Measurement of the neutron electric-to-magnetic form factor ratio at high momentum transfer

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for the SBS collaboration

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Nucleon form factors

- Fundamental quantities describing spatial nucleon structure
- Neutron electric form factor least known, limited to $Q^2 < 3.4 \ (\text{GeV}/c)^2$
- Measurements of $G_{En}$ in high $Q^2$ range provide important insight
  - Complete set of form factors in region with small pion cloud contributions
  - Separate isoscalar, isovector form factors, allow separation of up, down quark contributions (neglecting strangeness)
  - Directly sensitive to up and down quark distributions in quark core
  - Model-independent extraction of neutron infinite-momentum frame charge density [Miller (2007) ; Venkat et al. (2010)]
  - Important comparisons to QCD-based calculations
    - Lattice QCD: isovector form factor (e.g. $G_{Ep}-G_{En}$) cancels disconnected diagrams
    - Region of interest for Dyson-Schwinger Equation calculations
Extending the $Q^2$ range of form factors

Reach extended by Super-BigBite Spectrometer (SBS) in Hall A:

- Use high luminosity + open geometry + GEM detectors

Pushes $G_E^p/G_M^p$, $G_E^n$, $G_M^n$ to high $Q^2 (>10 \text{ GeV}^2)$

Allows for flavor decomposition to distance scales deep inside the nucleon
The SBS (form factor) program

Taking advantage of large acceptance and high luminosity

E12-09-019: Measurement of $G_{\text{Mn}}/G_{\text{Mp}}$ to $Q^2 = 13.5 \text{ (GeV/c)}^2$
Unpolarized deuterium target: $D(e,e'n)/D(e,e'p)$ cross section ratio
Installation will probably begin in May of 2020

E12-17-004: Measurement of $G_{\text{En}}/G_{\text{Mn}}$ at $Q^2 = 4.5 \text{ (GeV/c)}^2$
Unpolarized deuterium target: $D(e,e'n)$ polarization transfer
Planned to be run in combination with E12-09-019

E12-09-016: Measurement of $G_{\text{En}}/G_{\text{Mn}}$ to $Q^2 = 10 \text{ (GeV/c)}^2$
Polarized helium-3 target: $^3\text{He} (e,e'n)$ polarized beam and target

E12-07-109: Measurement of $G_{\text{Ep}}/G_{\text{Mp}}$ to $Q^2 = 12 \text{ (GeV/c)}^2$
Unpolarized hydrogen target: $H(e,e'p)$ polarization transfer

Additionally: SIDIS / TMD
E12-09-018: SIDIS Transverse single-spin asymmetries $^3\text{He}(e,e'h)X \ (h=\pi^{\pm,0}, K^\pm)$
PR12-15-006: Tagged DIS $A(e,e'N)$ for effective neutron and meson targets
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**“GEn-RP”**

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**PR12-15-006:** Tagged DIS $A(e,e'N)$ for effective neutron and meson targets
No free neutron target …

Use the deuteron as neutron target

Use $^3$He as a polarized neutron target

Incident Electron beam

L=0 L=2

Polarized and unpolarized

Account for nuclear structure and “FSI”

$P_n = 86\%$ and $P_p = -2.8\%$

J.L. Friar et al., PRC 42, (1990) 2310
**G^n_E in absence of a free neutron target**

No free neutron target → elastic and quasi-elastic scattering

Nuclear corrections (FSI, MEC, ...)

Smallness of G^n_E does not allow L-T sep. of d(e,e’n) or d(e,e’)--d(e,e’p)

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**2H(e,e’n) quasielastic**

Vector-polarized deuterium

G^n_EG^n_M interference

Nikhef, Bates/BLAST, Hall C

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**3He(e,e’n) quasielastic**

Polarized Helium-3

G^n_EG^n_M interference

MAMI A3, A1, Hall A

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**2H(e,e’d) elastic, A(Q^2)**

G^n_EG^p_E interference

Schiavilla+Sick

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**G_Q from A+T_{20} / 2H(e,e’d)**

G^n_EG^p_E interference

Galster, Platchkov, ...

