Beam Single Spin Asymmetries in Electron-Proton Scattering

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Introduction

The Q-weak experiment at Jefferson Lab aims to provide a precision test of the Standard Model by measuring the weak charge of the proton Q_W^p through electron-proton scattering experiments. In Q-weak, a polarized electron beam was scattered off an unpolarized proton target. The difference between the cross sections of the spin up and spin down cases results in a beam single spin asymmetry (BSSA), defined as

$$B = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow}, \tag{1}$$

where $\sigma_\uparrow$ ($\sigma_\downarrow$) is the cross section of the spin up (down) polarization. These BSSA may be longitudinal, transverse, or normal, depending on the polarization of the electrons.

Here we are concerned with the transverse polarization, where the spin is orthogonal to the beam direction and makes an angle ϕ_s with the scattering plane. This introduces a **transverse BSSA** $B_t \sim \cos\phi_s$ and a **normal BSSA** $B_n \sim \sin\phi_s$. Both these asymmetries vanish for one-photon exchange, and thus result from higher order effects.

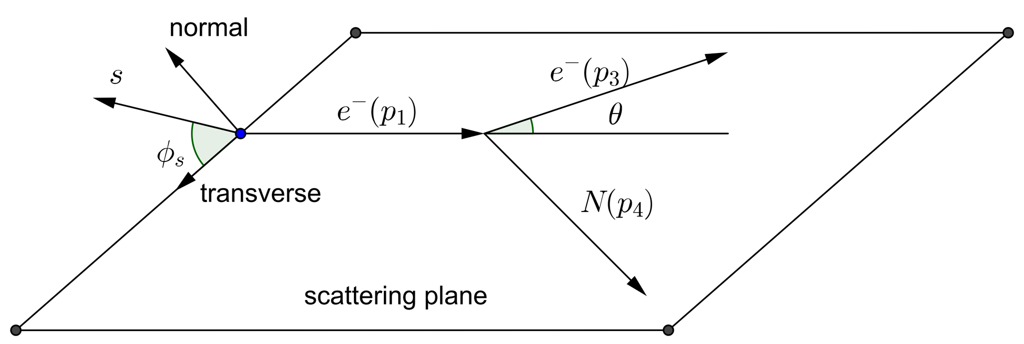

Figure 1. *Electron Scattering Plane*

In Q-weak, a beam normal single spin asymmetry (BNSSA) was measured with its sinusoidal dependence on ϕ_s shown below [1]. After Q-weak's commissioning run, experimentalists were concerned that unconsidered BSSA effects may have introduced a displacement in their measurements of the BNSSA.

