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Experiments on Nucleon Spin-Dependent Structure Functions

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ABSTRACT

In this presentation, the earlier measurements of the spin-dependent structure function of the proton in experiments at SLAC and at CERN are reviewed. In addition several new deep inelastic scattering experiments to measure the spin-dependent structure functions of the nucleon, both proton and neutron, will be discussed.

1. Introduction

An understanding of the internal structure of the nucleon as probed by deep inelastic scattering (DIS) requires a knowledge of four independent functions of the scaling variable x, where $x \equiv Q^2/(2M\nu)$ in the usual notation. Two of these functions, $F_1(x)$ and $F_2(x)$, are independent of the nucleon spin, and the other two, $g_1(x)$ and $g_2(x)$, depend on the nucleon spin. Much of what we know about nucleon structure, the basic theory of quantum chromodynamics, sum rules, and the validity of models of the nucleon such as the quark-parton model rests on the extensive experimental information obtained about $F_1(x)$ and $F_2(x)$ in many unpolarized DIS experiments.[1]

Knowledge of $g_1(x)$ and $g_2(x)$ allows different and important tests of quantum chromodynamics, in particular via sum rules, and provides crucial, sensitive tests of our models of nucleon structure.[2] Relatively little experimental data have been obtained on $g_1(x)$, with relatively poor precision, and no information has been obtained on $g_2(x)$.

The most fundamental sum rule is the Bjorken polarization sum rule, originally derived from current algebra, and now recognized as a rigorous consequence of QCD in the scaling limit. It reads

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$$S_{Bj} \equiv \Gamma_1^p - \Gamma_1^n = \frac{1}{6}\left|\frac{g_A}{g_v}\right| = 0.209(1) \tag{1}$$

in which Γ_1 is the first moment of g_1, i.e. $\Gamma_1 = \int_0^1 dx\, g_1(x)$, and $g_A(g_V)$ is the axial (vector) coupling constant in neutron beta decay. The first order perturbative correction in QCD modifies S_{Bj} slightly:

$$S_{Bj} = \frac{1}{6}\left|\frac{g_A}{g_V}\right|\left(1 - \frac{\alpha_s(Q^2)}{\pi}\right) = 0.191(2) \text{ at } Q^2 = 11\ (\text{GeV/c})^2 \tag{2}$$

Additional sum rules for the proton and neutron separately are model-dependent with the principal assumption that the strange quark sea is unpolarized. Including the first order QCD perturbative correction, the Ellis-Jaffe sum rules are:

$$\Gamma_1^p = 0.189 \pm 0.005, \quad \text{and} \quad \Gamma_1^n = -0.002 \pm 0.005 \tag{3}$$

2. Earlier Experiments

Measurements of the deep inelastic scattering of polarized electrons and muons from polarized nucleons can provide information on the spin-dependent structure functions of the proton, $g_1^p(x)$ and $g_2^p(x)$, and those of the neutron, $g_1^n(x)$ and $g_2^n(x)$. Two experiments, SLAC expt. E80/E130 (Bielefeld-SLAC-Tsukaba-Yale Collaboration)[3] and CERN expt. NA2' (European Muon Collaboration)[4] have determined the spin-dependent structure function $g_1^p(x)$. In the experiments the longitudinal spin-dependent asymmetry of the cross section is the principal quantity measured, $A = (d\sigma^{\uparrow\downarrow} - d\sigma^{\uparrow\uparrow})/(d\sigma^{\uparrow\downarrow} + d\sigma^{\uparrow\uparrow})$, in which the arrows designate the lepton and proton spin directions. Using A together with $F_2(x)$ and $R(x)$, the ratio of the transverse to longitudinal virtual photon-proton absorption cross sections, $g_1(x)$ is obtained from

$$g_1(x) = \frac{A_1(x)}{2x}\frac{F_2(x)}{(1+R)}. \tag{4}$$

in which $A_1(x) = A(x)/D(x)$, where D(x) is the depolarization factor for the virtual photon. The quantity A_1 is the virtual photon-proton asymmetry, $A_1 = \frac{\sigma^{\uparrow\downarrow} - \sigma^{\uparrow\uparrow}}{\sigma^{\uparrow\downarrow} + \sigma^{\uparrow\uparrow}}$, in which the arrows designate the spin directions of photon and proton.

