PROCEEDINGS OF SCIENCE

# The SpinQuest (E1039) experiment's polarized target system

**M. Farooq,**[1,2,*] **W. Ahmed**[1] **and D. Keller**[2]

[1] *National Centre for Physics, Islamabad, Pakistan;*

[2] *University of Virginia, Charlottesville, Virginia, USA*

*E-mail:* ufg5mf@virginia.edu, waqar.ahmed@cern.ch, dustin@virginia.edu

The SpinQuest experiment at Fermilab aims to measure the Sivers asymmetry for the light sea quarks in the longitudinal momentum fraction range of $0.1 < x_B < 0.5$ from the Drell-Yan process. A nonzero Sivers asymmetry measurement would be indicative of a nonzero orbital angular momentum contribution from the sea quarks. The SpinQuest experiment uses the proton beam from Fermilab's 120 GeV main injector, which will provide about $10^{11}$ protons per second during a 4.4-second spill. The SpinQuest polarized target uses a superconducting split-pair magnet with an operating magnetic field of 5T with transversely polarized $NH_3$ or $ND_3$ targets (8cm long target cells). The maximum intensity that the target can handle will be determined during beam-target commissioning. As proposed SpinQuest will be the highest integrated proton beam luminosity, around $2 \times 10^{42}$ cm$^{-2}$, ever on a solid polarized target. The helium-4 evaporation refrigerator operates at 1 Kelvin using high-powered evaporation from a roots stack with a pumping rate of nearly 17,000 m$^3$/hr. The anticipated average target polarization of 80% for protons and 32% for deuterons will be measured using three NMR coils equally spaced apart in the target cell.

*25th International Spin Symposium (Spin 2023)*
*September, 26, 2023*
*Duke University, Durham, NC*

*Speaker





PoS(SPIN2023)209

## 1. Physics Motivation

Spin Physics focuses on the investigation of partonic degrees of freedom and how these constituents contribute to the intrinsic spin of hadrons. In particular, the most pressing issue is to ascertain the precise contributions of these constituents to the nucleon's 1/2 spin. The EMC collaboration's significant discovery that roughly 70% of the proton's spin remained unexplained initiated the 'spin crisis' [1]. Subsequent investigations have clarified that valence quarks contribute around 30% to the proton's spin, while the role of gluon intrinsic angular momentum is still being explored, notably at the Relativistic Heavy Ion Collider [2]. Additionally, recent studies suggest that the orbital angular momentum of sea quarks could be responsible for a significant fraction of the proton's spin [3].

The SpinQuest (E1039) experiment, employing the Drell-Yan process, aims to measure the Sivers function of the sea quarks. This is conducted through the interaction of a 120 GeV unpolarized proton beam with transversely polarized proton and neutron targets. The Sivers function is critical for understanding the correlation between a quark's momentum and the spin of its parent nucleon. A nonzero Sivers function measured at SpinQuest would be indicative of a sea quark orbital angular momentum contribution to the corresponding nucleons spin. Figure (1) classifies quark transverse momentum distributions (TMDs) according to the polarization of the nucleon and the quark within it.

The SpinQuest is designed to explore the Sivers asymmetry for $\bar{d}$ and $\bar{u}$ quarks within the Bjorken-x range of $0.1 < \mathrm{x_B} < 0.5$. This investigation extends the methodologies applied in the E866 and E906 experiments, which focused on measuring the $\bar{d}/\bar{u}$ ratio in protons. In SpinQuest, a transversely polarized proton and deuteron target will be utilized to measure both the $\bar{u}$ and $\bar{d}$ Sivers function.

A critical goal is to accurately determine both the sign and magnitude of the Sivers functions, to assist with future studies of the QCD relation $\mathrm{f}_{1\mathrm{T}}^{\perp}|_{\mathrm{SIDIS}} = -\mathrm{f}_{1\mathrm{T}}^{\perp}|_{\mathrm{DY}}$. The data will also provide essential sea quark information needed in global fits of TMDs. Additionally, SpinQuest is set to measure the Sivers function for gluons using the polarized proton target. This involves studying the production of $J/\psi$ mesons, with some contributions arising from gluon-gluon fusion at small $x_F$ in the forward region, at $\sqrt{\mathrm{s}}$= 15 GeV and $x_F$ ~0.5. This will be contrasted with RHIC-PHENIX studies conducted at $\sqrt{\mathrm{s}}$= 200 GeV and $x_F$ ~0.1.

