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Beam Commissioning Result of Polarized Target at SpinQuest

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SpinQuest is a fixed-target experiment at Fermilab to measure the Drell-Yan process using transversely polarized NH_3 and ND_3 targets and unpolarized 120-GeV proton beam. In the Drell-Yan process, a quark in one scattering hadron and an anti-quark in the other hadron annihilate into a virtual photon and then decay into a muon (lepton) pair. The angular distribution of final-state muon pairs with respect to the target polarization is sensitive to the Sivers function of light anti-quarks in the nucleon, which is one of the eight Transverse Momentum Dependent (TMD) parton distribution functions. The intensity of the proton beam is as high as 10^{12} protons/second, in order to accumulate the required statistics of Drell-Yan events. The polarized target system at SpinQuest has been carefully designed to accommodate such a high beam intensity. It is equipped with an evaporation refrigerator with a cooling power of around 5 W at 1 K. The target temperature is maintained at 1 K even under heat load caused by the proton beam and the DNP microwave. The target system and the spectrometer were commissioned with the proton beam from May through July 2024. The experimental setup of SpinQuest and the performance of the target system during the beam commissioning is reported.

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1. Introduction

SpinQuest[1, 2] is a fixed-target experiment at Fermilab to measure the Drell-Yan process[3] using transversely polarized NH_3 and ND_3 targets and unpolarized 120-GeV proton beam. In the Drell-Yan process, a quark in one scattering hadron and an anti-quark in the other hadron annihilate into a virtual photon and then decay into a muon (lepton) pair. The angular distribution of final-state muon pairs with respect to the target polarization is sensitive to the Sivers function of light anti-quarks in the nucleon[4], which is one of the eight Transverse Momentum Dependent (TMD) parton distribution functions. The intensity of the proton beam is as high as 10^{12} protons/second, in order to accumulate the required statistics of Drell-Yan events. The polarized target system at SpinQuest has been carefully designed to accommodate such a high beam intensity. The target system and the spectrometer were commissioned with the proton beam from May through July 2024. The performance of the target system during the beam commissioning is reported here.

2. SpinQuest Experimental Setup

The unpolarized proton beam is extracted from the Main Injector to SpinQuest (cf. Fig. 1). Its energy is 120 GeV, which corresponds to $\sqrt{s}$ = 15 GeV. Extracted protons have a bunched structure with an interval of 19 nsec (53 MHz). One bunch contains about 10k protons. One extraction (called "spill") delivers about 2×10^{12} protons. The spectrometer was inherited from the SeaQuest experiment[6]. It has been designed to detect pairs of μ^+ and μ^- having large invariant mass.

The design and the functions of the SpinQuest target system are described in details in [5]. The target cryostat is placed in an area called "Cave", which is surrounded by concrete blocks for radiation shielding as seen in Fig. 2. The evaporation fridge has been designed to be operated at $T \approx 1$ K and $B = 5$ T. The helium liquefaction plant and the roots pump for the evaporation fridge are placed on the "Cryo Platform" which was built above the concrete blocks. A gaseous helium tank is placed at the outside of the experimental hall, to form a closed helium circulation system.

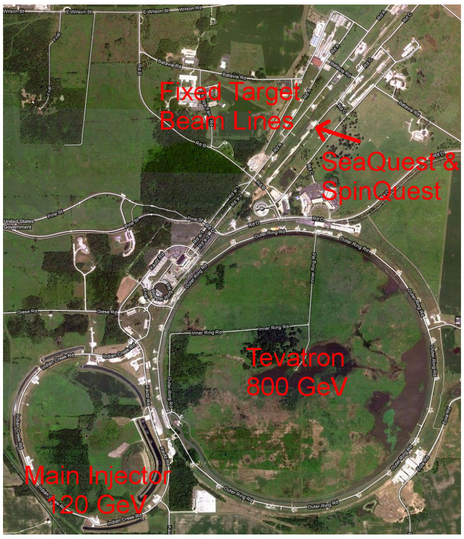

Figure 1: Fermilab Main Injector.

Figure 2: Target cave.

SpinQuest had been commissioning the spectrometer using cosmic ray in and before 2023. Safety assessment of the beam operation for SpinQuest was completed by Fermilab in March 2024. The first proton beam was delivered to SpinQuest in May 2024. SpinQuest then carried out beam commissioning in May through July. The experimental apparatus including the beam, the target and the spectrometer has been improved in terms of stability and efficiency of system operation. A set of "physics" data was also acquired with the NH_3 target polarized and the spectrometer fully operational. Data analyses and system upgrades are ongoing toward the next data taking.

3. Achievements during Beam Commissioning

The most important objective of the beam commissioning was to establish the operation of the polarized target under the high-intensity proton beam. An overview of the commissiong result is described below, where quantitative analyses of the commissioning data are in progress.

