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1 Introduction

This document is a renewal proposal for DOE grant number DEFG02-01ER41168. Broadly speaking, with one exception, the physics being studied under this proposal falls into two categories: the study of the structure of the nucleon, and precision tests of electroweak physics. In both cases, the experiments generally involve the manipulation of spin degrees of freedom, sometimes with polarized electrons, and sometimes with both polarized electrons and nuclear-polarized $^3$He. The one additional physics topic with which we are involved is that being studied in PREx, an experiment that will determine to 1% the neutron radius of $^{208}$Pb.

Historically, our group’s interest in nucleon structure began with SLAC E142, an experiment in which we measured the spin structure functions of the neutron in deep inelastic scattering (DIS) [1]. This was followed by SLAC E154, which to this day, provides the most precise data on the neutron spin structure functions over the kinematic range we covered [2]. These experiments have been critical to achieving a better understanding of the fraction of the nucleon spin carried by quarks, and provide an important test of the Bjorken Sum Rule. At JLab, we initiated a study of the extended GDH integral in which we studied the neutron spin structure in the resonance region [3]. Among other things, our measurements of the GDH integral at JLab, together with other measurements from Hall B (on the proton) have made it possible to chart the $Q^2$ evolution of the Bjorken Sum Rule [4]. Our paper describing this work was used recently by Marciano and Sirlin to constrain electroweak radiative corrections that are critical to understanding the unitarity of the CKM matrix [5]. Our investigations of the spin structure of $^3$He at JLab have since broadened considerably, including, among other things, measurements of the spin asymmetry $A_1^n$ at high values of Bjorken $x$ [6] (a subject of particular interest for the 12 GeV era), and most recently, studies of single-spin asymmetries in semi-inclusive DIS processes and a measurement of the twist-three matrix element $d_2$. We also initiated a study of the electric form factor of the neutron, $G_E^n$, measuring to a sufficiently high $Q^2$ (3.5 GeV$^2$) that we probed the interesting regime in which surprising results have been seen in the behavior of the electric form factor of the proton [7]. The measurements of the electric form-factor of the proton have profoundly influenced our understanding of nucleon structure, and they are now joined by measurements on the neutron as well.

The progression of experiments described above were only made possible because of dramatic improvements in polarized $^3$He targets. Our group built all of the glass target cells that were used at SLAC, and at the time, they represented an improvement in figure-of-merit of almost two orders of magnitude over the polarized $^3$He targets we had been using previously [8]. At JLab, we have continued to push target technology in order to probe physics that would otherwise have been inaccessible. We have also built strong collaborations in our JLab target work, particularly with Temple University, JLab itself and William and Mary. In the earlier experiments, we fabricated all of the actual target cells that were used. From the time of the $A_1^n$
experiment on, however, for each set of experiments, 50% of the target cells have been fabricated at UVa, and 50% have been fabricated at William and Mary. While all target cells are still characterized (various parameters important to both polarimetry and operation) at UVa, this has never-the-less made it possible to substantially increase the number of polarized $^3$He experiments that can be run. In recent years we have also focused on employing new technologies, resulting in more than a six-fold increase in figure-of-merit for the aforementioned $G_E^p$ experiment, and roughly another factor of two during the “Transversity experiments” (both discussed more later). We have gotten a second experiment approved to measure $G_E^p$ (up to $Q^2 = 10 \text{ GeV}^2$) after the 12 GeV upgrade, and it will be the first experiment to run with a new generation of targets substantially different from those we have now, and capable of handling at least five time more beam current (up to 5 $\mu$A).

The other side to our activities include parity violation experiments that have explored both the strange form factors of the proton as well as precision measurements of electroweak physics. We have played a central role in the HAPPEX program, including the HAPPEX-II proton experiment, on which G. Cates was a spokesperson. The HAPPEX experiments, together with other studies of the strange form factors both at JLab and world-wide, provide critical understanding of nucleon structure that compliments other form factor studies. They have also set the stage for experiments such as Qweak, that will use the proton as a precision probe of the weak-mixing angle $\sin^2 \theta_W$ in the semi-leptonic sector. Our other efforts in electroweak measurements include SLAC E158, which provides the most accurate measurement of $\sin^2 \theta_W$ at low $Q^2$ well below the $Z^0$ pole. E158 provides a stringent test of the Standard Model with sensitivity as high as the several-TeV scale.

As is the case with our polarized $^3$He work, the activities of our group in relation to parity violation have often focussed on experimental techniques that have enabled experiments to probe physics that would otherwise have been impossible. E158, for instance, relied on new techniques for suppressing helicity-correlated systematic effects associated with the polarized electron source that were largely developed by G. Cates’ graduate student Brian Humensky. His work is summarized in a NIM article on which Brian is first author [9]. Brian Humensky later went to JLab where he shared many of the lessons learned at SLAC with the HAPPEX group, which at that time included Ryan Synder (G. Cates’ graduate student), and among other people, Kent Paschke (then a UMass post-doc and now an assistant professor at UVa). During the HAPPEX-II proton experiment we were able to push what was learned during E158 to new levels, identifying a new class of systematic effects, ultimately resulting in a level of control over helicity-correlated position differences that were at the 1-2 nanometer level [10]. We continue working in this area, having primary responsibility for source-related systematic control for both PREx and Qweak. Our group is also taking a leading role in controlling source systematics for the recently approved Möller experiment that will run at 11 GeV after the JLab upgrade.

Our activities during the upcoming funding period will focus on two upcoming
experiments, PREx and Qweak, as well as preparations for several experiments that will run during the 12 GeV era. On PREx and QWeak, we will focus largely on the polarized electron source, but will also be involved in a supporting role with the Compton polarimeters. For the 12 GeV era, G. Cates is a spokesperson on four experiments, one to measure $G_E^n$ up to $Q^2 = 10 \text{GeV}^2$, two that will study the spin asymmetry $A_1^\pi$ at high values of Bjorken $x$, and one that will study single-spin asymmetries in semi-inclusive DIS (SSAs in SIDIS). All of these experiments will require a new generation of polarized $^3\text{He}$ targets which, in two cases, will have a figure-of-merit that is yet another order of magnitude beyond those with which we have already run. We note that we have already demonstrated some of the key advances that will make this possible. The development of this new generation of polarized $^3\text{He}$ targets will be one of our central activities over the next several years.

Finally, we note that the PI, G. Cates, has recently assumed the role of contact person on the “Super Bigbite” proposal, and was its primary author. The Super Bigbite project represents a set of hardware that will make possible a new generation of form-factor measurements with unprecedented precision and range in $Q^2$. Among other things, the Super Bigbite project is critical to the next $G_E^n$ experiment, and will also make it possible to measure the ratio $G_E^n/G_M^n$ of the proton up to $Q^2 = 14.5 \text{GeV}^2$ with high precision. We will also use it to measure $G_M^n$ up to at least $Q^2 = 13.5 \text{GeV}^2$ (already approved), and perhaps $Q^2 = 18 \text{GeV}^2$ (which was in our original proposal). The Super Bigbite project is also central to our experiment to study SSAs in SIDIS.

In short, we are continuing in our studies of nucleon (and with PREx, nuclear) structure and electroweak physics. As we will discuss in section 2, we are trying to concentrate on experiments that challenge our current understanding, and thus have exciting potential to bring new insights and discoveries. Toward these goals, we are putting particular effort into developing techniques that will make it possible to study physics that was previously inaccessible. In sections 3 and 4 we go into some detail regarding our work on polarized $^3\text{He}$ targets and efforts to suppress helicity-correlated systematic effects associated with polarized electron sources. We finish in section 5 by going into some additional detail on our completed experiment that measured $G_E^n$ to $Q^2 = 3.5 \text{GeV}^2$, and our plans to measure $G_E^n$ up to $Q^2 = 10 \text{GeV}^2$ after the 12 GeV upgrade.

2 Physics discussion and motivation

2.1 The ground-state electromagnetic form factors

The electric form factor of the neutron

A central part of our program is the study of the electric form factor of the neutron $G_E^n$. This quantity has taken on particular significance in recent years because of the surprising discovery by Jones et al. that the ratio the electric and magnetic form
factors of the proton, $G_E^p/G_M^p$, decreases almost linearly with $Q^2$ [7]. The expectation had been that the quantity would be roughly constant. Indeed, this observation has forced a fundamental rethinking of nucleon structure, and caused considerable theoretical activity, as evidenced by nearly 500 citations. The various theoretical studies that have been performed in response to ref. [7] represent some of the most sophisticated efforts to date to understand the nucleon in terms of QCD degrees of freedom, and have brought to light new features of nucleon structure that had not previously been appreciated. Examples include refined perturbative QCD calculations in which an $L = 1$ component in the quark light-cone wave function has been included [11]. The implication here is that quark orbital angular momentum (OAM) plays an important dynamic role, something that is explicitly excluded when pQCD calculations are performed that include hadron helicity conservation (HHC). Another class of examples include relativistic constituent-quark model (RCQM) calculations such as the light-front cloudy bag model of Gerry Miller [12]. These calculations, some of which actually preceded ref. [7], again include an important role for quark OAM. Perhaps the most realistic model is a calculation out of Argonne by Cloët, Roberts and coworkers that uses an approach based on the Dyson Schwinger Equations (DSEs) together with the Faddeev equations [13]. Here, the constituent quarks have their masses dynamically generated using the DSE formalism, and then serve as the degrees of freedom for further calculation. Curves associated with these three calculations, along with several others, are shown in Fig. 1 for both the proton (at left) and the neutron (at right).

One thing that is quite apparent from studying Fig. 1 is that the theories that have been quite successful in reproducing the proton data often give quite different predictions for the neutron. This was an important factor in motivating E02-013 (on which G. Cates is a spokesperson), an experiment that measured the ratio $G_E^n/G_M^n$ up to $Q^2 = 3.5$ GeV$^2$. We will refer to this experiment as GEn(1). The near final results$^1$ from GEn(1), which have just become available this month, are shown with the solid red triangles in the right-hand panel of Fig. 1. They represent the highest $Q^2$ points ever obtained on $G_E^n$ of the neutron, and are the only results that probe well into the momentum-transfer range in which the surprising behavior of $G_E^p/G_M^p$ was observed. Our data fall very much in the midst of some of the calculations that were most successful in describing the proton results. Our points are more-or-less sandwiched between the RCQM calculation of Miller and co-workers and the DSE calculation of Roberts and co-workers. The modified pQCD calculation of Balitsky, Ji and co-workers, however, fall well above our data. We note, however, the calculation of ref. [11] was directed specifically at the proton, and one should be careful before drawing any strong conclusions regarding their approach. Our data disfavor the vector-meson dominance models, and strongly disfavor the historically prevalent Galster fit. The GEn(1) results can be interpreted as providing support for some of

$^1$The only things holding up publication is that we are awaiting a small correction to a $^3$He nuclear structure calculation from M. Sargsian.
Figure 1: Shown are existing data and projected errors for measurements of the ratios of the electric and magnetic form factors of the proton (left panel) and neutron (right panel). The near final results of GEn(1) (E02-013), our neutron form factor experiment, are shown on the right-hand panel with red triangles. We also show the projected errors for GEn(2) (E12-09-016), our approved experiment to measure $G^n_E$ to 10 GeV$^2$, and GEp(5), our approved measurement to measure $G^p_E$ to 14.5 GeV$^2$. The statistical power of these experiments over competing experiments is readily apparent, and amounts to a factor of 10 in the case of GEp(5), and 50 in the case of GEn(2). Also shown are several theoretical curves that are discussed in the text.

the new ideas that have emerged regarding nucleon structure, and as such, present an exciting new picture of the neutron.

GEn(1) represented a major experimental challenge. The counting rate for a form-factor experiment can be expected to scale roughly as $E_{beam}^2/Q_{16}^1$. This, coupled with the (understandably) small value of $G^n_E$, makes $G^n_E$ a difficult quantity to access. There were essentially three things that made it possible: 1) A polarized $^3$He target with a figure-of-merit more than six times higher than had previously been achieved, 2) an open geometry spectrometer (BigBite) that provided a large acceptance and excellent statistics and 3) what was then (and perhaps still is) the world’s largest neutron detector. We note that large parts of the detector package for BigBite were built by the UVa group (using an NSF MRI) and the neutron detector also contained many UVa neutron bars. The effort to build the $^3$He target was led by our group and involved a close collaboration with both JLab and Todd Averett’s group at William and Mary. With all three of the major components of GEn(1) being built specifically for the experiment, E02-013 was the largest installation in Hall A since the hall was commissioned.