In the experiment the counting rate asymmetry Δ is measured.

$$\Delta = \left(N^{\uparrow\downarrow} - N^{\uparrow\uparrow}\right) / \left(N^{\uparrow\downarrow} + N^{\uparrow\uparrow}\right) = A P_b P_T f \ , \tag{5}$$

where P_b (P_T) is the beam (target) polarization, f is the dilution factor for the target (ratio of the number of polarizable protons to total number of nucleons). Since the product of P_b P_T f is small, the counting rate asymmetry Δ is usually less than 0.01, so high statistics are required and false asymmetries must be kept small.

The SLAC experiment used a high polarization (80%) electron beam with energies up to about 22 GeV based on an atomic beam source of low energy polarized electrons and a polarized butanol target produced by dynamic nuclear polarization. Data were obtained on A_1^p in the interval x = 0.1 to 0.7 (see Figure 1). The first moment of $g_1^p(x)$ was evaluated using the data together with extrapolations and gave $\Gamma_1^p = 0.17 \pm 0.05$, in reasonable agreement with the Ellis-Jaffe sum rule, $\Gamma_p = 0.189 \pm 0.005$.

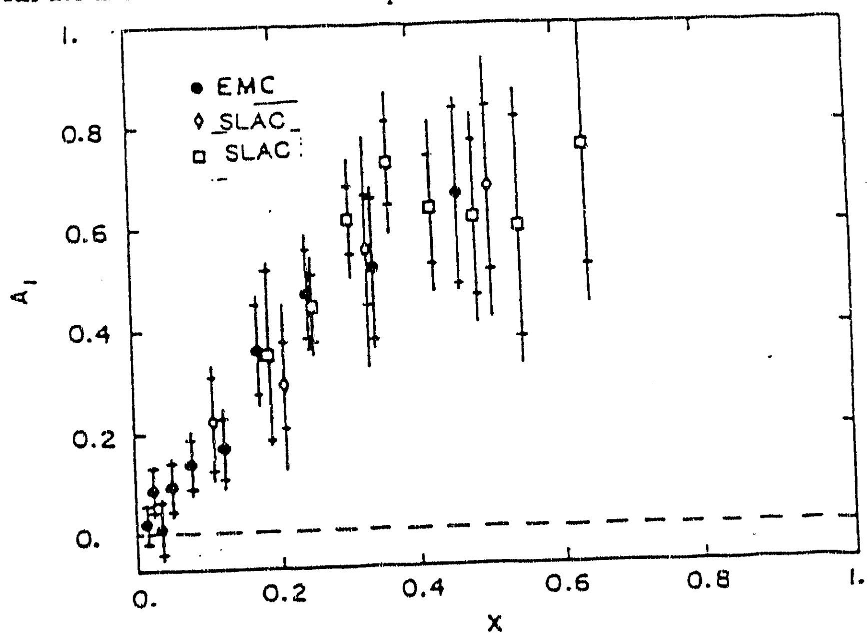

Figure 1: The asymmetry A_1 versus x (linear plot)

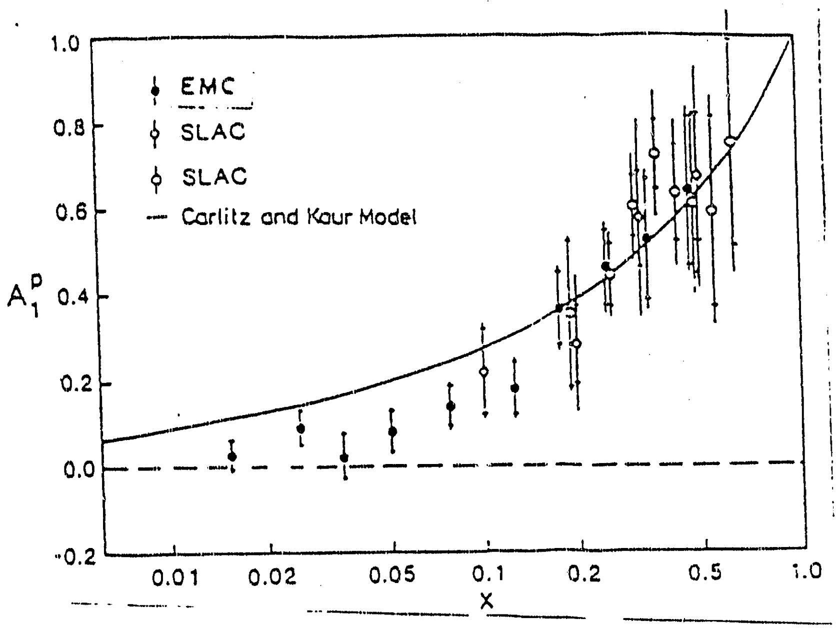

Figure 2: The asymmetry A_1 versus x (semilog plot)

