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MEASUREMENT OF NUCLEON SPIN STRUCTURE WITH 50 GEV POLARIZED ELECTRONS*

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ABSTRACT

Calculations are presented on the precision achievable for the measurement of nucleon spin structure functions using a 50 GeV polarized electron beam scattering off polarized proton, deuterium, and ^{3}He targets. The main advantage of such a program is the high statistical precision of the measurements. The implications for testing QCD sum rules and studying the Q^2 evolution of the nucleon spin structure functions are reviewed.

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I. INTRODUCTION

A three and a half sigma discrepancy between the prediction of a relatively weak QCD sum rule by Ellis and Jaffe [1] and a first measurement of the proton spin structure function at low x [2] has generated a plethora of experiments at particle physics labs around the world. In the next round, these experiments will attempt to test the Bjorken sum rule [3] by measuring the neutron spin structure function for the first time. As the results emerge, one of three scenarios will appear: a dramatic violation of the Bjorken sum rule, a marginal violation of the sum rule, or a confirmation of the sum rule.

A large discrepancy between the results of the spin structure function measurements and the Bjorken sum rule would threaten QCD. The Bjorken sum rule is generally regarded as a theoretically solid relation, derived from current algebra prior to QCD. QCD enters into the Bjorken sum rule testing in that it predicts only small corrections to the sum rule for finite Q^2. If the sum rule is violated experimentally, then this will imply that the true corrections to the sum rule are large. In this case, QCD would have failed to account for the behavior of the spin structure of the nucleons.

If the sum rule is violated mildly, then future experiments will strive to measure the spin structure functions with a higher precision in order to pin down whether the problem is a true sum rule violation or an experimental difficulty. Precision measurements will be necessary to untangle effects such as higher twists and the asymptotic behavior of the structure functions at low x. At the same time, higher order QCD corrections to the Bjorken sum rule will become a fashionable topic for study.

Finally, if the sum rule is confirmed, then precision measurements of the nucleon spin structure functions will still serve to test nucleon spin models and to calibrate nucleon spin studies in other particle and nuclear physics applications. Independent of the scenario, precision measurements of the spin structure functions will be valuable.

A 50 GeV polarized electron scattering program to study the nucleon spin structure functions at SLAC may make the definitive measurements of these structure functions to a high precision over a wide range in x and Q^2, possibly better than any other electron scattering programs. This paper reviews the issues of sum rules, x and Q^2 ranges and precision achievable with such a program at SLAC.

Data on spin structure functions is scarce. The existing proton spin structure function data has been measured over a wide range of x but only with limited statistical precision. Figure 1 shows the world's data on the asymmetry measurements for proton spin structure function. On a point to point basis, the statistical uncertainties are about twice as large as the systematic uncertainties. The neutron spin structure function, on the other hand, has not yet been measured.

For testing sum rules, the large point to point statistical uncertainties do not have a large impact. Since the measurements as a function of x are assumed to be statistically uncorrelated, the total statistical error on the integral becomes small.

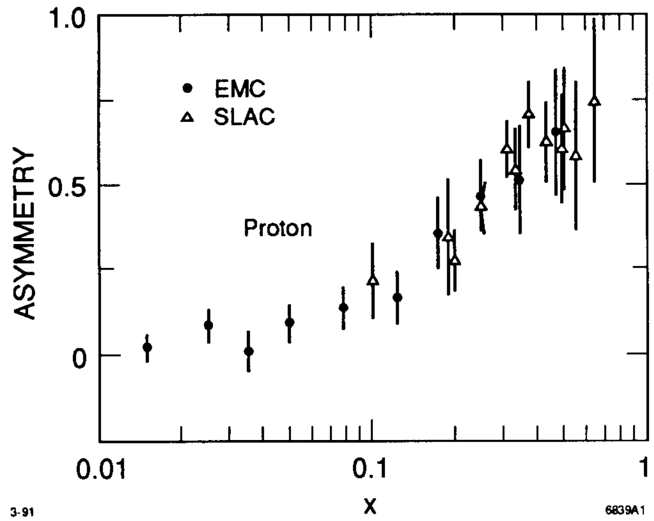

Fig. 1. World's data on the proton spin structure function measurements. Proton asymmetries versus x from the EMC experiment and SLAC experiments E80 and E130.

