The Nuclear Transparency of Pion-photoproduction from ^{4}He at 12 GeV

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Abstract

We propose to perform a coincidence $\gamma n \to \pi^- p$ differential cross section measurements at the quasi-free kinematics from deuterium and ^{4}He in order to extract nuclear transparency over a momentum transferred square ($|t|$) range of 3.0 - 9.0 GeV^2. A rise in the nuclear transparency as a function of $|t|$ is predicted to be a signature of the onset of Color Transparency. Recent experiments have reported hints of Color Transparency like effects at relatively low momentum transfer squared in pion photo- and electro-production from nuclei. Unambiguous observation of Color Transparency would uniquely point to the role of color in exclusive processes at high momentum transfers. In addition, the occurrence of such effects is a necessary (but not sufficient) condition for the approach to the factorization regime in meson electroproduction experiments, necessary for accessing the Generalized Parton Distributions. In conjunction, by straddling the Charm threshold, this experiment will exploring the rather mysterious energy dependence that the BNL A(p,2p) nuclear transparency experiments have indicated.

The proposed experiment will be carried out in the upgraded Hall-C, using a 20-50 μA electron beam impinging on a 6% copper radiator, a liquid deuterium target and liquid helium target. The proposed experiment seeks to measure the nuclear transparency of the the $\gamma n \to \pi^- p$ process from ^{4}He at the center-of-mass angle of 90°, up to the highest $|t|$ values that can easily be reached at a 12-GeV JLab, using the HMS and SHMS spectrometers. We request a total of 350 hours of beam time with a maximum beam current of 50 μA. This measurement requires five different photon energies between 3.3 and 11.0 GeV.

Contents

1 Technical Participation of Research Groups

1.1 Mississippi State University

One spokesperson is part of the Mississippi State University medium energy nuclear physics group. The MSU groups intends to take responsibility for the design and commissioning of the collimator and sieve-slit mechanism for the SHMS spectrometer. The MSU group is actively seeking DOE funding for this project. The MSU group will also develop a TRD detector program (not part of the baseline equipment) for the SHMS.

1.2 Hampton University

The Hampton University group is part of an MRI proposal to the NSF and will be responsible for the construction of the wire chambers for the SHMS spectrometer.

1.3 Yerevan Physics Institute

The Yerevan group is actively involved in this proposal and this group intends to design and build the lead-glass calorimeter for the SHMS, and be instrumental in obtaining the lead-glass calorimeter blocks for this detector.

2 Physics Motivation

2.1 Introduction

Exclusive processes play an essential role in studies of transitions between the hadronic degrees of freedom to the partonic degrees of freedom of QCD. The quarks and gluons of QCD are hidden. Protons and neutrons that are the constituents of nuclei are identified with color singlet states and have strong interactions very different from that of the gluon exchange by colored quarks and gluons. Protons and neutrons rather seem bound together by the exchange of evanescent mesons. Hence, at low energies or long distances the nucleon-meson picture in the standard model of nuclear physics is very successful in describing the overall features of the strong interaction. Nevertheless, at sufficiently high energies or short distances perturbative QCD (pQCD) with its quark-gluon degrees of freedom must allow for extremely precise description of nuclei. Unfortunately, there is no clear understanding of how these two regimes are connected. Exclusive processes are the key to exploring this transition, as they provide the opportunity to study the role of color in high-momentum transfer processes and thereby search for the presence of QCD as the ultimate source of the strong interaction. The manifestation of the underlying quark-gluon degrees of freedom of QCD naturally gives rise to a distinct set of phenomena in exclusive processes on nucleons and nuclei. One such fundamental prediction of QCD is the phenomenon of Color Transparency (CT), that refers to the vanishing of the final (and initial) state interactions of hadrons with the nuclear medium in exclusive processes at high momentum transfers [1].

The concept of Color Transparency (CT) was first introduced by Brodsky and Mueller in 1982 [1] in the context of perturbative QCD, they predicted that a hadron could be produced at sufficiently high momentum transfers as a 'color neutral' object of reduced transverse size. If this compact size is maintained for some distance in traversing the nuclear medium, it would pass undisturbed through the nuclear medium. A similar phenomenon occurs in QED, where an e^+e^- pair of small size has a small cross section determined by its electric dipole moment [2]. In QCD, a $q\bar{q}$ or qqq system can act as an analogous small color dipole moment.

Nuclear transparency, defined as the ratio of the cross section per nucleon for a process on a bound nucleon in the nucleus to that from a free nucleon, is the observable used in searches for CT. A clear signature for the onset of CT would involve a rise in the nuclear transparency as a function of Q^2, i.e. a positive slope with respect to Q^2. Later works [3] have indicated that this phenomenon also occurs in a wide variety of models which feature non-perturbative reaction mechanisms. Unambiguous observation of CT would provide a new window to study the strong interaction in nuclei.

More recently, CT has been discussed in the context of a QCD factorization theorem derived for meson electroproduction [4]- [7], which states that the meson production amplitude can be expressed in terms of a hard scattering process, a distribution amplitude for the final state meson and a parametrization of the non-perturbative physics inside the nucleon known as Generalized Parton Distributions (GPDs) [8, 9]. Thus QCD factorization is intrinsically related to the access to Generalized Parton Distributions (GPD's). The discovery of these GPD's and their connection to certain totally exclusive cross sections has made it possible in principle to rigorously map out the complete nucleon wave functions themselves. The GPD's contain a wealth of information about the transverse momentum and angular momentum carried by the quarks in the proton. Presently, experimental access to such GPD's is amongst the highest priorities in intermediate energy nuclear/particle physics.

