PROCEEDINGS OF SCIENCE

The Polarized Target SpinQuest Experiment at Fermilab

Arthur Conover,[a,*] **Dustin Keller**[a] **and Zulkaida Akbar**[a]

[a] *University of Virginia,*
382 McCormick Road, Charlottesville, USA

E-mail: acc5dn@virginia.edu, dustin@virginia.edu, za2hd@virginia.edu

The SpinQuest experiment (E1039) at Fermilab will measure the azimuthal asymmetry of dimuon pair production via scattering of unpolarized protons from transversely polarized NH3 and ND3 targets. The asymmetry will be measured for both Drell-Yan scattering and J/ψ production. By measuring the asymmetry for the Drell-Yan process, it is possible to extract the Sivers Function for the light anti-quarks in the nucleon. A non-zero asymmetry would be "smoking gun" evidence for a non-zero orbital angular momentum of the light sea quarks: a possible contributor to the proton's spin. An overview of the experiment and details on the SpinQuest polarized target built at the University of Virginia will be presented.

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*Speaker

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1. Motivation

Since the 1980s, it has been known that the intrinsic spin of the valence quarks is not sufficient to explain the overall spin of the proton.[1] Through scattering experiments, it has been established that although the intrinsic spin of the quarks and gluons do contribute, there is also believed to be a contribution from the orbital angular momentum (OAM) of the valence quarks, sea quarks, and gluons. One way to represent the total spin, as given by Jaffe and Manohar[2], can be given as follows:

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_{\bar{q}} + L_G \tag{1}$$

where $\frac{1}{2}\Delta\Sigma$ is the contribution of the intrinsic spin of the valence quarks, ΔG is the contribution of the intrinsic spin of the gluons, and L_q,$L_{\bar{q}}$, and L_G are the contributions of the orbital angular momentum of the valence quarks, sea quarks, and gluons, respectively.

One way to access the orbital angular momenta is through the Transverse Momentum Distributions (TMDs). TMDs describe the correlation between the transverse momenta of partons and the transverse spin of their nucleon. They include information about parton distribution asymmetries, which allows them to encode the internal dynamics of the nucleon. They are derived using the quark-quark correlation function, which can be found in [3]. The eight TMDs are shown in figure 1.

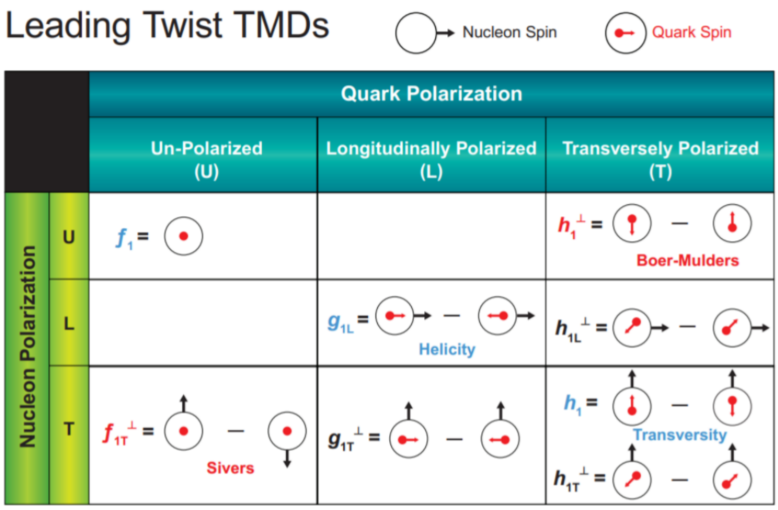

Figure 1: The quark TMDs, taken from reference [3]

The Sivers function represents the relationship between the transverse momentum of an unpolarized parton with the spin of a transversely polarized nucleon. Although there is no model-independent relation between the Sivers function and the OAM, if the Sivers function for the sea quarks is zero, that would imply a zero OAM of the sea quarks. Thus, a non-zero Sivers function would be a smoking gun for contribution of sea quark OAM contribution to the spin of the nucleon.[4]

The SpinQuest Experiment aims to measure the $\bar{u}$ and $\bar{d}$ sea quark Sivers function via polarized proton-proton and proton-deuteron Drell-Yan scattering. This will be the first time this measurement is made. There are three main parts to the experimental setup: the beam, the detector, and the target. The beam and the detector will each be discussed briefly, and the target in more detail.

