CEBAF PROPOSAL COVER SHEET

This Proposal must be mailed to:

CEBAF
Scientific Director's Office
12000 Jefferson Avenue
Newport News, VA 23606

and received on or before OCTOBER 30, 1989

A. TITLE: MEASUREMENT OF THE NUCLEAR Dependence AND Momentum Transfer Dependence of Quasielastic (e,e'p) SCATTERING AT LARGE Momentum Transfer

B. CONTACT PERSON: Richard Milner

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C. THIS PROPOSAL IS BASED ON A PREVIOUSLY SUBMITTED LETTER OF INTENT

- [x] YES
- [ ] NO

IF YES, TITLE OF PREVIOUSLY SUBMITTED LETTER OF INTENT

A Letter of Intent to Measure the A-Dependence and Q^2 Dependence of Quasielastic (e,e'p) Scattering at High Q^2 at CEBAF

D. ATTACH A SEPARATE PAGE LISTING ALL COLLABORATION MEMBERS AND THEIR INSTITUTIONS

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contact Milner

CEBAF PROPOSAL

Measurement of the Nuclear Dependence and Momentum Transfer Dependence of Quasielastic (e,e′p) Scattering at Large Momentum Transfer

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October 27, 1989

ABSTRACT

Exclusive processes in QCD can be considered in a Fock state expansion of the nucleon wave function projected onto the basis of free quark and gluon Fock states. At large momentum transfer the lowest particle-number 'valence' Fock component with all the quarks within an impact distance $b_\perp \leq \frac{1}{Q}$ controls the form-factor at large Q^2. Such a Fock state component has a small color dipole moment, and thus interacts only weakly with nuclear matter. Hence, in quasielastic electron scattering inside a nucleus one predicts negligible final-state interactions in the target as Q becomes large. This effect is called 'color transparency'. In the limit of complete transparency the cross section per nucleon should be independent of A. From elastic scattering on the proton, we know that above Q^2 of ~ 5 $(\mathrm{GeV/c})^2$ (proton recoil momentum of 3.5 GeV/c) the data is consistent with quark counting rule behaviour. In addition, a recent quantum mechanical treatment of high momentum transfer nuclear processes indicates that complete color transparency arises if the recoil proton energy is much greater than 1.2 $A^{\frac{1}{3}}$ GeV.

We propose to use the nucleus as a laboratory to study this prediction of QCD by measurement of the A dependence and Q^2 dependence of the cross section at the quasielastic peak up to the highest attainable Q^2 in Hall C at CEBAF. The proposal is based on previously submitted Letters of Intent #LOI46 (September 1987) and an updated version CEBAF 88-09 (February 1988). The Short Orbit Spectrometer (SOS) will be used for electron detection and the High Momentum Spectrometer (HMS) used for recoil proton detection. With the 4 GeV CEBAF beam and Hall C spectrometers, the quasielastic (e,e′p) cross-section can be measured up to $Q^2 = 6.2$ $(\mathrm{GeV/c})^2$. At this momentum transfer the struck proton recoils with a momentum of 4.1 GeV/c and hence is significantly relativistic. The advantages of CEBAF over existing facilities are its high duty factor, high intensity beam currents, and large solid angle, high resolution spectrometers. The experiment will provide important information on the approach to perturbative QCD in exclusive processes. It provides the possibility of directly studying the underlying theory of the strong interaction in the nucleus using the electromagnetic interaction as a probe.

I. Physics Motivation

QCD has the important simplifying feature at high Q^2 of asymptotic freedom[1]. This implies that the magnitude of the strong coupling constant should diminish as Q^2 increases. This permits the use of perturbation theory in QCD calculations. This theory has been quite successful in the areas of deep inelastic scattering of leptons from nucleons[2], hadron-hadron collisions at large transverse momentum[3], baryon and meson spectroscopy[4], and jets in e^+e^- and hadronic collisions[5].

