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Nuclear transparency with the $\gamma n \rightarrow \pi^- p$ process in ^{4}He

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We have measured the nuclear transparency of the fundamental process $\gamma n \rightarrow \pi^- p$ in ^{4}He. These measurements were performed at Jefferson Lab in the photon energy range of 1.6–4.5 GeV and at $\theta_{cm}^{\pi} = 70°$ and 90°. These measurements are the first of their kind in the study of nuclear transparency in photoreactions. They also provide a benchmark test of Glauber calculations based on traditional models of nuclear physics. The transparency results suggest deviations from the traditional nuclear physics picture. The momentum transfer dependence of the measured nuclear transparency is consistent with Glauber calculations that include the quantum chromodynamics phenomenon of color transparency.

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Nuclear transparency is a very useful quantity for testing calculations based on traditional models of nuclear physics. It is defined as the ratio of the cross section per nucleon for a process on a bound nucleon in the nucleus to the cross section for the process on a free nucleon. It is also a typical quantity used in searches for deviations from the expectations of traditional nuclear physics such as the phenomenon of color transparency (CT). CT refers to the vanishing of the final (and initial) state interactions of hadrons with the nuclear medium in exclusive processes at high momentum transfer [1], and is a natural consequence of QCD. It is based on the idea that, at sufficiently high momentum transfer, the dominant amplitudes for exclusive reactions involve hadrons of reduced transverse size, which can then pass undisturbed through the nuclear medium. This is a novel QCD phenomenon, which, if observed, would be a clear manifestation of hadrons fluctuating to a small size in the nucleus. Moreover, it also contradicts the traditional Glauber multiple scattering theory in the domain of its validity. Therefore, measurements of nuclear transparency have attracted a significant amount of effort during the last two decades. A clear signature for the onset of CT would involve a dramatic rise in the nuclear transparency as a function of the momentum transfer involved in the process, i.e., a positive slope with respect to the momentum transfer.

A number of searches for color transparency have been carried out in the last decade in experiments using the $A(p,2p)$ and $A(e,e'p)$ reactions and coherent and incoherent meson production from nuclei [2–8]. The $A(p,2p)$ nuclear transparency experiments carried out at Brookhaven [2] show a rise followed by a decrease in the momentum transfer squared range of $Q^2 \approx 3-10$ (GeV/c)^2. This surprising behavior can be explained in terms of mechanisms other than color transparency [9,10]. $A(e,e'p)$ experiments at SLAC [3] and more recently at Jefferson Lab (JLab) [4,5] have not found any evidence for an increase of the nuclear transparency up to a Q^2 value of 8.1 (GeV/c)^2. One would

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expect an earlier onset of CT for meson production than for proton scattering [11], as it is much more probable to produce a small transverse size in a $q\overline{q}$ system than in a qqq system. Experiments performed at Fermilab and DESY seem to support this idea [6–8]. More recently, the HERMES collaboration [7] has reported a positive slope in the Q^2 dependence of nuclear transparency from coherent and incoherent ρ^0 production from nuclei at fixed coherence length.

In this paper, we report the first measurement of nuclear transparency of the $\gamma n \rightarrow \pi^- p$ process from ^{4}He. There are several important advantages to the choice of the ^{4}He nucleus and the $\gamma n \rightarrow \pi^- p$ process. Nucleon configurations obtained from the Monte Carlo method based on the exact nuclear ground state wave function are available for ^{4}He [12]. These configurations along with the elementary hadron-nucleon cross sections can be used to carry out precise calculations of the nuclear transparency [13] in the framework of the Glauber theory [14]. Therefore, precise measurement of nuclear transparency from ^{4}He nuclei is a benchmark test of these traditional nuclear calculations and can be used to explore where the calculations start to break down. This could help identify the transition from the nucleon-meson degrees of freedom of the traditional nuclear physics to the quark-gluon degrees of freedom of QCD. Furthermore, light nuclei such as ^{4}He are predicted to be better for the search of CT phenomenon because of their relatively small nuclear sizes, which are smaller than the length scales over which the hadrons of reduced transverse size revert back to their equilibrium size [15,16].

