Polarized Fixed Target Dimuon Drell-Yan Experiment at Fermilab

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E1039 Experiment @Fermilab

Take advantage of the current E906 Drell-Yan Exp. @Fermilab, develop a new polarized hadron physics program

A New Polarized Target

Drell-Yan Transverse Single Spin Asymmetry Study at Fermilab:

- Polarized Target Drell-Yan, E1039 (LOI submitted 2013)
  - Polarized proton (NH$_3$) target, design & construction at LANL
- Polarized 120 GeV proton beam from the Fermilab’s Main Injector, E-1027
The Physics: all about sea quarks

- **Sea-quark** flavor asymmetry
- **Sea-quark** orbital angular motion and Sivers functions at $x = 0.0 \sim 0.4$
- Proton spin puzzle

$$|P\rangle = c_1 |p\rangle + c_2 |p,\pi^0\rangle + c_3 |n,\pi^+\rangle + \ldots$$

**dbar/ubar asymmetry**

$$\Delta q \sim 30\% \quad (\text{pol. SIDIS})$$

$$\Delta G \sim \frac{1}{2} \times 30\% \quad (\text{RHIC – spin})$$

$$L \sim 30\%? \quad (\text{FNAL}?)$$
Single-spin asymmetry in

\[ A_N = \frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow} \]

\( \pi^+ \) (up) favors left
\( \pi^- \) (down) favors right

One possible explanation (Sivers effect): quark transversers motion generates a left-right asymmetry

Fig. 4. \( A_N \) versus \( x_F \) for \( \pi^+ \), \( \pi^- \) and \( \pi^0 \) data.
Access Sea Quarks Sivers Distributions

- $1 \times 10^{13}$ p/spill, one 5s spill/minute
- Kinematic range $4 < M < 8$ GeV

E906 Spectrometer

Target sea-quark

E906/E1039 Coverage

M1
LANL/UVa High Density Pol. Proton (Neutron) Target

• Superconducting dipole magnet
  – Temperature ~ 1 K
  – Magnetic Field: 5 Tesla
  – 8cm long NH₃ target

• Proved capable of handling high luminosity
  – Same technology used at Jlab

• Magnet tested good at UVa in early 2014

• At Oxford now to rotate the field orientation
Magnet Tested at UVa

\[ \frac{dB}{B} < 10^{-4} \]
LANL/UVa NH$_3$ Target Parameters:

- Cylinder $\Phi : 2\text{cm} (x,y)$, length $8\text{cm} (z)$
- $\rho = 0.82 \text{g/cm}^3$ frozen NH$_3$
- Packing Fraction = 0.6
- Dilution Factor = $3/17$ NH$_3$
- 5.1 g/cm$^2$ (NH$_3$) + 0.44 g/cm$^2$ He
- $4.2 \times 10^{23}$ H/cm$^2$

$\mu$-wave horn

JLAB target

Refrigerator from UVa
Target Polarization and NMR System

- Measure proton polarization with NMR at 214 MHz, Q-meter system for signals, large dynamic range with high sensitivity.
- Absorption of RF indicates spin up, stimulated emission for spin down.

\[ P_i = \tanh \left( \frac{\mu_i g_i \mu_i \mathbf{H}}{2k_B T} \right) \]

Thermal Equilibrium TE:
\[ T=1K, \ H=5T \]
\[ P_e = .998 \]
\[ P_p = .005 \text{ since } \mu_N / \mu_B \sim 10^{-3} \]

\( \nu_e = 140 \text{ GHz} \)

Hydrogen energy levels

Unpaired electrons

Pump: spin down

<table>
<thead>
<tr>
<th>Energy Level</th>
<th>( \nu_e )</th>
<th>( \nu_p )</th>
<th>( \nu_e + \nu_p )</th>
<th>( \nu_e - \nu_p )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Pump: spin down</td>
<td>spin up</td>
</tr>
</tbody>
</table>

\( \nu_p = 214 \text{ MHz}, \) Larmor freq, measure Q factor

Hyperfine splitting

Fine structure splitting

Ming Liu, Spin 2014

10/24/2014
Polarization Measurement: NMR Basics

The polarised nucleons give the target material a complex susceptibility \( x(\omega) \) where
\[
x(\omega) = x'(\omega) - i x''(\omega)
\]
and is a function of the applied angular frequency \( \omega \).
The polarisation \( P \) is related to \( x(\omega) \) by the relation
\[
P = K \int_{0}^{\infty} x''(\omega) \, d\omega.
\]

The method used for observing the resonance signal in most polarised targets is the \( Q \)-meter technique. The whole or a sample of the polarised target material is contained within a coil of inductance \( L_0 \). The material modifies the inductance of this coil by the relation
\[
L(\omega) = L_0(1 + 4\pi \eta x(\omega)),
\]

**Diagram:**
- RF absorption
- Mixer
- Output
- Low noise Amplifier
- Liverpool Q-Meter conceptual design
- Inductor surrounding \( \text{NH}_3 \)

**Equations:**
1. \( x(\omega) = x'(\omega) - i x''(\omega) \)
2. \( P = K \int_{0}^{\infty} x''(\omega) \, d\omega \)
3. \( L(\omega) = L_0(1 + 4\pi \eta x(\omega)) \)

**Notes:**
- Applies a constant RF current to a series LC tank circuit.
- Measures voltage across tank.
- Voltage increases for absorption, decreases for emission.
- \( Q \approx (\omega_0 L) / R_0 \)
- \( V \alpha 1/Q \)
Actual NMR System from JLab (E93-026)

Note: Often inserts will be configured with only deuteron coils or only proton coils. A full configuration is shown here.
LANL Q-meter Design

