

**Nuclear transparency and effective kaon-nucleon cross section from the  $A(e, e'K^+)$  reaction**

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We have determined the transparency of the nuclear medium to kaons from  $A(e, e'K^+)$  measurements on  $^{12}\text{C}$ ,  $^{63}\text{Cu}$ , and  $^{197}\text{Au}$  targets. The measurements were performed at the Jefferson Laboratory and span a range in four-momentum-transfer squared  $Q^2 = 1.1\text{--}3.0\text{ GeV}^2$ . The nuclear transparency was defined as the ratio of measured kaon electroproduction cross sections with respect to deuterium ( $\sigma^A/\sigma^D$ ). We further extracted the atomic number ( $A$ ) dependence of the transparency as parametrized by  $T = (A/2)^{\alpha-1}$  and, within a simple model assumption, the in-medium effective kaon-nucleon cross sections. The effective cross sections extracted from the electroproduction data were found to be smaller than the free cross sections determined from kaon-nucleon scattering experiments, and the parameter  $\alpha$  was found to be significantly larger than those obtained from kaon-nucleus scattering. We have included similar comparisons between pion- and proton-nucleon effective cross sections as determined from electron-scattering experiments and pion-nucleus and proton-nucleus scattering data.

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The propagation of hadrons in the nuclear medium is an essential element for the understanding of the nuclear many-body system as constructed from the more basic meson-nucleon and nucleon-nucleon amplitudes. Quasifree electron scattering from nuclei provides an excellent tool for a microscopic examination of such hadron propagation effects in the nuclear medium. The combination of the relative weakness of the electromagnetic probe and a well-understood interaction at the production vertex are well-known advantages of the electron-scattering process. Because of this, quasifree

production can be viewed as tagging a source of hadrons, which emerge from throughout the nuclear volume with minimal disruption of the nuclear system. Thus, over the past two decades, proton propagation in nuclei has been studied extensively using quasifree electron scattering [1–4]. More recently, pion propagation in nuclei was studied by using exclusive electroproduction of pions from nuclei [5,6].

Electroproduction of positively charged kaons  $K^+$  from nuclei can provide an additional strangeness degree of freedom, which is inaccessible with nucleon and/or pion knockout. It is

well known that strangeness production provides a unique window into the nuclear many-body problem via access to energy levels that protons and neutrons cannot occupy. Moreover, the  $K^+$ -nucleon ( $K^+$ - $N$ ) interaction also is also relatively weak itself and varies smoothly with energy [7], which simplifies the extraction of the in-medium  $K^+$ -nucleus interaction as well as the physics of hadron formation. Typically, the  $K^+$ -nucleus interaction has been studied by using  $K^+$  scattering from nuclear targets, and these experiments can be considered as analogous to electron scattering since both involve weakly interacting probes.

Despite the  $K^+$ - $N$  interaction being relatively weak and relatively free of resonance structure, it has proven difficult to obtain a successful description of kaon-nucleus scattering from the elementary  $K^+$ - $N$  interaction [8]. Both differential and total cross-sectional measurements [9–14] from  $K^+$ -scattering experiments show significant discrepancies when they are compared to theoretical calculations [8,15–17]. Even when taking the ratio of total cross sections for nuclear and deuterium targets [9,11–14], where some of the theoretical uncertainties are expected to cancel, experimental results are found to be systematically larger than the theoretical expectations [8,15–17]. Given the apparent failure of conventional nuclear-physics models to account for the data, several exotic mechanisms have been proposed by various authors [18]. These include modification of the nucleon size in the nuclear medium [8], reduced meson masses in the nuclear medium [19], meson exchange currents [20,21], long-range correlations [22], and various other mechanisms [23].

