Single-Spin Asymmetries in Elastic Electron-Hadron Scattering

Andrei Afanasev
The George Washington University

Workshop to Explore Physics Opportunities with Intense, Polarized Electron Beams up to 300 MeV
March 14-16, 2013
MIT, Cambridge, Massachusetts
Plan of talk

• Elastic electron-proton scattering beyond the leading order in QED
• Models for two-photon exchange
• Single-spin asymmetries
  – Inelastic intermediate state in ep-scattering via two-photon exchange
  – Novel features of a single-spin asymmetry
  – Comparison with experiment
• Summary
Do the techniques agree? 

- Both early SLAC and Recent JLab experiments on (super)Rosenbluth separations followed Ge/Gm~const, see I.A. Quattan et al., Phys.Rev.Lett. 94:142301,2005
- JLab measurements using polarization transfer technique give different results (Jones’00, Gayou’02)

Radiative corrections, in particular, a short-range part of 2-photon exchange is a likely origin of the discrepancy
Complete radiative correction in $O(\alpha_{em})$

Radiative Corrections:
• Electron vertex correction (a)
• Vacuum polarization (b)
• Electron bremsstrahlung (c,d)
• Two-photon exchange (e,f)
• Proton vertex and VCS (g,h)
• Corrections (e-h) depend on the nucleon structure
  • Meister&Yennie; Mo&Tsai
  • Further work by Bardin&Shumeiko; Maximon&Tjon; AA, Akushevich, Merenkov;
  • Guichon&Vanderhaeghen’03: Can (e-f) account for the Rosenbluth vs. polarization experimental discrepancy? Look for ~3% ...

Main issue: Corrections dependent on nucleon structure

Model calculations:
Single-Spin Asymmetries in Elastic Scattering

Parity-conserving
• Observed spin-momentum correlation of the type:

\[ \vec{s} \cdot \vec{k}_1 \times \vec{k}_2 \]

where \( k_{1,2} \) are initial and final electron momenta, \( s \) is a polarization vector of a target OR beam
• For elastic scattering asymmetries are due to absorptive part of 2-photon exchange amplitude

Parity-Violating

\[ \vec{s} \cdot \vec{k}_1 \]
Normal Beam Asymmetry in Moller Scattering

• Pure QED process, $e^-+e^-\rightarrow e^-+e^-$
  
  - Barut, Fronsdal, Phys.Rev.120:1871 (1960): Calculated the asymmetry in first non-vanishing order in QED $O(\alpha)$
  

\[
A_n \propto \frac{2M_\gamma \text{Im}(M_{2\gamma})}{M_\gamma^2} \frac{\sqrt{s} \gg m_e}{\sqrt{s} f(\theta)}
\]

SLAC E158 Results [Phys.Rev.Lett. 95 (2005) 081601]

$A_n(\text{exp})=7.04\pm0.25(\text{stat}) \text{ ppm}$

$A_n(\text{theory})=6.91\pm0.04 \text{ ppm}$
De Rujula, Kaplan, De Rafael, Nucl.Phys. B53, 545 (1973): Transverse polarization effect is due to the absorptive part of the non-forward Compton amplitude for off-shell photons scattering from nucleons
See also AA, Akushevich, Merenkov, hep-ph/0208260

\[ A_{l,p}^{el,in} = \frac{8\alpha}{\pi^2} \frac{Q'^2}{D(Q'^2)} \int dW^2 \frac{S + M^2 - W^2}{S + M^2} dQ'^2_1 dQ'^2_2 \frac{1}{\sqrt{K}} B_{l,p}^{el,in} \]

Figure 2. Integration region over \( Q'^2_1 \) and \( Q'^2_2 \) in Eq.(2) for elastic \( (W^2 = M^2) \) and inelastic contributions. The latter (left) is given for \( Q'^2 = 4 \text{ GeV}^2 \) and two values of \( W^2 \), which is an integration variable in this case. The elastic case is shown on the right as a function of external \( Q'^2 \). The electron beam energy is \( E_b = 5 \text{ GeV} \).
Calculations using Generalized Parton Distributions

