only bound two-nucleon system represents the simplest manifestation of the nuclear force. It therefore is a vital starting point from which to understand heavier nuclei including issues such as 3- or N-body forces and correlations. Understanding the deuteron is also necessary for the interpretation of various experiments employing the deuteron as an effective neutron target.

By examining high recoil momenta, this preliminary measurement is sensitive to the short distance character of the nucleon-nucleon (NN) interaction. Although high recoil momenta have been measured previously at other facilities, the relatively low energies of these accelerators compared to JLab required performing these measurements away from the quasifree peak. Thus, contributions from meson exchange currents and virtual nucleonic excitations make the extraction of information about the ground-state structure of the deuteron highly model dependent. In contrast, the higher beam energies of JLab allowed our experiment to be the first to sample high recoil momenta at kinematics near the quasifree peak.

The analysis is nearly final and the preliminary spectrum along with various calculations are shown in Fig. 25. The top panel shows the radiatively corrected reduced cross section, in which the half-off-shell electron proton cross section of de Forest [48] ($\sigma_{\text{OCC}}$) and various kinematic factors are divided out. The Jeschonnek calculation [57] was in the plane wave Born approximation (PWBA) and used a fully relativistic single-nucleon current operator with an alternate three-pole parameterization of the MMD nucleon form factors [58] and the Argonne V18 two-body interaction [59]. The calculations of Arenhövel [60] included relativity via an expansion in powers of $p/m$ in the nucleon current operator and also included the relativistic kinematic boost in the wave function. He used the Bonn $r$-space NN potential [61] along with dipole nucleon form factors. The various curves are for PWBA, DWBA (Distorted Wave Born Approximation, which includes FSI), and the "full" calculation which also includes non-nucleonic currents: Meson Exchange Currents (MEC) and Isobar Configurations (IC). The bottom panel shows the same results, except relative to the full calculation of Arenhövel. Also shown in the bottom panel is the systematic error band, arbitrarily placed vertically.
The two PWBA calculations are reasonably close to one another, but deviate at high \( p_r \), presumably largely due to the different nucleon-nucleon potentials employed. The data clearly indicate the need for FSI at high \( p_r \) and also significant contributions from non-nucleonic currents. For \( p_r < 200 \text{ MeV/c} \) the data deviate somewhat from Arenhövel’s full calculation. These discrepancies must be understood especially for the proper interpretation of the neutron form factor experiments which exploit the deuterons in this kinematic region.

A draft manuscript of these results is now in circulation among the collaboration and will be submitted to Physical Review Letters shortly. Clearly, additional measurements would be helpful in clarifying this situation. An experiment to systematically study this reaction over a broad kinematical range has already been proposed and conditionally approved by the JLab Program Advisory Committee [62].
Figure 25: Top panel: The reduced $d(e,e'n)$ cross section for this experiment along with various model calculations (see the text for details). Bottom panel: Measured cross sections and calculations shown as percentage deviations from the “full” calculation of Arenhövel. Also shown is the systematic error band ($\pm 1\sigma$), arbitrarily placed on the vertical axis. This error band contains an overall 7.2% contribution added in quadrature with the kinematic contribution, the latter varying slightly with $p_r$. 
2.6 E94-104

Photo-pion Production in Deuterium and \(^4\text{He}\) at 1.2-5.6 GeV

H. Xiang, H. Gao and R. Holt

for Experiment E94-104

2.6.1 The goal

The goal of the experiment is to probe the underlying quark structure of hadrons via a study of photo-reactions at high-energy, focusing on the processes of \(\gamma n \rightarrow \pi^- p\) and \(\gamma p \rightarrow \pi^+ n\) in deuterium at photon energies between 1.2 to 5.6 GeV, over which a transition might occur from the region of nucleon resonances to a region where the constituent (quark) counting rule governs. In addition, the experiment also set out to study the \(n(\gamma, \pi^- p)\) reaction in a \(^4\text{He}\) target.

2.6.2 The measurements

The data taking of the experiment took place in Hall A from mid-January through early March of 2001, with all three originally proposed measurements completed:

- Coincidence measurement of the quasi-elastic reaction \(\gamma n \rightarrow \pi^- p\) in a deuterium target, looking for the onset of the constituent counting rule behavior in this previously unexplored region of \(\sqrt{s} > 2.0\) GeV for this reaction.

- The cross-section ratio \(\pi^- / \pi^+\) of single-charged pion production in a deuterium target over a significantly extended \(|t|\) coverage: 0.3 through 5.6 (GeV/c)\(^2\). Previous measurements were limited to a small region of momentum transfer: \(|t| < 1.4\) (GeV/c)\(^2\).

- Coincidence measurement of the exclusive reaction \(\gamma n \rightarrow \pi^- p\) in a \(^4\text{He}\) target, studying the nuclear transparency of this fundamental process for the first time.

