Probing nucleon's spin structures with polarized Drell-Yan in the Fermilab SpinQuest experiment

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Although the proton was discovered about 100 years ago, its spin structure still remains a mystery. Recent studies suggest that the orbital angular momentum of sea quarks could significantly contribute to the proton's spin. The SeaQuest experiment, which recently completed data collection, probed the unpolarized light quark sea distributions of the proton using the Drell-Yan process. Its successor, the SpinQuest (E1039), will access the $\bar{u}$ and $\bar{d}$ Sivers functions using polarized NH_3 and ND_3 targets. A non-zero Sivers asymmetry, observed in SpinQuest, would be a strong indication of non-zero sea-quark orbital angular momentum. The SpinQuest experiment can also probe the sea quark's transversity distribution, which is relevant for the determination of proton's tensor charge. Recent study suggests that sea-quarks might contribute significantly to deuteron's tensor polarized structure functions. This can be further probed in SpinQuest using tensor polarized ND_3 target. The current status and future plan of the experiment are presented.

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1. Introduction

There has been intense theoretical and experimental interest in the subject of transverse momentum dependent (TMD) parton distributions of the nucleons [1] during the last two decades. For many years after the discovery of the partonic structure of the nucleons in the deep inelastic scattering (DIS), only their unpolarized and helicity distributions were investigated. New insights on the nucleon structure and QCD are expected to be revealed by the novel TMD distributions. One example is the striking prediction [2] of the process dependence of certain TMDs, which remains to be tested conclusively with ongoing and future experiments. The recent advance of the lattice QCD, including the prospect of calculating the Bjorken-x dependence of the parton distributions and TMDs [3], could also lead to a direct comparison between the experimental data and lattice calculations.

From the three transverse quantities of the nucleon and quark, namely, the nucleon's transverse spin, quark's transverse spin, and the quark's transverse momentum, three different correlations corresponding to three different TMDs can be formed. The Sivers function results from the correlation between quark's transverse momentum and nucleon's transverse spin [4]. The correlation between quark's and nucleon's transverse spins leads to the "transversity" distribution [1]. The correlation between quark's transverse spin and quark's transverse momentum gives the Boer-Mulders function [5]. Among the various types of TMDs, the bulk of recent interest and progress centered on these three TMDs.

The novel TMDs are accessible via experiments using either lepton or hadron beams. Most of the experimental information on the TMDs thus far has been collected from the semi-inclusive DIS (SIDIS) experiments carried out with muon or electron beams at DESY (HERMES), CERN (COMPASS), and the Jefferson Lab. Another important experimental tool to access the TMDs using hadron beams is the Drell-Yan process, which involves quark-antiquark annihilating into a virtual photon via electromagnetic interaction. As such, the Drell-Yan cross sections with unpolarized or transversely polarized nucleons are potentially sensitive to various TMDs of the colliding hadrons. First results on the Boer-Mulders functions have been extracted from the unpolarized Drell-Yan experiments with pion beams [6, 7] and proton beam [8, 9]. Very recently, Sivers function was probed in W-boson production (a generalized Drell-Yan process) using transversely polarized proton beam at RHIC by the STAR Collaboration [10] as well as in pion-induced Drell-Yan on a transversely polarized proton target at CERN by the COMPASS Collaboration [11].

In this paper, we present the physics motivation and experimental status of a recently approved polarized Drell-Yan experiment, SpinQuest (E1039), at Fermilab [12]. The SpinQuest experiment is a follow-up of the recently completed SeaQuest experiment [13], with an important new feature that transversely polarized targets will be implemented. The main physics goal of the SpinQuest is to measure proton's sea-quark Sivers function, which is expected to provide an unique information complementary to that obtained from the polarized Drell-Yan experiments at COMPASS and STAR. Additional physics opportunities of the SpinQuest, including the measurements of the nucleon's sea-quark transversity distribution and the tensor polarized structure function, b_1, of the deuteron, will also be discussed.

