Outline

• Scientific motivation
• BLAST program
• Stored beam and Compton polarimeter
• Internal target in the stored beam
• The BLAST detector
• Detector performance
Introduction

- Matter is made of atoms…

- The heart of the atom is the nucleus

- Nuclei contain protons and neutrons – or collectively, nucleons

- Goals are to test theories of nuclear and nucleon structure

- What is the nature of the NN interaction?

- How do we describe nuclear and nucleon structure?
Introduction

**Bates Large Acceptance Spectrometer Toroid**

- Symmetric, large acceptance, general purpose detector
- Polarized electron beam in storage ring (SHR)
  850 MeV, 200 mA, $P_e = 65\%$ (longitudinal)
- Highly polarized, internal gas target of H and D (ABS)
  $6 \times 10^{13}$ atoms/cm$^2$, $L = 6 \times 10^{31}/(\text{cm}^2 \text{s})$, $P_{H/D} = 80\%$, free spin orientation
- Study electromagnetic structure of the p, d, and n with spin-dependent inclusive and exclusive electron scattering at $Q^2 = 0.1 - 0.8 \ (\text{GeV}/c)^2$
Approved BLAST Scientific Program

Form Factor Measurements:  $Q^2 \leq 1.0 \text{ (GeV/c)}^2$

Proton Charge and Magnetism
   Elastic Scattering with Polarized Beam and $H$ Target (01-01)

Neutron Charge and Magnetism and Deuteron Electromagnetic Structure
   Quasi-elastic Scattering with Polarized Beam and $D$ Target (89-12 and 91-09)
   Elastic scattering off Tensor and Vector Polarized Deuterium (00-03 and 03-02)
BLAST - Underlying Idea

- Capitalize on the magnetism of the nucleus

- We can polarize a collection of nuclei

- Polarization observables will manifest themselves!
**BLAST Physics Program**

- High quality data for nucleon and deuteron structure by means of spin-dependent electron scattering

<table>
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<th>Pol.</th>
<th>H:</th>
<th>$\vec{p}(\bar{e},e')$</th>
<th>$\vec{p}(\bar{e},e'p)$</th>
<th>$\vec{p}(\bar{e},e'\pi^{+,0})$</th>
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<td>Inclusive</td>
<td>$G_E^p/G_M^p$</td>
<td>N-Δ: C2/M1</td>
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<tr>
<th>Vect.-Pol.</th>
<th>D:</th>
<th>$\vec{d}(\bar{e},e')$</th>
<th>$\vec{d}(\bar{e},e'd)$</th>
<th>$\vec{d}(\bar{e},e'p)$</th>
<th>$\vec{d}(\bar{e},e'n)$</th>
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<td>$A_{ed}^V$</td>
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<td>$T_{20}$</td>
<td>$A_d^T$</td>
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- p.3/40
Bates Linac

- 500MeV Linac recirculated to reach up to 1GeV
- Inject into South Hall Ring
- Polarization maintained by Siberian snakes
- Polarization monitored real time by Compton Polarimeter
- Internal Target located in the ring vacuum
MIT-Bates Polarized Source

- Three identical guns:
  - injector
  - backup
  - test setup

- 4 days to interchange.
High Power diode laser for Bates polarized source

Fiber-coupled diode array lasers

- wavelength: 808± 3 nm (fixed) (need matching wafers)
- emittance: ~200 mm.mr (short working distance)
- power: unpolarized: ~ 150 W pulsed  60 W CW
- stability: better than Ti:sapp laser by > 10
- no correction Pockels cells needed.
- need large diameter optics (75 diameter HPC).
MIT-Bates South Hall Ring

Monitoring of electron beam polarization

Injection with longitudinal spin at internal target

Siberian snake to restore longitudinal polarization

\[ \langle h \rangle = 0.65 \pm 0.04 \]
Electrons injected with longitudinal polarization (controlled by Wien filter)
- Internal target inside BLAST Spectrometer
- Full Siberian Snake used to preserve polarization in Ring
- Compton polarimeter, separated from internal target by 22.5° bend, measures longitudinal projection of beam polarization
- RF dipole to allow spin reversal with beam stored in Ring
Stored beam with injection currents up to 225 mA and lifetimes typically 20 – 30 minutes, monitored in real time
General Kinematics for Polarized e Scattering on a Polarized Target
Compton Polarimetry Overview

