Exploring the structure of matter with spin: recent technological developments and selected science highlights

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Abstract. Spin is a precise and powerful experimental tool which has become essential for the study of the structure of matter. It is now routinely utilized in both lepton and hadron beam studies of the structure of matter at laboratories worldwide over energies of order $meV$ to $250 GeV$. In this overview talk, significant recent technological advances will be described and selected scientific results will be highlighted.

1. Introduction
Spin is an essential tool in the frontier study of the structure of matter. In scattering experiments, spin is widely used as a ‘knob’ to enhance sensitivity to small, important observables, e.g. parity violating scattering processes; determination of the charge form factor of the neutron $G_E(Q^2)$; and tests of fundamental symmetries. The quest to understand the origin of nucleon spin in terms of the quarks and gluons of QCD continues to be a very active area of fundamental research both in theory and experiment. Spin polarized atoms at low temperatures constitute a new regime of matter where there are fascinating experiments in progress.

Essentially all facilities worldwide focused on the study of hadronic matter utilize polarized beams and targets as essential tools to carry out their scientific program. Future progress demands more powerful and sophisticated manipulation of spin and this drives continued substantial R&D programs in spin technology in the areas of accelerators, beams, targets, and polarimeters. Here I highlight a number of important, recent technological developments, discuss selected science highlights, and describe three active areas of R&D which look to the future of spin physics.

2. Technological developments
Four significant, recent technical developments in the area of polarized beams and targets are discussed here.

2.1 JLab polarized beams: source and polarimetry
Thomas Jefferson Laboratory in Newport News, Virginia is a major international facility which provides intense, polarized beams of electrons at multi-GeV energies to study the structure of hadronic matter. The CEBAF polarized injector [1] utilizes optical pumping of strained GaAs crystals to produce beams with polarizations up to 90% and intensities of order 1 mA. These beams have been used to carry out extensive programs of spin-dependent scattering from nucleon and nuclear targets. For example, the electromagnetic form factors of both the neutron and proton have been
systematically determined with precision over a large range in momentum transfer. In addition, an extensive set of measurements of parity violating electron scattering from the proton has been in progress for over a decade. Asymmetries as small as $2 \times 10^{-7}$ have been measured with maximum charge asymmetries of order $1 \times 10^{-7}$ demanded of the beam. These latter specifications have demanded higher gun voltage and 100 kV is now routine \[2\]. Plans to increase the gun voltage to 200 kV are in preparation.

Precise measurement of the electron beam polarization is essential for the research program. Using Moller scattering from atomic electrons in an iron foil magnetized in a superconducting solenoid, a precision better than 1% has been reported \[3\].

2.2 BNL polarized proton beam: development and polarimetry
The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory, Upton, NY is also the world’s first polarized proton collider with 65% beam polarization at 200 GeV center-of-mass energy routinely attained. The polarization of the protons is measured to about ±5% with both Carbon CNI and polarized gas jet techniques. In 2009, polarized protons were collided at a center-of-mass energy of 500 GeV for the first time \[4\]. In this commissioning run, beam polarizations of about 45% were reached. A detailed scan of polarization transmission efficiency as a function of vertical betatron tune showed that the RHIC operating vertical tune in that run was too close to the snake resonance at $Q_y=0.7$. The data suggest that higher beam polarization can be attained in RHIC if the vertical tune is placed at 0.675 or lower. This will be investigated during the next run.

2.3 COSY: towards polarized antiprotons
Polarized antiproton beams with sufficient intensity would provide a new tool to carry out important studies of hadron structure, e.g. measurement of polarized Drell-Yan would allow access to nucleon transversity in a new way. A scheme to preferentially scatter one spin-state of a beam of antiprotons stored in a ring is under development using the Cooler Synchrotron (COSY) facility, Forschungszentrum, Jülich, Germany. Beams of protons are scattered from a polarized hydrogen target in a low-β section of the ring. If the COSY tests are successful, then it is planned to move the target to the Antiproton Decelerator at CERN \[5\].