A primary focus for our group after the 12 GeV upgrade will be GEn(2) (E12-09-016), an experiment to measure the ratio $G^n_E/G^M^n$ up to $Q^2 = 10$ GeV$^2$. As is clear from Fig. 1, GEn(2) will have excellent precision even at quite high $Q^2$ where the various theories explaining the form-factor data are in sharp disagreement with one another. For instance, the Argonne calculation of ref. [13] actually shows a turnover,
perhaps due in part to the inclusion of non-pointlike diquark degrees of freedom. Also, while the logarithmic scaling in the pQCD calculation of Balitsky, Ji and Yaun does not appear to agree with GEn(1), it is quite possible that the scaling behavior will become more evident at higher $Q^2$. We will discuss more details of GEn(2) later.

The electric form factor of the neutron is a fundamental property that provides great insight into nucleon structure. Historically it contributed to a basic understanding of the neutron charge distribution, and now, at higher values of $Q^2$, it challenges state-of-the-art calculations based on QCD degrees of freedom. Furthermore, we believe that observations of form factors at high $Q^2$ have particularly good discovery potential. This was certainly true for $G_{E}^{p}/G_{M}^{p}$, and in a very different context, it was also true for the $\gamma\gamma^{*} \rightarrow \pi^{0}$ transition form factor, which was found by BABAR to greatly exceed an asymptotic limit predicted by QCD [14]. Quite simply, data at high $Q^2$ can reveal features that are simply not yet apparent at lower energy scales. It is also important to note that ground-state electromagnetic form factors provide what are currently some of the most important constraints to general parton distributions (GPDs) [15, 16]. Eventually, through the what is sometimes called Ji’s angular momentum sum rule, GPD’s can provide a direct measure of quark angular momentum.

### 2.2 Spin structure using inclusive and semi-inclusive reactions

As discussed in the introduction, our group has a long history studying spin structure using inclusive reactions. More recently, during this past year, we also participated in a series of $^{3}$He experiments that included the so-called “Transversity” experiments that studied single-spin asymmetries (SSAs) in semi-inclusive deep inelastic scattering (SIDIS). These $^{3}$He experiments also included a measurement of the twist-three matrix element $d_{2}$. During these runs, the polarized $^{3}$He targets achieved unprecedented performance. We plan to continue our studies of spin structure following the 12 GeV upgrade. One experiment that is already approved is a measurement of $A_{1}^{p}$ using the BigBite spectrometer at high Bjorken $x$ and with DIS kinematics (E12-06-122, G. Cates co-spokesperson). Additional experiments include E-09-018, that will measure SSAs in SIDIS and a second $A_{1}^{n}$ experiment (in Hall C) both of which are conditionally approved. G. Cates is a spokesperson on these experiments as well. There are other experiments to which we are committed as well, including a measurement of $d_{2}$ in Hall C that is already approved. Like GEn(2), all these experiments will rely on a new generation of polarized $^{3}$He targets.

*The spin asymmetry $A_{1}^{n}$ at high Bjorken $x*

An important quantity in deep inelastic scattering is the spin asymmetry $A_{1}$ in the virtual photoabsorption cross section of the nucleon. At high Bjorken $x$, $A_{1}$ provides detailed information on the nucleon’s valence spin structure. Also, for both the proton
and the neutron, it is expected that $A_1 \to 1$ as Bjorken $x \to 1$. In the case of the neutron, this prediction is rather striking, because for many years, $A_n^1$ was observed to be either negative or consistent with zero. In early 2004, however, the results of JLab experiment E99-117 showed that $A_n^1$ becomes distinctly positive at roughly the highest value of Bjorken $x$ studied, 0.6 [6].

One of the principal reasons that $A_n^1$ is interesting is that, close to $x = 1$, it can be computed in a number of different ways. For instance, it was shown by Isgur that for a wide class of hyperfine-coupled constituent quark models (CQMs), $A_n^1$ should fall within a fairly narrow well-defined band at high Bjorken $x$ [17]. Isgur also showed that for these quark models one should expect that $A_1^1 \to 1$ as Bjorken $x \to 1$.

Predictions for the behavior of $A_1^1$ at high $x$ can also be made within the context of perturbative QCD. Brodsky, Burkardt, and Schmidt developed QCD constrained parameterizations for the spin structure functions [18] that were later refined by Leader, Sidorov, and Stamenov [19] (BBS,LSS). Both of these predictions are labeled on Fig. 2. It can be seen that the data point from E99-117 at $x = 0.6$ falls well below the BSS,LSS curve, but is reasonably consistent with the constituent quark model predictions. What is quite interesting is that the BSS,LSS curve includes the constraint of hadron helicity conservation, which essentially means that the quarks have no orbital angular momentum. In contrast, the CQMs considered by Isgur implicitly include orbital angular momentum. Thus, the results of E99-117 can be interpreted as supporting the notion that quark OAM plays an important dynamic role in nucleon structure, a notion already discussed earlier in the context of the data on $G_E^n/G_M^n$, and that is also supported by the more recent data on $G_E^n/G_M^n$.

Following the 12 GeV upgrade, an important focus of our group will be the continued study of the spin asymmetry $A_1^1$ at high values of Bjorken $x$. G. Cates is a spokesperson on two experiments that are planned. E12-06-122, which was approved by PAC 30 in August of 2006, will measure $A_1^1$ up to $x = 0.71$ using the BigBite spectrometer in Hall A. A second experiment, E12-06-110, was conditionally approved, and will use the Hall C SHMS and HMS to measure $A_1^1$ to $x = 0.77$. The projected errors of the proposed data points of both experiments are shown on Fig. 2. It can be seen in the figure that the BigBite experiment has greater statistical power, and can obtain the indicated statistics in roughly half the time as what is projected for the experiment in Hall C. It is is notable, however, that the Hall C experiment will have greater discriminatory power against pion background. It is predominantly for this reason that we did not propose using Bigbite for data taking above $x = 0.71$.

Considerable technical progress has been made since our two $A_1^1$ experiments were proposed in 2006. First, the effective luminosity that we can achieve with our $^3$He targets has gone up by roughly one order of magnitude. This, by itself, changes considerably what can be achieved in either of these two efforts. Secondly, our two $A_1^1$ experiments were proposed prior to the development of the Super Bigbite project. While we have not yet developed a new experimental design, a spectrometer based on the Super Bigbite magnet, together with a detector package based on the Super...
Bigbite GEM trackers, would clearly provide the capability of handling much higher luminosity with larger solid angle. In short, while our two proposed experiments would already provide unprecedented precision and reach in Bjorken $x$, we believe that we can develop a new proposal that will have an even better Figure-of-Merit. Exploring this possibility will be one of the activities in the upcoming funding period.

**Single Spin Asymmetries (SSAs) in semi-inclusive reactions**

As mentioned earlier, the most recent group of $^3$He experiments to run in Hall A included the so-called “Transversity Experiments”. These experiments involved the observation of “single-spin (azimuthal) asymmetries”, or SSAs, in semi-inclusive deep-inelastic scattering (SIDIS) processes such as the electro-production of pions in which the incident leptons are unpolarized and the asymmetry is associated with the reversal of the target spin. Two mechanisms that have been postulated to account for such SSAs are the “Collins mechanism” and the “Sivers mechanism”. There now seems to be evidence that both mechanisms contribute[20], and if true, the implications are quite intriguing. In the Collin’s mechanism, the SSA is related to the transverse spin distribution in the nucleon. In the Sivers mechanism, the SSA is related to transverse momentum dependent distributions that are in turn related to quark orbital angular momentum. SSA’s represent a promising new direction in the study of nucleon spin structure, and already, provide what may be the most direct evidence to date of the dynamical importance of quark OAM.

For many years, the unpolarized and polarized longitudinal momentum distribution functions $q(x, Q^2)$ and $\Delta q(x, Q^2)$ have provided a wealth of information on
nucleon structure. There is a third such distribution function, \( \delta q(x, Q^2) \), however, about which almost nothing is known. In the transverse spin basis \( \delta q = q^\uparrow - q^\downarrow \) tells us about the probability that a struck quark of longitudinal momentum fraction \( x \) has its spin aligned or anti-aligned to the (transverse) spin of the nucleon. SSA’s due to the Collins mechanism depend on \( \delta q \) (also referred to as \( h_1^q \)) in a well defined manner, suggesting the possibility that the measurement of SSA’s in SIDIS may provide a means for determining this largely unknown distribution function.

While the distribution functions \( q(x, Q^2) \) and \( \Delta q(x, Q^2) \) tell us about the distribution of longitudinal momentum, very little is known about the distribution of transverse momentum. If, for instance, quark orbital angular momentum were partially responsible for the spin of the nucleon, it would be natural to expect a correlation between transverse momentum and transverse spin. A distribution function embodying such correlations is an example of a transverse momentum dependent or TMD distribution function. In the Sivers mechanism it is postulated that a TMD distribution function known as \( f_{1T}^\perp \) is the origin of the SSA. In highly-simplified pictorial terms, the struck quark “remembers” its orbital motion as hadronization occurs resulting in the SSA. As such, SSA’s can provide information on TMD distribution functions, and hence, on quark orbital angular momentum.

Following the 12 GeV upgrade, our group hopes to continue our study of SSAs with E12-09-018, an experiment that would study the semi-inclusive deep inelastic scattering (SIDIS) process \( \vec{n}(e, e' \pi^\pm(K^\pm)) \) using a polarized \(^3\)He target. The experiment would use a modified version of the Super Bigbite spectrometer for the hadron arm, and a modified version of the (existing) BigBite spectrometer for the electron arm. The trackers in both arms would be GEM based, and would be constructed as part of the Super Bigbite project. An important feature of E12-09-018 is that it would use one of the HERMES RICH detectors for particle identification, something that will make it possible to look at SIDIS processes involving kaons as well as pions. The experiment will have excellent azimuthal coverage because of the ability to point the \(^3\)He spins in essentially any arbitrary direction. Using the same high-luminosity design as GEn(2), E12-09-018 will obtain, in a two month run, 100 times the statistics obtained on SSAs at HERMES.

The single-spin azimuthal asymmetry that we will measure can be written:

\[
A_{UT}(\phi_h, \phi_S) = \frac{1}{|S_T|} \frac{d\sigma(\phi_h, \phi_S) - d\sigma(\phi_h, \phi_S + \pi)}{d\sigma(\phi_h, \phi_S) + d\sigma(\phi_h, \phi_S + \pi)}
\]  

where \( d\sigma(\phi_h, \phi_S) \) is the differential cross section for the semi-inclusive process \( \vec{n}(e, e' \pi^\pm)X \) with azimuthal angles \( \phi_h \) and \( \phi_S \), and \( d\sigma(\phi_h, \phi_S + \pi) \) is the same differential cross section only with the target spin flipped. The angles \( \phi_h \) and \( \phi_S \) are defined in Fig. 3. The quantity \( |S_T| \) is the magnitude of the target polarization. With the further assumption that the Collins and Sivers mechanisms are the only two processes responsible (actually there is something called pretzelosity that we ignore here), the
SSA will have the form

$$A_{UT}(\phi_h, \phi_S) = A_{UT}^{Collins} \sin(\phi_h + \phi_S) + A_{UT}^{Sivers} \sin(\phi_h - \phi_S)$$  \hspace{1cm} (2)$$

where it is immediately apparent that the two mechanisms have distinctly different dependences on the two azimuthal angles $\phi_h$ and $\phi_S$. By using a transversely polarized target whose spin direction can be easily reversed, it becomes possible to isolate the contributions from the two mechanisms.

The Collins mechanism involves a correlation between the tranversity distribution function $h_1^q(x)$ and the T-Odd Collins fragmentation function $H_{1}^\perp$. In the limit of an ideal experiment with infinite coverage of $P_\perp$, the transverse momentum of the detected pion, we would have

$$A_{UT}^{Collins} = \frac{1 - y}{1 - y + \frac{y^2}{2}} \frac{\sum_q e_q^2 h_1^q(x) \cdot H_{1}^\perp(z)}{\sum_q e_q^2 f_1^q(x) \cdot D_1^q(z)}$$  \hspace{1cm} (3)$$

At present the Collins fragmentation function $H_{1}^\perp$ is unknown. In principle, however, if it were to be determined, and if our knowledge of $f_1^q(x)$ and $D_1^q(z)$ were sufficient at the kinematics of interest, we would gain access to the tranversity function $h_1^q(x)$.

The Sivers mechanism involves a correlation between the “Sivers function” $f_{1T}^{\perp(1)q}(x)$, which is one of a new class of “Transverse Momentum Distributions” or TMD’s, and the fragmentation function $D_1^q(z)$. If we consider the same idealization as was assumed in eq. 3, we would have

$$A_{UT}^{Sivers} = \frac{\sum_q e_q^2 f_{1T}^{\perp(1)q}(x) \cdot D_1^q(z)}{\sum_q e_q^2 f_1^q(x) \cdot D_1^q(z)}$$  \hspace{1cm} (4)$$
where again if we assume that our knowledge of $f^q_1(x)$ and $D^q_1(z)$ is sufficient, we gain access to the Sivers function $f^{L(1)q}_T(x)$.

