Draft 1.0 - to be circulated in the collaboration only. Some numbers in the asymmetry analysis are subjected to be changed.

A Precision Measurement of the Beam Normal Single Spin Asymmetry in Forward-Angle Elastic Electron Proton Scattering

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A beam normal single spin asymmetry generated in the scattering of transversely polarized electrons from unpolarized nucleons is an observable related to the imaginary part of the two-photon exchange process. It is the only observable which provides information necessary for the calculation of lepton helicity flip amplitudes in electron nucleon scattering. The lepton helicity flip amplitudes are seen to greatly reduce the magnitude of two-photon exchange corrections on the upcoming low Q^2 muon-proton scattering experiments aiming to understand the proton charge radius puzzle. We report a 2% measurement of beam normal single spin asymmetry in elastic electron proton scattering with a vertex scattering angle $\langle\theta_s\rangle = 7.9 \pm 0.3^\circ$ and vertex energy $\langle E\rangle = 1.155 \pm 0.003$ GeV. This is the most precise measurement of this quantity available at this time and therefore it provides a stringent test of two-photon exchange models at $\theta_s \to 0$. Indeed, because there is no contribution from target polarization uncertainties in the measurement, this also becomes one of the most precise asymmetry measurements ever made in electron proton scattering.

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Two-photon exchange (TPE) in electron nucleon scattering is a higher-order process which vanishes in the Born approximation. Such processes are generally treated as small virtual corrections on the unpolarized scattering cross section which are independent of hadronic structure [1, 2]. The first evidence of hadronic structure dependance of TPE corrections came from the early measurements of the proton's elastic electromagnetic form factor ratio (G_E^p/G_M^p) where a striking disagreement was seen between Rosenbluth separation [3] and polarization transfer [4] results at $Q^2 \geq 2\,(\mathrm{GeV/c})^2$. This discrepancy was empirically shown [5] to be resulting from a correction involving the real part of the TPE amplitude which modifies the Rosenbluth cross-section while being canceled out in the polarization ratios. The ensuing years after the observation of the Rosenbluth, Polarization-transfer discrepancy have seen a multitude of activity in both theory [6–10] and experiment [11–13] all aimed at improving TPE corrections on the form factor measurements.

Even though modern TPE calculations are able to partially resolve [13] the Rosenbluth, Polarization-transfer discrepancy at moderate and high Q^2, the corrections themselves are model dependent and have not been tested in a range of kinematics [14]. This is not surprising since a larger effort is made in improving calculations at the high Q^2 backward scattering region where the TPE corrections are dominant and where the Rosenbluth-Polarization transfer discrepancy is significant. However, the recent disagreement observed in the proton's magnetic radius extracted from measurements of G_E^p/G_M^p at $Q^2 < 1\,(\mathrm{GeV/c})^2$ using Rosenbluth separation [15] and polarization transfer [16] methods seems to indicate TPE effects at low Q^2 may not be as insignificant as initially thought to be. Furthermore, the value of the magnetic radius extracted by the Rosenbluth seperation method is seen to have a dependance on the TPE model used [15]. The charge radius extracted from both experiments are in good agreement with one another and world average from electron proton scattering measurements. Nonetheless, the charge radius extracted from ep scattering measurements [17] disagrees significantly ($\approx 7.7\ \sigma$) with the very precise extraction done using Lamb shift in muonic hydrogen [18] in what is known as the proton charge radius puzzle. One correction [19] which accounts for $\approx 11\%$ [20] of the discrepancy is a TPE term that depends on the proton polarizability in muonic hydrogen. Although this is a relatively small correction, it has the largest theoretical uncertainty associated with any of the known corrections on muonic hydrogen. On the experimental side, the MUon proton Scattering Experiment (MUSE) [21] at PSI aims to resolve the charge radius puzzle by studying the lepton universality in ep and μp scattering. A recent calculation [22] of TPE corrections on μp scattering has indicated that at MUSE kinematics, the TPE corrections could vary between $\approx$0.5% and 1% depending how well one knows the helicity flip amplitudes in electron scattering [5]. Even though the predicted TPE corrections for MUSE are small, the calculation only includes TPE with a proton in the intermediate state, an assumption that is generally made for $Q^2 \to 0$ TPE calculations. The effect on MUSE TPE corrections when including resonant and non-resonant intermediate states remains to be seen. But the only way the model prediction can be well constrained is by benchmarking against experimental observables of TPE involving lepton helicity flip. The only TPE observable which provide access to helicity flip amplitudes is the beam normal single spin asymmetry measured in electron nucleon scattering.

