SLAC-PROPOSAL-E159

Proposal to Measure $\Delta \sigma \gamma^N(k)$
and the High Energy Contribution
to the Gerasimov-Drell-Hearn Sum Rule

Bochum, UCLA, Frascati, Jefferson Lab,
Liverpool, Los Alamos, U. Massachusetts,
Old Dominion, Saclay, SLAC, Smith,
U. Virginia, William and Mary, Yerevan

P. Bosted, D. Crabb co-spokespersons
OUTLINE

● Introduction
● The GDH Sum Rule
● High energy behavior of $\Delta \sigma_{\gamma N}(k)$
● Connection of virtual photon results
● Experimental Overview
● Beam and Compton Polarimeter
● Target and Detectors
● Backgrounds
● Anticipated Results
INTRODUCTION

- Total photoabsorption cross section $\sigma^{\gamma N}(k)$ depends only on photon energy $k$ for real photons.
- Can be decomposed into spin $1/2$ and $3/2$ final states $\sigma_{3/2}$ and $\sigma_{1/2}$, corresponding to helicity of photon aligned or anti-aligned with spin of nucleon.
- Spin-averaged $\sigma^{\gamma N}(k) = (\sigma_{1/2} + \sigma_{3/2})/2$ well-measured (including SLAC early 1970’s). Roughly constant at 120 $\mu$b.
- We propose to measure

$$\Delta\sigma^{\gamma N}(k) = \sigma_{3/2} - \sigma_{1/2}$$

using circularly polarized photons and longitudinally polarized nucleons.
**SPIN-AVERAGED** $\sigma\gamma^N(k, Q^2)$

Large body of data: explore connection perturbative and non-perturbative regimes of QCD.
The GDH SUM RULE

- Relates integral over $\Delta \sigma(k)$ to anomalous magnetic moment $\kappa$ of target with spin $S$ (composite or elementary).

$$\int_{k^2}^{\infty} \frac{dk}{k} \Delta \sigma N(k) = \frac{2\pi^2 \alpha \kappa^2}{M^2}$$

- Follows from general principles of causality, universality, Lorentz and electromagnetic gauge invariance.

- One assumption: that unsubtracted dispersion relation can be used for $f_2(\nu)$ (the spin-dependent part of the forward Compton amplitude).

- Theorists debate whether a $J = 1$ fixed pole (violating GDH Sum Rule and possibly Bjorken Sum Rule also) is likely, unlikely, or ruled out in QCD.
• **Scale** of convergence gives scale of highest spin-flip excitations of target.

• Oscillations in $\Delta \sigma^N (k)$ signal important excitations (such as $\Delta(1232)$ Resonance). Are there any oscillations above 4 GeV?

• $\Delta \sigma^N (k)$ must **decrease** with $k$ at high $k$ for integral to converge. Contrast to $\sigma^N (k)$, known to **increase** with $k$ at high energies.

• Direct measurements only exist up to 800 MeV for proton, but various resonance region multi-pole analyses have made estimates of integrals.
<table>
<thead>
<tr>
<th>target</th>
<th>$2\pi^2\alpha\kappa^2/M^2$</th>
<th>Analyses</th>
</tr>
</thead>
<tbody>
<tr>
<td>proton</td>
<td>204 $\mu$b</td>
<td>257 to 289 $\mu$b</td>
</tr>
<tr>
<td>neutron</td>
<td>232 $\mu$b</td>
<td>169 to 189 $\mu$b</td>
</tr>
<tr>
<td>isoscalar $(p+n)/2$</td>
<td>219 $\mu$b</td>
<td>213 to 239 $\mu$b</td>
</tr>
<tr>
<td>isovector $(p-n)/2$</td>
<td>-15 $\mu$b</td>
<td>34 to 65 $\mu$b</td>
</tr>
</tbody>
</table>

- Large discrepancy, especially isovector case.
- Non-resonant contribution important?
- High energy contributions important?
- Need data on both proton and neutron to find out.
- Worldwide program at Mainz, Bonn, GRAAL, SPIN8, LEGS, Jefferson Lab, TUNL, other, but limited to 5 GeV.
LOW ENERGY BEHAVIOR OF $\Delta\sigma(k)$

Preliminary data from Mainz on proton. Resonant excitations are evident (especially $\Delta(1232)$).