These measurements were translated into a well-phased data collection at 7 beam energies from 1.173 GeV up to 5.618 GeV, performed at a total of 38 different kinematics settings. Three different cryogenic targets were used, i.e. liquid hydrogen, liquid deuterium, and gaseous \(^4\text{He}\) as required by the three unique measurements. Special runs with empty targets and carbon targets were also taken for background subtractions and spectrometer optics calibrations. A total of about 1.2 Tb raw data were registered on tape.

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2.6.3 The analysis

The calibrations and online analysis started during the data taking among collaborators from MIT, ANL, Rutgers and JLab. The major reconstruction program, ESPACE, was expanded to include the three newly added detectors in the left spectrometer in Hall A, i.e. the two aerogel counters and the reconfigured lead glass pion rejector. The experiment PID capability is significantly extended to higher momenta, with the implementation of two newly built aerogel Cerenkov counters, A1 and A2. Effective separations of pions from their backgrounds are achieved as shown in Figs. 26 and 27.

![Figure 26: $\pi^+/proton$ separation (left arm)](image1)

![Figure 27: $\pi^-/e^-$ separation (right arm)](image2)

Analysis of the cross section for the quasi-elastic $d(\gamma, \pi^-)p$ reaction will form the Ph.D. thesis work of Lingyan Zhu from MIT. Hong Xiang, a postdoc from MIT, is currently working on the single $\pi^-/\pi^+$ ratio analysis. Recently, another MIT student, Feng Xiong, started analyzing the coincidence $^4\text{He}(\gamma, \pi^-)X$ data taken at the quasi-elastic kinematics.

Singles $\pi^-/\pi^+$ data from the $\theta_{cm} = 90^\circ$ setting have been fully analyzed and preliminary results on the pion ratio measurement have been extracted. The systematics studies are the focus of the further analysis. Figure 28 shows the reconstructed $E_\gamma$ spectra for $\pi^+$ from deuterium (left), $\pi^+$ from hydrogen (middle) and $\pi^-$ from deuterium (right), at a beam energy of $E_\gamma = 2.558$ GeV.

The coincidence cross section analysis for quasi-elastic $\gamma n \rightarrow \pi^- p$ reactions in deuterium and $^4\text{He}$ targets is also making good progress. Figures 29 and 30 show the reconstructed $E_\gamma$ from both real data and MC simulations at $E_\gamma = 2558$ MeV(deuteron target), and at $E_\gamma = 4232$ MeV($^4\text{He}$ target). Very preliminary results of the $\sqrt{s}$ dependence of the cross sections have been obtained early this October. In addition to further studies on the spectrometer acceptance models, more data sets are to be included in the near future.
Figure 28: $E_\gamma$ spectra for single $\pi^+$ and $\pi^-$ from deuterium and hydrogen targets.

Figure 29: $E_\gamma$ spectra reconstructed from the $\gamma n \rightarrow \pi^- p$ reaction in a deuterium target.

Figure 30: $E_\gamma$ spectra reconstructed from the $\gamma n \rightarrow \pi^- p$ reaction in a $^4$He target.

2.6.4 Summary and Outlook

Single $\pi^-$ and $\pi^+$ data from the $\theta_{cm} = 90^\circ$ set have been fully analyzed, and preliminary results will be available on completion of further systematics studies. Substantial progress has been made with the coincidence cross-section analysis for the quasi-elastic $\gamma n \rightarrow \pi^- p$ reactions in deuterium and $^4$He targets.
2.7 E97-103

Search for Higher Twist Effects in the Neutron Spin Structure Function $g_2^N(x, Q^2)$

T. Averett and W. Korsch, Spokespersons

Experiment E97-103 was successfully completed in the late summer of 2001. Spin asymmetries were measured using longitudinally polarized electrons scattered from either longitudinal or transversely polarized $^3$He in the inclusive reaction $^3He(e, e')$. From these measured asymmetries, the neutron spin structure function $g_2^N(x, Q^2)$ can be obtained. Data were collected at five values of $Q^2$ (0.58, 0.80, 0.96, 1.14, 1.36 GeV$^2$) at fixed $x \sim 0.2$, and with $W^2 > 4$ GeV$^2$. The two Hall A HRS spectrometers were used independently, with separate data acquisition systems, for detecting the scattered electrons. The Hall A polarized $^3$He target was used and reached the highest average polarization (over 40%) ever achieved with 10 – 12 μA of beam on target. The $^3$He nuclei were polarized through spin-exchange collisions with optically-pumped, polarized rubidium atoms. The polarization direction could be oriented parallel or perpendicular to the beam line and three 30 W diode lasers were used in each configuration for optical pumping. Target polarization was measured with NMR and EPR systems.