A beam normal single spin asymmetry is an observable of the imaginary part of the TPE process and is measured in electron nucleon scattering when the electron is polarized normal to the scattering plane. It is a parity conserving, naively time reversal violating observable which vanish in the Born approximation. The asymmetry is generated by the interference of the one-photon and two-photon exchange processes and have the form [23]

$$B_n = \frac{\sigma\uparrow - \sigma\downarrow}{\sigma\uparrow + \sigma\downarrow} = \frac{\Im m\left[\sum\limits_{spins} (\mathcal{M}^{\gamma})^{*}(Abs\mathcal{M}^{\gamma\gamma})\right]}{\sum\limits_{spins} |\mathcal{M}^{\gamma}|^2}, \quad (1)$$

where $\sigma\uparrow$ ($\sigma\downarrow$) denotes the scattering cross section for electrons with spin parallel (anti-parallel) to a vector normal to the scattering plane, $\Im m$ is the imaginary part and $Abs\mathcal{M}^{\gamma\gamma}$ is the sum over all possible on-shell intermediate states in the two-photon exchange process. In terms of the invariants for electron nucleon scattering, B_n can be expressed as:

$$\begin{aligned} B_n = {} & \frac{2m_e}{Q}\sqrt{2\varepsilon(1-\varepsilon)}\sqrt{1+\frac{1}{\tau}}\left(G_M^2 + \frac{\varepsilon}{\tau}G_E^2\right)^{-1} \\ & \times\left[-\tau G_M \mathcal{I}m\left(\tilde{\mathcal{F}}_3 + \frac{1}{1+\tau}\frac{\nu}{M^2}\tilde{\mathcal{F}}_5\right)\right. \\ & \left. - G_E \mathcal{I}m\left(\tilde{\mathcal{F}}_4 + \frac{1}{1+\tau}\frac{\nu}{M^2}\tilde{\mathcal{F}}_6\right)\right] + \mathcal{O}^4 \end{aligned} \quad (2)$$

where G_E, G_M are the elastic form factors of the nucleon, ε is the polarization parameter of the virtual proton, $\tau = \frac{Q^2}{4M^2}$ and $\tilde{\mathcal{F}}_3, \tilde{\mathcal{F}}_4, \tilde{\mathcal{F}}_5, \tilde{\mathcal{F}}_6$ are invariant amplitudes which enters in the calculation of helicity flip amplitudes in electron proton scattering.

Theoretical calculations of B_n rely on Eq.1 and absorptive part of the Doubly Virtual Compton Scattering (or DVVS) tensor to model the hadronic tensor in $Abs\mathcal{M}^{\gamma\gamma}$. For the ground state of the nucleon, the DVVS tensor is exactly calculable using on-shell elastic electromagnetic form factors. On the contrary, the form factors of the resonant and non-resonant intermediate states are not well known and need to be parametrized through known experimental inputs of Compton scattering. This creates a model dependance in the B_n calculations similar to what is observed in the TPE corrections on the unpolarized cross-section. Existing models [24–28] of single spin asymmetries predict the asymmetry to be on the order of 10^{-6} [24] at few GeV electron beam energies, making a measurement of this quantity technically challenging. Nonetheless, with the precision achievable with the present parity-violating electron scattering (PVES) experiments, beam normal single spin asymmetry measurements have also become possible. These experiments are motivated by the fact that residual transverse polarization in the beam can cause B_n to generate a false asymmetry resulting in a few-percent correction of the measured parity-violating asymmetry.

We report a measurement of the beam normal single spin asymmetry generated in the scattering of elastic electrons from unpolarized protons using the Q_{weak} apparatus. This measurement is a part of a series of ancillary measurements performed by the Q_{weak} collaboration in order to constrain the systematic contribution to the measurement of the parity-violating asymmetry used in the first determination of the weak charge of the proton [29]. The general performance of the experimental apparatus has been described in detail in Ref. [29]. Details relevant to the extraction of B_n are presented here.