The availability of kaon production data in heavy-ion collisions [24] renewed interest in the properties of kaons in nuclear matter, since it was argued that such data have the capacity to signal chiral-symmetry restoration or give information on the possibility of kaon condensation in neutron stars [25]. Similar to what was found for the  $K^+$ -scattering experiments, the comparison between the heavy-ion collision data and calculations [26] indicates that the calculations substantially underestimate the experimental data. Recently, a calculation in the framework of the quark-meson coupling model [27], which goes beyond the conventional meson-nucleon nuclear many-body framework, was able to describe these kaon production data in heavy-ion collisions.

The electroproduction of kaons from nuclei is an excellent alternative to both kaon-nucleus scattering and kaon production in heavy-ion collisions, particularly to explore the propagation of kaons through the nuclear medium. It may help determine if the noted discrepancies between theory and experiment are related to the details of the reaction mechanism or if they are caused by the various approximations made in calculating the cross sections. The electroproduction of kaons from light nuclei [28,29] and  $^{12}\text{C}$  [30] at Jefferson Laboratory (JLab) has been reported before. In this paper, we report the results from the quasifree electroproduction of kaons from heavy nuclei. We report the atomic mass number  $A$  and four-momentum-transfer squared  $Q^2$  dependence of the nuclear transparency of kaons as extracted from the  $A(e, e'K^+)$  process.

The experiment was carried out in Hall C at JLab [31] in 2004. The kinematics are shown in Table I. The experiment was designed to measure the nuclear transparency

TABLE I. The central kinematics of the experiment.  $E_e$  ( $E_{e'}$ ) is the incident (scattered) electron energy,  $\theta_e^{\text{SOS}}$  ( $\theta_{\text{HMS}}$ ) is the scattered electron angle (kaon angle),  $p_{K^+}$  is the (central) kaon momentum, and  $|t|$  is the Mandelstam four-momentum transfer.  $\theta_{K^+}$  is the central kaon angle expected from the electron kinematics.

$Q^2$ (GeV <sup>2</sup> )	$-t$ (GeV <sup>2</sup> )	$E_e$ (GeV)	$\theta_e^{\text{SOS}}$ (deg)	$E_{e'}$ (GeV)	$\theta_{\text{HMS}}$ (deg)	$p_{K^+}$ (GeV)	$\theta_{K^+}$ (deg)
1.1	0.05	4.021	27.76	1.190	10.61	2.793	10.58
2.1	0.16	5.012	28.85	1.730	13.44	3.187	13.44
3.0	0.29	5.012	37.77	1.430	12.74	3.418	12.74

of pions following the  $A(e, e'\pi^+)$  reaction, but additional particle identification allowed us to simultaneously measure electroproduced positively charged kaons. The details about the experiment can be found in Ref. [6]. The scattered electrons were detected in the short-orbit spectrometer (SOS), and the electroproduced pions and kaons were detected in the high-momentum spectrometer (HMS). A detailed description of the spectrometers and the spectrometer hardware is given in Refs. [32,33]. The detector package of the HMS was equipped with a gas Čerenkov, an aerogel Čerenkov [34], and a lead glass calorimeter for  $p/K^+/\pi^+$  separation. For this experiment, the gas Čerenkov was filled with  $\text{C}_4\text{F}_{10}$  gas at 97 kPa. The corresponding index of refraction is 1.001 37, which results in momentum thresholds of 2.65 GeV for  $\pi^+$  and 9.4 GeV for  $K^+$ . The aerogel Čerenkov material had an index of refraction of 1.015, which gave thresholds of 0.8 GeV for pions and 2.85 GeV for kaons. It was used to distinguish between  $\pi^+$  and  $K^+$  for central-momentum settings below 3.1 GeV and to distinguish  $\pi^+$  and  $K^+$  from protons for momentum settings above 3.1 GeV. For momentum settings above 3.1 GeV, the gas Čerenkov counter was used to distinguish between kaons and pions. Coincidence timing between the HMS and the SOS, by using multiple scintillator hodoscopes, could be used to distinguish between  $K^+$  and protons with momenta up to  $\approx 3$  GeV.