While it will take time before the various quantities that contribute to SSAs can be cleanly extracted, one could argue already that the observation of the Sivers and Collins mechanisms have provided powerful new insight into nucleon structure. The Sivers effect may well be the most direct confirmation yet of the dynamic importance of quark OAM, and we have at least begun the process of understanding transverse spin structure. E12-09-018 will have unprecedented statistical power greatly exceeding what was achieved at HERMES, and the flexibility of the polarized $^3$He target will guarantee full azimuthal coverage. Indeed, in a field that has already caused great interest with observations from HERMES, COMPASS and JLab, E12-09-018 will provide data of unprecedented quality.

2.3 Low-energy exploration of electroweak physics

Precision measurements of parity-violating asymmetries due to weak neutral currents provide a powerful probe of new physics beyond the standard model. Within the standard model, such measurements depend, in one way or another, on the effective value of the weak mixing angle $\sin^2 \theta_W$, which is quite sensitive to electroweak radiative corrections. New physics beyond the standard model will in general modify its observed value. Historically, our group was quite involved in E158, an experiment at SLAC that measured the parity-violating asymmetry in Møller scattering at around 50 GeV. In the coming research period, we will be working on QWeak, that will measure the weak charge of the proton, and MOLLER, an experiment that will measure the parity-violating asymmetry in Møller scattering at around 11 GeV.

There are compelling reasons to make new precise measurements of $\sin^2 \theta_W$. At present, the world average for the weak mixing angle are dominated by two measurements: a left/right asymmetry in $Z^0$ production from SLD at SLAC, and a forward/backward asymmetry from $Z^0$ decays to b quarks at CERN. The average of these two results are in excellent agreement with the Standard Model. What is intriguing is that they disagree with one another at about the three-sigma level. This is illustrated in Fig. 4 which shows the two-dimensional parameter space spanned by the Higgs mass $m_H$ and the mass of the top quark. The SLC results favor a lower mass Higgs that is already ruled out by direct searches at colliders (shaded region). The LEP results favor a rather heavy Higgs, that is in tension with all indirect measurements (red ellipse). As long as we take the average of both the SLAC and CERN measurements of the weak mixing angle, a consistent picture of all electroweak measurements is preserved. If we had just one or the other, however, we would have a very different view of the data, and would led to consider various extensions of the Standard Model. It is clear that further measurements of $\sin^2 \theta_W$ are desirable, as will be provided by QWeak, and was already provided by E158. Also, with the recently approved MOLLER experiment, there will even be a measurement of comparable
Figure 4: Shown is the parameter space spanned by the Higgs mass $m_H$ and the top mass $m_t$. Also shown are constraints from various measurements, including the $\sin^2 \theta_W$ measurements from both SLC and LEP, which are in disagreement with one another at the three sigma level.

Low-energy measurements of parity violating asymmetries can be sensitive to significantly higher energy scales than are accessible in direct searches at colliders. They also compliment high-energy measurements in that they have sensitivity to different couplings, and of considerable importance, they will often be sensitive to the sign of the coupling.

It is possible to get a sense of the power of low-energy precision measurements by considering an over-simplified model that never-the-less illustrates some important features of low-energy measurements. Consider the three diagrams shown in Fig. 5, where $A^\gamma$ represents the amplitude due to electromagnetic scattering, $A^Z$ represents the exchange of a $Z^0$, and $A^X$ represents an amplitude due to new physics. A parity-violating spin asymmetry will be proportional to the interference between the $A_Z$, and $A^X$ amplitudes with the electromagnetic amplitude $A^\gamma$. We would thus expect the parity violating asymmetry $A_{PV}$ to have the form:

$$A_{PV} \equiv A_{RL} \sim \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim \frac{A^Z + A^X}{A^\gamma}.$$  \hspace{1cm} (5)

The asymmetry itself will be quite small, on the order of the ratio of the weak and electromagnetic amplitudes. The modification of the asymmetry, however, will go
Figure 5: Shown are three generic Feynman diagrams illustrating either $ee$ or $eq$ scattering through the exchange of a photon, a $Z^0$, or an as-yet undiscovered particle $X$ of significantly higher energy.

like

$$A_{PV} \to A_{PV} \left(1 + \frac{A^X}{A^Z}\right).$$

(6)

So changes in $A_{PV}$ will be proportional to the first power of $A^X$ and to its sign. In contrast, at places such as LEP-2 and SLD, searches took place on or near the $Z^0$ pole. Accordingly, the measured cross sections had the form $\sigma \sim |A^Z|^2 + |A^X|^2$. This is because near the $Z^0$ pole the amplitude $A^Z$ would be mostly imaginary whereas the amplitude $A^X$, corresponding to a very different energy scale, would be almost entirely real. In determinations of $\sin^2 \theta_W$, SLC measured left/right asymmetries and LEP measured forward/backward asymmetries. While the asymmetries themselves were relatively large, the modification of these asymmetries would go along the lines of

$$A_{PV} \to A_{PV} \left(1 + \frac{A^2_X}{A^2_Z}\right).$$

(7)

Thus, for two measurements of $\sin^2 \theta_W$, in the case of the high-energy measurement, the effect of the new physics is suppressed and sign information is lost. And as mentioned before, the asymmetry is sensitive to a different combination of couplings associated with new physics than is the case in the low-energy measurement.

Our group was very involved in SLAC E158, an experiment that measured the parity-violating asymmetry in Möller scattering at both 45 and 48.3 GeV. From the above discussion, it is apparent that when comparing two measurements of $\sin^2 \theta_W$ of similar precision, one near the $Z^0$ pole and one at low-energy, the low-energy measurement will often have the advantage in sensitivity to new physics. In fact, even a measurement of lesser precision at low energy can still have an advantage. This was certainly the case for E158, which measured

$$\sin^2 \theta_W^{eff} = 0.2397 \pm 0.0010(stat) \pm 0.0008(syst).$$

(8)

This represents a 0.53% measurement of $\sin^2 \theta_W^{eff}$, the most precise determination at an energy scale well away from the $Z^0$ pole ($Q^2 = 0.026$ GeV$^2$). The fractional error is significantly larger than 0.082%, however, the precision with which $\sin^2 \theta_W$ is
known from high-energy measurements. Even so, E158 sets the best limits are certain classes of interactions. For example, when considering contact interactions of a general model-independent form, an interaction of the form \( \mathcal{L} = \pm (4\pi/2\Lambda_{LL}^2)(\bar{e}_L \gamma_{\mu} e_L) \), is constrained by E158 such that \( \Lambda_{LL}^+ \geq 7 \text{ TeV} \) and \( \Lambda_{LL}^- \geq 16 \text{ TeV} \) with a 95% confidence level.

Measurements of the weak charge of the electron (E158 and MOLLER) and the proton (Qweak) have an important advantage in sensitivity due to a fortunate circumstance. In both cases, at tree level, the weak charge is proportional to \( 1 - 4 \sin^2 \theta_W \). Since \( \sin^2 \theta_W \) itself is close in value to \( \frac{1}{4} \), the relative uncertainty with which \( \sin^2 \theta_W \) is determined is considerably smaller than the relative uncertainty with which the parity violating asymmetry is determined. For E158, the parity violating asymmetry was determined at the level of roughly 13%, but \( \sin^2 \theta_W \) was determined at the level of 0.53%. The “leveraging” of the determination of \( \sin^2 \theta_W \) is even enhanced beyond what would otherwise be the case because of radiative corrections. At the low momentum transfer at which E158 made its measurement the effective value of \( \sin^2 \theta_W \), \( \sin^2 \theta_W^{eff} \), is significantly larger than it is at the \( Z^0 \) pole. E158 established the running of \( \sin^2 \theta_W \) at more than the 6 \( \sigma \) level.

Experimentally, one of the challenges of a parity violation experiment is measuring the tiny asymmetries involved without introducing any instrumentally induced false asymmetries that would skew the interpretation of the result. The asymmetry measured by E158 was

\[
A_{PV} = [-131 \pm 14(stat) \pm 10(syst)] \times 10^{-9} .
\]

With such a tiny asymmetry, it was important to keep all systematic errors as small as possible. Those associated with first and higher order beam effects were held to 1 and 3 ppb respectively. Two examples of first-order effects would be helicity-correlated changes in the position or angle of the beam as it hits the target. Another would be helicity-correlated charge differences that are not fully accounted for through normalizing to beam current. Effects such as these can easily be caused by helicity-correlated changes associated with the laser beam that causes photoemission in the polarized electron source. As mentioned earlier, the development of schemes for suppressing such systematic problems was one of our group’s primary responsibilities during E158. The control of helicity-correlated systematics is also central to the work our group is doing with Qweak and PREx, and will also be our focus during the 12 GeV Møller experiment.

Qweak

Qweak (E08-016) will measure the weak charge of the proton to with a relative accuracy of 4% of itself, resulting in a determination of \( \sin^2 \theta_W \) at the level of 0.3%, almost a factor of two better than what was achieved during E158. In addition to a smaller error, Qweak compliments E158 in that it is probing a semi-leptonic process, and thus has sensitivity to such important extensions of the Standard Model as leptoquarks and electron-quark compositeness. Qweak will begin running at the end of
May 2010, and is scheduled to take beam over a period of approximately two years prior to the 12 GeV upgrade.

The very fact that one can undertake an experiment such as Qweak is a testimony to the progress that has been made in the field of parity violation in electron scattering. The parity violating asymmetry when scattering off the proton can be written

\[ A_{PV}^H = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \times \left[ (1 - 4\sin^2\theta_W) \right. \\
- \frac{\epsilon G_E^{p}(G_E^{p} + G_E^{n}) + \tau G_M^{p}(G_M^{p} + G_M^{n}) - 2\epsilon'(1 - 4\sin^2\theta_W)G_M^{p}G_A^{p}}{\epsilon(G_E^{p})^2 + \tau(G_M^{p})^2} \right] \]

(10)

where \( \tau = Q^2/4M^2 \), \( \epsilon = [1 + 2(1 + \tau)\tan^2\frac{\theta}{2}]^{-1} \), \( \theta \) is the scattering angle in the lab frame, and \( \epsilon' = \sqrt{\tau(1 + \tau)(1 - \epsilon^2)} \). The quantities appearing on the right-hand side of eq. 10 include the electromagnetic form factors \( G_{E,M}^{p} \) and \( G_{E,M}^{n} \), the strange form factors \( G_{E,M}^{s} \), and the axial form factor \( G_A^{p} \). The first term in eq. 10 is the weak charge of the proton, and the second term represent hadronic contributions, including a potential contribution from strange form factors. At \( Q^2 = 0.026 \text{ GeV}^2 \), where Qweak will run, the hadronic contributions are reasonably suppressed, and assuming the Standard Model, would contribute around 28% of the measured asymmetry. For a precision measurement such as Qweak, however, it is critical that any uncertainties in this hadronic contribution be well under control. Luckily, experiments such as Sample, the HAPPEX experiments, Mainz’s A4 and G0 have sufficiently constrained the strange form factors that the hadronic piece of the asymmetry will only contribute a relative error of about 1.5%.

As mentioned earlier, our group’s main responsibility in Qweak is the control of helicity-correlated effects originating with the polarized electron source. The anticipated asymmetry in Qweak, assuming the Standard Model, is -234 parts per billion (ppb), which will be measured with a 2.1% (relative) statistical error, or a 4.9 ppb absolute statistical error. In our error budget, we would like to limit systematic uncertainties due to helicity-correlated beam effects to about 1.6 ppb. While this is a very challenging number, it is not as difficult as it might seem. Operationally, the important issue is the sensitivity of the cross section to helicity-correlated beam effects. In the case of Qweak, the sensitivities are smaller because of a high level of azimuthal symmetry.

12 GeV Möller

The 11 GeV Möller experiment, now known as MOLLER (E09-005), was approved at PAC 34. G. Cates sat on the steering committee that organized the experiment and developed the proposal, and currently heads up the working group on the polarized electron source.
Figure 6: Shown is the Higgs mass as a function of $\sin^2 \theta_W$ along with the values of $\sin^2 \theta_W$ measured by SLD and LEP. Also shown are the projected errors for the MOLLER experiment.

The experiment involves scattering polarized electrons from the electrons in a 1.5 m unpolarized liquid hydrogen target. In Moller scattering, it is redundant to detect both the forward and backward (center of mass frame) scattered electrons. The experiment will thus use a novel spectrometer in which certain sectors will detect forward-scattered electrons and other sectors will detect backward scattered electrons. In this way, full azimuthal coverage can be achieved.

