Polarized NH_3 and ND_3 Targets at FNAL-SpinQuest

Workshop on "Polarized Ion Sources and Targets", HAWAII 2023

2023/Nov/27, 4WBB.1

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Outline

1. Physics motivation
   - Sivers function of anti-quarks in proton
   - Drell-Yan process
2. Proton beam & spectrometer
3. Polarized-target system
   - System components
   - Required performance
4. Preparation status
   - Tests of Helium liquefaction, magnet cool-down & fridge cool-down
   - Improvement on systematic errors
5. Perspective & summary

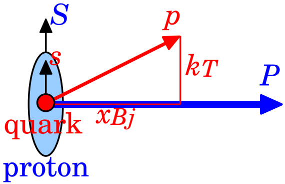
1. Physics Motivation

Sivers Function: $f_{1T}^{\perp}(x, k_T)$

- One of the eight Transverse-Momentum-Dependent (TMD) PDFs

		Parton spin		
		U	L	T
Nucleon	U	Density f_1		Boer-Mulders $h_1^{\perp}$
spin	L		Helicity g_1	Worm gear #2 $h_{1L}^{\perp}$
	T	Sivers $f_{1T}^{\perp}$	Worm gear #1 g_{1T}	Transversity h_1 & Pretzelosity $h_{1T}^{\perp}$

- Correlation between nucleon spin (S) & parton transverse momentum (k_T)
- Transversely-polarized target (or beam) is essential

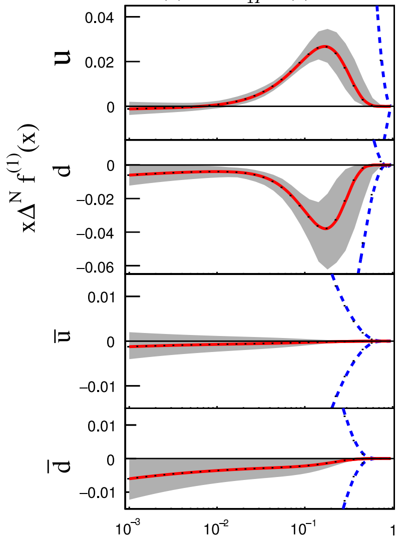


Sivers Function of Anti-Quarks

- Extraction by global analyses
  - PRD88 (2013) 114012
  - PRD89 (2014) 074013
  - JHEP 04 (2017) 046 $\Longrightarrow$
    - HERMES, COMPASS & JLab data
  - JHEP 01 (2021) 126; JHEP 05 (2021) 151
    - SIDIS, D-Y & W/Z data
- $f_{1T}^{\perp}(x)$ of anti-quarks is not well known
  - Since $\bar{q}$ & q are mixed up in SIDIS

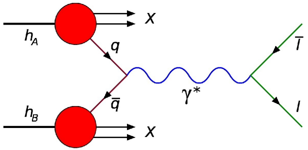
First moment of Sivers function:

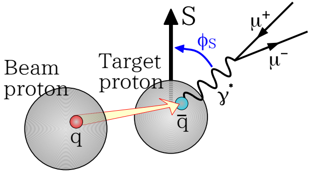
$x\Delta^N f^{(1)}(x) \equiv -x f_{1T}^{\perp(1)}(x)$



Measurement at FNAL-SpinQuest

- Proton beam + Transversely-polarized NH_3 & ND_3 targets
- Drell-Yan process in $p + \vec{p}$ & $p + \vec{d}$ @ forward rapidity
  - Anti-quark in polarized proton is involved





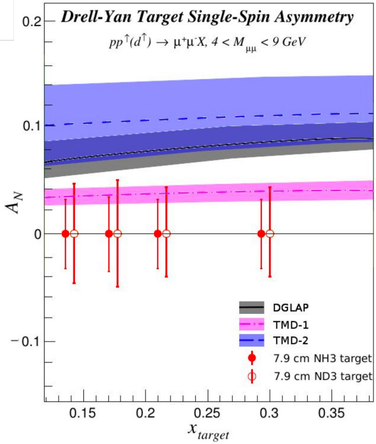
- Observable: Transverse Single Spin Asymmetry (TSSA): A_N

$$A_N(\phi_S) \equiv \frac{\sigma^{\uparrow}(\phi_S) - \sigma^{\downarrow}(\phi_S)}{\sigma^{\uparrow}(\phi_S) + \sigma^{\downarrow}(\phi_S)} \sim \frac{f(x_B) \cdot f_{1T}^{\perp,\bar{f}}(x_T)}{f(x_B) \cdot \bar{f}(x_T)}$$