Exclusive processes such as elastic electron-proton scattering have been recognized as an important area of interest from the point of view of QCD. The basic calculational technique[6] is to separate the process into an interaction term, which is calculated perturbatively, and distribution amplitudes or wavefunctions which describe the non-perturbative amplitude for finding the hadrons to be in any given state. This is shown schematically in Fig. 1. The interaction kernel describes the hard scattering amplitude, contains the main dynamical dependence of the perturbative calculation, and can be calculated in terms of quark-gluon subprocesses. These processes are shown in Fig. 2.

The most striking consequence of QCD predictions for exclusive processes at large momentum transfer is the power-law behaviour of the form-factors. Brodsky and Farrar showed[7] that in any scale-invariant theory, of which QCD is an example, the power-law fall-off of helicity conserving form-factors is

$$F_H = \frac{1}{(Q^2)^{n_H - 1}} \tag{1.1}$$

where n_H is the number of constituent fields in H. In particular, for elastic scattering from the proton we expect $G_M^p \sim Q^{-4}$ at high Q^2. The region of the data where this is true tells us that the scattering is hard scattering where the quarks exchange large momentum gluons. In this regime the perturbative methods described above should be applicable. The data[8] is shown in Fig. 3. We see that for $Q^2 \geq 5\ (\mathrm{GeV/c})^2$ the data are in good agreement with the perturbative QCD (PQCD) power-law behaviour and so in this kinematic regime it is reasonable to investigate for any effects predicted by perturbative QCD.

In addition, new information has been recently obtained on the application of quark counting rule behaviour in exclusive processes on nuclei. Recent measurements of the energy dependence of the two-body deuteron photodisintegration cross-section between 1.2 and 1.8 GeV at NPAS are consistent with quark counting rules[19]. However, in e-d elastic scattering measurements from the deuteron up to $Q^2 = 2.5\ (\mathrm{GeV/c})^2$, $B(Q^2)$ has a minimum at $Q^2 = 2\ (\mathrm{GeV/c})^2$. It has been pointed out by Holt[20] that the momentum

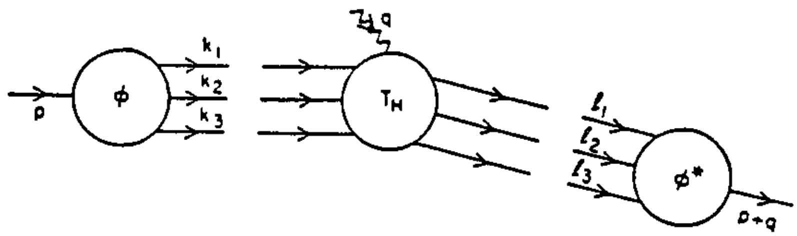

Figure 1. Factorization of the scattering amplitude for exclusive processes involving nucleons. The distribution amplitudes Φ contain the nonperturbative dynamics of the nucleon. The hard scattering kernel T_H is calculated in perturbation theory.

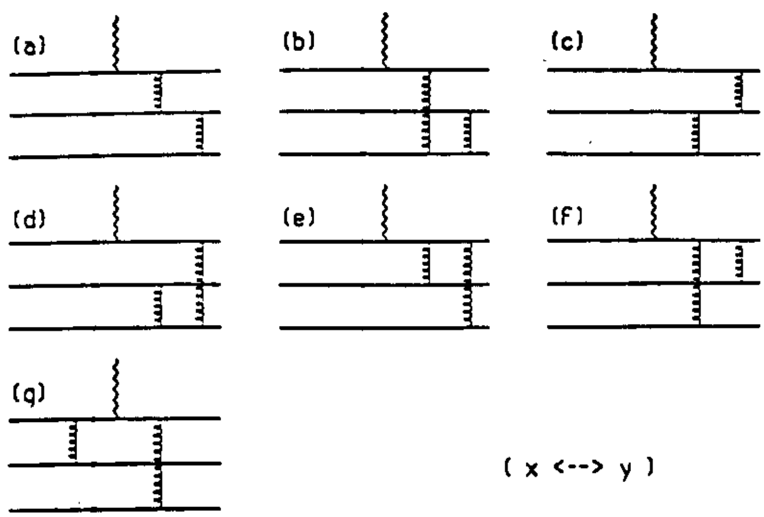

Figure 2. Diagrams which must be evaluated in the leading order calculation of nucleon form-factors.

