# Letter of Intent Test of Time Reversal Invariance Using Electron Scattering on Polarized Protons 

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#### Abstract

We propose to test the time reversal invariance properties of the electromagnetic interaction, improving the precision of current measurements by a factor of 100 to 250 , in 60 days of running. The measurement can be done using TJNAF's electron beam, a solid polarized target capable of polarizing $\mathrm{NH}_{3}$ material in the direction normal to the scattering plane using Hall A SoLID detector system with the JLab/UVA polarized target in the transverse direction.


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## 1 Motivation

Invariances of the laws of physics under discrete symmetry operations, such as space translations or space rotations, reflect fundamental properties of matter. For example, it is well known that the invariances just mentioned reflect the laws of linear and angular momentum conservation for isolated systems. It is also well known that not all physical processes are invariant under every symmetry operation: the weak interaction violates invariance under space reflection (parity, $P$ ) and the decay of the neutral $K$ meson violates invariance under the combined charge conjugation $(C)$ and parity operations $C P$.

However, it is not known for certain whether all the $C, P$ and $C P$ conserving interactions are also invariant under time reversal $(T)$. $T$ invariance is reflected in the law of conservation of energy for systems with conservative forces. A fundamental theorem of relativistic field theory states that all interactions must be invariant under the combined CPT operation[1], and therefore $C P$ invariance implies $T$ invariance, and correspondingly $C P$ violation implies $T$ violation, as in the $K^{0}$ decays. But there are no precision direct tests of $T$ non-invariance in the $C P$ conserving interactions, which would imply $C P T$ violation. Also, $P$ could be conserved while $C$ and $T$ are separately violated.

The strong interaction $H_{h}$ has been shown to a high precision to be invariant under parity $P_{h}$, time reversal $T_{h}$ and particle-anti particle conjugation $C_{h}$, where the subscript $h$ denotes operations on hadronic systems. Similarly, the electromagnetic interaction $H_{\gamma}$ is invariant under $P_{\gamma}, T_{\gamma}$ and charge conjugation $C_{\gamma}$. An example of $C_{\gamma}$ invariance is the high suppression of the decay $\pi^{0} \rightarrow 3 \gamma$ which has a $<3 \times 10^{-8}$ branching ratio[2]. Both $H_{\gamma}$ and $H_{h}$ are invariant under $P_{\gamma}=P_{h}$ and under the combination $C_{\gamma} P_{\gamma} T_{\gamma}=C_{h} P_{h} T_{h}$. However, as pointed out in ref.[3], $H_{\gamma}$ has not yet been shown to be invariant under particle-anti particle conjugation $C_{h}$, which for hadrons is not necessarily identical to charge conjugation $C_{\gamma}$. It is assumed that $H_{\gamma}$ is invariant under $C_{h}$, or $C_{h}=C_{\gamma}$, for both leptons and hadrons, but it has not been tested for hadrons in a model independent way to better than $\sim 10^{-4}[2,4]$. Any violation of $C_{h}$ by $H_{\gamma}$ implies $T_{h}$ non-invariance, by the $C P T$ theorem and the observed $P_{h}$ invariance of both $H_{h}$ and $H_{\gamma}$.

The non-invariance of the electromagnetic interaction under $T_{h}$ or $C_{h}$ would manifest itself as a non-zero additional component $K_{\mu}$ of the hadronic part of the electromagnetic current[3]

$$
\begin{equation*}
e \mathcal{J}_{\mu}=e\left(j_{\mu}+J_{\mu}+K_{\mu}\right) \tag{1}
\end{equation*}
$$

where $j_{\mu}$ is the leptonic current and $J_{\mu}$ is the normal hadronic current. $\mathcal{J}_{\mu}$ changes sign under $C_{\gamma} \mathcal{J}_{\mu} C_{\gamma}^{-1}=-\mathcal{J}_{\mu}$, but $K_{\mu}$ may not change sign under $C_{h} K_{\mu} C_{h}^{-1}=+K_{\mu}$. Then, by $C P T$, a non-zero $K_{\mu}$ implies that $H_{\gamma}$ is not $C_{h}$ and $T_{h}$ invariant, since

$$
\begin{gather*}
T_{\gamma} \mathcal{J}_{\mu} T_{\gamma}^{-1}=-\mathcal{J}_{\mu} \\
T_{h} J_{\mu} T_{h}^{-1}=-J_{\mu} \\
T_{h} K_{\mu} T_{h}^{-1}=K_{\mu} \tag{2}
\end{gather*}
$$

A direct test of $T_{h}$ violation in electromagnetic interactions would involve studying a process in which current signs in lepton-hadron scattering are reversed without resorting to charge conjugation. As suggested by several authors [3, 5, 6, 7] polarized scattering in which either the initial state is polarized, or the polarization of the final state is observed,
meet this condition. In what follows, we will concentrate on the first approach, since, unlike the second method, it does not require accounting for all contributions to the polarization from final states other than the chosen one.

It should also be pointed out that there are other processes that can be used to test $T$ invariance of the various interactions, either directly or through $C$ or $P$ invariance, such as the limits on the dipole moments of the electron, neutron and other particles. Among the direct tests, the angular correlations in neutron, muon and other weak decays are notable. These and other direct tests indicate that $T$ invariance for the weak interaction is obeyed at the $1 \%$ to $0.1 \%$ level[2].

## 2 Experimental Technique

We propose to carry out a direct test of $T$ invariance in the electromagnetic interactions of hadrons by measuring the inclusive asymmetry in the scattering of electrons on polarized protons in the region of the nucleon resonances. Any individual final state or all the final states combined can be considered, as long as they are not identical to the initial state. For the latter case, which corresponds to elastic scattering, the asymmetry is zero by current conservation and hermiticity, in the single photon exchange approximation. Therefore, we also plan a simultaneous measurement of the elastic asymmetry, to quantify the contributions to the asymmetry of deviations from single photon exchange.
$T$ non-invariance would manifest itself in the presence of non-zero structure functions proportional to the correlation[3]

$$
\begin{equation*}
\mathrm{S}_{\mathrm{in}} \cdot \mathrm{k} \times \mathrm{k}^{\prime} \tag{3}
\end{equation*}
$$

where $\mathbf{S}_{\mathbf{i n}}$ is the polarization of the nucleus, and $\mathbf{k}, \mathbf{k}^{\prime}$ are the initial and scattered electron three-momenta in the laboratory. Thus, for this test, the nucleus has to be polarized in a direction normal to the electron scattering plane, usually horizontal in the lab.