The CERN experiment NA2' of the EMC group used a polarized muon beam in the range of 100 to 200 GeV obtained from pion decay and a very large polarized proton target of NH_3. Data were obtained on A_1^p in the interval x = 0.01 to x = 0.7, and hence extending our knowledge to lower x values (see Figure 1 and Figure 2). In the x-region of overlap the SLAC and CERN values are in good agreement and we note that the SLAC and CERN data confirm, as predicted, that A_1 scales and hence is only a function of x and not of Q^2. The CERN experiment by extending data on A_1 to lower x showed that the Ellis-Jaffe sum rule on Γ_1^p was significantly violated. Figure 3 shows the combined CERN and SLAC data on the test of the sum rule, where the extrapolation to x = 0 is based on a smooth behaviour of $g_1(x)$ for $x \rightarrow 0$, as expected from Regge theory.

The discrepancy of Γ_1^p (expt.) and Γ_1^p (theor.) implies in the simplest interpretation that, firstly, the strange sea quarks are polarized and, secondly, according to the naive quark-parton model the quark spins do not contribute to the proton spin. This discrepancy and its simplest interpretation has stimulated enormous theoretical interest, with many new suggestions of how gluons and orbital angular momentum could contribute to the proton spin.[5] In addition a new generation of experiments on spin-dependent structure functions is being undertaken.

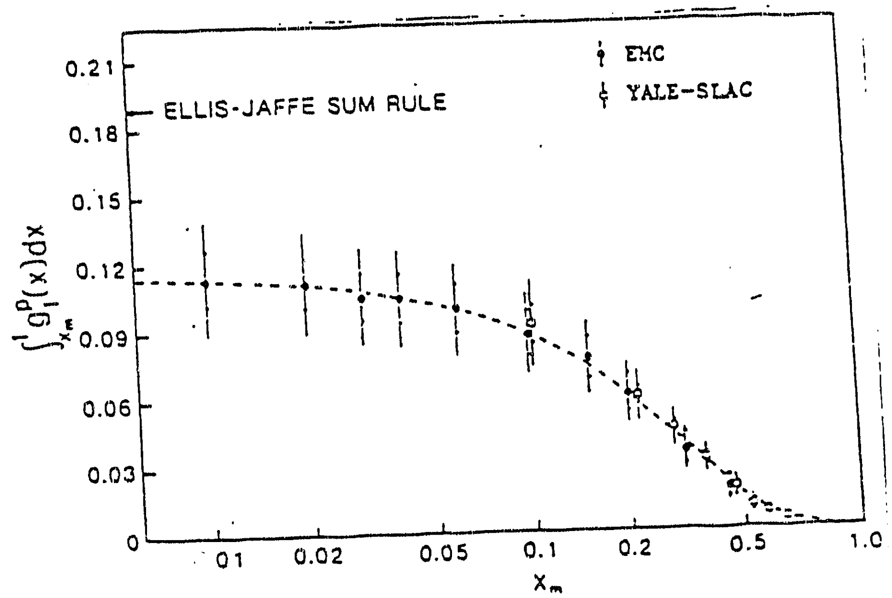

Figure 3: Evaluation of $\int_x^1 dx\, g_1(x)$.
The Ellis-Jaffe sum rule value is shown for comparison.

3. New Generation of Experiments

Because of the great current interest in this field a group of new experiments is being initiated to measure the spin-dependent structure functions of the proton and neutron. Two are fixed target experiments, and two involve internal targets in storage rings.

One experiment at CERN, NA47 by the Spin Muon Collaboration (SMC),[6] uses a polarized muon beam of 100 to 200 GeV and a large polarized target with butanol, hydrogenated or deuterated. A second approved experiment at SLAC (E142)[7] will use a 23 GeV polarized electron beam obtained with a GaAs type source and a polarized ^3He gas target. In addition at SLAC plans are being developed for experiments with a conventional solid target with NH_3 or ND_3, polarized by the method of dynamic nuclear polarization. These experiments would first use an electron beam with 23 GeV energy and later one with 50 GeV energy.