  - $\phi_S \sim$ Azimuth of proton spin to muon pair (=virtual photon)
  - $\sin \phi_S$ modulation $\Longrightarrow$ Non-zero $f_{1T}^{\perp}(x_T)$
- Sivers function of anti-quarks
  - Combined analysis of TSSAs in $p + \vec{p}$ & $p + \vec{d} \Longrightarrow$ Seperation of $\bar{u}$ & $\bar{d}$

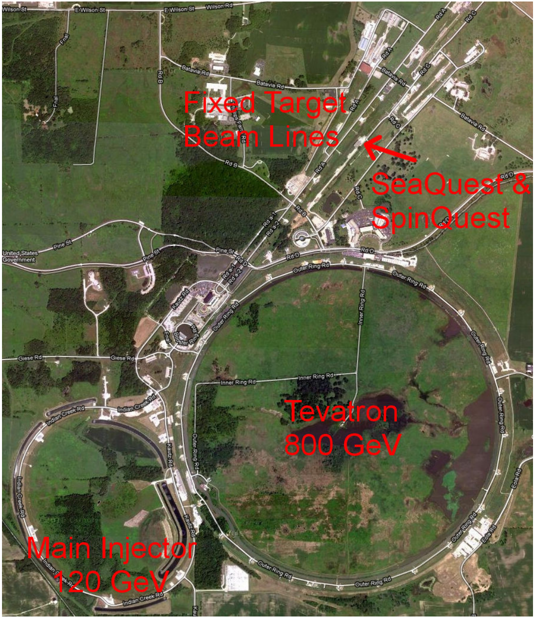
Anticipated Sensitivity

- Measurement condition
  - Two years of data taking
  - NH_3:ND_3 = 50%:50% in time
  - Details in the E1039 proposal
- Transverse Single-Spin Asymmetry (TSSA): A_N
  - $0.1 \lesssim x_{Target} \lesssim 0.3$
  - Precision $\delta_{A_N} \sim 0.04$
- Aim to observe non-zero anti-quark Sivers asymmetry!!
- Key requirement:
  High & stable polarization under high beam intensity
  - Since the cross section of Drell-Yan process is small



2. Proton Beam & Spectrometer

Proton Beam @ FNAL



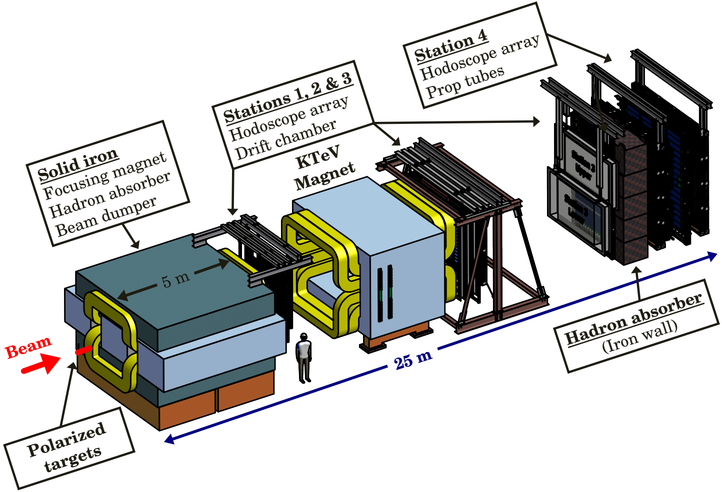
- Energy $E = 120$ GeV ($\sqrt{s} = 15$ GeV)
- Duty cycle
  - 5 sec for SpinQuest
  - 55 sec for ν exp.
- Bunch
  - Interval: 19 nsec (53 MHz)
  - 10^{13} protons in 5 sec
- Unpolarized