It is still uncertain at which Q^2 value one will reach the factorization regime, where leading-order perturbative QCD is fully applicable. It is expected to be between $Q^2 = 5$ and 10 $(\mathrm{GeV/c})^2$ for meson electroproduction. However, Eides, Frankfurt, and Strikman [10] point out that "It seems likely that a *precocious factorization* ... could be valid already at moderately high Q^2 [≥ 5 $(\mathrm{GeV/c})^2$], leading to precocious scaling of the spin asymmetries and of the ratios of cross sections as function of Q^2 and x". On the other hand if higher-twist contributions such as quark transverse momentum contributions are appreciable (they are predicted to be a factor of $\approx$ 2-3 compared to the leading order contribution, for $Q^2 \approx$ 3-10 $(\mathrm{GeV/c})^2$ [11, 12]), factorization in meson electroproduction may still be questionable at such Q^2.

During meson electroproduction, upon absorbing the virtual photon the meson and the baryon move fast in opposite directions. It has been suggested [13] that the outgoing meson maintains a small transverse size which results in a suppression of soft interactions (multiple gluon exchange) between the meson-baryon systems moving fast in opposite directions and thereby leading to factorization. Consequently, factorization is rigorously not possible without the onset of the Color Transparency (CT) phenomenon [13]. The underlying assumption here is that in exclusive "quasielastic" hadron production the hadron is produced at small inter-quark distances. However, just the onset of CT is not enough, because quark transverse momentum contributions can be large at lower Q^2s which could lead to breakdown of factorization. Thus it is critical to observe the onset of CT in hadron production as a precondition to the validity of factorization. Moreover, the observation of the onset of CT would uniquely point to the role of color in exclusive processes at high momentum transfers and provide direct evidence for the transition from nucleon-meson degrees of freedom to QCD degrees of freedom.

2.2 Previous Measurements

Over the last two decades a number of searches for color transparency have been carried out in experiments using the $A(p, 2p)$, $A(e, e'p)$ reactions, coherent and incoherent meson production from nuclei and pion photoproduction reactions [14] – [25]. The nuclear transparency measured in A(p,2p) at Brookhaven [14] has shown a rise consistent with CT for $Q^2 \simeq 3$ - 8 (GeV/c)^2, but decreases at higher momentum transfer. Data from a new experiment [15], completely reconstructing the final-state of the A(p,2p) reaction, confirm the surprising findings of the earlier Brookhaven experiment (see Fig. 1). The drop in the transparency can be understood [26, 27] in view of similar oscillatory energy dependence of s^{10} scaled p-p scattering cross-section [28] for a center-of-mass angle $\theta_{cm} = 90°$, and the large spin correlation effects [29, 30] observed in polarized p-p scattering. This has led to suggestions of the presence of interference mechanisms in this process [26], corresponding to an interplay between small- and large-size proton wave function configurations. However, Brodsky and de Teramond [31] claimed that the $A(p, 2p)$ transparency result can be attributed to $c\bar{c}uuduud$ resonant states. The opening of this channel gives rise to an amplitude with a phase shift similar to that predicted for gluonic radiative corrections.

The most recent among these to look for CT in qqq hadrons, the $A(e, e'p)$ experiment at Jefferson Laboratory (JLab) [18](Fig 2), does not show any increase of the nuclear transparency up to $Q^2 = 8.1$ (GeV/c)^2 and rules out several models predicting an early, rapid onset of CT.

It has been predicted [34] that exclusive processes in a nuclear medium are cleaner than the corresponding processes in free space. Large quark separations may tend not to propagate significantly in the strongly interacting medium. Configurations of small quark separations, on the other hand, will propagate with small attenuation. This phenomenon is termed nuclear filtering, and is the complement of CT phenomenon. If such nuclear filtering occurs, the nuclear medium should eliminate the long distance amplitudes. Thus, in the large A limit, one is left with a perturbatively calculable limit. Such nuclear filtering could, e.g., explain the apparent contradiction between the proton transparency results from A(p,2p) and A(e,e′p) experiments, mentioned above. The resolution [26] may be that the interference between short and long distance amplitudes in the free *p-p* cross section are responsible for these energy oscillations, where the nuclear medium acts as a filter for the long distance amplitudes. Questions still remain with the recent claim that the nuclear transparencies at $Q^2 \simeq 8$ (GeV/c)^2 in A(p,2p) experiments deviate from

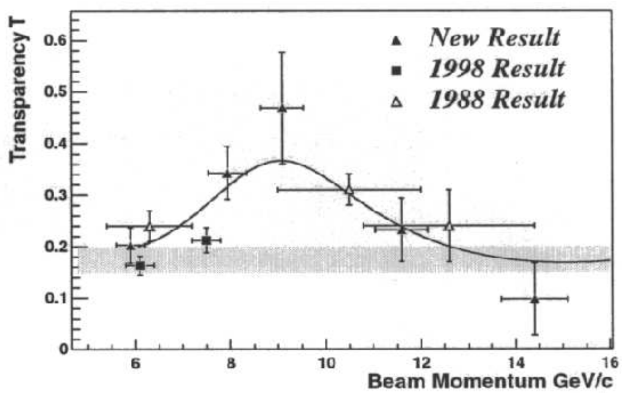

Figure 1: Nuclear transparency measured in $A(p,2p)$ reactions [14, 15]. The shaded band is a Glauber calculation for Carbon while the solid line is a fit to a function which is proportional (but out-of-phase by π radians) to the oscillations in the $p-p$ scattering cross-section scaled by s^{10}, where s is square of the center of mass energy. This is based on the nuclear filtering idea [26].