2.4 Polarized targets: FroST frozen spin target
The Jefferson Lab Frozen Spin Target (FroST) \[6\] is a nuclear-spin polarized target utilized for scattering experiments with a tagged photon beam inside the CEBAF Large Acceptance Spectrometer Toroid (CLAS). Protons in frozen, 1.5mm diameter beads of butanol are highly polarized via the technique of dynamic nuclear polarization at a temperature of about 0.3 K inside a 5 Tesla polarizing magnet. Microwaves transfer the polarization from the electrons to the protons. A dilution refrigerator is used to cool the target material. When the ultimate target polarization is reached, the microwave generator is turned off, and the refrigerator cools the target beads to a temperature of 30 mK. The target polarization is routinely above 80% and the direction of the spin can be oriented using holding fields (both longitudinal and transverse) of order 0.55 T at a temperature of 30 mK. With photon beam on target, the relaxation rate is of order 1% per day.

3 Selected science highlights
3.1 Charge and magnetism in the nucleon
The determination of the elastic form factors of the proton and neutron has been in progress for about sixty years. However, within the last decade the full utilization of spin observables has produced important new insights. For example, the ratio of the proton charge to magnetic form-factors shows a dramatic decrease at moderate momentum transfers, which is widely believed to be due to the contributions beyond single photon exchange. The neutron charge form factor has been determined
experimentally with precision comparable to that of the proton form factor using measurement of spin observables at several laboratories in Europe and the U.S.

Figure 1 shows recent data [7] from JLab on the determination of the proton form factor ratio $\mu_p G_p^E/G_p^M$ at high momentum transfer. This ratio is tending to zero, far from the dipole approximation value of unity. These data were obtained using a recoil polarimeter to determine the transfer in polarization from a polarized electron beam scattering from an unpolarized hydrogen target.

Figure 2 shows recent data [8], also from JLab, on the neutron form factor ratio $\mu_n G_n^E/G_n^M$ at high momentum transfer. These data were obtained in spin-dependent quasielastic electron scattering of polarized electrons from a polarized $^3$He target.
A worldwide program of parity violating electron scattering to quantify the contribution of strange quark to the magnetism and charge of the proton has been in progress for more than two decades. In the past year, the G0 experiment at JLab has published an analysis including both backward and forward angle data [9] at \( Q^2 = 0.22 \) and 0.63 (GeV/c)^2. The results indicate strange quark contributions \( \leq 10\% \) of the charge and magnetic nucleon form factors at these momentum transfers.

3.2 Complete photon experiments at ELSA/Bonn

Complete photon experiments, i.e. both circularly and linearly polarized photon beam incident on a polarized proton target, are a powerful means to study the resonance structure of the proton. At the ELSA accelerator at the University of Bonn, Germany a suite of detectors has been implemented together with polarized beam and target to carry out a program of measurements [10] of this type, e.g. \( \gamma + p \rightarrow p + \pi^0 \), where the initial state particles are fully polarized. The angular distribution of spin asymmetries is particularly sensitive to interference between proton resonances.

3.3 3D exploration of the nucleon

One of the major new directions in QCD over the last decade is the quest to understand the nucleon at high energies as a three dimensional object [11]. It has been realized that the longitudinal parton distributions discovered at SLAC in the 1960’s are only limits of more general parton distributions (GPDs). The discovery by HERMES [12] of non-zero transverse asymmetries in semi-inclusive scattering has generated substantial interest in new transverse momentum distributions (TMDs) which are sensitive to the motion of the partons in the nucleon. For example, theoretical studies of the HERMES pion data on the proton successfully predicted [13] the observed asymmetries from COMPASS on the deuteron [14]. These studies will continue at COMPASS and JLab.

3.4 Origin of the spin of the nucleon

The origin of the spin structure of the nucleon in term of the fundamental constituents of QCD is a major focus. From spin-dependent DIS experiments, the contribution of the quarks is known to be about 25\%. At the RHIC polarized collider, the contribution of the gluons in a relatively narrow \( x \) range has been determined [15,16] to be small. Under some reasonable assumptions, the contribution of the gluons is not larger than that of the quarks and could be smaller [17]. If this is correct, then at least half or more of the proton spin must arise from the orbital motion of the quarks (both valence and sea) and gluons. One difficulty at present is that it is unclear how to determine experimentally the orbital angular momentum of the partons in the nucleon. It is widely believed that the TMDs mentioned above contain information on the motion of the partons in the nucleon but unambiguous determination of the contribution to the proton’s spin remains an open and active line of research.

