Baryon Form Factors Program at JLab

Bogdan Wojtsekhowski, Jefferson Lab

- TJNAF electron beam
- Baryon EMFFs
- FF flavor decomposition
- 12-GeV era EMFF experiments
Jefferson Laboratory

The laboratory, founded in 1984 in Newport News, Virginia, operates a 6 GeV continuous electron beam accelerator.

A 12-GeV upgrade of the accelerator is underway.

Three experimental halls (A, B, C) are equipped to study electron and photon induced reactions.

A new hall D is being constructed for searches of the exotic states produced in γp interactions.
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Beam parameters:
- energy up to 12 GeV
- intensity up to 180 μA
- polarization 85%
- pol. flip systematic $10^{-9}$
- time structure 2 ns

Luminosity: $10^{39}$ cm$^{-2}$/s

Detector systems: many

Polarized targets (used):
- NH$_3$/ND$_3$: $L \sim 10^{35}$ cm$^{-2}$/s
- HD (for the photon beam)
- $^3$He: $L \sim 10^{36}$ cm$^{-2}$/s
The major research highlights include:

Proton and Neutron Electro-Magnetic Form Factors

\[ \frac{\mu_p G_{Ep}}{G_{Mp}} \]

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

\[ G_E^n \]

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

- VMD - E. Lomon (2005)
- q(qq) DSE - C. Roberts, ANL (2008)
- RCQM - G. Miller (2005)
- d(e,e'd) T\_2 - Schiavilla & Sick
- \( F_2/F_1 \times \ln(Q^2/\Lambda^2)/Q^2, \Lambda = 300 \text{ MeV} \)
- Galster fit (1971)

- Passchier
- Herberg
- Ostrick
- Madey
- Glazier
- Zhu
- Warren
- Meyerhoff
- Becker
- Bermuth
- Rohe
- Geis
- E02-013
EMC effect in the light nuclei: local vs. average densities

The major research highlights include:

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The magnetic moment of the proton was measured by the method of the magnetic deflection of molecular beams employing $\text{H}_2$ and HD. The result is $\mu_P=2.46\mu_0\pm3$ percent.

O. Stern, 1937

E. Fermi, 1947

**INTRODUCTION**

The purpose of this paper is to investigate an interaction between neutrons and electrons due to the possible existence of a short range potential between the two particles. If such a short range force should exist, one would expect some evidence of it in the scattering of neutrons by atoms. The scattering of neutrons by an atom is mostly due to an interaction of the of nuclear forces. According to these theories, proton and neutron are basically two states of the same particle, the nucleon. A neutron can transform into a proton according to the reaction:

$$N = P + \bar{\mu}.$$  (1)

($N =$ neutron, $P =$ proton, $\bar{\mu} =$ negative mesotron)

Actually, a neutron will spend a fraction of its time as neutron proper (left-hand side of Eq. (1))
Introduction of the Form Factors

Nucleon current, one-photon approximation, $\alpha_{\text{em}} = 1/137$,

Rosenbluth, 1950

$$\mathcal{J}^\mu_{\text{hadron}} = i e \bar{N}(p_f) \left[ \gamma^\nu F_1(Q^2) + \frac{i \sigma^{\mu\nu} q_\nu}{2 M} F_2(Q^2) \right] N(p_i)$$

Sachs, 1962

$$\frac{d\sigma}{d\Omega}(E, \theta) = \sigma_M \left[ \frac{G_E^2 + \tau G_M^2}{1 + \tau} + 2\tau G_M^2 \tan^2 \left( \frac{\theta}{2} \right) \right]$$
The goal is understanding of QCD

from the D. Gross Nobel Lecture:

“It is sometimes claimed that the origin of mass is the Higgs mechanism that is responsible for the breaking of the electroweak symmetry that unbroken would forbid quark masses. This is incorrect. Most, 99%, of the proton mass is due to the kinetic and potential energy of the massless gluons and the essentially massless quarks, confined within the proton.”
The goal is understanding of the nucleon

Elastic FFs of the proton and neutron: $F_1(Q^2)$, $F_2(Q^2)$
The goal is understanding of the nucleon

Elastic FFs of the proton and neutron: $F_1(Q^2), F_2(Q^2)$

Transition FFs of the $P_{33}(1232)$: $A_{1/2}, A_{3/2}, S_{1/2}$; $S_{11}(1535), P_{11}(1440)$: $A_{1/2}, S_{1/2}$
The goal is understanding of the nucleon

Elastic FFs of the proton and neutron: $F_1(Q^2)$, $F_2(Q^2)$

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$S_{11}(1535)$, $P_{11}(1440)$: $A_{1/2}$, $S_{1/2}$

Form factors of the Compton scattering: $R(Q^2), R_V, R_A$
SLAC results for the Form Factors

Sill et al, 1993

Bosted, 1995
The double polarization method and Form Factors of the nucleon

Akhiezer, 1957, JETP. $F_2$ contribution vs. $Q^2$. Double polarization approach will allow accurate measurements of the form factors.

