E-151

SLAC Proposal
End Station A

Measurement of Nuclear Structure Functions at x > 1 and Large Momentum Transfer

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ABSTRACT

We propose an inclusive electron-nucleus scattering experiment in the domain of large x and Q^2, to measure the nuclear structure function F_2^A. Previous data for $x > 1$ have been limited to $Q^2 < 4$ (GeV/c)^2. We propose to extend this Q^2 range for $x = 2$ up to $Q^2 = 10$ (GeV/c)^2 and for $x = 1.5$ up to $Q^2 = 33$ (GeV/c)^2. These data can provide important information on the scaling of the nuclear structure function, constrain the components of the nuclear wave function at large momentum and binding energy, and put limits on non-nucleonic degrees of freedom in nuclei.

The experiment requires the assembly of a new fixed-angle 16 GeV/c spectrometer. The detector packages can be assembled from existing hardware in End Station A. The beam requirements are one calendar month of long-pulse running at energies from 7 - 29 GeV which includes three beam weeks at 50% efficiency and one week of spectrometer checkout.

1. Introduction

Deep inelastic scattering (DIS) of electrons has proven to be a powerful tool in understanding the structure of the nucleon in terms of its constituents. In a naive parton model the deep inelastic structure functions can be related to the longitudinal momentum distribution of the quarks in the limit where both the electron energy transfer ν, and the square of the four-momentum transfer $Q^2 \to \infty$. In this limit, the structure functions display scaling, i.e. they possess little dependence on Q^2. The remaining dependence on the kinematic variable $x = Q^2/2M\nu$, with M the nucleon mass, yields the quark momentum distributions where x is interpreted as the longitudinal momentum fraction of the quarks. For a nucleon target, x varies from 0 to 1, while for a nuclear target with mass A, x can vary from 0 to A.

The inclusive differential cross section for electron scattering from nuclei can be expressed in the one-photon exchange approximation as

$$\frac{d^2\sigma}{d\Omega d\nu} = \sigma_{\rm Mott}[W_2^A + 2W_1^A \tan^2(\theta/2)]$$

where $\sigma_{\rm Mott} = 4\alpha^2 E'^2 \cos^2(\theta/2)/Q^4$ is the Mott cross section, E' is the scattered electron energy, and θ the electron scattering angle. In general W_2^A and W_1^A are functions of two kinematic variables, e.g. Q^2 and ν. In the naive parton model it is the functions $F_2 = \nu W_2$ and $F_1 = MW_1$ which are expected to scale and to be related to the longitudinal momentum distribution of the quarks. Significant data exist for the nuclear structure function F_2^A at large momentum transfer from the muon experiments at CERN. However, these data extend only to $x \lesssim 0.7$. The very small cross sections and small angles necessary for studying $x > 1$ with muons make this regime virtually inaccessible without the high luminosity available at SLAC.

With the observation that the nuclear structure functions (for $x < 1$) are not simply related to the free nucleon structure functions [1-3], it became clear that the nuclear medium has a non-trivial effect on the structure of the nucleon. There have been suggestions [4] that non-nucleonic (eg. 6-quark bags) components in the nucleus will have dramatic effects at large x. The importance of large x data in constraining the presence of "point-like configurations" in the nucleus has been discussed by Frankfurt and Strikman [5]. In addition, recent theoretical work [6] has emphasized the relevance of $x > 1$ data in extracting the nucleon's light cone momentum distribution in the nucleus. There is also an intriguing suggestion, in the recent analyses [7,21] of both low Q^2 [8] and moderate Q^2 [21] SLAC data, that a type of scaling reminiscent of "local duality" in the nucleon persists in the nucleus. To provide new data with which to challenge and constrain the role of QCD in the nucleus, we propose to extract the nuclear structure function F_2^A in a previously unexplored kinematic regime, via high energy electron scattering from nuclei at large x and large Q^2.

2. Physics Motivation

With the initial observation by the EMC collaboration [1] that the nuclear medium has a significant effect on the nucleon structure function, numerous theoretical studies have attempted to explain the data. From all these analyses it is clear that the presence of other nucleons within $\lesssim 1$ fm can alter the simple perturbative QCD picture of deep inelastic scattering. By probing the nucleons in a nucleus at $x > 1$, a kinematic domain forbidden for the free nucleon, we are directly attacking the nuclear medium effects on the quark structure of the nucleus. Measurements of F_2^A over the full kinematic range are crucial to understanding the role of quark degrees of freedom in the nucleus.