However, statistical precision does play an important role in testing sum rules in so far as it allows fits to the asymptotic behavior of the spin structure function at low x. Contributions to the sum rule from low x regions beyond the experiment's capabilities may be significant and lend a large theoretical uncertainty to the integral. Systematic uncertainties coming from the beam and target polarizations scale for all points with the values of the measured asymmetries, implying that the sum rule can only be tested as well as the relative systematic error. Future testing of sum rules should be limited exclusively by systematic and theoretical uncertainties.

A review of the important quantities and sum rules that appear in the nucleon spin structure function study are given in Table 1.

ELLIS JAFFE SUM RULE

$$\int g_1^p(x)dx = \frac{1}{18}[9F - D] = 0.189$$

$$\int g_1^n(x)dx = \frac{1}{9}[3F - 2D] = -0.002$$

BJORKEN SUM RULE

$$\int g_1^p(x) - g_1^n(x)dx = \frac{1}{6}(\frac{g_a}{g_v}) = 0.191$$

Three experimental programs have been approved to measure the nucleon spin structure functions.

$g_1^p(x)$	Proton spin structure function
$g_1^n(x)$	Neutron spin structure function
$A_1^p(x)$	Proton spin asymmetry
$A_1^n(x)$	Neutron spin asymmetry
$A^{raw} = A_1 P_t P_b f D$	
A^{raw}	Measured raw asymmetry
P_t	Target Polarization
P_b	Beam Polarization
f	Fraction of polarized nucleons in the target
D	QED virtual photon depolarization factor

Table 1. Fundamental parameters in spin structure function studies.

At CERN, the SMC collaboration has launched a program to measure the spin structure functions of the proton and deuterium using high energy (100 to 200 GeV) muon beams. This program will cover the largest range in x and Q^2 due to the high beam energy. The experiment will begin running this year and could possibly do the best job at testing the sum rules due to the low x accessibility. But their low beam current diminishes the statistical power of the structure function measurement. Systematic uncertainties will also be significant due to the long spin reversal times of the polarized targets and the inability to reverse the beam polarization.

At DESY, an experimental program has been conditionally approved to scatter 35 GeV polarized electron beams produced in the HERA storage ring off polarized internal gas targets of protons, deuterium and ^{3}He. The main advantage of this program is the ability to scatter the beam off pure nuclei free of background from unpolarized target materials. Data collection should occur with a high rate. However, this program requires a demonstration of transverse polarization of the electron beam at HERA before it is granted full approval.

At SLAC, experiment E142 will scatter 23 GeV polarized electrons off a polarized ^{3}He gas target in End Station A. The advantage of this experiment is the high counting rate, well defined scattering angles and fast spin reversals (possible every 8 ms). Its disadvantage is the limited x range (i.e., low energy beam) and the plan to only measure with a ^{3}He target. Nuclear uncertainties in the extraction of the neutron information from ^{3}He are expected to be small. But without the deuterium measurement for confirmation, these uncertainties will enter significantly in testing sum rules and nucleon spin models.

In summary, the motivations to continue the measurements of spin structure functions are:

- to confirm and study the "violation" of the Ellis Jaffe sum rule
- to test the Bjorken sum rule
- to study the Q^2 dependence of the spin structure functions
- to study the x^{-n} asymptotic behavior of the spin structure functions at low x
- to test models of nucleon spin structure.

The rest of this report concentrates on how well a 50 GeV electron beam program at SLAC would measure these structure functions. Section 2 describes briefly the experimental set up and, in particular, the assumptions on the performance of the beam, targets and spectrometers. The set up is modeled after the E142 experiment and can be regarded as an extension of this detection philosophy. Section 3 presents the statistical precision achievable using polarized proton, deuterium and ^{3}He targets. The issue of Q^2 studies and the relationship between systematic uncertainties and sum rule testing is briefly discussed. Section 4 mentions some of the difficulties particular to a 50 GeV beam. The final section summarizes the recommendations reviewed in this report.

II. EXPERIMENTAL SET UP

Polarized Beam

The seriousness of upgrading the A line at SLAC to reach energies near 50 GeV with polarized electron beams was initially investigated by D. R. Walz [4], recently reviewed by a committee from the EFD division at SLAC [5] and reported on at a 50 GeV workshop at SLAC [6]. The basic conclusion of this study was that a modification of the A line with existing SLAC magnets would be reasonable in cost and in effort.

The assumptions for measuring nucleon spin structure functions with such a beam delivered to End Station A are given in this section. The beam will run in a SLED (SLAC Energy Doubler) mode. Table 2 summarizes the beam parameters.