5 key mini-proposals to motivate the accelerator

1. Charge distribution of the neutron (very small!):
   - coincidence measurement
   - polarized beam

2. Charge distribution of the deuteron (masked by other contributions)
   - coincidence measurement
   - polarized beam

3. Single nucleon emission (distribution and motion of nucleons)
   - coincidence measurement

4. Excited states of the nucleon and search for “missing” states
   - coincidence measurement
   - multiple particle detection

5. Study of strangeness in nuclei
   - coincidence measurement
   - high resolution

F. Gross, 1980, CEBAF white paper
The double polarization method and electric FF of the nucleon

Akhiezer, 1957
F\textsubscript{2} contribution vs. Q\textsuperscript{2}. Double polarization approach will allow accurate measurements

Arnold, Carlson, Gross, 1980
GEp via polarization transfer at CEBAF
GEN up to 3 GeV\textsuperscript{2} as an important goal

\[ d\sigma = d\sigma_{NS} \left\{ \varepsilon(G_E)^2 + \tau(G_M)^2 \right\} \cdot [1 + h_e A(G_E, G_M)] \]

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

Perdrisat, Punjabi, 1989
Precision experiment with a polarimeter behind a dipole magnet which provides spin rotation
Results for the Form Factors

Sill et al, 1993

Perdrisat, 2001
Sachs Form Factors of the nucleon

\[ G_M^p / G_D^p \]

\[ G_M^n / G_D^n \]

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

\[ \mu_n G_E^n / G_M^n \]
The goal is understanding of the nucleon

From the Sachs FFs to the ratio $F_2/F_1$ and the BJY “log” scaling

$$F_1 = \frac{G_E + \tau G_M}{1+\tau} \quad F_2 = -\frac{G_E - G_M}{1+\tau}$$

$$\tau = \frac{Q^2}{4M^2}$$

$$Q^2 \frac{F_2}{F_1} \propto \frac{1 - \frac{G_E}{G_M}}{1 + \left[\frac{G_E}{G_M}\right]/\tau}$$

G. Miller: Orbital moment!

Balitsky-Ji-Yuan: modified scaling due to the orbital moment w.f.

\[ \Lambda = 236 \text{ MeV} \]
The goal is understanding of the nucleon

\[ S_x = \frac{Q^2 F_2^x}{F_1^x} \]

pQCD prediction for large \( Q^2 \):
\[ S \rightarrow Q^2 F_2/F_1 \]

pQCD updated prediction:
\[ S \rightarrow \left[ \frac{Q^2}{\ln^2(Q^2/\Lambda^2)} \right] F_2/F_1 \]

Flavor separated contribution:
The log scaling for the proton Form Factor ratio at few GeV\(^2\) is “accidental”.

The lines for individual flavor are straight!

Cates, Jager, Riordan, BW
The flavor disparity in the nucleon

When the virtual photon of 3 GeV$^2$ interacts with the down quark, the proton more likely falls apart than in the case of the up quark.

Using the D&K table of $F_u, F_d$

The down quark contribution to the $F_1$ proton form factor is strongly suppressed at high $Q^2$

CJRW (u/d with new GEn data)

Qattan, Arrington (2-γ effects)

M. Diehl and P. Kroll (GPDs)
The goal is understanding of the nucleon

Nucleon and Roper electromagnetic elastic and transition form factors

Wilson, Cloet, Chang, Roberts, PRC 85, 025205 (2012)

Interplay between the [qq] and {qq} diquarks creates a zero crossings

The goal is understanding of the nucleon

- More than 98% of dressed quark masses as well as their dynamical structure are generated non-perturbatively through dynamical chiral symmetry breaking (DCSB). The Higgs mechanism accounts for less than 2% of the nucleon & N* mass.

- The momentum dependence of the dressed quark mass reflects the transition from quark/gluon confinement to asymptotic freedom.