In order to address the physics of inelastic scattering at $x > 1$ we should first consider the behavior of the nucleon structure functions as $x \to 1$. It was shown by Drell and Yan [9] and West [10] that the deep inelastic structure functions of the nucleon connect smoothly with the elastic nucleon form factors. In addition, Bloom and Gilman [11] discovered that, in the resonance region, the resonance form factors fall with Q^2 at the same rate as the scaling structure functions. They observed that the resonance peaks seen at low Q^2 could be averaged over a finite range in x to yield the high Q^2 deep inelastic structure function. This duality between the scaling structure functions and the elastic and resonance form factors was initially discussed in a simple parton model [12]. DeRujula, Georgi, and Politzer [13] showed that this local duality was expected from perturbative QCD and should also be valid for the nucleon elastic peak at ($x = 1$) if the structure functions were analyzed in terms of the Nachtmann variable $\xi = 2x/[1 + (1 + 4M^2x^2/Q^2)^{1/2}]$. This is the correct variable [14] in which to study scaling violations at finite Q^2 and accounts for the finite target mass M. In this picture the elastic peak and resonances do not "disappear" into the DIS continuum but instead move to larger ξ, while maintaining a nearly constant strength with respect to the DIS structure functions, which fall rapidly with increasing ξ. There is thus a simple duality between the perturbative aspects of QCD and more complex "higher twist" effects [13] which should dominate as $x \to 1$ at moderate Q^2.

Let us now consider the nuclear structure function for $x > 1$. From a recent analysis [7] of SLAC experiment NE3 [8] shown in Fig. 1, we see the structure function per nucleon for Fe as a function of x, for a Q^2 range of 1–4 (GeV/c)^2. The increasing separation of the data at large x for different Q^2 can be attributed to the dominance of quasielastic scattering at larger x. Here the Q^2 dependence is governed by the nucleon elastic form

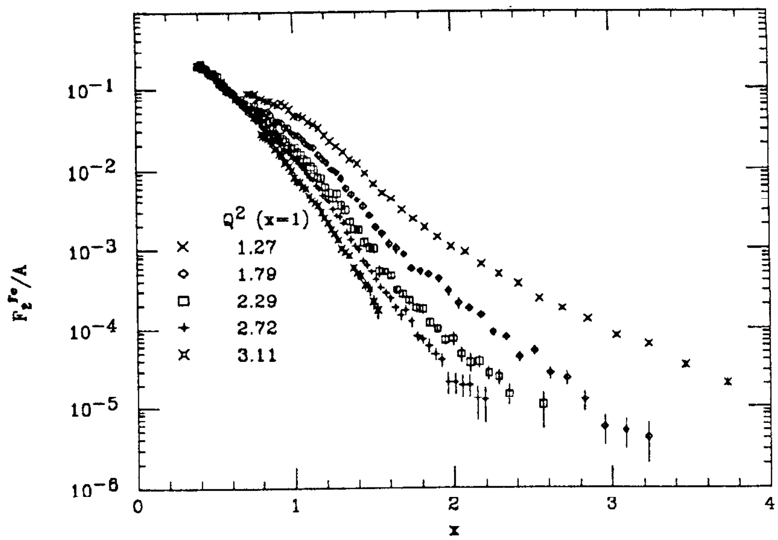

Figure 1. Measured structure function per nucleon for Fe vs. x from SLAC experiment NE3. The Q^2 value at $x = 1$ is also listed for each kinematics.

factors $G_E(Q^2)$ and $G_M(Q^2)$, which fall rapidly with increasing Q^2. At lower x, deep inelastic scattering (which should have little Q^2 dependence) becomes more important. Thus we observe the expected dominance of Fermi-smeared deep inelastic scattering at medium x and quasielastic scattering at high x.

