CEBAF Program Advisory Committee Nine Proposal Cover Sheet

This proposal must be received by close of business on Thursday, December 1, 1994 at:

CEBAF
User Liaison Office, Mail Stop 12 B
12000 Jefferson Avenue
Newport News, VA 23606

Proposal Title

The Fundamental $\gamma n \to \pi^- p$ Process in ^2H, ^4He, and ^{12}C in the 1.2 – 6.0 GeV Region

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Experimental Hall: A **Days Requested for Approval:** 24

Hall B proposals only, list any experiments and days for concurrent running:

CEBAF Use Only

Receipt Date: 12/14/94 PR 94-104

By: gp

BEAM REQUIREMENTS LIST

CEBAF Proposal No.: _____ Date: _____
(For CEBAF User Liaison Office use only.)

List all combinations of anticipated targets and beam conditions required to execute the experiment. (This list will form the primary basis for the Radiation Safety Assesment Document (RSAD) calculations that must be performed for each experiment.)

Condition #	Beam Energy (MeV)	Beam Current (μA)	Polarization and Other Special Requirements (e.g., time structure)	Target Material (use multiple rows for complex targets — e.g., w/windows)	Target Material Thickness (mg/cm²) ($\times 10^3$)
1	1200	10-25		^2H, ^4He, ^1H, ^{12}C	^2H: 2.55
2	2400	20-25		✓	^4He: 2.55
3	3600	20-25		✓	^1H: 1.05
4	4800	25		✓	^{12}C: 1.7
5	6000	25		✓	

The beam energies, E_{Beam}, available are: $E_{Beam} = N \times E_{Linac}$ where N = 1, 2, 3, 4, or 5. For 1995, E_{Linac} = 800 MeV, i.e., available E_{Beam} are 800, 1600, 2400, 3200, and 4000 MeV. Starting in 1996, in an evolutionary way (and not necessarily in the order given) the following additional values of E_{Linac} will become available: E_{Linac} = 400, 500, 600, 700, 900, 1000, 1100, and 1200 MeV. The sequence and timing of the available resultant energies, E_{Beam}, will be determined by physics priorities and technical capabilities.

HAZARD IDENTIFICATION CHECKLIST

CEBAF Proposal No.: _____ Date: _____
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Check all items for which there is an anticipated need.

Cryogenics ___ beamline magnets ___ analysis magnets X target type: ^1H, ^2H, ^4He flow rate: ___ capacity: ___ Standard Hall A Cryotargets	**Electrical Equipment** ___ cryo/electrical devices ___ capacitor banks ___ high voltage ___ exposed equipment	**Radioactive/Hazardous Materials** List any radioactive or hazadorous/ toxic materials planned for use: ___ ___ ___ ___
Pressure Vessels ___ inside diameter ___ operating pressure ___ window material ___ window thickness	**Flammable Gas or Liquids** type: ___ flow rate: ___ capacity: ___ **Drift Chambers** type: Standard Hall A flow rate: ___ capacity: ___	**Other Target Materials** ___ Beryllium (Be) ___ Lithium (Li) ___ Mercury (Hg) ___ Lead (Pb) ___ Tungsten (W) ___ Uranium (U) ✓ Other (list below) ^{12}C (4% r.l.) ___
Vacuum Vessels ___ inside diameter ___ operating pressure ___ window material ___ window thickness	**Radioactive Sources** ___ permanent installation ___ temporary use type: ___ strength: ___	**Large Mech. Structure/System** ___ lifting devices ___ motion controllers ___ scaffolding or ___ elevated platforms
Lasers type: ___ wattage: ___ class: ___ Installation: ___ permanent ___ temporary Use: ___ calibration ___ alignment	**Hazardous Materials** ___ cyanide plating materials ___ scintillation oil (from) ___ PCBs ___ methane ___ TMAE ___ TEA ___ photographic developers ___ other (list below) ___ ___	**General:** Experiment Class: X Base Equipment ___ Temp. Mod. to Base Equip. ___ Permanent Mod. to Base Equipment ___ Major New Apparatus Other: photon radiator will be used in beam line (copper)

LAB RESOURCES REQUIREMENTS LIST

CEBAF Proposal No.: _____ Date: _____
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List below significant resources — both equipment and human — that you are requesting *from CEBAF* in support of mounting and executing the proposed experiment. Do not include items that will be routinely supplied to all running experiments, such as the base equipment for the hall and technical support for routine operation, installation, and maintenance.

Major Installations *(either your equip. or new equip. requested from CEBAF)*

New Support Structures:

Data Acquisition/Reduction

Computing Resources:

New Software:

Major Equipment

Magnets

Power Supplies

Targets

Detectors

Electronics

Computer Hardware

Other

Other

Photon radiator (Cu) will be used in beam line, which is the same as proposed in 89-019, 94-012 experiments.

The Fundamental $\gamma\ n \rightarrow \pi^-\ p$ Process in ^{2}H, ^{4}He, and ^{12}C in the 1.2 - 6.0 GeV Region

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Abstract

The $\gamma\, n \rightarrow \pi^-\, p$ reaction is a process that is essential for studies of high energy photoreactions in nuclei and for studies of models in the high energy regime. We propose to measure the cross section of the quasifree exclusive $n(\gamma, \pi^- p)$ reaction in deuterium for photon energies between 1.2 to 6.0 GeV and at center of mass angles of 45°, 75° and 90°. This work will provide the first data for this reaction above 2 GeV. Furthermore, we propose to measure the π^-/π^+ photoproduction cross section ratio in deuterium at photon energies between 1.2 to 6.0 GeV and at center of mass angle of 45°, 75° and 90° to test the quark model prediction. Lastly, we propose to measure the cross section of the quasifree exclusive $n(\gamma, \pi^- p)$ reaction in ^{4}He and ^{12}C for photon energies of 1.2 to 6.0 GeV and at a center of mass angle of 75°. Nuclear transparency will be measured by the cross section ratios of $n(\gamma, \pi^- p)$ in ^{4}He and ^{12}C to that of deuterium. The energy and A-dependence of the cross section ratio is expected to address the issue of the final state interactions of hadrons with nucleons in nuclei. The proposed experiment would be performed in Hall A because of the simultaneous detection of protons and pions with momenta greater than 2 GeV/c and the relatively high luminosity required.

I. INTRODUCTION

The cross sections for many exclusive reactions at high energy appear to obey constituent counting rules [1]. Data on cross sections for the photo-pion production have shown similar agreement with constituent counting rule predictions [2], for example as shown in the upper panel of Fig. 1 for the $\gamma p \rightarrow \pi^+ n$ process. No data on the fundamental process $\gamma\, n \rightarrow \pi^-\, p$ exist above a photon energy of 2.0 GeV. Furthermore, discrepancies exist at lower energies between data taken at the same photon energies for this process, largely due to the large uncertainties in some of the measurements. We propose to study the $n(\gamma, \pi^- p)$ process by measuring the cross section of the quasifree exclusive $n(\gamma, \pi^- p)$ reaction on deuterium at photon energies of 1.2 to 6.0 GeV and at pion center of mass angles of 45°, 75° and 90°. The lower panel in Fig. 1 shows the existing data on the differential cross sections for the $\gamma\, n \rightarrow \pi^-\, p$ process together with the center of mass energy range of this experiment.