Model schematics:
• Hard eq-interaction
• GPDs describe quark emission/absorption
• Soft/hard separation
  • Use Grammer-Yennie prescription

Hard interaction with a quark

AA, Brodsky, Carlson, Chen, Vanderhaeghen,
Quark+Nucleon Contributions to Target Asymmetry

- Single-spin asymmetry or polarization normal to the scattering plane
- Handbag mechanism prediction for single-spin asymmetry of elastic eN-scattering on a polarized nucleon target (AA, Brodsky, Carlson, Chen, Vanderhaeghen)

\[ A_n = \sqrt{\frac{2\varepsilon(1+\varepsilon)}{\tau}} \frac{1}{{\sigma^R}} \left[ G_E \text{Im}(A) - \sqrt{\frac{1-\varepsilon}{2\varepsilon}} G_M \text{Im}(B) \right] \]

Only minor role of quark mass

No dependence on GPD \( \widetilde{H} \)

Data coming from JLAB E05-015
(Inclusive scattering on normally polarized \(^3\text{He}\) in Hall A)
Single-Spin Asymmetry in Elastic Scattering

Early Calculations

• Spin-orbit interaction of electron moving in a Coulomb field
  
  Need in spin-flip and spin-nonflip phase difference


• Interference of one-photon and two-photon exchange Feynman diagrams in electron-muon scattering: Barut, Fronsdal, Phys.Rev.120, 1871 (1960)

• Extended to quark-quark scattering SSA in pQCD: Kane, Pumplin, Repko, Phys.Rev.Lett. 41, 1689 (1978)

\[
\Delta(\theta) = \mp 2Z\alpha \frac{\nu \sqrt{1 - \nu^2}}{1 - \nu^2 \sin^2(\theta/2)} \frac{\sin^3(\theta/2)}{\cos(\theta/2)} \ln \frac{1}{\sin(\theta/2)}.
\]

\[
A_n \propto \frac{\alpha \cdot m_e \cdot \theta^3}{E}, \text{ for } \theta \ll 1
\]

(smaller angle scattering)
Proton Mott Asymmetry at Higher Energies

AA, Akushevich, Merenkov, hep-ph/0208260

Transverse beam SSA, units are parts per million

- Asymmetry due to absorptive part of two-photon exchange amplitude; shown is elastic intermediate state contribution
- Nonzero effect first observed by SAMPLE Collaboration (S.Wells et al., PRC63:064001, 2001) for 200 MeV electrons
- Also calculated by Diaconescu & Ramsey-Musolf (2004); used low-momentum expansion, questionable in SAMPLE kinematics
Beam Normal Asymmetry from Inelastic Intermediate States

\[ A_n^{e,p} = -\frac{\alpha Q^2}{\pi^2 D(s, Q^2)} \text{Im} \int \frac{d^3k}{2k_0} \cdot \frac{L_{\mu\alpha\beta} H_{\mu\alpha\beta}}{Q_1 Q_2^2} \]

\[ L_{\mu\alpha\beta} = \frac{1}{4} Tr(\hat{k}_2 + m_e) \gamma_\mu (\hat{k}_1 + m_e)(1 - \gamma^5 \hat{\xi}_e) \gamma_\beta (\hat{k} + m_e) \gamma_\alpha \]

\[ H_{\mu\alpha\beta} = \frac{1}{4} Tr(\hat{p}_2 + M) \Gamma_\mu (\hat{p}_1 + M)(1 - \gamma^5 \hat{\epsilon}_p) T_{\beta\alpha} \]

\( \hat{a} \equiv a_\mu \gamma_\mu \)

\[ L_{\mu\alpha\beta} q_\mu = L_{\mu\alpha\beta} q_{2\alpha} = L_{\mu\alpha\beta} q_{1\beta} = H_{\mu\alpha\beta} q_\mu = H_{\mu\alpha\beta} q_{2\alpha} = H_{\mu\alpha\beta} q_{1\beta} = 0 \]

Gauge invariance essential in cancellation of infra-red singularity for target asymmetry

\[ L_{\mu\alpha\beta} H_{\mu\alpha\beta} \rightarrow 0 \quad \text{if} \quad Q_1^2 \text{ and } Q_2^2 \rightarrow 0 \]

Feature of the normal beam asymmetry: After \( m_e \) is factored out, the remaining expression is singular when virtuality of the photons reach zero in the loop integral!