However, a completely different picture emerges if we consider F_2^A vs. the Nachtmann variable ξ, with the nucleon as the characteristic mass. This is displayed in Fig. 2 for the same data as in Fig. 1. Here we see that at low ξ the data cluster around a single curve, while at larger ξ they appear to approach this universal curve from below. We emphasize however that this data is for a very limited range of Q^2.

This apparent scaling of the nuclear structure function vs. the Nachtmann variable, suggests a possible link with another kind of scaling observed in nuclei: y-scaling [15,16]. Here, in the simplest picture, the electron-nucleus cross section is divided by the elastic nucleon cross section yielding a universal function $-F(y)-$ which is independent of Q^2 and can be related to the light cone momentum distribution of the nucleons in the nucleus [6]. The relation between the scaling of $F(y)$ and $F_2^A(\xi)$ is, however, not presently understood. In the simplest relativistic definition y can be related to ξ via $y = M(1 - \xi - \delta)/(1 + \delta)$ where $\delta = M^2\xi^2/Q^2$. For the previous data at $Q^2 < 4$ (GeV/c)^2, there is still a very large Q^2 dependence to this expression. But data such as proposed here, by extending the measurements an order of magnitude in Q^2, can seriously explore this connection.

The inclusive data at moderate Q^2 and large values of x also may have a bearing on the question of color transparency. This is a prediction of perturbative QCD which suggests that for exclusive reactions at high momentum transfer the (initial and) final state interactions of the hadrons with the nuclear medium should be reduced. In the kinematic region where the cross section is dominated by quasielastic scattering from individual

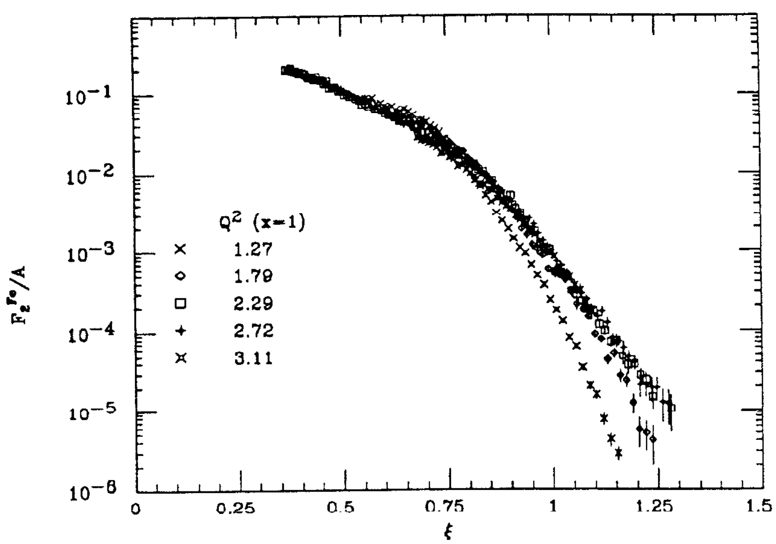

Figure 2. Measured structure function per nucleon for Fe vs. ξ.

nucleons, important contributions from the final-state interaction of the struck nucleon occur. The scattered electron is sensitive to the interaction of the recoil nucleon over a distance of order $1/Q$. If over this region the final-state interaction is significantly reduced due to color transparency, the effect will show up in the inclusive spectrum.

The proposed experiment can provide important information on short-range correlations (i.e., high momentum components), non-nucleonic degrees of freedom, and higher twist effects in nuclei. In addition, if the $F_2^A(\xi)$ behavior is in fact a scaling phenomena and persists at higher Q^2 one can hope to extract the large x, scaling limit nuclear structure function from moderate Q^2 inclusive scattering without "interference" from quasielastic scattering.

The use of several nuclear targets will also allow us to obtain new information on nuclear structure function ratios. Because we propose to take data with deuterium as well as carbon and iron targets, we will be able to construct EMC-type ratios (e.g. F_2^{Fe}/F_2^D). These ratios at $x > 1$ are especially sensitive to high momentum components in the nuclear wavefunctions [19], with an expected scaling with Q^2 that allows an extraction of the nucleon light-cone momentum distribution in the nucleus.