The SOS gas Čerenkov counter was used to select the scattered electrons with an efficiency of better than 99.2%. The charged kaons were selected by using the HMS aerogel [34] and gas Čerenkov counters, the net kaon detection efficiency was determined from the product of the HMS tracking efficiency, the aerogel, the gas Čerenkov efficiencies, and the time-of-flight cut efficiency. The kaon detection efficiency was found to be 82%–85%. The pion contamination in the kaon samples was estimated to be  $< 1\%$ . The spectrometer acceptance was determined with a relative uncertainty of 1% between targets by using a Monte Carlo simulation of the experimental apparatus, as described below. For each run, the  $e-K^+$  coincidence events were corrected for random coincidences by subtracting their contribution as determined by using out-of-time events. The charge-weighted coincidence yield was also corrected for blocked coincidences ( $< 0.7\%$ ), loss of synchronization between detectors ( $< 1.0\%$ ), trigger inefficiency ( $< 0.5\%$ ), electronic dead time ( $< 1.0\%$ ), computer dead time ( $< 25\%$ , known to be much better than 1%), tracking inefficiency ( $< 4.0\%$ ), and particle absorption in the spectrometer materials (5.0%, known to be better than 1.0%).

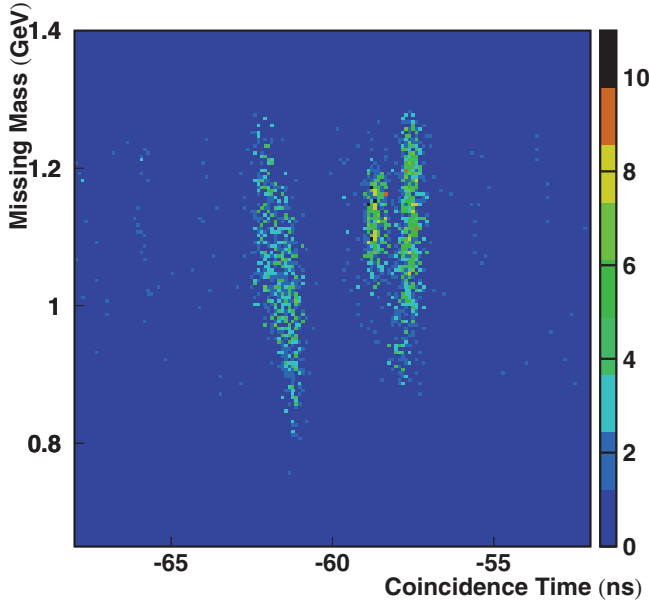


FIG. 1. (Color online) The missing mass versus coincidence time for  $^{12}\text{C}(e, e'K^+)$  events at  $Q^2 = 2.1 \text{ GeV}^2$ .

Furthermore, a cut on the missing-mass spectrum, which corresponded to the  $\Lambda^0$  and  $\Sigma^0/\Sigma^-$  hyperons was used to select the kaon events. The uncertainty from variation of these cuts was 2.5%. A typical two-dimensional spectrum of missing mass versus coincidence time (difference in time between the kaon reaching the HMS and the electron reaching the SOS spectrometers) is shown in Fig. 1. For  $A > 1$  targets, we are unable to separate the  $\Lambda^0$  and  $\Sigma^0/\Sigma^-$  hyperons, consequently, we integrate over all three hyperons.

The standard Hall C Monte Carlo simulation code SIMC was used to simulate the experimental apparatus [35]. The  $^1\text{H}(e, e'K^+)$  cross section required as the model input was iterated until there was good agreement between the simulation and the experimental data. The iteration was performed separately for each of the kinematic ( $Q^2$ ) settings in Table I. A parametrization of the  $^1\text{H}(e, e'K^+)$  cross section from previous data [30,36] was used as the starting model. The model-dependent uncertainty was estimated to be  $\sim 4\%$ .

The Fermi motion of the nucleons in  $A > 1$  targets was simulated by folding the elementary cross section with a spectral function for the target. For each target, an appropriate independent particle-shell model spectral function was used [33]. The simulation includes several corrections, such as kaon decay within the spectrometer and external and internal bremsstrahlung radiation. It also included corrections caused by various reaction mechanism effects, such as Coulomb distortions. More details on the Monte Carlo simulation can be found in Ref. [35].