The physics asymmetry, barring deviations from the Standard Model, will be 35.6 ppb. Running with a beam current of $85 \mu$A for 5000 hours, an error of 0.74 ppb (2.08%) can be achieved. This will result in a determination of $\sin^2 \theta_W$ with an accuracy of 0.00026.

As discussed at some length at the beginning of this section, there is considerable motivation to measure $\sin^2 \theta_W$ with a precision comparable to those that were achieved at SLD and LEP. We note that the determination of $\sin^2 \theta_W$ will not be improved by the LHC, so in the absence of a precision experiment like MOLLER, there will be no further improvements in our knowledge of the weak mixing angle from high-energy measurements before the ILC is built. As is illustrated in Fig. 6, MOLLER can provide an independent measurement of comparable precision.
This proposal

Figure 7: Shown is the parameter space spanned by possible couplings to left and right-handed electrons for two types of $Z'$s. The information that would come from the LHC would not be sufficient to determine the couplings, whereas the LHC when combined with limits from MOLLER would be sufficient.

Even if the LHC discovers new and unanticipated particles, in many cases it will be unable to determine their couplings, and hence, there will be limitations regarding interpretation. Two examples are the $Z_\chi$ that appears in SO(10) Grand Unified Theories, and the $Z_{LR}$ that appears in left-right symmetric models. It has been pointed out that in such cases, even with upgrades (the SLHC), the SLHC would at best be able to determine the ratio of coupling to left-handed and right-handed electrons [22]. This is illustrated in Fig. 7. When combined with the MOLLER measurement, as is also shown, it could be possible to extract the coupling, and hence learn about the underlying extension of the standard model that is being observed. Another example of complimentarity comes in reference to Kaluza-Klein gravitons in models with large extra dimensions. These might be difficult to disentangle from $Z'$s, but a low-energy precision measurement such as MOLLER would not see a shift in this case. Again, useful information would be obtained. It is also interesting to note that MOLLER might well be able to distinguish between R-parity conserving and R-parity violating supersymmetric models. This is of particular interest with regard to dark matter searches, as R-parity violating variations of SUSY would result in an unstable neutralino, thus eliminating that particle as a dark-matter candidate.

As will be discussed more in section 4, MOLLER will require the strongest suppression to date of helicity-correlated systematics. This work fits very nicely into the
preparations we are already doing for PREx and Qweak.

2.4 PREX: The neutron radius and skin of $^{208}$Pb

PREX, or the Parity Radius EXperiment, is an experiment in which parity violation in elastic scattering from lead is used to better understand the distribution of neutron matter. It is generally believed that in heavy nuclei the neutron radius $R_n$ is larger than the proton radius $R_p$ by something like several percent resulting in a “neutron skin”. While this idea is well supported by calculation, there is limited experimental evidence, and even some contradictory results[23]. The question is of considerable importance because it bears directly on the nature of neutron matter and hence carries implications for many fields. A measurement of $R_n$ would serve as a calibration of relativistic mean field theories, would significantly reduce uncertainties that currently limit atomic parity-violation experiments[24, 25], and would even shed some light on the phenomena of star quakes on neutron stars[26]. PREX has stimulated a remarkable amount of interest in the broader physics community.

Because of an accidental cancellation, the coupling of a $Z^0$ to a neutron is much stronger than the coupling of a $Z^0$ to a proton. Parity violating scattering from a heavy nucleus is thus an excellent probe of the distribution of the neutrons, an idea that was first suggested by Donnelly, Dubach, and Sick in '89[27]. In the PWIA the parity-violating asymmetry is given by

$$A_{LR} = \frac{G_F Q^2}{4 \pi \alpha \sqrt{2}} \left[ 1 - 4 \sin^2 \theta_W - \frac{F_n(Q^2)}{F_p(Q^2)} \right].$$

Horowitz has also performed more realistic calculations of the asymmetries, taking into account such effects as corrections to the plane-wave approximation[28]. Indications are that $R_n$ can be determined quite accurately by measuring a parity violating asymmetry at a single value of $Q^2$. The goal of PREX is to measure $R_n$ to 1% of itself, more than enough to demonstrate that $R_n > R_p$, or equivalently, that $^{208}$Pb and other heavy nuclei have a “neutron skin”.

Experimental overview

PREX will take place in Hall A at JLab. It will measure the parity-violating spin asymmetry in the elastic scattering of longitudinally polarized 850 MeV polarized electrons from an unpolarized $^{208}$Pb target. With a beam polarization of 80%, the expected asymmetry is only 0.51ppm. The goal is a statistical accuracy of 15.3 parts per billion (ppb), which will determine the neutron radius $R_n$ to about 1% of itself. To achieve such demanding statistics, the experiment will need a 50 $\mu$A beam and almost 700 hours of production data. Lead, with its low melting point, is notoriously difficult to use as a target with high beam currents. For this experiment a lead foil will be sandwiched between two sheets of diamond, which has excellent thermal conductivity. The lead/diamond sandwich will in turn be installed in the Hall A cryostat where it will be cooled by liquid helium.
The scattered electrons will be detected at 6° using the two Hall A high resolution spectrometers (HRS's). In order to reach 6°, which is outside the normal range of the HRS's, two non-superconducting septum magnets will be used. We will need to detect electrons at a rate of roughly 860 MHz in each spectrometer arm. To do this we will use total absorption detectors comprising a quartz-lead sandwich, and will integrate our signal from each helicity window. The detectors will be quite similar to those used during HAPPEX, with the exception that we will use quartz instead of lucite because of the higher radiation. The first excited state of lead is at 2.6 MeV. While the dispersion of the HRS's is quite sufficient to discriminate against this state, it is our plan to integrate up to 4 MeV so that we include a good fraction of the radiative tail. Inelastics will still only contribute about 0.5% of our total rate, and including a good fraction of the radiative tail should reduce our running time by about 25%.

From the perspective of controlling helicity-correlated systematics, PREX will be the most challenging experiment ever performed. With the great success of HAPPEX-II, however, the required parameters do not go far beyond what has already been achieved. This will be discussed in more detail in section 4.

**Plans for our group**

I start by noting that G. Cates has arranged for a leave from teaching for the spring semester of 2010 to participate more fully in the installation and running of PREX. G. Cates also has a graduate student, Rupesh Silwal, who has been working on a combination of HAPPEX-III and PREX since joining our group. We have been collaborating closely with Prof. Paschke in these efforts, including extensive studies on an optical table of some of the effects that we will need to control. Some of the results of our efforts will be presented in section 4.

**3 Polarized $^3$He target work**

Polarized $^3$He targets have been a critical enabling technology for many experiments that have taken place at JLab. As already mentioned, our group’s measurement of the electric form factor of the neutron $G_E^n$ during E02-013, the experiment we refer to as GEn(1), required a huge increase in the figure-of-merit. The same was true for the Transversity experiments that studied single-spin asymmetries in semi-inclusive deep inelastic scattering.

There are at least two figures-of-merit that are useful for characterizing our progress with targets. One is simply luminosity, weighted by the square of polarization. This is certainly a real and important measure of what has actually been accomplished in a real experiment. Another, however, that is more appropriate for projecting future target performance, is the total number of spins polarized per second, again weighted by the square of polarization. In Fig. 8, we show this second Figure-of-Merit as a function of time for our targets at JLab. We note that this figure was included in a recent brochure prepared by the DOE Division of Nuclear Physics.
Figure 8: Shown is a figure-of-merit of polarized $^3$He targets as a function of time. Specifically, what is shown (in arbitrary units) is the spins polarized per second weighted by the square of polarization. The years 2006 and 2008 refer to the GEn(1) run and the recent sequence of polarized $^3$He runs (including the Transversity experiments) respectively. Technologies that played a key role in the improvements are noted and discussed in the text.

There are three innovations that are largely responsible for the large improvements seen in Fig. 8 in 2006 and 2008, which correspond to the GEn(1) run and the sequence of $^3$He runs that included the Transversity experiments, respectively. They are:

1. Alkali-hybrid spin-exchange optical pumping (SEOP).
2. Optimization of alkali ratio and other operating parameters.
3. The use of spectrally narrow diode lasers.

We will say a few words about each item in the list above, and how it led to the improvements in target performance. We will then discuss how the polarized $^3$He technology is now poised for a new generation of targets with the capability of an order-of-magnitude improvement in luminosity. The development of those targets, in preparation for GEn(2), the Hall A SSA SIDIS experiment, as well as measurements of $A_1^p$ and $d_2$, will be a central activity of our group over the next three years.

Alkali-hybrid SEOP

Spin-exchange optical pumping (SEOP) is a two step process in which 1) an alkali-metal is optically pumped and 2) the nuclei of noble-gas atoms are polarized during collisions through a hyperfine interaction. SEOP is typically done in a glass cell, often sealed, containing a noble gas, a small amount of nitrogen, and a few hundred milligrams of an alkali metal. The pressure of the noble gas can be quite high, and is typically on the order of 10 atmospheres in polarized $^3$He targets. By controlling
the temperature of the cell, it is possible to achieve a wide range of number densities of alkali-metal atoms. The nitrogen is usually present at the level of 70 Torr or so, less than 1% in a cell containing around 10 atmospheres of $^3$He. The alkali metal atoms are optically pumped by irradiating the cell with laser light tuned to the first transition (the $D_1$ line) of the alkali metal. Subsequent collisions with the $^3$He atoms result in a polarization transfer to the $^3$He. In all of the targets that we have built for JLab, as well as all of the targets we built for use at SLAC, the sealed glass cells have actually had two chambers, an upper “pumping chamber” in which the SEOP takes place, and a lower “target chamber” through which the electron beam passes. A typical target cell such as those that we have been using at JLab is shown in Fig. 9.

The difference between conventional optical pumping and alkali-hybrid optical pumping is that instead of using only one species of alkali metal, two or more are employed [29, 30]. In all JLab targets from GEn(1) onwards we have used a combination of potassium (K) and rubidium (Rb). Previous targets at JLab and SLAC used only Rb. During the spin exchange process, not all of the angular momentum in the alkali-metal atoms is transferred to the noble-gas nuclei. Some is wasted due to a spin-rotation interaction with the noble-gas atoms. In the case of Rb, it turns out that, typically, only a few percent of the angular momentum is transferred to the $^3$He nucleus. In the case of K, however, around 20% of the angular momentum is transferred. For a variety of reasons, it is still desirable to optically pump the Rb. Spin exchange between the Rb and the K is extremely rapid, thus guaranteeing that the polarization of the Rb and K will always be almost exactly equal. Thus, by including a mixture of Rb and K in our cells, we have roughly a factor of ten increase
in the efficiency with which spin is transferred to the $^3$He nuclei, and hence, the laser light is used roughly a factor of ten more efficiently.

In our last renewal proposal, in 2006, we described the techniques in which we create customized mixtures of alkali-metals. We accomplish this in a glove box in which we have small heaters, analytical scales, and other implements. The mixtures are then transferred to small ampules which are subsequently removed through an air lock and sealed. In addition to using these ampules for the cells we fabricate at UVa, we note that we have also supplied these ampules to both Haiyan Gao at Duke and Todd Everett at William and Mary.

As will be discussed more in the next section, the cells containing hybrid mixtures performed enormously better than those that we used previously. During GEn(1) we ran for a large fraction of the experiment with roughly 50% target polarization, the highest sustained values that had been achieved at that time.

**Optimization of target cell parameters**

Over most of the period during which we have operated polarized $^3$He targets at JLab, our target diagnostics have been quite limited. This was even true during most of the time period leading up to GEn(1). In the last several years, however, we have developed several powerful tools that have enabled us to both optimize performance and maximize our ability to predict the performance of a particular cell. Prior to GEn(1), our diagnostics related to the SEOP itself were quite limited. We had two methods for measuring the $^3$He polarization, including the NMR technique of adiabatic fast passage (AFP) and another technique based on measuring shifts in the electron paramagnetic resonance (EPR) frequencies associated with the alkali metal. We also monitored the temperature of the target cell in numerous places. Offline, we also characterized the cells in a variety of ways, but it was clear that additional diagnostics during optical-pumping conditions would be helpful.

Our new diagnostics are based on two basic techniques. In one, we send linearly polarized light into the cell, and look for a rotation of the polarization vector due to Faraday rotation. This technique can be used determine the alkali density. We can also determine the alkali polarization by monitoring the Faraday rotation while scanning RF over the alkali’s EPR transition. The relative heights of the various EPR peaks determine the alkali polarization. The second technique involves sending circularly polarized light into the cell while again scanning RF over the EPR transitions. In this second technique we amplitude-modulate the RF, and detect the transmitted light with a lock-in amplifier. Again, the relative heights of the different peaks determines the alkali polarizations.