But why are the expressions regular for the target SSA?! Answer: small virtuality is due to small electron mass

\[ L_{\mu\alpha\beta} H_{\mu\alpha\beta} \rightarrow m_e \cdot \text{const} \quad \text{if} \quad Q_1^2 \text{ and } Q_2^2 \rightarrow 0 \Rightarrow A \sim m_e \log^2 \frac{Q^2}{m_e^2}, \quad m_e \log \frac{Q^2}{m_e^2} \]

AA, Merenkov, hep-ph/0407167: Models violating EM gauge invariance encounter collinear divergence for target SSA

Also calculations by Vanderhaeghen, Pasquini (2004); Gorchtein (2004); Kobushkin (2005) confirm \textit{quasi-real photon exchange} enhancement
Phase Space Contributing to the absorptive part of $2\gamma$-exchange amplitude

- 2-dimensional integration ($Q_1^2, Q_2^2$) for the elastic intermediate state
- 3-dimensional integration ($Q_1^2, Q_2^2, W^2$) for inelastic excitations

`Soft` intermediate electron;
Both photons are hard collinear
Dominates for backward scattering

One photon is hard collinear
Dominates for forward scattering

Examples: MAMI A4
E= 855 MeV
$\Theta_{cm}= 57$ deg;
SAMPLE, E=200 MeV
MAMI data on Mott Asymmetry

- F. Maas et al., [MAMI A4 Collab.]
- Pasquini, Vanderhaeghen:

Used single-pion electroproduction amplitudes from MAID to

Surprising result: Dominance of inelastic intermediate excitations

Elastic intermediate state

Inelastic excitations Dominate

However, it doesn’t make it into TPE for Rosenbluth
Special property of Mott asymmetry

• Mott asymmetry above the nucleon resonance region
  (a) does not decrease with beam energy
  (b) is enhanced by large logs

• Reason for the unexpected behavior: exchange of hard collinear quasi-real photons and diffractive mechanism of nucleon Compton scattering

  • For $s >>> t$ and above the resonance region, the asymmetry is given by:

    $$A_{n}^{e}(\text{diffractive}) = \sigma_{p}^{(-m_{e})} \sqrt{Q^{2}} \cdot \frac{F_{1} - \tau F_{2}}{F_{1}^{2} + \tau F_{2}^{2}} (\log(\frac{Q^{2}}{m_{e}^{2}}) - 2) \cdot \text{Exp}(-bQ^{2})$$

Compare with asymmetry caused by Coulomb distortion at small $\theta \Rightarrow$

may differ by orders of magnitude depending on scattering kinematics

$$A_{n}^{e}(\text{Coulomb}) \propto \alpha \frac{m_{e}}{\sqrt{s}} \theta^{3} \rightarrow A_{n}^{e}(\text{Diffractive}) \propto \alpha m_{e} (\sqrt{s}) \theta \cdot R_{\text{int}}^{2}$$
Input parameters

For small-angle (-t/s<<1) scattering of electrons with energies $E_e$, normal beam asymmetry is given by the energy-weighted integral

$$A_n \propto \frac{1}{E_e^2} \int_{v_{th}}^{E_e} dv \cdot v \sigma_{\gamma p}^{tot}(v; q_{1,2}^2 \approx 0)$$

The integral is energy-weighed, higher energies enhanced

$\sigma_{\gamma p}$ from N. Bianchi et al., Phys.Rev.C54 (1996)1688 (resonance region) and Block&Halzen,


$-A_n$ serves as an ideal tool to sum over a variety of intermediate states
Predictions vs experiment for Mott asymmetry

Use fit to experimental data on $\sigma_{\gamma p}$ (dotted lines include only one-pion+nucleon intermediate states)

