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A new polarized proton target for SIDIS and Drell-Yan measurements

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Summary. — We propose to construct a "next-generation" polarized proton target (NH_3) for high-luminosity semi-inclusive DIS experiments at JLab-12 GeV. A similar design of the polarized target would also fit for a fixed target Drell-Yan SSA experiment at Fermilab using the 120 GeV proton beam from the Main Injector. The main features of the new polarized proton target and design considerations are outlined.

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PACS 13.88.+e – Polarization in interactions and scattering.

1. – Introduction

Since the observation of surprisingly large single-transverse-spin asymmetries (SSAs) in $p^{\uparrow} + p \to \pi + X$ at Fermilab in the 1980s, the exploration of the physics behind the observed SSAs has become a very active branch in hadron physics. The field of transverse-spin physics has now become one of the hot spots in high-energy nuclear physics, generating tremendous excitement on both theoretical and experimental fronts, as we witnessed during this workshop.

Semi-Inclusive Deep-Inelastic Scattering (SIDIS) measurements on polarized targets have generated the first information on quark transverse spin (transversity) and transverse-momentum-dependent parton distributions (TMDs), such as the quark Sivers distributions. It has been a worldwide effort over the last several years to measure SSA in SIDIS reactions. The HERMES experiment at DESY carried out the first SSA measurement in SIDIS reaction on a transversely polarized proton target [1]. The COMPASS experiment at CERN carried out similar SSA measurements on transversely polarized deuteron and proton targets [2]. Most recently, Jefferson Lab Hall A published results of SSA measurements on a transversely polarized neutron (^{3}He) target [3].

The technology of polarized ^{3}He target has evolved tremendously over the last decade, especially at JLab Hall A, through many experiments. However, the performance of dynamically polarized proton targets (NH_3) in an electron beam has not seen much improvements since early 1990s when the SLAC/UVa/Hall-C target system was first built. With the upcoming JLab-12 GeV upgrade, high intensity (and high polarization) electron beam will make it possible for high precision transverse spin asymmetry measurements using a high luminosity polarized proton (NH_3) targets. On the other hand, as we begin to realize that polarized Drell-Yan measurements can provide a brand new tool to probe into the nucleon's structure, a high-luminosity polarized proton target Drell-Yan experiment with the high-intensity proton beam at Fermilab has become more attractive. Therefore, the construction of "the next generation" high-luminosity transversely polarized proton target will advance the field of spin physics on both the DIS and the Drell-Yan fronts.

2. – JLab SSA results on a polarized neutron (^{3}He) target

The first transversely polarized neutron target SIDIS experiment [3] (E06-010) has been carried out at JLab Hall A using a polarized ^{3}He gas target system. Target single-spin asymmetries in $(e, e'\pi^+)$ and $(e, e'\pi^-)$ reactions have been separated into Collins and Sivers moments for ^{3}He. The Collins moments for ^{3}He are consistent with zero, except for the π^+ moment at $x = 0.35$. While the π^- Sivers moments are consistent with zero, the π^+ Sivers moments favor negative values. The neutron results were extracted using the nucleon effective polarization and measured cross section ratios of proton to ^{3}He, and are consistent with the predictions of phenomenological fits and quark model calculations.

Since JLab's electron beam is polarized, the beam-target double spin asymmetry A_{LT} in SIDIS charged pion production was also measured for the first time on ^{3}He, and neutron A_{LT} was extracted [4]. These new data probe the transverse momentum dependent parton distribution function g_{1T}^q and therefore provide access to quark spin-orbit correlations. The results indicate a positive A_{LT} asymmetry for π^- production on ^{3}He and the neutron, while the π^+ asymmetries are consistent with zero.