transfer to the nucleon is significantly higher in the photodisintegration experiment ($t_N = 1.5\,(\mathrm{GeV/c})^2$) than in the e-d elastic experiment ($t_N = 0.6\,(\mathrm{GeV/c})^2$). If indeed momentum transfer to the nucleon is the relevant parameter for describing the approach to quark counting rule behaviour in exclusive processes on nuclei, quasielastic (e,e′p) scattering is particularly interesting as the complete momentum transfer of the virtual photon is transferred to the struck nucleon. At CEBAF with the 4 GeV incident beam it will be possible in quasielastic (e,e′p) scattering from nuclei to transfer up to $t_N = 6.2\ (\mathrm{GeV/c})^2$.

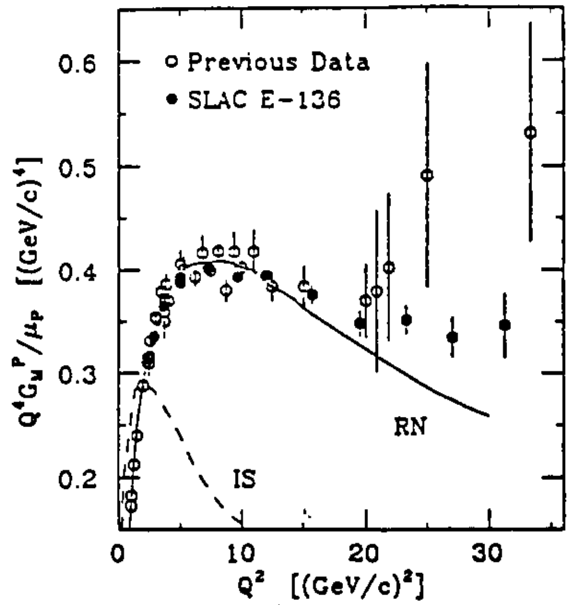

Figure 3. Extracted values of $Q^4 G_M^P \mu_P$ vs. Q^2 for elastic scattering on the proton.

At large Q^2 in elastic electron-proton scattering the virtual photon probes the small spatial components of the proton wave-function. In addition, at large Q^2 the scattering becomes harder with the exchange of large transverse momenta between the quarks. From the uncertainty principle, the transverse spatial extent of the struck proton must shrink to a distance of order $\frac{1}{Q}$. Thus, in high Q^2 electron-proton elastic scattering the recoil proton must have a diminished transverse size. Consider elastic electron-proton scattering as a quasielastic process inside a nucleus. The recoiling proton at high Q^2 will have a smaller transverse size than a normal proton and so, in a simple-minded picture will have a smaller interaction with the surrounding nucleons since to zeroth order the scattering is geometric. This novel effect, predicted independently by Mueller[9] and Brodsky[10], is called "color transparency".

If we assume that the observed power-law scaling in Q^2 of exclusive scattering reflects the dominance of light-cone physics, then the initial proton fluctuates with some amplitude f_A about its minimal Fock-state component (qqq). In order for large momentum scattering to occur the proton must occupy a region of transverse dimension $\sim \frac{1}{Q}$. The amplitude for such a fluctuation to occur is in general $[\frac{m}{Q}]^{k-1}$ where k is the number of constituents of the proton and m^{-1} is the transverse dimension of the typical configuration of the proton. This leads to the observed scaling behaviour.