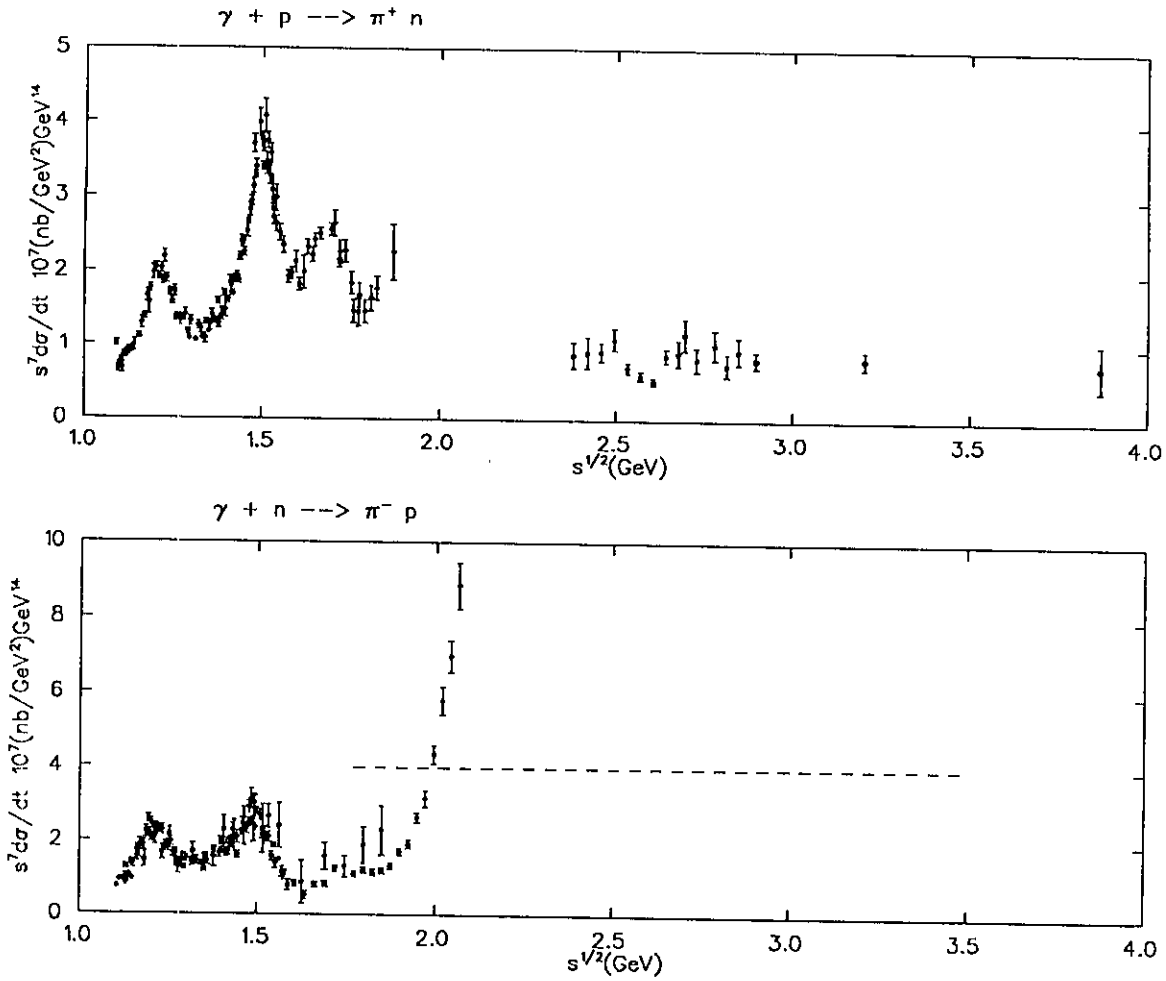

FIG. 1. **Existing data on the differential cross section for the $\gamma\ p \rightarrow \pi^+\ n$ and the $\gamma\ n \rightarrow \pi^-\ p$ processes as a function of the center of mass energy, $s^{1/2}$, at the center of mass angle near 90°. The y axis is the differential cross section $d\sigma/dt$ multiplied by s^7. In the bottom figure, the dashed line indicates the $s^{1/2}$ range of this experiment, its height is arbitrary.**

According to the quark model, the π^-/π^+ photo pion production ratio is expected to be unity for small values of t but decrease toward 1/4 as t and s increase, where t and s are the Mandelstam variables. While the value of the ratio decreases dramatically as t increases, a value of 1/4 has not been achieved as shown in Fig. 2 [3]. The range of t covered in Fig. 2 is from 0.0 to 0.8 $(\mathrm{GeV/c})^2$. We propose to measure the π^-/π^+ photo-pion production ratio in deuterium to extend the t range covered by previous experiments to test the quark model prediction. The t range of this experiment will be from 0.22 to 5.2 $(\mathrm{GeV/c})^2$.

The photo-pion production process is one of the few fundamental reactions that can be used to study the final state interactions of hadrons with nucleons in nuclei. The nuclear transparency for the photo-pion reaction has not been studied experimentally. We propose

to measure the cross section of the quasifree exclusive $n(\gamma, \pi^- p)$ reaction in ^{4}He and ^{12}C at photon energies of 1.2 to 6.0 GeV and at a pion center of mass angle of 75°. Whether the cross section data would show the same quark counting rule behavior as that of the fundamental $n(\gamma, \pi^- p)$ process or not will address the issue of the FSI of hadrons with nucleons in the residual nucleus. Furthermore, one can measure the nuclear transparency by forming the cross section ratios of $n(\gamma, \pi^- p)$ in ^{4}He and ^{12}C to that of deuterium. Experiment NE18 [4] [5] has measured the nuclear transparency from $A(e, e'p)$ reactions in ^{2}H, ^{12}C, ^{56}Fe, and ^{197}Au. The propagation of the high energy proton (a few GeV) through the nuclear medium is known from the NE18 data at kinematics where this experiment is relevant. So data on the nuclear transparency from this proposed experiment will give a good handle on the propagation of high energy pions through the nuclear medium. The energy range will span both the nucleon resonance region and the constituent counting rule regime for nuclei where rigorous Glauber theory calculations can be performed and over a momentum transfer region comparable to that of NE18 experiment.

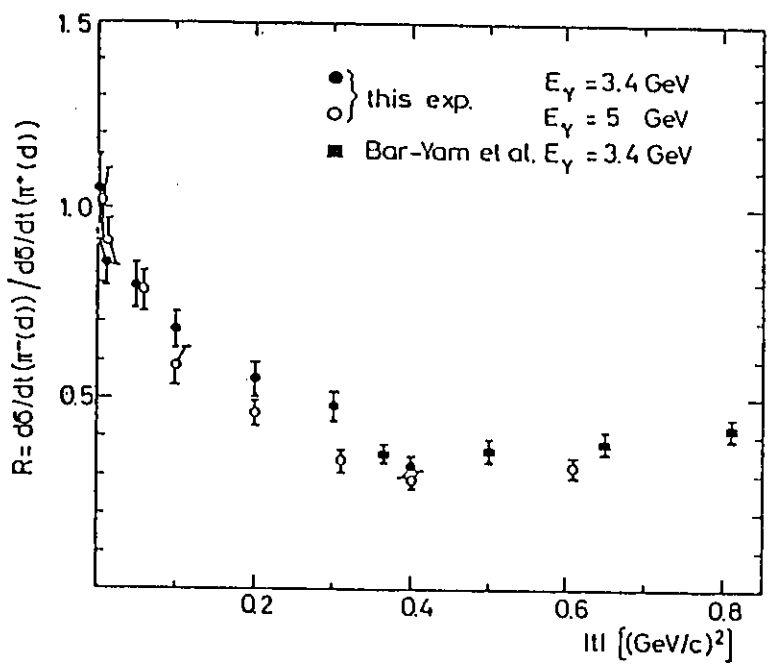

FIG. 2. **π^-/π^+ ratios at E_γ=3.4 and 5.0 GeV from deuterium as a function of $|t|$ taken from Ref. [3]**

An additional and interesting degree of freedom can occur for the $N(\gamma, \pi N)$ process. At the proposed energies below 3 GeV, nucleon resonance formation is likely whereas at the highest energies resonance formation is either unlikely or extremely short-lived. This means that at the lower energies, the transparency might be determined by the propagation of a resonance through the nucleus, while at the higher energies, it will be determined by individual propagation of a pion and nucleon through the nucleus. We propose to measure the nuclear transparency in ^{4}He and ^{12}C at photon energies between 1.2 to 6 GeV and at center of mass angle of 75°. The lifetime of any intermediate state is expected to have

a profound effect on the transparency signal. The use of both ^{4}He with a radius of 1.7 fm and ^{12}C with a radius of 3.2 fm provides a means to explore the propagation of any intermediate state through the nucleus. Furthermore, ^{4}He is one of the few nuclei where a rigorous calculation can be performed.

