Charge-Asymmetric Lepton Scattering as a Probe of Hadronic Structure

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Plan of talk

Radiative corrections for charged lepton scattering
Two-photon exchange effects
T-violation
Summary
Elastic Nucleon Form Factors

• Based on one-photon exchange approximation

\[ M_{f\bar{f}} = M_{f\bar{f}}^{1\gamma} \]

\[ M_{f\bar{f}}^{1\gamma} = e^2 \bar{u}_e \gamma_\mu u_e \bar{u}_p (F_1(t) \gamma_\mu - \frac{\sigma_{\mu\nu} q_\nu}{2m} F_2(t)) u_p \]

• Two techniques to measure

\[ \sigma = \sigma_0 (G_M^2 \tau + \varepsilon \cdot G_E^2) \ : \text{Rosenbluth technique} \]

\[ \frac{P_x}{P_z} = - \frac{G_E \sqrt{\tau} \sqrt{2\varepsilon(1-\varepsilon)}}{G_M \tau \sqrt{1-\varepsilon^2}} \ : \text{Polarization transfer technique} \]

\[ G_E = F_1 - \tau F_2, \quad G_M = F_1 + F_2 \]

\((P_y = 0)\)
Measuring Proton Form Factors

The ratio $G_{Ep}/G_{Mp}$ obtained by the recoil polarization technique (Punjabi et al. (2005) (filled blue circle), Puckett et al. (2012) (filled red squares) and Puckett et al. (2010) (filled black triangles)) compared to ratio obtained by the Rosenbluth technique (green open points).
Ge/Gm Ratio: Polarization vs Rosenbluth
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 $\sim 3\%$ ...

Main issue: Corrections dependent on nucleon structure

Model calculations:
Separating soft 2-photon exchange

- Tsai; Maximon & Tjon (k→0); similar to Coulomb corrections at low $Q^2$
- Grammer & Yennie prescription PRD 8, 4332 (1973) (also applied in QCD calculations)
- Shown is the resulting (soft) QED correction to cross section
- **Already included in experimental data analysis for elastic ep**
  - Also done for pion electroproduction in AA, Aleksejevs, Barkanova, Phys.Rev. D88 (2013) 5, 053008 (inclusion of lepton masses is straightforward)

Lepton mass is not essential for TPE calculation in ultra-relativistic case; Two-photon effect below 1% for lower energies and $Q^2<0.1\text{GeV}^2$
General Analysis of ep->ep (including 2-photon exchange)

- Reaction $e(1/2, \lambda_1) + p(1/2, h_1) \rightarrow e(1/2, \lambda_2) + p(1/2, h_2)$ => 16 possible helicity combinations

- Parity: $T_{\lambda_2 h_2}^{\lambda_1 h_1} = (-1)^{h_1 - h_2} T_{-\lambda_1 - h_1}^{\lambda_2 - h_2}$
  $\Rightarrow$ 8 amplitudes
- Time-reversal: $T_{\lambda_2 h_2}^{\lambda_1 h_1} = (-1)^{h_1 - h_2} T_{-\lambda_1 - h_1}^{\lambda_2 - h_2}$
  $\Rightarrow$ 6 amplitudes

Independent helicity amplitudes:

$A_1 = T_{\frac{1}{2} \frac{1}{2}}^{\frac{1}{2} \frac{1}{2}}$, $A_2 = T_{\frac{1}{2} \frac{1}{2}}^{\frac{1}{2} - \frac{1}{2}}$, $A_3 = T_{\frac{1}{2} \frac{1}{2}}^{\frac{1}{2} - \frac{1}{2}}$, $A_4 = T_{\frac{1}{2} \frac{1}{2}}^{-\frac{1}{2} - \frac{1}{2}}$, $A_5 = T_{\frac{1}{2} \frac{1}{2}}^{-\frac{1}{2} - \frac{1}{2}}$, $A_6 = T_{\frac{1}{2} \frac{1}{2}}^{-\frac{1}{2} - \frac{1}{2}}$

for $m_e = 0$, $A_{4-6} = 0$

$\sigma = N(|A_1|^2 + |A_2|^2 + 2|A_3|^2 + 2|A_4|^2 + |A_5|^2 + |A_6|^2)$

$\sigma P_y = 2N \text{Im}(F)$, $\sigma P_x = 2N \text{Re}(F)$

$F = (A_1 + A_2)A_3^* + A_4(A_6^* - A_5^*)$,

$\sigma P_z = N(|A_1|^2 - |A_2|^2 + |A_5|^2 - |A_6|^2)$
Short-range effects
(Chen,AA, Brodsky, Carlson,Vanderhaeghen)