Farrar, Liu, Frankfurt, and Strikman (FLFS)[11] have quantitatively investigated whether one can expect to observe the nuclear transparency effect in quasielastic scattering from nuclei. They use a model based on the above physical assumptions to study the dynamics of transverse shrinkage. They define the nuclear transparency, i.e. the probability for a proton to escape from a nucleus, as

$$\frac{A_{eff}(\mathbf{p})}{A} = \frac{1}{A}\int d^3\mathbf{r}\rho(\mathbf{r})P(\mathbf{r}) \tag{1.2}$$

where $\mathbf{p}$ is the momentum of the recoil proton. The probability function $P(\mathbf{r})$ is defined as

$$P(\mathbf{r}) = \exp[-\int_{path} dz\sigma^{eff}(\mathbf{p},z)\rho_A(z)] \tag{1.3}$$

where the integration $\int_{path}$ is along the physical path of the proton. As can be seen from the above two equations, those parts of the integration which contribute most to the nuclear absorption are parts where σ^{eff} is relatively large. Clearly PQCD is not accurate over this part of the recoil proton evolution so some models for the shrinkage mechanism have to be invented. FLFS have calculated the onset of nuclear transparency for two particular models of the evolution.

(1) The naive parton model.

(2) A PQCD model they term quantum diffusion.

The dependence of σ^{eff} on the distance z from the point where the hard interaction occurs is taken to have the following form

$$\sigma^{eff} = \sigma_{NN}^{tot}\left[\left[\left(\frac{z}{l}\right)^{\tau} + \frac{n^2 < k_t^2 >}{t}\left[1-\left(\frac{z}{l}\right)^{\tau}\right]\right]\theta(l-z)+\theta(z-l)\right] \tag{1.4}$$

where σ_{NN}^{tot} = 40 mb is the total NN cross-section; n =3 for a nucleon; $\sqrt{< k_k^2 >} \approx 0.35$ GeV/c is the average transverse momentum of a parton in a hadron and τ is the expansion exponent which describes how the proton size changes from its point like configuration. $\tau = 0$ means no transverse shrinkage occurs. $\tau = 1$ is the quantum diffusion model and $\tau = 2$ is the prediction of the naive parton model. In the naive parton model, $l \approx \frac{E}{M}$. A realistic nuclear density is used for $\rho(\mathbf{r})$. The results of the calculation are shown in Fig. 4.

The results of FLFS indicate that the probability for a proton to escape from the nucleus can be up to a factor of two greater at $Q^2 = 5$ (GeV/c)^2 than we would expect from a conventional final-state interaction picture. We see that the parton model of proton evolution is significantly larger than for the lowest order QCD picture. This results from the fact that $\sigma_{parton}^{eff} \propto [\frac{z}{p}]^2$ whereas $\sigma_{QCD}^{eff} \propto [\frac{z}{p}]$. It is quite unclear how to estimate

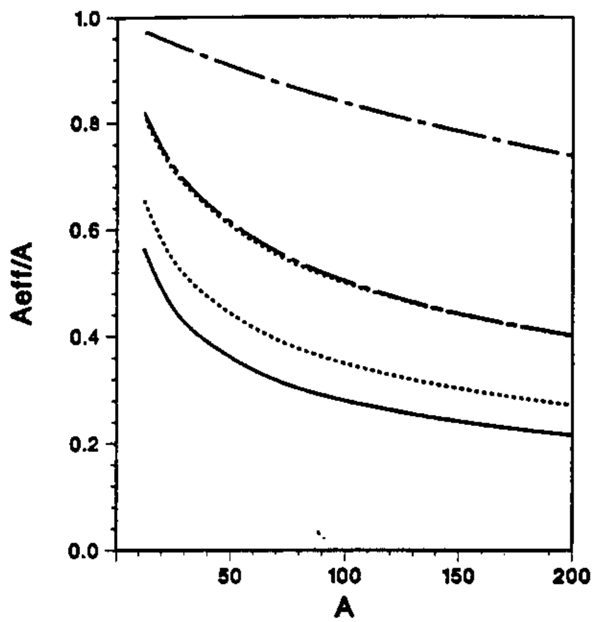

Figure 4. The nuclear transparency as estimated by the calculation of FLFS for quasielastic electron scattering on nuclei as a function of A and Q^2. $\tau = 0$ is the solid line; the dotted line is the model $\tau = 1$ and the dot-dashed line is the model $\tau = 2$. The transparency is calculated for each of these models at $(\mathrm{GeV/c})^2 = 5$ (lower set of curves) and $(\mathrm{GeV/c})^2 = 9$ $(\mathrm{GeV/c})^2$ (upper set of curves).