FNAL-SpinQuest/E1039 Collaboration

- Institutes
  - Abilene Christian Univ.
  - Argonne National Lab
  - Aligarh Muslim Univ. IN
  - Boston Univ.
  - Fermi National Accelerator Lab
  - KEK JP
  - Los Alamos National Lab
  - Mississippi State Univ.
  - New Mexico State Univ.
  - RIKEN JP
  - Shandong Univ. CN
  - Tokyo Tech JP
  - Univ. of Colombo LK
  - Univ. of Illinois
  - Univ. of Michigan
  - Univ. of New Hampshire
  - Tsinghua Univ. CN
  - Univ. of Virginia
  - Yamagata Univ. JP
  - Yerevan Physics Institute AM
  - Massachusetts Institute of Technology
  - National Centre for Physics PK

https://spinquest.fnal.gov

SpinQuest Spectrometer

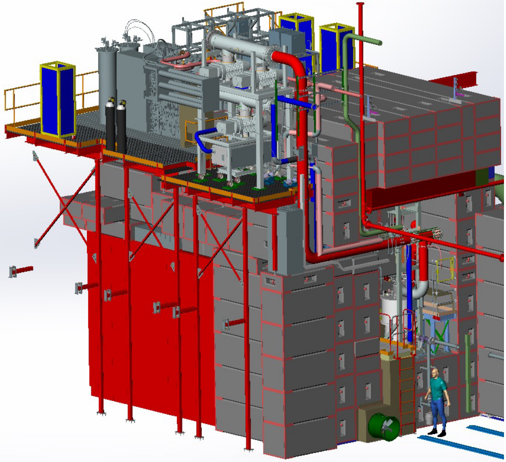


- Target: Transversely-polarized NH_3, ND_3
- Focusing magnet (FMag) & Tracking Magnet (KMag)
- Iron core of FMag = Hadron absorber & Beam dump

SpinQuest Hall (NM4) — 2022-August-26

3. Polarized-Target System

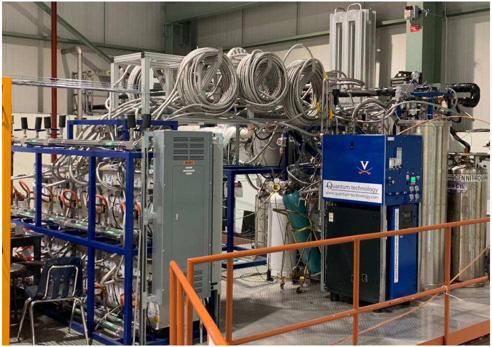
Target Cave



- Target cryostat surrounded by concrete blocks for radiation shielding
- On "Cryo Platform"
  - Helium liquefaction plant
  - "Roots pump" for evaporation fridge
- Gaseous helium tank at outside

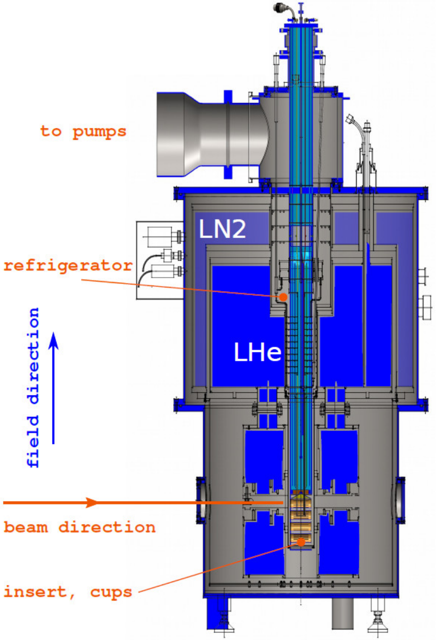
- Polarized target in Target Cave
  - Standalone test in 2018 at UVA
  - Installed in 2020
  - Being commissioned without beam

- Roots Pump & Helium liquefaction plant
  - High capacity for high beam intensity
    - Gas intake: 16,800 m^3/hour
    - Liquefaction: 200 L/day
  - Being commissioned without beam