• Laser backscattering provides a nondestructive means of sampling electrons from a high energy beam
• Compton scattering in highly relativistic frame compresses angular distribution into a narrow kinematic cone and shifts photon frequencies into gamma regime

Detect backscattered photons with a compact detector

• Compton scattering cross section is well known theoretically and has a term dependent on electron spin and laser helicity

Can extract e⁻ polarization by measuring asymmetries in scattering rates for circularly polarized laser light
Compton Polarimetry Overview

- Compton scattering in highly relativistic frame compresses angular distribution into a narrow kinematic cone and shifts photon frequencies into gamma regime
  - Detect backscattered photons with a compact detector
- Compton scattering cross section is well known theoretically and has a term dependent on electron spin and laser helicity
  - Can extract $e$ polarization by measuring asymmetries in scattering rates for circularly polarized laser light

Transverse polarization yields asymmetry in azimuthal distribution of scattered photons. Longitudinal polarization yields asymmetry in scattered photon energy spectrum
Compton Polarimetry Below 1 GeV

- Compton polarimetry is well established at high energy accelerators ($A_{\text{pol}} \sim 0.5$)
- Different challenges exist in applying at energies below 1 GeV.
  > Analyzing power falling with energy ($A_{\text{pol}} < 0.05$)
  > Broader angular distribution for photons
  > Background from low energy photons

- Bates seeks precise polarization measurement for each ring fill (15 minutes) for experiments with BLAST.
SHR Compton Polarimeter

- Design based on NIKHEF Compton Polarimeter
- Compton polarimeter located upstream of BLAST target to reduce background, measures longitudinal projection of electron beam polarization
- Laser resides in shielded hut with 18 m flight path to Int. Region (IR)
- Laser trajectory varied remotely to overlap with electron beam in 4 m long straight section IR
- Photon calorimeter located 10 m from IR
- Tune electron beam first to align using bremsstrahlung background. Backscattered gamma trajectory defined by electron trajectory
Calorimeter detector located 10 m from exit window to reduce background
Movable collimators used to eliminate background from beam halo
Thin windows minimize attenuation of backscattered flux
Sweep magnet, veto scintillator reject charged particles
Scintillator hodoscope provides position information for beam alignment
Pure CsI calorimeter offers resolution and speed for single photon mode
  - Gamma endpoint energy 25 MeV for 850 MeV electron beam
  - Transistorized PMT base gives linear response with very stable gain
Variable thickness stainless steel absorbers used to regulate rate
Laser System

- Solid-state continuous-wave laser (5W output at 532 nm)
- Simple, robust lens arrangement for transport to IR and focusing
- Laser mechanically chopped by rotating wheel allowing background measurements (duty cycle adjustable)
- Circular polarization imparted by Helicity Pockels Cell (HPC) for rapid helicity reversal, measured periodically
- Phase-compensated mirror arrangement
- Final mirror inside vacuum system. Dipole chambers modified to allow laser to enter and exit IR above plane of beamline
- Multiple degrees of freedom for laser scans. Laser spatially constrained to intercept electron beam at angle < 2 mrad
High Intensity Operation

- Measurements made up to 190 mA. Stainless steel absorbers act as neutral density filter to control rate.
- Signal-to-background worsens at high currents as beam size increases, but still tractable
- Energy calibration stable on short time scale for high rates in CsI, gradual degradation with time

Polarization reduction initially observed in going from low to higher currents. Loss found to be correlated with shifting of the beam tune and restored by retuning Ring.

Small systematic correction to asymmetry for absorber thickness
Cumulative Results

- Data stored in database of results for BLAST experiment in blocks of about 4 hours
- Polarization stable to within a few percent as a function of time. Changes usually correlated with beam properties.
- Mean polarization (2004): 0.663
- Mean polarization (July-Sep, 2004): 0.654
- Long term errors dominated by systematics
Atomic Beam Source (ABS)

- Isotopically pure H or D
  - Vector-polarized H
  - Vector- and tensor-polarized D

- Target thickness / luminosity
  - Flow $2.2 \times 10^{16}$ atoms/s
  - Density $6 \times 10^{13}$ atoms/cm$^2$
  - Luminosity $6 \times 10^{31}$ cm$^{-2}$s$^{-1}$

- Target polarization typically 70-80%
  - $P_z$, $P_{zz}$ from analysis at low $Q^2$
Atomic Beam Source

RF Dissociator
Sextupole System
RF Transition Units
Storage Cell
Breit-Rabi Polarimeter
Sextupole System

Used to focus atoms with pos. atomic electron spin and de-focus the rest.