Over the last two years, a long awaited and important new electroweak technique to study the quark structure of the proton has been realized. At the RHIC polarized proton collider, W\(^\pm\) bosons have been produced in proton-proton scattering at 500 GeV center-of-mass energy in the interaction of constituent quark and antiquark. The W\(^\pm\) decay to e\(^\pm\) and the final state lepton is detected. Through careful analysis and subtraction of the QCD background the events plotted as a function of the transverse energy show \( \approx M_{W}/2 \) a characteristic Jacobian peak at \( \approx M_{W}/2 \). The STAR experiment was able to identify 462(139) candidate events for W\(^\pm\). This allowed the formation of the asymmetry shown in Figure 3. The W\(^\pm\) production probes a combination of the polarization of the quark and antiquark. The measured A\(^{W\pm\rightarrow p\pi^0}\) is indeed negative demonstrating quark dominance. The central value of A\(^{W\pm\rightarrow p\pi^0}\) is positive as expected with a larger statistical uncertainty. The \( A_L \) results are consistent with predictions using polarized quark and antiquark PDFs constrained by inclusive and semi-inclusive DIS measurements. Future 500 GeV running at RHIC is expected to determine the quark polarizations with substantially better precision than heretofore.
Figure 3. Longitudinal single-spin asymmetry, $A_L$, for $W^\pm$ events from [18] as a function of the leptonic pseudorapidity, $\eta$, for $25 < E_T < 50$ GeV in comparison to theory predictions.

4 Future perspective

Continued progress in the study of the structure of matter drives the development of new, more powerful capabilities in polarized beam delivery and manipulation. Here I highlight three areas of considerable activity.

4.1 Fast spin reversal in RHIC

Fast spin reversal of polarized beams is acknowledged to be essential in minimizing systematic uncertainties associated with spin asymmetry measurements. At the RHIC polarized proton collider, an effort is underway to implement fast spin reversal of the stored polarized proton beam. A new spin flipper design has been developed [20] which is compatible with the spin tune of $1/2$ in RHIC with its two pairs of full Siberian snakes.

4.2 Electron Ion Collider (EIC) design

The enormous potential of a high luminosity polarized electron-ion collider to explore the fundamental structure of matter is widely accepted [21]. The polarized beam capability is essential to explore the spin structure of the nucleon at high energies where the contributions of the sea quarks and gluons are expected to dominate. In the U.S., an electron-ion collider has been identified by the QCD community as the next major accelerator to be realized in about a decade. EIC machine designs are in progress at both BNL/RHIC [22] and JLab/CEBAF [23]. In Europe, an electron-ion collider is under consideration both at the LHC at CERN, Geneva, Switzerland [24] and also at the future FAIR facility at GSI, Darmstadt, Germany [25]. In the EIC machine designs, there are a number of aspects which extend beyond present capabilities in polarized beam delivery and manipulation, e.g. high intensity polarized electron source; figure-8 storage rings; polarized $^3$He ion source; and 1% ion polarimetry.

4.3 Development of high intensity polarized electron sources

Motivated in large part by the requirements of eRHIC, research is underway at both MIT-Bates [26] and at BNL [27] to develop a polarized electron source with 1-2 orders of magnitude more intensity than the present state-of-the art. A fundamental limitation with the optically pumped GaAs source is
due to damage caused by ions backstreaming to the cathode. Typically, the gun is cylindrically symmetric around an axis on which the incident laser beam and the extracted electrons travel. At Bates, by using a ring of laser light rather than a spot, the region of optical pumping on the crystal is made distinct from the area where ion damage is largest. A substantial improvement in the lifetime of the crystal has been observed. Further, at Bates a new water-cooled cathode is under development to allow substantially higher laser powers.

At BNL, a concept [27] where the current from \( \approx 20 \) cathodes is combined is under development. The current required from each cathode is significantly lower than the total current and thus the specifications are closer to present state-of-the-art.

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