The simulation was able to reproduce the shapes of the measured  $Q^2$ ,  $W$ ,  $|t|$ , and  $\phi_{pq}$  distributions reasonably well for all targets and  $Q^2$  settings. Here,  $W$  is the invariant mass,  $|t|$  is the Mandelstam four-momentum transfer, and  $\phi_{pq}$  is the angle between the momentum-transfer vector and the electroproduced kaon. A typical comparison between data

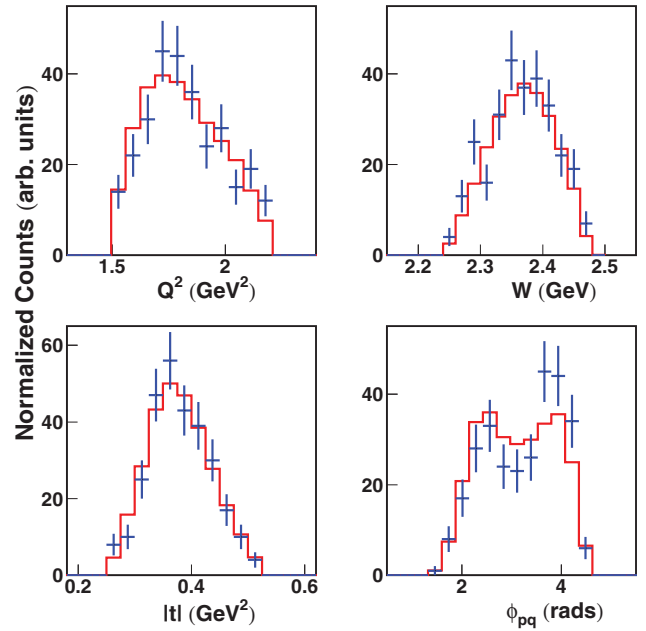


FIG. 2. (Color online) The  $^{12}\text{C}(e, e'K^+)$  data and Monte Carlo simulations at  $Q^2 = 2.1 \text{ GeV}^2$  are compared as a function of  $Q^2$ , invariant mass  $W$ , Mandelstam four-momentum transfer  $|t|$ , and the angle between the momentum-transfer vector and the electroproduced kaon  $\phi_{pq}$ . Experimental data are shown as blue crosses, along with their statistical uncertainty. Simulations are represented by the red histograms.

and simulation is shown in Fig. 2 for the  $^{12}\text{C}$  nucleus at  $Q^2 = 2.1 \text{ GeV}^2$ . The ratio of  $\Lambda$ - and  $\Sigma$ -hyperon production of kaons has been calculated by using hydrogen data, and the same ratio has been used for all other targets. To extract nuclear transparencies from the experimental yields, the cross section for the bound proton must be corrected for the effects of Fermi motion, the off-shell properties of the proton and the acceptances of the spectrometers. The nuclear transparency for a given target, with atomic number  $A$  was defined as

$$T = \frac{(\bar{Y}/\bar{Y}_{\text{MC}})_A}{(\bar{Y}/\bar{Y}_{\text{MC}})_D}, \quad (1)$$

where  $\bar{Y}$  is the experimental charge-normalized yield,  $\bar{Y}_{\text{MC}}$  is the charge-normalized Monte Carlo equivalent yield, and the denominator is the ratio of the yields from the  $^2\text{H}$  target. To reduce the impact of nonisoscalar effects, such as  $K^+\Sigma^-$  production of a neutron, we consider it more appropriate to define transparency as the ratio of nuclear cross sections with respect to a deuterium target instead of a free proton target. Since the Monte Carlo simulation does not include final-state interactions between the kaon and the residual nucleons, the nuclear transparency is a measure of the absorptive effect of such final-state interactions. The kaon transparencies are listed in Table II. For completeness, in Table II, we have also listed the transparencies extracted as a ratio of nuclear cross sections with respect to the  $^1\text{H}$  target.