3.1 Beam-to-Target Alignment

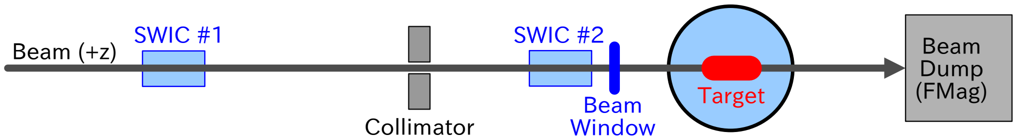

Figure 3: Schematic drawing of devices used for the alignment in top view.

The proton beam is required to be aligned to the target within a few mm, where the size of target cells is 21×27 mm and the width of the beam profile is ±3-4 mm. Multiple devices have been used as follows, to adjust and confirm the beam-to-target alignment.

The beam position was first measured with two beam profile monitors (SWIC; Segmented Wire Ionization Chamber[7]) that were placed at about 2 & 6 m from the target. The locations of the two SWICs are shown in Fig. 3. The outside appearance of the first (upstream) SWIC can be seen in Fig. 4. The horizontal profile observed in a spill is shown in Fig. 5, where an offset of −0.9 mm was observed. The beam parameters were tuned so that the beam profile measured with the SWICs became centered.

The beam position near the target was next measured with two G10 plates. One was mounted on the beam window at 2 m from the target, and the other on the target cells, as shown in Figs. 6 and 7. Burn marks appeared around the center after the G10 plates were irradiated with the proton beam over night.

The beam position was finalized using a "calibration" insert, which was equipped with two Tungsten plates. The horizontal plate in the top cup was irradiated with the proton beam, while the target insert was moved stepwise between spills. Charged particles produced perpendicular to the beam direction were counted with an array of four scintillation counters called "LUMI monitor". The relative position between the beam and the target cups has been evaluated within 1 mm.

3.2 Handling of Target Materials

Target materials will be replaced every week due to radiation damage during physics data taking. Therefore we have tested and established a set of procedures for material handling.

Figure 4: Photo of the first SWIC for SpinQuest.

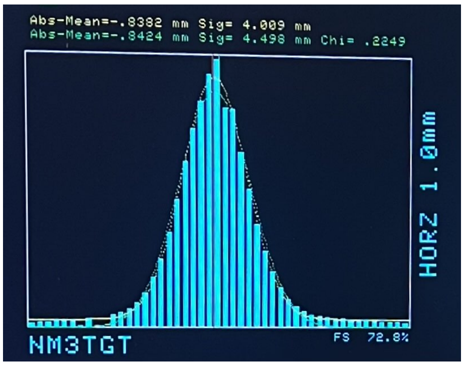

Figure 5: Horizontal profile of beam protons in a spill measured with SWIC.

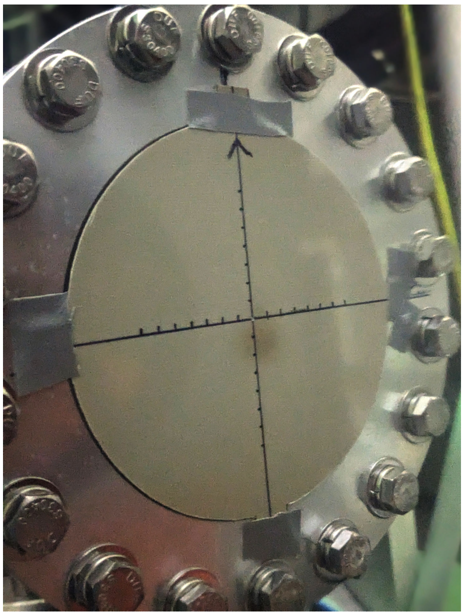

Figure 6: Photo of the G10 plate mounted on the beam window. A burn mark appeared at the center after the G10 plate was irradiated with the proton beam over night.

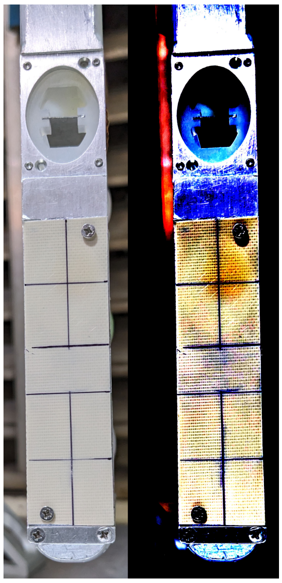

Figure 7: Photos of the G10 plate mounted on the target insert. The brightness and contract of the right-side image have been adjusted to emphasize the burn mark at the center of the middle cup.

Gas of NH_3 and ND_3 is each solidified at UVA and irradiated with electrons at NIST[8]. A sample of irradiated NH_3 is seen in Fig. 8, where it was stored in a plastic bottle in a storage LN2 Dewar dedicated for target materials, and loaded to a target cell when used. At the beginning of the commissioning, beads of high-density polyethylene (HDPE, CH_2) were used as a target material because this material is stable and thus safe for handling (cf. Fig. 9).