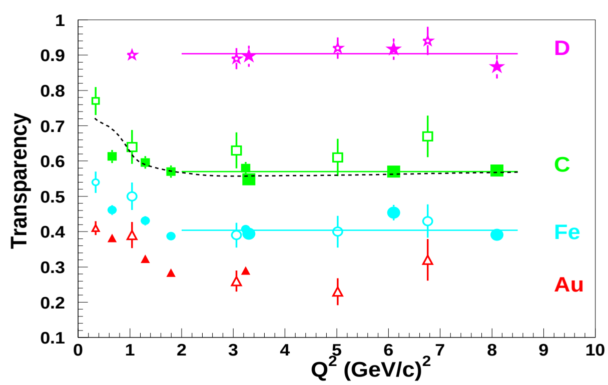

Figure 2: Nuclear transparency as a function of Q^2, for ^{2}H (stars), ^{12}C (squares), ^{56}Fe (circles) and ^{197}Au (triangles). The small open symbols are results from MIT-Bates [19], the large open symbols are results from the SLAC experiment NE-18 [16], the small solid symbols are results from the earlier JLab experiment [17] and the large solid symbols are results from the later JLab experiment [18]. The dashed line is a Glauber calculation of Pandharipande et al. [32, 33] and the solid lines are fit to a straight line of the results for $Q^2 > 2.0$ (GeV/c)^2.

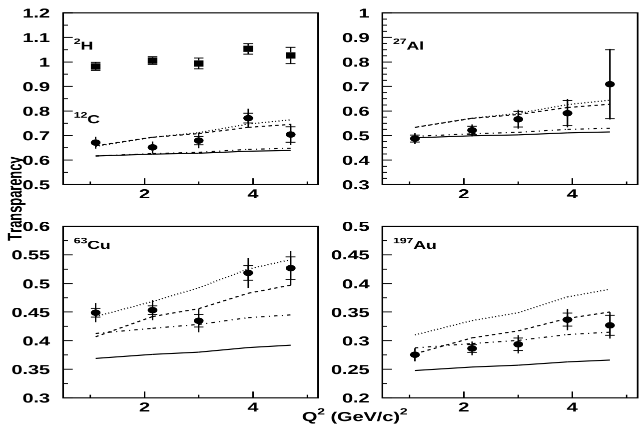

Figure 3: Nuclear transparency, T, vs. Q^2 for ^{2}H and ^{12}C (left, top panel), ^{29}Al (right, top), ^{63}Cu (left, bottom) and ^{197}Au (right, bottom). The inner error bars are the statistical uncertainties and the outer error bars are the statistical and point-to-point systematic uncertainties added in quadrature. The solid and dashed lines are Glauber and Glauber plus CT calculations, respectively [39, 40]. Similarly, the dot-dash and dotted lines are Glauber and Glauber plus CT calculations, respectively [41, 42]. These calculations also include the effect of short range correlations (SRC).

Glauber predictions [15]. On the other hand the anomalous energy dependence of the A(p,2p) results can also be explained in terms of excitation of charm resonances beyond the charm production threshold in these processes [31]. These ideas can also be explored with the $\gamma n \rightarrow \pi^- p$ on ^{4}He target by measuring the nuclear transparency on both sides of the charm production threshold.

2.2.1 Meson Production Experiments

Intuitively, one expects an earlier onset of CT for meson production than for hard proton scattering, as it is much more probable to produce a small transverse size in a $q\bar{q}$ system than in a three quark system [35]. Moreover the evolution distances (formation length) are easily larger than the nuclear radius even at moderate Q^2 (the evolution time is dilated by a factor E/M in the frame of the fast moving small transverse size object, with E and M being the the energy and mass of the meson). This increases the chances of the small transverse size object to pass undisturbed through the nucleus.

Recent experiments performed at Fermilab, DESY and JLab seem to support this idea [20, 21, 25]. The first such experiment looked at the incoherent ρ^0 meson production in muon scattering from nuclei. The cross-sections for these processes were parametrized as $\sigma_N = \sigma_0 A^\alpha$, where σ_0 is the hadron-N cross-section in free space. An increase in the parameter α as a function of Q^2 as observed in this experiments was interpreted as an onset of CT [22]. However, a later experiment by the HERMES collaboration [21] showed the increase in transparency to be related to the coherence length of the ρ^0 production process. More recently, the HERMES collaboration [23] has reported a positive slope, consistent