Energy	50 GeV
Polarization	40 %
Intensity	10^{11} electrons/pulse
Rate	120 Hz
Pulse length	100 ns

Table 2. Electron beam conditions.

This is the highest intensity achievable at 50 GeV and would only be used with the ^3He gas targets, identical to experiment E142. For the proton and deuterium measurements using ammonia targets, the assumption is that a maximum intensity of 5 x 10^9 e^- per pulse is possible before radiation damage becomes too severe. For all the calculations in this report, the assumption for the electron beam intensity with the ammonia targets is 5 x 10^{9} e^- per pulse independent of the pulse length or beam energy.

It is not inconceivable that high polarization cathodes [7] could be available for running by the time of a 50 GeV fixed target program, greatly enhancing the power of a polarized electron physics program. A 40 % beam polarization is assumed in this report for the calculations.

Polarized Targets

The polarized targets to be built for the 50 GeV program would be a solid NH_3 cryogenic target for measuring the proton spin structure function and a solid ND_3 target and a high density ^3He gas target for extracting the neutron spin structure function. Polarized hydrogen and deuterium gas targets do exist, but their densities are too low by about eight orders of magnitude to be usable in an End Station A experiment. For this reason, only solid polarized NH_3 and ND_3 targets are considered. The ammonia targets have demonstrated the best resistance to radiation damage by the SLAC beam [8], the most significant problem for such targets.

The target assumptions for the calculations in this report are given in Table 3.

	NH_3	ND_3	^3He Target
Density	0.6 gm/cc	0.7 gm/cc	3 x 10^{20} atoms/cc
Polarization	80 %	40 %	50 %
Target length	4 cm	4 cm	30 cm
Unpolarized Backgrounds	10 %	10 %	2 x 0.1 mm windows
Average Beam Current	100 nA	100 nA	10 μA

Table 3. Polarized target conditions.

The higher density targets suffer from radiation damage at high currents; however, in terms of luminosity the number of scattered electrons per pulse for all targets is comparable.

End Station A Spectrometers

The spectrometer package and set up is assumed to be similar to what is used in experiment E142. Figure 2 shows a schematic diagram of the two arm scheme to be assembled in End Station A at the end of this year. Each arm of the spectrometer consists of two dipole magnets which bend the scattered electrons into the detector where the electrons are identified and tracked for momentum measurement. This set up is a non-focussing scheme which maximizes the solid angle acceptance at the expense of some precision in the determination of the electron momentum.

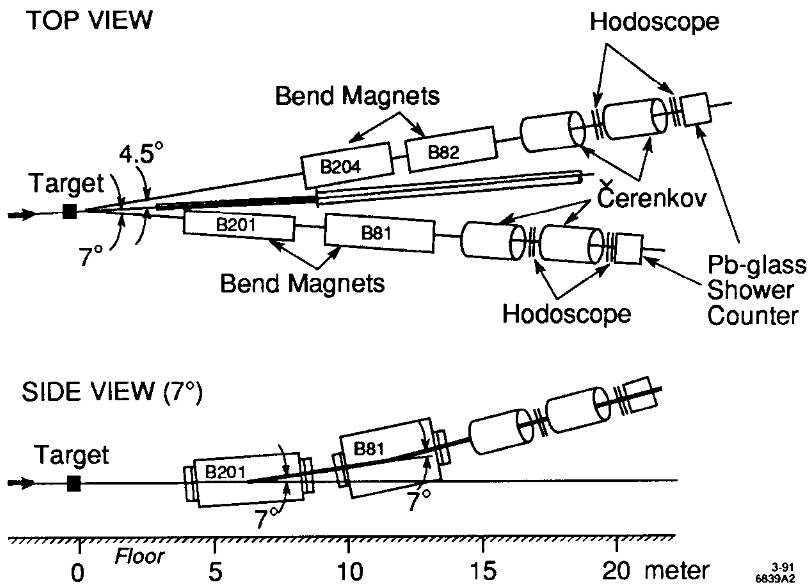

Fig. 2. Schematic view of the spectrometer set up for SLAC experiment E142.

