Color transparency of K^+ mesons in inclusive (e, e') reactions on nuclei

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The color transparency of K^+ mesons produced due to large four-momentum transfer in (e, e') reactions on nuclei is studied. The variations of K^+-meson color transparency (K^+CT) with the photon virtuality and the kaon momentum are investigated. The calculated results for K^+CT are compared with data reported from Jefferson Laboratory.

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I. INTRODUCTION

The characteristics of the K^+ meson are distinctly different from those of other hadrons. The interaction of this meson with a nucleon is relatively weak, free from resonance structure, and varies smoothly with the energy. Because of these behaviors, the K^+ meson can be thought of as a pertinent probe to investigate specific properties of a nucleus. The scattering of this meson from a nucleus can provide information complementary to that obtained from electron-nucleus scattering, because both are weakly interacting probes unlike the conventional strongly interacting hadronic probe. Additionally, the K^+ meson can open the avenue for studying the strangeness degrees of freedom in the nuclear reaction.

Despite the K^+ meson possessing such useful properties, the description of the K^+-meson–nucleus scattering from the elementary K^+-meson–nucleon scattering is not successful. The calculated K^+-meson–nucleus cross section [1,2] shows discrepancy with the data [3]. Even the calculated nuclear transparency [1,2], defined by the ratio of the total cross sections for a nucleus and a deuteron (where the uncertainties are expected to cancel), underestimates the experimental results [3]. Because of the failure of conventional nuclear physics to explain the quoted data, several exotic mechanisms for K^+-meson–nucleus scattering have been proposed. These include modification of the in-medium nucleon's size and mass [1,4], medium modification of the elementary K^+-meson–nucleon scattering amplitude [5], virtual pion contribution [6], mesons' exchange currents [7], long-range correlations [8], and various other mechanisms [9].

The electroproduction of the K^+ meson from a nucleus provides an alternate tool to investigate the K^+-meson–nucleus scattering and also to explore the propagation of this meson through the nucleus. The dependence of the K^+-meson transparency on the nuclear mass number A and the four-momentum transfer squared Q^2 (i.e., photon virtuality) in the $A(e, e')$ reaction has been reported from Jefferson Laboratory (JLab) [10]. The data available from JLab renews the interest in looking for whether the discrepancy between the theoretical and the experimental results also exists for the K^+-meson production reaction.

It has been shown that the conventional nuclear physics calculation fails to reproduce the electroproduced K^+-meson nuclear transparency data [10], similar to what occurred for the K^+-meson–nucleus scattering data. Therefore, color transparency [11] of K^+ mesons is envisaged as high four-momentum transfer is involved to produce this meson. Color transparency of a hadron describes the enhancement in its transparency in the nucleus. The quoted enhancement originates because of the reduction of the hadron-nucleon interaction (or the total cross section σ_t^{hN}) while the hadron undergoes large four-momentum transfer during its passage through the nucleus [12].

The high-momentum transfer Q^2 associated with a hadron reduces its transverse size (i.e., $d_\perp \sim 1/\sqrt{Q^2}$). The reduced (in size) hadron is referred to as small size or pointlike configuration (PLC). According to quantum chromodynamics, a color singlet PLC has reduced interaction with nucleons in the nucleus because the sum of the gluon emission amplitudes cancels [13]. The interaction of the PLC with the nucleon increases, as the PLC expands to the size of the physical hadron during its passage up to the length called the hadron formation length l_h [14]:

$$l_h = \frac{2k_h}{\Delta M^2}, \tag{1}$$

where k_h is the momentum of the hadron in the laboratory frame. ΔM^2 is related to the mass difference between the hadronic states originating due to the fluctuation of the (anti)quarks in the PLC. The value of ΔM^2 is very much uncertain, ranging from 0.25 to 1.4 GeV^2 [14]. Therefore, the effective hadron–nucleon total cross section $\sigma_{t,\text{eff}}^{hN}$ in the nucleus depends on both Q^2 and l_h, i.e., $\sigma_t^{hN} \rightarrow \sigma_{t,\text{eff}}^{hN}(Q^2, l_h)$ in the nucleus.