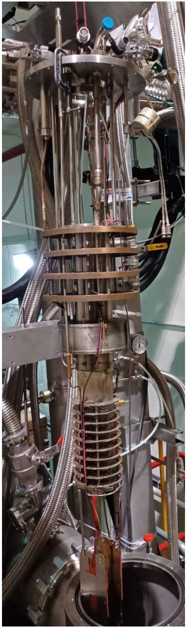
Cryostat for Pol. Target

- Superconducting magnet
  - Vertical field for transverse polarization
  - $B = 5$ T
  - $dB/B < 10^{-4}$ over $z = 8$ cm
- Cooling system for 1 K
  - Evaporation method
  - Power: 3 W at max
  - Heat load ~ 1 W from beam & microwave



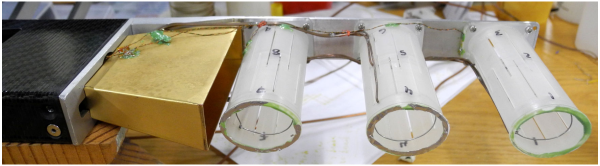
Vacuum Chamber Top

Fridge



Insert

Polarized-Target Material

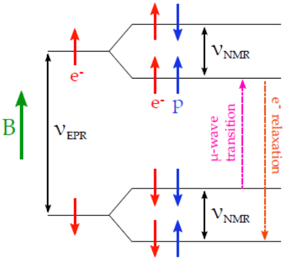


- Material spec
  - Solid NH_3 & ND_3 beads
  - Electron irradiation @ NIST — 10 MeV, 10^{17} e^-/cm^{-2}

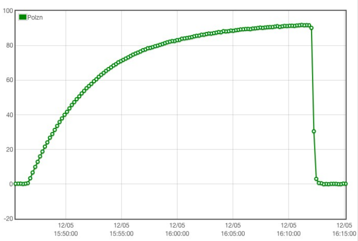
Material	Density	Dilution factor	Packing fraction	Polarization	Interaction length
NH_3	0.867 g/cm^3	0.176	0.60	>80%	5.3%
ND_3	1.007 g/cm^3	0.300	0.60	>32%	5.7%

- Target cell × 3
  - Dimensions: L 80 mm, ϕ 40 mm
  - Combination of NH_3, ND_3 & Empty
  - Annealing & polarization flip every 16 hours
  - Material replacement every 7 days

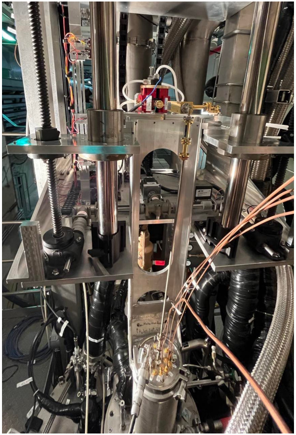
Polarization Method



- Dynamic nuclear polarization (DNP)
  - Magnetic field: $B = 5$ T
  - Microwave: $f \approx 140$ GHz
    - High-power EIO (CPI EIK) + Stepper Motor
- Polarization
  - Test without beam (2018/12, UVA)

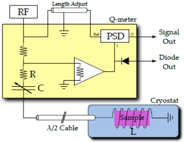


    - 95% for NH_3 & 50% for ND_3 at max
  - With beam? $\Longrightarrow$ Beam commissioining



Polarization Measurement

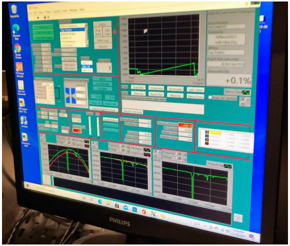
- Nuclear magnetic resonance (NMR)
- "NMR Rack" — Constructed by UVA
  - Resonance circuit: Liverpool Q-Meter



$f \approx 213$ MHz @ 5 T

(by J. Maxwell)

  - GUI: "Polarization Display Panel"