The transparencies and their  $Q^2$  dependence are shown for the three different heavy-target nuclei in Fig. 3. In an

TABLE II. (Left) The ratio of the nuclear cross sections with respect to the  $^1\text{H}$  cross sections at three different values of  $Q^2$ ; (right) the kaon transparency, or the ratio of (heavy) nuclear cross sections with respect to the  $^2\text{H}$  cross sections. The ratios are shown with both statistical and systematic uncertainties, which include model uncertainties.

$Q^2$	Ratio of nuclear and $^1\text{H}$ cross sections				Ratio of nuclear and $^2\text{H}$ cross sections		
	$^2\text{H}$	Carbon	Copper	Gold	Carbon	Copper	Gold
1.1	$0.88 \pm 0.09 \pm 0.11$	$0.80 \pm 0.07 \pm 0.13$	$0.55 \pm 0.04 \pm 0.07$	$0.39 \pm 0.04 \pm 0.03$	$0.91 \pm 0.10 \pm 0.17$	$0.62 \pm 0.06 \pm 0.10$	$0.43 \pm 0.04 \pm 0.05$
2.2	$0.86 \pm 0.06 \pm 0.06$	$0.91 \pm 0.07 \pm 0.09$	$0.64 \pm 0.04 \pm 0.04$	$0.51 \pm 0.05 \pm 0.03$	$1.06 \pm 0.09 \pm 0.11$	$0.74 \pm 0.05 \pm 0.06$	$0.60 \pm 0.06 \pm 0.05$
3.0	$0.92 \pm 0.09 \pm 0.11$	$0.84 \pm 0.10 \pm 0.07$	$0.73 \pm 0.07 \pm 0.07$	$0.58 \pm 0.08 \pm 0.05$	$0.91 \pm 0.11 \pm 0.12$	$0.79 \pm 0.08 \pm 0.11$	$0.63 \pm 0.09 \pm 0.08$

earlier experiment at JLab, the quasifree electroproduction of kaons from light nuclei was studied at  $Q^2 = 0.35 \text{ GeV}^2$ , and an effective proton number was extracted from these data [29]. The effective proton number was defined as the ratio of the kaon electroproduction cross section on light nuclei to the cross section on hydrogen. In Fig. 3, we have shown these effective proton numbers along with our results. To display equivalent quantities, we have shown the ratio of the effective proton number from light nuclei to that from  $^2\text{H}$ . The results from the two experiments are consistent with each other. Within the experimental uncertainties, the nuclear transparency of kaons does not exhibit any energy dependence. To guide further interpretation, we have analyzed the nuclear