The first experiment to search the color transparency of the proton, done at Brookhaven National Laboratory [15], in the high-momentum-transfer (p, pp) reactions on nuclei yielded a null result, and that was corroborated in later

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experiments [16]. According to the Landshoff mechanism [17], three well-separated quarks (qqq) in one proton interact with those in another proton exchanging three gluons [18]. Color transparency also is not seen in the $A(e, e'p)$ experiment done at the Stanford Linear Accelerator Center [19] and Jefferson Laboratory [20]. Therefore, it appears that the PLC required for color transparency is unlikely to form for the qqq system, e.g., a proton.

Color transparency is unambiguously reported from the Fermi National Accelerator Laboratory [21] in the experiment of the nuclear diffractive dissociation of pions (of 500 GeV/c) to dijets. Because a meson is a bound state of two quarks (i.e., quark-antiquark $q\bar{q}$), the PLC of it is more probable than that of a baryon, a qqq object. Color transparency of the meson (M) is also found in photon [22] and in electron-induced nuclear experiments [23,24]. In the latter reaction, i.e., the $A(e, e'M)$ reaction, the length of the $q\bar{q}$ (of mass $m_{q\bar{q}}$) fluctuation to a meson in the virtual photon γ^* (of energy ν and virtuality Q^2) is described by the coherence length (CL) [24]: $l_c = \frac{2\nu}{Q^2+m^2_{q\bar{q}}}$. T_A varies with l_c in the absence of color transparency. Therefore, l_c must be kept fixed to observe color transparency [25]. Several authors have studied the ρ-meson color transparency (ρCT), and the effect of the CL on the ρCT in the energy region available at JLab [12,26].

The nuclear transparencies for both π^+ [23] and K^+ [10] mesons versus the photon virtuality Q^2 (of few GeV) in the $A(e, e')$ reaction were measured at JLab. The data for both mesons could not be understood by using conventional nuclear physics. The pionic color transparency (πCT) in the above reaction is shown to occur by Kaskulov *et al.* [27] in their calculation done using a coupled-channel Boltzmann-Uehling-Uhlenbeck transport model. Larson *et al.* [28] illustrates the dependence of the πCT on the pion momentum and the momentum transfer to nuclei (instead of Q^2) using the semiclassical formula for the nuclear transparency. Cosyn *et al.* [29] calculated CT and short-range correlation in pion photo- and electroproduction from nuclei. The calculated results due to Larionov *et al.* [30] show the πCT in the $A(\pi^-, l^+l^-)$ process at ≈20 GeV/c, which can be measured at the forthcoming facilities in the Japan Proton Accelerator Research Complex (cf. Ref. [31] and the references therein). This study provides information analogous to that obtained in the $A(e, e'\pi)$ reaction. Miller and Strikman [32] show large color transparency in the pionic knockout of proton off nuclei, i.e., the $A(\pi, \pi p)$ reaction, at the energy of 500 GeV available at the CERN COMPASS experiment. The recent development of color transparency and its future direction are discussed in Ref. [13]. As illustrated later, the K^+-meson nuclear transparency calculated considering the color transparency of this meson reproduces well the data reported from JLab [10].

II. FORMALISM

The nuclear transparency $T_A(K^+)$ of the K^+ meson, including the small-angle kaon-nucleus elastic scattering, can be written as

$$T_A(K^+) = \frac{\sigma_{\rm in}^{K^+A} + \Delta\sigma_{\rm el}^{K^+A}}{A\sigma_t^{K^+N}}, \tag{2}$$

where $\sigma_{\rm in}^{K^+A}$ is the inelastic K^+-meson–nucleus cross section and $\Delta\sigma_{\rm el}^{K^+A}$ represents the small-angle kaon-nucleus elastic scattering cross section. $\sigma_t^{K^+N}$ is the elementary K^+-meson–nucleon total cross section: $\sigma_t^{K^+N} = \frac{Z}{A}\sigma_t^{K^+p} + \frac{A-Z}{A}\sigma_t^{K^+n}$. In the considered kaon momentum region, i.e., ≈3–10 GeV/c, the energy-dependent experimentally determined values of $\sigma_t^{K^+p}$ and $\sigma_t^{K^+n}$, as given in Ref. [33], are almost equal, i.e., $\sigma_t^{K^+p} \simeq \sigma_t^{K^+n}$.