2. The Beam

The Fermilab Main Injector, shown in figure 2, will provide 120 GeV protons to the experiment. Since SpinQuest is a fixed-target experiment, this means that the center-of-mass energy of collisions will be approximately 15.5 GeV. The beam will deliver a 4.4-second-long spill of approximately 5×10^{12} protons every minute. Over the course of a year, this is approximately equivalent to 10^{17} protons. This intensity of over 10^{12} protons per second would be the highest instantaneous proton intensity ever attempted on this type of target.

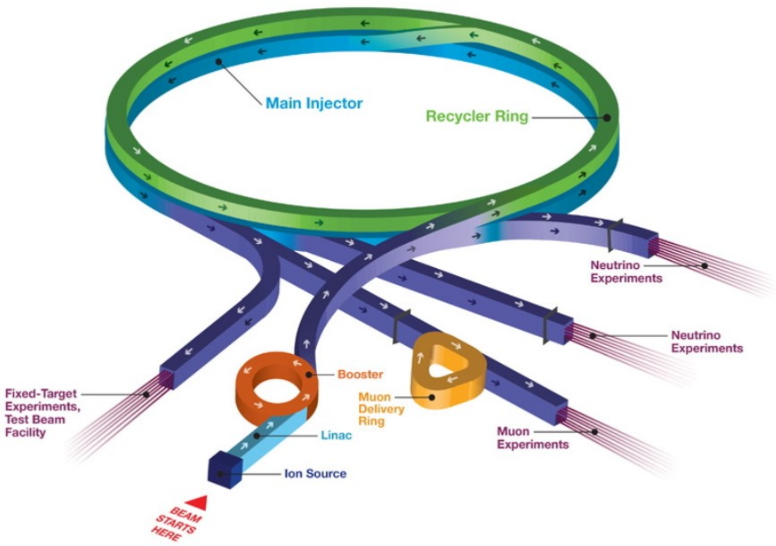

Figure 2: The Fermilab Accelerator Complex [5]

3. The Detector

SpinQuest will use the existing E906 (SeaQuest) spectrometer to detect and track the resulting muons. As shown in Figure 3 below, it consists of 2 magnets and four tracking stations.

The first magnet, a beam dump magnet, focuses the muons that pass through it. It is a solid iron magnet, and also acts as the beam dump for the experiment. Next, the muons pass through the first tracking station, which is comprised of 6 drift chambers and a hodoscope array. The muons then pass through the second magnet, a spectrometer analysis magnet. Based on the curving of the muons that pass through, it is then possible to measure the momenta of the particles.

After the magnets, the particles pass through three more tracking stations. Station 2 is similar to Station 1 in that it has six drift chambers and a hodoscope array. Station 3 has a total of 12 drift chambers, split into an upper set of six and a lower set of six, as well as a hodoscope array. And finally, station 4 has a hodoscope array and proportional tubes.

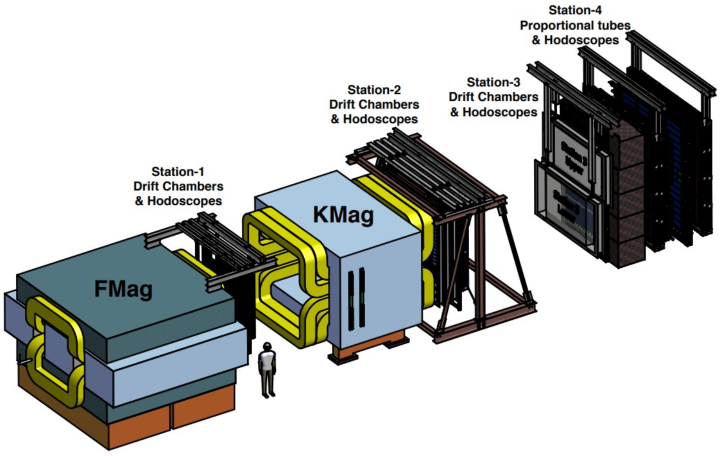

Figure 3: The SpinQuest Spectrometer [6]

