APS-DNP 2004 Session DA:
Probing the Gluonic and Quark Structure of Matter
DA1. First Experiments with a Polarized Hydrogen Jet Target in RHIC

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Measuring the Polarization of High-Energy Protons

WHY?
HOW?
What accounts for the spin of the nucleon?

The (old) proton spin puzzle:
Only \((20\pm4)\%\) of proton spin is accounted for by spins of quarks and antiquarks.

DIS of polarized HE leptons \((e,\mu)\) from polarized nucleons at SLAC, CERN, HERA:

Good agreement with two very different experimental methods........
COMPASS polarized LiD target

- **Target-Containers with opposite polarization**
  - 2 60 cm long Target-Containers

- **3He – 4He Dilution refrigerator (T~50mK)**
  - Superconductive Solenoid (2.5 T) Dipole (0.5 T)

- **Spin combinations:**
  - 1
  - 2

- Reversed every 8 hours

- **Target pol reversed every 8 hours**

- **Parameters:**
  - $E_\mu = 160$ GeV, $p_B \sim -76\%$
  - $1.8 \times 10^7 \mu^+/\text{sec (time ave)}$
  - Polarized LiD-target, $p_T \sim 50\%$
  - Luminosity: $\sim 5 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$

- **Polarization:** $\sim 50\%$

- **Dilution:** 40%
**HERMES internal target**

- Pure polarised gas targets: H, D, target
- Polarisation: $p_T \sim 85\%$
- Target thickness $10^{14} \text{ H/cm}^2$
- Luminosity: $6 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ (D @ 50 mA)
- $\rightarrow$ spin reversal every 120 sec

**Factor 100 gain from use of “storage cell”**
(S. Price)

![Diagram of polarised H,D injection system]
Gluons: key contributor to the proton spin?

\[ \frac{1}{2} = +\langle S_q \rangle + \langle S_g \rangle + \langle L_{q,g} \rangle \]

0.1 Gluon? Orbital?

\[ \langle S_g \rangle = \int_0^1 dx \Delta g(x, Q^2) \propto \frac{1}{\alpha_s(Q^2)} \text{ in QCD} \]

\[ \langle S_g \rangle = +0.3 \quad \text{(Rho et al., chiral bag)} \]
Gluons: Measurements of $\Delta G/G$

from F. H. Heinsius, COMPASS Collab - DIS April 2004

PHENIX and STAR at RHIC will measure $\Delta G$ by collisions of longitudinally polarized HE protons - $A_{\perp\ell}$

RHIC: c.m. energies up to 500 GeV
RHIC experiments will measure $\Delta G$

$$A_{LL} = \frac{1}{P_{\text{beam}}^2} \frac{N_{\downarrow\uparrow} - N_{\uparrow\uparrow}}{N_{\downarrow\uparrow} + N_{\uparrow\uparrow}}$$

Colliding polarized protons couple directly to gluons (rather than via charge) - measure parton asymmetries.

Measure polarization of gluons through $\gamma$, jets, $\pi$ pi’s, heavy quarks.

G. Bunce DUBNA-SPIN-03

BUT HOW DOES ONE KNOW $P_{\text{beam}}$?
The RHIC Complex \( 50 < \sqrt{s} < 500 \) GeV

*present performance: \( L=4 \times 10^{30} \text{s}^{-1} \text{cm}^{-2} \), \( P_{\text{beam}} \sim 40\% \)
Measuring polarization of proton beam

\[ \sigma_{L,R} = \sigma_0 (1 \pm A(\theta)P) \]

"asymmetry" \[ \varepsilon = PA = \frac{N_L - N_R}{N_L + N_R} \]

Reverse P to eliminate instrumental asymmetry

\[ \varepsilon = PA = \frac{R - 1}{R + 1} \text{ with } R = \sqrt{\left(\frac{N_L/N_R}\right)^\uparrow} \]

• What mechanism is sensitive to P at high energy?
• Need to know analyzing power A.
Mott (1929), J. Schwinger (Phys. Rev. 73, 1948)

“It is the purpose of this note to suggest a second mechanism for polarizing fast neutrons - the spin-orbit interaction arising from the motion of the neutron magnetic moment in the nuclear Coulomb field.”