While these new diagnostics were not trivial to implement, they provide powerful tools to navigate through the multi-parameter space that determines a target’s performance. For instance, a key parameter that affects a cell’s performance is the ratio of the number densities of the K and Rb. Naively, based on what is known about alkali-hybrid SEOP, one might imagine the optimal value to be anything from per-
haps 5–20. We found, however, that values of around 3.5–6 are actually conducive to the best performance. It is also tremendously powerful to be able to measure directly the alkali polarization. When the $^3$He polarization is low, it is often difficult if not impossible to isolate the cause. With alkali polarimetry, however, it becomes much easier.

To best understand the issues that need to be addressed, it is useful to consider the equation that determines the $^3$He polarization as a function of time:

$$P_{^3\text{He}}(t) = P_{\text{Alk}} \frac{\gamma_{se}}{\gamma_{se}(1 + X) + \Gamma} \left(1 - e^{-t(\gamma_{se}(1 + X) + \Gamma)} \right)$$ (12)

where $P_{^3\text{He}}$ is the nuclear polarization of the $^3$He, $P_{\text{Alk}}$ is the polarization of the alkali-metal vapor, $\gamma_{se}$ is the rate of spin-exchange rate between the $^3$He and the Rb, and $\Gamma$ is the spin-relaxation rate of the $^3$He nuclei due to all other processes. In eq. 12 we also make the assumption that diffusion between the pumping chamber and the target chamber is quite rapid. The factor $(1 + X)$ accounts for what is now a well-established additional relaxation mechanism whose presence has been empirically established but whose origin is unknown[31]. The factor $(1 + X)$ has the form given because the additional relaxation mechanism has been observed to be roughly proportional to the alkali-metal number density.

The spin exchange rate can be written

$$\gamma_{se} = f_{pc} (k^K_{se}[K] + k^Rb_{se}[Rb])$$ (13)

where $f_{pc}$ is the fraction of $^3$He atoms that are located within the pumping chamber, $k^K_{se}(k^Rb_{se})$ is the constant characterizing spin exchange between $^3$He and K(Rb), and $[K][Rb]$ is the number density of K(Rb) atoms within the pumping chamber [29].

Looking at eq. 12, it would appear that the way to achieve higher polarizations is to ensure that $\Gamma < \gamma_{se}$. In principal, if the alkali-metal number density can be made arbitrarily high, the $^3$He polarization can approach the limiting value of $P_{\text{Alk}}/(1 + X)$. The problem is that it becomes difficult to keep $P_{\text{Alk}} \approx 1$ as the alkali number density is increased. This is because the amount of laser power required goes up at a rate that is at least proportional to the alkali number density, and even slightly higher. With alkali-hybrid cells, however, the required laser power is much lower, and it becomes much easier to maintain high alkali polarization even at very high alkali number densities. The ability to measure both $P_{^3\text{He}}$ and $P_{\text{Alk}}$ has been critical to establishing the optimal way to operate our targets.

The physics determining the optimal ratio of K to Rb is not completely understood. Without going into details, one is faced with wanting the ratio to be as high as possible, to increase efficiency, but not so high that there isn’t enough Rb to keep the K fully polarized. Monitoring multiple aspects of the alkali-hybrid SEOP process for cells with varying ratios has been key to enabling us to establish the range of 3.5–6 as optimal.

Spectrally-narrowed diode lasers
For some time, several groups have reported improved polarization in spin-exchange polarized targets when using spectrally narrowed diode lasers. Unfortunately, however, the spectrally narrowed systems were largely homebuilt, based on un-narrowed high-power diode-laser arrays. In our own group we built several such systems, and although the results were encouraging, there were several aspects of the systems that we felt were less than ideal for long runs at JLab. First, the optical quality of the beams (in terms of spatial homogeneity) was relatively poor, and also, the systems tended not to be very robust.

Roughly two years ago, our group had the good fortune of obtaining four so-called “Comet” lasers, built by Spectra-Physics. These lasers came into our lab because of some medical imaging work we were doing, but we quickly performed tests to determine their effect on polarized $^3$He target cells. They typically had linewidths of around 0.15 nm, as opposed to roughly 2 nm, which were the linewidths of all the un-narrowed lasers we had been using. Using our new diagnostics to guide us, we quickly found operating parameters that yielded the highest polarizations we had ever achieved with full-sized target cells. Previously, the highest polarizations we had observed were around 55% using the alkali-hybrid cells. Fairly soon, we had broken 70%. We communicated these tests to our collaborators in the Transversity experiment, and shortly thereafter met with Larry Cardman to show him our results. Soon thereafter, JLab obtained several of the new Comet lasers, which were used for the series of $^3$He experiments in late 2008 and early 2009. These experiments typically ran with polarizations of 60–70%, in beam.

The polarized target for GEn(2)

For GEn(2), our approved experiment calls for an electron beam current of 60 µA, a factor of roughly 7–8 higher than what we ran during GEn(1), and about 5 times higher than what was run during Transversity. Furthermore, we would like to run 60 µA with a polarization over 60%. In fact, with recent design changes in GEn(2) (the introduction of a hadron calorimeter instead of a more traditional neutron detector) we are considering running at even higher beam currents.

As it turns out, we have now reached a point in our target work in which the target performance is limited by the basic design of the cells shown in Fig. 9. Ever since our work at SLAC, our basic target-cell design has included a pumping chamber and a target chamber connected by a single tube, that we refer to as the “transfer tube”. Gas that is polarized in the pumping chamber diffuses to the target cell, refreshing gas that has become depolarized by any number of mechanisms, including beam-induced relaxation. The time periods associated with this diffusion is on the order of 40 minutes, much faster the historically typical values of the time constant $(\gamma_{se}(1 + X) + \Gamma)^{-1}$ (that appears in eq. 12) that could often be on the order of 20 hours. With the alkali-hybrid cells, however, it is possible to run with such high alkali number density that the time constant can be as short as two hours! Under such conditions, the time required to move between the pumping chamber and the target
Figure 10: Shown are data indicating the polarization of a $^3$He target cell as a function of time while it is in the process of being polarized. Also shown are fits indicating the polarization in the pumping chamber (upper trace) and the target chamber (lower trace). Note the large polarization difference between the two chambers, even at saturation.

chamber is only a factor of 2–3 times slower than the time constant with which the gas is being polarized. Under these conditions, a significant polarization difference can develop between the pumping chamber and the target chamber, even in the absence of an electron beam. With an electron beam, the difference can be quite large, even approaching 10% at around 10 $\mu$A, and much worse at higher beam currents. This is illustrated in the “spinup curve” shown in Fig. 10 in which data on polarization versus time is shown for a particular target cell. Also shown are curves from a fit indicating the polarization in the pumping chamber (upper trace) and the polarization in the lower chamber (lower trace). At saturation, the polarization difference is found to be around 7%. While the polarization difference is clearly unwanted, it is also an indication of something intriguing; we are polarizing the gas very quickly compared to all other relaxation rates in the system. In short, with a properly designed cell, we could tolerate much higher beam currents.

For GEn(2), we need two accomplish two things: we need the gas to mix more quickly between the two chambers, and we need the target to be more robust against radiation damage. The first point addresses the question raised above. On the second point, we note that our current glass target cells tend to blow up after spending too much time in the beam. We generally try to limit their “in-beam” time to around four weeks when running with about 10 $\mu$A. It would be quite impractical to switch targets every few days, as would seem to be indicated if we make the assumption that the cells blow up after a certain amount of cumulative radiation damage.
Figure 11: Shown schematically is a conceptual design for the next-generation $^3$He targets. Gas flows convectively to make it possible to tolerate very high beam currents. Also, the target chamber is metal, making it quite radiation resistant.

To address these issues, we are developing a new generation of targets that are illustrated schematically in Fig. 11. A key feature of the cell is that it has not one but two transfer tubes. By heating one of the transfer tubes, we can drive convection in a controlled manner. This is a tremendously powerful innovation. With *no moving parts*, we can circulate the gas at will between the two chambers, which also means we can separate the pumping chamber from the target chamber by substantial distances. Also, for the first time, we are moving away from an all-glass target cell. We plan to use a target cell where the upper half, with the pumping chamber, is glass, while the lower half, with the target chamber, is metal. While this sounds like a big step, we note that in our group’s work on medical applications, we already have some limited experience in doing this. We will return to this issue shortly.

While convective flow should be largely calculable, we decided that it was important to demonstrate this key aspect of our new design. For this purpose we constructed the cell shown in the left-hand panel of Fig. 12. Unlike the final GEn(2)
target, it is all glass. Even so, it allowed us to test the idea of convective flow. One of
the two transfer tubes was wrapped with a heater, which is schematically represented
by the red box labeled “Heater to drive convection”. Around the other transfer tube
we wrapped wire, forming a crude solenoid (labeled “Zapper coil”) that could be
used to deliver an RF pulse locally to a small sample of gas in the transfer tube.
The purpose of the Zapper coil was to produce a slug of depolarized $^3$He gas that
could then be tracked as it moved through the cell. We then obtained repeated NMR
signals from the four coils (numbered #1–#4) over a period of 4–5 minutes. As can
be seen from the right-hand panel of Fig. 12, the passage of the depolarized slug of
gas is clearly visible as it passes each of the four coils. As the depolarized slug passes
by each coil, the NMR signal becomes smaller. We note that the width of the slug
spreads out with time due both to the small viscosity of the gas (it moves slower at
the walls) and due to diffusion.

Using data such as those shown in the right-hand panel of Fig. 12, it is possible to
calculate the speed with which the gas is moving from the arrival time of the slug at
each coil. Fig. 13 shows the gas speed as a function of the temperature of the heated
transfer tube. The gas speed varies from around 5 cm/min up to 80 cm/min. This
easily covers the range that we believe will be needed for optimal performance.

Beyond achieving convective flow, there are at least two important technologies
that must be developed within the context of the next-generation target. We plan
to make the lower cell out of either aluminum or titanium, onto which we plan to
place a gold coating. In the group of Ernst Otten, gold-coated glass was observed
to have a relaxation time of 20 hours [32]. While this relaxation time is more than
adequate, we note that there are reasons to believe that with the right preparation, a gold coating might well have a relaxation time significantly longer. Regardless, the results of reference [32] represent a proof-of-principle that gold coatings can be used for our purposes.

We have begun a series of tests to find the best way to apply gold coatings. In our first test, gold was evaporated onto the inner surface of glass under vacuum. The deposition was done for us by Zein-Eddine Meziani’s group at Temple University. Unfortunately, this coating had a relaxation time of only a few hours. We are now trying a chemical deposition technique that was used by a group at Rutgers that were interested in obtaining a microscopically smooth surface. To monitor our progress, we are making measurements using an atomic tunneling microscope that is available at the nanotechnology center across the street from the UVa physics building.

Once we have identified an acceptable coating technique, we will next focus on coating metal cells, and attaching them to the glass pumping chamber. Here we plan to mate a large flat glass flange to a large flat aluminum flange using an indium o-ring and a custom pressure fitting to bring the two flanges together.

At present, we are studying what might be called the spin-exchange dynamics of convective-flow cells in parallel with developing coating technologies. From there we will begin building our first full-scale second generation target cells. To make the cells resistant to depolarization from the beam, we plan to use a pumping volume that is fully twice that which was used during GEn(1). Optical pumping will be accomplished
using ten 30 Watt Comet or Comet-style lasers. We note that we actually used seven lasers during E94-010, our first polarized $^3$He experiment to run at JLab. Since then we have converted to using fiber-based optical systems that make combining multiple lasers particularly straightforward.

We believe we are being conservative in stating that we can have our first prototypes ready at least two years prior to the first beam being delivered to Hall A after the upgrade. More details on the GEn(2) target design are available in the proposal for E12-09-016 which can be found on the JLab web site.

4 Polarized electron source systematics

As discussed in section 2, an important fraction of our work over the next three years will be devoted to the control of helicity-correlated systematics during parity violation experiments, effects that are usually traceable to the optics system associated with the polarized electron source. This is an area in which G. Cates has worked for many years, including all of the HAPPEX experiments, SLAC E158, and most recently, both Qweak and PREx. G. Cates is also the working group leader for the polarized electron source of MOLLER (the 11 GeV Möller experiment). Our work controlling helicity-correlated systematics has generally involved three steps: 1) developing a thorough understanding of the underlying effects causing the systematics, 2) extensive measurements on an optics table verifying our understanding and developing a strategy to control the systematics and 3) taking the results of our work and applying them to the polarized electron source itself. At both SLAC and JLab, we have worked very closely with the respective polarized electron source groups in accomplishing these goals.