By measuring both the parallel and perpendicular spin asymmetries, $A_\parallel$ and $A_\perp$, one can obtain the $g_1$ and $g_2$ structure functions. A correction is made to the $^3$He results to obtain the structure functions for the neutron.

$$g_1(x, Q^2) = \frac{F_1(x, Q^2)}{D} \left[ A_\parallel + A_\perp \tan \theta / 2 \right]$$

$$g_2(x, Q^2) = \frac{F_1(x, Q^2)}{D'} \frac{y}{2 \sin \theta} \left[ A_\perp \frac{E + E' \cos \theta}{E'} - A_\parallel \sin \theta \right]$$

$$D' = \frac{(1 - \epsilon)(2 - y)}{y(1 + \epsilon R(x, Q^2))}$$

$$\epsilon = 1/(1 + 2(1 + \nu^2/Q^2)\tan^2 \theta / 2)$$

$$y = \nu / E$$

The $g_1$ structure function has been measured accurately at SLAC (deep-inelastic) and Jefferson Lab (E94-010, quasi-elastic and resonance regions) and is directly related to the spin decomposition of the nucleon in terms of quark flavors. For $g_2$, however, one must look beyond simple parton-model interpretations. It is generally described in the framework of the Operator Product Expansion, where the hadronic matrix element which describes the physics of $g_2$ is expanded in a series of operators and unknown coefficients grouped according to their twist [63]. The twist describes the degree to which a term contributes to the matrix element, where terms with successively higher twist are suppressed by additional factors of $1/\sqrt{Q^2}$. Leading twist (twist=2) describes the case where the virtual photon
probes a single, non-interacting quark. This contribution is also the leading contribution to the \( g_1 \) structure function. The twist=3 contributions arise when the virtual photon interacts with a quark that is simultaneously exchanging a gluon with another quark. These twist=3 terms do not contribute to \( g_1 \), which means that a precise measurement of \( g_2 \) allows one to isolate and quantify the most basic quark-quark interactions within the nucleon.

Based on the Operator Product Expansion, Wandzura and Wilczek [64] derived the following expression for the twist=2 part of \( g_2 \):

\[
g_2^{uw}(x, Q^2) = -g_1(x, Q^2) + \int_x^1 dy \frac{g_1(y, Q^2)}{y}
\]

Thus, by measuring \( g_2 \) precisely and subtracting the leading \( g_2^{uw} \) contribution, one is left with only the twist=3 and higher contributions to \( g_2 \).

The raw asymmetries measured in this experiment were at the \( 10^{-3} \) to \( 10^{-4} \) level and great care was taken to ensure there were no significant false asymmetries. In particular, a third DAQ system based on the HAPPEX system was used to continuously monitor the beam charge asymmetry. This information was fed to the polarized source every ten minutes, where a feedback system was used to zero the charge asymmetry with a rotatable half-wave plate at the source laser. Charge asymmetries were consistently kept well below the 200 ppm level. Data were also taken during the commissioning period using polarized beam and a series of thin carbon targets. The asymmetry during this period was measured to be \( 105 \pm 85 \) ppm (preliminary), which gives us confidence in our control of false asymmetries.

The data collected in E97-103 will allow us to calculate \( g_2^p \) at five values of \( Q^2 \), each with an absolute statistical error < \( 10^{-2} \), which is an order of magnitude improvement over existing data from SLAC (Experiment E155x, preliminary results). Analysis of the data is underway with preliminary results expected in the spring of 2002.
2.8 E97-111

Systematic Probe of Short-Range Correlations via the Reaction \(^4\text{He}(e,e'p)^3\text{He}\)


The goal of experiment E97-111 is to provide cross sections for the reaction \(^4\text{He}(e,e'p)^3\text{H}\) at recoil momenta up to 500 MeV/c in various kinematics. Many calculations have predicted a sharp minimum in the spectral function of \(^4\text{He} \rightarrow t + p\) for those recoil momenta. The location of this minimum, as well as the height of the second maximum are sensitive to the details of the nucleon–nucleon interaction used in those calculations. Because the minimum is predicted to occur at relatively high \(p_n\), we are especially sensitive to the short–range part of the interaction. The existence of this minimum itself is a feature of most of the exact calculations available, but has not been observed experimentally. Measuring this

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Table 7: Overview of the different kinematic settings of E97-111. For the constant \(Q\)-\(\omega\) settings (cq2a-c, cq3) the beam energy \(E_i\) was 3952 MeV, and the electron scattering angle \(\theta_e\) was 20.90°. The parallel kinematics were performed at \(E_i = 2389\) MeV, \(\theta_e = 16.9°\) (py1) and \(E_i = 3170\) MeV, \(\theta_e = 18.98°\) (py2).

cross section at various kinematical settings for the same recoil momentum also
allows a study of the reaction dynamics such as final–state interactions, meson–
exchange currents, and isobar configurations.