2. Probing Sea-quark Sivers Functions

Sivers first suggested that the correlation between the transverse spin of the nucleon and the transverse momentum of the quark (antiquark) can lead to single-spin asymmetry in various processes [4]. The Sivers function is a time-reversal odd object. Its existence depends on initial or final state interactions via soft gluons [2]. As shown in Refs. [2, 14], such interactions are incorporated naturally by the gauge link required for a gauge-invariant definition of the TMD. The Sivers function is related to the forward scattering amplitude where the helicity of the nucleon spin is flipped. This helicity flip must involve the orbital angular momentum of the quark, hence the existence of the Sivers function indicates non-zero orbital angular momentum carried by the quark.
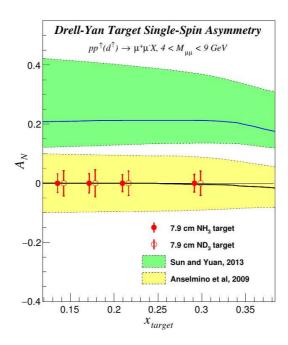
Measurements of the Sivers functions via the polarized SIDIS process with transversely polarized targets have been performed at HERMES [14, 15], COMPASS [16, 17, 18] and JLab [19]. Both valence and sea quark Sivers functions were extracted via global fits [20, 21] to existing data. The result confirmed the theoretical expectation of opposite sign for the u and d valence quark Sivers functions. Non-zero values, albeit with large uncertainties, were also obtained for the sea-quark Sivers functions [20, 21].

The connection between the Sivers function and the orbital angular momentum suggests that the Sivers function for antiquarks could be sizable. First of all, the meson-cloud model, which describes well [22] the observed $\bar{d}/\bar{u}$ asymmetry [23], implies that a significant fraction of nucleon's spin resides in the orbiting meson. Since mesons contain valence antiquarks, it is natural to expect that non-zero orbital angular momentum is carried by antiquarks. Secondly, using the chiral-quark soliton model, it was shown that antiquarks have a dominant contribution to proton's orbital angular momentum [24]. Finally, recent lattice calculation [25] also found a significant fraction of proton's spin originating from the $\bar{u}$ and $\bar{d}$ orbital angular momentum. All these theoretical results suggest that the sea-quark Sivers functions should be sizable and measurable. Proton-induced Drell-Yan experiment with transversely polarized target, such as the Fermilab SpinQuest experiment, provides a clean probe to extract sea-quark Sivers functions. Unlike the polarized SIDIS, where the effects of the sea-quark Sivers functions are often overshadowed by that of the valence-quark Sivers functions, the polarized Drell-Yan with proton beam is predominantly sensitive to the sea-quark Sivers functions.

To measure the sea-quark Sivers functions, SpinQuest will use 120 GeV proton beam bombarding on transversely polarized NH_3 or ND_3 targets. Using the upgraded SeaQuest dimuon spectrometer, the left-right azimuthal asymmetry, A_N, of dimuons due to the sea-quark Sivers functions in the target nucleon will be measured. This asymmetry is expressed as

$$A_N \propto \frac{\sum_q e_q^2 [f_1^q(x_1) \cdot f_{1T}^{\perp,\bar{q}}(x_2) + 1 \leftrightarrow 2]}{\sum_q e_q^2 [f_1^q(x_1) \cdot f_1^{\bar{q}}(x_2) + 1 \leftrightarrow 2]}, \tag{2.1}$$

where f_1^q and $f_{1T}^{\perp}$ denotes the unpolarized PDF and the Sivers function, respectively. The second term in both the numerator and denominator has negligible contribution due to the kinematic acceptance of the SpinQuest spectrometer. Figure 1 shows the projected sensitivities for the left-right asymmetry A_N as a function of x for the measurement on NH_3 and ND_3 targets. The green and yellow bands correspond to the calcuation of A_N for the NH_3 target using the Sivers functions obtained from two global fits to the SIDIS data [20, 21].

Figure 1: Projected sensitivities of the SpinQuest for the A_N measurements on NH_3 target. The two bands are calculations using the Sivers functions obtained from two different global fits to the SIDIS data [20, 21].

Figure 1 shows that the projected sensitivities of SpinQuest would allow a significant first measurement of the sea-quark Sivers function in the Drell-Yan process. A comparison between the NH_3 and ND_3 results could also be sensitive to the flavor dependence of the sea-quark Sivers function. If the magnitude of the sea-quark Sivers function is sizable, the sign of the sea-quark Sivers function might also be determined. The SpinQuest measurement would complement very well the COMPASS [11] and STAR [10] measurements, which are sensitive to the sign of the valence-quark Sivers functions.