![Graph showing data and models for $\Delta\sigma(k)$ vs. $k$ (GeV)]
HIGH ENERGY BEHAVIOR OF $\Delta \sigma(k)$

- **Regge theory** describes many reactions. Has been applied to measurements using virtual photons $\Delta \sigma(k, Q^2)$. Can fit SLAC data for $Q^2 > 0$ quite well.

- **Isovector** contribution dominated by poorly known $a_1(1260)$ axial vector meson trajectory.

- **Isoscalar** dominated by better known $f_1(1285)$ meson trajectory.

- **Isoscalar non-perturbative gluon exchange** $[(\ln s)/s]$?

- **Pomeron-pomeron cut contributions** $[1/\ln s^2]$?
INTEGRAL CONVERGENCE?

Curves are various Regge theory fits to virtual photoproduction data, plotted assuming proton integral converges.
FIT OF BIANCHI AND THOMAS

Regge theory fits virtual photon data well: predicts dramatic change in neutron at $Q^2 = 0$ compared to $Q^2 \geq 1$ GeV$^2$. 
WHY MEASURE $\Delta\sigma(k)$ AT SLAC?

- Measures a very fundamental quantity.
- Test convergence GDH Sum Rule.
- Compare isoscalar and isovector: latter has connection to Bjorken Sum Rule.
- Help in understanding of $g_1(x, Q^2)$ at low $x$, and convergence of integrals over $g_1$.
- Look for unexpected spin-flip strength: probe relevant energy scale.
- No existing data: field wide open for surprises.
- Drell and Hearn suggested SLAC should measure this in 1966. Now technology exists to do a good job.
EXPERIMENTAL OVERVIEW

- **Coherent bremsstrahlung** provides circularly polarized photons $4 < k < 40$ GeV.
- Subtract incoherent contributions to obtain $\Delta\sigma(k)$ at discrete values of $k$.
- Longitudinally polarized $NH_3$ and $ND_3$ targets.
- Measure total cross section asymmetry with large calorimeters.
- Reject E.M. backgrounds with cuts, longitudinal segmentation of detector, and/or calculations.
- Measure in **Counting Mode** for lower systematic error (each hadronic interaction is individually counted).
- Use **Flux Integration Mode** for smaller statistical errors (total hadronic energy summed over many interactions).
PHOTON BEAM

Described earlier. **Summary** of important parameters for four of 10 to 12 settings that will be used:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Setting 1</th>
<th>Setting 2</th>
<th>Setting 3</th>
<th>Setting 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron Energy (GeV)</td>
<td>9.9</td>
<td>13.2</td>
<td>26.6</td>
<td>48.3</td>
</tr>
<tr>
<td>$k_0/E$ of Main Coherent Peak</td>
<td>0.5</td>
<td>0.77</td>
<td>0.50</td>
<td>0.77</td>
</tr>
<tr>
<td>Incident Electrons/spill</td>
<td>$5 \times 10^9$</td>
<td>$8 \times 10^9$</td>
<td>$1.5 \times 10^9$</td>
<td>$2 \times 10^9$</td>
</tr>
<tr>
<td>Collimator Radius (mm)</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Total photons/spill</td>
<td>$1.5 \times 10^5$</td>
<td>$3.0 \times 10^5$</td>
<td>$5 \times 10^4$</td>
<td>$1.1 \times 10^5$</td>
</tr>
<tr>
<td>Coherent NI/spill</td>
<td>6.8</td>
<td>3.2</td>
<td>3.7</td>
<td>2.7</td>
</tr>
<tr>
<td>$&lt; P_\gamma / P_e &gt;$</td>
<td>0.59</td>
<td>0.87</td>
<td>0.57</td>
<td>0.82</td>
</tr>
<tr>
<td>$r$ with energy cut</td>
<td>0.59</td>
<td>0.31</td>
<td>0.80</td>
<td>0.58</td>
</tr>
<tr>
<td>$\delta \Delta \sigma^{\gamma p}$ (µb)</td>
<td>0.5</td>
<td>0.7</td>
<td>0.6</td>
<td>0.6</td>
</tr>
</tbody>
</table>
COMPTON POLARIMETER

- Designed to measure flux, energy distribution, and circular polarization of beam photons.
- Use Atomic Compton scattering $\gamma e \rightarrow \gamma e$.