Writing the correlation in the approximation $m_{e} / E \ll 1$, where $m_{e}$ is the electron mass, $\mathbf{S}_{\mathbf{i n}} \cdot \mathbf{k} \times \mathbf{k}^{\prime}$ reduces to $P_{t} E E^{\prime} \cos \phi \sin \theta$, where $P_{t}$ is the magnitude of the target polarization. The cross section for this type of scattering can then be written as

$$
\begin{equation*}
\frac{d^{2} \sigma}{d E^{\prime} d \Omega}=\sigma_{M o t t} \frac{E^{\prime}}{E}\left(2 W_{1} \tan ^{2}(\theta / 2)+W_{2}+\frac{E^{2}-E^{\prime 2}}{M^{2}} P_{t} W_{3} \cos \phi \tan (\theta / 2)\right) \tag{4}
\end{equation*}
$$

where $E, E^{\prime}$ are the beam and scattered electron energies in the lab system, $\theta$ is the scattering angle, $M$ is the nucleon mass and the Mott cross section is $\sigma_{M o t t}=\left(\alpha \cos (\theta / 2) / E \sin ^{2}(\theta / 2)\right)^{2}$. $W_{1}\left(Q^{2}, \nu\right)$ and $W_{2}\left(Q^{2}, \nu\right)$ are the usual inelastic structure functions of the four-momentum transfer squared $Q^{2}$ and the electron energy loss $\nu=E-E^{\prime}$, and $W_{3}\left(Q^{2}, \nu\right)$ is non-zero only if the electromagnetic interaction is not invariant under $T$. If $W_{3}$ is not zero, the $T$ transformation introduces an up-down asymmetry, because both the time-reversed momenta and the spin change sign.

The counts asymmetry

$$
\begin{equation*}
\varepsilon=\frac{U-D}{U+D} \tag{5}
\end{equation*}
$$

where $U, D$ are numbers of events for the nuclear spin $\mathbf{S}_{\mathbf{i n}}$ parallel or anti parallel to the $\mathbf{k} \times \mathbf{k}^{\prime}$ vector, can be written in terms of the counting rates for each orientation. For an
ammonia $\left(\mathrm{NH}_{3}\right)$ target ${ }^{1}$, including the polarization of hydrogen and nitrogen, one has

$$
\begin{array}{rlc}
U(D) & = & \Phi\left(N_{N} \sigma_{e N}^{U(D)}+N_{H} \sigma_{e H}^{U(D)}+\sum N_{A} \sigma_{e A}\right) \\
& = & \Phi\left(N_{N} \sigma_{e N}\left(1 \pm P_{N} A_{N}\right)+N_{H} \sigma_{e H}\left(1 \pm P_{H} A_{H}\right)+\sum N_{A} \sigma_{e A}\right) \tag{6}
\end{array}
$$

where the flux factor $\Phi$ includes the beam current and detector acceptance; the $N_{X=N, H, A}$ represent the numbers of nitrogen, hydrogen and other unpolarized nuclei in the target; $\sigma_{e X}\left(Q^{2}, \nu\right)$ is the inelastic inclusive unpolarized electron-nucleus cross section for each case; $A_{X=N, H}$ are the corresponding asymmetries $(+(-)$ sign corresponds to $U(D))$ and $P_{X=N, H}$ are the polarizations. Since the scattering is in the region of the nucleon resonances, only incoherent $e-$ nucleon processes are involved. The numerator of $\varepsilon$ is

$$
\begin{equation*}
U-D=2 \Phi N_{H} \sigma_{e H} P_{H} A_{H}\left(1+C_{N}\right) \tag{7}
\end{equation*}
$$

where $C_{N}=1 / 3\left(P_{N} / P_{H}\right) \beta$ is the contribution of the unpaired polarized proton in ${ }^{15} \mathrm{~N}$, with $\beta$ being the effective proton polarization in polarized nitrogen, approximately $1 / 3$. $C_{N}$ is on the order of $0.02 \pm 0.002$, although the accuracy of this figure can be improved by a factor of 5 or more. The denominator is

$$
\begin{equation*}
U+D=2 \Phi\left(N_{N} \sigma_{e N}+N_{H} \sigma_{e H}+\sum N_{A} \sigma_{e A}\right) \tag{8}
\end{equation*}
$$

The resulting counts asymmetry is

$$
\begin{align*}
& \varepsilon= \\
& f\left(P_{H} A_{H}\left(1+C_{N}\right)\right.  \tag{9}\\
&f, \nu)= \\
& N_{N} \sigma_{e N}+N_{H} \sigma_{e H}+\sum N_{A} \sigma_{e A}
\end{align*}
$$

$f\left(Q^{2}, \nu\right)$ is the dilution factor.
The ratio of the difference to the sum of the cross sections for the two opposite spin orientations for unit target polarization $P_{t}=1$ is

$$
\begin{equation*}
A_{H}=\frac{W_{3}\left(E^{2}-E^{\prime 2}\right) \cos \phi \tan (\theta / 2)}{M^{2}\left(2 W_{1} \tan ^{2}(\theta / 2)+W_{2}\right)} \tag{10}
\end{equation*}
$$

Any non-zero $\varepsilon$ is therefore an indication of a departure from $T_{h}$ invariance of $H_{\gamma}$, except for interference effects. One effect comes from interference between single photon exchange and multi-photon processes, which are suppressed by at least a factor $\alpha$. This effect is proportional to the lepton charge, so it can be calculated as well as tested and corrected for by $e^{+}$- polarized nucleon scattering. More details on this effect are given in a later section.