The experiment was performed in Hall A [17] at the Thomas Jefferson National Accelerator Facility (JLab). The continuous wave electron beam, with currents of approximately 30 μA and energies ranging from 1.6 to 4.5 GeV, impinged on a 6% copper radiator to generate an untagged bremsstrahlung photon beam. The combined photon and electron beam was then incident on a 15-cm target cell containing either helium or liquid deuterium. The two high resolution spectrometers (HRS) in Hall A, with a momentum resolution of better than 2×10^{-4} and a horizontal angular resolution of better than 2 mrad, were used to detect the outgoing pions and recoil protons in coincidence. The backgrounds from the electron beam and from the target cell walls were measured by taking data without the radiator inserted in the beam (only electron beam impinging on the production target) and also with an empty target cell inserted in the beam (both with and without the radiator inserted in the beam). Additional details on the experimental setup and the detectors used in this experiment can be found in Ref. [18].

Based on two-body kinematics the incident photon energy is reconstructed for each event using the measured angles and momenta of π^- and p. In case of ^{4}He we also assume that the residual nucleus is ^{3}He. The resulting photon energy spectrum is a convolution of the bremsstrahlung distribution, the Fermi motion of the neutrons, and the experimental acceptance. Cuts on trigger type, coincidence time, particle identification, and acceptance were also applied while obtaining these spectra. A typical reconstructed photon energy spectrum is shown in Fig. 1. The experimental yield is obtained from these spectra by integrating over a 100-MeV window starting 25 MeV below the electron beam energy. This ensures that the contributions from multipion processes are negligible. The background yield from the electrons incident on a target were obtained by repeating the same procedure on data taken on that target without the radiator inserted in the beam. Similarly the background yields from the real photons and electrons incident on the target cell walls were obtained from the data taken for an empty target cell with and without the radiator inserted in the beam.

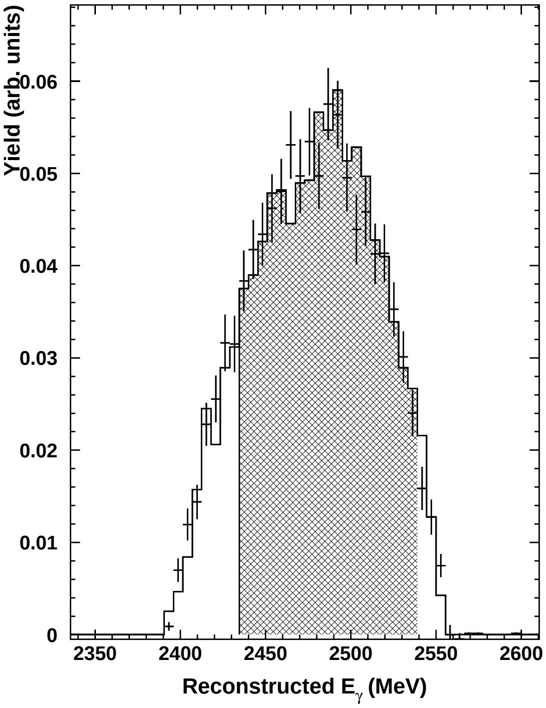

FIG. 1. Reconstructed photon energy spectrum at 2.56 GeV and $\theta_{cm} = 90°$. The curve is from the Monte Carlo simulation. The shaded area denotes the photon energy region used to extract the experimental yield.

The background-subtracted yield was then compared with the yield from a Monte Carlo simulation of the experiment with the same acceptance cuts. The Monte Carlo simulation was performed with the JLab Hall A Monte Carlo program, MCEEP [19], which was adapted for photopion production experiments [18]. The input angular distribution and cross section used in MCEEP were obtained from a fit to the π^+ photoproduction data at 4, 5, and 7.5 GeV [20]. The Fermi motion of the neutrons in the target nuclei was simulated using calculated momentum distributions (two-body breakup) and separation energy distributions of neutrons. For deuterium a calculated momentum distribution [21] and fixed binding energy were used in the simulation, while for ^{4}He, a calculated momentum distribution [22] and an energy distribution based on the missing energy spectra measured in $^4\mathrm{He}(e,e'p)$ experiments for missing momentum $p_m = 100 \pm 60$ MeV/c [23] were used. Additional details on the modifications to MCEEP for photopion production can be found in Ref. [18].