Two experiments of an interesting new type are being planned which would use a polarized electron beam of a storage ring and an internal target of polarized atoms - H,D or ^3He - as an atomic beam jet or as a stored gas. One is at HERA[8] and would use the electron beam in the electron storage ring of energy 30 to 35 GeV and a gas of polarized atoms stored in a bottle. This experiment designated HERMES has been proposed and full approval awaits the development of a polarized electron beam in the storage ring. A second experiment would use a polarized electron beam in LEP and a polarized jet atomic beam of H or D. A letter of intent has been submitted for this experiment.[9]

In this short article we shall discuss principally the SMC experiment at CERN since it is the farthest advanced and indeed has obtained initial data in a long run this summer. A fine review of all these new experiments[10] and presentations by their proponents are included in the Proceedings of the High Energy Spin Conference at Bonn in October, 1991.[11]

For the CERN experiment a modified muon beam line optimized for our data-taking with $E_\mu = 100$ GeV is in operation. The beam intensity is 4×10^7 μ^+/burst from a proton beam of 3×10^{12} on target with a spill time of 2.5 sec and a repetition interval of 14 sec. About 80% of the beam passes through the 1 m long polarized target of 5 cm diam, and the unscattered muon beam is focussed downstream of the spectrometer into the muon polarimeter. The beam was designed to minimize halo. The polarized target is essentially the same as that used in the earlier CERN experiment by EMC and contains upstream and downstream halves polarized in opposite directions. However, the target material is deuterated butanol + EHBA-Cr^V. With H = 25 kG and T = 0.5 K, an average deuteron polarization P_D of 25% was obtained (see Figure 4). The direction of the polarization in each target was reversed every 24 hours by the conventional method of depolarization with microwaves and repolarization in the opposite direction, which required 1 to 2 hrs under smooth operation. Significant changes in the acceptance and efficiency of the spectrometer are not expected between changes in polarization direction. A very efficient system of bead production was developed and a much improved target loading system was used. Substantial difficulties were experienced with the cryogenic system.

The forward muon spectrometer (Figure 5) has undergone important upgrades by NMC and SMC since the NA2' EMC experiment.[12] These include reworking of the drift chamber W12, the addition of two modules to the drift chamber W45, and reworking of the beam momentum system BMS and of many of the MWPC detectors. In addition, the drift chamber array downstream of the absorber wall is completely replaced by a streamer tube array ST67 together with a drift tube array DT67. The track reconstruction efficiency should be substantially improved compared to EMC. For off-line analysis a major set of SUN workstations has been acquired.