• LQCD - P.O. Bowman, et al., PRD 71, 054505 (2005) (points with error bars)

• DSE QCD – C.D. Roberts, Prog. Part. Nucl. Phys. 61, 50 (2008) (lines)
The goal is nucleon transition form factors

Resonant amplitudes

Non-resonant amplitudes

- $A_{1/2}(Q^2)$, $A_{3/2}(Q^2)$, $S_{1/2}(Q^2)$
- $G_1(Q^2)$, $G_2(Q^2)$, $G_3(Q^2)$
- $G_M(Q^2)$, $G_E(Q^2)$, $G_C(Q^2)$

$N^*$'s photo-/electrocouplings $\gamma_N N N^*$ are defined at $W=M_{N^*}$ through the $N^*$ electromagnetic decay width $\Gamma_\gamma$:

$$\Gamma_\gamma = \frac{q^2}{\pi} \frac{2 M_N}{2 J_r + 1} \frac{M_{N^*}}{M_N} \left[ |A_{1/2}|^2 + |A_{3/2}|^2 \right]$$

The Cebaf Large Acceptance Spectrometer

**CLAS12** supports a broad program in hadronic physics.

12-GeV plans to study excited baryons and mesons includes:

- Search for hybrid mesons & baryons
- Spectroscopy of $\Xi^*$, $\Omega^-$
- N* Transition FFs at high $Q^2$. 
The goal is understanding of the nucleon

\[ P_{11}(1232) \text{ transition Form Factors} \]

Magnetic Dipole Form Factor

Quadrupole Ratios

- **Meson-Baryon cloud**
- **bare quark core**

\[ G^{*}_{M, Ash} / 3G_{D} \]

\[ R_{EM} (\%) \]

- **pQCD**: \( R_{EM} \to 1.0 \)
- **pQCD**: \( R_{SM} \to \text{const} \)

\[ Q^{2} (\text{GeV}^{2}) \]
The goal is understanding of the nucleon

Other transition Form Factors

\( P_{11}(1440) \)  
\( D_{13}(1520) \)  
\( S_{11}(1535) \)
The Compton process from the proton

\[
\frac{d\sigma_{RCS}}{d\sigma_{KN}} = \frac{(\hat{s} - \hat{u})^2}{\hat{s}^2 + \hat{u}^2} R_v^2(t) + \frac{2\hat{s}\hat{u}}{\hat{s}^2 + \hat{u}^2} R_A^2(t)
\]
Optimization of the experimental setup

Energy; Solid angle; Efficiency

Form factor $\propto Q^{-4}$

Cross section $\propto E^2/Q^4 \times Q^{-8}$

Figure-of-Merit $\epsilon A^2_y \times \sigma \times \Omega$

$\propto E^2/Q^{16}$
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

9/11/13

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Super Bigbite Spectrometer in GEp

Vacuum snout
Scattering Chamber
Incident beam
Magnetic Shield

Second Tracker
Third Tracker

CH2
Hadron Calorimeter
Beam pipe
Beam Line shield

48D48 magnet

Incident beam
12 GeV GEp experiment

Transverse polarization of the proton in the polarized electron-proton scattering

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

\[ Q^2 \] [GeV^2]

\[ F_2/F_1 \propto \ln^2(Q^2/\Lambda^2)/Q^2, \Lambda = 300 \text{ MeV} \]
12 GeV GMn experiment

Ratio of the cross sections $D(e, e'n)$ and $D(e, e'p)$
12 GeV GEn experiment

Asymmetry in the polarized electron scattering from the polarized $^3$He

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

- VMD - Lomon (2006)
- DSE - Cloet (2010)
- Galster fit/Kelly $G_E^n$ fit
- BLAST fit/Kelly $G_M^M$ fit
- E02-013 Fit
- E02-013, BigBite, PRL 105, 262302 (2010)
- E12-09-016, SBS (projected)
- E12-11-009 (projected)

$Q^2 [GeV^2]$
The cross section of $H(e,e')p$.

By using two existing Hall A High Resolution Spectrometers with several new ideas for improved control of systematic.

![Graph showing cross section measurements](graph.png)
The JLab FF measurements which were not presented

- High precision GEp/GMp Rosenbluth and “SR” results
- High precision 2-photon experiments
- High precision low $Q^2$ proton FF ratio results
- Experiments GEp/GMp on the polarized target
- Neutron GMn from the double polarized $^3$He(e,e’)
- GMn/GMp with a large acceptance CLAS12 detector
- GEn/GMn with the neutron polarimeters
Summary

- Nucleon Form Factors, first investigated 60 years ago, is an active field which has many questions to be answered.

- Baryon Form Factor physics at large $Q^2$ has a huge program at JLab with the 12-GeV beam.
GMn/GMp and GPDs

F_1^d < 0 presents an interesting challenge to such a model

GPD model (Guidal et al):

\[ F_{1}^{u}(t) = \int_{0}^{1} dx u_{v}(x) e^{-t\alpha' \ln x}, \]

\[ F_{1}^{d}(t) = \int_{0}^{1} dx d_{v}(x) e^{-t\alpha' \ln x}. \]
GEn/GMn update from Mainz