The photon energy spectrum was reconstructed in the

Monte Carlo simulation using the same method as used for the data, which includes the assumption in the case of ^{4}He that the residual nucleus is ^{3}He. The quality of the simulation was studied by comparing the reconstructed angular and momentum distributions and the reconstructed photon energy spectrum with those obtained from the simulation. An example of the comparison of the reconstructed photon energy spectrum for a ^{4}He target is shown in Fig. 1.

As per the definition of nuclear transparency one needs the cross section for $\gamma n \rightarrow \pi^- p$ reaction in ^{4}He and in free space to extract transparency. However, since there are no free neutron targets we used a deuterium target and corrected for deuterium transparency. The transparency was extracted from the data and Monte Carlo yields from ^{4}He and ^{2}H targets, using the relation

$$T(^4\mathrm{He}) = \frac{\dfrac{\mathrm{Yield}_{\mathrm{Data}}(^4\mathrm{He})}{\mathrm{Yield}_{\mathrm{Monte\ Carlo}}(^4\mathrm{He})}}{\dfrac{\mathrm{Yield}_{\mathrm{Data}}(^2\mathrm{H})}{\mathrm{Yield}_{\mathrm{Monte\ Carlo}}(^2\mathrm{H})}} \quad T(^2\mathrm{H}). \tag{1}$$

All data yields were corrected for computer dead time. A number of corrections, such as pion decay, detector efficiencies, and absorption, in the spectrometer cancel when forming the ratio, shown in Eq. (1). The ratio of the yields is corrected for the nuclear transparency of deuteron ($T_{^2H}$), which was obtained from the measured transparency of protons in $d(e,e'p)$ quasielastic scattering [5] and a Glauber calculation [13] of the transparency of π^- in the deuteron. This correction was found to be on the order of 20%. The point-to-point variation of the transparency in the deuteron is negligible, but there is a 3% normalization systematic uncertainty associated with this correction. The assumption that the residual nucleus is ^{3}He, which is used in reconstructing the photon energy, introduces a normalization systematic uncertainty of $\approx 1.5\%$ and a point-to-point uncertainty of $< 0.5\%$. This was determined from the fraction of the Monte Carlo events that are generated from the tail of the input energy distribution above the two-body breakup energy. Another source of normalization systematic uncertainty is the neutron momentum and energy distribution used in the Monte Carlo simulation. This was found to be 1% for ^{2}H and 2% for ^{4}He by using different calculated momentum distributions. The total normalization systematic uncertainty is 4.0%.

In this procedure of extracting transparency using a super-ratio [Eq. (1)], a number of systematic uncertainties such as charge, beam energy, and bremsstrahlung photon flux cancel. This was checked rigorously by varying each of these quantities within their respective systematic uncertainties and then looking for the corresponding changes in the super-ratio. This test was also repeated on all the different cuts applied to the data, which were varied by 10–20%. From these tests the point-to-point systematic uncertainty is estimated to be 2.7% with most of the contribution coming from uncertainty in the target density due to local beam heating effects (^{2}H 1%, ^{4}He 1.5%) and the energy loss calculation (1.4%). Thus the total systematic uncertainty of the transparency measurement is 4.8%.

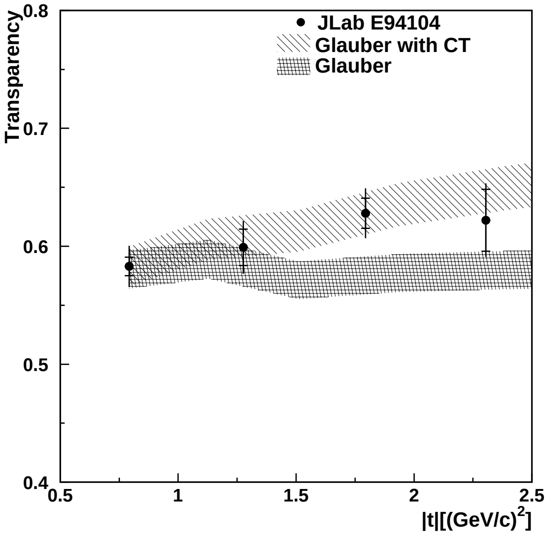

FIG. 2. The nuclear transparency of ^{4}He$(\gamma,p\pi^-)$ at $\theta^{\pi}_{cm} = 70°$, as a function of momentum transfer square $|t|$. The inner error bars shown are statistical uncertainties only, while the outer error bars are statistical and point-to-point systematic uncertainties (2.7%) added in quadrature. In addition, there is a 4% normalization/scale systematic uncertainty that leads to a total systematic uncertainty of 4.8%.

