Neutron Form Factors

Bogdan Wojtsekhowski, Jefferson Lab

- Neutron structure and EM form factors
- Recent experiment $^3\text{He}(e,e'n)$ at Jlab
- Flavor decomposition of nucleon FFs
- The transverse neutron densities
- Future GEN&GMN and GMN/GMP at high Q2
Highlights of the neutron

- Prediction: Rutherford 1920
- Discovery: Chadwick 1932
- Magnetic moment: Esterman & Stern 1934, Alvarez & Bloch 1940
- Determination of spin 1/2: Schwinger 1937
- Direct observation of the structure: Hofstadter 1950th
- SLAC measurement of $G_M^n$ up to 10 GeV$^2$
- Time like FFs: DM2, FENICE
- Polarizabilities: SAL, Mainz, Lund
- Polarized electron beam era: Sinclair’s electron source in 1977
- CEBAF with polarimeter and polarized targets in 1990th
- Unification of DIS/FFs/DVCS in GPDs by Muller, Ji, Radyushkin
- $G_M^n/G_P^n$ precision measurement by Brooks et al in 2001
- Polarized He-3: laser pumping
- $G_E^n/G_M^n$ measurements at NIKHEF, Mainz, JLab, BATES
Electro-Magnetic Form Factors

One-photon approximation, $\alpha_{em} = 1/137$, hadron current

$$J_{hadronic}^{\mu} = i e N(p') \left[ \gamma^\mu F_1(Q^2) + \frac{i q_{\nu}}{2 M} F_2(Q^2) \right] N(p)$$

Rosenbluth (1950)

At large $Q^2$ study of $G_E$ require use of
polarization observables - FFs at CEBAF

Akhiezer (1958)
Arnold, Carlson
and Gross (1981)

Full expression for $M$ has three complex functions, $F_{1\nu}, F_{2\nu}, F_{3\nu}$

$$M = \frac{4\pi \alpha}{Q^2} \bar{u}' \gamma_\mu u \cdot \bar{N}' \left( \tilde{F}_1 \gamma^\mu - \tilde{F}_2 [\gamma^\mu, \gamma^\nu] \frac{q_{\nu}}{4M} + \tilde{F}_3 K_{\nu} \gamma^\nu \frac{P^\mu}{M^2} \right) N$$

Guichon & Vanderhaeghen

Afanasev et al.
Blunden et al.

old $G_{E,M}$ are real
functions of $t=-Q^2$

Extra terms
contribute less
than few % to $\sigma_R$

October 4, 2010

slide 3

Bogdan Wojtsekhowski

Baldin 2010
Photon - Neutron Interaction

At $Q^2$ of several GeV$^2$ massive photon vibrates in $q$-$\bar{q}$, which can’t propagate far - already inside of the nucleon ⇒ still such $q$-$\bar{q}$ propagates as a VM
GPDs of nucleon

Müller (94), Ji (97), Radyushkin (97)

GPDs

\[
\xi = \frac{(p_q^+ - p_{q'}^+)/(p_q^+ + p_{q'}^+)}{x - \xi}
\]

Quark dynamics of nucleon encoded in GPD functions

\( H(x, \xi, t) \), \( \tilde{H}(x, \xi, t) \) hadron helicity-conserving; vector and axial-vector

\( E(x, \xi, t) \), and \( \tilde{E}(x, \xi, t) \) helicity-flipping; tensor and pseudo-scalar
GPDs information

Reduction formulas at $\xi = t = 0$ for DIS and $\xi = 0$ for FFs

$H^q(x, \xi = 0, t = 0) = q(x)$

$\tilde{H}^q(x, \xi = 0, t = 0) = \Delta q(x)$

$\int_{-1}^{+1} dx \, H^q(x, 0, Q^2) = F_1^q(Q^2)$

$\int_{-1}^{+1} dx \, E^q(x, 0, Q^2) = F_2^q(Q^2)$

Ji’s sum rule for quark orbital momentum

$\langle L^q_v \rangle = \frac{1}{2} \int_0^1 dx \left[ xE^q_v(x, \xi = 0, t = 0) + xq_v(x) - \Delta q_v(x) \right]$  

DVCS will access low $t$, large $Q^2$ kinematics
3-d picture of the nucleon

Proton form factors, transverse charge & current densities

Correlated quark momentum and helicity distributions in transverse space - GPDs

Structure functions, quark longitudinal momentum & helicity distributions
Sachs Form Factors of the nucleon

\[ G_M^p / G_D^p \]

\[ G_V^p / G_M^p \]

\[ G_N^p / G_D^p \]

\[ G_V^n / G_M^n \]

\[ \mu_p G_E^p / G_M^p \]

\[ \mu_n G_E^n / G_M^n \]

\[ Q^2 \text{ [GeV}^2\text{]} \]

\[ \text{BBBA05} \]
Recent experiment at Jlab
Jlab high $Q^2$ GEN experiment

✓ Since 1984, when Blankleider & Woloshin suggested $^3\overrightarrow{He}(\overline{e}, e'n)$, several experiments of this type have been performed at NIKHEF-K and Mainz (A1, A3) for $Q^2$ up to 0.7 GeV$^2$, a big success in part due to a new accurate 3-body calculation possible at low $Q^2$ (Glockle et al.)