E97-111 ran in September and October of 2000. Cross sections have been
measured at several kinematics, which are summarized in Table 7. Additionally,
cross sections for elastic scattering off $^3$He have been measured at each beam
energy.

The first–pass online analysis did not show a clear signature of the expected
minimum, but did also not rule it out completely. Because the minimum might be
smeared out – due to reaction mechanisms – there might still be a change in the
slope of the cross section as function of the recoil momentum. Therefore a very
careful second–pass analysis is in progress. So far only the elastic $^3$He scattering
data have been analyzed, with respect to obtaining absolute yield factors. The ef-
fect of different beam currents on the target density has been studied (see Fig. 31),
and the databases, detector offsets, etc. have been optimized. Because the exper-
iment was running at very high singles rates, the understanding of the tracking
efficiencies of the VDCs, especially with respect to multi–cluster and multi–track
events is crucial for the extracting of the cross section. Studies of those effects as
well as of trigger efficiencies are still ongoing, but are necessary preparations for
the second–pass analysis, which is expected to be performed next year.

![Graphs showing data for Electron Singles and Hadron Singles for E97-111 ($^3$He)]

Figure 31: Preliminary results from the E97-111 beam-current scan to study beam-
current related density effects.
2.9 E98-108

Electroproduction of Kaons up to $Q^2 = 3 \text{ (GeV/c)}^2$


The E98-108 collaboration\(^4\) collected data at two dozen kinematics for the $\text{He}e^eK^+$ reaction in January, March and April 2001. At momentum transfers of 1.90 and 2.35 (GeV/c)\(^2\), the cross section was measured at invariant masses between 1.8 and 2.2 GeV for three values of $\varepsilon$ (the photon longitudinal polarization). The $\sigma_L$, $\sigma_T$, and $\sigma_{LT}$ cross sections will be extracted from the data. The transverse cross section $\sigma_T$, and longitudinal-transverse interference cross section $\sigma_{LT}$ will be used to constrain the reaction mechanism. The behavior of the longitudinal cross section $\sigma_L$ will be studied as a function of the Mandelstam variable $t$ at fixed $Q^2$. The kaon form factor is expected to show sensitivity to $\sigma_L$, albeit in a model-dependent way. The data will allow the kaon electroproduction reaction mechanism to be determined and eventually allow the kaon form factor to be modelled as well.

There are two doctoral students analyzing the data. Marius Coman of Florida International University and Leon Cole of Hampton University are working on the analysis. The experiment required building two new aerogel Čerenkov radiation

\(^3\)http://www.jlab.org/ markowitz/index.html
\(^4\)O. K. Baker, C. C. Chang, S. Frullani, M. Iodice, P. Markowitz, spokespersons
detectors with indices of refraction of 1.015 and 1.055. The first detector, due to the low index of refraction, required special handling of the delicate aerogel radiator. The first detector fired only on pions or lighter particles, but not on kaons or protons. The second aerogel was built primarily by the MIT group and fired on either kaons or protons but not pions. The use of two aerogels in anticoincidence is a novel PID idea. The response of the two new aerogels as a function of momenta has been studied in detail for protons, kaons and pions and is nearly finished. The wire chamber efficiency, electronic and computer dead times, and cut efficiencies have been determined. Radiative corrections have been done using the MCEEP simulation code; a comparison to the SIMC simulation code is underway.

The preliminary cross section results as a result of the invariant mass W are shown in Fig. 2.9. The left panel shows the Hall A data at $Q^2=2.35$ (GeV/c)$^2$ along with an empirical curve describing the $W$-dependence in terms of phase space and a resonance at 1.72 GeV. The right panel shows the real photon data ($Q^2=0$) published by the SAPHIR [66] collaboration. The same dependence is shown in both plots, indicating that the $W$-dependence is understood. The error bars will decrease by a factor of 4–5 when the analysis is final.

**Figure 32:** Shown on the left are the preliminary E98-108 H($e,e'K^+$) cross section results as a function of the invariant mass, $W$, on the right the published real photon data of Bockhorst et al. from SAPHIR plotted with the same empirical fit to the $W$-dependence.

The preliminary unseparated cross section data are plotted versus $Q^2$ in Fig. 2.9. The two arrows on the bottom indicate the location of our points. Again, the error
bars will decrease by a factor of 4–5 when the analysis is final. The world data were taken at a variety of \( \varepsilon \) meaning our agreement, while encouraging, should not be taken as a determination of the kaon form factor. The E98-108 data here represent the high energy (or large \( \varepsilon \)) points.