4. The Target

The SpinQuest target, built at the University of Virginia, needed to be designed to address several challenges inherent to the experiment. First, because the Drell-Yan process has a very low cross-section and the asymmetry to be measured is small, it is necessary to maximize the number of interactions while making sure to minimize the possibility of false asymmetries. Because of the large amount of heat delivered by the beam to the target in each spill, it is also a challenge to prevent magnet quenches and keep the target polarized. Additionally, radiation damage to the target will necessitate frequent target change-outs, while high radiation in the target cave means that sensitive electronics need to be moved outside of the cave, and time spent in the cave must be limited for safety.

4.1 Target Material

The material selected for the target was frozen NH_3 and ND_3 beads. This was done because ammonia offers both a high dilution factor and a high radiation resistance. In order to prime the material for polarization, the ammonia is irradiated using a low-energy, high-intensity electron beam, originally used for medical treatments.

During the experiment, the material will be polarized using dynamic nuclear polarization. Based on experience, we expect the average polarization for NH_3 and ND_3 to be approximately 86% and 32% respectively. Because of the radiation damage on the material, it is expected that the target will need to be changed out every 8-10 days during the experiment.

4.2 Target Insert

The target insert, shown in Figure 4, was built at the University of Virginia for this experiment. It is made of carbon fiber and holds three cups of target material, only one of which will be in the beam at any one time. To increase the number of interactions, the target cups are very long at 8 cm. The insert will be attached to an actuator table, which will allow the cup in the beam to be switched remotely. By doing this, the frequency of hall access will be greatly reduced.

There is also a gold microwave horn at the end of the insert that spreads the microwave evenly over the entire target to ensure even polarization.

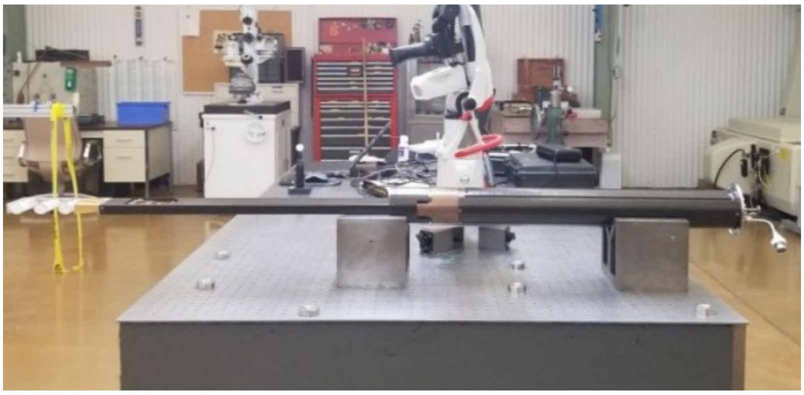

Figure 4: The SpinQuest Insert

4.3 Nuclear Magnetic Resonance

Due to the length of the target cup, each cup has been fitted with three NMR coils spread evenly over the length of the cup to provide a more complete picture of the polarization of the whole target.

Another challenge with the NMR system in SpinQuest is the placement of the NMR Q-Meter relative to the coils. Because of the high radiation in the cave, it is necessary to place it further away from the target than is optimal. This means that the NMR cable is $14\lambda/2$ long, as opposed to the normal maximum of $7\lambda/2$. This means that special care and clever analysis will be necessary to read the signal through the extra noise.

4.4 Microwave Source

Dynamic nuclear polarization (DNP) requires a microwave source, which in the case of SpinQuest is a 140 GHz source. The microwaves are produced using an Extended Interaction Oscillator. Because the optimal frequency for DNP depends on the polarization direction and the radiation damage, the frequency of the source is tunable.