24 segments glued together.
Create radial field.

RAYTRACE simulations used to optimize location / opening of apertures, location of sextupoles.
Atomic Beam Source

- Standard technology
- Dissociator & nozzle
- 2 sextupole systems
- 3 RF transitions

Spin State Selection:

\[ E / E_{\text{r.f.}} \]

\[ m_s \quad m_l \]

- \( \frac{+1}{2} \quad +1/2 \)
- \( -1/2 \quad -1/2 \)
- \( -1/2 \quad +1/2 \)

nozzle

6-pole

MFT (2->3)

6-pole
The Polarized ABS Target

- RF dissociator produces atomic deuterium
- Sextupoles to select atomic states
- RF transitions to access nuclear polarizations
- Average Intensity $\sim 2.6 \times 10^{16} \text{ atoms} \cdot \text{s}^{-1}$
RF Transition Units

To induce transitions between the hyperfine states.

MFT UNIT

DEUTERIUM TRANSITIONS

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<tr>
<th>MODE</th>
<th>Vector plus</th>
<th>Vector minus</th>
<th>Tensor minus</th>
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<tr>
<td>MFT</td>
<td>3-4</td>
<td>3-4</td>
<td>1-4</td>
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<tr>
<td>WFT</td>
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<td>1-4 and 2-3</td>
<td>Off</td>
</tr>
<tr>
<td>SFT</td>
<td>2-6</td>
<td>Off</td>
<td>3-5</td>
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<tr>
<td>$P_x$</td>
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<tr>
<td>$P_y$</td>
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<tr>
<td>$P_{zz}$</td>
<td>+1</td>
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<td>$B_{hold}$</td>
<td>350G</td>
<td>350G</td>
<td>350G</td>
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<tr>
<td>$n_{target}$</td>
<td>1+6</td>
<td>3+4</td>
<td>2+5</td>
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Deuterium Vector Polarization

\[
\begin{pmatrix}
    n_1 \\
    n_2 \\
    n_3 \\
    n_4 \\
    n_5 \\
    n_6
\end{pmatrix}
\xrightarrow{6-pol}
\begin{pmatrix}
    n_1 \\
    n_2 \\
    n_3 \\
    0 \\
    0 \\
    0
\end{pmatrix}
\xrightarrow{MFT}
\begin{pmatrix}
    n_1 \\
    n_2 \\
    0 \\
    n_4 \\
    0 \\
    0
\end{pmatrix}
\xrightarrow{6-pol}
\begin{pmatrix}
    n_1 \\
    n_2 \\
    0 \\
    0 \\
    0 \\
    0
\end{pmatrix}
\xrightarrow{SFT}
\begin{pmatrix}
    n_1 \\
    0 \\
    0 \\
    0 \\
    0 \\
    n_6
\end{pmatrix},
\]

\[
\begin{pmatrix}
    n_1 \\
    n_2 \\
    n_3 \\
    n_4 \\
    n_5 \\
    n_6
\end{pmatrix}
\xrightarrow{6-pol}
\begin{pmatrix}
    n_1 \\
    n_2 \\
    n_3 \\
    0 \\
    0 \\
    0
\end{pmatrix}
\xrightarrow{MFT}
\begin{pmatrix}
    n_1 \\
    n_2 \\
    0 \\
    n_4 \\
    0 \\
    0
\end{pmatrix}
\xrightarrow{6-pol}
\begin{pmatrix}
    n_1 \\
    n_2 \\
    0 \\
    0 \\
    0 \\
    0
\end{pmatrix}
\xrightarrow{WFT}
\begin{pmatrix}
    0 \\
    0 \\
    0 \\
    n_3 \\
    n_4 \\
    0
\end{pmatrix}.
\]
Polarized Deuterium