SpinQuest is poised to investigate quark and gluon transversity within a kinematic range that complements other high-x facilities, facilitating crucial tests of universality. This is a proposed extension to the SpinQuest experiment aiming to investigate exotic gluon contributions in the deuteron nucleus. This effort will also significantly contributing to our understanding of the tensor charge in nucleons. Transversity is vital not only for exploring the spin structure of nucleons but also for probing the electric dipole moment of neutrons, which may reveal new phenomena beyond the standard model. The quark transversity distributions of the nucleon are decoupled from the deuteron gluon transversity in the $Q^2$ evolution due to the chiral-odd property in the transversely-polarized target. The gluon transversity TMD only exists for targets of spin greater or equal to 1 and does not mix with quark distributions at leading twist. This provides a particularly clean probe of gluonic degrees of freedom [5].

## 2. (Un)Polarized Drell-Yan Experiments

Leading research institutions worldwide are conducting experiments to measure polarized Drell-Yan processes, employing either polarized beams or targets, as depicted in Figure (2). These

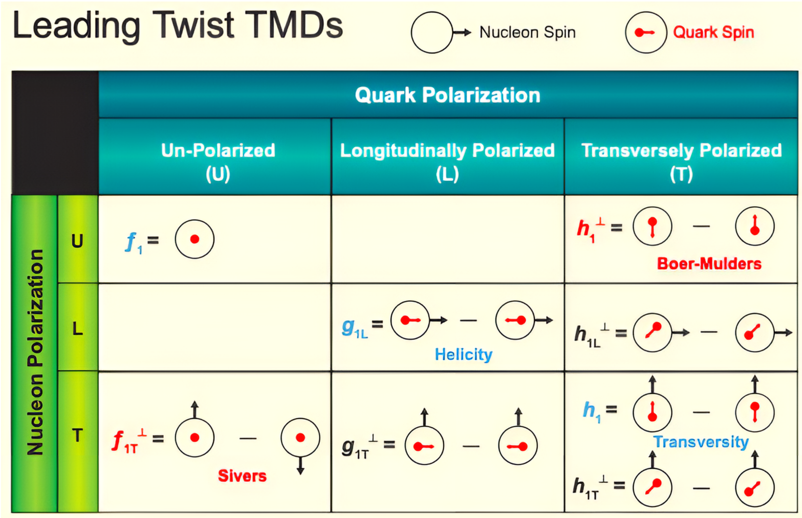



**Figure 1:** Classification of the quark TMDs. The table is taken from [4]

experiments, in both fixed target and collider formats, play a crucial role in shedding light on aspects of partonic dynamics and TMD information.

Significant advancements in fixed target experiments include COMPASS at CERN using pion beams, and SeaQuest at FNAL with proton beams, while PANDA at GSI is set to further this research using anti-proton beams. Collider experiments like PAX at GSI, NICA at JINR, and sPHENIX, utilize polarized proton beams. Fixed target experiments generally achieve higher luminosities, whereas collider experiments can usually operate at higher center-of-mass energies. Both provide essential data.

COMPASS has focused on valence quark and anti-quark interactions, conducting experiments at 190 GeV with a $\pi^-$ beam and a polarized target. SeaQuest has examined valence quark and sea anti-quark interactions, operating at 120 GeV with a proton beam. Building upon these findings, the SpinQuest (E1039) experiment aims to conduct high-intensity research (5x$10^{35}$cm$^{-2}$s$^{-1}$) using a 120 GeV proton beam on an $NH_3$ polarized target.

## 3. SpinQuest Polarized Target System

The SpinQuest Experiment uses a Dynamic Nuclear Polarization (DNP) technique, developed in the 1960s [6], significantly enhanced solid target polarization in physics experiments, achieving up to 100% proton and 50% deuteron polarization through spin transfer in external magnetic fields and dipole interactions. It also integrates a 200-liter/day helium liquefaction system with advanced storage and flow management, a 140 GHz Microwave system for spin polarization, and a superconducting 5 Tesla magnet, tailored for precision. It employs dynamically polarized $NH_3$ and $ND_3$ targets, maintaining high polarization with low systematic errors, and utilizes a sophisticated NMR system for accurate polarization measurements. The evaporation refrigerator, stabilized at 1 K using Oerlikon Root pumps and a helium recovery system, is key to its functionality, ensuring efficient temperature control. The experiment also features cutting-edge Q-meters and AI tools for enhanced measurement accuracy and data analysis. The full SpinQuest (E1039) is explained in the following sub-sections and depicted in the figure 3. Special care is taken to have all electronics that