During our preparations for E158, we identified a class of effects that we refer to as “phase-gradient” effects, whose control was critical to suppressing systematic errors in the experiment. This work is described in great detail in a paper written by Brian Humensky, G. Cates’ graduate student at the time [9]. During HAPPEX II, our group, including Brian Humensky, working in close collaboration with Kent Paschke and Lisa Kauffman (who at that time were in Krishna Kumar’s group at UMass) identified a new source of these so-called phase-gradient effects, and developed a protocol to minimize them. At the time, however, we had only limited understanding of their underlying cause. In preparation for Qweak and PREx, we have further studied these effects, with the particular goal of ensuring that they are sufficiently small so as not to cause undue false asymmetries. Understanding these effects during Qweak and PREx is also important for the upcoming MOLLER experiment which will require even finer levels of control.

*Phase-gradient effects and the “skew effect”*

The cause of many optics-related systematic effects in parity violation experiments can be traced to charge asymmetries that arise from light that is not perfectly
Figure 14: A mechanism is illustrated (sometimes referred to as the PITA effect) that can cause charge asymmetries. The vertical lines on the GaAs crystals indicate that, for linearly polarized light, the quantum efficiency will be slightly higher for vertical polarization. The two pairs of ellipses represent the polarization ellipses for nearly circularly polarized light.

circularly polarized. It is generally the case that for linearly polarized light, the efficiency of the optical transport system, or the quantum efficiency of the GaAs crystal itself, depends on the orientation of the polarization vector. Light that is nearly but not perfectly circularly polarized contains a linear component. If the orientation of that component changes when the helicity is reversed, the result can be a helicity-dependent charge asymmetry. This process is illustrated in Fig. 14. Pictured is a GaAs crystal where the vertical lines indicate that the quantum efficiency is slightly higher for light that is vertically polarized than it is for light that is horizontally polarized. The pair of ellipses below each crystal represent the polarization ellipses associated with light when it has positive (+) and negative (−) helicity. For the situation illustrated on the left, more electrons will be photoemitted when the incident light has positive helicity than will be the case when the light has negative helicity. For the situation illustrated on the right, even though the degree of circular polarization is the same, there will be no change in photoemission for the two helicity states. This is because the ellipses are oriented such that they are not sensitive to the analyzing power of the crystal. For historical reasons, we sometimes refer to the generation of charge asymmetries in this manner as the “PITA” effect, for “polarization induced transport asymmetry”[33]. In addition to simply illustrating the PITA effect, Fig. 14 also illustrates how it is possible to reduce sensitivity to any analyzing power that may be in the system.

For a Pockels cell, without loss of generality, the phases introduced to produce
positive and negative helicity light can be written
\[
\delta_+ = +\left(\frac{\pi}{2} + \alpha\right) + \Delta \quad \text{and} \quad \delta_- = -\left(\frac{\pi}{2} + \alpha\right) + \Delta
\] (14)

where if \(\alpha = 0\) and \(\Delta = 0\) the resulting light is perfectly circularly polarized. It turns out that charge asymmetries related to the PITA effect are to first order proportional to \(\Delta\). From equation 14, it can also be seen that \(\Delta\) does not change sign when the helicity flips. The implication is that any optical component, from the Pockels cell itself to a vacuum window under stress, can have a small amount of birefringence and thus introduce a non-zero \(\Delta^2\). While essentially any optics system will have some stray birefringence, and thus a non-zero phase \(\Delta\), it is easy to compensate by adjusting the voltages on the Pockels cells. You can essentially “dial the charge asymmetry” to be whatever you want, including zero. This was done with active feedback during the \(^{12}\)C parity experiment that took place at Bates[34], and has been done for every parity violation experiment (in electron scattering) since. It is thus possible to ensure very small charge asymmetries when averaged over the course of the experiment.

If the phase \(\Delta\) is constant across the profile of the laser beam, the result is a simple charge asymmetry. It is also possible, however, to have a value of \(\Delta\) that varies with position. We have come to refer to such effects as a “phase gradients”. The result of a phase gradient is a charge asymmetry that varies across the profile of the laser beam. To first order, such an effect appears as a helicity-dependent beam-position difference. Such position differences were seen during the \(^{12}\)C experiment at Bates, but were livable. During E158 at SLAC, however, we had no choice but to significantly reduce them. Once we understood the origin of position differences due to phase gradients, we were able to devise ways of measuring and characterizing them. We found that phase gradients are often intrinsic to a Pockels cell, and if you have a way to measure them, it is possible to select only those Pockels cells with very small phase gradients. We were even able to convince the Pockels cell manufacturer to minimize phase gradients during the fabrication process. In short, once we understood the problem, we were able to find strategies to control it.

In preparing for the HAPPEX II runs, it became clear that there was a small but troublesome source of phase gradients that was unrelated to the quality of the Pockels cell. Part of our preparations for HAPPEX II involved establishing an optics lab in the so-called “Test Lab” at JLab. This was done as a collective effort between our group, Krishna Kumar’s group from UMass, and the JLab source group. At our optics lab, away from the pressures of running experiments on the accelerator, we were able to conduct extensive studies of various systematic effects. What we eventually determined was that small phase gradients can result from a coupling of the divergence of the laser beam to the angle between the axis of symmetry of the

\footnote{We note in passing that to describe the “\(\Delta\)” phase for an arbitrary optical element, you actually need two \(\Delta\)’s that refer to two sets of axes at 45° to one another. This is discussed in detail in ref. [9], and is not discussed further here because it would introduce unnecessary complication}
Figure 15: One of the underlying causes of “phase gradients” is illustrated. In (a), the gradient results from a coupling between the divergence of a laser beam to the angle between the beam and the optical axis of the Pockels cell. The result is a reasonably constant phase gradient that can cause helicity-correlated position differences. In (b), it is shown that phase gradients exist even in the absence of a tilt in the Pockels cell. The divergence of the laser beam alone is enough to causes sensitivity to the extraordinary index of refraction of the Pockels cell, resulting in a helicity-correlated “breathing mode” (see text).

laser beam and the optical axis of the Pockels cell. The effect is illustrated in Fig. 17a. It is generally still present even when great care is taken to use a parallel laser beam and a well aligned Pockels cell. The problem is that the effect is so small that it does not show up until you begin taking data on position differences in much the way you would during a parity run. If, however, you “tweak” the Pockels cell while checking your progress through accumulating statistics on a large number of pulse pairs, it is possible to minimize the effect. Again, once we understood the underlying problem, we could establish a sufficiently sensitive procedure for aligning the Pockels cells. Indeed, once we did so, the results were dramatic. Whereas we previously saw helicity-correlated position differences in the range of 50–100 nm, they were instead in the range of perhaps 10–20 nm. What was more important, however, is that they readily averaged down as the run progressed. In the end, position differences, averaged over the entire run, were on the order of 1–2 nm for each of our beam-position monitors.

With further analysis, it is now clear that this same skew effect is even present in
Figure 16: Data illustrating the skew effect. While the angle of the Pockels cell is changed, the charge differences (top panel), position differences (middle panel) and beam-size differences (lowest panel) change due to coupling between the divergence of a laser beam and the angle with respect to the optical axis of the Pockels cell.

the total absence of any misalignment of the Pockels cell. The unwanted retardation arises because light traveling at a non-zero angle with respect to the Pockels cell is sensitive to the extraordinary index of refraction of the crystal. Even if the Pockels cell and the laser beam are absolutely coincident, any non-zero divergence in the laser will result in a small superfluous retardation that varies depending on the angle of the “ray” of light. The pattern of the asymmetry is illustrated in Fig. 17b. This “non-tilt skew effect” results in a helicity-correlated difference in the size of the beam along certain axes. The result in something we refer to as a breathing mode in which first the beam get fatter along one axis and skinnier along the orthogonal axis, and then gets skinnier along the axis along which it was fatter, and fatter along the axis on which it was skinnier. If the detector had perfect azimuthal symmetry, this would not matter. Unfortunately that is not the case. It is thus important to incorporate “flips” that will leave this effect unaffected while changing the sign of the physics asymmetry.

Optics table tests for PREx and Qweak

In preparation for PREx and Qweak, we have been studying helicity-correlated
Figure 17: Data showing spot-size differences while the Pockels cell is being translated. The effect is there even in the absence of a polarizer.

laser-beam effects on an optics table. Most of these measurements were made by Rupesh Silwal, a graduate student of G. Cates, and the work was done in close collaboration with Prof. Kent Paschke.

In one set of measurements, we have studied skew effects by measuring the helicity-correlated charge asymmetry, position differences, and beam-size differences (along particular axes) while simultaneously tilting a Pockels cell. The results of these tests are shown in Fig. 16. Since skew-related effects are polarization induced, we needed an analyzer to see them. For these tests we used a polarizer cube, essentially introducing an analyzing power of 100%. The analyzing power of a super-lattice GaAs cathode, the type that will be used for both PREx and Qweak, is only about 3%. Thus, conservatively, any effects we measured will be reduced by at least a factor of 20 (assuming a cathode with an analyzing power of 5%).

An notable feature of these studies is the value of the beam-size differences for zero tilt angle. The fact that beam-size differences with no tilt are non-zero is anticipated from the above discussion, and from the plot, we can see they are roughly 0.6 µ. The beam diameter during these studies was roughly 0.6 mm, so this corresponds to a $1 \times 10^{-3}$ fractional diameter change with 100% analyzing power, and a $5 \times 10^{-5}$ fractional diameter change with a 5% analyzing power. The requirement for PREx is $10^{-4}$. Thus, even without additional “flips”, the demonstrated performance is acceptable.

The so-called skew effects are not the only mechanisms that can cause helicity-correlated differences in the beam diameter. We have long known that pulsing the Pockels cell at high voltage causes a class of effects we loosely call “lensing effects”. The Pockels cell has a nonzero piezoelectric effect, and its length, and indeed its shape is altered when the voltage is pulsed. Lensing effects can cause pronounced helicity correlated position differences if no care is taken to avoid them. The remedy is simply to measure the effects while translating the Pockels cell in two dimensions. Once the laser beam is well centered in the cell, the effects are minimized. Beam-diameter differences, however, can still be nonzero. In Fig. 17, we show helicity-correlated
beam diameter differences as the Pockels cell is translated. The effect is observed
to be roughly at the level of $3 \times 10^{-4}$. Since the effect is not polarization related,
however, the effect does not change when a half-wave plate is inserted. The second set
of data shown in Fig. 17 was taken with a half-wave plate inserted, and a minus sign
has been arbitrarily introduced to account for the fact that under these conditions
the physics asymmetry would be reversed. During the HAPPEX-helium experiment
we had an effect far worse than this with position differences that was invariant with
respect to the insertion of a half-wave plate. In that case, the half-wave plate reversal
canceled the effect at a level of better than two orders of magnitude. We are thus
quit confident that the “lensing-related” beam-size differences will be well within our
specs during PREx and Qweak. Still, it is important to be aware of the problem and
to monitor it as best as possible for change.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>physics asymmetry</th>
<th>stat. error</th>
<th>sys. error due to beam</th>
<th>limits on position differences</th>
<th>limits on angle differences</th>
<th>limits on diameter differences</th>
</tr>
</thead>
<tbody>
<tr>
<td>HAPPEX I</td>
<td>-15,050 ppb</td>
<td>980 ppb</td>
<td>$\pm 20$ ppb</td>
<td>$&lt; 12$ nm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLAC E158</td>
<td>-131 ppb</td>
<td>14 ppb</td>
<td>$\pm 3$ ppb</td>
<td>$&lt; 12$ nm</td>
<td>0.4 nrad</td>
<td>$&lt; 10^{-5}$</td>
</tr>
<tr>
<td>HAPPEX II-p</td>
<td>-1,580 ppb</td>
<td>120 ppb</td>
<td>$\pm 17$ ppb</td>
<td>$&lt; 1.7$ nm</td>
<td>0.2 nrad</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Shown are various parameters for several parity experiments, including
HAPPEX I, E158, and HAPPEX II-p, which are completed and published, HAPPEX
III that recently ran, PREx and QWeak, that are running quite soon, and MOLLER
(the 11 GeV Møller experiment) which will run after the 12 GeV upgrade. The
second and third columns show the actual measured or projected asymmetries and
statistical errors. The fourth column shows the actual or projected error associated
with corrections for helicity-correlated beam-parameters. The remaining columns
indicate actual or projected limits on helicity-correlated beam parameter differences.

**Requirements for PREx, Qweak, and MOLLER**

In Table 1, we show some of the beam requirements for PREx, Qweak and
MOLLER. In terms of beam-position differences, PREx requires less than 1 nm, and
MOLLER requires less than 0.5 nm. During HAPPEX-II roughly 2 nm was achieved
with no active feedback. With feedback, significantly smaller numbers should be
achievable, making the requirements of these two experiments quite attainable. With
care, we can probably even live without feedback for the case of PREx. A parameter
that has historically gotten less attention is helicity-correlated beam diameter differ-
ences. As discussed above, the level of control we have achieved on the optics table suggests that this systematic is under adequate control, particularly when including the effects of half-wave plate insertions. We note also that during E158, beam-size differences were held to less than $10^{-5}$ for all runs, and a few times $10^{-6}$ during run #1. The beam-size differences were measured on a wire array. It should be noted, however, that a combination of synchrotron radiation and skew quads blew the beam up in a manner that partially masked some sources of systematic effects originating from the polarized electron source. Never-the-less, the E158 numbers are encouraging.

