Studying the Nucleon Structure with Spin

Overview
BLAST Experiment
Nucleon Form Factors
Deuterium
Nucleon Elastic Form Factors

Fundamental for understanding nucleon structure in non-perturbative regime.

Parameterises coherent scattering without exciting internal degrees of freedom with single photon exchange.

- for point-like, spin=1/2 particles QED gives:

\[
\sigma_{\text{Dirac}} = \sigma_{\text{Mott}} \left( 1 + 2\tau \tan^2 \frac{\theta}{2} \right)
\]

- for extended objects, like nucleons, require form factors:

\[
\sigma_{\text{lab}} = \sigma_{\text{Mott}} \left[ \left( \frac{G_E^N}{1 + \tau} + \tau G_M^N \right)^2 + 2\tau G_M^N \tan^2 \frac{\theta}{2} \right]
\]

- traditionally measure using Rosenbluth technique

\[
\sigma_{\text{Rosenbluth}} = \sigma_{\text{Mott}} \left( A^N(Q^2) + 2\tau B^N(Q^2) \tan^2 \frac{\theta}{2} \right)
\]
Nucleon Elastic Form Factors
Parameterised as dipole distribution in momentum space.

- corresponds to an exponential distribution in position space
- single dipole describes $G_{pE}$, $G_{pM}$, and $G_{nM}$
- $G_{nE}$ is the exception, order of magnitude smaller
  - traditionally hard to measure, small, no convenient neutron targets

But dipole not perfect, does not describe details $Q^2 < 1 \text{ (GeV/c)}^2$
Friedrich and Walcher have proposed a new parameterisation:

$$G^N(Q^2) = G^N_S(Q^2) + \alpha_B Q^2 G^N_B(Q^2)$$

- S - smooth term of two dipoles
- B - bump part of two gaussians
- fit to a collection of the world’s data
Friedrich and Walcher Fit to $G_{Ep}^p$
Friedrich and Walcher Fit to $G_{pE}$
Friedrich and Walcher Fit to $G_{pM}^p$
Friedrich and Walcher Fit to $G_{M}^{p}$

\[ G_{M}/\mu_{p} \]

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Discrepancy in Ratio $\mu_p G^p_E/G^p_M$

But details of bump not only interesting topic with nucleon form factors.

Recent results from JLAB

- polarisation transfer measurements disagree with Rosenbluth separation

Possible explanation by two photon effects

- calls into question present interpretation of data and understanding of nucleon form factors
- requires a re-interpretation of all Rosenbluth data
- more later
Systematic study of spin-dependent electromagnetic interaction

**Bates Large Acceptance Spectrometer Toroid**

Longitudinally polarised electrons MIT-Bates storage ring

- 850 MeV, 200 mA (typical), 65% polarisation (typical)

Highly polarised, internal gas target of isotopically pure H or D

- $6 \times 10^{13}$ atoms/cm$^2$, 80% polarisation (typical)

Symmetric, large acceptance, general purpose detector

- Simultaneous detection of $e^\pm$, $\pi^\pm$, p, n, d
Polarised Electron Source
- strained GaAs$_{0.95}$P$_{0.05}$
- 70% polarisation typical
- 1/2 wave plate to flip helicity each run

500 MeV Linac with recirculator
- polarised electrons up to 1 GeV

North and South Expt. Halls
- SAMPLE - north hall
- OOPS/BLAST - south hall

South Hall Ring
- stack to 225 mA typical
- 30 minute lifetime
- 65% polarisation typical
- Siberian snake maintains longitudinal spin at target
Compton Polarimeter

**Monitor beam polarisation in ring**

- 5 W laser, 532 nm, circularly polarised incident on oncoming electron beam
- Backscattered photons detected in CsI
- Laser helicity flipped in Pockels cell
- Asymmetry yields beam polarisation
- Chopper wheel allows simultaneous measure of background
- Typical beam polarisation 65 %
- Systematic uncertainty <3%