A material sample to be used is loaded to a target cell, using a stand and LN2 bath shown in Fig. 10. It is then inserted into the fridge, using a manual crane shown in Fig. 11.

Anhydrous ammonia is considered hazardous regardless of amount. The procedure for material transport and handling has been established in accordance with FNAL safety criteria. Many SpinQuest collaborators have been trained on it during the commissioning.

Figure 8: Sample of NH_3 in storage bottle (left) and target cell (right).

Figure 9: Sample of CH_2 in storage bottle.

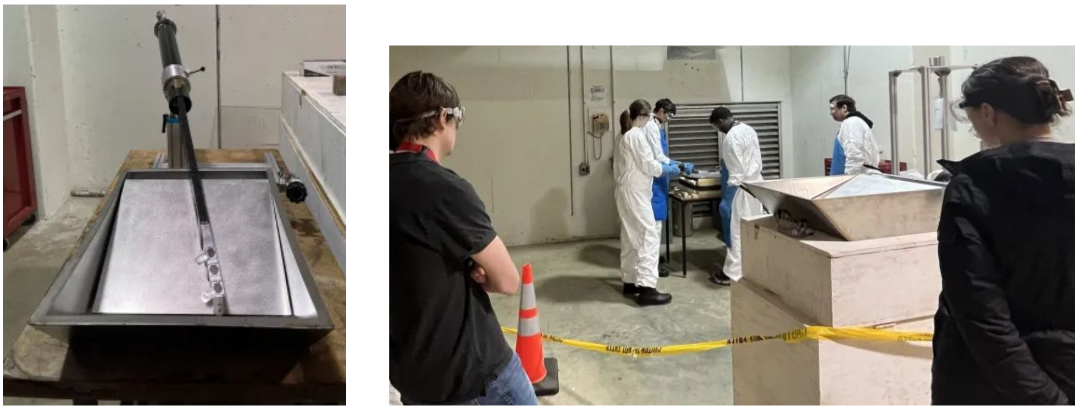

Figure 10: Stand and LN2 bath used to load target materials to target cells.

Figure 11: Scene of loading target material into the fridge.

3.3 Polarization and Annealing of Target Materials

The procedure for loading the target materials into the fridge was approved by the lab in January 2024. Since then we successfully polarized multiple samples using the DNP (dynamic nuclear polarization) technique[9].

We first loaded a sample of CH_2, which was irradiated with the beam protons *in situ* over night to create free radicals. The polarization reached 26% based on an online analysis of NMR data.

We then loaded two samples of NH_3. We adjusted the power of the DNP microwave to balance the maximum polarization and the polarizing time. The polarization of both the samples reached about 90% within two hours in both the positive and negative directions.

We observed that the maximum polarization of the second sample was decreased to about 40% after the sample was on the beam for a week. We then carried out the annealing process, namely the material was heated up to around 100 K for 10 minutes. The maximum polarization was found recovered to 80%.

We measured the polarization as a function of time during spills (for four seconds). No polarization drop was observed at a beam intensity of $3{\times}10^{12}$ protons per spill.

The NMR data are being re-analyzed offline to evaluate the polarizations with better precision.

3.4 Operation of LHe System

The helium system for the SpinQuest polarized target is of closed helium circulation, namely all evaporated helium is usually captured and liquefied for circular use. The system is equipped with two liquefiers (called "A" and "B") with a volume of 200 L each. Each liquefier produces 4 L per hour.

About a half of LHe is evaporated when transferred from the liquefiers to the target magnet due to heat load. The transfer efficiency has been measured and improved during the commissioning. LHe in the target cryogenics is consumed to keep the system cold, due to the heat load to the magnet, the fridge evaporation, the DNP microwave and the beam-proton heat. We have confirmed that the total consumption rate balanced with the liquefaction rate under the normal condition. But the liquefaction rate was sometimes lowered by an overtemperature of cooling water. The cooling water is supplied by Fermilab to the liquefiers as well as the roots pump and the spectrometer magnets. It was found not powerful enough to operate the systems 24 hours a day, due to high outdoor temperature in May-July and faults on cooling devices. Therefore the liquefiers had to be turned off time-to-time. We plan to repair the cooling water system and also reduce the consumption rate further.

4. Conclusions

The SpinQuest experiment is a high-intensity frontier of polarized target dealing with $O(10^{12})$ of protons in four seconds (per spill). It is equipped with an evaporation refrigerator with the highest known cooling power to date and also the longest target cell operated at 1 K.

The commissioning with the proton beam was carried out in May through July 2024. The high polarization has been achieved, which was 26% for CH_2 and about 90% for NH_3 in both the positive and negative directions. The practical operations have been established, including the handling of target materials, the control of the magnet under high-intensity beam, and the sustainable circulation of liquid and gaseous helium.

Data analyses and system upgrades are ongoing toward the next data taking.

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Acknowledgments

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