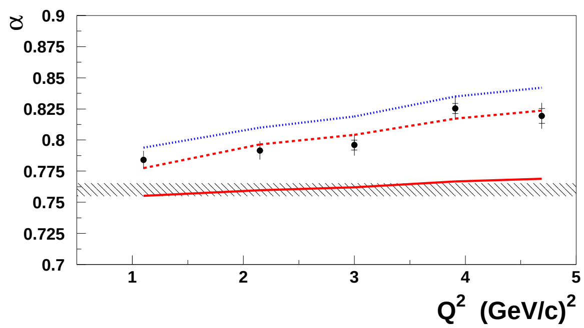

Figure 4: The parameter α (from the fit to the form $\mathrm{T} = \mathrm{A}^{\alpha-1}$ at fixed Q^2) is shown vs Q^2. The inner error bars are the statistical uncertainty and the outer error bars are the quadrature sum of statistical and systematic and model uncertainties. The hatched line is the value of α extracted from pion-nucleus scattering data [43]. The solid, dashed, and dotted lines are α obtained from fitting the A dependence of the theoretical calculations, Glauber, Glauber +CT [39, 40], and Glauber+SRC+CT [41, 42] respectively.

with CT, in the Q^2 dependence of nuclear transparency from coherent and incoherent ρ^0 production from nuclei at fixed coherence length. Moreover, an experiment carried out in Hall-B in JLab, measuring the nuclear transparency of incoherently produced ρ^0 mesons at fixed coherence length will provide high statistics results in the near future [36].

Another experiment is the Fermilab experiment on coherent diffractive dissociation of 500 GeV/c negative pions into di-jets [24]. The inferred Q^2 for this reaction was $\geq$ 7 (GeV/c)^2. The A-dependence of the data was fit assuming $\sigma \propto A^\alpha$. The alpha values were determined to be $\alpha \sim 1.6$, far larger than the $\sigma \propto A^{0.7}$ dependence typically observed in inclusive π-nucleus scattering, and the experimental results were consistent with the predicted theoretical [37] values that include CT. The authors of this experiment consider the data to have conclusively shown full CT for pions at these high momentum transfers. But of course, these data are from a completely different energy regime and therefore do not inform us about the energy scale of the onset of CT.

The most recent experiment to look for CT was also performed at JLab, where the (e,e'π^+) process on ^{1}H, ^{2}H, ^{12}C, ^{26}Al, ^{64}Cu and ^{197}Au was used to measure the pion transparency over a Q^2 range of 1 – 5 (GeV/c)^2 [38]. The nuclear transparency was extracted in this experiment by comparing the pion production from heavy nuclei to that from hydrogen. The preliminary results from experiment E01-107 (Figs. 3 and 4) for both the Q^2 and A dependence of the transparency, hint at a CT-like effect above Q^2 of 2 (GeV/c)^2, similar to the observations of other meson production experiments mentioned earlier.

Experiment E94104 at JLab carried out the first measurement of nuclear transparency of the $\gamma n \rightarrow \pi^- p$ process on ^{4}He nuclei [44]. This experiment exploited several advantages of ^{4}He such as the relatively small size of the ^{4}He nucleus. The extracted nuclear transparency for the ^{4}He target along with calculations is shown in Fig. 5. The traditional nuclear physics calculation appears to deviate from the data at the higher energies. However, some recent relativistic calculations [41] which include short-range correlations but do not include CT, also seem to be consistent with the data. These data suggest there could be an onset of deviation from traditional calculations in the energy regimes already explored, but future experiments with significantly improved statistical and systematic precision are essential to put these results on a firmer basis.

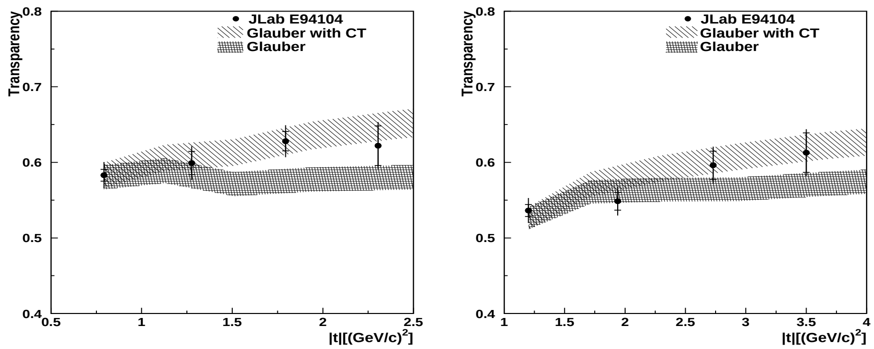

Figure 5: The nuclear transparency of ^{4}He(γ,p π^-) at θ^{π}_{cm} =70° and 90°, as a function of momentum transfer square $|t|$. The inner error bars shown are statistical uncertainties only, while the outer error bars are statistical and point-to-point systematic uncertainties (2.7%) added in quadrature. In addition there is a 4% normalization/scale systematic uncertainty which leads to a total systematic uncertainty of 4.8%.

All these experiments suggest that the onset of CT phenomena for mesons, is most likely at momentum transfers of a few GeV^2. Please note that E94104 was the first nuclear transparency measurement of the pion-photoproduction process and was a test experiment. We prefer to view the data from the E94-104 experiment as the first reliable "baseline" for this process. The CT effects can be unambiguously verified only as a deviation from a baseline nuclear physics calculation. A recent calculation predicts a large deviation from traditional calculations at $|t| > 4$ (GeV/c)^2 [41]. This calculation uses a relavistic Glauber multiple scattering approximation and also include the effect of short range correlations [41]. CT is incorporated in these calculations using the quantum diffusion model of Ref. [45]. Using a 11 GeV beam one can extend the $\gamma n \to \pi^- p$ measurement on ^{4}He to $|t|$ of 9.0 (GeV/c)^2. Thus, the new data could help confirm and help establish the CT phenomena in mesons on a firm footing.