The kinematic flexibility of the full SLAC linac with high current and long pulse beam combined with a proposed large solid angle 16 GeV/c spectrometer in End Station A make this experiment possible. The kinematic domain accessible with the proposed experiment is shown in Fig. 3. Also shown are the region in Q^2 and x where the nuclear structure function has previously been measured. The proposed experiment would thus concentrate on a kinematic region which is largely unexplored.

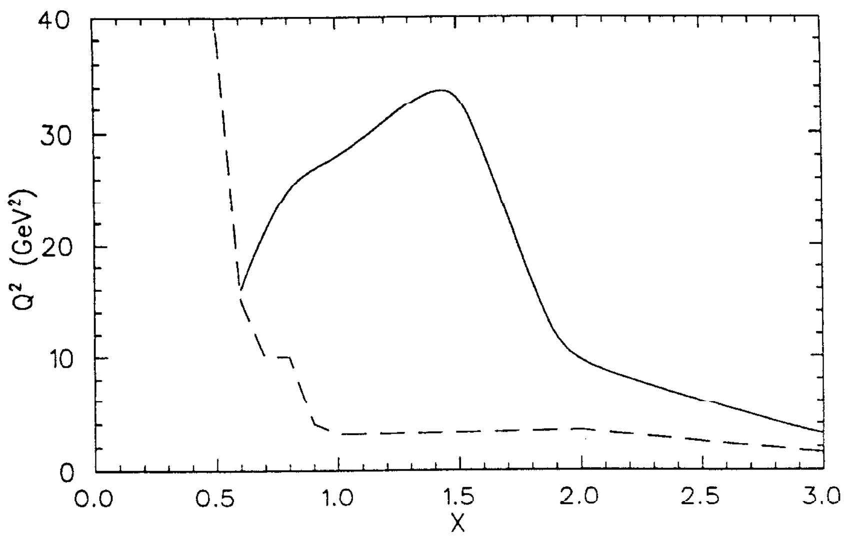

Figure 3. The kinematic range in x and Q^2 accessible with the proposed experiment are shown. The region below the dashed line has been studied in previous SLAC and CERN experiments. The region between the solid and dashed lines can be studied with the proposed experiment.

3. Experimental Overview

The experiment utilizes the 16 GeV/c spectrometer discussed in Section 5. In order to extract F_2^A from the measured inclusive cross section a number of corrections and backgrounds must be dealt with.

The measured inclusive spectrum must be corrected for radiative effects in the target and at the scattering vertex. This can be accomplished using a model for the cross section and an iterative "bootstrap" procedure that is very reliable after the first few points have been corrected. Our experience from the analysis of NE3 indicates that the radiative correction procedure is very insensitive to the model used. We estimate that the error in the final cross sections due to radiative corrections will be less than 2%.

In order to extract the structure function, νW_2, from the measured cross section without doing a full Rosenbluth separation (i.e. an angular distribution at fixed Q^2 and ν) a knowledge of $R = \sigma_L/\sigma_T$ is required. We can write the structure function in terms of the measured deep inelastic scattering cross section $\sigma_{Tot} = d^2\sigma/dE'd\Omega$ and R as

$$\nu W_2 = \nu(\sigma_{Tot}/\sigma_{Mott})\frac{1}{1+\beta}$$

where

$$\beta = 2\tan^2(\theta/2)\frac{(1+\frac{Q^2}{4M^2x^2})}{(1+R)}.$$

Uncertainties in the value of R can lead to uncertainties in the structure function at large angles as seen from the definition of β above. Contributions to R in the x range of this experiment can result from Fermi-smeared deep inelastic scattering as well as quasielastic nucleon scattering. The data on R for Fe in the deep inelastic range [20] indicate that $R_{\rm Fe}^{\rm DIS} < 0.5$ (with little nuclear mass dependence) for Q^2 = 1–5 GeV/c^2 and x = 0.2–0.5. A reasonable description of the data is provided by $R_{\rm Fe}^{\rm DIS} = \frac{0.5}{Q^2}$ with Q^2 in (GeV/c)^2 and with little x dependence. For the quasielastic contribution, an impulse approximation estimate yields $R^{QE} \simeq \frac{G_E^2}{\tau G_M^2}$, where $\tau = \frac{Q^2}{4M^2}$, and G_E, G_M are the elastic electric and magnetic form factors. To see the sensitivity of the proposed experiment to uncertainties in R, we assume the above parameterizations of R with an uncertainty range of $\Delta R = \pm 0.25$. This leads to a worst case uncertainty for the proposed measurement of $\pm$ 15% in the determination of the structure function.