In addition to SIDIS channels, SSAs were also measured for inclusive hadron production $^3\mathrm{He}(e, \pi^\pm)$, $^3\mathrm{He}(e, p)$ and inclusive electron scattering in DIS as well as in quasi-elastic $^3\mathrm{He}(e, e')$ scattering. Two sets of target-spin orientations were taken, transverse-vertical and transverse in-plane, and the target spin were flipped automatically once every 20 minutes through Adiabatic Fast Passage. Beam charge monitors upstream of the target provided integrated beam charge information corresponding to each target spin states. Single-spin asymmetries were formed based on accepted event counts, corrected by DAQ dead-time and beam charge difference between target spin-up and spin-down states. Since target in-plane SSAs of inclusive channels are parity-forbidden due to $(\vec{k_1} \times \vec{k_2}) \cdot \vec{S_T} = 0$, measurements of SSAs in such a configuration would clearly demonstrate the control of false asymmetry. In JLab E06-010 experiment, ^{3}He SSA of all inclusive channels in target polarized in-plane configuration were well below 1.0×10^{-3}, demonstrated that false asymmetries were under control. The SSAs measured in target-vertical configuration were clearly non-zero for inclusive hadron production, at $\sim 1.0\%$ level with the same sign for π^+ and proton, opposite to that of π^- For inclusive electron channel at DIS kinematics, preliminary results indicated that SSA were less than the level of 1.0×10^{-3}. At quasi-elastic kinematics of $Q^2 = 1.0\,\mathrm{GeV}^2$, non-zero SSAs signals at the level of a few parts 10^{-3} were clearly observed in inclusive $^3\mathrm{He}(e, e')$ reaction.

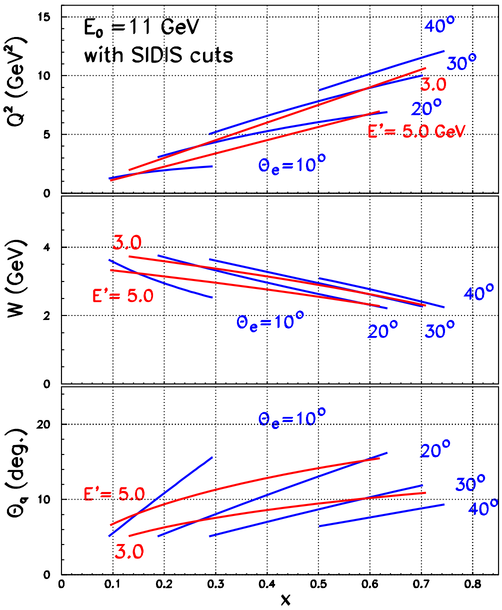

Fig. 1. – JLab SIDIS kinematics with cuts described in the text. Correlations of Q^2, invariant mass W and the virtual photon angle θ_q in respect to x are shown.

3. – SIDIS kinematics for JLab-12 GeV and considerations for a polarized proton (NH_3) target

With the planned JLab-12 GeV upgrade, polarized electron beam up to 11.0 GeV will be delivered to three experimental halls. Experiments of SIDIS reactions, especially with transversely polarized targets, will be the highlight of JLab's physics program. Given the apparent 30–40% disagreements of proton's Sivers SSAs between the published HERMES data and the preliminary COMPASS data in the valence region, and in view of the recently discovered Sivers function "sign-mismatch" between extractions from SIDIS data and from $p + p$ data in the twist-three approach, it has become extremely urgent for JLab to produce a high precision SIDIS data set on a polarized proton target in the kinematic regions of high x and high p_T. A high-luminosity polarized target will provide access to high-x kinematics while at high Q^2.

The kinematic coverage of SIDIS reactions with $E_0 = 11\,\text{GeV}$ is shown in fig. 1, with typical SIDIS cuts of $Q^2 > 1.0\,\text{GeV}^2$, $W > 2.0\,\text{GeV}$, $y = (E - E')/E < 0.85$ and corresponding to $z_h = 0.5$ we require hadron momentum $p_h > 2.0\,\text{GeV}/c$ and the missing mass of the undetected system $W' > 1.63\,\text{GeV}$ to avoid resonances in the final states. Kinematic contour lines are shown for constant electron scattering angle (θ_e) and for constant scattered electron energy (E'). Correlations of Q^2, invariant mass W and the direction of the virtual photon θ_q in respect to x are shown. It is clear that in order to cover the high-x ($0.4 \sim 0.7$) and high-Q^2 ($7 \sim 9\,\text{GeV}^2$) region, scattering angle coverage up to 30° is required. At JLab Hall A, two SIDIS experiments on a polarized ^{3}He target have been approved recently, one with a pair of large acceptance dipole-spectrometers (BigBite and Super-BigBite), the other with a large acceptance solenoid spectrometer (SoLID). Both set-ups are with detector designs capable to operate at a total luminosity of $\sim 10^{37}\,/\text{cm}^2/\text{s}$ and cover electron scattering angle up to 30°.