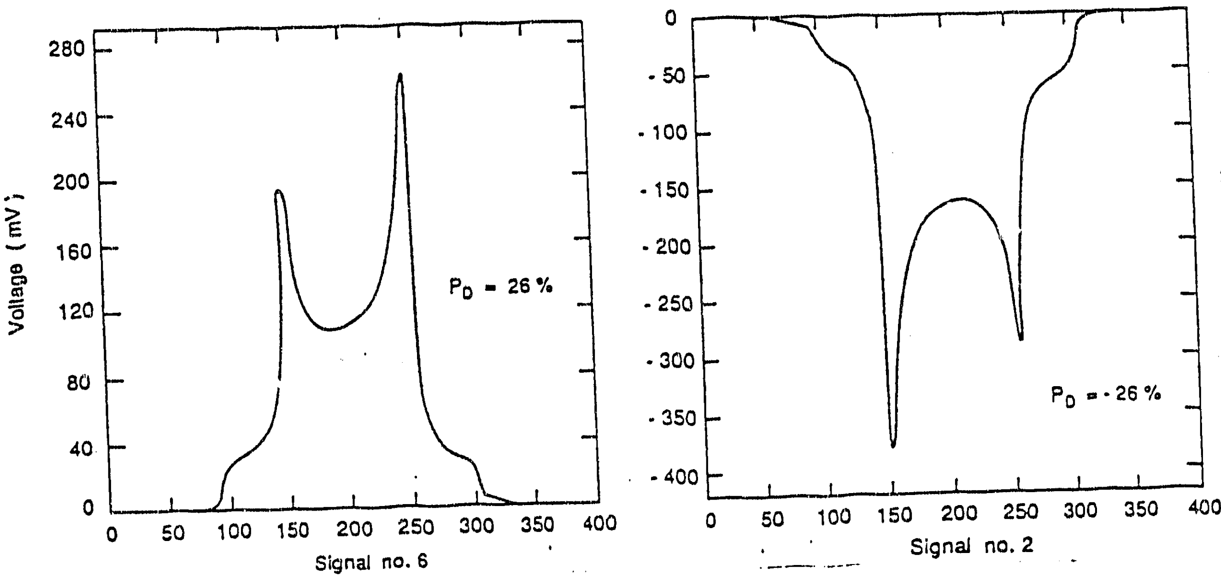

Figure 4: Signals for enhanced deuteron polarization

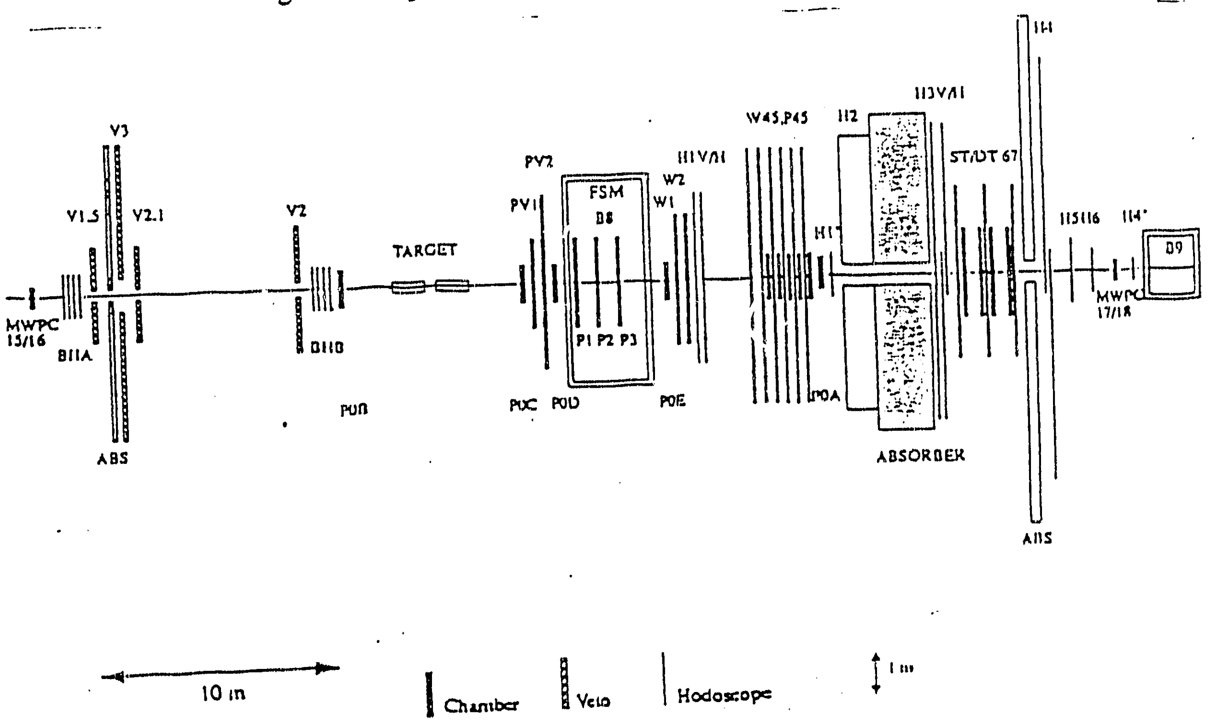

Figure 5: The SMC forward spectrometer

A polarimeter has been built (Figure 6) to measure the muon beam polarization P_μ by the muon decay method, which relies on the dependence on polarization of the decay ($\mu^+ \to e^+ \nu_e \nu_\mu$) e^+ energy spectrum. This polarimeter is located downstream of the muon spectrometer and uses the unscattered, refocussed muon beam. A measurement of P_μ with a statistical accuracy of 5% should require about 8 hrs.