Parameterizations of previous data indicate that at the smallest momentum of this experiment the ratio of π^-/e^- may be as high as ~ 2. The π rejection factor of $10^4 - 10^5$ from the detector package (see Section 6) should keep the uncertainty due to π backgrounds well below 1%.

The presence of background electrons from charge symmetric processes (e.g. Dalitz pairs and γ conversion) can be checked by reversing the spectrometer momentum and measuring the yield of e^+.

4. Run Plan

In order to estimate counting rates and running times we have attempted to scale the previous data from SLAC experiment NE3. The approximate scaling in ξ discussed above provides a useful guide, so we have taken the highest Q^2 results and assumed no further dependence on Q^2; thus the structure function is assumed to depend only on ξ.

The run plan for the proposed experiment is shown in Table 1. Counting rates are the main limitation to the kinematic range of the experiment, with a minimum of $\sim$ 1 count/hr at the center of the spectrometer acceptance being the assumed limit. For estimating running times we have assumed 120 pulses per second and 5×10^{11} electrons per pulse from the full linac. The range in x is determined at low x by the desire to overlap with existing SLAC data (NE3 and E139) and restricted at high x by small counting rates. The running times were calculated for a fixed fractional x bin of $\frac{\Delta x}{x} = 0.05$. The uncertainty is calculated from the number of counts in the central x bin. In order to cover the full range in x, the momentum of the 16 GeV/c spectrometer will be stepped in intervals of 10%. While the bulk of the running time (210 beam hours) will be devoted to the 6% radiation length Fe target, we will also take data with a 6% C target (30 beam hours) and a 15 cm LD_2 target (25 beam hours). The C data will provide information on the A dependence, while the deuterium data will allow comparisons with the nucleon structure functions via Fe/D ratios. As there exists previous SLAC data (E133 and NE11) on LD_2 up to $Q^2 = 10$ (GeV/c)^2, we will concentrate the deuterium data at the higher Q^2's.

At several incident energies elastic scattering data from LH_2 will provide a check of the spectrometer acceptance, the overall experimental efficiency, and the energy calibration. The LH_2 runs (10 beam hours) will be followed by corresponding 'dummy' empty target runs to allow the subtraction of the window background. At large Q^2 and small x we will measure the contribution of electrons from charge symmetric background processes by reversing the polarity of the spectrometer (5 beam hours). This brings our total request for this experiment to 280 beam hours, or 560 calender hours assuming an efficiency of 50%.

Table 1. Run Plan for 6% Fe target. The 16 GeV/c spectrometer is fixed at 15°. We assume 10 μA average current and the cross section model discussed in the text. The running times (in beam hours) and the statistical errors are for a central x bin with $\frac{\Delta x}{x} = 0.05$.

E (GeV)	$E'_{16\ range}$ (GeV)	x_{range}	ξ_{range}	Q^2_{range} (GeV/c^2)	time (hrs)	Error	π/e
7	4.6-5.6	0.5-1.0	0.5-0.8	2.2-2.7	0.5	5%	0.2
	6.5	1.3-3.3	1.0-1.4	3.1	33	25%	2.5
10	5.8-7.4	0.5-1.0	0.5-0.9	3.9-5.0	0.5	5%	0.2
	8.4	1.1-2.0	1.0-1.4	5.7	31	20%	0.2
15	7.2-9.7	0.5-1.0	0.5-0.9	7.3-9.9	0.5	5%	0.3
	11.1	1.1-1.7	1.0-1.4	11.4	26	25%	0.06
20	8.2-11.5	0.5-1.0	0.5-0.9	11.2-15.7	1	5%	0.2
	13.4	1.1-1.5	1.0-1.4	18.3	32	30%	0.01
25	8.9-13.1	0.5-1.0	0.5-1.0	15.2-22.4	3	5%	$< 10^{-2}$
	15.2	1.1-1.5	1.1-1.4	25.9	36	30%	$< 10^{-2}$
29	9.4-14.1	0.5-1.0	0.5-1.0	18.6-27.9	5	5%	$< 10^{-2}$
	16.0	1.1-1.5	1.1-1.4	32.4	39	30%	$< 10^{-2}$