Moreover, it should be noted that although recent meson electroproduction and photo-production experiments (at JLab and elsewhere) suggest the onset of CT like behavior at Q^2 of a few GeV^2, the CT phenomena can be confirmed conclusively only if the observed trends continue at higher Q^2 in all the meson production reactions; and if it can be shown that the largest effects are at Q$^2 \sim 10$ GeV^2 as predicted by most CT calculations [39, 41]. Hence it is essential to extend all the meson production measurements to higher energies. PAC-30 has approved (conditionally approved) two CT searches which extend the rho (pion) [46] electroproduction measurements to 12 GeV. This proposal aims to extend the pion photo-production measurement to 12 GeV.

There are several complications in the reaction mechanism of the rho and pion electroproduction reactions, such as pion absorption in the nucleus for the rho production and short range correlations for the pion production. These complications can be more easily addressed in the photo-production experiments on light nuclei. The choice of ^{4}He as the target makes exact calculations possible given the availability of precision ^{4}He wave-functions [47] and the photo-production reaction mechanism is inherently simpler and better understood. Thus we propose to measure the nuclear transparency in the photo-production of pion from 4He up to the highest momentum transfer accessible with JLab at 12 GeV and help confirm the CT phenomena.

2.3 Summary

The suggested 12-GeV experiment will allow:
1. A sensitive search for the onset of Color Transparency phenomenon in a region of momentum transfer that seems optimally suited for this search.
2. Measurement on both sides of the charm production threshold, which will provide valuable information on the interpretation of the rise in nuclear transparency found by the BNL A(p,2p) experiments.
3. Validate the strict applicability of factorization theorems for meson electroproduction experiments.

3 Proposed Measurements

We propose to carry out a measurement of the photo-pion production cross-section for the fundamental $\gamma n \rightarrow \pi^- p$ process from a ^{2}H , ^{4}He at a center-of-mass angle of 90^o, over the $|t|$ range of 3 - 9 GeV^2 in steps of $\sim$ 1.5 GeV^2. The maximum beam energy requested is 11 GeV, in addition four other energies are requested. Transparency will be formed by taking the ratio of the production cross-section from ^{4}He to the production cross-section from ^{2}H. We plan to make individual cross-section measurements with a $\sim$ 2% statistical uncertainty and point-to-point systematic uncertainties of $<$ 3%. The systematic uncertainties for the transparency measurement will be greatly reduced when we take the ratio of Helium to ^{2}H. Thus, for transparency we plan to make measurements with combined statistical and systematic uncertainties of $<$ 5%. For ^{4}He a 2% statistical uncertainty will enable us to confirm the deviations from the Glauber predictions or CT-like behavior as hinted by the E94-104 data and also verify the large deviations predicted at higher values of $|t|$.

The proposed experiment requires the standard Hall C equipment which is part of the upgrade and an aerogel Cerenkov detector in the SHMS. The proposed experiment will only be possible with the unique JLab capability of high luminosity. The proposed momentum range for the coincidence measurement of the $\gamma n \rightarrow \pi^- p$ process makes Hall C the only possible place at JLab where such a measurement can be carried out.

3.1 Overview

The experiment will employ the 15 cm Hall C cryogenic liquid deuterium and liquid helium targets along with the Hall C copper 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. The quasifree kinematics are chosen for the $n(\gamma, \pi^- p)$. The coincidence measurement will be performed using the Hall C HMS for the π^- detection, and the SHMS for the proton detection. The PID requirements of this experiment include the high pressure gas Cerenkov detector which is part of the standard package and an aerogel detectors which is not part of the baseline equipment but is being planned. At each setting data will also be collected with the radiator removed from the beam path. This data will be used to subtract the virtual photon contribution from the primary electron beam.

The $\gamma n \to \pi^- p$ reaction is a two-body process. By either detecting the momentum and the angle of the photo-proton or detecting the momentum and angle of the photo-produced pion, one can determine the incident photon energy. In this experiment, nuclear targets (deuterium ^{4}He) will be employed instead of a free neutron target which does not exist in nature. Thus, measurement of the momenta and scattering angles of both the proton and the pion are necessary in order to reconstruct the incident photon energy. Other inelastic channel, such as 2π production can be essentially eliminated, since this is a coincidence measurement and only the highest energy protons and pions are detected. This technique has been well established in experiment E94-104 which was completed in Hall A in 2002. Using the data from E94-104, we have compared the reconstructed photon energy spectrum for a ^{4}He target with Monte Carlo simulation of the same (Fig 6). The excellent agreement between the two gives us added confidence in this technique.

3.2 The Electron Beam and the Radiator

An electron beam with a beam current up to 50 μA is required for this experiment. The experiment will use a copper radiator of 6% radiation length, which is placed upstream of the target chamber. The copper radiator is a standard Hall-C equipment.