The main features of the spectrometer are:

- large acceptance with 0.5 msr over a scattered electron momentum range from 7 GeV to 20 GeV
- good electron identification with two Čerenkov counters per arm and segmented Pb glass counters
- reasonable momentum resolution with $\Delta p/p \sim 2$ to 3 %

Unless stated otherwise, the calculations in this report with a 50 GeV beam assume a spectrometer angle of 3° in order to measure the structure functions at low x. In all cases, the acceptance in the small angle spectrometer is taken as 0.1 msr, so that the detector does not get flooded with too high an event rate.

Flexibility to increase the solid angle to 0.5 msr for the low angle spectrometer and correspondingly lower the beam current ($\sim 10^9$ electrons/pulse) for the solid targets is possible. This may be necessary if the radiation damage to the ammonia targets is worse than expected. The drawback of such a plan would be the loss of rates in the 7° spectrometer.

III. ANALYSIS

Proton Runs

The statistical uncertainties of the previous proton spin structure function measurements are large (Figure 1). The large uncertainties from the EMC experiment is a consequence of the low intensity from the muon beam. The old SLAC results also had large uncertainties; however, these results reflect the use of an inefficient low intensity electron beam generated by a Lithium source [9].

The present GaAs sources now being installed at SLAC produce higher currents with good efficiencies [10].

Another drawback to the old SLAC experiment was the use of a polarized butanol target which suffered from $\sim$ 30 times less resistance to radiation damage than the ammonia targets [8].

Using an NH_3 target, the number of events per pulse scattered into each arm of the spectrometer is expected to be on the order of one electron event per pulse independent of the beam energy. The rates with a 4.5° spectrometer at 23 GeV is comparable to the rates of a 3° spectrometer at 50 GeV. Figure 3 shows the statistical precision on the proton asymmetry measurement, $\Delta A_1^p(x)$, comparing the existing proton measurements with rate calculations from a 7° and a 4.5° spectrometer at 23 GeV and a 3° spectrometer at 50 GeV. All data consist of events with Q^2 greater than 1 $(GeV/c)^2$. Bins in x correspond to a 1 GeV separation in scattered electron momentum (i.e. $\Delta E_{out} \sim 1\ GeV$). For each case, 100 hours of perfect data collected to tape is assumed. It is clear that the statistical precision of the proposed run is a great improvement over the existing proton data. Real time inefficiencies due to beam rastering and down time to repolarize the target are not estimated for this study.

Figure 4 shows the same information as Figure 3 except that a simulated result for the asymmetry values is given. A 50 GeV beam would even allow a measurement of a point in x lower than what presently exists from the muon scattering experiments due to the low value of the scattering angle.

A conversion of these uncertainties into a result for the spin structure function itself is given in Figure 5. The seemingly small errors on $g_1^p(x)$ at high x is nothing more than a reflection of the fact that $g_1^p(x)$ vanishes as x approaches one. Once again, the improvement in the measurement of the proton spin structure function with a 50 GeV SLAC beam is evident.

Neutron Runs

The goal of experiment E142 is to make a first measurement of the neutron spin structure function with a polarized ^{3}He target. In the simplest picture of ^{3}He, the two proton spins in the nucleus align themselves anti-parallel to one another due to the Pauli exclusion principle. The neutron spin, correspondingly, aligns itself parallel to the ^{3}He spin direction. Figure 6 shows the predicted neutron asymmetry precision extracted from the proposed measurement for experiment E142. The size of the error

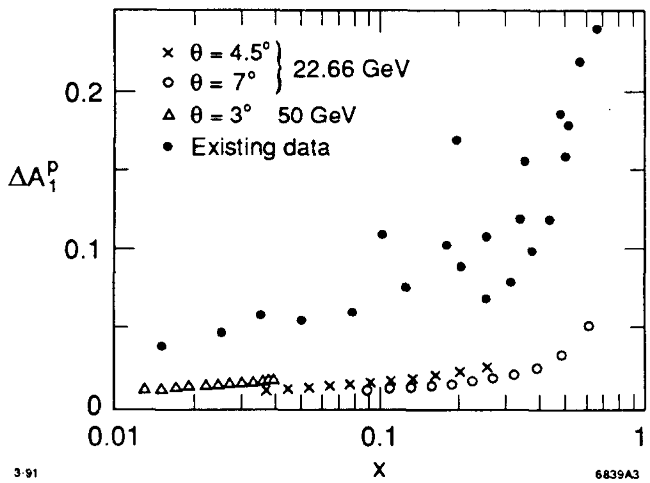

Fig. 3. Statistical error in the proposed proton asymmetry measurement as a function of x for a 22.66 GeV beam with the E142 set up and a 50 GeV beam with the spectrometer at 3°. Statistical uncertainties on the existing data are also given.