A more detailed discussion of the physics motivation for the experiment appears in Section II. Section III will outline the proposed measurement. Section IV will be a discussion of the experimental technique, in which there will also be a discussion of the expected backgrounds and systematic uncertainties. Section V will contain the beam time request. Section VI discusses the collaboration background and responsibilities. The last section contains the acknowledgements.

II. PHYSICS MOTIVATION

The scientific motivation for this proposal is three-fold. First, we will determine whether the fundamental process $\gamma\ n \rightarrow \pi^-\ p$ follows constituent counting rules as a function of both the energy and the angle. Secondly, the π^-/π^+ photo-pion production ratio in deuterium as a function of the photon energy and center of mass angle will be measured to test the quark model prediction. Finally, with the energy dependence for this process known we will measure the A and energy dependence of the $\gamma\ n \rightarrow \pi^-\ p$ process in nuclei. The transparency measured from this process will determine whether the simple Glauber approximation applies to this process in nuclei.

A. Fundamental $\gamma\ n \rightarrow \pi^-\ p$ Process

For the exclusive scattering processes at high energy and large transverse momentum, constituent counting rules predict the following scaling law for the differential cross section:

$$(d\sigma/dt)_{AB\rightarrow CD} \sim s^{2-n} f(cos\theta^*). \tag{1}$$

Here n is the total number of elementary fields, θ^* is the center of mass angle. t and s are the Mandelstam variables defined as follows:

$$t = (p_A - p_C)^2 = (p_B - p_D)^2 \tag{2}$$
$$s = (p_A + p_B)^2 = (p_C + p_D)^2, \tag{3}$$

where p_A and P_B are the four-momenta of the incoming particles, and p_C and P_D are the four-momenta of the outgoing particles. For photo-pion production γ N $\rightarrow \pi$ N processes, $s = {M_N}^2 + 2M_N E_\gamma$, where M_N is the nucleon mass and E_γ is the photon energy.

For fundamental processes like $\gamma\ p \rightarrow \pi^+\ n$, $\gamma\ p \rightarrow \pi^0\ p$, and $\gamma\ n \rightarrow \pi^-\ p$, the total number of elementary fields is nine. So constituent counting rules give:

$$(d\sigma/dt)_{AB\rightarrow CD} \sim s^{-7} f(cos\theta^*). \tag{4}$$

Data on $\gamma\ p \rightarrow \pi^+\ n$ [2] show that the cross section follows the quark counting rule prediction above a photon beam energy of 2.0 GeV (see Fig. 1). Fit of data at center of mass angle

of 90° gives the $s^{-7.3\pm0.4}$ dependence of the cross section for the $\gamma\ p \rightarrow \pi^+\ n$ process. It is not clear whether the $\gamma\ p \rightarrow \pi^0\ p$ reaction follows the same counting rule behavior because discrepancies exist between different measurements. For the $\gamma\ n \rightarrow \pi^-\ p$ process, no cross section data exist above a photon energy of 2.0 GeV and no scaling behavior in the cross section is seen for this reaction below 2 GeV. By choosing photon energies of 1.2 to 6.0 GeV, this experiment will overlap with the previous measurement at $s^{1/2} \sim 1.77$ GeV as shown in Fig. 1, as well as go to much higher energy to test the scaling law for this process.

Though the differential cross section for $\gamma\ p \rightarrow \pi^0\ p$ is expected to be half of that for the $\gamma\ p \rightarrow \pi^+\ n$ process from the naive quark model, a comparison of the central region ($\theta^* \sim 90°$) values of $d\sigma/dt$ for the $\pi^0 p$ and $\pi^+ n$ data [2] at 4 and 5 GeV shows that the cross sections are similar but that the $\pi^0 p$ cross sections are higher by a factor of approximately two. This is in contradiction with the naive quark model prediction.

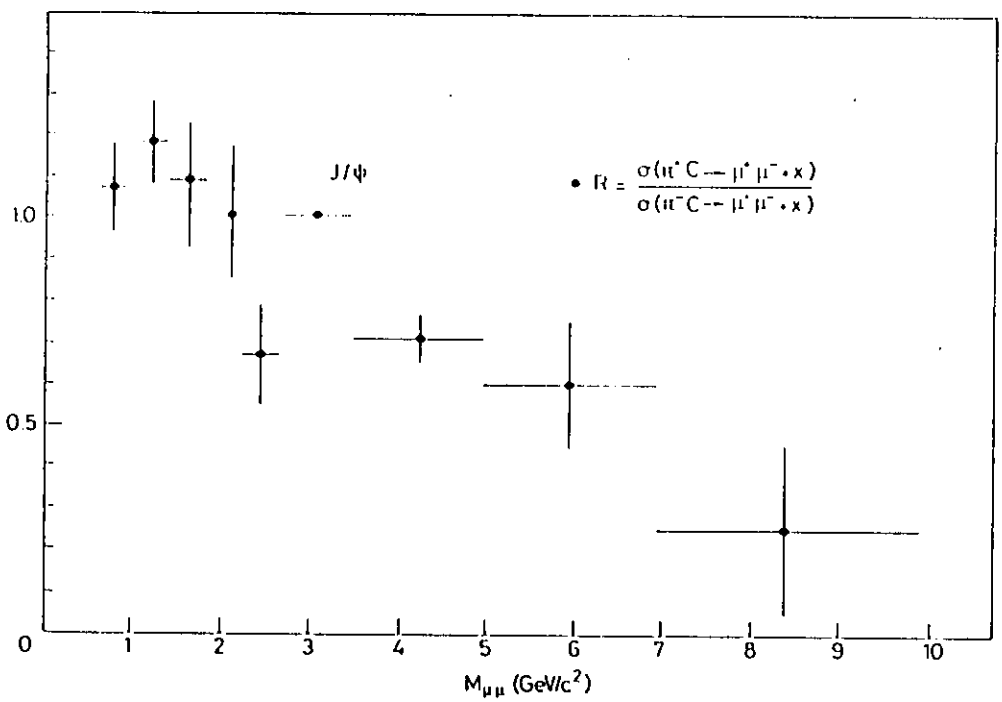

FIG. 3. **Ratio of $\mu^+\mu^-$ production cross-section in π^+ and π^- induced reactions taken from Ref. [6].**