The proposed running conditions of this experiment can be extrapolated from those of E94-104 running conditions, the background from the copper radiator due to the production of low energy neutrons and high energy pions were demonstrated not to be a problem by E94-104. Another experiment, E03-101, which uses a 50 μA beam on a copper radiator is currently collecting data in Hall-A.

3.3 Target

We plan to use the Hall C liquid deuterium (density = 0.169 g/cc), and liquid helium (density = 0.124 g/cc) cryotargets (2% r.l. each). The dummy target cell will be used to subtract the contribution from the target cell walls. We also use a liquid hydrogen target for background studies. We propose to run the experiment at a maximum electron beam current of 50 μA, which is significantly below the heat load that the Hall A cryotarget

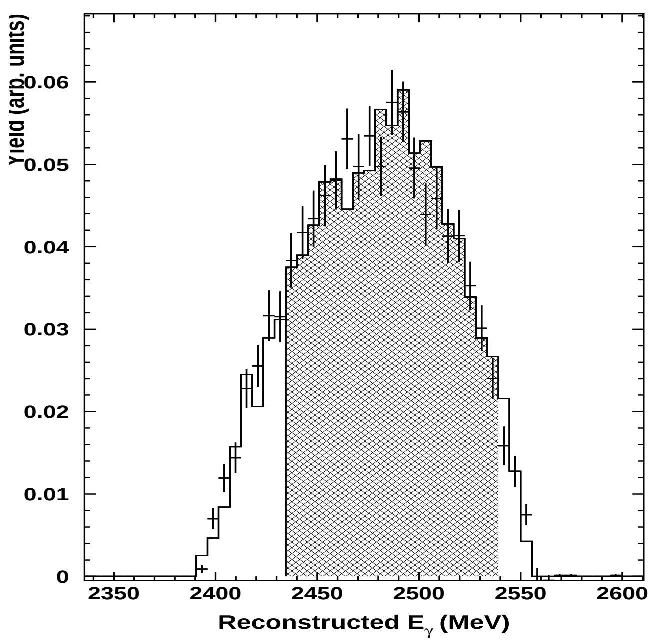

Figure 6: Reconstructed photon energy spectrum at 2.56 GeV and $\theta_{cm} = 90°$ for a ^{4}He target. The curve is from the Monte Carlo simulation. The shaded area denotes the photon energy region which is used to extract the experimental yield.

routinely handles. The energy deposited at the highest energy (11 GeV) with 50μA of beam is below the 100 Watts equivalent thick target power limit.

3.4 Spectrometer

The HMS-SHMS spectrometer pair will be used to make the coincidence measurement. The HMS will be used for the π^- detection, and the SHMS for the proton detection for most of the experiment. The pion arm momentum setting ranges from 1.989 - 5.246 GeV/c and the angle ranges from 23.8 - 37.5°. The proton arm momentum and angle setting ranges from 2.323 - 5.649 GeV/c and 22.02 - 31.40°. These momentum and angular ranges fall within the limits of the pair of spectrometers when set to detect for the appropriate particle. The beam current for each kinematic setting has been adjusted such that the highest singles rate in any spectrometer is less than 2 MHz, which is still below the trigger rate limits for the spectrometers.

3.5 Background

The dominant background process for this experiment is the quasi-elastic A(e,e'p) reaction. The quasi-elastically scattered electron has nearly the same momentum and angle as the photo-produced pion in the pion arm, and the scattered proton also has nearly the same momentum and scattering angle as that of the photo-proton in the proton spectrometer. We have estimated the singles rates of p and π^+ and the e^- and π^- for the LD2 target, based on the observed rates at lower energies and estimates using the code EPC [48]. The combination of the gas Cerenkov counter, pre-shower and shower counters can provide an electron rejection factor of 5000, which is sufficient for the proposed experiment. In the proton arm, good particle identification of protons, π^+ particles and positrons is required. The positron background arises from pair production of the bremsstrahlung photons and can be rejected sufficiently using the gas Cerenkov counter because the rate has been estimated to be rather low. Although the π^+ particles from the $\gamma p \rightarrow \pi^+ n$ reactions are kinematically eliminated in the proton arm, the π^+ background event can come from multiple processes, which have relatively low rates because of the phase space constraint. The aerogel detector will provide more than sufficient π^+ rejection.

Furthermore, the coincidence requirement effectively suppresses all background channels, except the (e,e'p) channel. Experiment E94-104 demonstrated that the coincidence (e,e'p) background events are sufficiently rejected with the particle identification capabilities provided by the standard detector packages.

3.6 Kinematics

Table 1 shows the kinematics for the quasifree $n(\gamma, \pi^- p)$ reaction. The photon energy is taken to be 75 MeV below the electron beam energy, since the range of photon energies to be used is a 100 MeV bin from 25 MeV below the end point energy to 125 MeV below

E_{beam}	E_γ	$\sqrt{s}$	$\|t\|$	θ_{π^-} (lab)	θ_p (lab)	P_{π^-}	P_p
GeV	GeV	GeV	GeV^2	deg	deg	GeV/c	GeV/c
3.636	3.561	2.75	-2.94	37.49	31.40	1.989	2.323
5.391	5.316	3.30	-4.58	31.68	27.76	2.876	3.242
6.921	6.846	3.71	-6.00	28.34	25.44	3.645	4.028
8.520	8.445	4.09	-7.51	25.78	23.55	4.448	4.843
10.11	10.036	4.44	-9.00	23.82	22.02	5.246	5.649

Table 1: Table of kinematics for the quasifree $n(\gamma, \pi^- p)$ reaction at pion C.M. angle of 90^o. The photon energy listed is 75 MeV less than the electron beam energy.

the end point energy. The pion center-of-mass angle is 90^o at all settings. The kinematics have been chosen to cover the region between momentum transferred square of $|t|$ = 3.0 - 9.0 GeV^2, in steps of approximately 1.5 GeV^2.