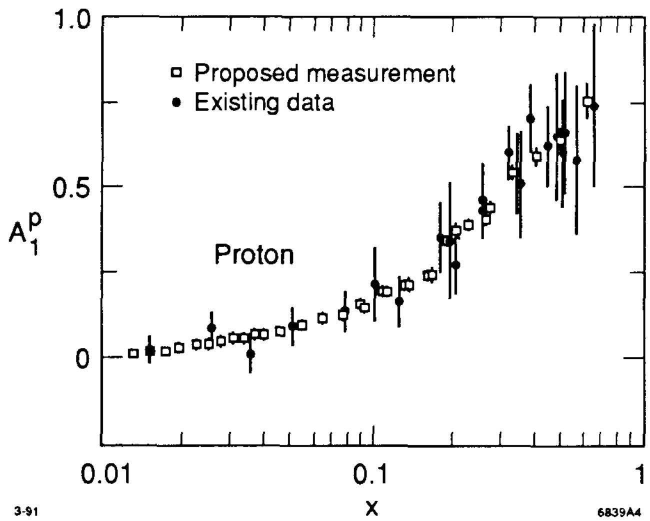

Fig. 4. Comparison between the proposed proton asymmetry measurements and the existing data as a function of x. Asymmetry values for the proposed data are chosen to agree with the existing data.

bars and the spacing of the points represents the goal of the E142 experiment. The neutron asymmetry is assumed arbitrarily to be zero over all x.

Figure 6 gives the additional prediction for the statistics achievable for the measurement of $A_1^n(x)$ assuming a 50 GeV polarized electron beam scattering off a ^{3}He target into a 3° spectrometer with 0.1 msr acceptance and a beam current of 10^{11}

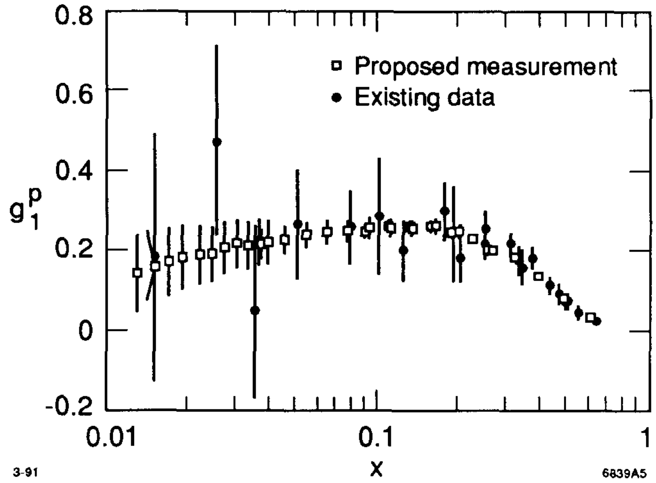

Fig. 5. Comparison between the proposed proton spin structure function measurement with the existing measurement as a function of x.

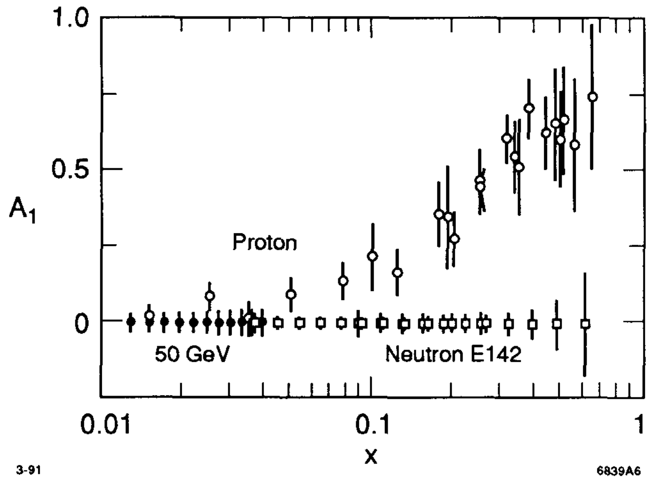

Fig. 6. Comparison of the asymmetry from the existing proton data with the proposed neutron measurement from experiment E142 as a function of x. Proposed values for a 50 GeV beam with a spectrometer set up at 3 degrees are also given.

electrons per pulse running for 100 perfect hours. The lower current of the SLED beam compared to E142 give the larger error bars for the 50 GeV data; however, the coverage at low x is impressive.