For the π^-/π^+ photo-pion production cross section ratio, the quark model gives the following prediction. In the limit of $t \simeq 0$, the sea quarks dominate which gives $\pi^-/\pi^+ \simeq 1$. On the other hand, as t and s increase valence quarks dominate. Thus,

$$\frac{\frac{d\sigma}{dt}(\gamma\ n \rightarrow \pi^-\ p)}{\frac{d\sigma}{dt}(\gamma\ p \rightarrow \pi^+\ n)} = \frac{e_d^2 f_d^n f_d^{\pi^-}}{e_u^2 f_u^p f_u^{\pi^+}} = \frac{e_d^2}{e_u^2} = \frac{1}{4}, \tag{5}$$

since $f_d^{\pi^-} = f_u^{\pi^+}$, and the number of down quarks in the neutron is equal to that of up

quarks in the proton. The above quark model prediction is not inconsistent with data for Drell-Yan process for an (isoscalar) carbon target [6]. There, the ratio

$$\frac{\sigma(\pi^+ C \to \mu^+\mu^- X)}{\sigma(\pi^- C \to \mu^+\mu^- X)} \tag{6}$$

is approximately unity for small values of t but decrease toward $\frac{1}{4}$ as t increases as shown in Fig. 3. Unfortunately, the errors are too large for the Drell-Yan experiment to confirm the quark model value of 1/4. Ito *et al.* [7] measured the ratio R of the π^- and π^+ photoproduction cross sections from deuterium in the forward direction to be $\sim 0.6 - 1$ for $0.6 \leq E_\gamma \leq 1.7$. Heide *et al.* [3] measured the singles π^- and π^+ photoproduction from deuterium at photon energies of 3.4 and 5.0 GeV and momentum transfer between 0.005 to 0.6 $(\mathrm{GeV/c})^2$. The π^-/π^+ ratio is found to be unity near forward direction and drops to about 0.4 at larger angles. Both measurements agree within experimental errors with the quark model prediction for small values of t. The measurements of Heide *et al.* [3] suggest a decrease of the π^-/π^+ ratio at large angles, i.e, larger values of t. We propose to measure the singles ratio of π^-/π^+ in deuterium up to t range by a factor of approximately six of the t range of the previous experiments [7] [3].

Previous data on $\gamma\ p \to \pi^+\ n$ [2] were taken up to a photon energy of 7.5 GeV. This experiment will provide data on $d\sigma/dt$ for $\gamma\ n \to \pi^-\ p$ in the photon energy range of 1.2 to 6.0 GeV and the center of mass angle of $45°, 75°$, and $90°$. Also by measuring the ratio of π^-/π^+, this experiment will provide data on the cross section for the $\gamma\ p \to \pi^+\ n$ process, which overlaps with the previous $\pi^+\ n$ data in most of the energy region and at center of mass angle of 90°. The comparison with the previous $\pi^+\ n$ data would address the issue of the discrepancy between the $(\gamma\ p \to \pi^0\ p)/(\gamma\ p \to \pi^+\ n)$ cross section ratio and the quark model prediction.

Because there is no free neutron target, deuteron serves as the best approximation to a neutron target in many cases for studying the fundamental properties of neutron because it is weakly bound (2.2 MeV) and there is only one "background" proton. We propose to study the fundamental process $\gamma\ n \to \pi^-\ p$ by performing the quasifree exclusive $n(\gamma, \pi^- p)$ measurement on deuterium target. There are three main complicating effects involved in using a deuteron target: fermi motion, shadowing, and the Pauli principle. Fermi momentum broadens the energy resolution of the experiment and also lowers the threshold photon energy for 2π photoproduction which could contaminate the π^- rates. The Pauli principle lowers the cross section by restricting the final states available to the two final protons in the reaction $\gamma + d \to \pi^- + 2p$. This effect was studied by Chew and Lewis [8] and determined to be less than 20% for the total momentum of the recoiling nucleon less than 100 MeV. By detecting the final proton and π^- in coincidence, the energy resolution of the experiment can easily be improved. Furthermore, production of π^- mesons from high-velocity neutrons is suppressed, and 2π contamination is greatly reduced [9]. Also, by performing coincidence measurement other photo-pion processes like $\gamma\ p \to \pi^0\ p$, $\gamma\ p \to \pi^+\ n$, as well as $d(\gamma, p)n$ are excluded.

In the energy region of this experiment (1.2 - 6.0 GeV), the 2.2 MeV binding energy of deuteron is not expected to be significant. However, corrections need to be applied to the measured cross section of the quasifree $\gamma\ n \to \pi^-\ p$ process on deuterium in order to extract the fundamental amplitude of the $\gamma\ n \to \pi^-\ p$ process. The shadowing effect is about 5%

[10] in the energy region of this experiment. Another correction comes from the fact that neutron is off mass shell as it undergoes fermi motion in the deuteron. The motion of the target nucleons affects the cross sections in two distinctive ways. First the total center-of-mass energy seen by the bound nucleon is shifted by a "Doppler effect". Secondly, the flux of incident particles in the rest frame of the moving nucleon is different from that in which the cross section of the free nucleon is measured. These effects, which were studied in detail by Atwood and West [10], depend upon the momentum distribution of the nucleon and in particular upon the tail of the momentum distribution inside the deuteron. These effects were estimated to be small ($\sim 5\%$) by Atwood and West [10] and can be corrected for the photo-reaction by their procedure.

B. $\gamma\ n \rightarrow \pi^-\ p$ Process in ^{4}He and ^{12}C

Calculations for the transparency for the $\gamma\ n \rightarrow \pi^-\ p$ process can be made rigorously for the ^{2}H, ^{4}He and ^{16}O nuclei either by using ground state wave functions directly or by using configurations obtained from the Monte Carlo method using the ground state wave functions. The ground state wave functions for these nuclei were calculated by Pandharipande, Pieper and Wiringa [11] using realistic potentials for the NN interaction. Much progress in calculating transparency in ^{2}H has already been made [12] and agrees well with the NE18 data [4] [5] for ^{2}H. We chose ^{12}C rather than ^{16}O for this study because of the existing NE18 data and the technical practicalities of the target. Nuclear transparency for the $n(\gamma, \pi^- p)$ reaction can be extracted from the cross section ratio of ^{12}C and ^{4}He to that of deuterium. The shadowing effect for the cross section ratio in the energy region of this experiment is on the order of 10% as shown in [13]. The quasifree exclusive $n(\gamma, \pi^- p)$ reaction on a nuclear target may be thought of as a two step process which consists of forming a baryonic intermediate state and the subsequent decay of this state into the two-hadron final state of proton and pion. The typical width for known baryonic resonances is between 100 to 400 MeV corresponding to a lifetime on the order of 0.5 - 2 fm. If the above picture holds, the two hadron final state is likely to be formed outside of the nuclear medium for a light nuclear target, for example ^{4}He. The total cross section for this intermediate state with the nucleons in the residual nucleus is not known. However, if one assumes this state has a cross section on the order of 40 mb similar to that of the proton, then a significantly larger nuclear transparency signal could occur as compared to the standard Glauber prediction for the two hadron final state of a proton and pion propagating through the nuclear medium, which has a total p-N cross section of about 43 mb and a total π^--N cross section of approximately 30 mb. The nuclear transparency is estimated to be about 25% different from ^{4}He to ^{12}C in this scenario.

Alternatively, if we are in the constituent counting regime, one would expect the intermediate state to be short-lived because the time scale is inversely proportional to the center of mass energy of the system. For a photon beam energy of 6 GeV, an intermediate state lifetime on the order of 0.2 fermi is expected. Thus, the final state proton and pion travel essentially through the nuclear medium before they are detected. Nuclear transparencies for quasifree exclusive $n(\gamma, \pi^- p)$ reaction in ^{12}C and ^{4}He were calculated by G. Miller [14] using uncorrelated Glauber theory and assuming that the final state pion and proton are produced instantaneously. Although there is debate [15] over whether correlated Glauber theory is

appropriate as well as whether the π and N are produced instantaneously, its use would give a much higher nuclear transparency. Fig. 4 shows the calculated nuclear transparency for ^{4}He and ^{12}C by Gao and Pandharipande. The transparency for ^{12}C was calculated using the standard Glauber approximation (GA), together with the correlated Glauber approximation (CGA). The transparency for ^{4}He was calculated using the standard Glauber approximation with realistic particle configurations obtained from the ^{4}He ground state wave function using the Monte Carlo method. The ^{12}C nuclear density obtained by fitting the elastic electron-nucleus scattering data [16] and the ^{4}He nuclear density calculated by Wiringa [17], which agrees with the measured form factors very well, were used in the Glauber calculations. The uncorrelated Glauber prediction for ^{12}C by Gao and Pandharipande agrees well with the calculation by G. Miller [14]. The correlated Glauber calculations were performed with the same assumptions as given in Benhar *et al.* [15] which describe the NE18 Data. The correlated Glauber calculations give nuclear transparencies more than 30% larger than those from the uncorrelated Glauber theory for ^{12}C. The configuration calculations give ^{4}He transparencies more than 25% larger than those predicted from the Glauber approximation. Recent theoretical work [12] indicates that the spectator effect, which was argued to cancel the correlation effect [18], is only a few percent in ^{16}O. Thus, the correlation effect is expected to be large.