- $S = 1, \quad M_S = \pm 1, 0$
- Population numbers $N = N_+ + N_- + N_0$
  
  $n_+ = \frac{N_+}{N}$, \quad $n_- = \frac{N_-}{N}$, \quad $n_0 = \frac{N_0}{N}$

Vector polarization

$P_z = n_+ - n_- \in (-1, 1)$

S-state: $\vec{N}$-target

$\vec{d}(\vec{e}, e' n) \rightarrow G^m_E / G^m_M$

$\vec{d}(\vec{e}, e') \rightarrow G^m_M$

$\vec{d}(\vec{e}, e' p) \rightarrow A^V_{ed}$: D-state + FSI, MEC, IC, RC

Tensor polarization

$P_{zz} = n_+ + n_- - 2n_0 = 1 - 3n_0 \in (-2, 1)$

D-state: S=1-target elastic $\rightarrow T_{20}, T_{21}, T_{22}$

$\vec{d}(e, e' p) \rightarrow A^T_d$: D-state + FSI, MEC, IC, RC
Atomic Beam Source (ABS)

- Quasielastic $^2\tilde{H}(e,e'p)$
- Beam-target asymmetry $A_{ed}^V$
- $A_{ed}^V(\text{exp}) = hP_z A_{ed}^V(\text{th})$
- $< hP_z > = 0.558 \pm 0.009$,  
  $< h > = 0.65 \pm 0.04$,  
  $\rightarrow < P_z > = 0.86 \pm 0.05$
Atomic Beam Source (ABS)

- Elastic $^2\text{H}(e,e'd)$
- Tensor asymmetry $A^T_d$
- $A^T_d(\text{exp}) = P_{zz} A^T_d(\text{th})$
- $< P_{zz} > = 0.678 \pm 0.014$
- However: theory error 5–10%
Storage Cell

Used to increase target thickness for internal target.

60 cm long, 15 mm diameter, Al.

De-polarization effects:
Recombination
Spin Relaxation

To limit de-polarization:
Cooled to 100 K.
Coated with Dryfilm.
The BLAST Spectrometer

- Left-right symmetric detector
  - simultaneous parallel and perpendicular asymmetry determination
- Large acceptance
  - covers $0.1 \text{GeV}^2 \leq Q^2 \leq 1 \text{GeV}^2$
  - out-of-plane measurements
- DRIFT CHAMBERS
  - momentum determination, particle identification
- CERENKOV COUNTERS
  - electron/pion discrimination
- SCINTILLATORS
  - TOF, particle identification
- NEUTRON COUNTERS
  - neutron determination
- MAGNETIC COILS
  - 3.8kG toroidal field
Experimental Layout

upstream

WC
CC
TOF
LADS
NC
downstream

L20
L15

2m
Parallel & Perpendicular Kinematics

Parallel Kinematics:
Electron Right
\( \vec{q} \) Left \( \sim \parallel \theta_T \)

Perpendicular Kinematics:
Electron Left
\( \vec{q} \) Right \( \sim \perp \theta_T \)
Drift Chamber Design

- Three drift chambers in either detector sector
- Each chamber consists of two layers of drift cells
- Each drift cell consists of three sense wires

$$3 \times 2 \times 3 = 18 \text{ hits per track}$$

- ~1000 total sense wires
- ~9000 total field wires
Wire Chambers

- 2 sectors × 3 chambers
- 954 sense wires
- resolution 200μm
- signal to noise 20:1
Drift Chamber Theory

- Apply uniform electric field
  - Function of HV wire setup
- Charged particles leave stochastic trail of ionized electrons
  - Series of accelerations and decelerations
- Electron amplification near readout wires (~$10^5$)
- Pulses $\rightarrow$ TDCs $\rightarrow$ distances
- Electrons “drift” to readout wires
Time-of-Flight System

- scintillating material: BC-408 (Bicron)
- dimensions (cm):
  - backward angle: 180 - 26.10 - 2.54
  - forward angle: 120 - 17.8 - 2.54
- light-guides: BC-800
- optical adhesive: OP-21G (Dymax)
- 3” PMTs - 9822 (Electron Tubes)
- active (transistorized bases)
- optical grease: BC-630
Time-of-Flight Scintillators