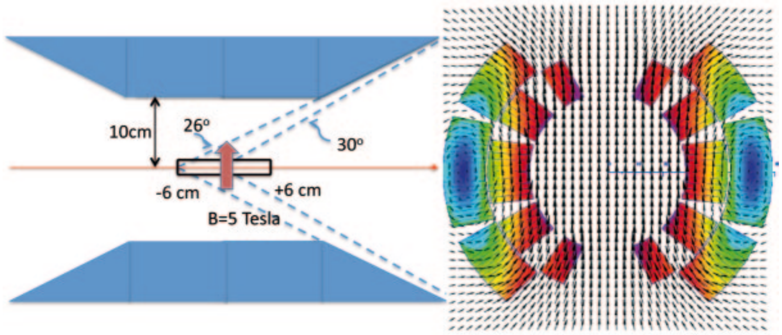

Fig. 2. – An illustration of the polarized target geometry, a cut-off view along the beam direction (left), and an illustration of magnet coil arrangements (right, end view against the beam). The target area is from -6 cm to $+6$ cm, with 5 tesla magnetic field in the transverse direction. The nominal forward opening cone is $\pm 30°$ ($\pm 26°$) from the center (upper-end) of the target. The shaded areas indicate the location of magnet coils. Target magnet is symmetric about the beam center line.

The existing SLAC/UVa/Hall-C dynamically polarized proton (NH_3) target system was build in early 1990s, and has been used in several experiments at SLAC and Hall C. It operates at a temperature of 1 K with a ^{4}He evaporation refrigerator, and with a 5 tesla magnetic field provided by a set of super-conducting magnet coils. Up to 100 nA electron beam can be taken over a target length of 3 cm, leading to a total luminosity of $\sim 5 \times 10^{35}$ /cm^2/s and a in-beam average polarization of $70 \sim 80\%$. This existing target system was designed mainly for longitudinal spin experiments, with limited forward acceptance ($\pm 16°$) when the coils are rotated to provide a transverse field. Approaching 20 years in its age, this target system has become less reliable in recent operations. Magnet quenches in 2009 caused significant delays and cancellations of experiments. Building a "next-generation" polarized proton target for high luminosity transverse spin experiments at JLab-12 GeV has become an urgent technical demand. Given the considerable costs and R&D efforts of building a new target system, an improvement in Figure-Of-Merit of a factor of four is desirable.

The new polarized proton target system will be based on the same dynamical polarization technique, operate at 1 K, with a 5 tesla magnetic field transverse to the beam direction, and a nominal 10 cm target length. The main design features include a ^{4}He evaporation refrigerator with pumps capable of removing 4 Watts of heat load, four times more powerful than the existing target system. The same target, or a similarly designed twin target, will also fit for a polarized Drell-Yan experiment at Fermilab. An illustration of the target geometry is shown in fig. 2, and major target parameters are listed in table I. A super-conducting magnet will provide a 5 tesla magnetic field, and an overall field integral of ~ 2.5 tesla meter, with a field uniformity of $\delta B/B < 10^{-4}$ over a cylindrical target volume of 12 cm in length and 5 cm in diameter. For SIDIS experiments at JLab, in which better than 5 mm target position resolution can be achieved, two 5 cm long cells 2 cm in diameter separated by 2 cm can be polarized to opposite directions using difference RF frequencies to reduce systematic uncertainties. The forward opening cone is $\pm 30°$ ($\pm 26°$) from the center (upper-end) of the target. The estimated total cost is \$2.0 millions, the construction time needed is two years.