---

**2H(e,e’n) quasielastic**

Neutron recoil polarization

G^n_EG^n_M interference

Bates, MAMI A3, A1, Hall C
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\[ ^3\text{He}(e,e’n) \text{ quasielastic} \]
\[ \text{Polarized Helium-3} \]
\[ G^n_E G^n_M \text{ interference} \]
\[ \text{MAMI A3, A1, Hall A} \]

\[ ^2\text{H}(e,e’n) \text{ quasielastic} \]
\[ \text{Vector-polarized deuterium} \]
\[ G^n_E G^n_M \text{ interference} \]
\[ \text{Nikhef, Bates/BLAST, Hall C} \]

\[ G^Q \text{ from A+T}_20 / ^2\text{H}(e,e’d) \]
\[ G^n_E G^n_P \text{ interference} \]
\[ \text{Schiavilla+Sick} \]

\[ ^2\text{H}(e,e’d) \text{ elastic, A}(Q^2) \]
\[ G^n_E G^n_P \text{ interference} \]
\[ \text{Galster, Platchkov, ...} \]

\[ ^2\text{H}(e,e’n) \text{ quasielastic} \]
\[ \text{Neutron recoil polarization} \]
\[ G^n_E G^n_M \text{ interference} \]
\[ \text{Bates, MAMI A3, A1, Hall C} \]
Lepton-nucleon scattering

- Lepton-lepton scattering:
  \[-iM = \bar{u}(k')(ig_e\gamma^\mu)u(k) \left(-i\frac{g_{\mu\nu}}{q^2}\right) \bar{u}(p')( -ig_e\gamma^\nu)u(p)\]

- Lepton-nucleon scattering:
  \[-iM = \bar{u}(k')(ig_e\gamma^\mu)u(k) \left(-i\frac{g_{\mu\nu}}{q^2}\right) \bar{u}(p')( -i\gamma^\nu u(p)\]

- Nucleon vertex factor (current)
  \[\Gamma^\nu = \gamma^\nu F_1(q^2) + i\sigma^{\nu\alpha} \frac{q_\alpha}{2M} F_2(q^2)\]

  Dirac \(F_1\) and Pauli \(F_2\) “form factors”

  \[Q^2 = -q^2, \quad \tau = \frac{Q^2}{4M^2}\]

  Electric and magnetic “Sachs” form factors

- Spin dependent, polarized cross section:
  no more averaging over initial and summing over final spins
  in the matrix element leads to interference terms
Double polarization in elastic $eN$ scattering: Recoil polarization or (vector) polarized target $N(e,e'N), \quad \tilde{N}(e,e'N), \quad (N=p,n)$

Polarized cross section

$$\sigma = \sigma_0 \left( 1 + P_e \vec{P}_p \cdot \vec{A} \right)$$

Double polarization observable = spin correlation

$$-\sigma_0 \vec{P}_p \cdot \vec{A} = \sqrt{2\tau \epsilon (1 - \epsilon)} G_E G_M \sin \theta^* \cos \phi^* + \tau \sqrt{1 - \epsilon^2} G_M^2 \cos \theta^*$$

Asymmetry ratio (“Super ratio”)

$$\frac{P_\perp}{P_\parallel} = \frac{A_\perp}{A_\parallel} \propto \frac{G_E}{G_M}$$

independent of polarization or analyzing power
Recoil polarization technique

- Use dipole field for spin precession to rotate $P_l$ and $P_n$
- Applicable to protons and neutrons

$$I_0 P_t = -2 \sqrt{\tau(1+\tau)G_E G_M} \tan \frac{\theta_e}{2}$$

$$I_0 P_\ell = \frac{1}{M} \left( E_e + E'_e \right) \sqrt{\tau(1+\tau)G^2_M} \tan^2 \frac{\theta_e}{2}$$

$$\frac{G_E}{G_M} = - \frac{P_t}{P_\ell} \frac{(E_e + E'_e)}{2M_p} \tan \left( \frac{\theta_e}{2} \right)$$

$$I_0 \propto G^2_E + \frac{\tau}{\epsilon} G^2_M$$
Polarimetry

- Strong LS interaction energy allows **hadron polarization** measurements with large analyzing powers
- Analyzing power forward-peaked and decreasing with higher energy
- Normal polarization causes left-right asymmetry
- Sideways polarization causes top-bottom asymmetry

Neutron polarimetry:
- Elastic / Proton-Recoil (PR): np → np
- Charge Exchange (CE): np → pn
Experimental technique

Measure double-polarized \( \frac{2}{H(e', e' n)} \)

Final-state neutron \( P_x / P_z \rightarrow G_{En} / G_{Mn} \)
(precess \( P_z \rightarrow P_y \) in dipole magnetic field)

Liquid D\(_2\) target (10 cm),
40 \( \mu \)A polarized electron beam (P=80%)
Luminosity \( L = 1.26 \times 10^{38} \text{ cm}^{-2} \text{ s}^{-1} \)

BigBite electron spectrometer and SBS hadron spectrometer
apart from polarimeter, identical to \( G_{Mn} / G_{Mp} \) E12-09-019 setup