![Graph](image)

**Figure 33:** The preliminary E98-108 \( H(e, e'K^+) \) unseparated cross section is shown versus \( Q^2 \). Previously published world data are also shown.
Measurement of $G_E^p/G_M^p$ to $Q^2 = 5.6$ GeV$^2$ by the recoil polarization method


This experiment received 35 days of beam time in November and December 2000, with a beam current of $\sim 40 \mu$A. The ratio $\mu_p G_{Ep}/G_{Mp}$ has been measured at 4 different values of $Q^2$, the four-momentum transfer squared, between 3.5 and 5.6 GeV$^2$.

The recoil proton polarization was measured with the Focal Plane Polarimeter located at the focal plane of the left HRS. It measured the components of the proton polarization perpendicular to the momentum at the focal plane, and the spin was transported back to the target through the magnetic elements of the spectrometer using the differential algebra-based code COSY.

The scattered electron was detected in a large acceptance calorimeter. This calorimeter was assembled on the Hall floor with 9 columns and 17 rows of lead-glass blocks, of cross sectional area $15 \times 15$ cm$^2$ each. Software cuts on the coincidence time and the angular correlation with the recoil proton provided a very good selection of elastic events.

The analysis has been completed, and a Phys. Rev. Lett. was submitted in November 2001. The results of the experiment are presented in Fig. 34, together with the results of the first phase of this measurement, E93-027 [44]. The major source of systematic errors is related to the knowledge of the spin precession. A careful study of the misalignment of the quadrupoles, performed in 16 hours of beam time in April 2001 [65], reduced this error at $Q^2 = 3.5$ GeV$^2$ compared to Ref. [44] by a factor six, as shown in the top part of Fig. 34.

The data show that the roughly linear decrease of the ratio with $Q^2$ observed in E93-027 continues to 5.6 GeV$^2$. An extrapolation of this behavior to slightly higher $Q^2$ predicts a zero of $G_E^p$ around $Q^2 \sim 7.7$ GeV$^2$. Figure 35 shows a surprising scaling behavior of the ratio $QF_2^p/F_1^p$, starting at $Q^2 \sim 2$ GeV$^2$, rather than the pQCD prediction of a scaling of $Q^2 F_2^p/F_1^p$.

Extension of this measurement to higher $Q^2$ in Hall C was approved by PAC 20 [67]. Together with measurement of the other nucleon form factors at JLab, a much better understanding of the nucleon structure should become reality in the near future.
Figure 34: Ratio $\mu_p G_E^p/G_M^p$ measured in E93-027 and E99-007, with theoretical calculations. The systematic errors are represented by the band at the top.

Figure 35: Ratio $QF_2^p/F_1^p$ measured in E93-027 and E99-007, with theoretical calculations.
2.11 E99-114

The Real Compton Scattering (RCS) Experiment

Alan Nathan for the RCS Experiment Collaboration

2.11.1 Introduction

The Real Compton Scattering (RCS) experiment (E99-114) will measure the differential cross section for Compton scattering from the proton at incident photon energies between 2 and 5.5 GeV over a wide range of CM scattering angles ($s$ in the range 5-11 GeV$^2$ and $-t$ in the range 1.6-6.2 GeV$^2$). In addition, at a single kinematic point ($-t=4$ GeV$^2$), a longitudinally polarized beam will be used and the polarization transferred to the recoil proton will be measured. A high duty-factor electron beam with current $\geq 10$ $\mu$A is incident on a 6% copper radiator located just upstream of the scattering target. The mixed beam of electrons and bremsstrahlung photons is incident on a 15-cm LH$_2$ target. The experimental layout is shown schematically in Fig. 36. For incident photons near the bremsstrahlung endpoint, the recoil proton and scattered photon are detected with high angular precision in a magnetic spectrometer and photon spectrometer, respectively. The magnetic spectrometer is one of the pair of High Resolution Spectrometers (HRS-L) that are part of the standard Hall A equipment, along with the cryogenic hydrogen target and bremsstrahlung radiator. The Focal Plane Polarimeter (FPP) will be used in HRS-L for the polarization transfer measurement. The photon spectrometer is a new piece of equipment which has been constructed for this experiment. It consists of a large-area, 704-block lead-glass calorimeter, two planes of segmented (216) veto detector made of Lucite Cerenkov radiators, and a deflection magnet. The calorimeter detects electrons or photons that have scattered from the LH$_2$ target. The combination of veto detector and deflection magnet allows one to distinguish RCS events from $e-p$ elastic scattering event, since they are otherwise indistinguishable kinematically. The angular resolution of the combined HRS-RCS detector systems allows one to reduce to an acceptable level the background from photons that are the decay products of $\pi^0$'s that are photoproduced in the target. The complexity of this “third-arm” detector required a completely new data acquisition and data analysis system.