By measuring the nuclear transparency from this reaction, one can test whether Glauber theory is appropriate at all for this process. If the pion and proton are produced in the small configuration state, they would experience reduced interactions with the nuclear medium on their way out. With good understanding of the energy dependence and the A-dependence of the nuclear transparency for the $\gamma\ n \rightarrow \pi^-\ p$ process in 'low' energy region (1.2 - 6.0 GeV), ultimately, this reaction may be attractive to study the color transparency effect at higher energy (10 GeV) because two hadrons must propagate through the nucleus and the color transparency signal would be substantially larger than in either $A(e, e'p)$ or $A(e, e'\pi)$ experiments. In any event, this work will provide transparency data for a fundamental process over a large energy range spanning the resonance and possibly constituent counting regime where reasonably rigorous nuclear calculations can be performed.

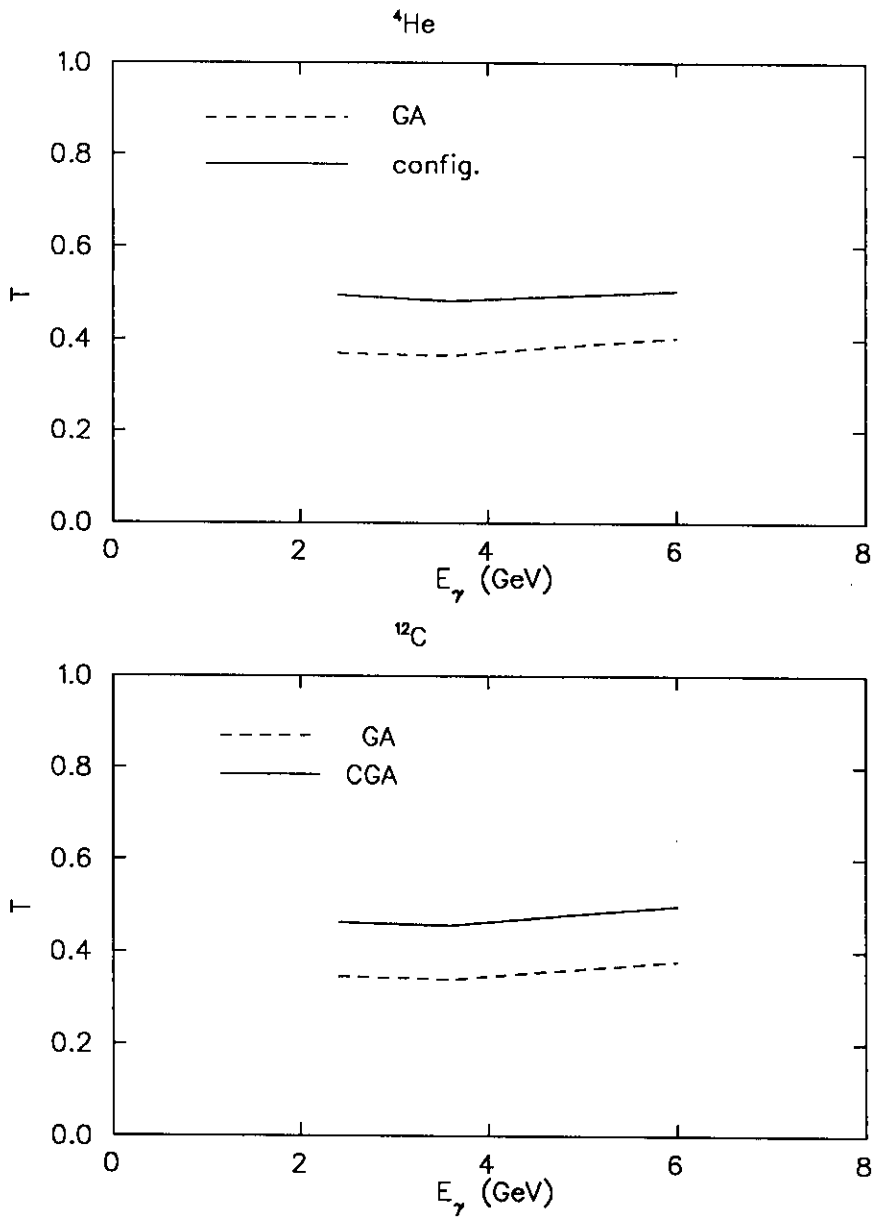

FIG. 4. **Predictions of the nuclear transparencies for the quasifree exclusive $n(\gamma, \pi^- p)$ reaction in ^{4}He and ^{12}C. Config. stands for the configuration calculation (see text).**

III. PROPOSED MEASUREMENTS

We propose to perform the coincidence measurements of the quasifree exclusive $n(\gamma, \pi^- p)$ reaction in ^{2}H at photon energies of 1.2 to 6.0 GeV, in steps of 1.2 GeV, and at pion center of mass angle of 45°, 75°, and 90°. Data will also be taken in singles mode to measure the π^-/π^+ ratio in deuterium at the same photon energies and center of mass angles as described above. As a check of the systematics for the π^-/π^+ ratio measurements, we propose to perform a calibration run on hydrogen for the π^+ photo-production reaction. This measurement

will also provide comparison to the previous data for this reaction. Lastly, we propose to measure the quasifree exclusive $n(\gamma, \pi^- p)$ reaction in ^{4}He and ^{12}C at photon energies of 1.2 to 6.0 GeV, in steps of 1.2 GeV, and at pion center of mass angle of 75°.

Three center of mass angles, 45°, 75° and 90°, were chosen to study the angular dependence of the $\gamma\ n \rightarrow \pi^-\ p$ process. No backward angle was proposed because of the low counting rate. A reaction angle of 75° for ^{4}He and ^{12}C was chosen by optimizing the nuclear transparency signal and the counting rate, ensuring that the momentum of the scattered hadrons is less than 4.0 GeV, the highest measurable momentum of the HRS spectrometers. The motivation for the choice of the beam energies was the compatibility with the highest beam energy attainable at CEBAF, enough energy range covered to study the energy dependence in the cross section for the fundamental process $\gamma\ n \rightarrow \pi^-\ p$ and the energy dependence of the nuclear transparency, and the most convenient energy changes.

This experiment requires the simultaneous detection of both the proton and π^- with momentum larger than 2.0 GeV/c at the highest energies as listed in Table 1. It also requires relatively high luminosity because of the low coincidence rates involved. Thus with two HRS spectrometers, Hall A is the place where this experiment can be performed.

IV. EXPERIMENT

A. OVERVIEW

The experiment will employ the Hall A cryogenic liquid hydrogen, deuterium, gas ^{4}He, solid carbon targets, and the Hall A radiator. The maximum energy of the Bremsstrahlung beam is essentially equal to the electron kinetic energy. The target, located downstream of the radiator, is irradiated by the photons and the primary electron beam. Quasifree kinematics are chosen for the exclusive $n(\gamma, \pi^- p)$ reaction. The coincidence measurements will be performed using Hall A electron spectrometer for detecting the pions and the hadron spectrometer for protons. Singles measurement of π^- from deuterium will be taken simultaneously with the coincidence measurement.