Two-photon probe directly interacts with a (massless) quark.
Emission/reabsorption of the quark is described by GPDs

\[ A_{\text{eq} \rightarrow \text{eq}}^{2\gamma} = \frac{e_q^2 \alpha_{em}}{t} \left( V_e \otimes V_q \times f_V + A_e \otimes A_q \times f_A \right) \]

\[ f_V = -2[\log\left(\frac{-u}{s}\right) + i\pi] \log\left(\frac{-t}{\lambda^2}\right) - t \left[ \frac{1}{2} \left( \log\left(\frac{-u}{t}\right) + i\pi \right) \right. \left. - \frac{1}{u} \log\left(\frac{-s}{t}\right) \right] + \]
\[ \frac{(u^2 - s^2)}{4} \left[ \frac{1}{s^2} (\log^2\left(\frac{u}{t}\right) + \pi^2) + \frac{1}{u^2} \log\left(\frac{-s}{t}\right) (\log\left(\frac{-s}{t}\right) + i2\pi) \right] + i\pi \frac{u^2 - s^2}{2su} \]

\[ f_A = -\frac{t}{2} \left[ \frac{1}{s} (\log\left(\frac{u}{t}\right) + i\pi) \right. \left. + \frac{1}{u} \log\left(\frac{-s}{t}\right) \right] + \]
\[ \frac{(u^2 - s^2)}{4} \left[ \frac{1}{s^2} (\log^2\left(\frac{u}{t}\right) + \pi^2) - \frac{1}{u^2} \log\left(\frac{-s}{t}\right) (\log\left(\frac{-s}{t}\right) + i2\pi) \right] + i\pi \frac{t^2}{2su} \]

Phys.Rev.D72:013008,2005
Quark-Level Calculations

Phys.Rev.D 72:013008, 2005

Kivel, Vanderhaeghen, PRL 103 092004 (2009)
Results for cross section measurements

- New correction brings results of Rosenbluth and polarization techniques into agreement (data shown are from Andivahis et al, PRD 50, 5491 (1994))
Updated Ge/Gm plot


- Significant part of the discrepancy is removed by the TPE mechanism
- Verification coming from
  - VEPP: PRL 114 (2015) 6, 062005
  - CLAS: PRL 114 (2015) 6, 062003
  - OLYMPUS: PRL 118 (2017) 092501

Recent review: A. Afanasev, P. Blunden, D. Hassell, B. Raue, 
https://arxiv.org/abs/1703.03874, 
Electron/Positron Ratios

- Recent results from CLAS, VEPP and OLYMPUS
2γ-exchange Correction to Parity-Violating Electron Scattering

Parity violating terms due to \((2\gamma)x(Z^0)\) interference should be added:

\[
\text{Re} A_{AA}^\gamma A_{AV}^Z \propto (-\frac{1}{2}) \sqrt{\tau(1 + \tau)(1 - \varepsilon^2)} \text{Re}(G_A^\gamma G_M^Z) \lambda_e
\]

\[
\text{Re} A_{AA}^\gamma A_{VA}^Z \propto (-\frac{1}{2})(1 - 4 \sin^2 \theta_W)(1 + \tau) \text{Re}(G_A^\gamma G_A^Z) \lambda_e
\]

Two-boson box for Parity-Violating Electron Scattering (as presented by C. E. Carlson)

Gorchein and Horowitz (PRL 102, 091806 (2009)) had insight to calculate the amplitude dispersively

DR → calculate whole amplitude form imaginary part.

Imaginary part comes when intermediate states on shell.

About (8.1±1.4)% of QW^p at E_{elec}=1.165 GeV. Proportional to E_{elec}.

About (6.3±0.6%) of QW^p at E_{elec} threshold. Small dependence on E_{elec}. Might still like to improve.

Parity violation with positrons?

High current and polarization is a challenge
Proton radius puzzle

- The $6\sigma$ discrepancy in the $r_p$ measurements.

Slide credit: Miha Mihavilovic, JLAB Seminar, March’17
The HUJI Straw Tube Tracker for the MUSE Experiment

D. Cohen, G. Ron - The Hebrew University of Jerusalem

**Abstract**

In order to probe the physics of the world, we use the Straw Tube Tracker (STT) to measure the properties of particles as they pass through our detector. The STT is a crucial component for understanding the interactions of particles in the universe.