| Experiment | Particles | Energy (GeV) | $x_b$ or $x_t$ | Luminosity $(cm^{-2}s^{-1})$ | $A_T^{sin\emptyset_s}$ | $P_b$ or $P_t$ $(f)$ | $rFOM^{\#}$ | Timeline |
|---|---|---|---|---|---|---|---|---|
| COMPASS (CERN) | $\pi^- + p^\uparrow$ | 190 $\sqrt{s} = 17.4$ | $x_t = 0.1 - 0.3$ | $2 \times 10^{33}$ | 0.14 | $P_t = 90\%$ f=0.22 | $1.1 \times 10^{-3}$ | 2015, 2018 |
| PANDA (GSI) | $\bar{p} + p^\uparrow$ | 15 $\sqrt{s} = 5.5$ | $x_t = 0.2 - 0.4$ | $2 \times 10^{32}$ | 0.07 | $P_t = 90\%$ f=0.22 | $1.1 \times 10^{-4}$ | 2032 |
| PAX (GSI) | $p^\uparrow + \bar{p}$ | Collider $\sqrt{s} = 14$ | $x_b = 0.1 - 0.9$ | $2 \times 10^{30}$ | 0.06 | $P_b = 90\%$ | $2.3 \times 10^{-5}$ | ? |
| NICA (JINR) | $p^\uparrow + p^\uparrow$ | Collider $\sqrt{s} = 27$ | $x_b = 0.02 - 0.9$ | $1 \times 10^{32}$ | 0.04 | $P_b = 70\%$ | $6.8 \times 10^{-5}$ | 2028 |
| PHENIX/STAR (RHIC) | $p^\uparrow + p^\uparrow$ | Collider $\sqrt{s} = 510$ | $x_b = 0.05 - 0.1$ | $2 \times 10^{32}$ | 0.08 | $P_b = 60\%$ | $1.0 \times 10^{-3}$ | 2000-2016 |
| sPHENIX (RHIC) | $p^\uparrow + p^\uparrow$ | $\sqrt{s} = 200$ $\sqrt{s} = 510$ | $x_b = 0.1 - 0.5$ $x_b = 0.05 - 0.6$ | $8 \times 10^{31}$ $6 \times 10^{32}$ | 0.08 | $P_b = 60\%$ $P_b = 50\%$ | $4.0 \times 10^{-4}$ $2.1 \times 10^{-3}$ | 2023-2025 |
| SeaQuest (FNAL: E-906) | $p + p$ | 120 $\sqrt{s} = 15$ | $x_t = 0.1 - 0.45$ $x_b = 0.35 - 0.85$ | $3.4 \times 10^{35}$ | ..... | ..... | ...... | 2012-2017 |
| SpinQuest ‡ (FNAL: E-1039) | $p + p^\uparrow$ | 120 $\sqrt{s} = 15$ | $x_t = 0.1 - 0.5$ | $5 \times 10^{35}$ | 0-0.2* | $P_t = 80\%$ f=0.176 | 0.15 or 0.09 | 2024-2025 |
| SpinQuest #(Transversity + Dark Photon) | $p + p^\uparrow$ | 120 $\sqrt{s} = 15$ | $x_b = 0.1 - 0.5$ | $5 \times 10^{35}$ | 0-0.2* | $P_b = 80\%$ f=0.176 | 0.15 or 0.09 | 2026-2029 |

‡ 8 cm $NH_3$ target / $L = 1 \times 10^{36} cm^{-2}s^{-1}$, #(Tensor Polarized Spin-1 target) / $L = 1 \times 10^{36} cm^{-2}s^{-1}$
*not constrained by SIDIS data / #rFOM = relative lumi * P² * f² w.r.t E-1027 (f=1 for pol. P beams, f=0.02 for $\pi^-$ beam on $NH_3$)