The inelastic cross section $\sigma_{\rm in}^{K^+A}$ in Eq. (2), according to the optical approach in the Glauber model [34], is given by

$$\sigma_{\rm in}^{K^+A} = \int d\mathbf{b}[1 - |e^{i\chi_{OK}(\mathbf{b})}|^2]. \tag{3}$$

Here, $\chi_{OK}(\mathbf{b})$ denotes the optical phase-shift for the K^+ meson, i.e.,

$$\chi_{OK}(\mathbf{b}) = -\frac{1}{v}\int_{-\infty}^{+\infty} dz V_{OK}(\mathbf{b}, z), \tag{4}$$

where $V_{OK}(\mathbf{r})$ is the K^+-meson–nucleus optical potential [34]:

$$-\frac{1}{v}V_{OK}(\mathbf{r}) = \frac{1}{2}(\alpha_{K^+N} + i)\sigma_t^{K^+N}\varrho(\mathbf{r}), \tag{5}$$

where α_{K^+N} represents the ratio of the real part to the imaginary part of the K^+-meson–nucleon elastic scattering amplitude [33]. $\varrho(\mathbf{r})$ describes the density distribution of the nucleus; i.e., it is to be normalized to the mass number of the nucleus.

Using Eqs. (4) and (5), $\sigma_{\rm in}^{K^+A}$ in Eq. (3) can be written as

$$\begin{aligned}\sigma_{\rm in}^{K^+A} &= \int d\mathbf{b}\int_{-\infty}^{+\infty} dz\left[-\frac{2}{v}{\rm Im}V_{OK}(\mathbf{b}, z)\right] \\ &\quad\times \exp\left\{\int_z^{+\infty}\left[\frac{2}{v}{\rm Im}V_{OK}(\mathbf{b}, z')dz'\right]\right\} \\ &= \sigma_t^{K^+N}\int d\mathbf{b}\int_{-\infty}^{+\infty} dz\varrho(\mathbf{b}, z) \\ &\quad\times \exp\left[-\sigma_t^{K^+N}\int_z^{+\infty}\varrho(\mathbf{b}, z')dz'\right].\end{aligned} \tag{6}$$

The nuclear transparency defined by $T_A = \frac{\sigma_{in}^{K^+A}}{A\sigma_t^{K^+N}}$ refers to the expression due to the semiclassical model as mentioned in Ref. [14]; i.e.,

$$T_A(K^+) = \frac{1}{A}\int d\mathbf{r}\varrho(\mathbf{b}, z)\exp\left[-\sigma_t^{K^+N}\int_z^{+\infty}\varrho_A(\mathbf{b}, z')dz'\right]. \tag{7}$$

The cross section $\Delta\sigma_{\rm el}^{K^+A}$ in Eq. (2) is given by

$$\Delta\sigma_{\rm el}^{K^+A} = \frac{d\sigma_{\rm el}^{K^+A}}{d\Omega}\Delta\Omega = |F_{K^+A}|^2\Delta\Omega, \tag{8}$$

where $\Delta\Omega$ (=6.7 msr [23]) is the angular aperture of the detector. F_{K^+A} represents the kaon-nucleus elastic scattering amplitude [34]:

$$F_{K^+A} = \frac{k_{K^+}}{2\pi i}\int d\mathbf{b}e^{i\mathbf{q}_\perp\cdot\mathbf{b}}[e^{i\chi_{OK}(\mathbf{b})} - 1], \tag{9}$$

where $q_\perp(= -k_{K^+}\sin\theta_{K^+})$ represents the transverse momentum transfer.

III. RESULTS AND DISCUSSION

The nuclear transparency $T_A(K^+)$ of the K^+ meson produced in the (e, e') reaction on d, ^{12}C, ^{63}Cu, and ^{197}Au nuclei has been calculated using the Glauber model, where the experimentally determined free-space kaon-nucleon total cross section $\sigma_t^{K^+N}$ [33] has been used. The density distribution $\varrho(r)$ of the deuteron (d) nucleus is evaluated using its wave function generated due to the Paris potential [35]. ϱ for other nuclei, as extracted from the electron scattering data, is tabulated in Ref. [36]. According to Ref. [36], ϱ for the ^{12}C nucleus is described by the harmonic oscillator Gaussian form, whereas that for other nuclei (i.e., ^{63}Cu and ^{197}Au) is illustrated by the two-parameter Fermi distribution.