- Helicity-dependent cross section:
  $$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{2m_e^2} \left( \frac{k}{k_0} \right)^2 \left[ \frac{k}{k_0} + \frac{k_0}{k} - \sin^2 \theta - P_e P_e (1 - \cos \theta) \cos \frac{(k + k_0)}{m_e} \right],$$

- For flux measurements, electrons in NH$_3$ and ND$_3$ targets can be used for continuous monitoring.

- For circular polarization measurements, use special purpose iron target (similar to that used in E155, etc. for Møller measurements).

- Electrons in foil polarized using same magnet as for NH$_3$ (5 T). Expect average $P_e$ about 0.08.
- Polarimeter uses dipole magnet (1-m-long 18D36) to bend electrons to north.
- Electrons and photon energies measured in 3 by 10 arrays of lead glass blocks, one below, one above the beam line.
- Small scintillator hodoscope used to separate scattered electrons and photons.
- Allows energy measurement of primary photon to 3%-5%.
- Polarimeter is movable on a cart to accommodate opening angle decrease with increasing photon energy.
- With reasonable counting rates (a few per spill), polarization can be measured to 3% in about 1 hour.

<table>
<thead>
<tr>
<th>$z_{det}$ (m)</th>
<th>$\theta$ range</th>
<th>$\gamma_{coh}$/spill</th>
<th>$k$-range</th>
<th>$C$/spl</th>
<th>time(hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.5</td>
<td>6-20 mr</td>
<td>$3 \times 10^5$</td>
<td>8-14</td>
<td>1.5</td>
<td>0.5</td>
</tr>
<tr>
<td>9.0</td>
<td>3-10 mr</td>
<td>$2 \times 10^6$</td>
<td>20-40</td>
<td>1.0</td>
<td>0.9</td>
</tr>
</tbody>
</table>
TARGETS

- Very similar to those used in E143, E155, and E155x.

- Will use 3-cm-long cells with NH$_3$ for longitudinally polarized protons. Expect polarization $P_t = 0.9$ and dilution factor $f = 0.18$.

- Will use ND$_3$ for longitudinally polarized deuterons. Expect polarization $P_t = 0.4$ and dilution factor $f = 0.30$.

- Beam heating and radiation damage very low compared to E155: expect higher average polarizations, less time for annealing, etc.
• Will use 5T field (new magnet) and 140 GHz microwaves (existing klystrons), as in E155. Dilution refrigerator will be used for cooler temperatures.

• Magnet allows front calorimeter to be close, and accept particles up to ±20 degrees.

• Will extract neutron results with small corrections for D-state and shadowing.

• Deuteron photodisintegration, coherent $\pi^0$ production, relativistic effects, etc. expected to be very small at high energies of this experiment (have big effects only for $k < 500$ MeV).
DETECTORS


- No Magnetic Field or Tracking

- Two identical detectors: Small Angle for as low as 0.5 to 5 degrees (moves): Large Angle for 5 to 20 degrees (does not move).

- Detectors are sampling calorimeters, made from 80 alternating layers of 3-mm-thick scintillator hodoscopes and lead plates 6 mm (1 r.l.) thick.
Target and Detectors

Target:
5 T Field
NH3 / ND3
140 GHz Microwaves
Dynamic Nuclear Pol.
90% proton pol.
40% deuteron pol.
nitrogen unpolarized

Large-Theta Detector

Small-Theta Detector

Coils

20 deg.

