The Super Bigbite Program for Hall A at Jefferson Lab

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Outline

- Nucleon Form Factors at High $Q^2$
- The Super Bigbite Project
- Outlook
What does electron elastic scattering tell us?

For electron scattering from spin-0 particle, Born approx.:

$$\frac{d\sigma}{d\Omega} = \left. \frac{d\sigma}{d\Omega} \right|_{\text{Mott}} \times |F(Q^2)|^2$$

- Differential cross section factorizes into point-like and structure part
- Structure part is just function dependent on 4-momentum transfer, \( Q^2 = 2EE'(1 - \cos \theta) \)
- Non-relativistically, is just the Fourier-transform
Sachs Form Factors and Rosenbluth

Sachs Form Factors

\[
G_E = F_1 - \kappa \tau F_2 \\
G_M = F_1 + \kappa F_2
\]

\(F_1 = \text{Dirac, } \chi - \text{nonflip}\)  \(F_2 = \text{Pauli, } \chi - \text{flip}\)

Rosenbluth Formula

\[
\frac{d\sigma}{d\Omega} = \left. \frac{d\sigma}{d\Omega} \right|_{\text{Mott}} \frac{E'}{E} \left[ \frac{G_E^2 + \tau G_M^2}{1 + \tau} + 2\tau G_M^2 \tan^2 \frac{\theta}{2} \right], \tau = \frac{Q^2}{4M^2}
\]

Difficulties

- \(G_E\) becomes highly suppressed at higher \(Q^2\)
- Neutron is uncharged, \(G_E\) relatively very small
- Free neutrons decay in \(\sim 15\) min. Needs to be bound in a nucleus
$G_E / G_M$ through Spin Observables

- Akhiezer and Rekalo (1968) - Polarization offers access to $G_E / G_M$
- Typically have fewer systematic contributions from radiative effects and nuclear structure

Polarization Transfer, $\vec{e}N, e'\vec{N'}$

$$\frac{G_E}{G_M} = -\frac{P_t}{P_I} \frac{(E_e + E_{e'}) \tan \theta_e / 2}{2M}$$

Polarized Beam/Target $\vec{e}\vec{N}, e'\vec{N'}$

$$A_\perp = -\frac{2\sqrt{\tau(\tau + 1)} \tan(\theta / 2) G_E / G_M}{(G_E / G_M)^2 + (\tau + 2\tau(1 + \tau) \tan^2(\theta / 2))}$$
Continuous Electron Beam Accelerator Facility at Jefferson Lab, Newport News, VA
“World’s most powerful microscope”
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- Electron accelerator by superconducting RF cavities
- 4 experimental halls
- $E$ up to 11 GeV ($\lambda \sim r_p/50$)
- $I_{\text{max}} = 200 \, \mu\text{A}$
- $P_e = \sim 90\%$
- Ideal for studying insides of nucleons and nuclei!
Proton Results

- $G_M^p$ generally follow dipole-exponential distribution

\[ G_D = \frac{1}{\left(1 + \frac{Q^2}{0.71 \text{ GeV}^2}\right)^2} \]

- JLab, Jones et al., $G_E^p$ different from $G_M^n$ using polarization
- Charles Perdrisat 2017 Bonner Prize
- Textbooks still will show you $G_E^p/G_M^p \sim \text{const}$
  - Hard two-photon exchange systematic errors in extraction?
  - OLYMPUS most recent results to test this (Kohl talk Thurs)
Challenges:

- Neutron studies require nuclear corrections
- $G_E^n$ is small
- $Q^2$ coverage typically factor 2 smaller than proton
DSE - Mapping Out Quark Mass Generation

Cloet et al.


- DSE approach describes dressed quarks, naturally includes diquarks
- Higher precision at higher $Q^2$ sensitive to dressed quark mass
- Symbolic zero crossing for $G_E^p$ is sensitive
Quark Flavor Decomposition

\[ Q^4 F^{u,d}_{1,2} \]

\[ F^p_{1,2} = \frac{2}{3} F^u_{1,2} - \frac{1}{3} F^d_{1,2} \]

\[ F^n_{1,2} = -\frac{1}{3} F^u_{1,2} + \frac{2}{3} F^d_{1,2} \]

- High \( Q^2 \) for \( G^n_E \) data allows for quark decomposition
- Same flavor quarks show similar scaling behavior in \( F_2, F_1 \)
- Not shown in proton or neutron data
- \( F_2/F_1 \) ratio different from 1/\( Q^2 \) prediction