✓ At $Q^2$ above 1–2 GeV$^2$ Glauber method becomes sufficiently accurate (Sarksian)

✓ Electron-polarized neutron luminosity and high polarization of $^3$He target made measurement about 10 times more effective than with ND$_3$. In combination with a large acceptance electron spectrometer the total enhancement is more than 100, which allows to reach 3.5 GeV$^2$

Require super

- Polarized target
- Electron spectrometer
- Neutron detector
Double polarization method

\[ A_{phys} = A_{\perp} + A_{\parallel} = \frac{a \cdot G_E G_M}{G_E^2 + c \cdot G_M^2} \sin \theta^* \cos \phi^* + \frac{b \cdot G_M^2}{G_E^2 + c \cdot G_M^2} \cos \theta^* \]

\[ \theta^* \sim 90^\circ \]

\[ A_{phys} \propto G_E^n \]

\[ p_{\perp} = |(\vec{p}_n - \vec{q}) \perp \vec{q}| \]

\[ \vec{H} \text{He}(\vec{e}, \vec{e}'n) \]

Selection of QE by cut \( p_{\perp} < 150 \text{ MeV} \)
Hall A $G^\text{n}_E$ experiment

Beam

Electron arm

Target

Neutron arm

$^3\text{He}(\vec{e}, e'n)$
Hall A $G_E^n$ experiment

Beam

Laser light

Pumping chamber

Rb + K

Polarized beam

Target chamber

Scattered electron

Recoiled neutron

Polarization pumping

$J_{\text{polarized nuclei}} \times P^2_{\text{nuclei}}$
Hall A $G_E^n$ experiment

- Solid angle of 76 msr (12 times higher than HRS)
- 40 cm long target
- Momentum resolution of 1%
Electron Spectrometer

Useful $\Delta Q^2/Q^2 \sim 0.1$ with max $\Omega$ leads to a large aspect ratio, limited just of $30^\circ$ for the polar target. BigBite was designed at NIKHEF for aspect ratio $\Delta \theta/\Delta \phi = 1/5$. Spectrometer has solid angle up to 95 msr.

With luminosity of JLab polarized target, $10^{37} \text{ cm}^{-2}/\text{s}$, the open geometry - a dipole spectrometer - works well when all MWDCs located behind the magnet.
Neutron Detector

- Match BigBite solid angle for QE kinematics
- Flight distance ~ 10 m
- Operation at $3 \cdot 10^{37} \text{ cm}^2/\text{s}$

- $1.6 \times 5 \text{ m}^2$ active area
- 6–7 layers (~ 250 bars)
- 2 veto layers (~ 200)
- 0.38 ns time resolution
Target monitoring

small value of $A_{obs} = A_{||} + A_{\perp} \approx 2 - 5\%$

smaller is better for reduction of the systematic errors
Data analysis: step 1 - Time-of-Flight

Raw events (BLACK lines) have significant accidental level and large tail for slower protons.

RED lines present events after cut on e’-n angular correlation: accidentals and tails almost gone.
Analysis: step 2 - $q_{\text{perp}}$ vs $W$; 1.7 GeV$^2$

perpendicular “$q$” = $q \times \tan(\theta_{qh})$; $W^2 = M^2 + 2M(E-E') - Q^2$

Quasi elastic events dominates after Full Cuts applied

max value of used perp. $q$
Analysis: step 3 - W distribution

for 3.5 GeV² quasi-elastic signal very small in e,e’
after angular correlation cut peak is just as suppose to be
The results $G_E^n$ experiment

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure.png}
\caption{Graph showing the results of the $G_E^n$ experiment.}
\end{figure}
The JLab $G_E^n$ experiments

without JLab GEn experiments

significantly better accuracy for high $Q^2$

Electric Form Factor of the Neutron
Recent experiment at Bates

\[ \vec{D}(e,e'n) \]

\[ G^E_\pi \]

\[ Q^2 / (\text{GeV}/c)^2 \]