3. Probing the Sea-quark Transversity

In addition to the primary physics goal of SpinQuest to measure the sea-qaurk Sivers function, an interesting potential by-product of SpinQuest is the measurement of nucleon's sea-quark transversity distribution. The transversity distribution describes the correlation between quark's transverse spin and nucleon's transverse spin. As a chiral-odd object, the transversity is not accesible in inclusive DIS, but can be extracted in semi-inclusive DIS or polarized Drell-Yan experiments, such as SpinQuest [1]. In order to probe the chiral-odd transversity distribution, another chiral-odd object is involved in the measurement. For the SIDIS, the chiral-odd Collins fragmentation function [26] or the interference fragmentation function are involved. For the Drell-Yan process, a convolution of a transversity distribution with either another transversity distribution or the chiral-odd Boer-Mulders function is involved.
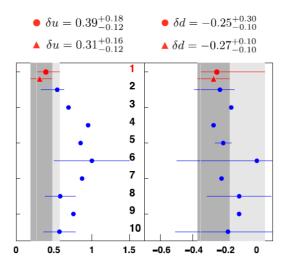
Extensive efforts to measure the transversity distributions via SIDIS have been performed at HERMES [14, 27], COMPASS [28, 29], and JLab [19]. A global fit [30] to these SIDIS data,

as well as the e^+e^- data from Belle [31] relevant for the Collins fragmentation function, has led to the extraction of the quark transversity distributions in the proton. However, in this global analysis, the sea-quark transversity distributions were assumed to be zero. Again, this reflects the challenge encountered in the SIDIS to separate the antiquark contribution from the dominant quark contribution.

The tensor charge of the proton is defined as the first moment of the difference of the quark and antiquark transversity distribution as

$$\delta q = \int_0^1 [h_1^q(x) - h_1^{\bar{q}}(x)]dx \tag{3.1}$$

From the global fit to the SIDIS data, the u and d quark tensor charges were obtained [30] as shown in Figure 2. While the tensor charge for the d quark is in reasonable agreement with model calculations, Figure 2 shows a significant discrepancy between the data and model calculations (and lattice calculations) for the tensor charge of the u quark. A possible explanation is that the sea-quark transversity distributions, which were neglected in the global analysis, might be quite sizable. It would be of great interest to measure the $\bar{u}$ and $\bar{d}$ transversity distributions using the Drell-Yan process.
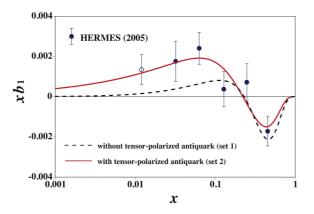

Figure 2: Tensor charges for the u and d quarks extracted in the global fit to SIDIS data [30]. Predictions from various models and the lattice calculations are also shown.

In the SpinQuest experiment, the antiquark transversity distributions can be accessed through the measurement of the correlation between the azimuthal angle of the charged leptons from the Drell-Yan process and the transverse polarization direction of the target nucleon. Specifically, the Drell-Yan differential cross section on a transversely polarized nucleon contains a term proportional to $\sin(2\phi - \phi_s)$, where ϕ is the azimuthal angle of charged lepton in the dilepton rest frame and ϕ_s is the azimuthal angle of the nucleon's spin direction [11]. The amplitude of this term is proportional to the convolution of the quark Boer-Mulders function of the proton and the antiquark transversity distribution of the target proton. As the Boer-Mulders function can be determined from the $\cos 2\phi$ distribution of the unpolarized Drell-Yan data [6, 7, 8, 9], it is quite feasible to probe the sea-

quark transversity distributions. Further study of the expected sensitivity in SpinQuest for such measurement is underway.
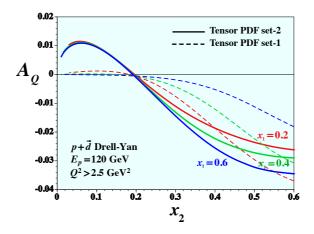
4. Study of Deuteron Tensor Polarization Function

With tensor polarized ND_3 target, the SpinQuest experiment can measure the tensor polarization function of the deuteron. Deuteron has spin 1 thus has three magnetic sub-states, m = +1, 0, -1. This leads to new PDF functions, b_1, b_2, b_3 and b_4. Among which b_1 is related to the difference between |m| = 1 and 0. Figure 3 shows the HERMES SIDIS measurement [32] of xb_1 vs x, where x is the Bjorken-x. The HERMES b_1 data suggest an oscillating pattern with a node occuring at $x \sim 0.3$, in qualitative agreement with a conventional description for b_1 [33]. The two curves in Figure 3 correspond to theoretical calculations [34] for the xb_1 distribution. The solid curve, which assumes non-zero antiquark contribution to b_1, gives significantly better description than the calculation (dashed curve) which assumes no antiquark b_1 contribution. This suggests a sizable antiquark contribution to the deuteron's b_1 structure function.
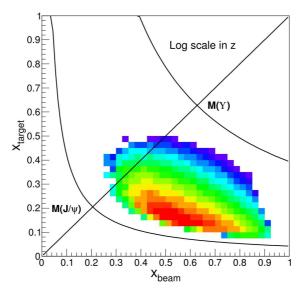

Figure 3: Comparison between the HERMES data [32] and the theoretical prediction [34]. The solid and dashed curves correspond to calculation with, or without, finite antiquark tensor polarization respectively.