**Figure 2:** Un(Polarized Drell-Yan Experiments)

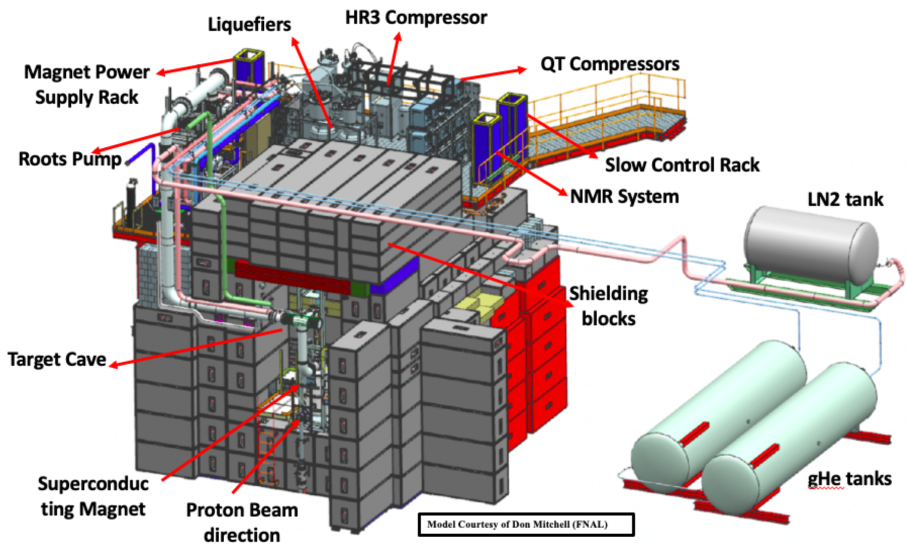



**Figure 3:** SpinQuest Polarized Target System)

control, monitor and operate the target system far away from the in-cave high radiation area which is estimated to be more that an order of magnitude greater than the target area at Jefferson Labs high radiation experiments.

### 3.1 SpinQuest Liquefier System

The SpinQuest Experiment is equipped with its own 200 liquid litter per day helium liquefaction system [7]. These units feature a considerable storage capacity, holding up to 250 liters of liquid helium in each dewar. The helium level in each dewar is accurately monitored using a pressure differential probes. There are two liquefiers each fitted with five cold heads, functioning similarly to Gifford-McMahon (GM) Cryo-coolers, linked to five cold head compressors. For safety, each dewar is equipped with a system of relief valves designed to prevent over-pressurization. The management

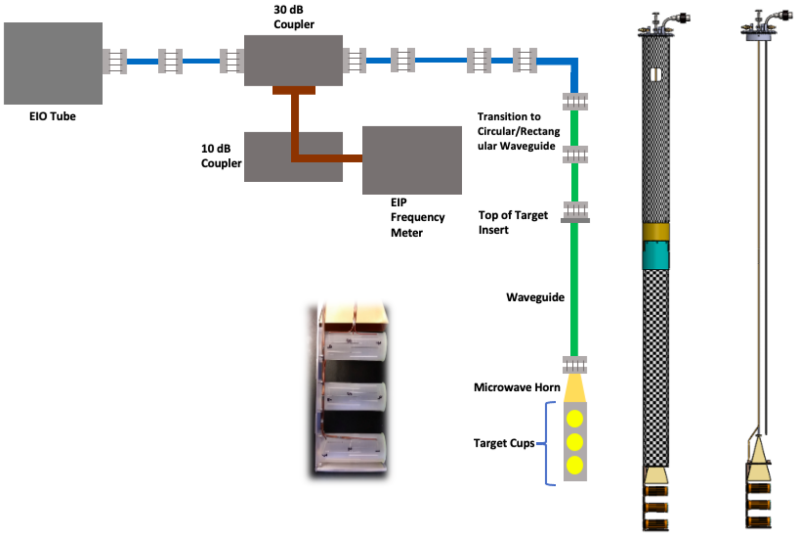



**Figure 4:** 140 GHz Microwave System

of helium inflow and outflow in each dewar is precisely regulated using Teledyne Hasting flow controllers, facilitating optimal production rates.

### 3.2 Microwave System

The SpinQuest Experiment includes a Microwave system operating at 140 GHz (28 GHz/T), powered by an Extended-Interaction Oscillator (EIO) [10]. This system is essential for transferring spin polarization from electrons to nuclei through radio frequency (RF) irradiation in an external magnetic field. The EIO generates the RF signal by interacting with an electron beam, produced via a kilovolt cathode/anode setup with resonant cavities. This interaction is finely tuned to maximize frequency effectiveness for spin flips and to minimize radiation damage to the target from the beam. Frequency adjustments in the EIO are achieved by modifying the beam current, permitting fine-tuning up to 0.4%, and by varying the cavity size using a stepper motor, allowing for an additional 1.5% precision in tuning. The EIO connects to the target cups through waveguides, which direct the microwaves via the target stick/insert to a gold-plated horn, as illustrated in figure (4).
The EIO's distributes microwaves to the target at approximately 20-100 mW/g depending on the attenuation setting. In normal production mode the microwaves are distributed between two couplers – 30 dB and 10 dB. A portion of this power is sent to the EIP frequency meter via the 10 dB coupler, while the majority is channeled to the target cups through the 30 dB coupler via the waveguides. For maintenance purposes, such as replacing target material or conducting microwave tests, the power at the end of the 30 dB coupler can be safely diverted to a microwave dump.