5 The neutron electric form factor: GEn(1) an GEn(2)

Because GEn(1) (E02-013) has been such an important part of our activities for several years, and because the design and development of GEn(2) has been and continues to be such an important part of our future, we close by saying a few words about these two efforts. As mentioned earlier, GEn(1) was the largest installation in Hall A since the hall was commissioned. Many aspects of GEn(1) were quite novel, including the open geometry spectrometer BigBite which is based on a single dipole magnet. Serious questions existed regarding the degree to which BigBite could operate in such a high-rate environment. The huge success of the experiment, however, opened the door for a variety of experiments, and laid the groundwork for the Super Bigbite project that was discussed earlier. Indeed, the lessons learned from GEn(1) were central to the design of the Super Bigbite apparatus and GEn(2) itself.

The GEn(1) experiment (E02-013) measured a double-spin asymmetry in the quasi-elastic scattering of polarized electrons from a high-luminosity polarized $^3\text{He}$ target using the reaction $^3\text{He}(e,e'n)pp$. Coincidences were detected using the Bigbite spectrometer for the electron arm, and a large (we believe the world’s largest) neutron detector for the hadron arm. The detector package for Bigbite included 15 planes of high-resolution high-segmentation multilayer drift chambers, a scintillator plane and a two-layer lead-glass calorimeter for triggering and pion rejection. The neutron detector had an active area of 1.4 by 4 meters, and was comprised of seven layers of plastic scintillators and iron. Energy resolution came from the time-of-flight of the nucleon. The front face also had a set of veto counters for charge identification. A schematic representation of the experimental setup is shown in Fig. 18.

While the singles rates on the front tracking planes were quite high, the rate of energetic electrons in our calorimeter causing a trigger was only a few kHz. Using a good electron, we could construct the three-momentum transfer $\vec{q}$, and from this, determine the expected location of a hit in our neutron detector. Because of the Fermi momentum of the nucleons in the $^3\text{He}$ nuclei, there was a distribution of hits in the neutron detector centered on the expected location as determined from $\vec{q}$. We could then compute the missing momentum $p_\perp$ between the actual hit in the neutron
Figure 18: Shown is a schematic representation of GEn(1).

detector the location we would expect if the nucleon momentum $\vec{p}$ and the three-momentum $\vec{q}$ were one and the same. The quantity $p_\perp$, whose calculation is mostly given by the position of the hit on the neutron detector, was our most powerful cut. Our next most effective cut was the quasi-invariant mass $W$ that we would calculate under the assumption that the struck nucleon was at rest.

The cleanliness of our resulting signal is illustrated in Fig. 19, in which the data are shown in both panels with a black line. The panel on the left shows our data with only minimal cuts, and the panel on the right shows the result of demanding that $p_\perp < 150$ MeV, and that $p_\parallel$ (the longitudinal component of the nucleon’s momentum) be within 250 MeV of the expected value. The quasi-elastic peak immediately emerges. Also shown in Fig. 19 are the results of a careful Monte Carlo of our experiment, incorporating MAID and other constraints to understand our inelastic background. The Monte Carlo does an excellent job reproducing our data, and when we impose our cuts, the there is only minimal leakage of inelastics underneath the quasi-elastic peak.

The GEn(1) experiment had a figure-of-merit well over an order-of-magnitude higher than previous measurements of $G_E^n$. We ran with high luminosity (roughly $5 \times 10^{35}$ cm$^{-2}$s$^{-1}$), a solid angle in BigBite of around 76 msr, a matching acceptance in our neutron detector and a target polarization significantly higher than what we projected in our proposal. The single rates were quite high in our front trackers, and the single rates in the neutron detector were also high. Even so, we achieved error bars just over 20% higher than in our original proposal, something we saw as quite a triumph given that we were using all-new un-commissioned apparatus and a technique that was quite novel.

While the $Q^2$ we achieved during GEn(1) was unprecedented, it is natural to ask how we might build a next-generation experiment. GEn(2) was approved by PAC

37
Figure 19: Two histograms showing GEn(1) data at $Q^2 = 1.7 \text{GeV}^2$ as a function of the quasi-invariant mass $W$ with minimal cuts (at left) and cuts to extract quasi-elastic events (at right). Also shown is a Monte Carlo that gives an excellent fit to the data, and indicates that with our quasi-elastic cuts, we have very little contamination from inelastics.

34, and the proposal is available on the JLab web site. We want to point out here just a few aspects of the experiment that illustrate how we can leverage the lessons learned during GEn(1). We have already discussed in section 3 the next-generation polarized $^3\text{He}$ target that will be able to tolerate beam currents approaching 100$\mu$A. To handle the resulting singles rates on the electron arm, we are building trackers using GEM technology. For GEn(2), the rates will be far below what has already been demonstrated successfully with GEMs. For the neutron arm, we are doing two things differently. First, we are using the “Super Bigbite” magnet, a large dipole with a cut in the yoke to pass the electron beam, to deflect charged particles. This will make it quite easy to distinguish neutrons from protons, and will largely obviate the need for a veto detector. These changes will significantly increase our neutron detection efficiency. We are also moving from a neutron detector based on scintillator bars to a hadron calorimeter. This will have the wonderful effect of allowing us to greatly increase our thresholds, making it possible to tolerate much higher luminosity.

GEn(2) will make measurements at 5.0, 6.8 and 10 GeV$^2$, and will obtain the errors shown in Fig.1 in 58 days of running. By doing so, the exploration of the electric form factor that has been so productive on the proton will continue with the neutron as well. These measurements will challenge theories that describe nucleon structure using QCD degrees of freedom, provide vital input to the constraint of GPDs, and, among other things, allow the flavor decomposition of the ground-state electromagnetic form factors at high $Q^2$. Furthermore, the experimental techniques we will employ are almost certain to make new investigations possible that have not yet even been considered.
6 The Bibliography

References


[10] A. Acha et al. (HAPPEX collaboration), Precision Measurements of the Nucleon Strange Form Factors at $Q^2 \sim 0.1$ GeV$^2$, Phys. Rev. Lett. 98, 032301 (2007).


7 Budget justification

The budget we propose is quite similar in scope (within 6%) of the final year of our current funding cycle with one exception. We are requesting a third full-time graduate student. In fact, for most of the past three years we have had 3–4 graduate students in the group, the funding for whom has come from a variety of sources. Often, we have been able to get JLab to support one extra student. Even with this many students in the group, we are turning away excellent graduate students on a regular basis, and would very much like to make three graduate students the normal base for our program.

On permanent equipment, it is important to mention two things. First, as you may know (it even appeared in the New York Times) $^3$He is becoming scarce because of very high demand from the Department of Homeland Security. Luckily, we have, within the UVa nuclear physics group, enough $^3$He for our needs. Unfortunately, however, this $^3$He has been used in a dilution refrigerator and does not have a contamination level low enough for our needs. We thus propose to build a simple $^3$He purification system in which we will run the $^3$He through liquid $^4$He to condense out any contaminants. It is important for us to do this as soon as possible, so the costs associated with this system appear in the first year. Secondly, as described in the proposal, we are developing a second generation polarized $^3$He target that will be able to withstand very-high ($50-100 \mu A$) beam currents. This system will require a new type of polarimetry system, the cost for which appears in the second year. Finally, we will need to buy at least one spectrally-narrowed high-power diode laser array system during the next three years, and we show that purchase during the third year. We note we are buying two such systems this year, and will be able to make do with an old laser in the interim. We note, however, that two out of three of our old lasers have died, so we see this purchase as quite important.

The main costs in our budget are as follows:

- 1.90 FTE's at the post-doc/research scientist level.
- 3 graduate students for the academic year, and 4 graduate students during the summer.
- travel
- expendable materials
- 2.0 months summary salary for G. Cates
- glass blowing (at Princeton U.) and shop time at UVa
7.1 People at the Post-doc/Research Scientist level

At present there are two people in our group at the post-doc/research scientist level:

**Dr. W. Alexander Tobias** oversees and coordinates efforts in our UVa laboratory on a day-to-day basis. This includes providing guidance to our students, and dealing with any number of administrative issues, particularly purchasing. Perhaps more than anything, Dr. Tobias is our point person on all matters related to the development, fabrication, and characterization of \(^3\)He target cells. He is, among other things, an expert on cryogenics and high vacuum technology. He has also been a key figure in supporting the William and Mary target-cell effort, both in transferring technology as well as interfacing with the glass blower with whom we work.

**Dr. Vladimir Nelyubin** has three major areas of responsibility. He is our local expert maintaining and operating a Coherent Model 899 computer-controlled scanable single-frequency laser. This complex system, which forms the heart of many laser-spectroscopy labs across the country, is the primary instrument that we use for characterizing our polarized \(^3\)He target cells. By doing precision measurements of alkali-metal absorption lines we are able to determine the pressure in our (sealed) glass cells to better than 1\%, as well as the ratio of rubidium (Rb) to potassium (K) in the alkali-mixtures that are central to the new hybrid technology that we employ. We also use interference techniques to measure the thickness of the glass cells at various key locations. Dr. Nelyubin was also the person who oversaw most of the day-to-day activity when UVa was building the wire chambers for the Bigbite spectrometer. Finally, Dr. Nelyubin has been central to the design of new experiments. He wrote simulations that formed the basis of the first \(^m\)GE experiment, and has done much of the design work for the next \(^m\)GE experiment as well. He also wrote several of the simulations that were central to the design of E12-06-122, our \(^A\)l experiment that will run with Bigbite after the 12 GeV upgrade.

7.2 Graduate students

We are requesting funding for three “year-round” graduate students, as well as funds for one additional graduate student during the summer. We presently have four graduate students doing JLab-related work. Thus, the requested funding would allow us to maintain our current number of graduate students at a constant level. We note that bringing in a student during the summer is usually our best method for recruiting, something that is quite important right now with two students in the group who will soon be graduating within two months. The current list of students doing JLab-related work is:


• Peter Dolph – (5th year) – Currently working on next-generation target for GEn(2).

• Rupesh Silwal – (4th year) – Working on a combination of PREx and HAPPEX-II.

7.3 Travel

Our projected travel costs are computed by taking the actual money spent from this grant over a eight years and taking the average. We thus believe that our request is a very accurate projection.

7.4 Expendable materials

Our request for expendable materials is based on actual money spent from this grant over an eight year period and taking the average. This category is always high for us because the fabrication of target cells requires large amounts of cryogens, both liquid nitrogen and liquid helium. We also need to purchase various specialty gases, such as $^3$He, and high purity nitrogen, although this coming funding cycle we will probably purify old $^3$He gas rather than purchase new gas. This will require fabricating a purification system, however, which will more than make up for any savings gained by buying fewer specialty gases. Other expendable materials include both glass and metal plumbing fittings, miscellaneous electronics, etc.

7.5 Summer salary

We are requesting 2.0 months of summer salary, in keeping with recent years. We note that G. Cates also receives a 3rd month of summer salary through the medical school (mostly NIH funding). It is worth noting that G. Cates is officially 75% Arts and Sciences an 25% School of Medicine (SOM). Thus, the SOM is paying a slightly higher fraction (1/6) of G. Cates’ summer salary than is the case during the nine-month school year.

7.6 Glass blowing and Shop time

Our cell making activities require the services of a glass blower. We will also be using considerable amounts of shop time as we construct our He-3 purification system. In general, the construction of hardware related to targets is quite costly. As with our other categories, we base this estimate largely on past history.
7.7 Permanent Equipment

Over the first two years of the grant, we will need to construct two new systems as described below. During the third year of the grant we will need to replace one of our lasers.

Year #1

He-3 Purification System.
This system will be used to process old $^3$He to bring it up to target requirements.

- Edwards XDS5 Dry Vacuum pump $\$3,999$
- Alcatel ATH200 UHV 100 turbo-pump $\$7,950$
- Varian Multi-gauge controller $\$1,295$
- Pressure transducer and readout $\$3,000$
- High-purity stainless steel valves $\$3,750$
- General plumbing (VCR’s, tubing, etc.) $\$2,300$
- Gas regulators $\$1,000$

**Full cost for system** $\$23,294$

Year #2

Pulse NMR Polarimetry System.
Polarimetry system for new second-generation polarized He-3 target.