Approximately 54 hours of data were collected in two separate time periods in 2011 (Run I) and 2012 (Run II) using a transversely polarized electron beam. The 150μA circularly polarized electron beam was generated by the use of photo-production from a strained GaAs cathode at the injector of the Thomas Jefferson National Accelerator Facility. The electron polarization was adjusted to transverse orientation via two Wien filters [30] which are capable of rotating the electron spin in the vertical and horizontal planes independently. The full data set consists of data taken with two orthogonal transverse beam polarization configurations, horizontal (spin pointing to beam left at the target) and vertical (spin pointing up). Polarized electrons were accelerated to an energy 1.160 GeV before reaching the Q_{weak} setup located in the experimental Hall C and scattering from unpolarized liquid hydrogen (LH_2) encased in a 34.4 cm long aluminum cell with aluminum alloy windows. The electron energy at the scattering vertex after radiation losses is $\langle E \rangle = 1.155 \pm 0.003$ GeV. The polarization of the beam was measured with the Hall C Møller polarimeter which yielded an average beam polarization of $\langle P \rangle = (88.04 \pm 0.87)$ %. A set of collimators located downstream of the target was used to select electrons with scattering angles of 5.6° to 10°. A toroidal magnet was then used to select and focus elastic electrons onto a set of 8 Čerenkov detectors located symmetrically around the beam axis 12.2 m downstream of the target.

For the purpose of suppressing false asymmetry contributions, the helicity of the electrons was flipped at a rate of 960 Hz in a pseudo-random sequence of + - - + or - + + - patterns of four events (quartets) where + represents the standard spin orientation (spin up or to beam left) and - represents a 180^0 rotation in the plane. For each helicity state, the signals from the Čerenkov detectors were read out in an integrating manner, without any pre-event selection, to maximize statistics. The signal yields were then grouped into quartets to form asymmetries. The helicity-correlated changes in the beam position, angle, and energy which result in false asymmetries into the detector asymmetries were largely removed by an active cancellation provided by the periodical insertion of an insertable half wave plate (IHWP) located in the injector. The remaining correlations were removed during the asymmetry analysis with the use of multi-variable linear regression yielding regressed detector asymmetries.

For transversely polarized electrons scattering from unpolarized nucleons, the asymmetry in a detector placed in the scattering plane has an azimuthal dependence given by

$$A_{det}(\phi_{det}) = B_n \vec{P}.\hat{k} = -B_n |\vec{P}| \sin(\phi_{det} - \phi_s), \quad (3)$$

where $\vec{P}$ is the electron polarization vector, $\hat{k}$ is a unit vector normal to the scattering plane, ϕ_s is the azimuthal angle of $\vec{P}$ and ϕ_{det} is the azimuthal angle of the detector in the plane normal to the beam axis. Using this relation, the regressed detector asymmetries were fitted to extract the measured asymmetry, A_{exp}, as shown in Fig. 1. The fit included a floating phase offset in ϕ_{det} to take into account the detector offsets in the azimuthal plane and a floating constant to take into account the detector offsets in the radial and polar coordinates. The results of the fits for the different data sets are summarized in Tab. I. Due to similar kinematics in the three data sets, the error-

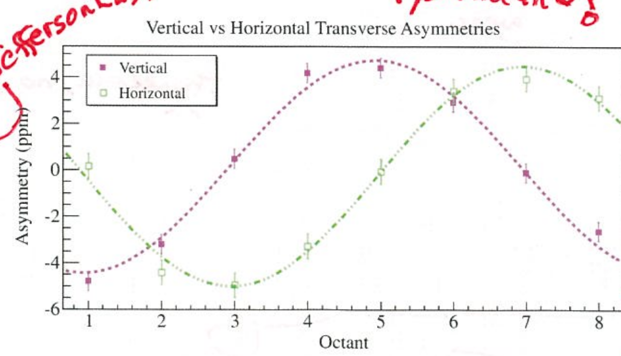

FIG. 1. Representation of the technique used to extract the physics asymmetry from the full data set. In this particular case, each data set represents an 8 hour measurement. The octant number corresponds to the azimuthal location of the detectors starting from beam left where ϕ=0 and going clockwise. The reduced chi-square in the vertical and horizontal fits are 1.4 and 0.9, respectively. The relationship between the measured asymmetry and the orientation of the beam polarization is clearly visible here.

weighted average of the asymmetry extracted from the fits is used as the experimental asymmetry from the LH_2 target. By design, the acceptance of a single Čerenkov detector is only 49% of 45°. The experimental asymmetry is therefore scaled by a factor of 0.9938 to take into account the averaging of the asymmetry over the effective detector acceptance.