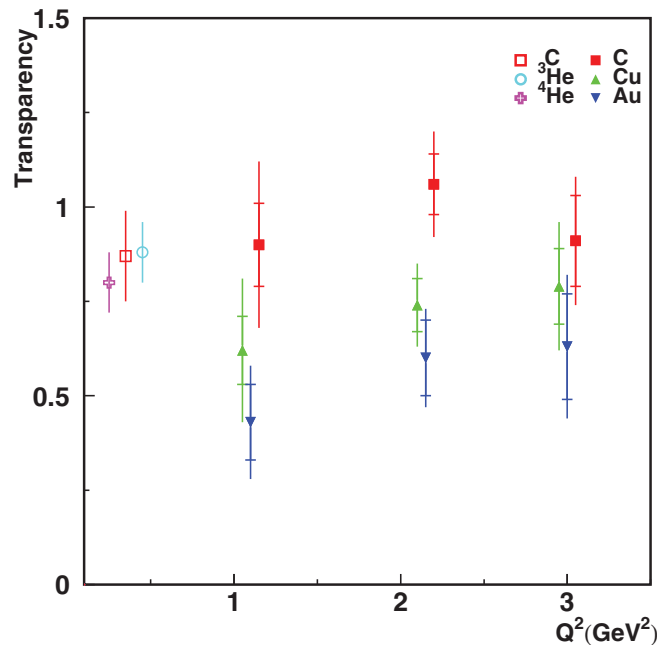


FIG. 3. (Color online) Nuclear transparency for kaons (as defined in the text) for different targets versus  $Q^2$ . The copper and carbon points are shifted by  $-0.05$  and  $0.05 \text{ GeV}^2$  in  $Q^2$ , respectively, for ease of display. The inner error bars are the statistical uncertainties only, the outer error bars are the sum in quadrature of statistical and systematic uncertainties. The solid points are the results from this experiment. Results from a previous experiment on light nuclei [28,29] at  $Q^2 = 0.35 \text{ GeV}^2$ , modified to display equivalent quantities (see text), are shown as open symbols.

and energy dependences of these transparency data in terms of two simple one-parameter descriptions as detailed below.

We describe the measured transparencies in terms of the simple geometrical model outlined in Ref. [4]. This model assumes classical attenuation of hadrons propagating in the nucleus with an effective hadron-nucleon cross section  $\sigma_{\text{eff}}$  that is *independent* of density, and the transparency can be written as

$$T_{\text{hadron}} = \frac{1}{A} \int d^3r \rho_A(\vec{r}) \exp \left[ - \int dz' \sigma_{\text{eff}} \rho_{A-1}(\vec{r}') \right], \quad (2)$$

with  $\rho_A$  representing the nucleon number density in the nucleus  $A$ . The nucleus is struck at position  $\vec{r} = (x, y, z)$ , and the direction of the outgoing hadron is labeled  $z'$  with  $\rho_{A-1}(\vec{r}')$  as the nucleon number density of the recoil  $A-1$  system at the position  $\vec{r}' = (x, y, z')$  on the hadron's path. Regardless of its limitations caused by the simplicity of the geometrical model, we hope to gain insight in the relative behavior of the effective cross sections versus both momentum transfer and other electroproduced hadrons.

We proceeded to extract such an effective cross section by fitting the measured transparencies to the model described (Ref. [37]). For this, we took the nuclear- (charge-) density distributions from Ref. [38]. Then, the effective cross section is the only free parameter. Finally, we take the average of the effective cross sections obtained for  $^{12}\text{C}$ ,  $^{56}\text{Fe}$ , and  $^{197}\text{Au}$  nuclei weighted by their respective statistical uncertainty. The standard deviation for each hadron is shown by the hatched bands in Fig. 4. In addition to the kaon, we have shown the effective cross section for protons obtained from Ref. [4], and we have similarly calculated the effective cross sections from the published pion transparencies [6]. All results are shown as a function of the hadron kinetic energies in Fig. 4. For comparison, we also show a fit (solid curves) to the experimental free hadron-nucleon cross-sectional data from Ref. [39]. The effective cross sections extracted from the proton transparencies are in excellent agreement, in their dependence on kinetic energy, with the free proton-nucleon case. The absolute magnitude is underpredicted, but good agreement can be obtained by scaling the free proton-nucleon cross section by  $0.68$  ( $0.03$ ). To a lesser extent, the kinetic-energy dependence of the effective pion-nucleon cross sections extracted from pion-transparency data also agrees with that expected from free pion-nucleon scattering. For pions, the scale factor was  $0.81$  ( $0.03$ ). The free kaon-nucleon cross sections were scaled by  $0.65$  ( $0.14$ ) to agree with the extracted effective kaon-nucleon cross sections. The numbers shown