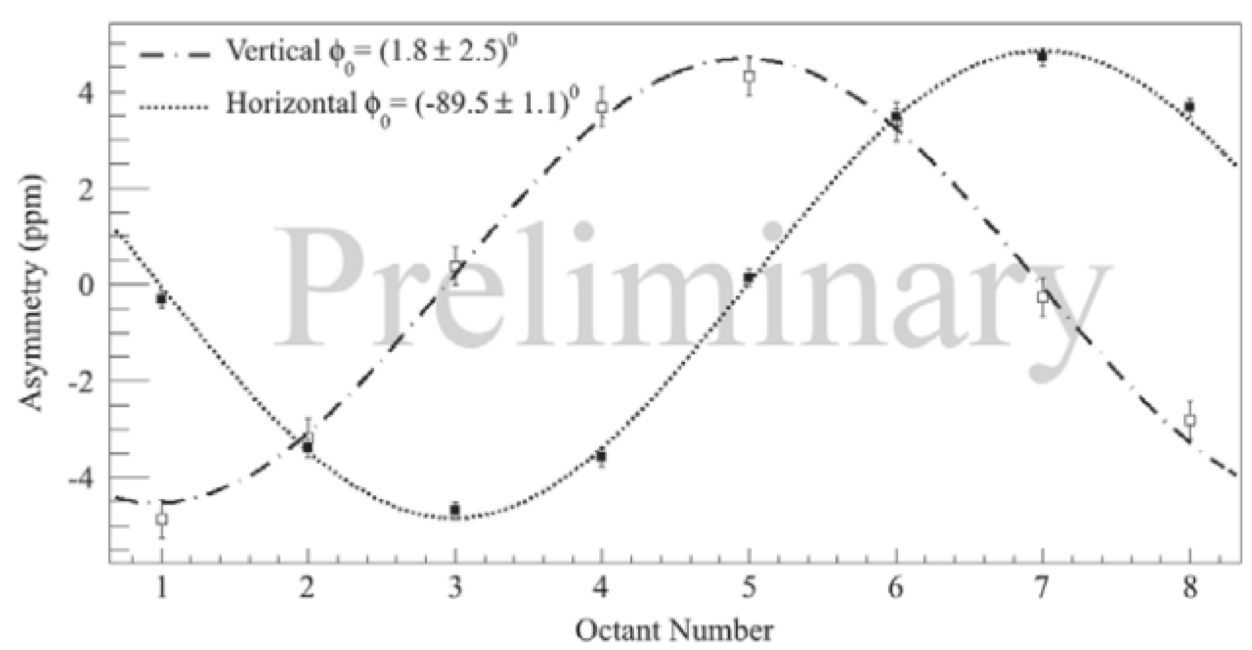

Figure 2. *Beam Normal Single Spin Asymmetry for Q-weak*

Thus, the goal of this project is to explore BSSA in this kinematic regime to determine whether such a displacement could exist.

Method

To determine if there was a displacement, it became necessary to better understand BSSA for electron-proton scattering:

- We computed the beam transverse single spin asymmetry (BTSSA) that results from the interference of the one-photon and Z exchange amplitude,
- We compared this BTSSA to the beam normal single spin asymmetry (BNSSA), which results from the interference of the one- and two-photon exchange amplitudes.
- We also computed BNSSA in the case of an inelastic hadronic intermediate state as a comparison to the Q-weak measurement.

We computed these quantities in the near forward limit and used deep inelastic structure functions to evaluate the BNSSA.

Beam Normal Single Spin Asymmetry

For the **elastic** kinematic process

$$e(p_1) + N(p_2) \to e(p_3) + N(p_4)$$

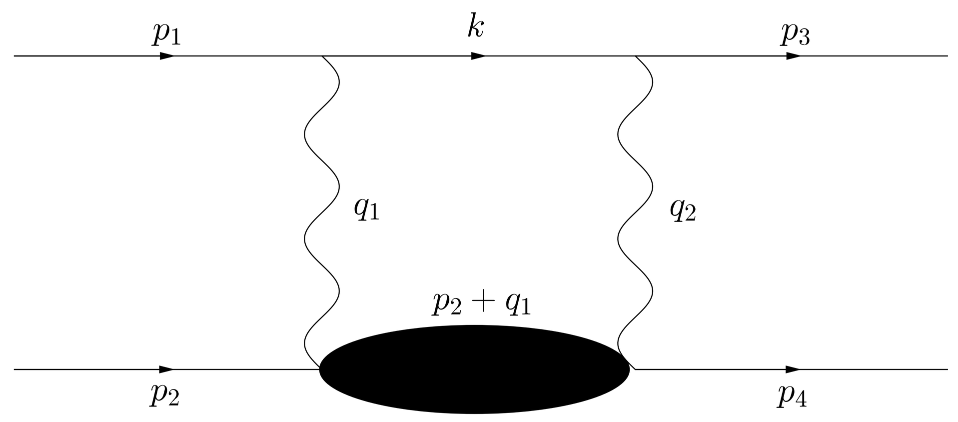

Figure 3. *Feynman Diagram for Two-Photon Exchange*

where the electron mass is m_e and hadron mass is M, define the standard kinematic variables as

$$P = \frac{p_2 + p_4}{2}, \quad K = \frac{p_1 + p_3}{2}, \quad q = p_1 - p_3, \quad Q^2 = -q^2;$$
$$s = (p_1 + p_2)^2, \quad \tau = \frac{Q^2}{4M^2}, \quad \nu = P \cdot K, \quad \epsilon = \frac{\nu^2 - M^4\tau(1+\tau)}{\nu^2 + M^4\tau(1+\tau)}.$$

de Rujula et al. [2] using a beam normal polarization found that an asymmetry ensues due to the interference of the one-photon and multi-photon exchange amplitudes. This asymmetry is [3]

$$B_n = \frac{2m_e}{Q}\sqrt{2\epsilon(1-\epsilon)}\sqrt{1+\frac{1}{\tau}}\left(G_M^2 + \frac{\epsilon}{\tau}G_E^2\right)^{-1} \times \left\{-\tau G_M \,\mathrm{Im}\left(\widetilde{F}_3 + \frac{1}{1+\tau}\frac{\nu}{M^2}\widetilde{F}_5\right) - G_E \,\mathrm{Im}\left(\widetilde{F}_4 + \frac{1}{1+\tau}\frac{\nu}{M^2}\widetilde{F}_5\right)\right\}, \tag{2}$$

where G_E and G_M are the electric and magnetic form factors and $\widetilde{F}_3$, $\widetilde{F}_4$, $\widetilde{F}_5$ are generalized form factors. Generalized to a transverse spin, this asymmetry behaves as $B_{n,\,\mathrm{gen}} = B_n \sin\phi_s$.