### 3.3 Polarized Target material

In fixed target experiments, the investigation of the internal structure of nucleons necessitates the use of various polarizable materials as targets. The selection of these target materials is guided by the specific scientific objectives and the design of the experiment. Particularly for applications involving dynamic nuclear polarization (DNP), the ideal target material is characterized by its maximum achievable polarization, dilution factor (indicative of its total nuclear content with respect

to the polarized nucleon or nucleus), and resistance to radiation damage.
Paramagnetic centers are introduced into the target material using chemical or radiation doping methods. For instance, in the SpinQuest (E1039) experiment, the $NH_3/ND_3$ target material is prepared by infusing it with paramagnetic free radicals through irradiation. The SpinQuest target consists of 8 cm long PTFE cells filled with ammonia beads, optimally positioned at the nose level within the evaporation refrigerator. The figure of merit (FOM) of the target material, calculated as FOM = $\mathrm{p_T^2\, f^2}\,\rho\,\kappa$, is a crucial metric. This measure incorporates factors such as the dilution, target polarization, and the filling factor $\kappa$, which is related to the thermal conductivity and the shape of the target material. Ammonia is chosen due to its significant resistance to radiation [10]. The experimental procedure involves regular replacement of the target material every 8-10 days for background analysis and the introduction of new material for continuous experimentation.
In the field of transversely polarized target experiments, dynamically polarized ammonia ($NH_3$) and deuterated ammonia ($ND_3$), prepared through irradiation techniques, are preferred materials. The dilution factor for $NH_3$ is 0.176, and for $ND_3$, it is 0.3. These substances are capable of achieving polarization levels exceeding 90% for protons and 50% for deuterons. When analyzing Drell-Yan (DY) events at forward rapidity ($x_F$), the emphasis is on selecting u-quarks (from the beam) and $\bar{u}$-quarks (from the target) to reduce interference from other quark combinations. In $ND_3$ experiments, the Sivers asymmetry $\bar{d}$ is derived by comparing asymmetries in protons and deuterons. Strategies to minimize systematic errors include reversing the target polarization and modifying magnetic fields in the spectrometer.
After two years of using both $NH_3$ and $ND_3$ polarized targets, projections estimate a statistical error of about 3% for $NH_3$ and 4% for $ND_3$, with a similar scale of systematic error for both [7] and [8]. These predictions are based on global fits to existing Semi-Inclusive Deep Inelastic Scattering (SIDIS) data, as shown in figure (5). A notable difference in these projections indicates that current SIDIS data may have limited sensitivity to sea-quark contributions, with the width of the uncertainty bands revealing significant computational uncertainties.
Further analysis, as mentioned in [9], suggests that the proton-DNN model, represented by red-colored bands in the $\mathrm{x_2}$ bins, consistently supports the existence of a non-zero Sivers asymmetry from sea quarks. This model offers enhanced precision compared to previous projections shown in the $\mathrm{x_t}$ bins in Figure (5). On the other hand, the deuteron-DNN model, depicted by orange-colored bands in the $x_2$ bins, highlights the expected polarized DY asymmetries for the $ND_3$ target in the SpinQuest (E1039) experiment.

### 3.4 Superconducting Magnet

The experimental setup features a superconducting magnet generating a 5 Tesla transverse magnetic field, notable for its exceptional uniformity, as indicated by a dB/B ratio less than $10^{-4}$ in Figure (6). This magnet is constructed with NbTi (niobium-titanium) coils set in epoxy, ensuring stability during operation. The coils are housed within type 316 stainless steel for added structural strength. Originally utilized by Los Alamos National Laboratory (LANL) for axial field applications in neutron beams, the magnet underwent modifications by Oxford Instruments to suit the demands of transverse polarization. After initial commissioning and testing at the University of Virginia (UVa), it was transferred to Fermilab (FNAL) for reassembly and installation, a process jointly undertaken by the UVA Polarized Target Group and FNAL technicians. The thermal dynamics within the