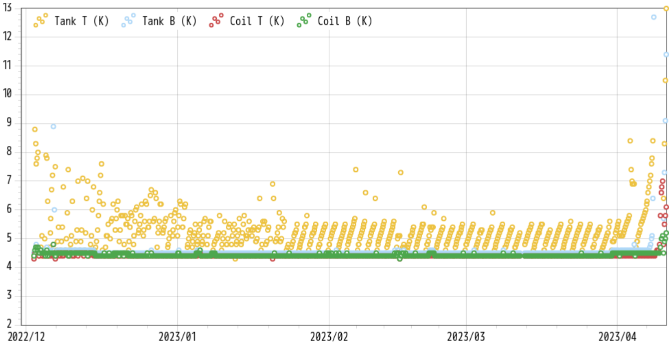


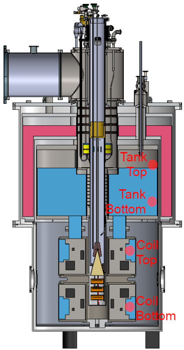
- Preparing new system by LANL — NIMA 995, 165045

4. Preparation Status

Magnet Cool-Down

- Test without beam from 2022/12 to 2023/04

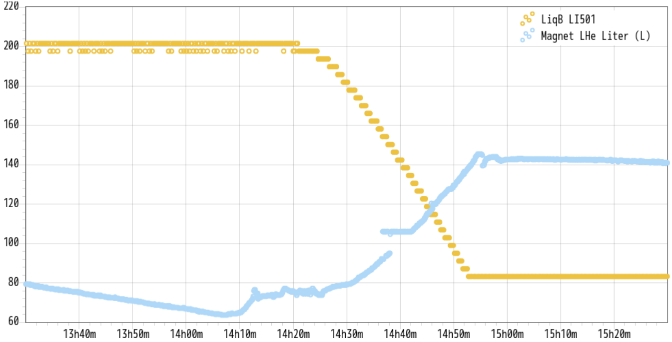




  - LHe was transfered from the liquefier once per 1-2 days
  - The magnet coil was kept at 4 K

LHe Transfer from Liquefier to Magnet

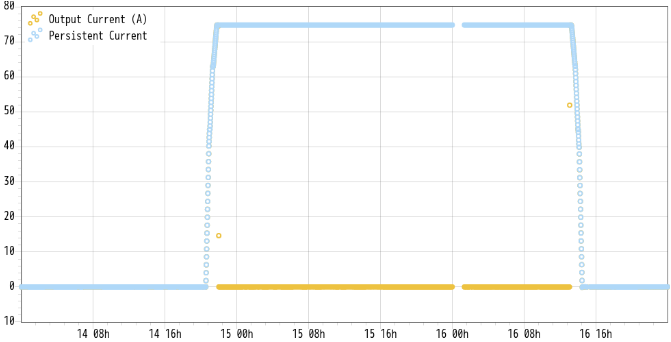
- Many repeated studies to optimize the transfer efficiency
  - LHe evaporates in the long (∼20 m) transfer line & the magnet
- An example in 2023/03



  - Efficiency = 70% ∼ design value

Magnet Ramp-Up

- Test without beam in 2023/01

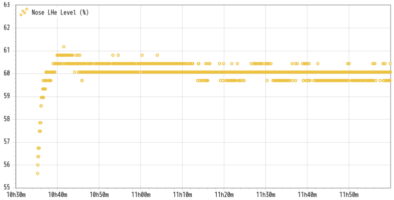


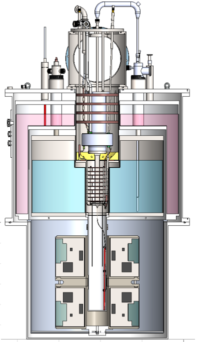
  - $I = 75$ A for $B = 5$ T
  - Switched to/from "persistent" mode smoothly
  - Stable for 40 hours

Oxford Mercury iPS

Fridge Cool-Down

- Test without beam on 2023/01/14
  - The roots pump was fully running for max cooling power
  - The LHe level was kept constant (60%) by adding LHe from magnet with PID control
  - Saturated vapor pressure of gHe $\Longrightarrow$ Temperature of LHe
  - Reached at 0.24 Torr $\Longrightarrow$ 1.07 K