Neutron Recoil Polarization
Polarized Deuterium
Polarized He-3
This work
BLAST fit

- Glazier
- VMD + DR [Lomon]
- VMD + DR [Belushkin]
- Cloudy Bag RCQM [Miller]

BEAM
TARGET
DRIFT CHAMBERS
COILS
CERENKOV COUNTERS
NEUTRON COUNTERS
SCINTILLATORS
Running experiment at Mainz

Setup for $G_{en}$ @ $Q^2=1.5$ GeV$^2$

Test run

Test with 5cm Pb in front of hadron detector

October 4, 2010  slide 24  Bogdan Wojtsekhowski  Baldin 2010
Flavor view with EMFFs
The goal is understanding of the nucleon

\[ F_p = \frac{2}{3} F_{\text{dual}} + \frac{1}{3} F_{\text{lone}} \]
\[ F_n = \frac{1}{3} F_{\text{dual}} + \frac{2}{3} F_{\text{lone}} \]

\[ F_{1,\text{dual}} = F_{1}^{u,p} = 2 F_{1p} + F_{1n} \quad F_{1,\text{lone}} = F_{1}^{d,p} = 2 F_{1n} + F_{1p} \]
$F_{1d}^{(2)}/F_{1u}^{(2)}$ with proton and neutron FFs

\[
F_1 = \frac{G_E + \tau G_M}{1 + \tau}
\]

\[
F_2 = -\frac{G_E - G_M}{1 + \tau}
\]

\[
F_1^u = 2F_{1p} + F_{1n}
\]

\[
F_1^d = 2F_{1n} + F_{1p}
\]

Lattice calculation => very good agreement with the trend, need accuracy
DSE (ANL) => good, possibly a signature of dominant degrees of freedom
Our data will require a new fit of $E_d$ and $E_u$ GPDs
Form Factors ratios
Form Factors ratios

correspondence e.g. via GPDs

$F_{1,\text{one}} / F_{1,\text{dual}}$

$\kappa_{\text{one}}^{-1} F_{2,\text{one}} / F_{1,\text{one}}$

$\kappa_{\text{dual}}^{-1} F_{2,\text{dual}} / F_{1,\text{dual}}$

$Q^2$ [GeV$^2$]

$Q^2$ [GeV$^2$]
Form Factors ratios

Dual and Lone quark distribution FFs
The goal is understanding of the nucleon

- What is a unique signature of the diquark configuration?

\[
F_p = \frac{+2}{3} F_{\text{dual}} + \frac{-1}{3} F_{\text{lone}}
\]

\[
F_n = \frac{-1}{3} F_{\text{dual}} + \frac{+2}{3} F_{\text{lone}}
\]

Results of E02-013 Hall A GEn
The goal is understanding of the nucleon

- A diquark configuration?
- An effect of orbital motion?

\[ F_{1,dual} = F_{1}^{u,p} = 2 F_{1p} + F_{1n} \]
\[ F_{1,lone} = F_{1}^{d,p} = 2 F_{1n} + F_{1p} \]

Results of E02-013 Hall A GEn

Interesting observation:
\[ F2/F1 = R \text{ is constant in the } Q^2\text{-range } 1 - 3.5 \text{ GeV}^2 \]
EMFFs and GPDs

Reduction formulas at $\xi = t = 0$
for DIS and $\xi = 0$ for FFs

$H^q(x, \xi = 0, t = 0) = q(x)$

$\tilde{H}^q(x, \xi = 0, t = 0) = \Delta q(x)$

$\int_{-1}^{+1} dx \ H^q(x, 0, Q^2) = F_1^q(Q^2)$

$\int_{-1}^{+1} dx \ E^q(x, 0, Q^2) = F_2^q(Q^2)$
GMn/GMp and GPDs

\[ F_1^d < 0 \text{ presents an interesting challenge to such a model.} \]

GPD model (Guidal et al.):

\[
F_1^u(t) = \int_0^1 dx u(x) e^{-t\alpha' \ln x}, \\
F_1^d(t) = \int_0^1 dx d(x) e^{-t\alpha' \ln x}.
\]
The transverse neutron densities
Impact parameter GPDs

\[ F_1(t) = \sum_q e_q \int dx H_q(x, t) \]

Muller, Ji, Radyushkin

\[ q(x, b) = \int \frac{d^2 q}{(2\pi)^2} e^{i \cdot q \cdot b} H_q(x, t = -q^2) \]

M. Burkardt

\[ \rho(b) \equiv \sum_q e_q \int dx \ q(x, b) = \int d^2 q F_1(q^2) e^{i \cdot q \cdot b} \]