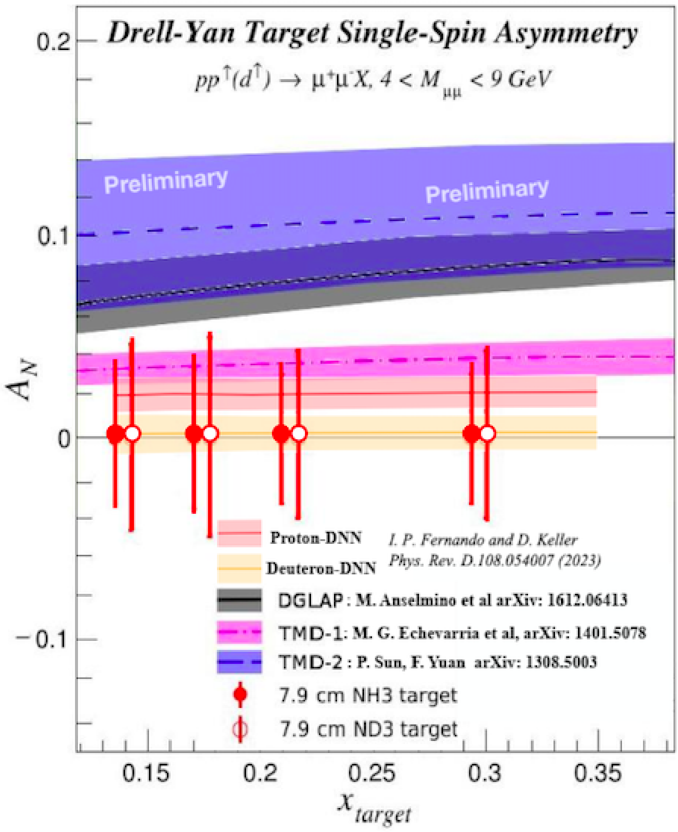



**Figure 5:** The red error bars shows the statistical error for $NH_3$ (3%) and $ND_3$ (4%). Whereas the proton-DNN model (red colored) and the Deutreron-DNN model (orange colored) are projections including 68% CL (confidence level) error bars for Sivers asymmetries in $x_2$ (target) bins.

magnet are governed by a crucial heat transfer equation:

$$c\frac{\partial T}{\partial t} = \nabla(\kappa \nabla T) + P_{ext} + P_{He} \tag{1}$$

Here, $P_{ext}$ represents the external heat source, primarily arising from beam-target interactions, and $P_{He}$ denotes the heat transfer to the liquid helium. The heat absorption by the magnet ($P_{ext}$) is precisely modeled using Geant4 simulations [12].

### 3.5 Liverpool NMR System

The SpinQuest Experiment incorporates an advanced Nuclear Magnetic Resonance (NMR) system featuring a constant current, phase-sensitive Q-meter. This system comprises two configurations: one developed by the University of Virginia (UVa) and the other by Los Alamos National Laboratory (LANL), both evolving from the original Liverpool design [13]. Operating within a 5 Tesla magnetic field, the system employs radio frequency (RF) fields at Larmor frequencies of 213 MHz for protons and 32.7 MHz for deuterons, using a continuous wave NMR technique for non-destructive measurement of absorption and dispersion. Each target cup in the system is equipped with three NMR channels, connected to a Q-meter, which is linked to an NMR coil embedded in the target material. These coils, characterized by their inductance $L_c$ and resistance $r_c$, generate an RF field

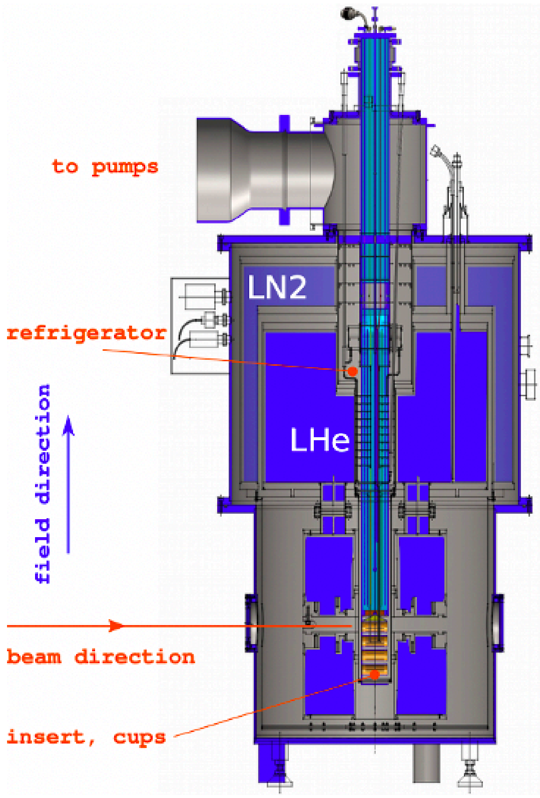



**Figure 6:** Figure shows the superconducting magnet, the evaporation refrigerator, the target insert loaded in the fridge, the beam direction, and the LN2 and LHe reservoirs in the polarized target.