Variable distance

Photon Beam

5 deg

TOP VIEW

Cross Section of one layer

Alternating planes of horizontal and vertical scintillator strips

27 EM and 53 Had layers summed with longitudinal wave-shifter bars

Target:
5 T Field
NH3 / ND3
140 GHz Microwaves
Dynamic Nuclear Pol.
90% proton pol.
40% deuteron pol.
nitrogen unpolarized
• Scintillator hodoscopes alternate horizontal and vertical, with about 40 elements/plane.

• **Longitudinal segmentation** of each detector: separate read-out of first 27 r.l. (E.M.) and subsequent 53 r.l. (HAD).

• Readout uses longitudinal wave-shifter bars with PMT’s down-beam ends. Total is 640 PMTs.

• **Electronics:** each PMT output to ADC, discriminator, and multi-hit TDC (as in E155).

• **Large-\(\theta\)** calorimeter at fixed distance from target, **Small-\(\theta\)** moves on cart so \(\theta_{\text{min}} = 10\sqrt{40/k_0}\) mr
DETECTOR RATES

• In Counting mode, 30 to 50 hadrons/spill in Small-θ detector. This establishes luminosity limit, given 500 nsec beam pulse length.

• About 4 to 12 hadrons/spill in Large-θ detector.

• Several 100 low energy (10 to 50 MeV) electrons and photons/spill. Most will be below discriminator threshold. Tolerable “sprinkle hit” rate remaining.

• Estimate 100 neutrons/spill, most with kinetic energy less than 50 MeV. Most below detector threshold.

• In Flux Integration mode, total energy from neutrons estimated to be less than 1% of hadronic energy.
**HADRONIC SIGNAL**

- Using PYTHIA, find 99.5% (99%) probability, at least one final state “hadron” (includes photon from $\pi^0$ decay) has $p_T > 0.05$ GeV ($p_T > 0.1$ GeV).

- Most (> 80%) events have a charged pion or kaon in final state with $P > 1$ GeV.

- Good efficiency (> 97%) obtained in counting mode with requirements $p_T > 0.1$ GeV or $E_{min} = 0.6 \ln(k_0)$ and $p_{HAD}^T > 0.05$ GeV.

- Efficiency slightly lower if count only energy in HAD calorimeter [flux integration method B].
HADRONIC EVENTS

Fractional energy into charged pions (solid), photons/electrons (short dashed), nucleons/anti-nucleons (dot-dashed), kaons (long dashed), and neutrinos (dotted).
Hadronic Efficiency

- Less than 1% of events lost using $\theta_{\text{min}} = 0.010\sqrt{40/k}$ mr. Similar to $\theta_{\text{min}} = 400/k$ mr cut used by Caldwell.

- Find $\theta_{\text{max}} = 20$ degrees gives good efficiency for $k > 10$ GeV. Some loss at lower energies, but need this compromise to keep reasonable target costs.

- Find using energy cut $E_{\text{min}} = 0.6 \ln(k_0)$ preserves almost all events from coherent peak.
EFFICIENCY VERSUS $K$

Flux integration Methods:

A: E.M. background subtracted;
B: only energy in HAD calorimeter
PHYSICS BACKGROUND SUMMARY

<table>
<thead>
<tr>
<th></th>
<th>Data Analysis</th>
<th>B.H. Rates</th>
<th>Compton Rates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Counting Mode</td>
<td>&lt; 1%</td>
<td>negligible</td>
<td></td>
</tr>
<tr>
<td>Flux Integration A</td>
<td>50%</td>
<td>10% to 20%</td>
<td></td>
</tr>
<tr>
<td>Flux Integration B</td>
<td>negligible</td>
<td>negligible</td>
<td></td>
</tr>
</tbody>
</table>

Rates and physics asymmetry for both backgrounds well-known and **calculable**.
BETHE-HEITLER BACKGROUND

- Calculations include quasi-elastic and nuclear elastic $e^+e^-$ pair production.
- Inelastic not included (part of GDH).
- Cross sections and asymmetry readily calculated in terms of $F_1$, $F_2$, $g_1$, and $g_2$.
- Find several 100/spill, but have low energy and mainly come from low energy incoherent photons. Total energy/spill similar to total hadronic energy per spill, with asymmetry close to zero. Applies to flux integration method A.
- Rate very low ($< 1\%$) with $p_T > 0.1$ GeV cut and subtraction of incoherent photon contribution (applies to counting mode).
- Negligible contribution to flux integration method B since all of energy absorbed in EM calorimeter.
BETHE-HEITLER RATES