The extracted nuclear transparency for the ^{4}He target along with calculations is shown in Figs. 2 and 3; the results are also listed in Table I. The Glauber calculation uses ^{4}He

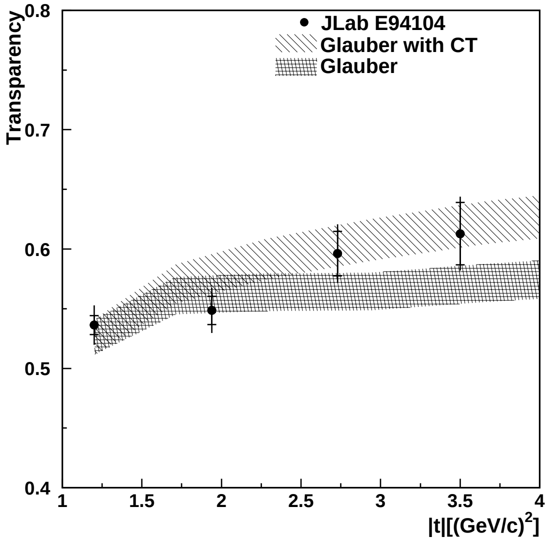

FIG. 3. The nuclear transparency of ^{4}He$(\gamma,p\pi^-)$ at $\theta^{\pi}_{cm} = 90°$, as a function of momentum transfer square $|t|$. The inner error bars shown are statistical uncertainties only, while the outer error bars are statistical and point-to-point systematic uncertainties (2.7%) added in quadrature. In addition, there is a 4% normalization/scale systematic uncertainty that leads to a total systematic uncertainty of 4.8%.

TABLE I. The extracted nuclear transparency for $\gamma n \rightarrow \pi^- p$ in ^{4}He nucleus at $\theta_{cm}^{\pi} = 70°$ and 90°. There is an additional 4% normalization systematic uncertainty and thus the total systematic uncertainty is 4.8%. The ^{2}H transparency used in the extraction is also shown.

E_γ	$\|t\|$	T (^{4}He)	Uncertainties		T (^{2}H)
GeV	(GeV/c)^2		Statistical	point-to-point systematic	
			$\theta_{cm}^{\pi} = 70°$		
1.648	0.79	0.583	0.008	0.015	0.815
2.486	1.28	0.599	0.015	0.015	0.820
3.324	1.79	0.628	0.013	0.016	0.815
4.157	2.31	0.622	0.026	0.017	0.826
			$\theta_{cm}^{\pi} = 90°$		
1.648	1.20	0.553	0.008	0.015	0.729
2.486	1.94	0.559	0.012	0.015	0.812
3.324	2.73	0.602	0.019	0.016	0.819
4.157	3.50	0.614	0.026	0.017	0.827

configurations, which are snapshots of the positions of the nucleons in the nucleus, obtained from the variational wave function of Arriaga *et al.* [12].

These contain correlations generated by the Argonne v_{14} and Urbana VIII models of the two-body and three-body nuclear forces, respectively. The classical transparency was calculated from these configurations using the method described in Ref. [13]. The hadron-nucleon total cross sections were taken from Ref. [24]. The calculation that includes the CT effect was obtained by repeating the calculation mentioned above with the hadron-nucleon total cross-section modified according to the quantum diffusion model [15]. This procedure is also described in Ref. [13] and was normalized to the Glauber calculation without CT at the lowest energy point ($E_\gamma = 1.648$ GeV). There is $\approx 3\%$ uncertainty in the Glauber and CT calculations, arising from the uncertainty in the measured hadron-nucleon total cross sections and the ^{4}He wave function. The difference between the calculation with and without CT show the possible range of effect allowed by the choice of parameters of the quantum diffusion model used in the CT calculation.