that sweeps through the frequency spectrum, as described by:

$$Z_C = r_c + i\omega L_C(1 + 4\pi\eta\chi(\omega)) \tag{2}$$

Post background subtraction, the NMR signal's area correlates with polarization. The polarization at thermal equilibrium ($P_{TE}$) and the measured polarization ($A_{TE}$), derived from the NMR signal's area at thermal equilibrium, are given by:

$$P_{TE} = \tanh\left(\frac{\mu B}{kT}\right) \quad \text{and} \quad A_{TE} = \int_0^\infty S_{TE}(\omega)d\omega \tag{3}$$

In SpinQuest, the calibration constant $C = \frac{P_{TE}}{A_{TE}}$ is key to enhancing the accuracy of absolute polarization measurements, determined at various thermal equilibrium temperatures. The substantial radiation levels necessitate a very long cable, at least half the wavelength ($\lambda/2 \geq 14$), especially for proton measurements.

To ensure systematic precision, SpinQuest employs three measurement techniques: the artificial intelligence configured Q-meter from with a cold NMR from UVA, and modern Q-meter from LANL. Standard measurements at thermal equilibrium are conducted at 2-1.4 K temperature in the nose of the evaporation refrigerator. Typical proton polarization under these conditions is about 0.36%, compared to a lower 0.075% for deuterons. The relatively low deuteron polarization poses a measurement challenge, effectively addressed through cold NMR [13], significantly enhancing the signal-to-noise ratio. However, many new AI tools are now developed to improve the situation.

### 3.6 Evaporation Refrigerator and Roots pump

The evaporation refrigerator in the SpinQuest Experiment is composed of heat exchangers, a phase separator, annealing plates, and a nose. Liquid helium, sourced from the magnet, is channeled into the phase separator through a U-tube. A dedicated pump continuously extracts helium in the phase separator to effectively separate vapors from the liquid. The Root pumps play a critical role in achieving and maintaining the lowest temperature of 1 K at a pressure of 0.12 torr. Different liquid temperatures can be attained by varying the helium pumping rate within the fridge nose. For an in-depth exploration, the SPIN2023 presentation provides comprehensive details on the SpinQuest Evaporation Refrigerator [14] and figure (6).

A key component of our system is the Oerlikon stacked Root pumps, which consist of three RUVAC WH700 boosters and a Sogavac SV 630 backing rotary vane pump. This configuration yields a remarkable cooling power of 17,000 $m^3$/hr. The Roots pump, featuring a 30 cm inlet figure (6), connects to the evaporation refrigerator through a large pneumatic gate valve. Its exhaust is linked to the helium recovery manifold. This setup includes a series of filters to trap oil contaminants from the pumps, along with a mass flow monitor and a purity meter to oversee the flow directed into the refrigerator. These Root pumps are essential for maintaining a consistent temperature of 1K at the target material's nose, owing to their integration with the evaporation refrigerator.

## 4. Target System Status

The system's infrastructure encompasses a microwave setup in the experimental hall, controlled by software. The superconducting magnet, with minimal boil-off ( 5 slm) due to its $10^{-7}$ Torr vacuum, has undergone several cooldowns to 4K and ramp-up/down cycles at Fermilab. The evaporation refrigerator, operational at 1K, has been rigorously tested in three modes: Standby, Thermal-Equilibrium (TE), and Operational. A comprehensive multichannel nuclear magnetic resonance (NMR) system is installed in the hall, connected with lambda/2 cables. We have refined our procedures for handling ammonia as the target material and managing cryogenics, and have established an online monitoring system equipped with alert-triggering alarms.