The calculated results for $T_A(K^+)$ in Eq. (2) show that the contribution of the small-angle elastic scattering cross section, i.e., $\Delta\sigma_{\rm el}^{K^+A}$, to $T_A(K^+)$ is negligible compared to that of $\sigma_{\rm in}^{K^+A}$. It should be mentioned that the kinematics of the experiment is so chosen that the elastic scattering of the kaon from the nucleus would be suppressed [13,23]. Therefore, $\Delta\sigma_{\rm el}^{K^+A}$ is neglected to evaluate $T_A(K^+)$.

The dependence of the calculated $T_A(K^+)$ in Eq. (7) on the photon virtuality Q^2 is presented in Fig. 1 along with the data [10]. The short-dashed curves distinctly show that $T_A(K^+)$ evaluated using $\sigma_t^{K^+N}$ in the Glauber model significantly underestimate the electroproduction data for the K^+-meson nuclear transparency. Because few GeV four-momentum transfer Q^2 is involved in the K^+-meson production, color transparency of this meson is considered. According to it, the effective kaon-nucleon total cross section $\sigma_{t,\rm eff}^{K^+N}$ in the nucleus is less than $\sigma_t^{K^+N}$ because of the PLC formation of the K^+ meson in the nucleus. Using the quantum diffusion model [14], $\sigma_{t,\rm eff}^{K^+N}$ can be written as

$$\sigma_{t,\rm eff}^{K^+N}(Q^2, l_h; l_z) = \sigma_t^{K^+N}\left\{\left[\frac{l_z}{l_h} + \frac{n_q^2\langle k_t^2\rangle}{Q^2}\left(1 - \frac{l_z}{l_h}\right)\right] \times \theta(l_h - l_z) + \theta(l_z - l_h)\right\}, \qquad (10)$$

where $n_q(=2)$ denotes the number of the valence quark-antiquark $q\bar{q}$ in the meson. k_t illustrates the transverse momentum of the (anti)quark: $\langle k^2\rangle^{1/2} = 0.35$ GeV/c. l_z is the path length traversed by the meson ($q\bar{q}$) after its production. The hadron formation length $l_h(\propto\frac{1}{\Delta M^2})$ is already defined in Eq. (1). For $l_h = 0$, i.e., $\Delta M^2 = \infty$, the above equation is reduced to $\sigma_t^{K^+N}$.

$T_A(K^+)$ evaluated using $\sigma_{t,\rm eff}^{K^+N}$ in Eq. (10) is also shown in Fig. 1. The dot-dot-dashed curves represent the calculated $T_A(K^+)$ for $\Delta M^2 = 1.4$ GeV^2, whereas the dot-dashed and solid curves represent ΔM^2 taken equal to 0.7 and 0.3 GeV^2, respectively. The calculated results illustrate that $T_A(K^+)$ increases with Q^2 because of $\sigma_{t,\rm eff}^{K^+N}$. It is noticeable in the figure that $T_A(K^+)$ evaluated for $\Delta M^2 = 0.3$ GeV^2 (solid curves) agrees well with the data [10] for all nuclei. The calculated results describe the color transparency of K^+ mesons produced in (e, e') reactions on nuclei.

The calculated kaonic transparency ratio $T_{A/d}(K^+)$ with respect to the deuteron, i.e., $T_{A/d}(K^+) = T_A(K^+)/T_d(K^+)$, is compared with data from Ref. [10] in Fig. 2. This ratio includes the contribution of K^+-meson production from the neutron and the Fermi-motion correction. The curves appearing in this figure are as described in Fig. 1. The color transparency of the K^+ meson is also distinctly visible in Fig. 2, as the calculated $T_{A/d}(K^+)$ for $\Delta M^2 = 0.3$ GeV^2 (solid curves) reproduce the data [10] reasonably well.

The kaon momentum k_{K^+}-dependent $T_A(K^+)$ is shown in Fig. 3 for different values of ΔM^2. In fact, it describes