Beam Transverse Single Spin Asymmetry

Using the same formalism, we found that a transverse asymmetry also occurs due to the interference of the one-photon and Z exchange amplitudes, $\mathscr{M}_\gamma^* \mathscr{M}_Z$. This transverse asymmetry B_t is

$$B_t = \frac{8G_F m_e M^3}{e^2(s - M^2)}\sqrt{\frac{\epsilon(1-\epsilon)}{\tau+1}}\left(G_M^2 + \frac{\epsilon}{\tau}G_E^2\right)^{-1}\left\{g_V^e G_M G_M^Z \tau(\tau+1) + g_A^e\left(G_M G_A^Z \tau(\tau - \nu + 1) - G_E G_E^Z(\nu + \tau - 1)\right)\right\}, \tag{3}$$

where G_M^Z and G_E^Z are the weak form factors and G_F is Fermi's coupling constant. Similarly, for the general transverse spin, $B_{t,\,\mathrm{gen}} = B_t \cos\phi_s$.

Combination of Asymmetries

The combination of these asymmetries gives

$$B = B_t \cos\phi_s + B_n \sin\phi_s = \sqrt{B_t^2 + B_n^2}\,\sin(\phi_s + \delta),$$

where

$$\delta = \tan^{-1}\left(\frac{B_t}{B_n}\right).$$

In Q-weak kinematics, with $Q^2 = 0.025$ GeV^2 and incident electron beam of energy $E_1 = 1.155$ GeV, this phase shift is roughly equal to

$$|\delta| = 2.086 \times 10^{-6}.$$

This is too small to affect Q-weak measurements.

Inelastic Intermediate State

We considered the kinematic process $eN \to eN$ with an inelastic hadron intermediate state. A beam asymmetry results from the absorptive part of the two-photon exchange amplitude. Let k be the momentum of the on-shell intermediate electron and ϕ_k its azimuthal angle, and let q_1,q_2 be the momenta of the exchanged photons. We have [4]

$$\mathrm{Abs}\,\mathscr{M}_{\gamma\gamma} = e^4 \int \frac{d^3\vec{k}}{(2\pi)^3 2E_k} L_{\mu\nu} W^{\mu\nu} \frac{1}{Q_1^2 Q_2^2},$$

where $L_{\mu\nu}$ and $W^{\mu\nu}$ are the leptonic and hadronic tensors, respectively. The imaginary part of the the one- and two- photon exchange amplitudes produces the beam asymmetry. We can write

$$B_n = \frac{2\,\mathrm{Im}\left(\sum_{\text{spins}} \mathscr{M}_{1\gamma}^* \cdot \mathrm{Abs}\,\mathscr{M}_{2\gamma}\right)}{\sum_{\text{spins}} |\mathscr{M}_{1\gamma}|^2}.$$

To simplify calculations, we took the forward limit $Q^2 \to 0$ on the *hadron* tensor only, using [2]

$$W^{\mu\nu} = \left(-g^{\mu\nu} + \frac{q_1^\mu q_1^\nu}{q_1^2}\right) W_1 + \frac{1}{M^2}\left(p_2^\mu - \frac{p_2 \cdot q_1}{q_1^2} q_1^\mu\right)\left(p_2^\nu - \frac{p_2 \cdot q_1}{q_1^2} q_1^\nu\right) W_2.$$

Evaluating B_n gives us

$$B_n = -\frac{1}{(2\pi)^3}\frac{e^2 Q^2}{D(s,Q^2)}\frac{1}{8E_1E_3M}\int_0^{2\pi} d\phi_k \int_{M^2}^{s} dW^2 \int_0^{Q^2_{1,\max}} dQ_1^2 \frac{\mathrm{Im}\left\{L_{\alpha\mu\nu}H^{\alpha\mu\nu}\right\}}{Q_1^2 Q_2^2},$$

where $D(s, Q^2)$ is a function given by [4]. We are currently evaluating this expression in the Q-weak regime.

Conclusion

It was found that

- A BNSSA is produced by $\mathscr{M}_\gamma^* \mathscr{M}_{\gamma\gamma}$ while a BTSSA is produced by $\mathscr{M}_\gamma^* \mathscr{M}_Z$.
- The combination of the BNSSA and the BTSSA results in a small phase shift in the total asymmetry. The phase shift, however, is too small to be detectable, implying that the Q-weak measurements are accurate.
- The phase shift may be detectable in the future at experiments involving higher energies, such as the Electron-Ion Collider (EIC).
- The inelastic hadronic intermediate state produces an important contribution to the BSSA (soon to be quantified).
- The framework we developed could potentially be used to evaluate BSSA in other experimental settings in the near forward limit.

References

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Acknowledgements

I would like to thank Jefferson Laboratory and the Department of Energy for providing the opportunity to work on this project.