Another effect could be due to the interference between $\gamma$ and $Z$ exchanges, which could mimic $T_{h}$ violation through the parity violating electroweak interaction. This effect would be present only if polarized lepton beams were used, and it may be minimized by taking equal amounts of data with positive and negative target polarization.

[^0]
## 3 Existing Results

Only two measurements of the asymmetry $A_{H}$ have been done to date[8, 9], over thirty years ago. The slightly more precise results of SLAC experiment 029 [9] found no $T$ violating asymmetry to a $\sim 2 \%$ precision, for four-momentum values ranging from $Q^{2}=0.4$ $\mathrm{GeV}^{2}$ to $1 \mathrm{GeV}^{2}$, in the invariant mass $W$ regions of the $\Delta(1232), N^{*}(1512)$ and $N^{*}(1688)$ resonances (data in the range $1100 \mathrm{MeV} \leq W \leq 2600 \mathrm{MeV}$ were measured). This kinematic region was chosen because the data available at the time seemed to indicate that the longitudinal photon absorption cross section $\sigma_{L}$ was significant. An interference between the transverse cross section $\sigma_{T}=4 \pi^{2} \alpha W_{1} / K$ and $\sigma_{L}=4 \pi^{2} \alpha\left(\left(Q^{2}+\nu^{2}\right) W_{2} / Q^{2}-W_{1}\right) / K$ is equivalent to a non-zero $\sigma_{L T}=4 \pi^{2} \alpha \nu W_{3} /\left(K \sqrt{Q}^{2}\right)$. Here, $K=\left(W^{2}-M^{2}\right) /(2 M)$ is the real photon energy needed to produce the final state mass $W$. Both electron and positron beams gave similar null result. These results have been interpreted in detail in ref.[10].

The asymmetry for elastic scattering was also measured at SLAC in the same experiment[12]. No significant effects were observed at a similar 1 to $2 \%$ level.

SLAC E029 used a butanol target with an average polarization of 0.2 and a dilution factor $0.06 \leq f \leq 0.11$. The 20 GeV spectrometer in SLAC ESA with a 0.14 msr solid angle was used to detect the scattered electrons. Obviously, in the intervening time there has been substantial progress in polarized target, detector and accelerator technologies, that make it worthwhile to revisit this question. In what follows, we outline a proposed measurement that could improve the precision of the existing results by a factor of 100 to 250 .

A recent measurement of the vector analyzing power in transversely polarized elastic $e-p$ scattering[13] indicates that the asymmetry due to multiphoton exchanges at $Q^{2}=$ $0.1 \mathrm{GeV}^{2}$ ( 200 MeV beam at $146^{\circ}$ scattering angle) is $-15.4 \pm 5.4 \mathrm{ppm}$. The momentum transfer and energy dependence of this asymmetry are unknown. Taking into account the $m_{e} / E$ supression of transverse beam polarization effects relative to longitudinal polarization ( $m_{e}$ is the electron mass, $E$ the beam energy,) the observed effect would correspond to a sizable $0.6 \%$ asymmetry with longitudinally polarized beams. Confirming this result would be an interesting measurement in itself.

COSY has planed a novel (P-even, T-odd) null test of time-reversal invariance to an accuracy of $10^{-6}$ as an internal target transmission experiment [11].

## 4 Proposed Measurement

We propose to study $T$ violation in inclusive inelastic scattering of electrons on polarized protons using an ammonia $\left({ }^{15} \mathrm{NH}_{3}\right)$ solid polarized target, a 20 to 100 nA electron beam, and an electron spectrometer.

The kinematic region of interest is the region of the nucleon resonances at several values of $Q^{2}$. The presence of a significant $\sigma_{L}$ component at some momentum transfer is a favorable indication, but is not necessarily a requirement, since the interference term may be larger than the $\sigma_{L}$ component as, for instance, in the case of the neutron charge form factor. Elastic scattering data will be collected simultaneously, to control the multiphoton exchange contributions.

The polarized target needs to have a transverse oriented magnetic field, making a cylindrically symmetric detector system like SoLID at JLab's Hall A. Dynamic nuclear polarization (DNP) in a 5 T field at 1 K , using a He evaporation refrigerator to polarized ammonia is required. This choice simplifies some of the design requirements, especially of the auxiliary beam raster system needed to distribute the beam dose uniformly over the target cell face. A chicane system is needed to correct for the horizontal deflection of the beam introduced by the target field.

As mentioned earlier, ammonia is the material of choice because of its favorable characteristics. Although the initial polarization of the material decays during data taking due to radiation damage, ammonia can be restored repeatedly to near original conditions by annealing at $\sim 100 \mathrm{~K}$. The average time between anneals depends on the beam current, and ranges from about 5 hours to longer than 12 hours. The overhead due to the anneals can be kept to a minimum by optimizing the beam current for the best counting rate.

The SoLID detector system provided adequate resolution for the physics at hand. The associated detector package must have the electron detection and particle identification capabilities commonly used in single arm $e$ - nucleus scattering. The Hall C HMS and Hall A HRS meet these requirements. A dedicated device specifically assembled for this measurement is another possibility. It is also possible to consider the Hall C HMS and Hall A HRS meet which these requirements in combination with a new rotated coil magnet. A dedicated device specifically assembled for this measurement is another possibility.

With existing polarized target luminosities of $10^{35} \mathrm{~cm}^{-2} \mathrm{~Hz}$, and detector solid angles of several msr, the precision of the proposed measurement is determined by the counting rate that can be accepted by the detector system and the length of the data taking run. The average $P_{t}=0.85$ and the dilution factor $f \sim 0.19$ for ammonia are a factor of $\sim 8$ better than in E029. This factor would need to be combined with an additional factor of 12 to 15 to attain the proposed improvement of 100 or better. Such factor would require about 150 times more events detected than in the SLAC experiment. E029 had statistics of 4 million events $/ 60 \mathrm{MeV}$-wide bin, implying that 600 million would be needed in our case. These can be accumulated in a 60 days run at $100 \%$ efficiency, if the rate per bin is about 120 Hz in the region of the $\Delta(1232)$, or $\sim 1.2 \mathrm{kHz}$ for the invariant mass region from the elastic peak to $\sim 2000 \mathrm{MeV}$. This rate can easily be achieved at JLab at the $Q^{2}$ of interest.