3.7 Counting Rates

The counting rate were estimated using the cross-section measured by experiment E94-104 at 90^o C.M. angle, at the highest $\sqrt{s}$ covered in that experiment. We assumed the cross-section scales as s^{-7} for the energy dependence, and scaling the solid angle acceptances of the spectrometers from the HRS pair to the HMS-SHMS pair. All rates were estimated for a 100 MeV photon energy window starting 25 MeV below the end point energy. A maximum beam current of 50 μA, a 6% copper radiator was used in the estimation. A 15 cm target length (2% r.l.) was assumed for both LD2 and ^{4}He. A complete Monte Carlo simulation of the experiment using the Hall-C Monte Carlo code SIMC is underway. The estimated counting rates are shown below in Table 2

The singles $d(\gamma, \pi^-)$, $d(\gamma, p)$ and $d(\gamma, \pi^+)$rates were estimated using EPC [48] modified to use bremsstrahlung photon spectrum instead of virtual photon spectrum. The singles $d(e, \pi^-)$, $d(e, p)$ and $d(e, \pi^+)$ rates were estimated based on the code EPC [48]. The coincidence timing resolution was taken to be 1 ns in the estimation of the accidental rates. The e^-/π^- ratio was estimated using the code QFS [49]. The singles rates, the accidental rates and and the e^-/π^- ratio for the LD2 targets is shown in Tables 3 and 4. The e^-/π^- ratio are expected to be similar for ^{4}He compared to those for the LD2 target.

3.8 Beam Time Estimate

Beam times requirements for data with the radiator were estimated for a goal of 2% statistical uncertainty for the ^{4}He and LD2 targets (except at $\sqrt{s}$=4.44 GeV, where the statistical uncertainty is 2.8%). The beam time estimates for the data without the radiator are taken to be a third of the time required with the radiator. The beam time estimates are shown below in table 5. It includes 23 hours of background studies for the coincidence

E_{beam}	$\sqrt{s}$	Current	LD2 rates	^{4}He rates
GeV	GeV	μA	Hz	Hz
3.636	2.75	20	1.53	0.68
5.391	3.30	35	0.31	0.14
6.921	3.71	50	0.11	4.8E-02
8.520	4.09	50	3.3E-02	1.4E-02
10.11	4.44	50	1.2E-02	5.4E-03

Table 2: Estimated rates for LD2, ^{4}He in a a 100 MeV window starting 25 MeV below the end point energy.

$\sqrt{s}$	$d(\gamma, p)$ rates	$d(e^-, p)$ rates	$d(\gamma, \pi^+)$ rates	$d(e, \pi^+)$ rates
GeV	Hz	Hz	Hz	Hz
2.75	469.0	7.5E+05	0.5	0.4
3.30	7.62	0.98E+06	0.01	0.01
3.71	2.97	1.30E+06	0.005	0.007
4.09	0.78	1.24E+06	0.001	0.004
4.42	0.17	1.17650E+06	0.0015	0.01

Table 3: Estimated singles rates in the p spectrometer, for an LD2 target in a 100 MeV photon energy window starting 25 MeV below the end point energy.

$\sqrt{s}$	$d(\gamma, \pi^-)$ rates	$d(e^-, \pi^-)$ rates	e^-/π^-	accidentals
GeV	Hz	Hz		Hz
2.75	5.6	24.5	12.1	0.220
3.30	1.0	3.63	2.90	0.012
3.71	0.49	1.80	0.69	0.005
4.09	0.09	0.40	0.19	0.0005
4.44	0.02	0.10	0.08	0.0001

Table 4: Estimated singles rates in the π^- spectrometer, for an LD2 target in a 100 MeV photon energy window starting 25 MeV below the end point energy. The total accidental rate is also shown in this table.

$\sqrt{s}$	LD2 beam time	^{4}He beam time	Total
GeV	hours	hours	hours
2.75	0.5	1.0	1.5
3.30	2.5	6.0	8.5
3.71	6.5	15.5	22.0
4.09	21.0	48.0	89.0
4.44	36.0	81	117.0
Radiator IN	66.5	151.5	218.0
Radiator OUT	22.0	52.0	74
Bgd Studies	7	16	23
Total			315
Overhead			25+10
Grand Total	95.5	219.5	350

Table 5: Estimated beam time requirements for the LD2 and ^{4}He targets.

measurement with a liquid hydrogen target. In addition to the 315 hours of beam time listed in the table, we estimate the time for beam energy change [50] for the 5 kinematic points (4 changes) to be an average of 6 hrs each. Thus the total overhead for beam energy and target change is expected to be around 25 hours. The spectrometer momentum and angle settings will have to be changed a total of 4 times these changes have been assigned a time of 2.5 hr each change. Thus a total of $\sim$ 10 hours of overhead will be required for the spectrometer changes. Thus, the total overhead is expected to be 35 hours and the total time required for the experiment is 350 hours (14.5 days).