**What are we looking for?**

- Neutrino scattering from a nucleus
- Top Quark production at the Large Hadron Collider

**Straw Tube Tracker (STT)**

- The STT consists of a series of straw tubes arranged in a lattice pattern. Each tube is filled with a gas and detects the passage of particles.
- The data collected from the STT is used to determine the properties of the particles that interacted with the detector.

**More Setup**

- The Muon Scattering Experiment (MUSE) will measure the form factor of the muon.
- The STT is used to study the properties of muons and other particles.

**Preliminary Results for STT**

- Measurements of the mean square momentum charge radius of muon-proton elastic scattering in the low momentum transfer squared region.

**Conclusion**

- The STT results help us understand the fundamental properties of particles and the forces that govern their interactions.
- Continued research with the STT will provide insights into the structure of matter and the universe.
Helicity-Flip in TPE; estimate of inelastic contribution

- New dynamics from scalars ($\sigma$, f-mesons). No pseudo-scalar contribution for unpolarized particles
- Scalar t-channel exchange contributes to TPE (no longer setting $m_{\text{lepton}}$ to zero!)

![Diagram of one-photon and one $\sigma$ ($\pi$) meson exchange diagrams](image)

- No information on $F_{\sigma\mu\mu}$ coupling is available. Need model estimates.

Can be studied directly in the ratio of $\mu^+$ and $\mu^-$ cross sections
Inelastic + Elastic

Both inelastic and elastic contributions included
Elastic TPE dominates, Inelastic $\sim 10^{-4}$ effects;
TPE for electrons is about twice larger than for muons.
MUSE Prospectives

MUSE:

- Experiment preparation underway in PSI and MUSE collaborating institutions
- The effort on the radiative corrections aims at proper accounting of the radiative effects, that appear to show significant difference between electron and muon scattering (Afanasev, Strauch, Bernauer, Koshchii)
- Radiative corrections shown to be <1% for muons; included in MUSE analysis
- Two-photon effects can be studied directly in the ratio of $\mu^+$ and $\mu^-$ cross sections
RadCor for MUSE

- Radiative corrections show significant difference between electron and muon scattering in MUSE, must be properly accounted for
- Radiative corrections calculated to be about 1-1.5% for muons and varies from -4% to +3% for electrons
  - Uncertainties mainly from acceptances, need to include in detector simulations (Monte Carlo generator of radiative events was developed for MUSE). Theory uncertainties <0.1% (muons), <0.5% (electrons)
- Two-photon exchange <1% (electrons), <0.5% (muons), ~0.01% (inelastic excitations)
- Two-photon effects can be studied directly in the ratio of $\mu^+$ and $\mu^-$, $e^+$ and $e^-$ cross sections; TPE cancel in the sum of particle+antiparticle cross sections
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 $O(\alpha)$

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

SLAC E158 Results [Phys.Rev.Lett. 95 (2005) 081601]
$A_n(\text{exp}) = 7.04 \pm 0.25(\text{stat}) \text{ ppm}$
$A_n(\text{theory}) = 6.91 \pm 0.04 \text{ ppm}$
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)

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

No dependence on GPD $\tilde{H}$

*Only minor role of quark mass*

Data coming from JLAB E05-015
(Inclusive scattering on normally polarized $^3$He in Hall A)

Andrei Afanasev, JPOS17, Jefferson Lab, Sept 12, 2017
Single-spin Asymmetries at JLAB

- Polarized target (He3) JLAB E-05-015 (Zhang et al, Phys. Rev. Lett. 115, 172502 (2015))
- Recoil polarimetry (proton): possible but challenging due to systematic corrections
Transverse Beam Asymmetries on Nuclei (HAPPEX+PREX)

  - 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 ($= \text{effects of higher order in } \alpha_{\text{em}}$). Interesting nuclear effect! Experimentally, need additional measurements for intermediate-mass targets (e.g., Al, Ca, Fe)