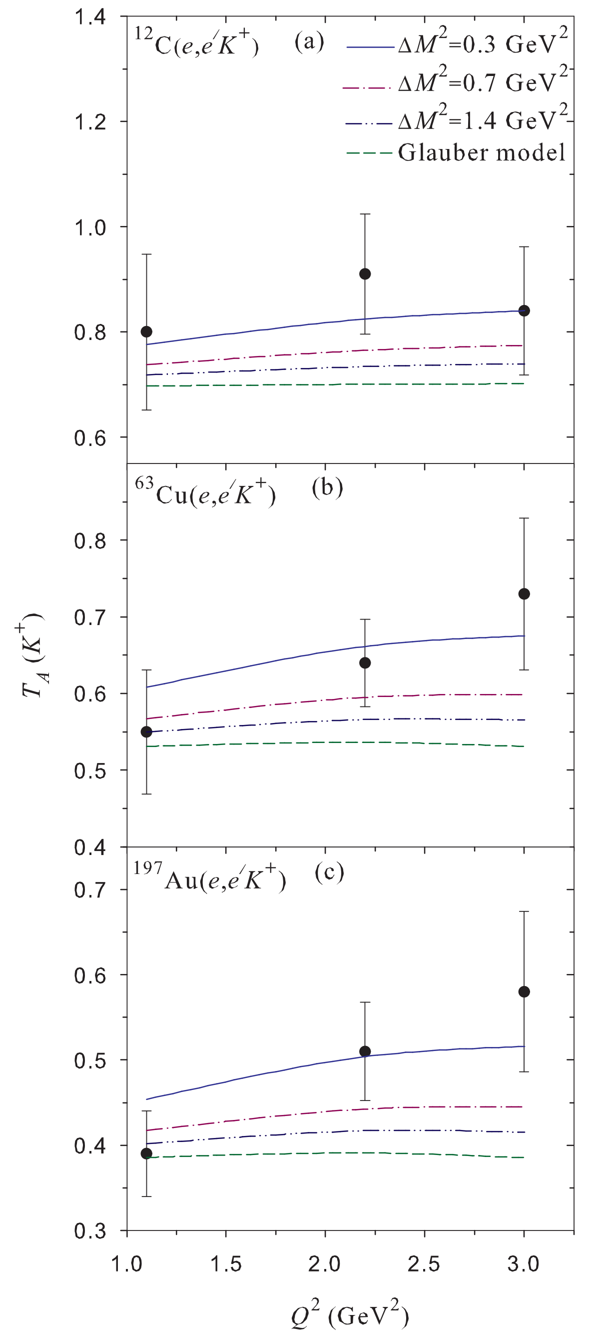

FIG. 1. The photon virtuality Q^2-dependent nuclear transparency $T_A(K^+)$ of K^+ mesons produced in (e, e') reactions on nuclei. The dashed curves denote $T_A(K^+)$ calculated using the Glauber model. Other curves illustrate the K^+-meson color transparency for different values of ΔM^2 (see text). The data are taken from Ref. [10].