TABLE I. Magnitude of the physics asymmetries extracted from the LH2 target via the fitting method represented in Fig. 1. Errors are statistical only.

Data set	A_{exp} (ppm)
RunI-Vertical	-4.807 ± 0.090
RunII-Vertical	-4.701 ± 0.142
RunII-Horizontal	-4.841 ± 0.085

The largest background source in the detector acceptance is elastic and quasi-elastic electron scattering from the aluminum alloy beam entrance and exit windows of the LH_2 target cell. Dedicated measurements using an aluminum alloy foil, similar to the one used in the target cell but thicker, was performed to determine the asymmetry. The correction determined from these measurements for a aluminum background dilution of 3.3±0.2% is 0.331 ppm. Additionally, a background correction of 0.007 ppm is applied to take into account the 0.02±0.01% inelastic background generated by the N→ Δ transition. The inelastic asymmetry was measured using dedicated measurements. B_n generated from elastic e+Al scattering and N→ Δ transition will be presented in separate publications in the near future. In addition to these dominant background sources, neutral backgrounds in the acceptance generated by sources in the beamline (a 0.2±0.1% dilution) and other sources (a 0.2±0.2% dilution) was also studied and found not to generate an azimuthal modulating asymmetry component at the current precision of the measurement. No correction was applied for these backgrounds. However, their dilutions were taken into consideration when extracting the final asymmetry.

A unique false asymmetry in a beam normal single spin asymmetry measurement is a parity-violating beam transverse single spin asymmetry (B_t) which is generated by the interference between one-photon exchange and the Z-exchange processes. The measured asymmetry has a $\cos\phi$ dependence and therefore can induce a phase offset in the B_n measurement. At our kinematics, B_t is estimated to be in the order of 10^{-11} [31]. Thus the induced phase shift will be in the order of 10^{-5} which is too small to be observed.

To extract the physics asymmetry at the effective acceptance averaged $\langle Q^2 \rangle = 0.0250 \pm 0.0006$ (GeV/c^2) of the experiment, an additional correction factor of $R_{rc} = 1.01 \pm 0.004$ was used to take into account energy losses and depolarization due to electromagnetic radiation, $R_{det} = 0.988 \pm 0.001$ to take into account the light-collection bias in the Čerenkov detectors, and $R_{Q^2} = 1.000 \pm 0.004$ to take into account non-uniform Q^2 variation across the detectors.

Above corrections are applied using the standard formula

$$B_n = R_{tot} \left[\frac{A_{phy}/P - \sum_{i=1}^{4} f_i A_i}{1 - \sum_{i=1}^{4} f_i} \right] \quad (4)$$

where $R_{tot} = R_{rc} \times R_{det} \times R_{Q^2}$ and A_i are background asymmetries generated by aluminum windows, inelastics, beamline neutrals and other soft neutrals with dilution f_i. From the fully corrected physics asymmetry we obtain the beam normal single spin asymmetry of -5.368 ± 0.067_{stat} ± 0.076_{sys} ppm generated by elastic electron proton scattering at a nominal scattering angle of $\langle\theta_s\rangle = 7.9 \pm 0.3°$ and a vertex energy of $\langle E \rangle = 1.155 \pm 0.003$ GeV. The contributions from different error sources into this result are summarized in Tab. II and are discussed in more detail in Ref. [32].

TABLE II. Summary of measurement errors.

Error Source	Relative Contribution (%)
Statistics	1.250
Systematics	
Beam polarization	1.047
Regression scheme dependence	0.635
Acceptance averaging	0.328
Experimental bias	0.288
Aluminum background asymmetry	0.431
Aluminum dilution	0.166
Inelastic background asymmetry	0.025
Inelastic dilution	0.073
Beamline background asymmetry	0.004
Beamline background dilution	0.104
Soft neutral background asymmetry	0.008
Soft neutral background dilution	0.208
Systematics only	1.401
Total	1.877

Figure 2 shows the comparison of our measurement to three model calculations: Pasquini & Vanderhaeghen [24], Afanasev & Merenkov [25] and Gorchtein [27], and Tab. III shows the exact model predictions at the nominal scattering angle. Only one calculation shows a clear agreement with this measurement. The Pasquini & Vanderhaeghen calculation uses unitarity to model the DVVS tensor in the resonance regime in terms of electroabsorption amplitudes whereas both Afanasev & Merenkov and Gorchtein use the Optical theorem to relate the forward DVVC tensor to the total photoabsorption cross section. Although the three calculations predict the same behavior for the asymmetry in our acceptance, their central values vary vastly from one another.