G.D. Cates et al., PRL 106, 252003 (2011)
Jerry Miller’s suggestion explaining the different scaling by using diquarks

u-quark scattering amplitude is dominated by scattering from the lone “outside” quark. Two constituents implies $1/Q^2$

d-quark scattering amplitude is necessarily probing inside the diquark. Two gluons are exchanged, so scaling is roughly $1/Q^4$

From G. Cates

While at present this idea is at the conceptual stage, it is an intriguingly simple interpretation for the very different behaviors.
Lattice Calculations

Isoscalar $G_E, G_M$

Isovector $G_E, G_M$

- $m_\pi = 149$ MeV, $Q^2$ to 0.5 GeV$^2$
- Calculations are now reaching into the low few GeV$^2$ range
- Low $Q^2$ results are becoming more precise but cannot give radius results but have uncertainties on the order of proton radius puzzle
Overview

- Super Bigbite program measures three nucleon elastic form factors to high $Q^2$, SIDIS on $^3\text{He}$, (Cond. Appv. TDIS)
- Form factors $\rightarrow$ $5\text{M DOE Project}$
- Total 184 days of running approved (+27 cond.)
- Earliest start date Spring 2019
Super Bigbite Program - FFs to High $Q^2$

- $G_E^p/G_M^p$ to 12 GeV$^2$, E12-07-109: Cisbani, Jones, Khandaker, Liyanage, Pentchev, Perdrisat, Punjabi, Wojtsekhowski

- $G_E^n/G_M^n$ to 10 GeV$^2$, E12-09-016: Cates, Riordan, Wojtsekhowski

- $G_M^n$ to 13.5 GeV$^2$, E12-09-019: Gilman, Quinn, Wojtsekhowski

Seamus Riordan — GHP 2017
Several major new systems -
Experiments have different combinations

<table>
<thead>
<tr>
<th>Event rate</th>
<th>up to $\sim$5 kHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Several sets of GEM trackers</td>
<td>$\sim$100k strips (up to $\sim$ 20% occ.)</td>
</tr>
<tr>
<td>Hadronic Calorimeter</td>
<td>288 FADC ch</td>
</tr>
<tr>
<td>Electromagnetic Calorimeter</td>
<td>1700 ADC ch</td>
</tr>
<tr>
<td>Scint. Coord. Det</td>
<td>2k TDC ch</td>
</tr>
<tr>
<td>Gas Cherenkov</td>
<td>550 TDC ch</td>
</tr>
<tr>
<td>Scintillator Timing Plane</td>
<td>360 TDC/ADC ch</td>
</tr>
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- Reuse of existing Bigbite EM calorimetry ($\sim$200 PMTs), HERMES RICH ($\sim$2k PMTs)
Recoil polarimetry through two CH$_2$ analyzers
$e^-$ detected in electromagnetic calorimeter with coordinate detector
$Q^2$ up to 12 GeV$^2$

- 75 $\mu$A on 40 cm target
- $\theta_h$ down to 17°
- Background rates up to 150 kHz/cm$^2$
ECal absorbs 0.5 kRad/hour for $Q^2 = 12 \text{ GeV}^2$ (no magnetic elements)

Thermal annealing with $\sim 200^\circ C$ temperature provides method for optical transparancy

Full construction by NCCU
Hadronic calorimeter provides 30% energy resolution and \(\sim 700\) ps ToF resolution

- 288 modules, \(3.6 \times 1.8\) m for acceptance matching at 17 m
- > 95% recoil proton and neutron detection efficiency with virtual total suppression of all low energy backgrounds < 1 GeV
Upgraded Bigbite detector stack for higher rates, better PID
Hadron calorimeter at 17 m, need 0.5 ns ToF
48D48 deflects protons
New addition of Cherenkov and GEMs for $\pi^-$ rejection and high rate tracking
Polarized $^3$He Target

- Upgraded $^3$He cell allows for $I = 8 \rightarrow 60$ $\mu$A, $I = 40 \rightarrow 55$ cm
- Convection and metal cell ends allow for higher sustained $\vec{P}$ ($\sim 60\%$)
- Bench testing underway
Relative QE deuterium $\sigma_n/\sigma_p$ gives $G_M^n/G_M^p$

- 7 $Q^2$ points ranging from 3.5 GeV$^2$ to 13.5 GeV$^2$
- Setup similar to $G_E^n$ with LD$_2$ target
All four up to same $Q^2$ range $\sim 10$ GeV$^2$