![Diagram of Compton Polarimeter setup]
Internal, Polarised Gas Target

Atomic Beam Source

- series of focusing magnets and RF transition units populate and transport the desired spin state to the target cell
- target cell - thin walled, open ended tube, 60 cm long, Ø15 mm
- isotopically pure $^1\text{H}$ or $^2\text{H}$
- vector polarised $^1\text{H}$
- vector and tensor polarised $^2\text{H}$
- randomly change spin state every 5’ during run
- target density $6 \times 10^{13}$ atoms/cm$^2$
- vector polarisation 80 % typical
- tensor polarisation 68 % typical
BLAST Detector
BLAST Detector

- 8 sector toroid magnet
- Minimise effect on beam and target polarisation
- 3.8 kG maximum field
- Two horizontal sectors instrumented
BLAST Detector

- 3 wire chambers / sector
  - single gas volume
- 2 superlayers / chamber
  - +/- 10° stereo
- 3 sense layers / superlayer
- total 18 layers of tracking
- momentum analysis
- scattering angles
- event vertex
- particle charge
BLAST Detector

- Aerogel Cerenkov
- pion / electron separation
BLAST Detector

- time of flight scintillator walls
- relative timing
- trigger timing
• thick scintillators for neutron detector
• asymmetric favouring right sector
BLAST Detector

- back angle detectors
- extend coverage, no tracking
BLAST Detector

- left-right symmetric
- $20^\circ - 80^\circ \theta$, $\pm15^\circ \varphi$
- $0.1 < Q^2 < 0.8 \ (\text{GeV}/c)^2$
- $e^\pm$, $p$, $n$, $d$, $\pi^\pm$
BLAST Detector Components

Bates

MIT

UNH

ASU

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BLAST Detector Components

Neutron Detectors

MIT

Ohio University
Event Selection

Charge+/-
Coplanarity
Kinematics
Timing

$1^H(e,e'p)$
- $e^-$ left, $p^+$ right
- $e^-$ right, $p^+$ left

$2^H(e,e'd)$
- $e^-$ left, $d^+$ right
- $e^-$ right, $d^+$ left
Orientation of Target Spin

Target spin angle

- horizontal into the left sector
Orientation of Target Spin

Target spin angle

• horizontal into the left sector

Electron scatters to left sector

• \( q \approx \) perpendicular to target spin
• \( \theta^* \approx 90° \)
• “spin perpendicular” kinematics
Orientation of Target Spin

Target spin angle

- \(32^\circ\) (2004) / \(45^\circ\) (2005)
- horizontal into the left sector

Electron scatters to right sector

- \(q \approx\) parallel to target spin
- \(\theta^* \approx 0^\circ\)
- “spin parallel” kinematics
Orientation of Target Spin

Target spin angle

- horizontal into the left sector

Electron scatters to left sector

- \( q \approx \) perpendicular to target spin
- \( \theta^* \approx 90° \)
- “spin perpendicular” kinematics

Electron scatters to right sector

- \( q \approx \) parallel to target spin
- \( \theta^* \approx 0° \)
- “spin parallel” kinematics
BLAST Physics

Polarised Hydrogen

\[1 \bar{H}(\vec{e}, e') X \quad 1 \bar{H}(\vec{e}, e'p) \quad 1 \bar{H}(\vec{e}, e'p)\gamma, \pi^0 \quad 1 \bar{H}(\vec{e}, e'\pi^+\pi^-) n \quad 1 \bar{H}(\vec{e}, e'\pi^+n)\]

Inclusive \(G^p_E/G^p_M\) \(N-\Delta: EMR, CMR\) Photoprod.