A second method for extracting the neutron spin structure function is to measure the deuterium spin structure function, $g_1^d(x)$ and to subtract out the proton contribution. This is the method adopted by the SMC collaboration at CERN.

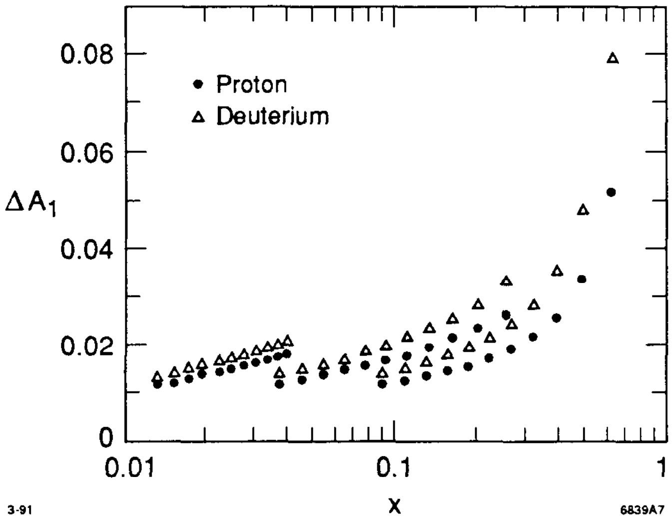

Fig. 7. Comparison between the statistical uncertainty achievable on the asymmetries as a function of x for a proton target versus a deuterium target.

The precision on $g_1^d(x)$ for 100 hours of perfect running is similar to that of $g_1^p(x)$ for the same run time. Figure 7 shows the comparison in terms of the predicted statistical uncertainty on the measured asymmetry from the deuterium and proton runs. Although the proton target has twice the polarization, it has half the dilution factor (i.e. the number of polarized nucleons). These two effects compensate for each other to give a similar statistical precision.

To extract the neutron asymmetry, the following relation is used:

$$A_1^n = (1 + \frac{\sigma_p}{\sigma_n})A_1^d - (\frac{\sigma_p}{\sigma_n})A_1^p$$

Figure 8 shows the comparison between the extraction of the neutron asymmetries from ^{3}He versus deuterium. The methods have a comparable precision and are practically identical for a 50 GeV beam. However, the ^{3}He target is superior for lower energy running and higher x measurements. The small error bars on the neutron measurement from deuterium requires, of course, a good run for both proton and deuterium targets (Figure 7). Figure 9 shows the predicted uncertainty on $g_1^n(x)$ itself from a ^{3}He and deuterium measurement. Once again, the small errors at high x are simply a reflection of the fact that $g_1^p(x)$ is approaching zero.

Nuclear uncertainties from the ^{3}He nucleus are expected to be larger than those in deuterium due to the fact that the nucleons in ^{3}He are more tightly bound. However, extracting the neutron from ND_3 may be tricky, since both the N and D nuclei are spin 1 objects. It is highly desirable to measure the neutron spin structure function with both targets in the same experimental program.

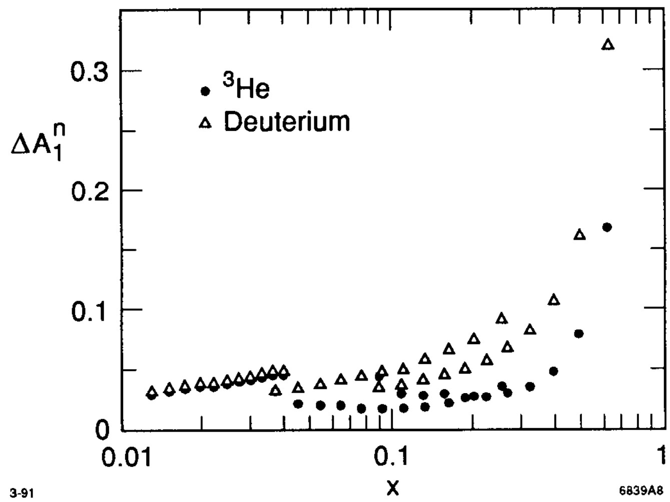

Fig. 8. Comparison between the statistical uncertainty achievable on the asymmetry measurement of the neutron as a function of x for a ^{3}He and deuterium target. For extracting the neutron information from deuterium, both the proton and deuterium target runs are needed.

