Studying Nucleon Structure with Spin at BLAST

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:

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

- traditionally measure using Rosenbluth technique

\[ \sigma_{\text{Rosenbluth}} = \sigma_{\text{Mott}} \left( A^{N}(Q^{2}) + 2\tau B^{N}(Q^{2}) \tan^2 \frac{\theta}{2} \right) \]
Discrepancy in Proton Form Factor Ratio

Polarization transfer results in striking discrepancy with unpolarized data

Possible explanation - two photon contributions

Unpolarised results Rosenbluth separation

Discrepancy fundamental to understanding of nucleon structure
Importance of Spin Measurements

JLAB results highlight the importance of using spin in studying nucleon structure

• more information
• more detailed information

A Definitive Experiment to Quantify Multi-photon Exchange in Lepton Scattering

M. Kohl, MIT
09:00 Thursday
Nucleon Elastic Form Factors

Parameterised as dipole distribution in momentum space.

- corresponds to an exponential distribution in position space
- single dipole describes $G_p^E$, $G_p^M$, and $G_n^M$
- $G_n^E$ 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 $G_{PE}$
Friedrich and Walcher Fit to $G_{Ep}^P$
Friedrich and Walcher Fit to $G_{pM}^p$
Friedrich and Walcher Fit to $G^p_M$
**Bates Large Acceptance Spectrometer Toroid**

Systematic study of spin-dependent electromagnetic interaction

**Polarized electrons in MIT-Bates SHR storage ring**

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

**Highly polarized, internal gas target, isotopically pure H or D**

- $6 \times 10^{13}$ atoms/cm$^2$, 80% vector (H and D), 70% tensor (D) polarization

**L/R Symmetric, large acceptance, general purpose detector**

- 20°-80° polar, ±15° azimuthal, $0.1 < Q^2 < 0.8$ (GeV/c)$^2$
- 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%
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 $^1$H or $^2$H
- vector polarised $^1$H
- vector and tensor polarised $^2$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
BLAST Detector

- thick scintillators for neutron detector
- asymmetric favouring right sector
BLAST Detector

- back angle detectors
- extend coverage, no tracking
- left-right symmetric
- $20^\circ - 80^\circ \theta$, $\pm 15^\circ \phi$
- $0.1 < Q^2 < 0.8 \text{ (GeV/c)}^2$
- $e^\pm$, p, n, d, $\pi^\pm$
BLAST Detector Components

Bates

MIT

UNH

ASU

D.K. Hasell

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BLAST Detector Components

Neutron Detectors

MIT

Ohio University
Event Selection

Charge+/-
Coplanarity
Kinematics
Timing

\[ H(e,e'p) \]
\[ H(e,e'd) \]
\[ H(e,e'p) \]
\[ H(e,e'd) \]

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Orientation of Target Spin

Target spin angle
- horizontal into the left sector
Orientation of Target Spin

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

Electron scatters to left sector
- \(q \approx\) perpendicular to target spin
- \(\theta^* \approx 90^\circ\)
- “spin perpendicular” kinematics
Orientation of Target Spin

Target spin angle

- 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
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BLAST Physics

Polarised Hydrogen

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

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

Vector Polarised Deuterium

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

\[ G^n_M \quad T_{e11} : G^d_M \quad A^v_{ed} : L=2 \quad G^n_E \quad N-\Delta \]

Tensor Polarised Deuterium

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

\[ T_{20} : G^d_Q \quad A^T_d : L=2 \quad \text{photodisint.} \quad ^1S_0 \]
Elastic Scattering from Hydrogen

With polarized beam and target can measure asymmetries

\[ A_{exp} = P_b P_t \frac{-2 \tau v_T' \cos \theta^* G_M^p}{(1 + \tau) v_l G_E^p} + 2 \sqrt{2 \tau (1 + \tau)} v_{TL}' \sin \theta^* \cos \phi^* G_M^p G_E^p \]

- 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
Ratio of Proton Elastic Form Factors

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

\[ Q^2 \quad \left[ \text{GeV/c}^2 \right] \]

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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

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World data combined

- averaged and rebinned
- over BLAST range

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World data combined
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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 $G^d_Q(0) = M^2 \, Q_d$

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

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

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Reduced $T_{20}$

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


BLAST

Preliminary

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$G_C$ and $G_Q$

![Graphs showing $G_C(Q)$ and $G_Q(Q)$](Image)

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$G_C$ and $G_Q$

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$T_{e10}$ and $T_{e11}$ and $G_{M}^{d}$

$\delta hP/hP_z$ global shift: 0.6% (stat), 1.8% (sys)

$\delta T_{e11}(\theta_T)$
$\delta T_{e11}(\theta_\phi)$
$\delta T_{e10}(\theta_\phi) << 1\%$

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$G_{M}$

$\delta G_{M}(\theta_T)$
$\delta G_{M}(\theta_\phi)$
$\delta G_{M}(P_{zz})$

$\delta hP_z/hP_z$ global shift: 0.6% (stat), ±1.8% (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:

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

$\propto G_E/G_M$

$= 0$ for S state
Extracting $G^n_E$ from $A^V_{ed}$

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

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

![Diagram showing various processes and notations related to nucleon electromagnetic form factors and asymmetry parameters.](image)
$G_{nE}^{E}$ from BLAST

Constraint of the neutron’s charge radius

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Dipole Contribution

Bump Contribution

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Charge Densities

Neutron

Preliminary
Charge Densities

Neutron

Proton

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$G^m_N$ from Inclusive Scattering

Ph.D. Thesis N. Meitanis
Deuteron Wavefunction

Deuteron wavefunction:

- $L=0, 2$ admixture

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

- 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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