Significant improvements in optimizing the kinematics settings and the beam current are possible, which would result in a shortening of the run time, or improved statistics, if a high rate data acquisition system were available. The option of replacing the current wire chambers with hodoscopes to increase the rate capabilities of the packages and reduce the event record size is very attractive, given the moderate $W$ resolution needed ( $\sim 60 \mathrm{MeV}$ ). Thus, an overall improvement of a factor of at least 100 and possibly 250 or higher in the statistical uncertainty is achievable in a reasonably long run. It should be mentioned that independent of the detector rate limitations, high energy beams are preferred in order to have the highest scattering rates possible.

The systematic uncertainties must be kept at the same or lower level as the statistical error. The important systematic errors are those that would introduce false asymmetries (add extra up or down counts). Since the beam is unpolarized, there is no concern over a beam charge asymmetry. More important are rate effects, since the detector, electronics
and computer dead time are sensitive to the slightly different counting rates for up versus down counts. These effects need to be monitored carefully for appropriate correction. The errors in the normalization factors $P_{t}$ and $f$ do not introduce false asymmetries but, of course, must be kept as small as possible.

Numerous reversals of the target polarization will average out much of the fluctuations in detector and current monitor efficiencies. The polarization can be inverted by changing the frequency of the microwaves that induce the DNP. The time needed to invert the polarization under microwave pumping is less than 25 minutes, and can be reduced further. A target system with two cells, one of which is in the beam, can speed the time needed for polarization reversals. Also, half of the reversals can be synchronized with the anneals, further reducing overhead. A reversal every 4 hours is one option, which would represent a total of 360 reversals for the run.

An alternative configuration would be to have two cells in the beam path each with opposite polarization orientations. This configuration requires the microwave cavities of the target cells to be isolated from each other so that they can be independently pumped at their corresponding frequencies. Vertex reconstruction resolution capable of identifying events as originating in either cell is also needed for this option.

## 5 Positron asymmetry

As indicated earlier, some processes other than single photon exchange can produce an up-down asymmetry that may interfere with the $T$ violating process we want to study. The authors of ref.[10] have thoroughly studied the question and their result indicates that only processes of order $\alpha^{3}$ are of concern. They have derived the formulas needed for calculating the size of this effect. In addition, the terms involved in the $\alpha^{3}$ asymmetry are of opposite signs for positrons and electrons. Thus, this asymmetry cancels when $A_{H}$ measured with a positron beam is combined with the corresponding electrons asymmetry.

Since the usable beam current is very small ( $<150 \mathrm{nA}$ ), the performance required of a positron source is not excessive. With a $6 \mathrm{GeV} 60 \mu \mathrm{~A}$ beam incident on a $1 X_{0}$ thick production target, the average energy of a shower particle would be 3 GeV and the average shower multiplicity 2. A system capable of collecting one 3 GeV positron in $\sim$ 1000 would generate a 60 nA beam. Detailed simulations and calculations are obviously needed to design an efficient system, that would have to meet specifications defined by the choice of kinematics of the experiment.

## 6 Polarized beam effects

When polarized beams are used there are four additional correlations[3] between the spins and momenta, that give rise to 3 more structure functions $W_{4,5,6} .{ }^{2}$ Of these, only the correlation $\mathbf{S}_{\mathbf{N}} \cdot\left(\mathbf{k}-\mathbf{k}^{\prime}\right) \times\left(-\mathbf{S}_{\mathbf{l}}\right) \cdot \mathbf{k}$ involving $W_{6}$ would show a possible $T$ violation. Here $\mathbf{S}_{1}$ is the beam helicity. The existing literature gives little additional information

[^1]on the significance of $W_{6}$ (or on the other $W^{\prime}$ 's and $G^{\prime}$ 's) and of the possible advantages of measuring its associated correlation over the one for unpolarized beam regarding, for example, multiple photon exchange effects. This approach will be investigated further by our collaboration, and additional input from theoreticians and members of the lepton scattering community is welcome.

## 7 Summary

We believe that a major improvement in our knowledge of the invariant properties of the electromagnetic interactions of hadrons can be achieved thanks to the advances in beam, target and detector technologies. It is likely that a null result will be found. On the other hand, we should not forget that $P$ and even $C P$ turned out to be non-invariant when examined at the right level of precision. The more than two orders of magnitude improvement that we propose will test $T$ in an entirely new regime.

## 8 Polarized $\mathrm{NH}_{3}$ target

We propose to us an upgraded version of the JLab/UVa/SLAC polarized NH3 target. The main upgrade will be to use a new magnet to replace the aging Helmholtz-coil magnet and to have fast spin-flip capability with the AFP technique. The target is based on the principle of dynamic nuclear polarization (DNP) by using microwave pumping to reach high proton polarizations $[25,26]$.

The target is operating at a low temperature of 1 K and a strong magnetic field of 5 T . The NH3 material is chosen because of its proven property of excellent radiationresistance to electron beam damage to the target polarization. The current achieved best performance for such kind of experiments with a polarized lepton-beam on a polarized proton target was with this target which reached a luminosity of $10^{35}$ proton $/ \mathrm{cm}^{2} / \mathrm{s}$ with an in-beam average polarization of $80 \%$. In this experiment, the ability to flip the target polarization frequently is important for the suggested measurements in terms of reducing systematics. Adiabatic fast passage (AFP) NMR has been demonstrated as an effective ( $90 \%$ efficiency) way of spin flip for a DNP target with ${ }^{7} \mathrm{LiH}$ as a target material [27] and recently a AFP spin flip test has been achieved by the UVA polarized target group for $\mathrm{NH}_{3}$ with approximately $52 \%$ efficiency for the condition at $5 \mathrm{~T} / 1 \mathrm{~K}$ confirming predictions ( [28]). It is expected that efficiency can be still improve by optimizing the Q -value of the circuit which is sensitive to the coil geometry and amount of material. The AFP results already indicate that 20 minutes could potentially be safe for every target helicity change.