3.9 Systematic Uncertainties and Projected Results

The experience gained in E94-104 suggests that the systematic uncertainties of this kind of experiment are well under control. For the cross-section measurements the systematic uncertainties are expected to be $< 5\%$. However, the systematic uncertainty in energy dependence of the cross-section will be $< 3\%$. Since the transparency measurement is a ratio measurement, many of the spectrometer related systematic errors will cancel. We expect the net systematic uncertainty for the transparency measurement to be $< 3\%$. The projected transparency results are shown in Fig. 7, also shown is the calculated transparency. Two Glauber calculations are shown in Fig. 7, the gray band is a semi-classical calculation based on Ref. [33], the dashed red line is a relativistic Glauber calculation [41] including SRC. The solid red line is calculations of Ref. [41, 42] which includes CT. It is clear that the projected statistical and systematic uncertainties are more than sufficient to make definitive statements on the predicted enhancement in the ^{4}He nuclear transparency.

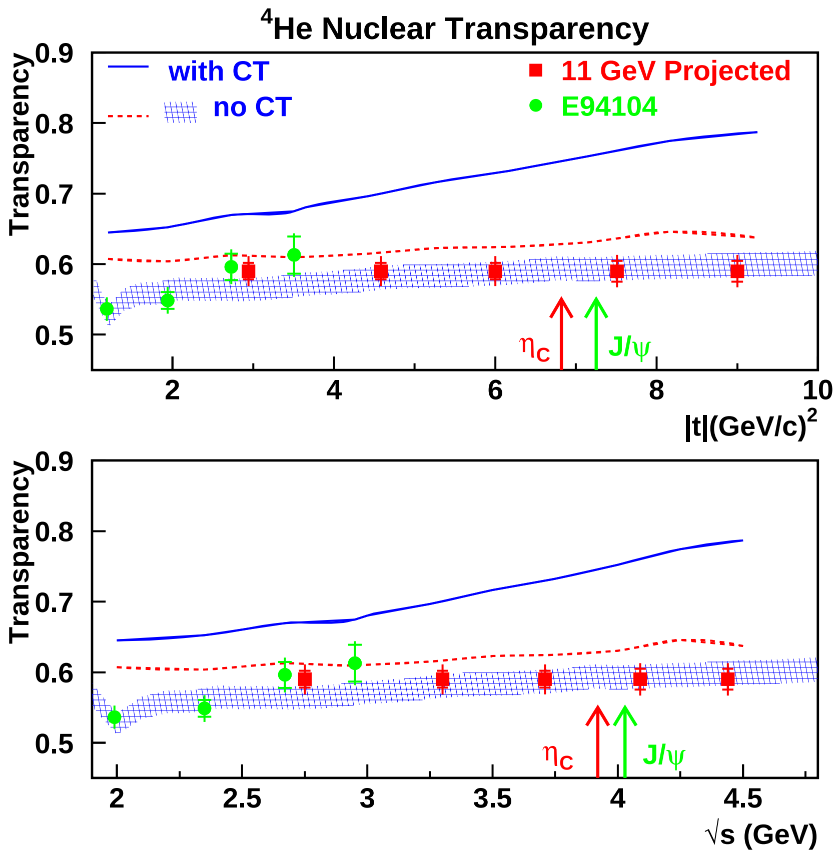

Figure 7: The predicted nuclear transparency for ^{4}He as a function of momentum transfer squared $|t|$ in $(\mathrm{GeV/c})^2$ (top panel) and as a function of C.M. energy $\sqrt{s}$ (GeV) (bottom panel), along with the projected measurements. A 2% statistical uncertainty (2.5% at the highest $|t|$) and a systematic uncertainty of 3% added in quadrature is shown in the projection. The results from E94104 are also shown along with semi-classical Glauber calculations based on [33] (hatched lines) while the solid (with CT) and dashed lines (without CT) are from [41, 42] which use a relativistic Glauber calculation and include SRC as well.

4 Collaboration Background and Responsibilities

Many members of the current collaboration have been involved in a number of bremsstrahlung photon beam experiments at SLAC and JLab. Most members of the group are experienced in running the Hall-A radiator, cryotargets and spectrometers. This experiment is a follow-up of experiment E94-104 and most members had participated in that experiment as well as the Hall A photo-proton polarization experiments (E89-019 and E94-012).

5 Summary

We have proposed a measurement of the $\gamma n \to \pi^- p$ at a center-of-mass angle of 90^o. We plan to map out the region of $|t|$ 2.94 - 9.0 GeV in steps of approximately 1.5 GeV. We will make photo-pion transparency measurement with the $n(\gamma, \pi^- p)$ process at the quasi-free kinematics on a ^{4}He target. These measurements would test the oscillatory behavior of the scaled free space differential cross-sections about the quark counting prediction. And by finely mapping out the nuclear transparency over the scaling region it should be possible to test the ideas of CT and nuclear filtering effect in a new regime. We will use the standard Hall-C equipment along with a 6% copper radiator, and the Hall-C cryogenic liquid deuterium and ^{4}He. A total of 350 hours (14.5 days) of beam time will be required for this experiment.

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