Vector Polarised Deuterium

\[2 \bar{H}(\vec{e}, e') \quad 2 \bar{H}(\vec{e}, e'd) \quad 2 \bar{H}(\vec{e}, e'p)n \quad 2 \bar{H}(\vec{e}, e'n)p \quad 2 \bar{H}(\vec{e}, e'\pi^\pm, 0)\]

\(G^n_M\) \(T_{e11} : G^d_M\) \(A^{vd}_{ed} : L=2\) \(G^n_E\) \(N-\Delta\)

Tensor Polarised Deuterium

\[2 \bar{H}(e, e'd) \quad 2 \bar{H}(e, e'p)n \quad 2 \bar{H}(e, e'n)p \quad 2 \bar{H}(\gamma, pn) \quad 2 \bar{H}(\vec{e}, e'\pi^\pm)\]

\(T_{20} : G^d_Q\) \(A^{Td} : L=2\) photodisint. \(1S_0\)
Elastic Scattering from Hydrogen

With polarised beam and target can measure asymmetries

\[
A_{\text{exp}} = P_b P_t \frac{-2\tau v_T' \cos \theta^* G_M^p}{(1 + \tau) v_L G_E^p} \left( G_M^p \right)^2 + 2\sqrt{2\tau (1 + \tau)} v_T L' \sin \theta^* \cos \phi^* G_M^p G_E^p
\]

- note some terms vanish in perpendicular or parallel kinematics

With symmetric detector can form ratio of left/right asymmetries

\[
R_A = \frac{A_L}{A_R} = \frac{z_L^* - x_L^* G_E^p / G_M^p}{z_R^* - x_R^* G_E^p / G_M^p}
\]

- beam and target polarisations cancel
- all that remains is kinematic terms

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Ratio of Proton Elastic Form Factors

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Impact of BLAST Results on World Data

Proton elastic form factors

- $G^P_E$ and $G^P_M$
- divided by dipole
- collection of unpolarised data

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Impact of BLAST Results on World Data

Proton elastic form factors
- $G^p_E$ and $G^p_M$
- divided by dipole
- collection of unpolarised data

World data combined
- averaged and rebinned
- over BLAST range

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Impact of BLAST Results on World Data

Proton elastic form factors
- $G^p_E$ and $G^p_M$
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World data combined
- averaged and rebinned
- over BLAST range

Constraining with BLAST
- uncertainties reduced factor 2

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BLAST Data with Friedrich and Walcher

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BLAST Data with Friedrich and Walcher

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Elastic Electron - Deuteron Scattering

Deuteron spin \( S = 1 \)

- three form factors \( G^d_C, G^d_M, \) and \( G^d_Q \)
- \( G^d_Q \) arises from tensor force, D-wave
- normalisation \( G^d_Q(0) = M^2_d Q_d \)

Unpolarised elastic cross section - insufficient

\[
A(Q^2) = G^d_C^2 + \frac{8}{9} \eta^2 G^d_Q^2 + \frac{2}{3} \eta G^d_M^2
\]

\[
B(Q^2) = \frac{4}{3} \eta (1 + \eta) G^d_M^2; \quad \eta = Q^2 / (4M^2_d)
\]

Need additional measurement - tensor asymmetry

\[
T_{20} = -\frac{1}{\sqrt{2} S} \left[ \frac{8}{3} \eta G_C G_Q + \frac{8}{9} \eta^2 G_Q^2 + \frac{1}{3} \eta [1 + 2(1 + \eta) \tan^2(\frac{\theta}{2}) G_M^2] \right]
\]
Reduced $T_{20}$

$$\tilde{T}_{20R} = -\frac{3}{\sqrt{2Q_d Q^2}} \tilde{T}_{20}$$


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Preliminary

BLAST
$T_{21}$

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$G_C$ and $G_Q$

Preliminary

World Data
- Bates (1994)
- VEPP-2 (1985-86)
- VEPP-3 (1990)
- VEPP-3 (2003)
- Bonn (1991)
- NIKHEF (1996)
- NIKHEF (1999)
- JLAB (2000)
- JLAB (2000) 2nd solution
- BLAST

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G_C and G_Q

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$T_{e10}$ and $T_{e11}$ and $G^d_M$

\[ \delta h_{P_z}/h_{P_z} \text{ global shift: } 0.6\% \text{ (stat), } 1.8\% \text{ (sys)} \]

\[ \delta T_{e10}^e(\theta_T) \]

\[ \delta T_{e11}^e(\theta_\theta) \]

\[ \delta T_{e11}^e(\phi_\theta) \ll 1\% \]