Spin-orbit coupling:

\[ \vec{\mu} \cdot \vec{B} \rightarrow \vec{\ell} \cdot \vec{s} \]

Analyzing power in small-angle neutron scattering….
Coulomb-nuclear interference ("CNI")

Phil. Mag. 1, 175 (1956)

XV. The Scattering of High Energy Neutrons by a Coulomb Field

By R. G. P. Voss* and R. Wilson†
The Clarendon Laboratory, Oxford‡

[Received October 28, 1955]

differential cross sections averaged over polarization. The data are compared with the theoretical curve normalized to unity at 1/3°.

g a beryllium target at 26°, plotted vs. the theoretical curve, normalized to 1.0

U(n,n)U
100 MeV
A_N vs momentum transfer

Polarized protons from Hyperon decay (low rate)

FIG. 8. A_N data for pp elastic scattering as a function of \(-t\). The solid curve is the theoretical prediction [2] in the Coulomb-nuclear interference region. \(\bigcirc\) is measured at 185 GeV/c [24] and the results of this measurement are indicated by \(\bullet\). The other data points are measured at 300 GeV/c (cross) and 100 GeV/c (diamond) [16], 176 \(\pm\) 12 GeV/c (triangle) [17], and at 150 GeV/c (black square) [15], using a polarized target.
CNI Analyzing Power p-Carbon Scattering

\[ M(\theta, \phi) = g(\theta) + h(\theta)(\hat{n} \cdot \vec{\sigma}) \]

no hadronic spin-flip

with hadronic spin-flip

calibration only at 22 GeV/c
small \( A_N \)
Scale uncertainty \( \sim 30\% \)
Unknown energy dependence
But large count rates

need for accurate absolute \( A_N \) measurement
Beam Polarization Calibration

Elastic scattering of IDENTICAL particles (pp):
beam analyzing power = target analyzing power
(Change in reference frame)

- Measure asymmetry \( \varepsilon_{tgt} \) when unpolarized beam is scattered from polarized target of KNOWN polarization \( P_t \) - measures \( A \)

- Measure asymmetry \( \varepsilon_{beam} \) when polarized beam is scattered from unpolarized target

Both experiments done simultaneously

\[
\varepsilon_{tgt} = P_t A
\]

\[
\varepsilon_{beam} = (-) P_b A
\]

\[
P_b = P_t \left( \frac{\varepsilon_{beam}}{\varepsilon_{tgt}} \right)
\]
The Polarized Target - Principle

\[ |B| \propto r^2 \]

\[ \vec{F}_r = \pm k\vec{r} \]

acceptance angle \( \alpha \)
and Practice

- Cooled dissociator nozzle to reduce $v$ and $v$-spread.
- Recombination: dissociation depends on gas flow and nozzle temp
- Beam attenuation: rest gas and intrabeam scattering
- Magnet design (taper, lengths, $z$-position) needs:
  - velocity distribution, dissociator H output vs gas flow, nozzle T
  - beam forming geometry
- differential pumping

OPTIMIZATION: COMPUTER MODELLING
H-jet sextupole separation magnet system.
The Polarized H-jet at RHIC

Hyperfine state 
(1),(2),(3),(4)

H₂ dissociator

separation magnets (sextupoles)

(1),(2)

RF transitions

Pz⁺ : (1),(4) (transition (2) → (4))

Pz⁻ : (2),(3) (transition (1) → (3))

Beam intensity: 
(1.2±0.2)×10¹⁷ H/s

Holding field magnet 1.2 kG

Polarimeter

Focusing magnets (sextupoles)

Recoil Chamber Silicon Det.
Nuclear polarization of H-atoms

Efficiency of RF transitions: \((99.7\pm0.2)\%\)

ideal proton polarization for \(B=1.2\text{kG}\): \(P = 0.960\)

plus \(~3\%\) dilution from \(\text{H}_2\)

\[ P = 0.924 \pm 2\% \]

bunch-field depolarization <0.1\%
Scattering Chamber (top view)