the accuracy of this calculation. At the point of hard scattering PQCD should be a good description of what is happening. However, as the proton evolves back to its normal size the problem becomes non-perturbative. In the absence of a rigorous QCD calculation it is very difficult to decide on the validity of either the naive parton picture or the lowest order QCD picture. In deep-inelastic scattering we know that the parton model is a good description of what is happening, even at a Q^2 of 1 $(\mathrm{GeV/c})^2$. PQCD does not begin to describe the data until Q^2 of 5 to 10 $(\mathrm{GeV/c})^2$. Thus, a possible point of view to take[23] is that the nuclear color transparency effect is best described in a parton picture at lower Q^2 where $\sigma^{eff} \propto [\frac{z}{p}]^2$ and at higher Q^2 the PQCD picture describes the effect and so $\sigma^{eff} \propto [\frac{z}{p}]$.

A quantum mechanical treatment of high momentum transfer nuclear processes where the nucleon leaves the nucleus has recently been carried out[18]. It is found that initial and final state interaction effects are suppressed if the closure approximation is valid. This time-independent approach is shown to be equivalent to the time dependent approach of Mueller[9]. It leads to the following condition for complete transparency to exist

$$E \gg 1.2A^{\frac{1}{3}} GeV \tag{1.5}$$

where E is the energy of the recoil proton. This leads to an estimate of E $\gg$ 2.7 GeV (recoil momentum $\gg$ 2.5 (GeV/c)) for ^{12}C and E $\gg$ 3.6 GeV (recoil momentum $\gg$ 3.5 (GeV/c)) for ^{27}Al for complete transparency. It is clear that the onset of the suppression of final state interactions could be observed at significantly lower momentum transfers and that the 4 GeV CEBAF beam with the SOS and HMS Hall C spectrometers can probe this very interesting physics.

The unambiguous observation of color transparency will require that the conventional nuclear physics picture is in good agreement with the data over moderate Q^2. At $Q^2 \geq 1\ (\mathrm{GeV/c})^2$ where we believe the scattering should be single-particle and the final-state proton-proton interaction is essentially constant at 40 mb, the relativistic eikonal approximation should be a good description. Such a calculation is in progress for the kinematics of the proposed experiment[17].

It is important to realize that in measurement of exclusive processes we are providing a much more detailed test of QCD than in measurements of inclusive processes. The evolution of the proton from the point of hard scattering back to its normal size is a difficult non-perturbative problem to solve within the framework of QCD. In additon, there is a point of view which argues that exclusive processes do not become perturbative until very large momentum transfers. In the absence of real QCD calculations it is clear that it is very important to obtain experimental information on this problem by experiments such as the one we propose. The observation of nuclear color transparency in quasielastic electron scattering from nuclei would be striking confirmation of the onset of the PQCD regime. It would provide the possibility of directly studying the underlying theory of the strong interaction in the nucleus using the electromagnetic interaction as a probe. Hence, it is important to carry out (e,e′p) quasielastic experiments on nuclei at the highest Q^2 available.