A set of superconducting Helmholtz coils provide a 5-T field with a highly uniform area, about $3 \mathrm{~cm} \times 3 \mathrm{~cm} \times 3 \mathrm{~cm}$ in the center. The existing magnet was designed mainly for longitudinal polarization while also allowing transverse polarization. In the longitudinal case, it has a large opening in the forward region $\left( \pm 45^{\circ}\right)$ for scattered particles to be able to reach the spectrometer/detector system, while in the transverse case, it has only about $\pm 17^{\circ}$ nominal opening in the forward region. The new design will optimize to allow both transverse and longitudinal to have a nominal forward opening of more than $\pm 28^{\circ}$, while maintain the same maximum field and uniform field region in the center.

A couple of target cells with length of 3 cm are immersed in a vessel filled with liquid helium which was maintained at 1 K by a series of large pumping system. The target cell is filled with beads of solid NH3 material with a typical packing factor of about $50 \%$ with the rest of the space filled with helium.

The target material is usually prepared by irradiation before-hand at a low energy electron facility, such as NIST. During the experiment, the target material is exposed to 140 GHz microwaves to drive the hyperfine transition which aligns the proton spins. The DNP technique produces proton polarizations of greater than $90 \%$ in the NH3 target. The heating of the target by the beam causes a drop of a few percent in the polarization, and the polarization slowly decreases with time due to radiation damage. Most of the radiation damage can be repaired by annealing the target at about 80 K , until the accumulated dose reached is greater than about $17 \times 10^{15} \mathrm{e}^{-} / \mathrm{cm}^{2}$, at which time the target material needs to be replaced.

Target polarization is measured with an NMR system, which is calibrated with a measurement of polarization in thermal equilibrium (TE). Typical precision reached in the polarization measurement is about $3 \%$ (but less than $2 \%$ for ideal test lab conditions).

To achieve highest polarization levels in dynamic nuclear polarization (DNP) experiments, target materials must be subjected to microwave irradiation at a particular frequency determined by the difference in the nuclear Larmor and electron paramagnetic resonance (EPR) frequencies. However, this resonant frequency is variable; it drifts as a result of radiation damage. Manually adjusting the frequency to accommodate for this fluctuation can be difficult, and improper adjustments negatively impact the polarization. In response to this problem, a controller has been developed which automates the process of seeking and maintaining optimal frequency. The creation of such a controller has necessitated research into the correlation between microwave frequency and corresponding polarization growth or decay rates in DNP experiments. Knowledge gained from the research of this unique relationship has additionally lead to the development of a Monte-Carlo simulation which accurately models polarization as a function of frequency and a number of other parameters. The simulation and controller continue to be refined, however, recent DNP experimentation has confirmed the controller's effectiveness.


Figure 1: Polarized target system
For transverse polarization, the target field is perpendicular to the beam axis. This creates a deflection of electron beam (which is more significant for lower beam energies). To ensure proper transport of the beam, a chicane will be employed. A beam chicane system has been developed for the g2p/GEp experiments which will be more than enough to satisfy the need of this proposed experiment. Th electron beam will be pre-bended such that the outgoing beam after the target will be going straight to the regular Hall Abeam dump. No local beam dump will be necessary as in the g2p/GEp case.

To reduce the target depolarization due to beam, a large size ( 2.5 cm ) raster system (slow-raster) will be used in addition to the existing Hall A fast-raster system. The typical beam current this target can tolerate is about 100 nA . Beam diagnostic system (beam
current and position measurement system) which can handle such a low current will be needed.

Fortunately, all of the above beam-line system has been developed and is being implemented for the upcoming g2p/GEp experiments. The beam diagnostic system is compatible with the high beam energies. Minor modifications will be needed to make the slow raster working with high beam energies.

## 9 Acceptance and Kinematic Coverage

With the target field, the polar angle coverage for electrons $\theta_{e}$ is from $3^{\circ}$ to $28^{\circ}$. Although the current UVA/JLab polarized $\mathrm{NH}_{3}$ target has about $\pm 16^{0}$ forward opening in the transverse spin configuration, the planned upgrade will have a new magnet designed to have optimized geometry for transverse polarization such that it will have forward opening of more than $\pm 28^{\circ}$. The acceptance study assumed the upgraded configuration with no forward angle limitation.

The effect on the azimuthal angular coverage from the polarized $\mathrm{NH}_{3}$ target field is significant, and has been studied by GEANT3 Monte Carlo simulation which includes realistic spectrometer models, detector geometries, and the target field ${ }^{3}$. A very important experimental issue associated with such a target in a strong transverse field, known as "line of flame" is clearly shown in our simulations, where extremely high backgrounds are seen in highly localized areas of the acceptance. One way to get around this issue is to "remove" certain areas of the detectors where "line of flame" passes through by turning off part of the detectors. The other way is to add collimators in the target region to block these high rate regions more efficiently. Based on previous GEANT3 studies for SoLID experiment PR12-10-014 and E12-10-006, resolutions are not an issue for the proposed experiment. Reconstruction of angles is more important which can be addressed by careful simulations of the optics before the experiment and calibration during the experiment. Optics studies based on Monte Carlo simulations have been completed recently for the g2p/GEp experiment employing also the transversely polarized $\mathrm{NH}_{3}$ target in Hall-A, and a careful optics study with beam is being planned for the these experiments. Our proposed experiment will benefit from the experience of the upcoming g2p/GEp experiments which are scheduled to run in the fall of 2011.