The SpinQuest experiment can provide a direct measurement of the sea-quark contribution to the b_1 structure function. Using a tensor polarized ND_3 target, the tensor polarization asymmetry, A_Q, in the Drell-Yan process can be measured. A_Q is defined as the ratio of the unpolarized PDFs and the tensor-polarized PDFs [34]. Figure 4 shows the prediction for A_Q for the SpinQuest kinematics [34]. The solid lines are the prediction assuming non-zero antiquark tensor polarization PDFs with various values of x_1, the momentum fraction of quark inside the beam proton. While the dashed lines assume zero antiquark tensor polarization. This shows that A_Q can distinguish the two predictions, especially at the $x_2 < 0.2$ region. Figure 5 shows that the SpinQuest experiment covers the appropriate ranges of x_1 and x_2 to measure the b_1 of deuteron. Dedicated beam time to take both tensor polarized and unpolarized data would be necessary to make a quality measurement.

Figure 4: A prediction of the asymmetry A_Q for the SpinQuest experiment based on two tensor PDF sets obtained from a fit to the HERMES data.[34] The solid curves were obtained with finite antiquark tensor polarization, while the dashed curves correspond to calculations assuming vanishing antiquark tensor polarization.

Figure 5: The 2D distribution of x_{target} (x_2) vs x_{beam} (x_1) showing that the SpinQuest can cover x_2 down to 0.1 to measure the tensor polarization function.

5. The SpinQuest Experiment

The SpinQuest spectrometer is basically the same as that used in the SeaQuest/E906 experiment [13], shown in Figure 6. The liquid H_2 and D_2 targets, used in the SeaQuest experiment, will be replaced by the polarized NH_3 or ND_3 target; also moved upstream by 1.5 meter to improve the separation of dimuon events from target and from dump. New fiber scintillators will be added in stations 1 and 2. This provides better y position resolution thus improving the z resolution and background rejection. The target is followed by a solid iron bending magnet, which also servers as

a beam dump. Dimuons are tracked by stations 1-3 consisting of drift chambers and hodoscopes, while a second magnet (KMAG) is for analyzing the muon momentum. Station 4, placed downstream of an iron block, consists of hodoscope and proportional tubes for muon identification. The hit patterns of the hodoscopes are utilized to select muon events at the trigger level.
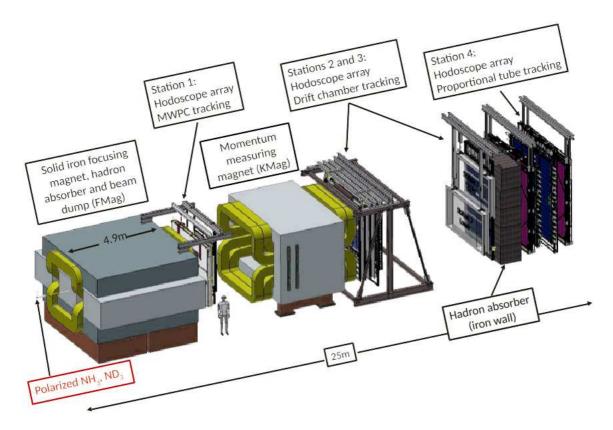

Figure 6: The spectrometer of the SeaQuest/E906 is used in SpinQuest experiment.

Shown in Figure 7 is the polarized target system of the SpinQuest. The target is polarized using Dynamic Nuclear Polarization as described in [35]. The frozen ammonia beads of NH_3 and ND_3 will be placed in the target holder in a 5 T magnet field. The whole container is cooled down to 1 K in a He evaporation refrigerator. In a 5 T field at 1 K, electrons are nearly fully polarized. The electron polarization is then transferred to nucleon polarization through dipole-dipole interaction between the electron and the nucleon. By applying a suitable microwave signal, the desired spin state is populated. NMR detectors are placed near the targets to monitor the target polarization. An average polarization of 80% is expected for the NH_3 target.

The preparation of the SpinQuest is well underway and first physics data-taking is expected to begin in September of 2019. Stay tuned.

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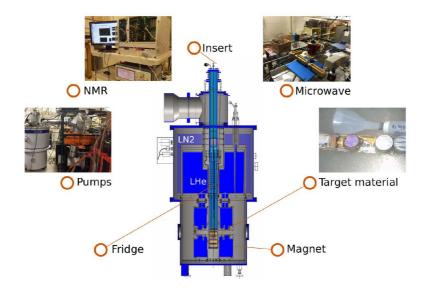
Figure 7: The target system of SpinQuest shown together with its supporting devices.

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