Anticipated Systematic Errors

- Contribution to TSSA of Drell-Yan process

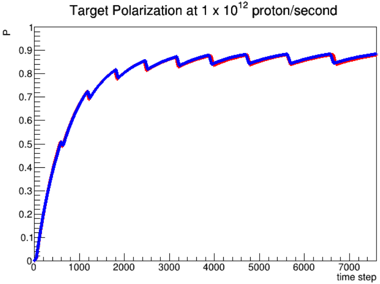
Polarized target	Total	6-7%
	TE calibration	2.5% (p), 4.5% (d)
	Polarization inhomogenity	2%
	Material density	1%
	Non-uniform radiation damage	3%
	Beam-target misalignment	0.5%
	Packing Fraction	2%
	Dilution Factor	3%
Beam	Total	2.5%
Analysis	Total	3.5%

(E1039 proposal)

  - Investigating more precise estimates & reduction methods

Position Dependence & De-polarization

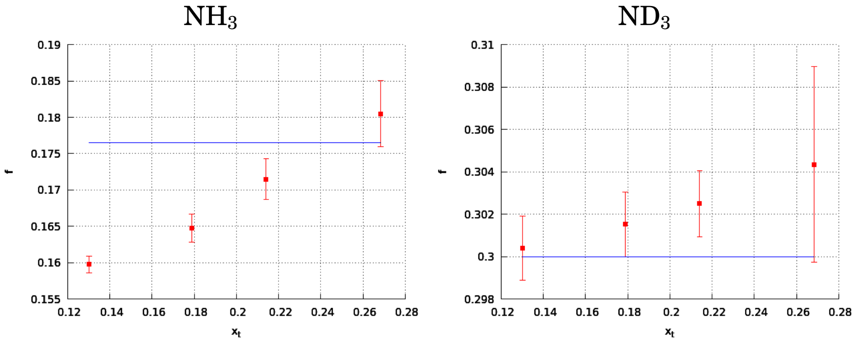
- Measurements of polarization vs time & position (with beam)
  - 3 NMR coils/cell ($\delta_z = 8$ cm)
  - 4 NMR measurements/spill ($\delta_t = 4$ sec)
- Simulation of polarization
  - Geant4 & LabVIEW
  - Heat load = Beam particles + Microwave
  - Extraction of functional form: $P(z, t)$



- Polarization per beam spill = Average of measured polarization with interpolation by $P(z, t)$

Dilution Factor

- Dilution factor: $f \approx N_{\text{protons}}/N_{\text{nucleons}} = 3/17$ for NH_3
- Dependence on kinematic variables (i.e. x_{Beam} & x_{Target})
  - $f(x_T) = \frac{3d\sigma_H/dx_T}{3d\sigma_H/dx_T + d\sigma_N/dx_T}$
  - Numerical estimate with MCFM
    (Monte-Carlo for Femtobarn Process, https://mcfm.fnal.gov/)



5. Perspective & Summary

Perspective

- Schedule for data taking
  - Lab-wide safety assessments are ongoing at Fermilab
    $\Longrightarrow$ Approval for beam operation for SpinQuest in March 2024
  - Safety reviews on the handling of target materials (NH_3) at SpinQuest are nearly complete
  - 2024/01: Commissioning of target without beam
  - 2024/04: Commissioning with beam
    $\Longrightarrow$ Demonstrate the full performance of the target system
  - 2024-2025: Physics data taking
- SpinQuest upgrades
  - Tensor polarization of anti-quarks in deuteron — PRD 94, 054022 (2016)
  - "DarkQuest": Dark-photon search

Summary

- SpinQuest
  - Sivers function of anti-quarks in proton
  - High-intensity 120-GeV proton beam @ FNAL
  - Transversely-polarized NH_3 & ND_3 targets
  - TSSA of Drell-Yan process
- Polarized-target system
  - High cooling power for high beam intensity
  - Each component has been tested & functioning
  - Beam commissioning is starting soon
- If you are interested in target and/or physics at SpinQuest, please contact me or spokespersons;
  - Dustin Keller (UVA, dustin@virginia.edu) & Kun Liu (LANL, liuk@lanl.gov)
- This work is supported by DOE contract DE-FG02-96ER40950