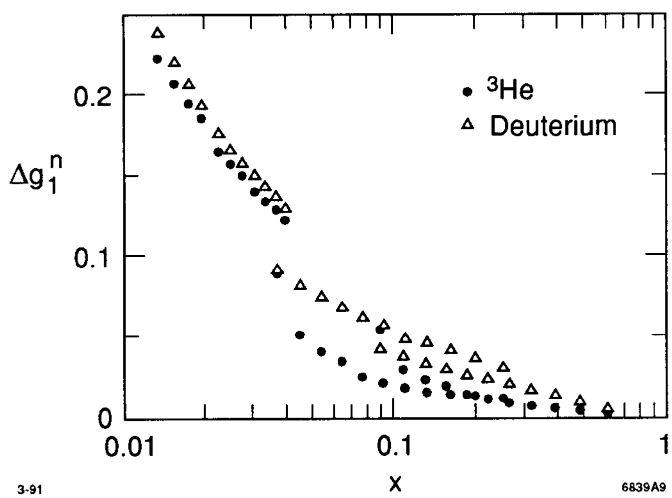

Fig. 9. Comparison between the statistical uncertainty achievable on the structure function measurement as a function of x for a ^{3}He and deuterium target run.

Q^2 Studies

With a 50 GeV beam an impressive range in Q^2 can be covered in the structure function measurements. Figure 10 shows the x vs. Q^2 range that can be covered with 50 hours of running at energies of 20, 30, 40, 50 GeV with a 4.5° and 7° spectrometer on a NH_3 target. The results are given with the statistical precision attained at each point. Without the upgraded 50 GeV capability, only the two lowest bands would be possible for a fixed angle spectrometer at reasonably high Q^2.

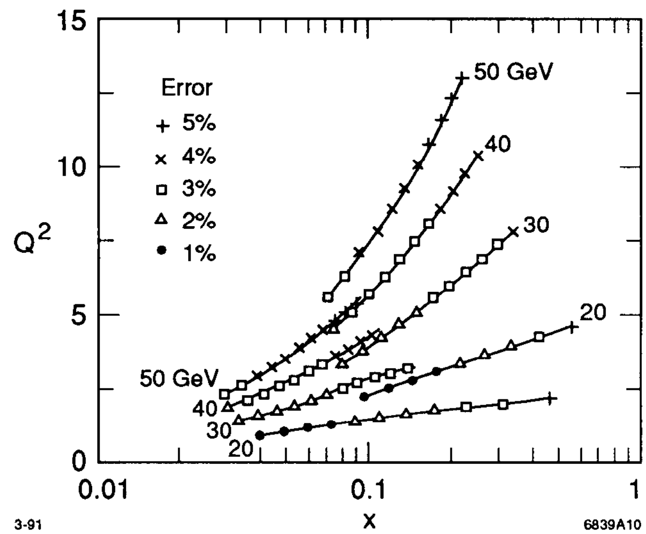

Fig. 10. Q^2 versus x regions accessible in a proton spin structure function measurement run with a 20 to 50 GeV beam. The spectrometer is assumed to be at 4.5° and 7°. Statistical errors on the asymmetry measurement are given for each point.

Similar results are achievable with deuterium and ^{3}He targets in order to study the Q^2 dependence of the neutron spin structure function.

Systematics and Sum Rules

All the predictions with a 50 GeV beam experimental program give statistical errors which imply a negligible contribution to the sum rules of $\int g_1^p(x)dx$ and $\int g_1^n(x)dx$. The extraction of these integrals will be dominated by the systematic uncertainties and by lingering doubts on the contributions to the integrals from low x regions outside the range of the experiment. The total uncertainty on the sum rules will be limited in the near future to $\sim$ 10 %. Five percent uncertainties from the beam and target polarization measurements are the main sources of this overall uncertainty.

For more long term future experiments, it is imaginable that the target and beam polarizations measurements could be improved with more precise NMR techniques for the target and Compton polarimeters for the beam. Testing the sum rules to 5 % is conceivable, though at the same time, difficult to contemplate in light of the theoretical nuclear uncertainties and the low x extrapolation uncertainties.

IV. 50 GEV DIFFICULTIES

A 50 GeV program will bring its own set of problems. Higher energy and shorter duty cycles imply more background and less gating possibilities. Two problems which will need some work are the substantially larger pion background and the large radiative corrections.