Target thickness: $(1.3 \pm 0.2) \times 10^{12} \text{ H/cm}^2$
Recoil Detectors

**Recoil detectors (blue beam):**

- 6 detectors 70x64 mm
- 16 strips (5 mrad each)

**Measure**

- **Energy:** 1~7MeV
  - resolution < 50 keV
- **TOF:** 16~80 ns
  - resolution < 2 ns
- **Angle:** 10~100 mrad (89.5 - 84°)
  - resolution 5 mrad
Recoil energy vs. time-of-flight
Identifying recoil protons vs recoil angle (=strip #)

TOF vs $T_R$ Si detector of first 8 channels

Recoil energy strip by strip

$\Delta$TOF < +/-8 ns

analysis

$^{241}$Am

$^1$ Strip # $^{16}$
pp Analyzing Power 100 GeV/c

$A_N$ vs. momentum transfer

pp elastic 100 GeV/c
FNAL E704 200 GeV/c

no hadronic spin-flip

data to analyze
Polarization of 100 GeV Beam

\[ P_{\text{beam}} = P_{\text{target}} \left( \frac{\varepsilon_{\text{beam}}}{\varepsilon_{\text{target}}} \right) = 0.39 \pm 0.03 \text{ (stat)} \]

\[ \sim 10^6 \text{ pp events} \]

Plans:

- study systematic errors and improve statistics for absolute calibration accuracy \( \pm 5\% \)
- analyze wider t-range to study pp interaction
- bunch field depolarization with 110 bunches
- improved measurement of H\(_2\) contamination of H-beam
- measure beam polarization at injection
- measure blue and yellow beam polarization
H-Jet collaborators:

Wisconsin: T. Wise, M. Chapman, W.H.
BNL: A. Bravar, G. Bunce, R. Gill, Z. Li,
    A. Khodinov, A. Kponou, Y. Makdisi,
    W. Meng, A. Nass, S. Rescia, A. Zeler
Kyoto: H. Okada, N. Saito
ITEP-Moscow: I. Alekseev, D. Svirida
IUCF: E. Stephenson
RIKEN-BNL: O. Jinnouchi,
Rikkyo U: K. Kurita
ANL: H. Spinka
1.26 km
pp Analyzing Power 100 GeV/c

Recoil angle: 89.5°
Recoil energy: 0.53 MeV
5.3 MeV
Plans

Plans:
• improve statistics, study systematic errors for absolute calibration accuracy $\pm 5\%$
• analyze wider t-range to study pp interaction
• bunch field depolarization with 110 bunches
• improved measurement of $H_2$ contamination of H-beam
• measure beam polarization at injection
• measure blue and yellow beam polarization
RHIC pp accelerator complex

Absolute Polarimeter (H jét)

p-C Polarimeters

$L=4 \times 10^{30} \text{s}^{-1} \text{cm}^{-2}$, $P_{\text{beam}} \sim 40\%$

BRAHMS & PP2PP ($p$)

Siberian Snakes

0.7$ \times \ 10^{11}$ pol. protons/bunch

56 bunches

PHENIX ($p$)

STAR ($p$)

Spin Rotators

Partial Siberian Snake

Strong AGS Snake

Pol. Proton Source

500 $\mu$A, 300 $\mu$s

LINAC

BOOSTER

200 MeV Polarimeter

Rf Dipoles

AGS

AGS pC Polarimeters

AGS Internal Polarimeter

$\text{AGS}$
RHIC experiments will measure $\Delta G$

$$A_{LL} = \frac{1}{P_{\text{beam}}^2} \frac{N^{\uparrow \uparrow} - N^{\uparrow \downarrow}}{N^{\uparrow \downarrow} + N^{\uparrow \uparrow}}$$
HERMES internal target

- Pure polarised gas targets: $\text{H, D,}$
- Target polarisation: $p_T \sim 85\%$
- Luminosity: $6 \times 10^{33} \, \text{cm}^{-2} \, \text{s}^{-1} (\text{D @ 50 mA})$
- $\rightarrow$ Spin reversal every 120 sec

Factor 100 gain from use of storage cell
The Data (a sample)

Reconstructed
Missing Mass²

FWHM ~ 0.1 GeV²

Inelastic
Threshold

Simulation
MM²

FWHM ~ 0.1 GeV²
What accounts for the spin of the nucleon?