The $\gamma\ n \rightarrow \pi^-\ p$ reaction is a two body process. By either detecting the momentum and angle of the photoproton or detecting the momentum and angle of the photo-produced pion, one can determine the incident photon beam energy. In this experiment, we propose to perform the quasifree $n(\gamma, \pi^- p)$ reaction on nuclear targets. Because of the recoil nucleus and the fermi motion, measurement of the momenta and scattering angles of both proton and pion are necessary in order to reconstruct the incident photon energy. Furthermore, by coincidence measurement and measuring only the highest energy protons and pions other inelastic channels, eg. from 2π decay can be essentially eliminated.

B. RADIATOR

The radiator will be Cu with 6% of a radiation length. The Cu will be placed in the scattering chamber at least 30 cm upstream of the pivot so that the spectrometers do not view it directly at the chosen scattering angles. Energy loss in the Cu is about 50 Watts for a beam current of 25μA. The radiator assembly will be the same as that planned for the

approved Hall A experiments 89-019 [19] and 94-012 [20]. The background from the copper radiator due to the production of the low energy neutrons and the high energy pions has been considered in 94-012 and determined not to be a problem in terms of triggering the detectors based on the estimated singles rate to each scintillator in the detector stack.

C. TARGET

We plan to use the Hall A liquid deuterium (2% r.l.), gas ^{4}He (2% r.l.) cryotargets and solid carbon (4% r.l.) target. Liquid hydrogen target (2% r.l.) will be used for calibration runs and some of the background studies. The design heat load for Hall A cryotarget is up to 1 KW, much greater than the 150 W load for this experiment. For a 15 cm long target cell, at an incident electron beam current of 25 μA, the luminosity is $\mathcal{L} = 6.0 \times 10^{37}$ /cm^2/s for ^{4}He at 70 atm and 10 K , and $\mathcal{L} = 1.2 \times 10^{38}$ /cm^2/s for liquid deuterium at 20 K and operating pressure of 17 atm . The design goal for the cryotarget density fluctuation is below 5%. At the heat load of this proposed experiment, the average temperature change of the target liquid and gas will be much less than 1 K, so the density fluctuation should be negligible. The total energy deposited at the highest energy (6 GeV) with 25 μA of beam is below the 100 Watts equivalent thick target power limit.

D. SPECTROMETER

The two Hall A HRS spectrometers with highest central momentum of 4.0 GeV/c make the coincidence measurement possible at the highest energies of this experiment. We will use both Hall A HRS spectrometers in their standard configurations for detecting π^- and protons in coincidence mode. The highest momentum setting for the pion arm spectrometer is 3.94 GeV/c and the most forward angle is 16.1°. For the proton arm, the highest momentum setting is 3.57 GeV/c and the most forward angle is 26.7°. The highest singles rate in the spectrometer is less than 40 KHz, as compared to design goal of 1 MHz (to allow 10 KHz coincidence trigger rate). The momentum and angle settings for both spectrometers are listed in Table I. Change of the pion arm spectrometer magnet polarities is required for detecting the π^+ particles from deuterium in singles mode. The momentum distributions for ^{2}H and ^{12}C are known from NE18 experiment [4] [5]. Thus for this experiment, we plan to map the fermi cone for the ^{4}He target at the two lowest energies and center of mass angle of 75° by fixing the pion arm HRS spectrometer angle and varying the angle of the proton arm spectrometer as was done in NE18 for the $(e, e'p)$ measurements [4] [5].

E. BACKGROUND

The dominant background process for this experiment is the quasielastic $A(e, e'p)$ reaction, as well as the elastic radiative tail. The quasi-elastically scattered electron has nearly the same momentum and scattering angle as the photo-produced pion in the pion arm, and the scattered proton has also nearly the same momentum and scattering angle as that of the photoproton in the proton spectrometer. We have calculated the singles ratios of e^-/π^- for all the kinematics proposed in this experiment. The singles rate for electrons includes

both the quasielastically scattered electrons from protons and neutrons in the nuclei. The calculated e^-/π^- ratios are listed in the last column of Table 2. The actual experimental conditions will be better since this estimate does not include the reduction in electron rate from radiative effects. In the worst case at the electron beam energy of 6 GeV and center of mass angle of 75°, the calculated singles rate ratio of e^-/π^- is 660. A 2% measurement therefore requires an electron rejection ratio of 3.3×10^4. According to the CDR [21] for the electron arm HRS, a 1 meter CO_2 Čerenkov counter (85 cm effective length, accounting for the curvature of the mirrors) gives 10 photoelectrons. This gives $\sim 99.7\%$ π/e detection efficiency for a threshold of 3 photons. The University of Maryland shower counter simulations indicate a factor of 500 suppression of π^- relative to electrons. In combination with the shower counter, an overall rejection ratio of 2×10^6 can be achieved according to the CDR, which is more than a factor of 50 better than we need. Thus, the electron rejection efficiency is adequate for this experiment. We would like to emphasize here that the required electron rejection ratio for this experiment is less than the required pion rejection ratio (10^5) for the approved Hall A L/T separation measurements [22] [23]. The trigger in the pion arm should be flexible to read out pions and electrons in singles mode.

In the proton arm (HRS), good particle identification of protons, π^+ particles and positrons is required. The positron background arises from the pair production of the bremsstralung photons which can easily be rejected using the shower counter and Čerenkov counter. Although the π^+ particles from the $\gamma\ p \rightarrow \pi^+\ n$ reaction are kinematically eliminated in the proton HRS spectrometer, the π^+ background comes mainly from the multiple processes which have relatively low rates because of the phase space constrain. According to the CDR, the π^+ background can easily be rejected using the TOF for pion momentum below 2.0 GeV/c and an aerogel Čerenkov counter for pion momentum higher than 2.0 GeV/c.

The quasielastically scattered protons in the proton arm can also be removed by rejecting the electrons in the pion arm by coincidence measurement. All the other background nuclear pion photo-production reactions will not be a problem because we propose to detect both the protons and the π^-s in coincidence. Because of CEBAF's high duty factor, the accidental rate is low as seen from Table 2. For the solid carbon target, the remaining background can be readily subtracted by measuring the yield with radiator in and radiator out. For the cryotarget, additional background also comes from the Al endcaps of the target. This can be removed by measuring the yields on a liquid hydrogen target with the same radiation length as that of liquid deuterium for radiator in and out, in combination with measurements on deuterium with radiator in and out.

For singles π^+ measurements, protons from the $d(\gamma, p)n$ process will contaminate the π^+ rate. The singles ratio of p/π^+ has been estimated using the NE17 data [24] and found to be at maximum of two. Thus for $P \leq 1.0$ GeV/c, TOF is sufficient to achieve a 2% measurement; while for $P \geq 1.0$ GeV/c, aerogel čerenkov counter is adequate.

F. SYSTEMATIC ERRORS

We aim at an overall 5% systematic error for the study of the energy and angular dependence in the cross section for the fundamental $\gamma\ n \rightarrow \pi^-\ p$ process, and a 5% systematic uncertainty for the transparency measurements. For the singles π^-/π^+ ratio measurements,

all major systematic uncertainties cancel out because the same spectrometer, radiator, target will be used. An overall systematic uncertainty $2-3\%$ can be achieved for this ratio measurement. We want to emphasize here that we rely on forming the cross section ratio in the transparency measurements. Any systematic uncertainty which does not have energy dependence should not have an effect on the measured energy dependence of the nuclear transparency. Also by forming the cross section ratio, many systematic uncertainties will cancel. In this section, we will discuss the main systematic uncertainties for the experiment.