5. Spectrometer

The 16 GeV/c spectrometer consists of two bending magnets and two quadrupoles. It will be assembled from magnetic elements from the SLAC 20 GeV/c spectrometer which has been disassembled for the needs of the E142 experiment. The concrete structure required to shield the detectors from room background will be assembled from existing EX1A shielding blocks. The spectrometer will be at a fixed angle of 15.0° with respect to the incident electron beam direction and will point to the ESA target pivot. A schematic of the spectrometer system and the detectors is given in Fig. 4.

The spectrometer system has been designed to achieve the maximum solid angle possible with tolerable momentum and angular resolutions. The maximum central momentum is 16 GeV/c. The momentum dispersion and the magnification in the bend plane are 2.9 cm/% and 5.2 cm/cm (D/M–0.55). The expected first-order resolutions are 0.26% for the relative momentum measurement, 0.5 mr for the scattering angle in the horizontal direction and 2.0 mr for the angle in the vertical direction. The spectrometer resolutions have been calculated for the tracking resolutions of the wire chamber system.

The momentum acceptance of the spectrometer extends from −10% to +10%. The solid angle for the central momentum bin is 0.85 msr. The average solid angle in the ±10% momentum range is 0.71 msr. The accepted angular ranges are ±26 mr in the bend plane and ±10 mr in the non-bend plane for a target length of 4.0 cm (at 90°) as can be seen in Figs. 5 and 6.