Normal beam asymmetry for elastic ep-scattering

Unitarity-based model predictions

$E_e = 3$ GeV

HAPPEX

Estimated normal beam asymmetry for $Q_{\text{weak}}$: -5ppm

G0 arXiv 0705.1525[nucl-ex]
Predict no suppression for Mott asymmetry with energy at fixed $Q^2$

- At 45 GeV predict beam asymmetry parts-per-million (diffraction) vs. parts-per-billion (Coulomb distortion)
Comparison with E158 data

- **SLAC E158:**
  \( A_n = -2.89 \pm 0.36 \text{(stat)} \pm 0.17 \text{(syst)} \) ppm
  (K. Kumar, private communication)

- **Theory (AA, Merenkov):**
  \( A_n = -3.2 \text{ppm} \)

- Good agreement justifies application of this approach to the real part of two-boson exchange (\( \gamma Z \) box)
Mott Asymmetry on Nuclei


**Five orders of magnitude** enhancement in HAPPEX kinematics due to excitation of inelastic intermediate states in $2\gamma$-exchange (AA, Merenkov; use Compton data from Erevan )

- Good agreement with theory for nucleon and light nuclei
- Puzzling disagreement for $^{208}$Pb measurement; if confirmed, need to include additional electron interaction with highly excited intermediate nuclear state, magnetic terms, etc ( = effects of higher order in $\alpha_{em}$). **Interesting nuclear effect!** Experimentally, need additional measurements for intermediate-mass targets (e.g., Al,
Inclusive Electroproduction of Pions

- Reaction $p(e_{pol}, \pi)X$
  - Parity-conserving spin-momentum correlation $\vec{s}_e \cdot \vec{k}_e \times \vec{k}_\pi$
    - Can be shown to be a) due to $R_{TL'}$ response function (=fifth structure function) and b) not to integrate to zero after integration over momenta of the scattered electron
    - This is NOT a two-photon exchange effect (but suppressed by an electron mass)
      - Order-of magnitude estimate: $A_n(e p \rightarrow \pi X) \sim A_{LT'}(e p \rightarrow e' \pi N) \times m_e / E' \sin(\theta_e)$
        - Use MAMI data $A_{LT'}(e p \rightarrow e' \pi N) \sim 7\%$, from Bartsch et al Phys.Rev.Lett. 88:142001,2002 => $A_n(e p \rightarrow \pi X) \sim 250\text{ppm}$

- Physics probe of (strong) final-state interactions in electroproduction reactions
  - Why not simply measuring SF in $A(e_{pol}, e\pi)X$ directly with longitudinal polarization? Because transverse SSA gives access to very low $Q^2$, may not available to spectrometers
Summary:
SSA in Elastic ep- and eA-Scattering

- VCS amplitude in beam asymmetry is enhanced in different kinematic regions compared to target asymmetry or corrections to Rosenbluth cross section
- Physics probe of an absorptive part of a non-forward Compton amplitude
- Important systematic effect for PREX, $Q_{\text{weak}}$
- Mott asymmetry in small-angle ep-scattering above the pion threshold is controlled by quasi-real photoproduction cross section with photon energy approximately matching beam energy – similarity with Weiszacker-Williams Approximation – collinear photon exchange
- Due to excitation of inelastic intermediate states $A_n$ is
  (a) not suppressed with beam energy and
  (b) does not grow with Z (proportional to instead $A/Z$)
  (c) At small angles $\sim \theta$ (vs $\theta^3$ for Coulomb distortion)
- Confirmed experimentally for a wide range of beam energies
Outlook

• Beam and target SSA for elastic electron scattering probe imaginary part of virtual Compton amplitude.
  – Beam SSA: target helicity flip$^2$+nonflip$^2$
  – Target SSA: Im[target helicity flip*nonflip]
  – Ideal “4\pi detector” to probe electroproduction amplitudes for a variety of final states (\pi, 2\pi, etc)

• Beam SSA for nuclear targets in good agreement with theory except for a high-Z target 208Pb. Interesting nuclear physics effects beyond two-photon exchange

• Beam SSA in Reaction $A(e_{pol},\pi)X$ probes strong final-state interactions – due to “fifth stucture function” in $A(e,e' \pi)X$