TABLE I. – *Major design parameters of the polarized proton target.*

	NH_3 Target
Target length (cm): t	2×5.0 (or 10.0)
Density (g/cm^3): ρ	0.917
Packing factor: κ	0.55
Average in-beam polarization: P_T	0.80
Dilution factor: f	~ 0.17
Average e-beam current (nA): I	80.0
Total luminosity at JLab (cm^{-2}s^{-1}): L_{eN}	$\sim 1.5 \times 10^{36}$
Total luminosity at Fermilab (cm^{-2}s^{-1}): L_{pN}	$\sim 3.0 \times 10^{35}$
Refrigerator cooling power (Watt):	~ 4.0

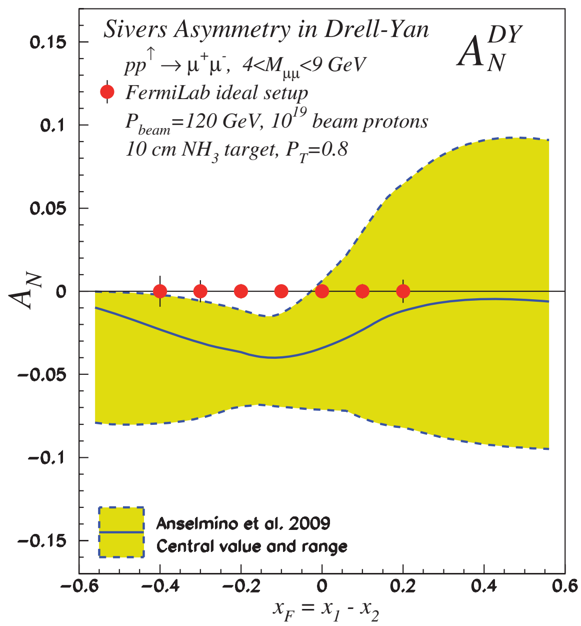

Fig. 3. – For a fixed polarized target Drell-Yan SSA experiment at Fermilab, expected statistical uncertainties of a three-year run compared with the theoretical predictions of Anselmino *et al.* [5]. The band reflects the uncertainties of Sivers functions obtained from the fit of HERMES proton and COMPASS deuteron Sivers asymmetry data.

4. – A polarized Drell-Yan experiment at Fermilab and considerations for a polarized proton target

This "modified universality" of quark Sivers distributions, with a sign change between SIDIS and Drell-Yan reactions, is an important test of the QCD gauge-link formalism, and the underline assumption of QCD factorization used to calculate the initial/final state colored interactions. A direct test of such a fundamental QCD prediction has become a major challenge to spin physics, and it has been designated an DOE/NSAC milestone. Polarized Drell-Yan experiments are currently under preparation at COMPASS and at RHIC IP2, and in the planning stage for both STAR and PHENIX upgrades at RHIC, as reported at this workshop.

We investigated the option of a fixed polarized proton target Drell-Yan SSA measurement using the 120 GeV proton beam extracted from Fermilab's Main Injector. For an "ideal" experiment setup similar to that of the on-going unpolarized Drell-Yan experiment E906, assuming a similar proton beam flux, with a 10 cm long transversely polarized proton target an averaging polarization of 80% and 18 months of beam (10^{19} beam protons), the expected statistical uncertainties of target SSA are shown in fig. 3 in comparison with theory predictions of Anselmino *et al.* [5] with the Sivers function signs reversed from that of SIDIS. In the high-x_F region, this measurement will provide the first information on sea-quark's Sivers distributions. Since SSA at this high-x_F kinematics is sensitive to the ratio of sea-quark Sivers function over sea-quark density ($f_{1T}^{\perp,\bar{u}}/f_1^{\bar{u}}$), even if both quantities are small in size, their ratio might turn out to be sizable.

In the negative x_F region, with events of large angle Drell-Yan pairs, in which SSA is sensitive to the Sivers function of the target valence quark, this measurement has the capability to clearly identify the sign change of Sivers function from that of SIDIS.

5. – Conclusions

We outlined the main design features of the new polarized proton target (NH_3) for high luminosity semi-inclusive DIS experiments at JLab-12 GeV. A similar design would also fit for a fixed target Drell-Yan SSA experiment at Fermilab using the 120 GeV proton beam from the Main Injector.

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