II. Proposed Experiment

It is important to note that the (e,e′p) reaction at the quasielastic peak is highly correlated kinematically. Thus, if an electron scatters quasielastically from a proton in the nucleus with momentum transfer $\mathbf{q}$, the recoil proton is located within a cone of opening angle $\tan^{-1}(2\frac{\mathbf{k_F}}{\mathbf{q}})$ centered on $\mathbf{q}$, if we assume a Fermi distribution with Fermi momentum $\mathbf{k_F}$ for the nucleons in the nucleus. We see that the opening angle of the Fermi cone decreases rapidly for $\mathbf{q} \geq 2\mathbf{k_F}$. This allows more of the cone to be detected for a given proton arm acceptance. In addition, all scattering rates decrease with increasing Q^2. The ratio of the accidental rate to true coincidence rate is given by

$$\frac{A}{T} = \frac{\tau R_e R_p}{R_{coinc}} \frac{1}{d} \tag{2.1}$$

where τ is the resolving time, d is the duty factor of the accelerator, R_{coinc} is the coincidence rate, R_e is the electron arm singles rate, and R_p is the proton arm singles rate. This ratio decreases as Q^2 increases because the accidental rate is proportional to the product of two decreasing rates while the coincidence rate is proportional to a single rate.

The proposed experiment will measure the (e,e′p) cross-section as a function of A and Q^2 at the highest Q^2 attainable at CEBAF. We first note that the maximum Q^2 attainable is determined both by the maximum beam energy and the maximum recoil proton momentum measureable. With the 4 GeV CEBAF beam the quasielastic (e,e′p) cross-section can be measured up to $Q^2 = 6.2\ (\mathrm{GeV/c})^2$. We have estimated rates from a y-scaling model extracted from NE3 data[13]. The coincidence rate has been determined by first calculating the inclusive cross-section for quasielastic electron scattering into the SOS spectrometer from protons; secondly, determining the losses due to final-state interactions; and finally calculating the fraction of the Fermi-cone events which are scattered into the HMS spectrometer. This method is phenomenological but should be accurate if the quasielastic scattering mechanism is dominantly single particle in nature. In determining the losses due to final state interactions we have used the classical calculation of Fig. 4. If there are significant transparency effects the rates will be correspondingly higher. At high Q^2 at x=1 the electron singles rate is dominated by deep-inelastic scattering, which has been estimated by Fermi-smearing of SLAC data[14]. The inclusive hadron rates have been estimated using existing (e,hadron) data from SLAC in this kinematic regime[15] in conjunction with the program ELPROD[16]. The proton singles rates are in good agreement with independent (e,p) estimates obtained by the Caltech group from measurements carried out during experiments E-140 and NE-9 at SLAC. We have calculated rates and kinematics using the following assumptions:

$$\text{duty} - \text{factor} = 100\%$$

$$\text{target} = 0.06 \text{ radiation lengths of Fe}$$

$$\text{incident electron intensity} = 100\ \mu A$$

$$\text{solid angle of electron spectrometer} = 10 \text{ msr}$$

$$\text{solid angle of proton spectrometer} = 6.4 \text{ msr}$$

$$\frac{p_{max}}{p_{min}} = 1.10$$

$$\text{Fermi momentum} = 260 \text{ MeV/c}$$

$$\text{resolving time} = 1.5 \text{ ns}$$

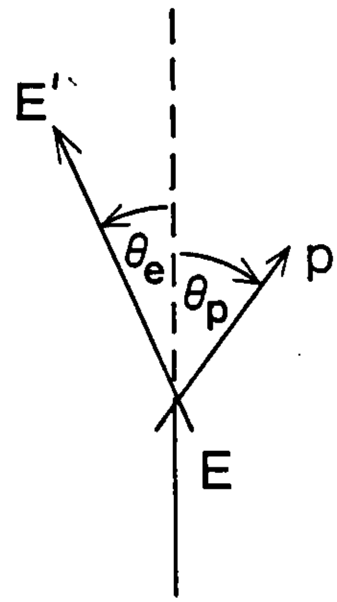

Figure 5. The incident electron of energy E scatters quasielastically through an angle θ_e to a final energy E'. The scattered proton recoils with momentum p through an angle θ_p.