SBS Neutron polarimeter: acceptance well matched to electron arm

Dipole magnet, integrated field \( \sim 2 \text{ Tm} \)

Hadron calorimeter, high p & n efficiency, effective suppression soft background
+ passive Cu analyzer
+ GEM charged-particle tracking systems
+ active CH analyzer and side scintillator planes

Detecting high-momentum, small angle protons produced by np→pn
AND low-momentum large-angle protons produced by np→np scattering
Analyzers, GEM trackers and scintillator planes for $G_{En}/G_{Mn}$
Engineering layout

- Configured to run with GMn experiment

Polarimeters

May 2019 ERR (R. Wines)
Charge Exchange (CE) Polarimeter

- High-momentum forward protons (towards HCAL) after CE np → pn
- 2 INFN GEM planes
- 6 UVa GEM planes
- 1 Cu analyzer
**SBS Neutron Polarimeter**

**Charge Exchange (CE) Polarimeter**
- High-momentum forward protons (towards HCAL) after CE \( np \rightarrow pn \)
- 2 INFN GEM planes
- 6 UVa GEM planes
- 1 Cu analyzer

**Proton Recoil (PR) Polarimeter**
- Low-momentum large-angle recoiling protons after \( np \rightarrow np \)
- Active CH analyzer
- 2 sections, one each side of CE Polarimeter
- Each section has:
  - 2 UVa GEM planes
  - 1 plastic scintillator plane
SBS GEM detectors

Charge-Exchange (CE) Polarimeter:
- 2 INFN + 2 UVa layers, in front of Cu analyzer
- 4 UVa layers behind the Cu analyzer

Proton-Recoil (PR) Polarimeter:
- 2 Identical arms, 2 UVa GEM layers in each arm

UVa: K. Gnanvo, S. Jian, N. Liyanage, A. Rathnayake
HU: M. Kohl, M. Rathnayake, T. Gautam
INFN: E. Cisbani, P. Musico, R. Perrino, L. Re and many more ....
SBS GEM detector commissioning (UVa)

Commissioning with cosmics in 2019
Spin precession in SBS dipole

- Nucleon spin precession calculated in Geant4 with TOSCA field map
- Maximum spin transfer $z \rightarrow x \sim 3\%$
- Smoothly varying, can be corrected as polarimeter has good position resolution
- Maximum systematic error on $P_x/P_z \sim 1\%$

\[
\chi = \frac{2\mu_N}{\hbar c \beta_N} \int_B \mu \cdot dl
\]

48D48: ~2 Tm

\[
A(\chi) = \frac{P_0}{\sqrt{P_x^2 + P_z^2}} \sin(\chi - \chi_0)
\]

\[
\tan \chi_0 = \frac{P_x}{P_z} \propto G_E/G_M
\]
Elastic np → np or pp → pp for highest $A_y$ value

Proton $A_y$ measurements C, CH$_2$
- empirical p+C value of $A_y$ ~0.5 of free elastic p+p scattering
- due to Fermi-motion smearing of the elastic signal and inelastic contamination

pp → pp scales as $1/p_{lab}$

np → np has similar slope but negative offset

Up to now no data on nC → npX at $p_{lab}$ ~ several GeV/c (nor for any medium to high-Z nucleus)

Peak Analyzing Power of N-N Scattering $A_y^{max} @ p$ ~ 300 – 400 MeV/c

Nucleon polarimetry: N-N analyzing power
Analyzing power for elastic n-p scattering

\( A_y \) for n-p (or p-n) falling rapidly with increasing neutron momentum

\( A_y \) for charge-exchange n-p large at sufficiently large \( t \) (\( \theta_p \sim \) few deg.)

No apparent strong incident momentum dependence for charge-exchange \( A_y \)

\( \sigma_{np \rightarrow np} \) factor \( \sim10 \) higher than \( \sigma_{np \rightarrow pn} \)

Diebold et al., PRL 35, (1975), 632

Elastic n-p Polarisation

Abolins et al., PRL 30, 1973, 1183
Robrish et al., PLB31 (1970), 617

Calculate efficiency of polarimeter as function of $\theta_n$ by Monte Carlo

$A_y$ for free $np \rightarrow np$: JINR fit to $p_n$ and $\theta_n$ dependence, scale $A_y$ by 0.5 for $^{12}$C scattering (agrees with JINR 2016-17 data)

$A_u$ for $np \rightarrow pn$ on Cu: new 2016-17 measurement from JINR
Realistic description of polarimeter components in g4sbs