• Follow general Liverpool design, but:
  - Use modern RF microwave electronics from Mini-Circuits, etc.
  - Use 16 bit ADCs and DACs from Analog Devices, etc.
  - Replace mechanical controls/adjustments with electronic ones (DACs or digital)
  - On board temperature and voltage monitors

• House in double wide VME modules and VME crate
  - VME module has 1 analog and 1 digital circuit board
  - Includes RF and analog processing, ADCs + DACs
  - USB interface on each module for standalone testing

• Ethernet <-> VME interface module for readout and controls using LabVIEW

• Power and forced air cooling from crate, <7 W per VME module
RF/IF detailed Diagram

MIXER

Target Sample

Controls:
5 RF atten bits, TTL, octal rotary switch
2 RF switch bits, TTL, DPDT switch
Vstretch, 0 to +10V, 10 turn 1K pot
2 Voffssets, 0 to -1V, -10V, 10 turn 1K, 500 ohm pots
Vtune, 0 to +8V, 10 turn 1K pot

Inputs:
RF In, 0dBm 214MHz

Outputs:
IF Buf Out, 50 ohm, +2.5V
Log Amp Buf Out, 50 ohm, +2.5V
Remote Inductor, ~75nH

NOTE: Pin numbers / letters on block element on this page are arbitrary!
2 DVMs not shown, see sheet 4
Digital section on sheet 8 and 9

Polarized Drell-Yan NMR System

Size: A  No: 1  Analog Block Diagram  Rev: 140

Sheet: 1 of 9  Sheet: 10-24-2014

Drawn by: PLM  Created: 29-Oct-2013

File: z:\users\patrick\auzhey\desktop\nmr schematic\prodnmr8.sch
Prototype RF/IF Deck Using Commercial Parts

- Successfully tested at Uva with NH$_3$ target in 2014
- Extremely low noise
- Excellent thermal stability, no need for additional cooling fan
- Currently working on VME system design, whole-chain tested working last week
NMR Control VME System: Work in Progress

ADC input: 4 channels/16-bit
DACs output: 4 channels/16-bit

Tested fully functional last week!
Summary and Outlook

- A new high density polarized proton (deuteron) targets being developed at LANL/Uva
- A new Drell-Yan experiment approved with polarized target at Fermilab, E1039
- Expect the first precise measurements of the poorly known sea-quark Sivers distributions, and explore sea quark orbital motion effects, help to solve the “Nucleon Spin Crisis”
- First run: ~ 2016
backup
Expected Signal: Target and Beam Performance

**Target**
- Polarization: 85%
- Packing fraction 0.6
- Dilution factor: 0.176
- Density: 0.89 g/cm³

**Beam**
- Beam: 1*10^{13} p/spill; spill is 5 s
- Luminosity: 4.4*10^{35} /cm²/sec
- 120 GeV protons
- KTeV beam line
- $\sqrt{s} = 15$ GeV
- One year $L = 7.2 \times 10^{42}$/cm²
- POT = 2.7*10^{18} (187 days)
Changes under Study

Add third magnet SM0 ~500cm upstream

- Improves Dump-Target separation
- Moves $<x_2>$ from .21 to .176
- Reduces overall acceptance
- Adds shielding problems
- Tracking near target to improve vtx
LANL Polarized Target System

Microwave: Induces electron spin flips
- Tube + Power equip:

Cryostat: UVa

NMR: Polarization measurement
- Roots pump system used to pump on $^4$He vapor to reach 1K

Superconducting Coils for Magnet: 5T
- Rotation needed

Target material: frozen NH$_3$ (ND$_3$)
- Irradiation @ NIST
NMR Connections to Target System

NMR: Constantly measures proton polarization

Target Ladder

μ-wave horn
NMR coils

NH₃

μ-wave horn
NMR coils

Empty

Polarized target, magnet + cryostat
Beam effects on polarized Target

- Anneal every 24 hours ~ 1hr at 80K (yellow line)
- Replace target material every 10 days (two active targets), will take one shift
  - Replace target stick
  - Cool down
  - perform TE measurement
  - Turn on microwave, measure again

Polarization as a function of accumulated beam dose 2.5T target
(D. Crab private communication)

Systematics control:
- Reverse Polarization Direction once a day
- Reverse magnet field of Fmag and Kmag every two days
- Reverse magnetic field of target magnet every target replacement
- Background measurements every shift with target out

Systematic errors:
- Absolute: 1% (Luminosity precision on different pol directions)
- $\Delta A/A \sim 4\%$ (Dominant effect polarization measurement)
E906/E1039 Dimuon Spectrometer

- 4 scintillator hodoscope stations (x and y)
- 4 tracking stations (x and stereos) MWPC
Quark Sivers Distributions: fit to HERMES and COMPASS data (2009)

Semi-Inclusive Deep-Inelastic Scattering on transversely polarized targets

\[
A_N = \frac{\sum_q e_q^2 f_{1T}^{q,T}(x) \otimes D_1^q(z)}{\sum_q e_q^2 f_{1}^{q}(x) \otimes D_1^q(z)}
\]

1. Involves quark fragmentation functions.
2. Valence quark overwhelmingly dominate.
3. Limited sensitivity to sea quark leads to zero sea quark Sivers distribution.
4. Large uncertainties in Sivers distribution.

\[N^\uparrow(l, l', h)\]

\[
\pi^0 \quad \text{HERMES} \quad \text{Proton}
\]

\[
\pi^+ \quad \text{COMPASS} \quad \text{Deuteron}
\]

\[\pi^- \quad \text{Deuteron}=\text{Proton}+\text{Neutron}\]

\[\pi^- \quad \text{2002-2004}\]

Up-quark favors left \((L_u > 0)\),

Down-quark favors right \(-L_d < 0\).