The kinematics and rates are shown in Tables 1 and 2 respectively and refer the reader to Figure 5 for nomenclature. At each kinematic setting we will measure the known proton elastic scattering cross-section from a hydrogen target. The narrow hydrogen elastic peak will provide a check on our kinematics, and will allow a direct measurement of the timing and missing energy resolutions and coincidence detection efficiency. The hydrogen target will then be removed and replaced with a given nuclear target and the proton spectrometer retuned to account for the binding energy of the proton in the nuclear medium. We will then proceed to measure the proton quasielastic cross-section as a function of recoil momentum and missing energy. It is clear from Table 1 that even at $Q^2 = 6.2$ (GeV/c)^2 we have a rate on the iron target of about 200 counts/hr. We propose to investigate the A dependence of the cross-section by carrying out measurements on ^{4}He, ^{12}C, ^{56}Fe, and ^{197}Au targets.

Table 1. Kinematics for the proposed experiment.

Q^2	E	E'	P	θ_e	θ_p
$(\mathrm{GeV/c})^2$	GeV	GeV	GeV/c	degrees	degrees
6.2	4.0	0.74	4.1	92.7	10.4
5.0	4.0	1.3	3.5	59.0	18.4
3.0	3.0	1.4	2.4	50.8	26.0
1.0	2.0	1.4	1.2	34.4	44.6

Table 2. Rates for the proposed experiment for a 6% radiation length iron target. A reduction in the coincidence rate due to final-state interactions of 70% has been assumed. A resolving time of 1.5 ns and a duty factor of 100% are assumed in the calculation of the ratio of accidentals to trues.

Q^2	incl. q.f. rate	I	R_{coinc}	$e-$singles	$p-$singles	A/T
$(\mathrm{GeV/c})^2$	Hz	μA	Hz	Hz	Hz	
6.2	0.5	100	0.06	4	1×10^3	1×10^{-4}
5.0	5.1	100	0.6	9.3	3×10^3	6×10^{-5}
3.0	17	20	1.0	20	4×10^3	1×10^{-4}
1.0	135	1	1.6	150	1×10^3	2×10^{-4}

At each Q^2 we will run in perpendicular kinematics and carry out measurements of the spectral function S(E,**p**) over a missing energy range of 0 to 140 MeV and a recoil

Table 3. Summary of running time request.

$Q^2 = 1$	28 hours
$Q^2 = 3$	24 hours
$Q^2 = 5$	36 hours
$Q^2 = 6.2$	80 hours
calibration	24 hours
tuneup and checkout	70 hours
overhead	50 hours
total	312 hours

momentum range of 0 to 250 Mev/c. The scattering angle acceptance of the HMS is 3.7° and at each Q^2 we require several settings of the recoil proton angle to span the complete scattered proton distribution. At $Q^2 = 1$, 3, 5, and 6.2 $(\mathrm{GeV/c})^2$ we require 7, 4, 3, and 2 settings respectively. We demand 5000 counts for a given target at a given setting. Table 3 summarizes the beam request.

III. Resources Required

The proposed experiment will use the SOS for electron detection and the HMS for recoil proton detection. This spectrometer configuration allows the high Q^2 quasielastic measurements necessary for this experiment. Cryogenic hydrogen and helium and solid carbon, iron and gold targets will be used. We request 312 hours of beamtime. We point out that the experiment can run as soon as CEBAF turns on, provided the construction of the HMS and SOS spectrometers is carried out in a timely fashion.

IV. Collaboration

This group, in collaboration with other groups, has submitted a proposal to NPAS to carry out this experiment. If the NPAS experiment is approved and run before CEBAF commences operations, it will be further stimulus to pursue the measurements proposed here. The NPAS experiment has much worse missing energy resolution, lower luminosity, and smaller solid angle spectrometers. In the event that effects of suppression of final state interactions are seen at NPAS, there will be an entire program of measurements to pursue at CEBAF. In the event that no effects of color transparency are seen at NPAS, it will be important to carry out the much higher precision experiment proposed here at CEBAF.

All groups involved in this collaboration have plans to take part in the design and construction of the Hall C experimental area and equipment.

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