Precision Study of the Standard Model at Low Energies

*In honor of Roy Holt’s contributions to Nuclear Physics*

- Early, formative interactions with Roy
- Some present activities:

  ![OLYMPUS](image-url)

  ![DARKLIGHT](image-url)
Nuclear Physics At SLAC

• Where I learned to do experimental electron scattering
• Collaborator with ANL group: scaling in exclusive processes (Holt)
• NE17+NE18
  Very productive final running
• Outstanding young people now leaders in our field:
  
  N. Makins, R. Ent, W. Lorenzon
My Research Trajectory (1985-2014)

- Early interactions with Roy established a line of research extending over three decades: identify important problems, typically in hadron structure, which are studied using lepton beams
  - spin structure of $^3$He (CE-25 at IUCF)
  - spin structure of nucleon (hermes at DESY)
  - spin-dependent electron scattering from polarized $^1$H and $^2$H (BEAST at MIT- Bates)
  - contributions beyond single photon exchange in elastic electron-proton scattering (OLYMPUS at DESY)
  - search for a dark photon (DARKLIGHT at JLab ERL)
Technical advantages of windowless gas targets

• Precision of electron probe is fully realized when scattering only from the target of interest.
• This is of particular importance in scattering from a polarized target. Scattering from extraneous material dilutes the asymmetry.
• Polarized internal gas targets realized in full glory in both:
  - : 27 GeV DIS scattering from quarks
  - : 0.85 GeV scattering from polarized \(^2\text{H}\)
Elastic electron-proton scattering cross section

In the one-photon exchange approximation, the cross section is a product of the Mott cross section and the form factor functions:

\[
\left(\frac{d\sigma}{d\Omega}\right)_{Mott} = \frac{\alpha^2}{4E^2} \frac{1}{\sin^4 \frac{\theta}{2}} \cdot \cos^2 \frac{\theta}{2} \cdot \frac{E'}{E}
\]

\[
\frac{d\sigma}{d\Omega} = S_0 = A(Q^2) + B(Q^2) \tan^2 \frac{\theta}{2}
\]

\[
\tau = \frac{Q^2}{4M_p^2}
\]

\[
\frac{G_E^2(Q^2) + \tau G_M^2(Q^2)}{1 + \tau} + 2\tau G_M^2(Q^2) \tan^2 \frac{\theta}{2}
\]

\[
\epsilon = \frac{G_E^2 + \tau G_M^2}{\epsilon (1 + \tau)}
\]

\[
\epsilon = \left[ 1 + 2(1 + \tau) \tan^2 \frac{\theta}{2} \right]^{-1}
\]

\(\epsilon\) = relative flux of longitudinally polarized virtual photons
Proton Form Factor Ratio

Jefferson Lab 2000

- All Rosenbluth data from SLAC and JLab in agreement
- Dramatic discrepancy between Rosenbluth and recoil polarization technique
- Contribution of multi-photon exchange widely accepted explanation of discrepancy

Dramatic discrepancy!

>1000 citations

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Exploring the Heart of Matter
September 26, 2014
Definitive determination of contributions beyond single photon exchange

\[ \sigma = (1\gamma)^2 \alpha^2 + (1\gamma)(2\gamma)\alpha^3 + \ldots \]

\[ e^- \Leftrightarrow e^+ \Rightarrow \alpha \Leftrightarrow -\alpha \]

\[ \sigma(\text{electron-proton}) = (1\gamma)^2 \alpha^2 - (1\gamma)(2\gamma)\alpha^3 + \ldots \]

\[ \sigma(\text{positron-proton}) = (1\gamma)^2 \alpha^2 + (1\gamma)(2\gamma)\alpha^3 + \ldots \]

\[ \frac{\sigma(e^+p)}{\sigma(e^-p)} = 1 + (2\alpha) \frac{2\gamma}{1\gamma} \]
The OLYMPUS Experiment

- Electrons/positrons (100mA) in multi-GeV storage ring DORIS at DESY, Hamburg, Germany

- Unpolarized internal hydrogen target (buffer system) $3 \times 10^{15}$ at/cm$^2$ @ 50 mA $\rightarrow L = 10^{33} / (\text{cm}^2\text{s})$

- Large acceptance detector for e-p in coincidence: utilized existing BLAST detector from MIT-Bates

- Redundant monitoring of luminosity: Pressure, temperature, flow, current measurements
  Small-angle elastic scattering at high epsilon / low $Q^2$
  Symmetric Moller/Bhabha scattering

- Measured ratio of positron-proton to electron-proton unpolarized elastic scattering with goal of $\approx 1\%$ stat.+sys.
The Magnetic Toroid

MIT and DESY

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target chamber and vacuum system

DORIS quadrupoles

Target Chamber with internal gas target

DORIS quadrupoles

6 turbo pumps
4 NEG pumps

Target cell and wakefield suppressors required reengineering, after excessive wakefield heating during light source operation

MIT, Ferrara
Data taking

- well-balanced $e^+$, $e^-$ data sets
- additional negative toroid data (systematics!)
- $\mathcal{L}_{\text{int}}$ goal of 4 fb$^{-1}$ exceeded!
Comparison of Experiments