- Mixers, etc. from Minicircuits $\$1,200$
- 3 synthesized function generators ($\$2090$ each) $\$6,270$
- RF power amplifier $\$4,995$
- Computer control system (includes DAQ cards, etc.) $\$5,200$
- Textronix storage scope $\$2,495$
- MITEQ NMR preamp $\$400$
- SRS Preamp $\$2,195$

**Full cost for system** $\$22,755$

Year #3

Comet Laser System. $\$25,750$
8 Current and pending support

Title: “Medium Energy Spin Physics with Lasers” (This grant)
Principal Investigator: Gordon D. Cates
Agency: United States Department of Energy
Grant No. DEFG02-01ER41168
Grant Period: April 1, 2010 – March 31, 2013
Amount: $1,611,300
Comments: Pending. This grant provides G. Cates support for two months of the summer.

Title: “Medium Energy Spin Physics with Lasers” (current)
Principal Investigator: Gordon D. Cates
Agency: United States Department of Energy
Grant No. DEFG02-01ER41168
Grant Period: April 1, 2004 – March 31, 2007
Amount: $1,305,000
Comments: Current. This is the grant provides G. Cates support for two months of the summer.

Title: “Electromagnetic Form Factors of the Nucleon using the 12-GeV CEBAF ” (pending)
Connect person: Gordon D. Cates
Agency: United States Department of Energy
Grant No. n/a
Grant Period: April 1, 2010 – March 31, 2014
Amount: $2,380,000
Comments: This grant is in the process of being submitted by JLab. It is the proposal covering the Super Bigbite project, and includes equipment for the experiments known as GEn(1), GEp(5), and the Hall A GMn experiment.

Title: “Improved Methods for Hyperpolarized-Gas MRI of the Lung” (current)
Principle Investigator: John Mugler
Agency: National Heart, Lung and Blood Institute (NIH/NHLBI)
Grant No. 1 R01 HL079077
Grant Period: 1 July 2005 – 30 June 2009
Amount: $2,404,305
Comments: Current, under no-cost extension. G. Cates is a co-investigator and receives 1/3 of a month of summer salary from this grant.
Title: “Lung Pathology Detection Using Hyperpolarized 129Xe” (pending)
Principle Investigator: Kai Ruppert
Agency: National Heart, Lung and Blood Institute (NIH/NHLBI)
Grant No. R01 EB003202
Grant Period: 7/1/10-6/30/15 Amount: $1,324,400
Comments: This is a renewal grant. G. Cates is a co-investigator and will receive 1/3 of a month of summer salary from this grant.

Title: “Very-short-time Diffusion MRI of Hyperpolarized Gases” (current)
Principal Investigator: G. Wilson Miller
Agency: National Heart Lung and Blood Institute
Grant No. 1 R21 HL 089525-01
Grant Period, July 1, 2007 – May 31, 2009
Amount: $401,833
Comments: Under no-cost extension. Renewal in progress. G. Cates is a co-investigator and will receive 1/3 of a month of summer salary from this grant.

9 Facilities and Resources

G. Cates maintains several laboratories at UVa that collectively represent an enormous resource for the proposed program. The equipment in these labs represents a conglomeration of equipment accumulated over many years (approximately 16.5) of doing research at Princeton University, as well as roughly 9.5 years of doing research at UVa. The equipment from Princeton includes items bought with an NSF infrastructure grant that funded a “Multidisciplinary Laser Laboratory” as well as equipment bought with the substantial start-up funds provided by the University of Virginia. A few resources in G. Cates’ lab that deserve highlighting include:

- A gas system that is used for producing polarized 3He target cells. We note that this system was also used for producing polarization cells that were used in the world’s first noble-gas imaging experiments.

- A Coherent Model 899 computer-controlled single-frequency scannable Ti::sapphire laser system, used to characterize target cells.

- A glove box with an air lock that provides an inert atmosphere for producing hybrid mixtures of alkali metals and sealing them into glass ampules. The glove box is outfitted with an analytical scale, heater plates, and other necessary apparatus. We note that we have made these ampules of hybrid alkali mixtures available to groups outside of UVa including William and Mary and Duke.
• A system for doing experiments related to spin-exchange optical pumping that (when the lasers are in good shape!) fully simulates the conditions in the polarized $^3$He target at JLab.

• A high-field pulse NMR system for doing spin-relaxation studies relevant to spin-exchange optical pumping.

The University of Virginia has active research in many fields, and extensive experience administering such research. The Department of Physics in particular, located within the Jesse W. Beams Laboratory of Physics, has excellent facilities including a machine shop that is utilized by many different academic departments.

10 Estimate of Unobligated Balances

We currently project a small negative balance at the conclusion of our current three-year funding cycle.
Gordon D. Cates Jr.

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2672 Ellen Spring Road
Gordonsville, VA 22942
Phone: (540) 832-0927

Education
B.A. in Physics, Amherst College, 1977.
M.S. and M.Ph. in Physics, Yale University, 1982.
Ph.D. in Physics (with Prof. Vernon W. Hughes), Yale University, 1987.

Academic Employment
Research Assistant, Yale University 1980-1986
Research Associate, Princeton University 1987-1988
Instructor of Physics, Princeton University 1988-1989
Assistant Professor of Physics, Princeton University 1989-1993
Associate Professor of Physics, Princeton University 1993-1998
Professor of Physics, Princeton University 1998-2000
Professor of Physics and Radiology, University of Virginia 2000-

Selected Other Professional Activities
Co-founder of Magnetic Imaging Technologies Inc. 1995
Board of Directors, Magnetic Imaging Technologies Inc. 1995-1999
Member of the Nuclear Science Advisory Committee’s
Director, Institute of Nuclear and Particle Physics
   (INPP) at the University of Virginia 2001-
Panel member on the DOE Science and Technology Review
   of Jefferson Laboratory 2002-2005
Member of NSF Committee of Visitors for Mathematics and
   Physical Sciences (MPS) Division 2003
Chair-elect of JLab Users Group 2004
Member of NSAC subcommittee on the implementation
   of the 2002 Long Range Plan (“Tribble Committee”) 2004-2005
Chair, JLab User Group Board of Directors 2005-2007
Jefferson Laboratory Program Advisory Committee or PAC.
   2005-2007
Member of the Nuclear Science Advisory Committee’s
Member of the Jefferson Science Associates (JSA) Science
APS Public Policy Committee (PPC) 2008–
APS Division of Nuclear Physics (DNP)
   Bonner Prize Selection Committee 2009–

Academic and Professional Honors
Graduated Amherst College Summa Cum Laude (1977)
Elected to Phi Beta Kappa (1977)
Elected Fellow of the American Physical Society (1998)
Thomas Alva Edison Patent Award (R&D Council of NJ, 2000)
Selected Publications

(in reverse chronological order)


A. Acha et al. (HAPPEX collaboration), *Precision Measurements of the Nucleon Strange Form Factors at $Q^2 \sim 0.1$ GeV$^2$*, arxiv: nucl-ex/0609002, Phys. Rev. Lett. 98, 032301 (2007).


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EDUCATION
Ph.D. Experimental Nuclear & Particle Physics, January 2001, University of Virginia, Charlottesville, VA “Measurement of the Proton and Deuteron Spin Structure Functions $g_1$ and $g_2$”
M.A. Physics, May 1995, University of Virginia, Charlottesville, VA
B.S. Physics, cum laude, May 1992, College of William & Mary, Williamsburg, VA

RESEARCH POSITIONS
Jan. 2001-Jan. 2004: Postdoctoral Research Associate, University of Virginia, Charlottesville, VA
Jan. 2004-Mar. 2007: Research Scientist, University of Virginia, Charlottesville, VA
Mar. 2007-present: Senior Research Scientist, University of Virginia, Charlottesville, VA

PROFESSIONAL ACTIVITIES and AWARDS
Member of the CEBAF Users Group, 1994-present
Member of the American Physical Society and SPS, 1999-present
Member of the American Association for the Advancement of Science
Virginia Physics Department graduate student member of the Safety Committee, 1999
Treasurer of the Virginia Physics Journal Club, 1994
Member of William & Mary chapter of SPS, 1991-1992
Winner of SPS Honor Society award and member of Sigma Pi Sigma Honor Society, 1991

LANGUAGES AND SKILLS
Spoken languages include English, Hungarian and some knowledge of Spanish
Operating system knowledge include UNIX, Linux, MacOS and Windows
Computer language knowledge include FORTRAN, LaTeX and HTML
Cryogenic and vacuum system knowledge
Optics and laser system knowledge

RESEARCH
Research interests include studies in nucleon structure, tests of the standard model in the framework of nuclear physics, atomic systems, and applying nuclear and atomic experimental techniques to develop practical devices used in such applications as in medical research. I currently participate in several experiments running in Jefferson Lab Hall A and clinical work utilizing hyperpolarized noble gases in the University of Virginia Department of Radiology.

SELECTED PUBLICATIONS


“Precision Measurement of the Nucleon Strange Form Factors at $Q^2 \approx 0.1 \text{ GeV}^2$,” A. Acha, et al. (HAPPEX Collaboration), Phys. Rev. Lett. 98, 032301 (2007).


Vladimir Nelyubin

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Education:
Ph. D. St.Petersburg Nuclear Physics Institute
of the Russian Academy of Science ,
Nuclear and Particle Physics, 1983.
M.S. St.Petersburg Technical University,
Experimental Nuclear Physics, 1969.

Professional Experience:
Research Scientist, University of Virginia since 2007
Research Associate, University of Virginia 2003 - 2007
Visiting Scientist, University of Virginia and Jefferson Lab 2000 - 2002
Visiting scientist, RCNP, Osaka University, Japan 1997 - 1998
Senior Research Scientist,St.Petersburg Nuclear Physics Institute 1992 - 2006
Research Assistant, St.Petersburg Nuclear Physics Institute 1969 - 1970

Honors and Awards
Academy of Sciences of Russia, 275th Anniversary Commendation for Excellence in Research, 1999.
Center of Excellence position of Research Professor, Osaka University, 1997
Soros Fund Grant, 1992

Professional Activities:
Member, Jefferson Lab users group, since 2001
Member, User Group at COSY, Juelich, Germany, 1993 – 2003
Member, User Group at RCNP-SPring8, Osaka , Japan, 1997–1998
Member, User Group at BINF, Novosibirsk , Russia, since 1986
Member, User Group at JINR, Dubna , Russia, 1986–1993
Member, User Group at PNPI, Gatchina, Russia, since 1969

Instrumental Experience
Development, construction and testing the large multiwire drift chambers
$^3$He polarized target, production and characterization target cells
Development of the polarizer optics for the high power laser beam
Development of the precise magnet system for the holding field of the $^3$He polarized target
Development of the hydrogen and deuterium polarized atom beam source
Development a high density hydrogen target for the internal beam in the storage ring
Development of a large aperture scintillation detector for high energy neutrons
Selected Recent Publications

RECENT ADVANCES IN POLARIZED He-3 TARGETS
J. Singh et al., Published in AIP Conference Proceedings 1149, Spin Physics 18-th International Spin Physics Symposium, Charlottesville, Virginia USA, 6-11 October 2008, pp. 823-828

A SEARCH FOR $\Sigma_0^0$, $N_0^3$ and $\Theta^{++}$ PENTAQUARK STATES
Y. Qiang et al., Published in hep-ex/0609025 (September 2006)

PARITY-VIOLATING ELECTRON SCATTERING FROM $^4$He AND THE STRANGE ELECTRIC FORM-FACTOR OF THE NUCLEON.

EFFECT OF NUCLEAR TRANSPERANCY FROM THE (p,2p) MEASUREMENT ON $^6$Li AND $^{12}$C AT 1 GeV.
V. N. Baturin et al., Published in Nuclear Physics A 736 (2004) 283-299

MEASUREMENT OF TENSOR ANALYZING POWER IN ELASTIC ELECTRON-DEUTERON SCATTERING AT MOMENTUM TRANSFER RANGE 2.8 - 4.6 fm$^{-1}$

MEASUREMENT OF THE TENSOR ANALYZING POWERS $T_{20}$ and $T_{21}$ IN ELASTIC ELECTRON-DEUTERON SCATTERING

PRECISION MEASUREMENTS OF ELECTROPRODUCTION OF $\pi^0$ NEAR THRESHOLD: A TEST OF CHIRAL QCD DYNAMICS

POLARIZATION IN QUASI-ELASTIC (p,2p) REACTION ON $^7$Li NUCLEUS IN COMPLETE KINETICS AT 1 GeV

ANKE, A NEW FACILITY FOR MEDIUM ENERGY HADRON PHYSICS AT COSY-JUELICH.

MEASUREMENT OF POLARIZATION OBSERVABLES IN ELASTIC AND INELASTIC ELECTRON DEUTERON SCATTERING AT THE VEPP-3 STORAGE RING.

COMPTON BACK-SCATTERING OF X-PHOTONS FROM 8 GeV ELECTRONS AT SPring-8.