Hadronic (Coherent photons)

Rate/Spill

B.H. All photons
B.H. Coherent only

PT_min (GeV)
ATOMIC COMPTON BACKGROUND

- Cross section strongly peaked at low energy photons.
- Final state includes both soft photon and electron, typical energy 10 to 50 MeV.
- Asymmetry expected to be essentially zero for polarized target (electrons not polarized when microwaves are on).
- Find several 100/spill, but total energy less than Bethe-Heitler (about 10% to 20% of total hadronic energy).
- Makes 10% to 20% dilution for flux integration method A.
- Rate drops to zero for $p_T > 0.1$ GeV (kinematic limit), so no background to counting mode.
- No contribution to flux integration method B [no energy in HAD calorimeter].
ATOMIC COMPTON RATES

Hadronic (Coherent photons)

Compton All photons
Compton Coherent only
EXPECTED RESULTS

- More conservative (larger error) analysis method assumes subtraction of results with/without coherent bremsstrahlung peaks.
- Error on $A_1(k) = \Delta \sigma \gamma^N(k)/2\sigma \gamma^N(k)$ given by
  \[ \delta A_1(k) = \frac{1}{P_\gamma P_t f \sqrt{N_c}} \frac{\sqrt{2 - r}}{\sqrt{r}} \]
  where $r$ is fraction of counts from coherent peaks, and $0.3 < r < 0.8$, depending on setting.
- In counting mode, rate of coherent counts $N_c \approx 4 \times 10^7$/day. In flux integration mode, $N_C \approx 10^9$/day.
- Error on $\Delta \sigma$ obtained by scaling by $2\sigma \approx 250 \, \mu$b.
• Analysis using **simultaneous fit** to all data (includes highly polarized incoherent photons near endpoint) estimated to reduce statistical errors by factor of two.

• Most **systematic errors** in counting mode scale with size of $A_1$: estimate 6% to 8% relative error from combined beam and target parameters and modeling uncertainties. Expect to be smaller than counting mode statistical errors.

• **Run plan** will be optimized depending on preliminary results: if asymmetries large, more time will be spent on counting mode.

• Final results on both **proton** and **neutron** will be small enough to clearly determine magnitude and energy dependence of $\Delta\sigma$ for $4 < k < 40$ GeV.
EXPECTED ERRORS FOR PROTON

Systematic errors (not shown) expected to be 6\% to 8\% (relative).
EXPECTED ERRORS FOR NEUTRON

Systematic errors (not shown) expected to be 6% to 8% (relative).
ERROR ON GDH INTEGRALS

- To estimate systematic error and provide scale of expected results, will arbitrary assume results follow Bianchi and Thomas Fit II.

- Total errors are small compared to expected values and total integrals.

- Can readily determine sign and magnitude of controversial isovector contribution (limit of Bjorken Sum Rule at $Q^2 = 0$).

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REQUEST

- **Two weeks** checkout (plus one week for photon beam).

- **Two months** data taking at nominal 120 Hz, assuming 50% efficiency due to PEP-II.

- **Resources** for photon beam, polarimeter, detectors, and some target equipment.

- **Collaboration** will provide much target equipment, some diamonds, and assembly of detectors.
SUMMARY

- A solid, fundamental experiment, providing baseline for studies of spin structure of nucleon.
- Test convergence of isovector and isoscalar GDH Sum Rule.
- Connections to $g_1$ at low $x$, Bjorken Sum Rule.
- No existing data: surprises possible!
- Study QCD in non-perturbative regime with one of simplest possible interactions.
- SLAC is only place experiment can be done $5 < k < 40$ GeV.
- Energy range extends factor 8 beyond Jefferson Lab.
- Strong collaboration with experience and resources needed to do experiment.