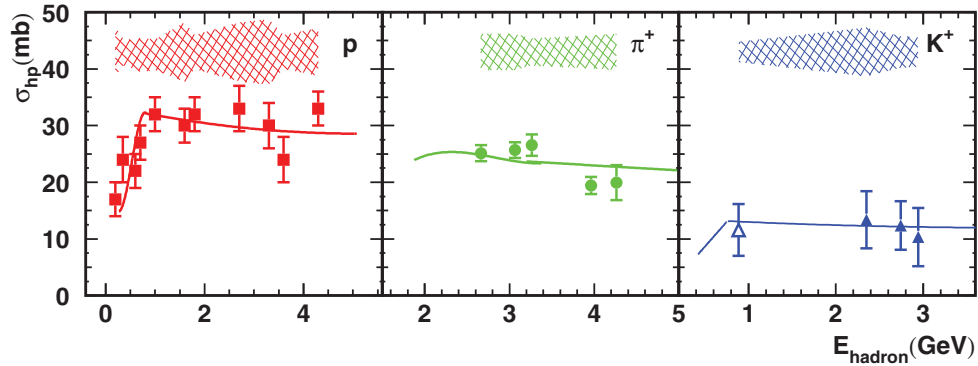


FIG. 4. (Color online) Effective cross sections as a function of the hadron kinetic energy for protons, pions, and kaons. The solid points are the results from this experiment. Results from a previous experiment on light nuclei [28,29] at  $Q^2 = 0.35 \text{ GeV}^2$  are shown as open symbols. The solid curves are fits to the global proton-nucleon (red), pion-nucleon (green), and kaon-nucleon scattering data (blue) [39], scaled by 0.68 (0.03), 0.81 (0.03), and 0.65 (0.14), respectively. The numbers within parentheses are the uncertainties associated with the scale factors. The data shown are the averages over different targets, weighted by the statistical uncertainty only and the standard deviation shown by the hatched bands.

within parentheses are the uncertainty associated with the scale factors.

It is interesting to note that the energy dependence of the effective cross section for the protons and pions is consistent with the energy dependence of the free cross sections (for kaons, the large experimental uncertainties are too large to make any strong conclusions), however, the absolute magnitude of the effective cross section is reduced. This renormalization is interpreted [2] to take effects that cannot be absorbed in the density-independent assumptions of the simple geometric model into account. For instance, the simple model does not account for effects, such as Pauli blocking and short-range correlations. In general, one would expect these effects to be the smallest for kaons since they introduce a strangeness degree of freedom [40]. However, in contrast, we find that the kaon-nucleon effective cross sections extracted from electroproduction are significantly smaller than the free cross section, with the reduction larger than that for pions and comparable to the reduction for protons. We note that, for both protons and pions, more sophisticated models [41,42] have been shown to be in good agreement with the absolute magnitude of the measured transparencies, for example, see Refs. [4,5] for more details. Such theoretical calculations are currently unavailable for kaons.

In addition to the  $Q^2$  dependence, we examined the dependence of the measured kaon transparencies on the atomic

mass number  $A$  at fixed  $Q^2$  with a single-parameter fit form,  $T = (A/2)^{\alpha-1}$ . Here,  $\alpha$  is used to parametrize the nuclear cross section. This simple ansatz is equivalent to the more commonly used  $\sigma_N = \sigma_0 A^\alpha$  parametrization with  $\sigma_N$  as the nuclear cross section and  $\sigma_0$  as the elementary (isoscalar) nucleon cross section [43]. The extracted values of the parameter  $\alpha$  are shown in Fig. 5. We have included the  $\alpha$  values from fits to the proton and pion transparency data [4,6]. To be consistent with the kaons, the proton and pion transparencies for  $A > 2$  targets were recalculated as the ratios of cross sections from nuclear targets to deuterium, and the recalculated transparencies were fit to the single-parameter form  $T = (A/2)^{\alpha-1}$ . This recalculation will render values for  $\alpha$  slightly different from our previous publications for protons and pions. In addition, we show, as lines, the  $\alpha$  values as extracted from high-energy hadron-nucleus collisions by Carroll *et al.* [43], for kaons, pions, and protons. For all three hadrons, we find the  $\alpha$  value as extracted from the electron-scattering experiments to be somewhat larger than those from hadron-nucleus collisions. This can partly be attributed to the nature of the probe used in these collisions: The strong hadronic probe is more surface dominated, whereas, the electromagnetic probe likely samples the entire nuclear volume. For kaons, the parameter  $\alpha$  from electroproduction is significantly larger than the value extracted from high-energy kaon-nucleus scattering. This is contrary to the traditional nuclear-physics expectations,