- **VEPP3 @ Novosibirsk**: \( E_{\text{beam}} = 1.6, 1.0, \text{ and } 0.6 \text{ GeV} \)
- **CLAS @ JLAB**: \( E_{\text{beam}} = 0.5 - 4.0 \text{ GeV continuous} \)
- **OLYMPUS @ DESY**: \( E_{\text{beam}} = 2.0 \text{ GeV} \)
TPE experiments: Novosibirsk/VEPP-3

Run I (2009)
E = 1.6 GeV

Run II (2011/12)
E = 1.0 GeV

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TPE experiments: CLAS (E04-116)

Dasuni Adikaram (ODU)
APS April Meeting,
Savannah, GA, Apr ’14
to be published
Projected uncertainties

- 2 GeV incident beam energy
- Luminosity = $2 \times 10^{33}$ cm$^{-2}$ s$^{-1}$
- 500 hours each for e+ and e-
- 3.6 fb$^{-1}$ integrated luminosity
Tracking: very preliminary …

Based on 100 runs (~2% of the data)

Electron beam

Positron beam

Polar angle in the right sector versus polar angle in left sector
Based on 100 runs (~2% of the data)

Polar angle in the right sector versus polar angle in left sector
Coplanarity cut ±5 degrees
Tracking: very preliminary …

Based on 100 runs (~2% of the data)

Electron beam

Positron beam

Polar angle in the right sector versus polar angle in left sector
Coplanarity cut ±5 degrees
Common vertex ±100 mm
Based on 100 runs (~2% of the data)

Electron beam

Positron beam

Polar angle in the right sector versus polar angle in left sector
Coplanarity cut ±5 degrees
Common vertex ±100 mm
Polar angle kinematic cut $|\theta_l - \theta_l(\theta_p)| < 5$ degrees
Based on 100 runs (~2% of the data)

Electron beam

Positron beam

Polar angle in the right sector versus polar angle in left sector
Coplanarity cut ±5 degrees
Common vertex ±100 mm
Polar angle kinematic cut $|\theta_l - \theta_l(\theta_p)| < 5$ degrees
Momentum kinematic cut $|P_p - P_p(\theta_p)| < 400$ MeV/c
Yields: very preliminary …

Based on 100 runs (~2% of the data)

Electron beam

Positron beam

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Schedule

• OLYMPUS proposed 09/2008
• OLYMPUS approved and funded 01/2010
• Experiment roll-in 07/2011
• First data taking run 02/2012
• Second data taking run 10-12/2012
• Post-experiment survey and field mapping 02-04/2013
• Data analysis in progress
• Results 2015
The Alpha Magnetic Spectrometer Experiment on the International Space Station

AMS is an MIT-led International Collaboration
16 Countries, 60 Institutes and 600 Physicists

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Recent AMS-02 data: there are new sources of positrons

Phys. Rev. Lett. 113, 121101
Phys. Rev. Lett. 113, 121102

Expectation based on collision of ordinary cosmic rays
Recent AMS-02 flux data

Phys. Rev. Lett. 113, 121101
Phys. Rev. Lett. 113, 121102
New fixed target experiments to search for dark gauge forces

- New dark Abelian forces can couple to the SM hypercharge through the kinetic mixing operator \( \frac{\epsilon}{2} F^Y_{\mu\nu} F'^{\mu\nu} \), where \( F'_\mu\nu = \partial_{[\mu} A'_{\nu]} \)
- \( \approx \) MeV to GeV scale mass for the \( A' \) gauge boson
- \( A' \) can be produced in collisions with charged particles and can decay to electrons or muons
- Production cross-section
- Decay length
- \( \alpha' = \epsilon^2 \alpha_{EM} \)
- Look for evidence of \( A' \) in the presence of QED radiation
Searching for a Dark Photon

Kinetic mixing:

\[ \frac{\epsilon}{2} F^Y_{\mu \nu} F'^{\mu \nu}, \text{ where } F'_\mu = \partial[\mu A'_\nu] \]

\[ \alpha' = \epsilon^2 \alpha_{EM} \]

Warning!
Check variable on vertical axis in sensitivity plots

FIG. 1. Radiative production of a $\gamma'$ in final (a) and initial state (b) on a heavy target nucleus $Z$. The subsequent decay of the $\gamma'$ to an electron-positron pair would be the unique signal of such a $\gamma'$ with a sharp mass distribution.