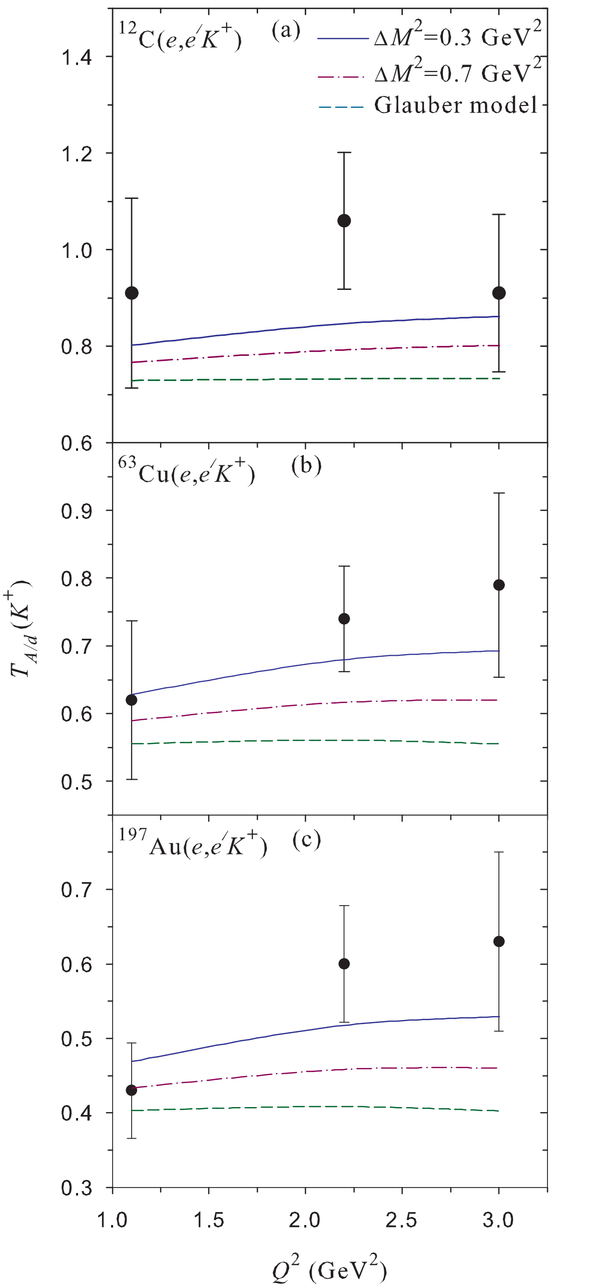

FIG. 2. The K^+-meson transparency ratio with respect to deuteron $T_{A/d} = T_A/T_d$. The curves are as described in Fig. 1. The data are taken from Ref. [10].

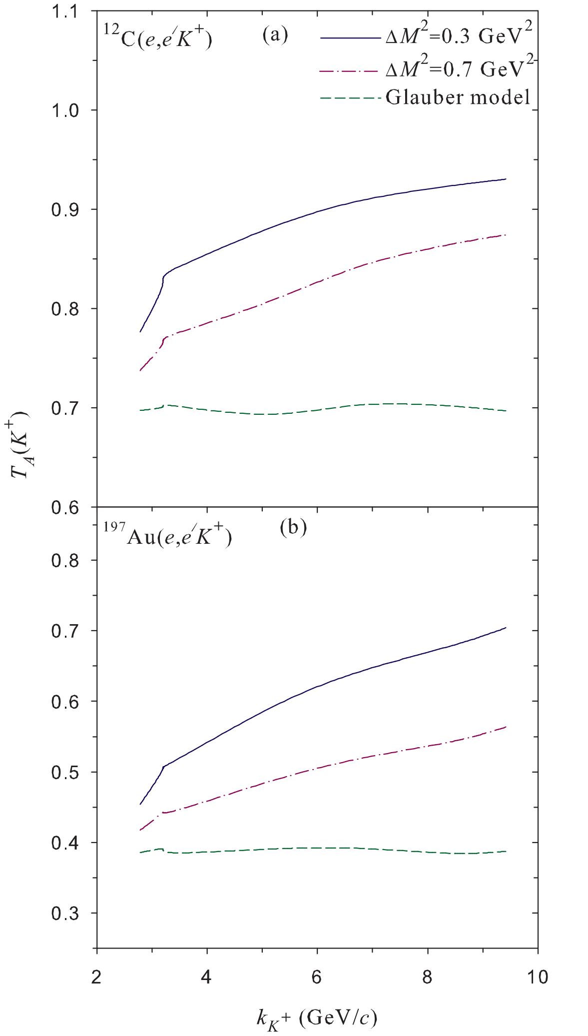

FIG. 3. The calculated results showing the variation of $T_A(K^+)$ with the K^+-meson momentum k_{K^+}. The curves are as described in Fig. 1.

the variation of $T_A(K^+)$ with the hadron formation length, mentioned in Eq. (1), of the K^+ meson. The range of k_{K^+} is considered up to 9.5 GeV/c, which would be accessible in the kinematics of 11-GeV JLab experiments. The calculated results show $T_A(K^+)$ increases with the kaon momentum.

IV. CONCLUSION

The nuclear transparency T_A and the transparency ratio, i.e., $T_{A/d} = T_A/T_d$, of K^+ mesons produced in $A(e, e')$ reactions have been calculated to look for the color transparency of K^+ mesons. The calculated results show that both T_A and $T_{A/d}$ evaluated using the free-space K^+-meson–nucleon cross section $\sigma_t^{K^+N}$ in the Glauber model significantly underestimate the data reported from JLab. The inclusion of the K^+-meson color transparency in the Glauber model (i.e., the use of the kaon-nucleon effective cross section $\sigma_{t,\text{eff}}^{K^+N}$, instead of $\sigma_t^{K^+N}$, arising due to the formation of the pointlike configuration of the kaon) leads to the enhancement in the calculated transparency. The calculated T_A and $T_{A/d}$ due to $\sigma_{t,\text{eff}}^{K^+N}$ (evaluated for $\Delta M^2 = 0.3$ GeV^2) are in good agreement with the data, i.e., they describe the color transparency of K^+ mesons produced in electronuclear reactions.

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