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

\[ \delta T_{e10}^e(\theta_T) \]

\[ \delta T_{e10}^e(\phi_\theta) \ll 1\% \]

---

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

\[ \delta G^e_M(\theta_T) \]

\[ \delta G^e_M(\phi_\theta) \]

\[ \delta G^e_M(P_{zz}) \]

\[ \delta h_{P_z}/h_{P_z} \text{ global shift: } 0.6\% \text{ (stat), } 1.8\% \text{ (sys)} \]

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Quasi-Elastic Scattering from Deuterium

Deuteron readily breaks up
- $e + d \rightarrow e' + p + n$
- electro-disintegration

Spin-dependent $d(e,e'N)$ cross section can be written as:

$$S(h, P_Z, P_{ZZ}) = S_0 \left[ 1 + P_Z A_d^V + P_{ZZ} A_d^T + h(A_e + P_Z A_{ed}^V + P_{ZZ} A_{ed}^T) \right]$$

In the Born approximation

$$A_d^V = A_e = A_{ed}^T = 0$$

Yielding:

$$S(h, P_Z, P_{ZZ}) = S_0 \left[ 1 + P_{ZZ} A_d^T + hP_Z A_{ed}^V \right]$$

$= 0$ for S state

$\propto G_E/G_M$
Extracting $G^n_E$ from $A^{V_{ed}}$

$$A^{V_{ed}} = \frac{aG^n_M^2 \cos \theta^* + bG^n_E G^n_M \sin \theta^* \cos \phi^*}{cG^n_E^2 + G^n_M^2} \approx a \cos \theta^* + b \frac{G^n_E}{G^n_M} \sin \theta^* \cos \phi^*$$

Beam-Target vector asymmetry gives $G^n_E$ assuming $G^n_M$ known

- full Monte Carlo simulation
- deuteron electro-disintegration by H. Arenhovel
- account for FSI, RC, IC, MEC
- “spin-perpendicular” kinematics shows largest effect

- PWIA e-p
- PWIA e-n
- PWBA FSI
- PWBA MEC
- PWBA Isobar

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$G^n_E$ from BLAST

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Neutron Charge Density

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Proton Charge Density

$4\pi r^2 \rho_{\text{Breit}}$ [fm$^{-1}$]

$r$ [fm]

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The diagram shows the dependence of $G^n_M$ on $Q^2 (\text{GeV}/c)^2$. The data points for various experiments, including Rock, Hanson, Arnold, Gao, Lung, Kubon, Anklis, and BLAST, are plotted against $Q^2$. The graph includes lines for theoretical predictions and experimental data, with labels for the different contributions. The preliminary nature of the data is indicated by the label "Preliminary."
Deuteron Wavefunction

Deuteron wavefunction:

- L=0, 2 admixture

\[ \psi^{md}(\vec{r}) = R_0(r)Y_{110}^{md}(\Omega_r) + R_2(r)Y_{112}^{md}(\Omega_r) \]

- S state minimum at \( p \sim 0.45 \) GeV
- D state significant at \( p > 0.3 \) GeV

D state normally 4-6 %
- but beyond 0.3 GeV dominant
- provides a regime to study tensor force
- in D state nucleon spins flip
Quasi-Elastic $e'p$ Scattering from Deuterium

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Quasi-Elastic e′p Scattering from Deuterium

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Two Photon Effect

\[ \frac{\mu_P G_E}{G_M} \]

- \( R_{L-T} \) [Bosted fit]
- \( R_{Pol} \)
- \( R_{Pol} + \text{TPE (e-)} \)
- \( R_{Pol} + \text{TPE (e+)} \)

\[ Q^2 [\text{GeV}^2] \]
Interference in $e^-p/e^+p$ Cross Sections

$Q^2=3.0 \text{ GeV}^2$
$2.0 \text{ GeV}^2$
$1.0 \text{ GeV}^2$
$0.6 \text{ GeV}^2$
BLAST@DORIS

DORIS

Injection

Rf Straight

Arc North-West

Bypass
BLAST Collaboration