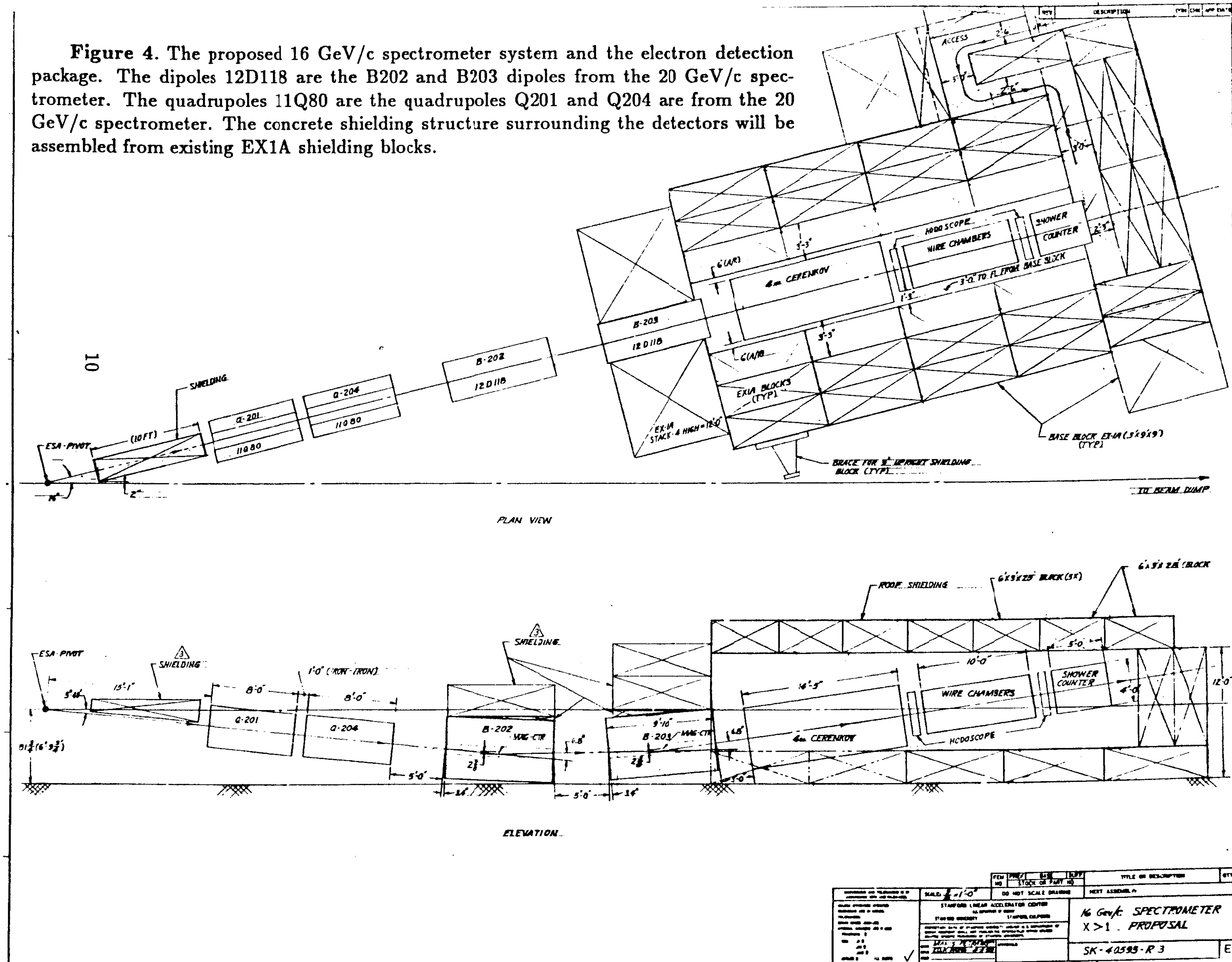

Figure 4. The proposed 16 GeV/c spectrometer system and the electron detection package. The dipoles 12D118 are the B202 and B203 dipoles from the 20 GeV/c spectrometer. The quadrupoles 11Q80 are the quadrupoles Q201 and Q204 are from the 20 GeV/c spectrometer. The concrete shielding structure surrounding the detectors will be assembled from existing EX1A shielding blocks.

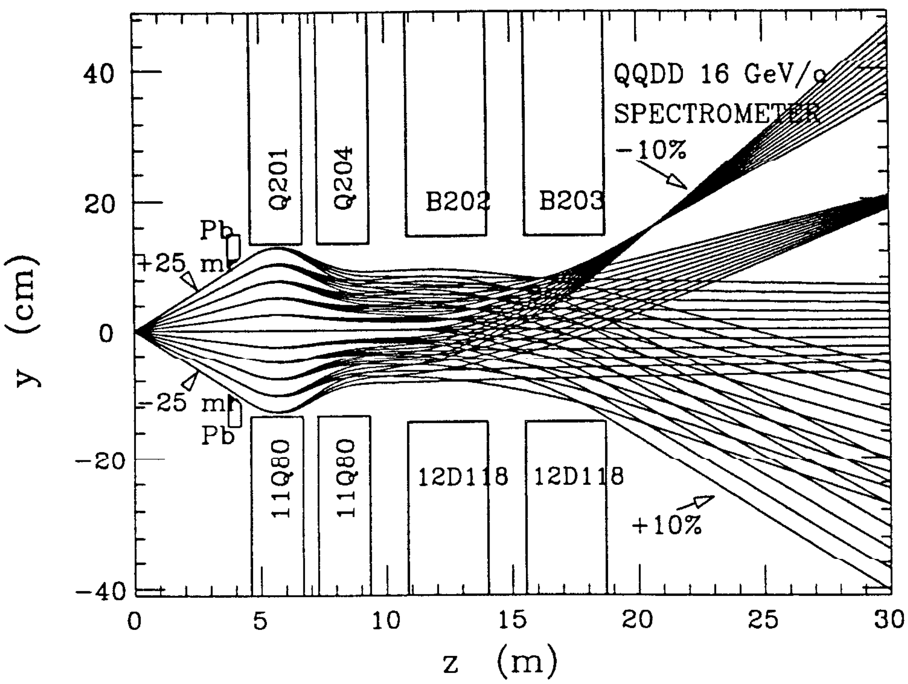

Figure 5. Bend plane raytrace for rays of different relative momenta originating from the target. All rays are drawn with respect to the central trajectory of the system. Also shown are the magnet pole pieces and lead collimators.