The rates of pions are on average an order of magnitude higher than for the 23 GeV beam runs. Figure 11 shows the predicted π/e ratio for a 50 GeV beam [11].

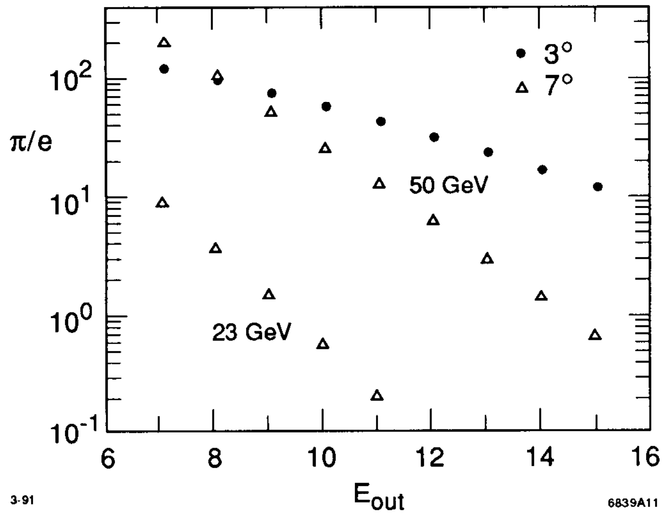

Fig. 11. π/e ratio as a function of outgoing electron momentum for a 50 GeV beam versus a 23 GeV beam.

With a 100 ns gate, it is likely that improved electronics to time out pions will be needed. Even though the electron rates are low (less than one electron per pulse), the pion rate may be on average from 10 to 100 per pulse in a 100 ns spill. Present commercial electronics can locate leading edge rise times to $\sim$ 1 ns. Another philosophy is to ignore timing completely and to focus solely on electron identification with upgraded detectors such as Ring Imaging Čerenkovs or TRDs. An array of TRDs would be especially elegant, since both electron identification with good rejection of high energy pions and electron tracking can be incorporated in the same device.

Radiative corrections become large as E_{out}/E becomes small. At 23 GeV with $E_{out} = 7$ GeV, the corrections are on the order of $\sim$ 30 %. To the extent that one knows how to calculate the corrections, the overall uncertainty on the asymmetries from radiative corrections may still be relatively small. At 50 GeV, with $E_{out} =$ 7 GeV, these corrections may, however, become enormous.

CONCLUSIONS

A polarized 50 GeV electron scattering program to study spin structure functions is viable and should be competitive. The higher energy muon program at CERN will always be limited statistically despite its large x and Q^2 coverage. It is the combination of high statistics with large range in x and Q^2 which ultimately determines the figure of merit of the experiment.

An expansion of SLAC's A line to include a 50 GeV program should be accompanied by a growth in the polarized target program. A polarized proton target run at SLAC is likely to provide the best statistical measurement of the proton spin structure function over a large x range, allowing for a solid test of the Ellis Jaffe sum rule violation. Measuring the spin structure functions of both deuterium and ^3He at SLAC would allow for the extraction of the neutron spin structure function as well as the study of the nuclear uncertainties independent of other programs. Finally, a 50 GeV beam at SLAC would provide the highest energy electron scattering program to do these and other deep inelastic experiments with high precision.

Acknowledgement

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References

1. J. Ellis, R. Jaffe, Phys. Rev. D9 (1974) 1444.
2. J. Ashman et al., Phys. Lett. B206 (1988) 364.
3. J.D. Bjorken, Phys. Rev. 148 (1966) 1467; Phys. Rev. D1 (1970) 1376.
4. D. R. Walz, "Potential Energy Capability of BSY A-Beam Transport System," SLAC internal memo, Sept. 12, 1988.
5. S. H. Rokni, "Minutes of Meeting on 50 GeV A-Line," SLAC internal memo, Jan. 8, 1991.
6. L. Keller, talk presented at the 50 GeV workshop on fixed target experiments at SLAC, Feb. 14, 1991.
7. T. Maruyama et al., SLAC Pub 5420, Feb. 1991
8. M.L. Seely et al., Nucl. Inst. and Methods 201 (1982) 303.
9. M.J. Alguard et al., Phys. Rev. Lett. 37 (1976) 1258; 37 (1976) 1261.
10. C.Y. Prescott et al., Phys. Lett. 84B (1979) 524.
11. D. E. Wiser, Ph.D. thesis, University of Wisconsin, 1977, unpublished.