2.11.2 Progress Report

The past year has seen considerable progress on the RCS experiment. The experiment is scheduled for installation in Hall A starting December 10, 2001 and for running starting January 12, 2002. With the exception of the deflection magnet, all hardware components (calorimeter, veto, and data acquisition) have been completed and tested using cosmic rays and light pulser in the test lab and are ready for installation. The magnet was designed in early 2001 and constructed
Figure 36: Plan view of the RCS experiment in Hall A.

ever the past few months. All major components (iron, coils, support stand, and power supply) are at JLab. Assembly and testing will take place over the next few weeks and installation into the Hall A will take place early in January. In order to improve the FPP figure of merit, the FPP has been reconfigured so that, in effect, there are two FPP’s back-to-back.
Much progress has also been made in the on-line data analysis (for detector performance and data quality monitoring) and off-line data analysis (to obtain physics quantities). The basic scheme is to use ESPACE to produce HRS physics parameters, a newly written RCS analyzer to produce physics parameters associated with the RCS detector, and a “merge” program to combine the two sets of data for physics analysis. In addition, a new FPP-ESPACE was written to accommodate the hardware modifications to the FPP. As of this writing, most of the analysis routines have been written and tested and are currently being ported to the counting house computers.
2.12 E99-117

Precision Measurement of the Neutron Asymmetry $A_{1n}^n$ at Large $x$ using CEBAF at 6 GeV

J.-P. Chen, Z.E. Meziani, and P. Souder, Spokespersons, and
the Hall A Collaboration

Experiment E99-117 was proposed to measure the neutron asymmetry $A_{1n}^n(Q^2, x)$ at three values of Bjorken $x$, $x=0.33$, $x=0.48$ and $x=0.61$ with an absolute statistical uncertainty of about 5% at every $x$ point. It was designed to explore the spin of the neutron in the valence quark region. If our present understanding of the nucleon spin in terms of constituent quarks is valid $A_{1n}^n$ should become positive at kinematics accessible in this experiment [68]. Models based on pQCD arguments [69] predict that $A_{1n}^n$ becomes positive and, in the deep inelastic limit $Q^2 \to \infty$ and $x \to 1$, approaches unity. On the other hand, all present data are consistent with $A_{1n}^n$ being negative or zero. We point out that using a naive SU(6) symmetric wave function in the quark model $A_{1n}^n = 0$, a value not ruled out by the existing data. It is important to point out that all data obtained at several other labs to date have insufficient statistics to provide relevant information.

The experiment ran successfully in Hall A during the period June 01, 2001 to July 31, 2001. It used the highly polarized electron beam ($P_h \geq 80\%$) of CEBAF at 5.7 GeV with beam currents up to 15 $\mu A$. Electrons were scattered off a polarized $^3$He target ($P_t \geq 40\%$ in beam) with parallel and perpendicular target polarization orientations relative to the incident beam direction. The measurement consisted of collecting data on two spectrometers (left and right spectrometers) at one incident energy (5.734 GeV), two scattering angles (45° and 35°) and three spectrometer settings ($p = 1.3192$ GeV, 1.7372 GeV and 1.4583 GeV) - see Table 8.

At each kinematic point the electron beam helicity was flipped at a rate of 30 Hz allowing the measurement of the parallel and perpendicular raw double spin asymmetries $A_{\parallel}$ and $A_{\perp}$:

$$A_{\parallel} = \frac{\sigma_{\downarrow\uparrow} - \sigma_{\uparrow\downarrow}}{\sigma_{\downarrow\uparrow} + \sigma_{\uparrow\downarrow}}, \quad A_{\perp} = \frac{\sigma_{\uparrow\Rightarrow} - \sigma_{\downarrow\Rightarrow}}{\sigma_{\uparrow\Rightarrow} + \sigma_{\downarrow\Rightarrow}}$$

For the parallel settings, the two spectrometers sitting on each side of the beam produced as expected asymmetries of the same sign while for the perpendicular setting, the resulting asymmetries are opposite in sign.

To reduce systematic errors related to polarization direction of the beam or the target, data were taken with four different configurations for the parallel setting and two different configurations for the perpendicular setting. These different configurations were achieved using two half-wave plates: one for the beam polarization and the other for the target polarization. The half-wave plate for the
<table>
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<th>E(GeV)</th>
<th>(\theta(\degree))</th>
<th>E'(GeV)</th>
<th>(x)</th>
<th>(Q^2) (GeV^2)</th>
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<tr>
<td>5.734</td>
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<td>1.737</td>
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<td>1.319</td>
<td>0.33</td>
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Table 8: Summary of kinematics for E99-117 measurements.