<table>
<thead>
<tr>
<th>Target</th>
<th>H</th>
<th>$^4$He</th>
<th>$^{12}$C</th>
<th>$^{208}$Pb</th>
</tr>
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<tbody>
<tr>
<td>$A_n$ (ppm)</td>
<td>-6.80</td>
<td>-13.97</td>
<td>-6.49</td>
<td>0.28</td>
</tr>
<tr>
<td>$\sigma(A_n)$ (ppm)</td>
<td>±1.54</td>
<td>±1.45</td>
<td>±0.38</td>
<td>±0.25</td>
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<tr>
<td>$\sqrt{Q^2}$ (GeV)</td>
<td>0.31</td>
<td>0.28</td>
<td>0.099</td>
<td>0.094</td>
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<tr>
<td>$A/Z$</td>
<td>1.0</td>
<td>2.0</td>
<td>2.0</td>
<td>2.53</td>
</tr>
<tr>
<td>$\hat{A}_n$ (ppm/GeV)</td>
<td>-21.9</td>
<td>-24.9</td>
<td>-32.8</td>
<td>+1.2</td>
</tr>
<tr>
<td>$\sigma(\hat{A}_n)$ (ppm/GeV)</td>
<td>±5.0</td>
<td>±2.6</td>
<td>±1.9</td>
<td>±1.1</td>
</tr>
</tbody>
</table>

Comparing with positrons can settle the puzzle
Two-Photon Exchange in inclusive DIS

  - Asymmetry due to $2\gamma$-exchange $\sim1/137$ suppression
  - Additional suppression due to transversity parton density $\Rightarrow$ predict asymmetry at $\sim10^{-4}$ level
  - EM gauge invariance is crucial for cancellation of collinear divergence in theory predictions
  - Hadronic non-perturbative $\sim1\%$ vs partonic $10^{-4}$
  - Prediction consistent with HERMES measurements who set upper limits $\sim(0.6-0.9)\times10^{-3}$ : Phys.Lett.B682:351-354,2010
Work by Andreas Metz and collaborators


- SIDIS: Schlegel, Metz, arXiv:0902.0781
  Emphasized \( \sin(2\phi) \) effect for SIDIS arising from two-photon exchange

\[
A_{LU}^{\sin(2\phi)} = \alpha \frac{y \left(1 + \frac{2-y}{1-y} \ln y\right)}{1-y + \frac{1}{2}y^2} \sin(2\phi) \sum_q e_q^3 \langle \frac{2(\vec{h}_T(\vec{h}_T\vec{p}_T) - \vec{k}_T\vec{p}_T)}{2M_{m_Z}} h_1^q H_1^{\perp q} \rangle \frac{\sum_q e_q^2 \langle f_1^{q} D_1^q \rangle}{\sum_q e_q^2 \langle f_1^{q} D_1^q \rangle}
\]

Target asymmetry:

\[
A_{UT}(x_B, y, \phi_s) = \alpha \frac{x_B M y(1-y)\sqrt{1-y}}{2Q} |S_T| \sin(\phi_s) \left(\ln \frac{Q^2}{\lambda^2 + \text{finite}}\right) \frac{\sum_q e_q^3 g_{1T}^q(x_B)}{\sum_q e_q^2 f_1^{q}(x_B)}
\]
Experiment in JLAB Hall A

  - Shows per-cent level asymmetry in $^3$He↑(e,e')X
  - Presents an issue for analysis for TMD extraction from T-odd asymmetries in SIDIS
Two-Photon Exchange in Exclusive Electroproduction of Pions

- Standard contributions considered, e.g., AA, Akushevich, Burkert, Joo, Phys.Rev.D66:074004,2002 (Code EXCLURAD used for data analysis)
  Calculated in soft-photon approximation

\[ Q^2 = 6 \text{ GeV}^2, \ W = 3.2 \text{ GeV}, \ E_e = 5.5 \text{ GeV}. \]

Shows \( \pm 2\% \) variation with \( \epsilon \).

Calculated \( \epsilon \)-dependence of TPE correction.
TPE vs T-violation

- Single-spin asymmetries in inclusive DIS may be caused by
  - Effects beyond Born approximation
  - Violation of time-reversal symmetry
- The effects can be separated using positron vs electron comparison
  - TPE effects are charge-odd
  - T-violation is time-even
- First suggested by Tsai
- Important Note: if CPT is a good symmetry, then constraints on CP-violation in leptonic sector is $<10^{-6}$. But higher-order QED loops will also produce C-even SSA (three-photon exchange) at a level of $10^{-4}$.
- Possible experiment with $e^+/e^-$: Looking for T-violation in lepton scattering at sub-percent level.
Summary

- Electron-positron asymmetries provide model-independent measurement of effects beyond Born approximation: an important tool for precision probes of hadronic structure
  - Elastic ep- and eA-scattering
  - Inelastic scattering: DIS, SIDIS, DVMP
  - Parity violation: need high currents and polarization
  - T-violation in lepton scattering: SSA technique works up to \( \sim 10^{-4} \), limitation due to higher-order QED loops (three-photon exchange)