Figure 1: Feynman diagrams for a) the lowest order electromagnetic $\pi^0 \rightarrow e^+e^-\gamma$ decay and a possible contribution of $U$ vector boson to: b) $\pi^0 \rightarrow e^+e^-\gamma$ and c) lepton $g \rightarrow \mu+\mu-$

BABAR
Search for resonance in dimuon inv. mass distribution in $\Upsilon(2S,3S) \rightarrow \gamma A'$ followed by $A' \rightarrow \mu+\mu-$
DARKLIGHT Collaboration

- Arizona State University
- Hampton University
- Jefferson Laboratory
- MIT
- Saclay
- Stony Brook University
- Temple University
Experimental considerations

• Elastic electron-proton scattering at about 100 MeV
• Stay below pion threshold to keep final state simplest
• Demand detection of complete final state: scattered electron, recoil proton, and e+e- pair from A’ decay => gas target so that the 1-5 MeV recoil proton can escape and be detected
• Require high luminosity: gas target of $10^{19}$ cm$^{-2}$ and 10 mA of electrons so that one can make a definitive measurement in 1 month
• JLab FEL is world’s only such accelerator: 1 MWatt of power
• Energy recovering linac
• Final state leptons have energy from 10 to 100 MeV => multiple scattering dominates resolution => thin material thicknesses
• Gas target of $10^{19}$ cm$^{-2}$ is challenging; actually pushing to $4 \times 10^{19}$ cm$^{-2}$
Table-top scale
• Precision test of QED radiative processes in electron-proton elastic scattering as $Q^2 \rightarrow 0$
• Search for both $e^+e^-$ and invisible decays
• Completely calculable
• Complete reconstruction of final-state
• 5σ discovery limit
• $1 \text{ ab}^{-1}$ attained in several months of data taking with 10 mA at 100 MeV on $10^{19} \text{ cm}^{-2}$ target
• Green region is present muon $(g-2)$ result explained by a dark force
  Freytsis, Ovanesyan, and Thaler
  JHEP 1001, (2011) 111
Successful beam test in July 2012

Target system designed and constructed at Bates R&E Center

- A test beam of 4.3 mA, 100 MeV (430 kWatt of e-beam power) was successfully transmitted through a 2 mm hole, 127 mm long, with a maximum loss of about 3 ppm for seven hours.
- Halo can be minimized and radiation in vault is manageable.
- The FEL has the stability required for DarkLight.
Existing solenoidal magnet from E906 at BNL

- E906 carried out at AGS D6 line
- 0.5 Tesla maximum field
- Inner diameter 712 mm
- Magnet with power supply now located at Stony Brook University
Optimized design in progress
Design process

• Full Geant4 computer simulation coordinated by Jan Balewski (MIT)
• Physics processes:
  - elastic electron-proton scattering
  - Moller scattering
  - their associated radiative processes
• Detailed experimental geometry:
  - windowless gas target
  - existing solenoidal magnet
  - realistic 3 D magnetic field map from OPERA
  - Moller dump
  - lepton tracker
  - recoil proton detector
  - photon veto detector
• Simulations are used to optimize the design of the experiment.
Development of a Radiative Møller Generator

• Under development by Charles Epstein (MIT): a Monte Carlo event generator for the radiative corrections to Møller scattering
• Improves understanding of background processes
  – Møller rate is exceptionally high and must be understood

• Produces two types of events:
  – Elastic e-e events with cross-section corrected for the emission of soft photons (Tsai, 1960)
  – Hard single-photon bremsstrahlung events (exact first-order calculation)
Goals of phase-I DarkLight

- Realize full luminosity: 10 mA on $10^{19} \text{ cm}^{-2}$ of hydrogen
- Realize solenoidal magnet for complete experiment
- Realize prototype detectors and readout systems for complete experiment which enable three science goals

- Science Goal 1: Accelerator Studies with the ERL (2 days)
- Science Goal 2: Measurement of Standard Model Processes (2 days)
- Science Goal 3: Search for the $A'$ (16 days)
Fig 4. (a) Schematic cutout figure of the phase-I DarkLight instrument showing the solenoidal magnet, GEM trackers, and Møller dump. (b) Schematic transverse section of the proposed detectors for the phase-I DarkLight instrument.
Complete (phase-II) Experiment

- Use phase-I solenoidal magnet
- Use modified phase-I target
- Micromegas are the leading candidate for the lepton tracker technology
- Use phase-I proton detector technology instrumented for full acceptance
- Finish phase-II design as phase-I is finalized over the next 3-6 months
- Seek funding for phase-II in parallel with mounting phase-I
DarkLight proposal approved at JLab PAC 39 in June 2012 with “A” scientific rating, conditional upon successful test being completed

- Test successfully completed in July 2012
- Full scientific approval granted in May 2013
- Phase-I experiment funded by NSF MRI July 2014
- Detailed simulations in progress to finalize design: lepton tracker, trigger and readout
- OLYMPUS target was shipped back to MIT in summer 2013 to allow start on development of DarkLight target
- Existing 0.5 T solenoid at Stony Brook University (A. Deshpande)
- Anticipate it will take about 2 years to carry out phase-I experiment
- In parallel, finish design of complete (phase-II) experiment and pursue funding
• Working in the CEBAF Internal Target Working Group with Roy and others in 1985 strongly influenced my research career.
• The use of intense (p, e-, e+) beams from 100 MeV to 27 GeV on windowless gas targets has helped me address a series of varied and important questions in hadron physics throughout my career.
• I was fortunate to enjoy Roy’s advice and counsel in the early, formative years of my career.
• I offer Roy warm congratulations on an outstanding career.
• I wish Roy continued professional success and many long, years of health and happiness with his family.