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<tr>
<th>Beam (\lambda/2)</th>
<th>Target (\lambda/2)</th>
<th>Helicity +1</th>
<th>Helicity -1</th>
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<tr>
<td>out</td>
<td>out</td>
<td>↑↑</td>
<td>↓↑</td>
</tr>
<tr>
<td>out</td>
<td>in</td>
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<tr>
<td>in</td>
<td>in</td>
<td>↓↑</td>
<td>↑↑</td>
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Table 9: Polarization directions for E99-117 parallel settings.

beam changes the direction of the beam polarization for a given helicity signal while the target half-wave plate rotates the target polarization by 180\(^\circ\). Table 9 summarizes polarization directions for each configuration in parallel setting. For the perpendicular setting, only the beam half-wave plate has been inserted or taken out without changing the target polarization direction. The summary of polarization directions for the perpendicular setting is given in Table 10. To further investigate and reduce the systematic errors we performed elastic scattering measurements where the asymmetry is well known.

The experiment has exceeded slightly its statistical goals as stated in the proposal. A total volume of 563 Gb of data has already gone through two passes of analysis by Xiaochao Zheng of MIT at JLab. Preliminary results of \(A_1^p\) without radiative corrections were shown at the DNP meeting in Hawaii. A second independent analysis performed at Temple by Seonho Choi is confirming these results. Work is in progress to finalize the numbers on several parameters entering in the evaluation of the asymmetry. We are in the process of performing a third pass to determine the systematic uncertainties of raw asymmetries (for example, further checks of the acceptance cut dependence of the spectrometers are underway), beam and target polarizations. We also plan to take into account information of the beam (like the beam position monitors and the raster) event by event instead

<table>
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<tr>
<th>Beam (\lambda/2)</th>
<th>Target (\lambda/2)</th>
<th>Helicity +1</th>
<th>Helicity -1</th>
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<tr>
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<td>out</td>
<td>↓⇒</td>
<td>↑⇒</td>
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Table 10: Polarization directions for E99-117 perpendicular settings.

80
of averaging over all events as was done for the preliminary results. Radiative corrections and their systematic uncertainties are to be evaluated before the results can be final.

In this experiment of which the primary goal is to produce the asymmetry $A_1^n$, we still plan to extract the absolute cross sections from our measurement and obtain the spin structure functions $g_1$ and $g_2$. We have also observed large inclusive pion production asymmetries which we believe are quite interesting and might be the subject of theoretical investigations in the future.

We expect to have reliable results early in 2002.
2.13 Test Run Report

Test Run in Preparation for a PAC21 Proposal:
A Search of Neutral Baryon Resonances
Below Pion Threshold Through $p(e,e'\pi^+)X^0$ Reaction

X. Jiang, G. Chang, T. Chang, L. Cole, L. Elouadrhiri, R. Gilman,
D. Higinbotham, M. Jones, N. Liyanage, D. Mack, J. Mitchell, P. Markowitz,
B. Wojtsekhowski

We conducted a 12 hour test in April of 2001 to study the $p(e,e'\pi^+)X^0$ reaction. The goal of this activity was to test an earlier claim of narrow baryon resonances below pion threshold and to provide guidance for a proposal of more detailed studies.

In 1997, a French group published possible evidence of neutral baryon resonances in p-p inelastic scattering [70]. The missing mass spectra in $pp \rightarrow p\pi^+X^0$ reaction demonstrated unexpected structures at 1004, 1044 and 1094 MeV. The strength of these resonances were close to the 1.0% level compared to the yield of the $pp \rightarrow p\pi^+n$ peak. These results are most astounding when one considers the countless experiments carried out with many different probes over the more than 50-year time period in which these resonances were never observed.

We chose to perform the $(e,e'\pi^+)$ measurement in the second resonance region ($W = 1.4$ GeV and $Q^2 = 0.20$ (GeV/c)$^2$) with the Hall-A high resolution spectrometer pair. The $X^0$ state would be a product of strong interaction process, as shown in Fig. 37 (where it is seen that; $p,\Delta, \text{or } N^* \rightarrow \pi^+ + X^0$), and would result in an abnormal structure in the reconstructed missing mass. The beam energy was 1.722 GeV, the right HRS was set to -1.040 GeV/c at 19.0° as the electron detector. The hadron arm setting is listed in Table 11. The choice of kinematics was made by optimizing the missing mass resolution while having a reasonable $p(e,e'\pi^+)n$ cross section. The values of $W$ and $Q^2$ were chosen to match that of Ref. [70].

![Diagram of the $p(e,e'\pi^+)X^0$ reaction.](image)

Figure 37: Diagram of the $p(e,e'\pi^+)X^0$ reaction.

The gas Cherenkov counter in the electron arm provided a clean $e/\pi^-$ separation while the measured particle speed combined with scintillator ADC signals on
the hadron arm provided a clean $\pi^+/p$ separation. The time-of-flight resolution was 2.0 ns (FWHM) after corrections were made for TDC-offsets, time-walks, and particle travel time differences. As shown in Fig. 38, beam structure was visible but beam pulses were not clearly separated from each other. This unfavorable time resolution restricted us to run at 33 $\mu$A beam in order to keep the signal-to-noise ratio at 1:1.