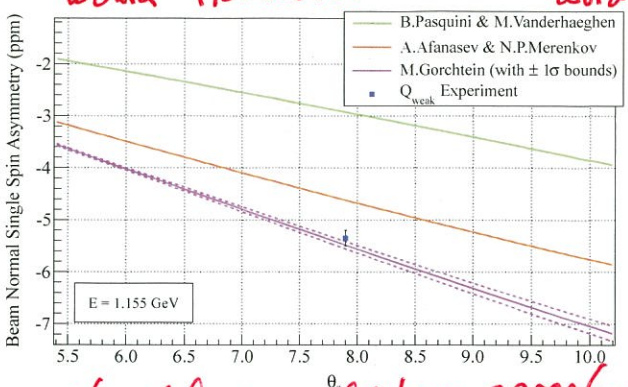

FIG. 2. Comparison of this measurement to model calculations by Pasquini & Vanderhaeghen [24], Afanasev & Merenkov [25], and Gorchtein [27] in the Q_{weak} acceptance of 5.6° to 10°. Our measurement is quoted at the nominal scattering angle of 7.9°.

Generally, single spin asymmetry models agree that the dominant contribution to the asymmetry comes from the excited intermediate states of the nucleon in the TPE. The Pasquini & Vanderhaeghen model considers all resonance and non-resonant intermediate states up to single π excitations whereas the Afanasev & Merenkov and the Gorchtein models both consider all resonance intermediate states with multi-π excitations. This selection criteria for resonance intermediate states causes the largest difference between the two types of model calculations. Furthermore, according to the Pasquini & Vanderhaeghen model, the resonance intermediate states of the proton that play a significant role in our kinematics are $\Delta(1232)$, $D_{13}(1520)$, and $F_{15}(1680)$[33] with the dominant contribution coming from the $\Delta(1232)$ resonance. Based on this observation, the factor of two difference between the Pasquini & Vanderhaeghen model and Afanasev & Merenkov and Gorchtein models may come from the exclusion of the $\pi\pi p$ decay of the $D_{13}(1520)$ and $F_{15}(1680)$ resonances which has a branching ratio of $\approx 50\%$ [34]. Nonetheless, our measurement indicates with a more than 3σ deviation that single π excitations do not adequately take into consideration all the possible resonance intermediate states in the TPE for electron energies above the 2π threshold of 1.216 GeV at the center of mass frame. Moreover, the ≈1 ppm difference between the Afanasev & Merenkov and Gorchtein calculations indicates the model error associated with the parametrization of the photo-production cross section and the Compton amplitude.

TABLE III. Theoretical predictions for the beam normal single spin asymmetry at the nominal scattering angle of 7.9^0 and vertex energy of 1.155 GeV provided by Pasquini & Vanderhaeghen [24], Afanasev & Merenkov [25], and Gorchtein [27]. σ=1.89 ppm, the experimental uncertainty in our measurement.

Model	Predicted BNSSA (ppm)	Deviation from this measurement
Pasquini & Vanderhaeghen	-2.92	$\approx 24\sigma$
Afanasev & Merenkov	-4.56	$\approx 8\sigma$
Gorchtein	-5.42±0.067	$\approx 1\sigma$

The differences in the beam normal single spin asymmetry model calculations and our measurement originate from the assumptions and techniques used to model the two-photon exchange amplitude. Therefore, this measurement is a stringent test of the two-photon exchange models at low momentum transfers. Specifically, in light of resolving the TPE correction dependency in proton magnetic radius extractions using form factors and for further improving TPE corrections on future μp scattering measurements aiming to resolve the proton charge radius discrepancy, precision measurements of TPE observables at low Q^2 kinematics will be vital for validating TPE models.

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