6. Detectors

The detectors for the 16 GeV/c spectrometer can be assembled using existing components from the 8 GeV/c and E142 spectrometers. The 16 GeV/c detector package will consist of a 4 m long gas Čerenkov counter and a lead glass array for π/e rejection, and 10 planes of multi-wire proportional chambers for tracking. In addition, we will install the scintillator hodoscopes which were rebuilt for experiment NE18 for triggering, timing and coarse position measurement.

The Cerenkov counter will be filled with N_2 at a pressure of 0.15 atmospheres, giving a pion threshold of 13.0 GeV/c and an electron efficiency of >99% (>7 photo-electrons as measured in Experiment E142). The lead glass array will be built from the existing SF5 (40 by 14.6 by 14.6 cm) and SF2 (32 by 15.8 by 10.4 cm) blocks currently used in the 8 GeV/c. Existing electronics modules from the Counting House A electronics pool can be used such that no additional acquisition of electronics should be necessary for the 16 GeV/c spectrometer.

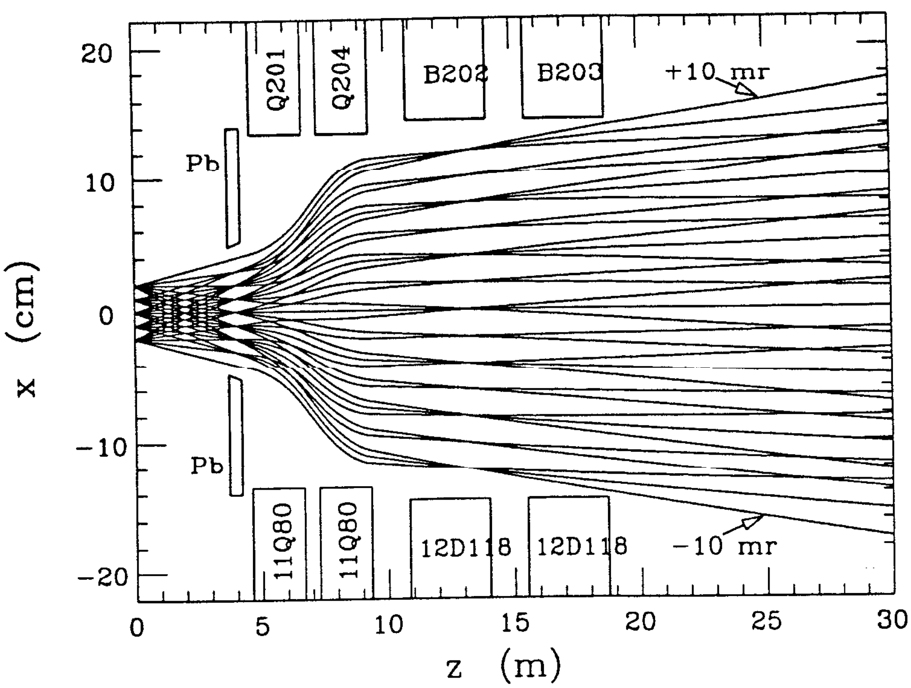

Figure 6. Non-bend plane raytrace for 0% relative momentum rays originating from different target positions. All rays are drawn with respect to the central trajectory of the system. Also shown are the magnet pole pieces and lead collimators.

7. Targets

We will require a liquid hydrogen target 15 cm in length, with corresponding dummy target for spectrometer calibration. The projected length of the target is well within the acceptance of the 16 GeV/c spectrometer. We will also use a liquid deuterium target of 15 cm length. These are essentially identical to targets used in the recent NE17 experiment and should present no difficulties. We will also require 4%, 6%, and 9% r.l. thick solid targets of ^{12}C, and 6%, 9%, and 12% targets of ^{56}Fe.

8. Request

We request a total of three calendar weeks to carry out the measurements. The request assumes a pulse rate of 120 Hz, a beam current of 5×10^{11} electrons per pulse and an efficiency factor of 0.5. The experiments will require beam energies from 7 to 29 GeV. A new 16 GeV/c spectrometer will be used to detect scattered electrons, fixed at an angle of 15 degrees. We will require 15 cm liquid hydrogen and deuterium targets and several thicknesses of carbon and iron. We request an additional one week of low pulse rate for calibration of the new 16 GeV/c spectrometer, and to check out the detector package.

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9. The Collaboration

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