![Figure 38: The time-of-flight spectrum from the $p(e, e'\pi^+)$ test run.](image)

The charge-normalized yield is plotted as a function of reconstructed missing mass in Fig. 39(a). The missing mass resolution was 2.0 MeV (FWHM) for the $p(e, e'\pi^+)n$ calibration. A third power polynomial function fits smoothly through the data, and the fit residues are normalized by the $p(e, e'\pi^+)n$ peak height as shown in Fig. 39(b). An upper limit can be obtained on the ratio of the $\pi N X$ coupling to the $\pi NN$ coupling. In the mass region of $0.96 < M_{X^0} < 1.06$ GeV, we conclude that

$$\left( \frac{g_{\pi N X}}{g_{\pi N N}} \right)^2 \frac{\sigma_{p(e, e'\pi^+)X^0}}{\sigma_{p(e, e'\pi^+)n}} \leq 10^{-3}$$

(6)

For this brief test, our sensitivity is compatible to that of Ref. [70], but we can not confirm the claim of narrow structures at 1004 and 1044 MeV. We note here that improvements can be made to significantly enhance the sensitivity of our search. A better calibrated transverse-optics database for both HRS spectrometers could allow tighter cuts on the interaction points, gain at least a factor of two in signal-to-noise ratio. In addition, the sampling frequency of BPM/Raster readout could

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<th>$P_L$ (GeV/c)</th>
<th>Time (Hours)</th>
<th>Comments</th>
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<td>0.621</td>
<td>1.0</td>
<td>calibration</td>
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<tr>
<td>Kin-B</td>
<td>41.6°</td>
<td>0.543</td>
<td>11.0</td>
<td>cover $0.96 &lt; M_{X^0} &lt; 1.06$ GeV.</td>
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</table>
be increased to improve the accuracy on beam position from 500 \( \mu \text{m} \) to 200 \( \mu \text{m} \). A 10 cm liquid H\(_2\) target instead of a 15 cm one can be used to improve the missing mass resolution by 30\%. The time-of-flight resolution can be improved to 500 ps (FWHM) following the scheme of Hall C [71]. These improvements will allow us to take the maximum current of 120 \( \mu \text{A} \). For a 300 hour measurement, 100 times more events can be collected and the sensitivity of our search can be enhanced by an order of magnitude.

![Graph](image)

Figure 39: The reconstructed \( p(e, e' \pi^+)n \) missing mass spectrum is shown in (a). The charge-normalized \( (e, e' \pi^+) \) yields in arbitrary units are plotted in 1.0 MeV bins. Corrections have been applied for pion decay, DAQ dead time, and the phase-space volumes. Figure (b) shows the residues from a third-power polynomial fit, normalized to the \( p(e, e' \pi^+)n \) peak-height. Errors bars are statistical only.

In conclusion, we performed a brief missing-mass search through the reaction of \( p(e, e' \pi^+)X^0 \). Within our very limited statistics, no abnormal structure can be identified in the mass region of \( 0.96 < M_{X^0} < 1.06 \text{ GeV} \). We learned that the kinematics was properly chosen such that the missing mass resolution was adequate. However, the 2.0 ns coincident time resolution severely limited our
sensitivity. A plan to significantly improve the timing resolution is in preparation which will benefit all Hall-A coincident experiments. A formal physics proposal will be prepared for PAC-21.
References


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[38] D. Drechsel et al., Nucl Phys A645, 145 (1999), and http://www.kph.uni-mainz.de/MAID/


[43] With the initial and final electron momentum \( \vec{k}_i \) and \( \vec{k}_f \), the coordinate system is given by the unit vectors \( \hat{z} = (\vec{k}_i - \vec{k}_f)/|\vec{k}_i - \vec{k}_f| \), \( \hat{y} = (\vec{k}_i \times \vec{k}_f)/|\vec{k}_i \times \vec{k}_f| \), and \( \hat{x} = \hat{y} \times \hat{z} \).


[52] VCSSIM code, L. Van Hoorebeke, Gent Univ., Gent, Belgium.


[65] L. Pentchev et al., Quadrupole Alignment Studies in teh HRSSs, JLab Technical Note TN-01-052.


4 Members of the Hall A Collaboration

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5 Hall A Publications

- Transverse Asymmetry \(A_T\) from the quasielastic \(^3\)He\((\vec{e},e)\) process and Neutron Magnetic Form Factor, W. Xu et al., Phys. Rev. Lett. 84, 3265 (2000).
• $G^n_E/G^n_M$ Ratio by Polarization Transfer in $\bar{e}p \rightarrow e\bar{p}$, M. K. Jones et al., Phys. Rev. Lett. 84, 1398 (2000).