One of the important systematic errors comes from the uncertainty in the spectrometer acceptance. We expect the absolute spectrometer acceptance for the coincidence measurements to be comparable to that for the NE18 experiment (5%) [5]. The spectrometer acceptance for extended target and as a function of central momentum setting will be studied by detecting the e-p elastic scattering electrons and protons in both HRS spectrometers in singles and coincidence modes. While the spectrometer acceptance across the focal plane and as a function of its central momentum setting will be understood very well from Hall A commissioning experiments, we request a small amount additional beam time (24 hrs) for spectrometer calibration for this experiment.

For coincidence measurements, there exists the issue of overlapping the spectrometer acceptance. Because of the fermi motion matching the spectrometer acceptance will be different for different nuclear targets. The efficiency of matching the spectrometer acceptance varies as a function of the spectrometer central momentum setting. All these issues will be studied by Monte Carlo simulations with realistic nuclear spectral functions and the spectrometer angular and momentum acceptances. As demonstrated in experiment NE18, this part of the systematic uncertainty is well under control.

The bremsstrahlung photon energy is reconstructed from the measured momenta and scattering angles of the final state proton and π^-. The bremsstrahlung photon flux can be calculated from the reconstructed photon energy using the procedure developed by Matthews and Owens. The uncertainty in calculating the bremsstrahlung flux is on the order of 3% as estimated in [24]. Again by measuring the cross section ratio, this part of the uncertainty should cancel out. But for different nuclear targets because of the fermi momentum and the recoiling residual nucleus, the reconstructed bremsstrahlung photon energy will be slightly different even though the final state proton and pion have the same momentum and scattering angle. The uncertainty in calculating the bremsstrahlung photon flux does not cancel out completely, but is estimated to be much smaller than the aimed overall systematic uncertainty. This uncertainty in calculating the bremsstrahlung photon flux has negligible energy dependence. The systematic uncertainty from rejecting the background particles is expected to be $\leq 2\%$.

V. BEAM REQUEST

Count rates have been calculated based on the following assumptions. From the quark model, the differential cross section for the $n(\gamma,\pi^-)p$ reaction was assumed to be a quarter of that for the $p(\gamma,\pi^+)n$ reaction for photon energies higher than 2.4 GeV. For photon energies below 2.4 GeV, counting rates were estimated using the previous π^-p data as shown in Fig. 1. The cross sections for $p(\gamma,\pi^+)n$ reaction are then extrapolated from the 5 GeV data [2] using the following scaling law for the kinematics proposed:

$$s^7 \frac{d\sigma}{dt} \sim \frac{1}{(1+cos\theta^*)^4} \frac{1}{(1-cos\theta^*)^5}, \tag{7}$$

We assume a 15-cm target which corresponds to 2.55 (gm/cm^2) for liquid deuterium, 1.1 (gm/cm^2) for liquid hydrogen (background runs and the spectrometer acceptance studies) and 2.55 (gm/cm^2) for the gas helium-4, respectively. A 4% solid carbon target will be used for the experiment corresponding to 1.7 (gm/cm^2). The bremsstrahlung photon flux is calculated for a 6% copper radiator. A solid angle of 7.0 msr was assumed for the HRS spectrometer in calculating the rates. Table 2 lists the calculated singles rates for $n(\gamma, \pi^-)$ and $n(\gamma, p)$, the coincidence rates for $n(\gamma, \pi^- p)$, the accidentals, and the singles e^-/π^- ratios for deuterium target. An electron beam current of 25μA was used in calculating the rates. A coincidence resolving time of 2 ns (full width at base) was assumed in calculating the accidentals. All the listed rates were calculated for 100% of nuclear transmission. The fermi cone acceptance for the singles and the coincidence rates was calculated to first order, in which a fermi momentum of 150 MeV/c was used for the deuteron, 200 MeV/c for ^{4}He, and 220 MeV/c for ^{12}C nucleus.

We propose to perform a three-step experiment. In the first part of the experiment, we will study the energy dependence and the angular distribution in the exclusive cross section for the $\gamma\ n \rightarrow \pi^-\ p$ reaction. Data will be taken on liquid deuterium target. We aim at 5% statistical error at all photon energies and angles, together with an overall 5% systematic uncertainty which is sufficient for investigating the quark counting rule behavior in the cross section for this exclusive process. Fig. 5 shows the proposed data with uncertainties for the cross section measurement, together with the existing data for this reaction. In the second part of the experiment for measuring the singles π^-/π^+ ratios, 3% statistical uncertainties were proposed for the π^+ measurements, and the statistical uncertainties for the singles π^- measurements would be smaller than 3%. Thus, an overall 5% uncertainty for the π^-/π^+ ratio measurement can be achieved.

In the third part of the experiment, data will be taken on gas ^{4}He and solid ^{12}C targets for studying the nuclear transparency. We focus on the energy and the A-dependence of the nuclear transparency signal. A 5% statistical uncertainty at the three lowest energies, 7% (statistical) at 4.75 GeV and 9% (statistical) at the highest energy were proposed for both targets, together with a 5% systematic uncertainty.

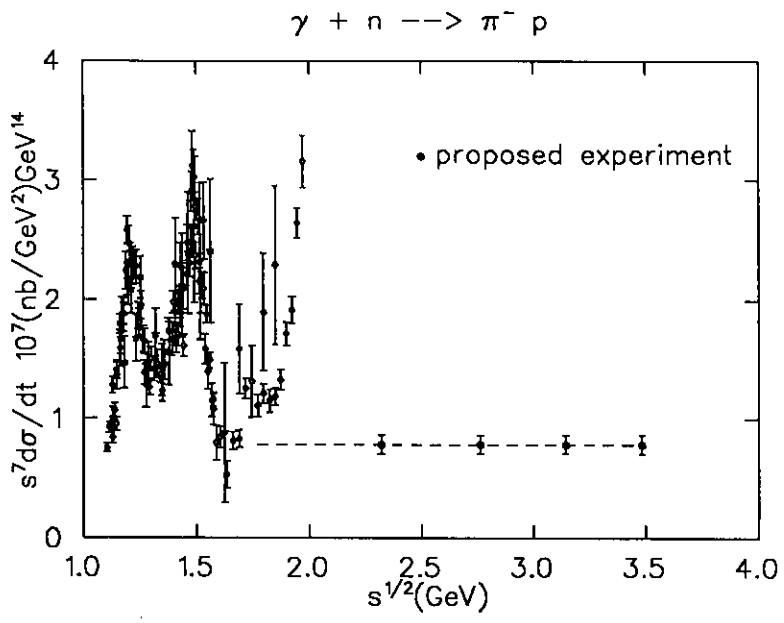

FIG. 5. **The proposed data with uncertainties for the differential cross section for the $\gamma\ n \rightarrow \pi^-\ p$ process, which were multiplied by a factor of 4 for readibility, together with the previous data at the center of mass angle near 90°. The dashed line shows the center of mass energy range covered by this experiment.**

In estimating the beam time, an overall detection efficiency of 90% was assumed together with the nuclear shadowing effect (10%), the pion survival fraction for a 25-m path and the calculated nuclear transparency for this exclusive $\gamma\ n \rightarrow \pi^-\ p$ process in nuclei (0.90 for deuterium, 0.59 for ^{4}He [14], and 0.51 for ^{12}C from correlated Glauber theory). A 50% efficiency for matching the spectrometer acceptances from the previous Monte Carlo simulation was used in estimating the beam time. The beam time requested for the fundamental cross section is 113 hours, 40 hours for the singles π^+ measurement, and 257 hours for the transparency measurement. The estimated beam time mentioned above includes runs for all the background studies. The total beam time requested for production runs is 410 hours. Assuming 4 hours for changing the electron beam energy, 0.5 hrs for changing the spectrometer angle, 12 hours for changing the cryotarget from deuterium to ^{4}He, 6 hours from deuterium to hydrogen, the estimated beam time overhead is 100 hours for the proposed experiment.