[^2]
## 10 Detectors

In this experiment, we propose to use the same setup as in the approved ${ }^{3} \mathrm{He}$ SoLID SIDIS proposals [19, 21, 22] with cerntain regions of detectors disabled (or removed) for the "line of flames". In this section, we will focus on the new dedicated studies on the current setup.

### 10.0.1 GEM Trackers and Background Rates

A total of six GEM trackers will be used to provide the momentum, angle and interaction vertex of the detected particle. For the forward-angle detection, except for the first layer, all other layers will be used. For the large-angle detection, the first four layers of GEMs will be used, where the background rate is expected to be smaller than the forward-angle.

The background rates on the GEM detectors were estimated using GEANT3 simulation with all the physics processes(such as Moller/Mott etc) turned on. The background simulation after removing the "line of flame" shows that the rates on the GEM chambers similar to those estimated for the ${ }^{3} \mathrm{He}$ proposal. Fig. 2 shows the results obtained from the simulation for two different beam energies ( 11 GeV and 8.8 GeV ). The estimated background rates are much smaller than $30 \mathrm{KHz} / \mathrm{mm}^{2}$, in which GEMs have been used in the COMPASS experiment. At the proposed background rates, tracking has been sucessfully demonstrated with the proposed configuration in ${ }^{3} \mathrm{He}$ proposal [19, 21, 22].

### 10.0.2 Expected Resolutions

The optics of the BaBar magnet is studied which includes the target field of the current UVA/JLab polarized proton target. Fig 3 shows the resolutions obtained from the simulation for different polar angles $(\theta)$, and shown as a function of momentum of the scattered particle. The interaction vertex position resolution is assumed to be 1.5 cm , which is determined by the target length. A $200 \mu m$ position resolution on GEM is assumed. The resulting momentum resolution $\frac{\delta p}{p}$ is about $1 \%(\sigma)$, with a larger resolution at high momentum. For angular resolution, instead of using the common polar angle $\theta$ and azimuthal angle $\phi$ in the lab frame, we decided to use $\frac{d x}{d z}$ and $\frac{d y}{d z}$. Here, $\frac{d x}{d z}$ is the slope of tracks in the plane perpendicular to the target holding field. $\frac{d y}{d z}$ is the slope of the tracks in the plane of the target holding field and the incident beam direction. The average $\frac{d x}{d z}$ and $\frac{d y}{d z}$ are about 0.007 and 0.0012 , respectively. The main reason that the resolution on $\frac{d x}{d z}$ is much larger than $\frac{d y}{d z}$ is due to the extended target length.

Fig. 4 shows the resolutions of the kinematic variables $x, Q^{2}, z, P_{T}, \phi_{s}$ and $\phi_{h}$, after including the resolution on momenta of the scatterted electron and the leading hadron and slopes of directions of incident electron, scattered electron and the leading hadron. The resolution in $x, Q^{2}, z$, and $P_{T}$ are much smaller than the proposed bin size. Furthermore, the maximum resolution in $\phi_{s}$ and $\phi_{h}$ are $1.14^{\circ}$ (small $x$ ) and $5.7^{\circ}$ (small $P_{T}$ ), respectively. The systematic uncertainties on Collins and Sivers effect are below $0.5 \%$ (relative), assuming a resolution of $1.14^{\circ}$ and $5.7^{\circ}$ of $\phi_{s}$ and $\phi_{h}$. The effect on pretzlosity is below $2.5 \%$ (relative) in comparison.


Figure 2: The simulated background for 11 (8.8) GeV beam is shown in upper (lower) panel. The rate on each GEM layer is plotted as a function of its radius. The label "L1" denotes the first layer in the large-angle. "LF2", "LF3" and "LF4" are shared between the large-angle and forward-angle detection. The "LF5" and "F6" are used in the forward-angle only.


Figure 3: The resolutions of $d x / d z, d y / d z$ and momentum. The $x$ axis is the momentum of the particle.

### 10.0.3 Electromagnetic Calorimeter

A "shashlyk" type electromagnetic calorimeter will be used in both forward and larger angle to identify electrons and hadrons. The calorimeter will be split into preshower/shower type configuration, which can give a pion rejection factor of $100: 1$ with $\mathrm{E}>1.0 \mathrm{GeV}$ and an energy resolution of $\leq 5 \% / \sqrt{E}$.

The Shashlyk type calorimeter is a sampling type calorimeter constructed from alternating layers of scintillator and heavy absorber. The scintillation light is carried to the photon detector by a wave-length shifting optical fibers running longitudinally through the calorimeter. The calorimeter design is currently being studied using a GEANT4 simulation. An optimal design is considered to reach the required goals on the pion-rejection and energy resolution. In a typical design, each layer consists of 1.5 mm thick scintillator plate and a 0.6 mm thick absorber. The effective radiation length $\left(X_{0}\right)$ is about 21 mm . More details on the status of the calorimeter design can be found in the updated proposal E12-11-007 to PAC38 [22].

The background rates on the calorimeter have been calculated using the GEANT3 simulation for this experiment, and the results are shown in Fig. 5. With further optimization of the setup we can reduce the background rates on the calorimeter. Overall the background level is at most comparable to that of the approved experiments using the ${ }^{3}$ He target [19, 22].

### 10.0.4 Particle Identification Detectors

For electron detection, a light gas Cerenkov will be used to combine the electromagnetic calorimeter system at forward angle. An E\&M calorimeter will be enough to provide electron PID at large angle, where the pion/e ratio is expected to be smaller than 1.5 for particles with momentum larger than 3.5 GeV . The pion PID will be provided by a MRPC time-of-flight detector (separate from protons, and kaons at low momentum), gas Cerenkov and E\&M calorimeter (separate from electrons), and a heavy gas Cerenkov (separate from kaons at high momentum). The background rate of MRPC is also simulated through GEANT3 program and shown in Fig. 2. The baseline parameters of detectors are assumed to be same as in Ref. [19, 22].


Figure 4: The resolutions of kinematic variables $x, Q^{2}, \phi_{s}, z, P_{T}, \phi_{h}$.