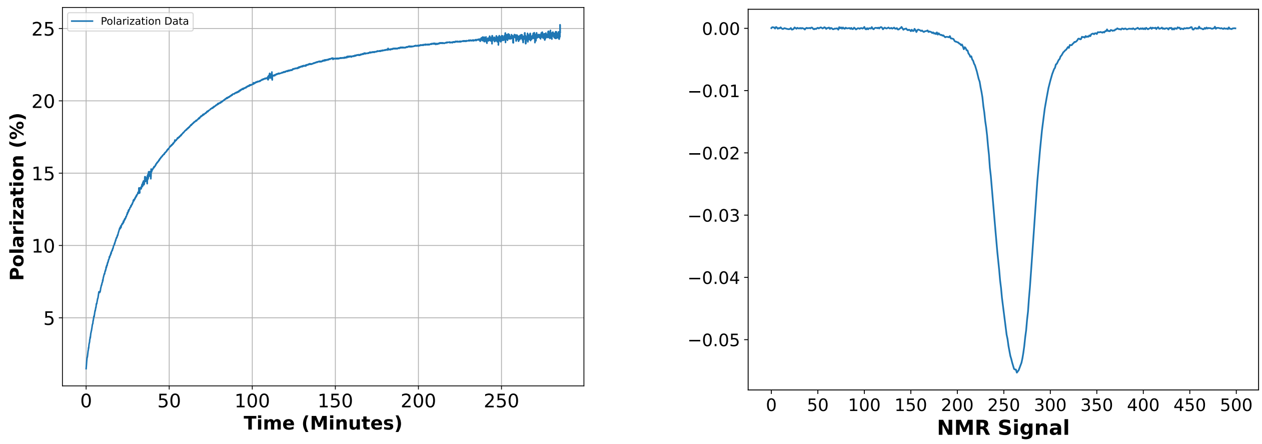
Fermilab conducted an Operational Readiness Review April 2023 and the final beam ready Operational Readiness Clearance (ORC) walkthrough for the SpinQuest experiment on January 19 and 22, 2024. Additionally, on January 24, 2024, the Department of Energy (DOE) and Fermilab executed an Internal Readiness Review (IRR), a critical step towards ARR for SpinQuest. All of theses reviews have been successfully completed.

Figure (7a) shows the results of a polarization test indicating a 25.26% polarization for CH2. Figure (7b) illustrates the final Nuclear Magnetic Resonance (NMR) signal after applying a polynomial fit to remove the background curve.

The target system has been ready to polarize and take beam since the early part of 2023 after a very long and rigorous FNAL cryogenic safety review. The experiment now waits for the completion of the site-wide DOE accelerator safety envelope (ASE) and the accelerator readiness review (ARR). First delivery of beam is expected in late Spring of 2024.

## References

[1] J. Ashman et al., Nucl. Phys. B 328,1 (1989).




**(a)** Polarization of Irradiated CH2

**(b)** Final NMR Signal

**Figure 7:** Figure (7a) shows the Dynamically polarization studies for Irradiated CH2 target material on January 25, 2024, whereas the Figure (7b) displays the final NMR signal with all background subtracted.


[2] E.C. Aschenauer, A. Bazilevsky and et al., arXiv:1304.0079 [nucl-ex] (2013).

[3] K.F. Liu, arXiv:2112.08416 [hep-lat] (2022).

[4] A. Accardi, J.L. Albacete and et al., arXiv:1212.1701 [nucl-ex] (2014).

[5] D. Keller and (the SpinQuest Collaboration)., FERMILAB-PUB-22-381-V, arXiv:2205.01249 [nucl-ex], 2022.

[6] A. Kessenikh, Spin Temperature and Dynamic Nuclear Polarization. From the History of Researches (1953 – 1983), 2021.

[7] A. Klein, D. Keller, K. Liu and et al., SeaQuest with a Transversely Polarized Target (E 1039), 2016.

[8] A. Conover, Kinematic Dependence of the Dilution Factor in the SpinQuest Experiment E1039 at Fermilab (Apr. 29, 2020) (University of Virginia, Physics - Graduate School of Arts and Sciences, MS (Master of Science), 2020).

[9] I. P. Fernando and D. Keller, Phys. Rev. D 108, 054007, 2023.

[10] D. G. Crabb and W. Meyer, Solid Polarized Targets for Nuclear and Particle Phsyics Experiments, 1997.

[11] W. Meyer, Volume 526, Issues 1–2, 21 June 2004, Pages 12-21, 2004.

[12] Akbar, Z., and Keller, "Thermal analysis and simulation of the superconducting magnet in the spinquest experiment at Fermilab," Proceedings of The 18th International Workshop on Polarized Sources, Targets, and Polarimetry PoS (PSTP2019), September 23, 2020, Volume 379, p. 057.

[13] G.R. Court, M.A. Houlden and et al., Volume 527, Issue 3, 21 July 2004, Pages 253-263, 2004.

[14] V. Bandara, "SpinQuest Evaporation Refrigerator," 25th International Spin Symposium (SPIN 2023), September 26, 2023, Durham Convention Center.