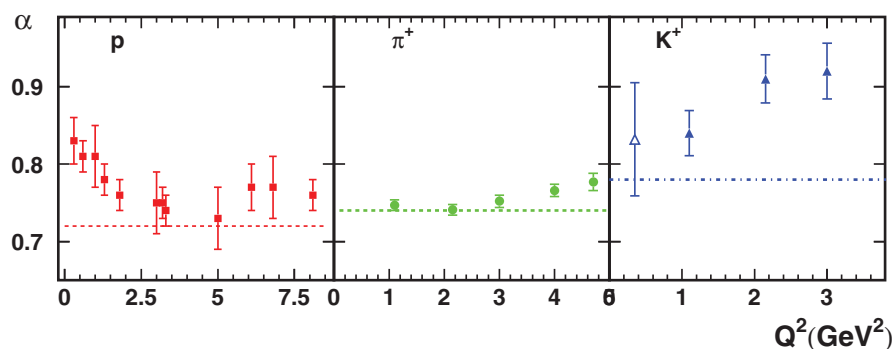


FIG. 5. (Color online) The parameter  $\alpha$  (see text) as a function of  $Q^2$  for protons (squares), pions (circles), and kaons (triangles) obtained from electron scattering. The solid points are the results from this experiment. Results from a previous experiment on light nuclei [28,29] at  $Q^2 = 0.35 \text{ GeV}^2$  are shown as open symbols. The dashed line shows the value of  $\alpha$  for protons, pions, and kaons respectively, obtained from hadron-nucleus scattering [43].

however, the relatively large experimental uncertainties and the lack of corresponding energy dependence in the nuclear transparency do not allow strong conclusions regarding quantum chromodynamic effects, such as the formation of compact states.

To summarize, we measured the reaction  $A(e, e'K^+)$  for  $^1\text{H}$ ,  $^2\text{H}$ ,  $^{12}\text{C}$ ,  $^{63}\text{Cu}$ , and  $^{197}\text{Au}$  at  $Q^2 = 1.1, 2.2, \text{ and } 3.0 \text{ GeV}^2$ . We extracted the nuclear transparency of kaons as the ratio of the kaon electroproduction cross sections of the heavy nuclei with deuterium. The energy dependence of the nuclear transparency is found to be consistent with traditional nuclear-physics expectations within experimental uncertainties. However, the absolute magnitude of the effective kaon-nucleon cross sections extracted from the nuclear transparency is found to be substantially smaller than that for the free kaon-nucleon cross sections in a simple geometric model. Effective hadron-nucleon cross sections for protons, pions, and kaons analyzed in a similar manner find reduction factors of 0.68(0.03), 0.81(0.03), and 0.65(0.14), respectively, as compared to the free hadron-nucleon cross sections. The kaon results are significantly smaller than the effective kaon-nucleon cross sections as obtained from kaon-nucleus scattering. Also, the  $A$  dependence of the kaon-nucleon cross section extracted from the transparency measurements was found to be significantly different from that obtained from kaon-nucleus

scattering. The difference between kaon electroproduction and kaon-nucleus-scattering results are significantly larger than the earlier differences observed for pions and protons. Because of the smaller absolute values of the free kaon-nucleon cross sections (as compared to the pion and proton), the opposite was expected. This could be an indication that these results cannot all be explained simultaneously in terms of traditional nuclear-physics effects, however, the relatively large experimental uncertainties and the lack of energy dependence in the nuclear transparency do not allow strong conclusions. It would be of great interest to also extend a recent calculation of kaon production data in heavy-ion collisions, going beyond the conventional meson-nucleon nuclear many-body calculations in the framework of the quark-meson coupling model [27], to these results.

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