Figure 5: The energy flux (in $\mathrm{GeV} / 10 \mathrm{~cm}^{2} / \mathrm{sec}$ ) on the calorimeter as a function of its radius. The left (right) panel shows the background for the forward-angle (large-angle) detector.


Figure 6: Setup of the light-gas Cherenkov: a system of 30 spherical mirrors (grey) will focus the Cherenkov photons (green) created by the passage of electrons (red) through a radiator gas onto photon detectors (cyan). Left panel: setup for the PMT option, side view (see text). Right panel: setup for the GEM + CsI option, back view - as seen from the beam dump (see text).

### 10.0.5 Update on Cerenkov Detectors

This experiment requires both electron and pion detection. In order to unambiguously identify both electrons and pions several PID detectors will be required. Two Cherenkov detectors will be an essential part of the PID scheme.

Electron identification: the light-gas Cherenkov
A Cherenkov detector filled with $\mathrm{CO}_{2}$ at 1 atm would ensure electron-pion separation up to a momentum of 4.65 GeV . This detector, extending 2.1 m along the beam line, would be positioned immediately after the SoLID coil. The close proximity to the SoLID magnet requires careful consideration of various options for the photon detectors. In addition, the detector optical system is expected to provide full coverage in the azimuthal angle.

Recently a GEANT4 simulation was used to optimize the design of the optical system. It was found that with just one system of 30 spherical mirrors (following the SoLID sectoring) near perfect collection efficiency, $>95 \%$, can be achieved with a $12^{\prime \prime}$ by $12^{\prime \prime}$ photon detector (active area). This size could be easily scaled down to $6^{\prime \prime}$ by $6^{\prime \prime}$ by employing Winston cones. A schematic of this setup is shown in Fig. 1 where Cherenkov photons (green) produced by the passage of electrons (red) through the radiator gas are reflected by 30 spherical mirrors (grey) and focused onto the photon detectors (cyan).

The one-mirror optical system is a significant improvement over the three-mirror design outlined in the proposal presented to PAC35. The Cherenkov photon yield lost due to reflections off multiple mirrors is reduced. This is particularly important for the GEM + CsI option where is technically challenging to manufacture and maintain mirrors with good reflectivity in the UV region. In addition the one-mirror design is more practical and cost efficient form the manufacturing and installation point of view.

The same GEANT4 simulation has been used to describe the photon detector response and this is yet another improvement since PAC35. Two options have been considered for the photon detectors: magnetic field resistant photomultiplier tubes, PMTs, (Fig. 1, left panel) to be used in combination with Winston cones and gaseous electron multipliers with Cesium Iodide coating, GEMs + CsI, (Fig. 1, right panel).

For the PMT option the Hamamatsu model H10966A-100 was considered. This is a $2^{\prime \prime}$ multi-anode PMT with up to $94 \%$ photocathode coverage and good quantum efficiency down to wavelengths of 200 nm . These characteristics make this model ideal for tiling and we plan to use 9 such PMTs per sector, in a 3 by 3 array, to cover a $6^{\prime \prime}$ by $6^{\prime \prime}$ area. It is fairly resistant in magnetic field: such unshielded PMT experiences up to $60 \%$ gain reduction in 100 Guass field according to data provided by Hamamatsu. This is a significant improvement when compared to a regular $5^{\prime \prime}$ PMT which,if unshielded, would experience a similar gain reduction at only 4 Gauss. To establish whether H10966A-100 could withstand the magnetic field of SoLID we plan to test it with shielding this Summer at Temple University. If the magnetic field test results are satisfactory we plan additional tests at Jefferson Lab to ensure suitability in high-background environment.

An estimate of the number of photoelectrons for this option with the configuration described above (Fig. 1, left panel) yields between 25 and 35 photoelectrons. The number depends slightly on the electron polar angle: because of the mirror positioning in the tank electrons with higher polar angles traverse a longer path in the radiator gas than those with lower polar angles. This estimate includes wavelength dependent corrections like mirror and Winston cones reflectivities and the PMTs quantum efficiency as well as an overall correction of 0.8 to account for the reduction in the photocathode effective area as a result of tiling.

The GEM + CsI is an alternative to the PMT option and has the clear advantage of being resistant in magnetic filed. This has been used successfully as a photon detector during PHENIX experiment at BNL in a Hadron Blind Detector [30] and a similar setup is being developed in Japan for use in JPARC experiments [31]. The photon detector consists of three layers of GEMs the first being covered with CsI which acts as a photocathode. The operational regime for CsI is the ultraviolet (UV) region, between 120 and 200 nm [32]. This requires a radiator gas with good transparency in the UV and with very good purity to avoid photon absorption by impurities. Thus for the GEM + CsI option, a suitable gas choice would be $\mathrm{CF}_{4}$ which, unlike $\mathrm{CO}_{2}$, is transmissive between 120 nm and 200 nm [33]. This gas would still give an acceptable threshold for electron-pion separation and it was the gas of choice for the successful PHENIX run.

The number of photoelectrons for this option was estimated using the GEANT4 simulation and assuming a $12^{\prime \prime}$ by $12^{\prime \prime}$ photon detector (Fig. 1, right panel). A signal of 20 to 30 photoelectrons was obtained. Wavelength dependent corrections as mirror reflectivity and quantum efficiency of CsI were taken into account as well as an overall correction of 0.54 to account for loss of signal due to gas transparency, reduced photocathode coverage of the GEM (about $20 \%$ of the GEM surface is occupied by holes), transport efficiency of avalanche electrons through gas, etc.

Pion identification: the heavy-gas Cherenkov
A Cherenkov detector filled with $\mathrm{C}_{4} \mathrm{~F}_{10}$ at 1.5 atm would be placed right after the


Figure 7: Optical system for the heavy-gas Cherenkov: a ring of 30 spherical mirrors (grey) will focus the Cherenkov photons (green) created by the passage of positive (left panel) and negative (center panel) pions through the $\mathrm{C}_{4} \mathrm{~F}_{10}$ radiator gas onto photon detectors (cyan). The placement of the mirrors and photon detectors in the tank (magenta) is also shown (right panel).
light-gas Cherenkov to provide pion-proton/kaon separation in a momentum range from 2.2 to 7.6 GeV . A GEANT4 simulation is underway for this detector and the same design ideas and concepts will be used as for the light-gas Cherenkov.