Flavor decomposition into new several GeV$^2$ range possible
SIDIS and TDIS

- 64 day $^3\text{He}$ SIDIS measurement for $\pi^\pm$ and $K^\pm$
- 27 day TDIS C1 approved with CLAS large angle calorimeter and GEM rTPC on LH$_2$ and LD$_2$
Detector Assembly

Detectors and infrastructure finalizing construction

Super Bigbite Spectrometer (SBS) Detectors

CDET module constructed at JLab
High rate X-ray testing 
setup for GEMs
INFN Front 
Tracker at JLab
Hadron Calorimeter modules 
at JLab
Rear GEM tracker 
modules at UVA

FT Chamber with Carbon Fiber frame

Infini Front Tracker at JLab

High rate X-ray testing setup for GEMs
### Hall A Projected Experiment Schedule, updated 1/2017

Experiments in red represent PAC42 “high impact” experiments

<table>
<thead>
<tr>
<th>CY 2016</th>
<th>Spring</th>
<th>Fall</th>
<th>CY 2017</th>
<th>Spring</th>
<th>Fall</th>
<th>CY 2018</th>
<th>Spring</th>
<th>Fall</th>
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<tbody>
<tr>
<td></td>
<td>DVCS –I/GMp</td>
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<td>Ar(e,e’p)*</td>
<td>3H/3He group</td>
<td>TBD: APEX PREX12 CREX $A_i^n$ DVCSII</td>
<td>3H/3He group</td>
<td>TBD</td>
<td></td>
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*possible best effort  
schedule not final  
SBS 2019?  
MOLLER, SoLID

via Thia Keppel
• By studying the EM properties of the nucleon, we can gain insight into the underlying mechanisms, helping refine theory and gain intuition
• Protons and neutrons together give flavor separation which provides excellent opportunities for model comparison
• Upcoming programs in high $Q^2$ form factors with SBS will provide information on underlying quark dynamics
BACKUP
Construct model of 3 massive quarks or quark/diquark, include pion cloud:

- $G_E^P$ suppression at higher $Q^2$ due to inclusion of quark orbital angular momentum
- Know only 1/3 of the spin of the proton is carried by the quark spins, reproduced with di-quark DOF
DSE/Fadeev q(qq) Calculations

- Model based on QCD’s Dyson-Schwinger equations to describe dressed quark propagator
- Fadeev amplitudes describe three-quark states
- Few free parameters tuned to reproduce nucleon properties such as masses

- Bhagwat et. al. arXiv:nucl-th/0610080
- Cloët et. al. arXiv:nucl-th/0804.3118
Can treat with pQCD for large $Q^2$

Log order calculations for $F_1$, $F_2$ by Belitsky et al. (including hadron helicity non-conservation through quark OAM) makes prediction that as $Q^2 \rightarrow \infty$

$$\frac{Q^2}{\log^2(Q^2/\Lambda^2)} \frac{F_2}{F_1} = \text{const.}$$

$\Lambda$ parameter related to size of the nucleon

Published proton data scaling starts at fairly low $Q^2$

Neutron scaling should also occur if this is pQCD
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E02-013 - Highest $Q^2 G^n_E$ through QE scattering

- Polarized $^3$He target acts as effective free neutron source
- Two arms to measure coincidence $e'$ and $n$, allow for cuts on $p_{\text{miss},\perp}$ to suppress FSI

- BigBite - large acceptance spectrometer, reconstructs $\vec{e}'$
- Neutron arm - matches BB acceptance, measures neutron momentum through ToF, performs nucleon charge ID
\( ^3\text{He} \) is spin 1/2, 3 body calculations describe polarization as

- 86% only for inclusive case
- D-wave state contributes \( \sim 10\% \) to w.f. - sensitive to missing momentum range
Update based on Kelly, PRC 66, 065203 (2002)

Form to account for relativistic distortions:

\[ \tilde{\rho}_{\text{ch}}(k) = (1 + \tau)^{\lambda_E} G_E(Q^2) \quad \tau = Q^2/(4M_p) \]

\[ \mu \tilde{\rho}_{\text{mag}}(k) = (1 + \tau)^{\lambda_M} G_M(Q^2) \quad k^2 = Q^2/(1 + \tau) \]

Use Fourier-Bessel expansion with general scaling constraints
( Mostly ) Model-Independent Fits

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