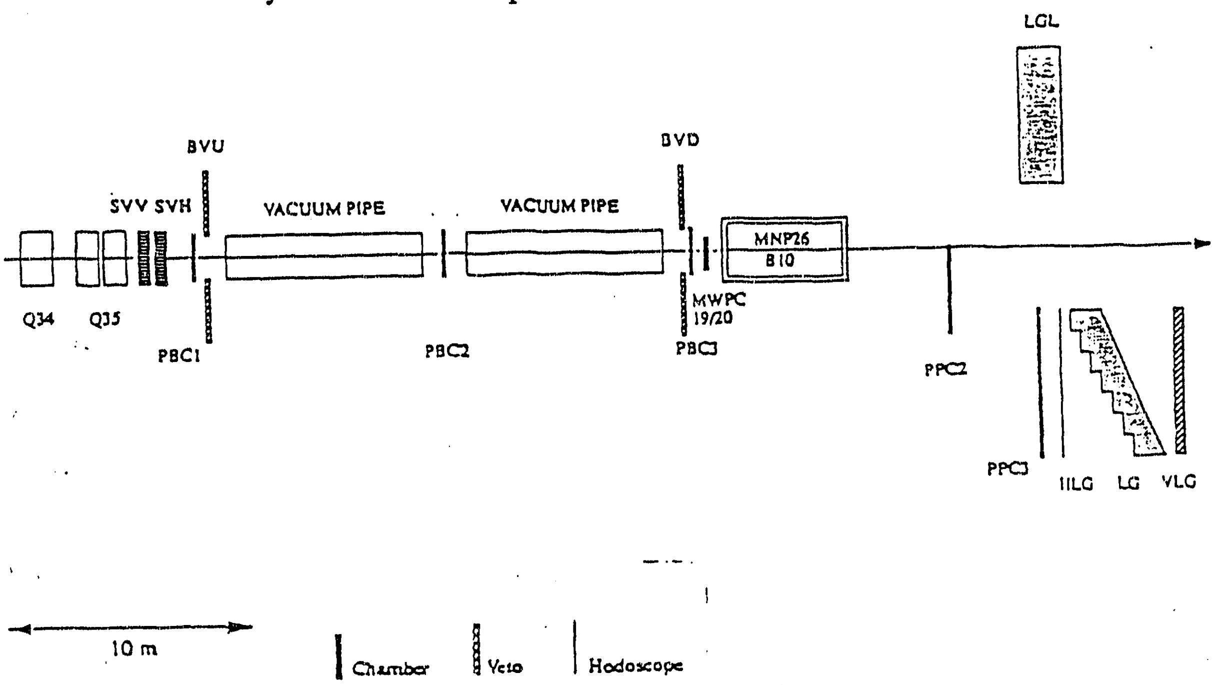

Figure 6: The SMC Muon - polarimeter

In a long run of some 4 months this summer, the entire apparatus has been checked out and appears thus far to operate successfully. The data collection rate agrees with that projected in the SMC proposal. With about 10 days of successful data taking with E_μ=100 GeV we estimate that we have acquired about 0.5 10^6 useful events. For comparison, the total number of events in the EMC experiment NA2' in 1984-85 was 1.1 x 10^6. About 2 weeks of running time remain with E_μ=200 GeV. With the new triggers implemented by NMC, the SMC experiment has an x range extending from $x=5x10^{-3}$ to x=0.7 with $Q^2>1$ $(GeV/c)^2$.

For SMC data-taking in the coming years we will have major new components and features in our polarized target. First there is a new superconducting solenoid/dipole magnet under construction at Saclay which will provide a longer (by 50%), more homogeneous, 2.5 T magnetic field ($\Delta H/H<2x10^{-5}$) which should increase the data collection rate and provide a higher value of deuteron polarization. The dipole field of 0.5 T will allow us to reverse the polarization direction by the method of field reversal within a period of about 30 m. It also makes it possible to have a transverse direction of the polarization and hence to measure A_2. A major new dilution refrigerator compatible with the new magnet system is being constructed at the Helsinki University of Technology and at CERN.

Table 1

Brief Description of Experiments and of Proposals to Measure Spin Structure Function Asymmetries (1991)

Collaboration/Site	Beam	Polarized Target
E142/SLAC	< 23 GeV, $\vec{e}$	^3He, high pressure
E143/SLAC	< 23 GeV, $\vec{e}$	Solid NH_3, ND_3
HELP/CERN	$\vec{e}$, (LEP)	H,D jet targets
HERMES/DESY	30 - 35 GeV, $\vec{e}$	H, D, ^3He, (windowless)
SMC/CERN	100-200 GeV, $\vec{\mu}$	Solid butanol, deuterated butanol, twin targets

Table 1 lists beam and target configurations of five collaborations, which are in various stages of programs to measure A_1^n and A_1^p.

E142/SLAC is building equipment in preparation for scheduled beam in the fall of 1992. E143/SLAC, a new collaboration (SLAC, Virginia, American, Livermore) is preparing a proposal for an experiment nearly identical in beam energy, x, and Q^2 coverage, and luminosity using a polarized target of solid NH_3 and ND_3 targets.

HERMES/DESY has recently completed a six day run measuring the asymmetry in 180^o Compton scattering of 2.41 eV circularly polarized photons from the electron beam in HERA. The data are currently being analyzed. The density and polarization of gas targets have been studied by measuring the yield and asymmetry in the elastic scattering of alpha particles from the target gas (hydrogen), with encouraging preliminary results.

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