Figure 2 displays preliminary results from this simulation: focusing of Cherenkov light with one spherical mirror is shown for both positive (left panel) and negative pions (center panel). The photon detector size is set to be $12^{\prime \prime}$ by $12^{\prime \prime}$ just as for the light-gas Cherenkov. With this setup the light collection efficiency is very good for the entire kinematic range of interest.

### 10.0.6 Trigger Setup and DAQ

The single rate in E12-12-108 will be about factor 5-10 lower than the sister experiment with a polarized ${ }^{3} \mathrm{He}$ target [19, 22]. Therefore, the design of trigger setup and DAQ of the ${ }^{3} \mathrm{He}$ experiment will satisfy our needs in this setup.

### 10.1 Beamline Instrumentation

### 10.1.1 Beam Chicane

In this experiment the polarization direction of the proton target will be held transverse to the beam direction. The strong magnetic field of the target will create a non-negligible deflection of the electron beam. To ensure the proper transport of the beam into the downstream exit beam pipe, a chicane will be employed. Two chicane magnets will be used for this purpose. The first one will be located 10 m upstream of the target and this will bend the beam out of the horizontal plane to vertically down. The second magnet which will be located about 4 m upstream of the target will bend back the beam at an angle that will compensate the 5 Tesla target field. We will choose the bend angle such that the beam will pass through the exit beam pipe after interacting with the target. A GEANT3 simulation was performed to optimize the bend angle. The simulations included


Figure 8: Event display of the beam transport at the target region with the initial bend of the beam before hitting the target. The red color denotes the 11 GeV beam and the blue color denotes the uncharged particles (mostly bremsstrahlung photons). The $\mathrm{NH}_{3}$ target field direction is pointing into the page.
physics processes such as synchrotron radiation and Bremsstrahlung. Fig. 8 shows an event display for the 11 GeV beam. Beam position monitors will be used before and after the chicane for the proper transport of the beam. They will also be used in determining the beam positions at the target.

### 10.1.2 Beam Charge Monitors

Typically low beam currents (up to 100 nA ) are used for the polarized proton target to reduce the depolarization effects and any significant changes to the density. The standard Hall-A BCM cavities are linear down to $1 \mu \mathrm{~A}$. An upgrade of the beam diagnostic elements such as BCM, BPM and Harps are planned for the g2p experiment (E08-028) in Hall-A, which uses the polarized proton target, and is scheduled to run in Oct 2011. The planned upgrade will allow us to measure the beam charge and positions up to 50 nA current. In order to calibrate the beam charge a tungsten calorimeter will be used. This device is also being refurbished and will be used in Hall-A during winter 2011 running. Tungsten calorimeter can provide an absolute calibration of Hall A BCM with an accuracy of better
than $2 \%$.

### 10.1.3 Slow and Fast Raster

Along with the existing Hall-A faster raster we will use a slow raster just upstream of the target. The fast raster will have a $2 \mathrm{~mm} \times 2 \mathrm{~mm}$ pattern and the slow raster will cover a circle of 20 mm diameter. This is done in order to uniformly cover most of the surface of the target cell which has a 25 mm diameter.

## 11 Some Systematics

To achieve the proposed precision, it is very important to control the systematic uncertainties. The large azimuthal angular coverage plays an important role in reducing the experimental systematic uncertainties. The large signal-to-noise ratio will also help to reduce the systematic uncertainties in subtracting backgrounds.

### 11.1 Target spin flip

To minimize systematic uncertainty, frequent target spin reversal is necessary. Due to the strong target magnetic field (5T), it is difficult to rotate target field direction to realize the spin reversal. The practical method is to use RF spin-flip with adiabatic-fast-passage AFP technique. There was an extensive study done by Haulte et al. [37] many years ago. It was shown that with ${ }^{7} \mathrm{LiH}$, the efficiency of AFP spin-flip reached up to $90 \%$. ${ }^{7} \mathrm{LiH}$, with its excellent radiation resistance and high dilution factor, could be a good candidate as a target material. AFP has also recently been shown to be at least $50 \%$ efficient with $\mathrm{NH}_{3}$ (researched at UVA Polarized Target Group). More research and development are currently underway. Studies are planned in the near future both for polarized experiments at Jlab as well as the polarized Drell-Yan experiments at Fermilab. Results indicate that as much as 20 minutes could be conserved with every flip cycle, which can add up to considerable overhead for the duration of an experiment.

### 11.2 Dilution Factors

For the target dilutions studies we will take several different sets of data including empty cell (with ${ }^{4} \mathrm{He}$ /windows/shielding etc.) runs and solid target runs such as ${ }^{12} \mathrm{C}$ and $\mathrm{CH}_{2}$. Typically, with this target, ${ }^{12} \mathrm{C}$ data is used to approximate the nitrogen contributions. The packing factor and dilutions can be studied with both elastic as well as DIS settings. There were many studies done on the extraction of packing factor/dilution factor from the previous experiments (E143, E155, E155x, GEn-I and GEn-II, RSS and SANE).

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[^0]:    ${ }^{1}$ Ammonia ${ }^{15} \mathrm{NH}_{3}$ is the best target material for polarized protons, for its high polarization, radiation resistance and fraction of polarizable nucleons

[^1]:    ${ }^{2}$ There are actually ten general structure functions that can be formed, six $W$ 's and four $G$ 's, including the well known $G_{1}$ and $G_{2}$ spin structure functions[17]

[^2]:    ${ }^{3}$ The exisiting SLAC/UVA/JLab $\mathrm{NH}_{3}$ target field map is used in the GEANT3 simulations, though a new magnet optimized for the proposed experiment will be needed.