P. Kroll: u/d segregation

\[ \rho(b) = \int_0^\infty \frac{Q \cdot dQ}{2\pi} J_0(Qb) \frac{G_E(Q^2) + \tau G_M(Q^2)}{1 + \tau} \]

G. Miller

center of momentum \( R_\perp = \sum_i x_i \cdot r_{\perp,i} \)

\( b \) is defined relative to \( R_\perp \)
Transverse densities

\[ \rho_T(\vec{b}) = \rho_U(b) \]

\[ - \sin(\phi_b - \phi_S) \int_0^\infty \frac{dQ}{2\pi} \frac{Q^2}{2M} J_1(bQ)F_2(Q^2) \]

\[ \rho_U(b) = \int_0^\infty \frac{dQ}{2\pi} Q J_0(bQ)F_1(Q^2) \]

Transversely polarized neutron has huge EDM
Flavor decomposition of IMF densities

**Dirac Transverse Charge Density**

- **u quark**
- **d quark**

**Polarized Transverse Charge Density**

- **u quark**
- **d quark**

**Pauli Transverse Charge Density**

- **u quark**
- **d quark**

**Ordinary charge density**

Charge Distribution in the Neutron
Density in polarized neutron

Transversity effects in
\[ \vec{n}(e, e'\pi^-)X \]
\[ \vec{n}(e, e'\pi^+)X \]
Rotation of u/d quarks in neutron

Let see how quark rotation leads to u/d separation:

*amplitude is small*

virtual photon quark

*amplitude is large*

motion inside nucleon
Rotation of u/d quarks in neutron

Let see how quark rotation leads to u/d separation:

M.Burkardt (2003)

amplitude is small

virtual photon quark

amplitude is large

Interaction selects one side because of rotation
Rotation of u/d quarks in neutron

u-quark

d-quark
Rotation of u/d quarks in neutron

The u/d “separation”, observed in Form Factor data, is likely a result of the collective rotation of the u-quark and the d-quark, which is going in opposite directions.
Future neutron FFs experiments
Future neutron FFs experiments

D(e,e’n)p / D(e,e’p)n – under preparation

Double pol. He-3(e,e’n)pp – under preparation

D(e,e’n)p – requires a new $A_Y$ data from JINR
   ( talk by J. Annand)
Optimization of the experimental setup

Proton magnetic form factor: E12–07–108

Proton form factors ratio, GEp(5): E12–07–109

Neutron/proton form factors ratio: E12–09–019

Neutron form factors ratio, GEn(2): E12–09–016

October 4, 2010  slide 46

Bogdan Wojtsekhowski  Baldin 2010
Neutron/proton form factors ratio: E12-09-019

\[ \frac{D(e,e'\text{n})p}{D(e,e'\text{p})n} \]
Neutron form factors ratio, GEn(2):E12-09-016

Double polarized He-3(e,e'p)pp

October 4, 2010 slide 48 Bogdan Wojtsekhowski Baldin 2010
12 GeV GMn experiment

Gilman, Quinn, and BW

W.Brook et al

CLAS 12

BigBite + SBS

October 4, 2010
12 GeV GEn experiment

Cates, Riordan, and BW

\[ \frac{G_E^p}{G_M^p} \]

\[ Q^2 \ [\text{GeV}^2] \]

- RCQM - Miller
- GPD - Diehl
- VMD - Lomon (2005)
- Faddeev&DSE - Roberts
- \( F_2/F_1, \Lambda = 300 \text{ MeV} \)

- Passchier, NIKHEF
- Herberg, MAMI
- Ostrick, MAMI
- Meyerhoff, MAMI
- Golak, MAMI
- Bermuth, MAMI
- Plaster, JLab
- Zhu, JLab
- Warren, JLab
- Glazier, MAMI
- Geis, BATES
- E02-013
- E12-09-016, Hall A
CEBAF electron beam in 2013(4)

- Beam energy: 11/12 GeV
- Beam power: 1 MW
- Beam current (Hall A/D): 85/5 µA
- Beam polarization: 85%
- Emittance @ 12 GeV: 10 nm-rad
- Energy spread @ 12 GeV: 0.02%
- Beam spot: ~ 0.1mm
- Simultaneous beam delivery: Up to 3 halls

Hall A will be the first hall which will get the beam
THANKS
Polarized target

\[ ^3\text{He} = p + p + n \]
\[ S + S' + P \text{ waves} \]
\[ P_n = 0.86 \ P_{\text{He}} \]

Rb + K mixture has shortened spin-up time to 5-8 hours. The hybrid method of optical pumping was used here for the first time in the nuclear target.