- **Fast Timing Information**
  - TDC 50 [ps/ch]
  - Key to BLAST Trigger

- **Energy Information**
  - ADC 50 [fC/ch]

- **Performance**
  - $\delta_T < 500$ [ps] ($FWHM$)
  - Efficiency > 99%
TOF Scintillators

- timing resolution: $\sigma = 350$ ps
- velocity resolution: $\sigma = 1\%$
Time-of-Flight System

- **Fast Timing Information**
  TDC – 50 ps/ch
  important for BLAST trigger

- **Energy Information**
  - ADC – 50 fC/ch

- **Performance**
  efficiency > 99%
  $\delta T < 500$ ps FWHM
The BLAST Cherenkov Design

Requirements:

• 
  • (π/e) over ΔΩ and Δp (Eπ < 700MeV)
  • >90% uniform efficiency
  • compact, strong, low mass
  • operate in magnetic field

Construction:

• clear Aerogel (Matsushita, Japan)
  index n=1.02 and 1.03
  thickness = 5cm and 7cm
• Coating: Diffusely Reflective Walls
  (LabSphere Inc.) (NH)
• PMTs: 5” Photonis (France) model XP4500B
  sensitive to 0.5 G
• Boxes: ASU machine shop

Simulations:

4-5 photoelectrons / 1 particle (β ≈ 1)

150cm x 100cm x 30cm
Čerenkov Detectors

- 1 cm thick aerogel tiles
- Refractive index 1.02-1.03
- White reflective paint
- 80-90 % efficiency

- 5" PMTs, sensitive to 0.5 Gauss
- Initial problems with B field
- Required additional shielding
- 50% efficiency without shielding
The BLAST Cherenkov Assembly

Top-Front Panels

Side Panels

PMT’s Frames

PMT’s Assemblies

Aerogel Inside

Final Counter
Neutron Detectors

- Negatively charged track in coincidence with straight track that leaves no wire hits in the WC and no hit in TOF
- Enhanced detection in the right sector
- Ohio Wall and Large Acceptance Detector System, both plastic scintillators
- Average detection efficiency is $\sim 30\%$ in the right sector and $\sim 10\%$ in the left
- Cosmic events are used to calibrate neutron timing
- Time-walk correction is applied
- Flasher system is used to monitor timing shifts during the experiment
- NIM & CAMAC electronics
- 16 bit sector MLU
- XMLU and Trigger Supervisor
- Fastbus TDCs and ADCs

Note: * all analog signal division in matched impedance passive splitters
BLAST Data Collection

- 3 MC integrated charge delivered to BLAST
- Programs for polarized hydrogen and vector/tensor-polarized deuterium

- Hydrogen run October-December 2004, spin angle 47°
  290 kC charge (90 pb⁻¹), P_z = 82% 

- Deuterium run May–October 2004, spin angle 32°
  450 kC charge (169 pb⁻¹), P_z = 86%, P_{zz} = 68%

- Deuterium run March–May 2005, spin angle 47°
  550 kC charge (150 pb⁻¹), P_z = 73%, P_{zz} = 56%

- Preliminary data presented for 2004 run (quasielastic) and for 2004+2005 runs (elastic)
Resolution and Yields

\[ \Delta p_e = 22 \text{MeV} \]

\[ p_e \text{ (GeV)} \]

\[ \theta_e \text{ (°)} \]

\[ \Delta \theta = 0.5° \]
\[ \Delta \phi = 0.6° \]
\[ \Delta z = 1 \text{cm} \]

BLAST Yield

preliminary

TOF Scintillator Paddle #
Detector Performance

• All detectors operating at or near designed level
  – Drift chambers \( \sim 98\% \) efficient per wire
  – TOF resolution of 300ps
    • Clean event selection
  – Cerenkov counters 85% efficient in electron/pion discrimination
  – Neutron counters 10% (25-30%) efficient in left (right) sectors
    • To be improved further
• Reconstruction resolutions good but still being improved

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<td>( \sigma_p )</td>
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<tr>
<td>( \sigma_z )</td>
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Introduction

Bates Large Acceptance Spectrometer Toroid
BLAST COLLABORATION

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