DIS of polarized HE leptons from polarized nucleons at SLAC, CERN, HERA:

The (old) proton spin puzzle:
Only ~20% of proton spin is accounted for by spins of quarks and antiquarks

QCD analysis of $Q^2$ dependence:

Two experimental methods:
- thick solid polarized target + low intensity $e$ or $\mu$ beam
- Thin polarized gas target + high intensity beam

$\Delta u + \Delta d + \Delta s \approx 0.20 \pm 0.04 \pm \ldots$
Comparison with some models (Not Fitting)

preliminary

(Re r5= -0.02)

Non-hadron spin flip

(Re r5= +0.02)
CONCLUSIONS:

- Demonstrated feasibility of accurate beam polarization calibration at high energy
- Calibration of p-C polarimeter
- Measurement of pp $A_N$ (8 angles, $\pm \sim 10\%$)
- H-jet does not interfere with p-beam lifetime
- 3% measurement requires $<200$ hrs with improved beam intensity
- Method covers entire energy range of RHIC

One important step towards a precise determination of $\Delta G$...
RHIC experiments will measure ΔG

\[ A_{LL} = \frac{1}{P_{beam}^2} \frac{N_{↑↑} - N_{↑↓}}{N_{↑↑} + N_{↑↓}} \]

BUT HOW DOES ONE KNOW P_{beam}?

- PHENIX
- STAR

- Axial Field
- Solenoidal field
\[ p \rightarrow g + gg \rightarrow \gamma \gamma \rightarrow \pi^0 + \text{jets} \]
Polarization of 100 GeV Beam

\[ P_{\text{beam}} = P_{\text{target}} \left( \frac{\epsilon_{\text{beam}}}{\epsilon_{\text{target}}} \right) = 0.40 \pm 0.03 \]

Eventual goal of calibration: ±3%

Plans:
- analyze wider t-range to study pp interaction
- improve statistics
- bunch field depolarization with 110 bunches
- improved measurement of H\(_2\) contamination of H-beam
- measure beam polarization at injection
- measure blue and yellow beam polarization
Forward scattering particle ID; Correlation of Energy and position

TOF vs $T_R$ Si detector of 16 channels

$T_R \approx 2m_p \sin \theta_{R}^{2} \Rightarrow 2m_p c h \#^{2}$

$\Delta TOF < +/-8 \text{ ns}$

analysis

$^{241}\text{Am}$
The Polarized Target - Principle

\[ |B| \propto \alpha r^2 \]
\[ \vec{F}_r = \pm k\vec{r} \]

acceptance angle \( \alpha \)
The Polarized Target - Principle

Dissociator

Sextupole Magnet

acceptance angle $\alpha$
H-Jet Design Features

- Sextupoles: rare-earth permanent magnets (gradient up to 6 T/cm)
- Magnet geometry:
  - 2 magnet groups reduce chromatic aberrations
- magnet gaps reduce gas attenuation
- taper increases acceptance
- RF transitions of high efficiency
- very uniform guide field to avoid bunch field depolarization
- Field shaping for adiabatic transport

permanent magnet sextupole
pole tip field 1.5T

responsible for design: T. Wise UW
H-jet sextupole separation magnet system.
The Polarized Target - Principle

\[ |B| \propto r^2 \]

\[ \vec{F}_r = \pm kr \]

acceptance angle \( \alpha \)

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**HYDROGEN**

- \( m_I \)
- \( m_F \)
- \( m_I = \pm \frac{1}{2} \)
- \( m_F = \pm \frac{1}{2} \)

**PROTONS**

- \( P \)
- \( \chi = \frac{B}{B_c} \)
The Polarized Target - Principle

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acceptance angle \( \alpha \)
H-Jet Design Features

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