4.5 Target Magnet

The magnet used to polarize the material is a superconducting 5T magnet made by Oxford Instruments. It has a homogeneity level of 10^{-4} over the target area.

Because of the large heat load that will be delivered to the target, it was important to do simulations to determine if the intensity would trigger a magnet quench. Zulkaida Akbar, a postdoc at the University of Virginia, used GEANT and COMSOL to simulate this, and found that with our system, we could tolerate approximately 1×10^{13} protons per spill, which is double the intensity that we plan on.[7]

4.6 Cryogenic System

To keep the magnet and target material as cold as possible, the target was designed as an evaporation refrigerator. It has a power of 1.4 W at 1 K, and 3 W at 1.1 K. There is also a system of pumps to remove the evaporated helium, which is able to remove 17,000 m^3/h of evaporated helium.

Because of the high intensity of this experiment, we will use a lot of liquid helium. Due to its cost, it was calculated to be more efficient to produce our own liquid helium by recapturing evaporated helium and re-liquefying it. The liquefier system can produce approximately 200 liquid liters per day of LHe, of which, due to transfer efficiency, approximately 70% of which can be delivered to the target magnet.

We expect to use approximately 110 liters per day of LHe, which means that we should be able to produce as much LHe as we need. In case of a quench, we also have 500 liters of storage to quickly refill the magnet.

5. Expected Sensitivity of SpinQuest

The SpinQuest experiment will run for two years in order to collect enough Drell-Yan events for low statistical uncertainty. Along with the Drell-Yan asymmetry, the experiment will also be able to measure dimuons produced by the J/ψ process. Because J/ψ has a much higher cross-section, the J/ψ asymmetry will be able to reach good statistics within weeks.

Figure 5 shows the expected uncertainty of the measured asymmetry based on an expected approximately 5×10^4 NH_3 or ND_3 events per bin and the expected systematic uncertainty.

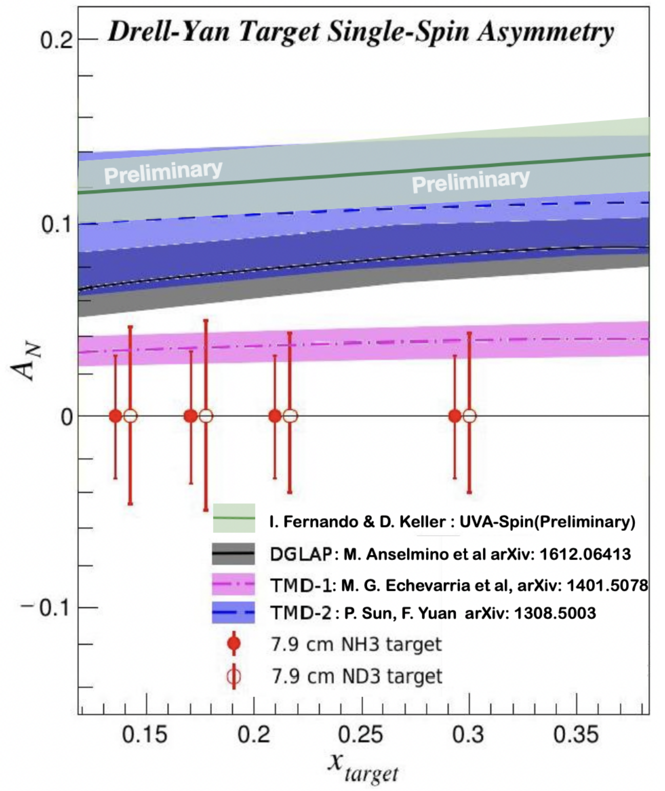

Figure 5: Expected Sensitivity of the SpinQuest Experiment

Figure 5 also shows a number of theory curves for the expected asymmetry. The expected error bars are small enough that the experiment should allow for sign determination of the asymmetry, which would allow the conclusion that sea quark OAM does indeed contribute to the spin of the nucleon.

6. Acknowledgements

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