A number of other CT calculations [25,26] have been performed for the $A(e,e'p)$ and $A(e,e'\pi)$ reactions. These different calculations generally predict 10–25 % effect for the ^{12}C$(e,e'p)$ reaction at a $Q^2 = 10$ (GeV/c)^2. Nevertheless, the positive slope of the transparency is very consistent among the different models.

In Figs. 2 and 3 the traditional nuclear physics calculation appears to deviate from the data at the higher energies. The absolute magnitude of the calculations with CT was normalized to the calculation without CT at the lowest energy point; however, it is the momentum transfer squared ($|t|$) dependence of the transparency which is of greater significance. The $|t|$ dependence is not affected by the normalization systematic uncertainties. The slopes of the measured transparency obtained from the three points that are above the resonance region (above $E_\gamma = 2.25$ GeV) are shown in Table II.

These slopes are in good agreement, within experimental uncertainties, with the slopes predicted by the calculations with CT and they seem to deviate from the slopes predicted by the Glauber calculations at $\approx 1\sigma$ (2σ) level for $\theta_{cm}^{\pi} = 70°$ (90°). The deviation from Glauber calculation is larger at $\theta_{cm}^{\pi} = 90°$, as expected for a CT-like effect, since it is at a higher pion $|t|$. It is also interesting that the results are consistent with the rise expected for CT at the same photon energy at which the onset of scaling behavior was observed in the cross section for the $\gamma n \rightarrow \pi^- p$ and the $\gamma p \rightarrow \pi^+ n$ processes [18]. Thus, these data suggest the onset of deviation from traditional calculations, but future experiments with significantly improved statistical and systematic precision are essential to put these results on a firmer basis.

In conclusion we have measured for the first time the nuclear transparency for the process $\gamma n \rightarrow \pi^- p$ on a ^{4}He target at $\theta_{cm}^{\pi} = 70°$ and 90° in the photon energy range from 1.6 to 4.5 GeV. These measurements provide important tests for calculations based on the traditional model of nuclear physics and on the Glauber theory. The measured transparency shows interesting momentum transfer squared dependence that seems to deviate from the traditional nuclear physics predictions at the higher momentum transfers, which suggests a CT-like behavior. A first indication of CT-like effect in this kind of reaction is interesting and calls for more data. Future experiments with better statistical and systematic precision in this energy range together with improved theoretical calculations are crucial for confirming these results.

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TABLE II. The slope for the $|t|$ dependence of the extracted nuclear transparency obtained from the three points that are above the resonance region (above $\sqrt{s} = 2.25$ GeV). The uncertainties are statistical and systematic, respectively.

θ_{cm}^{π}	Measured slope	CT	Glauber
(deg)	(GeV/c)$^{-2}$	(GeV/c)$^{-2}$	(GeV/c)$^{-2}$
70	$0.032 \pm 0.027 \pm 0.022$	0.037	0.009
90	$0.046 \pm 0.016 \pm 0.014$	0.024	0.006

this experiment. We thank K. Bailey and T. O' Connor for their help with preparation of this experiment. We thank H. Arenhövel and R. B. Wiringa for calculating the momentum distribution of the neutron in the deuteron and ^{4}He and S. C. Pieper for providing us the ^{4}He configurations. We thank Z. Chai for providing the codes to apply R-function cut on acceptance. We also thank T. W. Donnelly, P. Jain, and G. Miller for helpful discussions. This work was supported in part by the U.S. Department of Energy, DOE/EPSCoR, the U.S. National Science Foundation, the Ministero dell'Università e della Ricerca Scientifica e Tecnologica (Murst), the French Commissariat à l'Énergie Atomique, Centre National de la Recherche Scientifique (CNRS), and the Italian Istituto Nazionale di Fisica Nucleare (INFN). This work was supported by DOE Contract No. DE-AC05-84ER40150 under which the Southeastern Universities Research Association (SURA) operates the Thomas Jefferson National Accelerator Facility.

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