Included spin-dependent hadronic processes and precession

Full quasi-elastic pseudo-data set simulated for expected luminosity

Two-arm data analysis performed for both CE and PR polarimeter with realistic detector efficiencies and resolutions

Analyzing power parametrizations based on Ladygin (x0.5) for PR and Dubna results for CE

Extracted effective analyzing power (due to depolarization), overall efficiency, FOM and statistical uncertainty on polarization components and form factor ratio

FOM study: D. Hamilton (U. of Glasgow)

Rate studies: W. Tireman (Northern Michigan)
Simulated asymmetries

PR Polarimeter with Active Analyzer

- \( P = 1 \) in generator: extract dilution factor and effective analyzing power

- \( A_y (np \rightarrow np) \) parametrization for CH based on Ladygin elastic x0.5 (agrees with 2016-17 JINR results)

- Polarimeter Efficiency:
  \[ \varepsilon = 3.8 \times 10^{-2} \]

- Effective analyzing power of PR polarimeter:
  \[ A_y^{\text{eff}} = \text{Dilution} \times A_y(np \rightarrow np) = 0.77 \times 0.06 = 0.046 \]

- Figure of Merit:
  \[ \text{FOM} = \varepsilon \times (A_y^{\text{eff}})^2 = 0.8 \times 10^{-4} \]
Simulated asymmetries

CE Polarimeter with Cu Analyzer

P = 1 in generator:
extract dilution factor and effective analyzing power

A_y (np → pn) parametrization for Cu based on 2016-17 JINR results

Polarimeter Efficiency:
ε = 2.3 \times 10^{-2}

Effective analyzing power of CE polarimeter:
A_y^{\text{eff}} = \text{Dilution} \times A_y(np \rightarrow pn) = 0.89 \times 0.12 = 0.11

Figure of Merit:
FOM = \varepsilon \times (A_y^{\text{eff}})^2 = 2.6 \times 10^{-4}
Extracted recoil polarization components

4 comb. beam helicity, SBS dipole polarity

Unpolarized Distribution

Polarized Distributions

Simulated 20 million QE e-n events with $P_e = 0.8$, $P_x = 0.19$ and $P_z = 0.52$ (typical values)

Projected uncertainties consistent with FOM
Projected form factor ratio uncertainty

\[
\delta P = \sqrt{\frac{2}{N_{\text{inc}} F^2}} \quad R = \frac{\mu_n G_E^n}{G_M^n} \quad \left(\frac{\delta R}{R}\right)^2 = \left(\frac{\delta P_x}{P_x}\right)^2 + \left(\frac{\delta P_z}{P_z}\right)^2
\]

<table>
<thead>
<tr>
<th>$E_{\text{beam}}$ (GeV)</th>
<th>$Q^2$ (GeV/c$^2$)</th>
<th>$p_n$ (GeV/c)</th>
<th>Rate (Hz)</th>
<th>Time (hours)</th>
<th>FOM x10$^{-4}$</th>
<th>$dP$ (absolute)</th>
<th>$dR$ (absolute)</th>
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</thead>
<tbody>
<tr>
<td>4.4</td>
<td>4.5</td>
<td>3.15</td>
<td>48.8</td>
<td>120</td>
<td>2.6 (CE)</td>
<td>0.019</td>
<td>0.078</td>
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<td>0.8 (PR)</td>
<td>0.034</td>
<td>0.140</td>
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<td>3.4 (Total)</td>
<td>0.017</td>
<td>0.070</td>
</tr>
</tbody>
</table>

 Estimates from latest g4sbs agree very well with proposal

$dR$ based on Galster $G_{En}$ and Kelly $G_{Mn}$ parametrizations

Expect overall systematic error to be $\sim 3.0\%$
E12-17-004 will measure the ratio of neutron electric to magnetic form factors by quasielastic electron-deuteron scattering with neutron recoil polarimetry.

The SBS Neutron Polarimeter consists of two independent parts:

- A polarimeter with an active scintillator array analyzer based on n-p scattering (forward neutron, backward proton)
- A polarimeter with a copper analyzer based on n-p charge exchange (forward proton)

Simulations for realistic running conditions have been performed within the g4sbs framework (used for other SBS experiments)

We expect the experiment to run in the early phase of the SBS program (2020-21)
Backup
JINR Dubna Nov 2016 – Feb 2017

Measure asymmetries polarized $np \rightarrow pn$

C, CH, CH$_2$, Cu targets ($p_{lab} = 3.0 – 4.2$ GeV/c)

Extract $A_y$ as a function of $p_t = p_{lab} \sin \theta$

Cu asymmetry similar to C (also found, recently, for $pn \rightarrow np$)

Draft publication to be submitted soon