The ep elastic electrons and protons in singles and coincidence modes in both HRS spectrometers will be detected to study the spectrometer acceptance as a function of the central momentum setting, and the extended target acceptance as a function of the spectrometer angle. The liquid hydrogen cryotarget with a physical length of 15 cm corresponds to a luminosity of $\mathcal{L} = 2.7 \times 10^{37}/cm^2/s$ at an electron beam current of 10μA. Data will be taken on a 15 cm hydrogen target as well as a 15 cm dummy target. For the spectrometer calibration runs, the electron beam energy will be 1.2 to 6.0 GeV, in steps of 1.2 GeV, and the spectrometer angles will be set corresponding to the electron center of mass angles of 45°, 75°, and 90° as listed in Table 1. The total beam time required for the calibration run

is 1 day.

In conclusion, the beam time requested for the production run is 510 hrs which includes 100 hrs overhead. We request additional 24 hours for the spectrometer calibration run and 48 hours for the π^+ calibration run from hydrogen. So the total beam time requested is 582 hours. These estimated times include no contingency factor for accelerator or spectrometer operation.

The collaboration would prefer to begin this experiment as early as possible in the program. We note that because of the high physics motivation for this work up to 4 GeV and the relatively low demands on the performance of the Hall A equipment, we propose as an alternative that the experiment be performed in two parts. For the first part, we would request 277 hours at machine energies below 4 GeV and the second part, we request 305 hours at the energies above 4 GeV.

VI. COLLABORATION BACKGROUND AND RESPONSIBILITIES

This experiment requires Hall A cryotarget and bremsstrahlung photon beam at moderate luminosity, but no special equipment outside of that proposed in the Hall A CDR. Many members of the current collaboration were involved in the SLAC deuteron photodisintegration experiments NE8, NE17, and the SLAC color transparency experiment NE18. A significant fraction of the collaboration is also involved in the Hall C experiment (89-012) which will extend the SLAC NE17 experiment to photon energy of 4 GeV, Hall A approved experiment (89-019) to measure the photoproton polarization in the $d(\gamma,\vec{p})n$ reaction, as well as the approved Hall A experiment (94-012) to measure the photoproton polarization in the $p(\gamma,\vec{p})\pi^0$ reaction. This collaboration has much experience in running experiments using a bremsstrahlung photon beam. The radiator, same as that of the experiment 89-019 and 94-012, will be built by Rutgers. Many members of this collaboration also have experience in running the cryotarget. The Illinois group, the Caltech group and the group of U. Maryland are currently involved in a MIT-Bates parity violation experiment SAMPLE, in which a liquid hydrogen target is employed. The CEBAF staff will provide the necessary experience with the beam line and the spectrometers.

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E_γ GeV	θ_{cm} deg	θ_{π^-} (lab) deg	θ_p (lab) deg	P_{π^-} GeV/c	P_p GeV/c
1.15	45.0	24.9	62.7	1.023	0.484
	75.0	44.4	47.0	0.841	0.805
	90.0	55.9	39.5	0.735	0.957
2.35	45.0	19.1	59.1	2.060	0.785
	75.0	34.5	42.2	1.622	1.369
	90.0	44.1	34.9	1.369	1.665
3.55	45.0	16.1	55.8	3.090	1.033
	75.0	29.3	38.5	2.388	1.874
	90.0	37.5	31.4	1.983	2.317
4.75	75.0	25.8	35.6	3.149	2.356
	90.0	33.3	28.8	2.590	2.948
5.95	75.0	23.4	33.3	3.908	2.826
	90.0	30.2	26.7	3.195	3.569

Table 1: **Kinematics for the quasifree $n(\gamma,\pi^-)p$ reaction, calculated at the photon energy given, which is 50 MeV less than the electron beam energy. θ_{cm} is the π^- center of mass angle.**

E_γ GeV	θ_{cm} deg	$n(\gamma,\pi^-)$ Hz	$n(\gamma,p)$ Hz	trues Hz	accidentals Hz	e^-/π^-
1.15	45.0	6114	782.8	116.4	1.25	11.8
	75.0	92.4	117.3	8.9	8.8×10^{-3}	22.4
	90.0	30.9	114.3	4.0	1.1×10^{-3}	14.0
2.35	45.0	1002.8	43.8	26.0	6.1×10^{-1}	94.0
	75.0	15.94	9.0	3.3	1.5×10^{-3}	91.7
	90.0	3.63	9.9	1.38	1.1×10^{-4}	43.9
3.55	45.0	280.0	6.4	8.44	3.4×10^{-1}	346.5
	75.0	3.25	1.63	1.30	4.3×10^{-4}	219.6
	90.0	0.90	1.63	0.65	2.0×10^{-5}	91.6
4.75	75.0	1.19	0.46	0.46	1.3×10^{-4}	381.0
	90.0	0.325	0.59	0.29	7.3×10^{-6}	151.9
5.95	75.0	0.35	0.18	0.15	4.4×10^{-5}	661.8
	90.0	0.14	0.19	0.14	2.5×10^{-6}	247.7

Table 2: **The calculated $n(\gamma,\pi^-)p$ singles rates, coincidence rates, the accidental coincidence rates, and the singles e^-/π^- ratios. 7 msr was assumed for the HRS solid angle. A coincidence resolving time of 2 ns (full width at base) was assumed in calculating the accidental rates.**

E_γ GeV	θ_{cm} deg	I μA	time hours	statistical error(%)	time (π^+) hours
1.15	45.0	10.0	0.5	3%	1.0
	75.0	10.0	0.5	3%	1.0
	90.0	10.0	2.0	3%	1.0
2.35	45.0	20.0	1.0	3%	1.5
	75.0	20.0	2.5	3%	1.5
	90.0	25.0	5.0	3%	4.0
3.55	45.0	20.0	1.5	3%	1.5
	75.0	25.0	4.5	3%	1.5
	90.0	25.0	8.0	3%	2.5
4.75	75.0	25.0	11.0	3%	3.5
	90.0	25.0	20.0	3%	6.5
5.95	75.0	25.0	28.0	3%	4.0
	90.0	25.0	28.0	3%	10.5
		subtotal	112.5		40.0
				total	152.5

Table 3: **Beam time estimates for the coincidence and the singles π^+ measurements in liquid deuterium target. The time requested, which is the sum for all the runs including radiator in and out, determines the statistical uncertainties to be 5% for the coincidence measurements. The statistical uncertainties for the singles π^+ measurements are listed in the fifth column.**

E_γ GeV	Target	θ_{cm} deg	I μA	statistical error %	time hours
1.15	^{4}He	75.0	25.0	5	40.0
2.35			25.0	5	35.0
3.55			25.0	5	18.0
4.75			25.0	7	17.0
5.95			25.0	9	18.0
				subtotal	128.0
1.15	^{12}C	75.0	25.0	5	8.0
2.35			25.0	5	14.0
3.55			25.0	5	35.0
4.75			25.0	7	36.0
5.95			25.0	9	36.0
				subtotal	129.0
				total	257.0

Table 4: **Beam time estimate for the quasifree $n(\gamma,\pi^-)p$ reaction in gas ^{4}He and 4% solid ^{12}C targets. The time requested, which is the sum for all the runs including radiator in and out, determines the uncertainties to be 5% (statistical) at the three lowest energies, 7% (statistical) at 4.75 GeV and 9% (statistical) at the highest energy, note that the beam hours listed for the lowest two energy settings for ^{4}He take into account mapping the fermi cone.**