K^+-nucleus elastic scattering at intermediate energies

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Using the Coulomb modified Glauber model, we analyze the elastic angular distribution and reaction (σ_R) and total (σ_{tot}) cross sections of K^+-^{12}C at 635, 715, and 800 MeV/c, and of K^+-^{40}Ca at 800 MeV/c. The basic (input) K^+N amplitude is taken from the phase shift analysis, and for nuclear form factors we use the nucleon density distributions as obtained from the analyses of intermediate energy proton scattering experiments and the relativistic mean field (RMF) calculations. The analysis also considers the nuclear medium effects, and predicts the in-medium behavior of the K^+N amplitude. We find that the elastic angular distribution is sensitive to the choice of the nucleon density distributions, whereas the nuclear medium effects are better seen in the study of reaction and total cross sections.

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Introduction. Among the various hadronic probes, the K^+N strong interaction below 800 MeV/c, as characterized by total cross section, is relatively weak on the hadronic scale. Because of this, the K^+ meson has fairly long mean free path in nuclear matter and is therefore capable of probing deep into the nucleus. It is, thus, expected that the analysis of K^+-nucleus scattering data could add some valuable information about the interior region of the nucleus and possibly more accurate information about the neutron density distribution for which other intermediate energy hadrons (proton, pion, α particle) are not very helpful, due to their large absorption. On the theoretical front, different suggestions have been put forth that effectively modify properties of the K^+N interaction within nuclear matter. For example, Siegel *et al*. [1] proposed that the nuclear environment may modify the S11 K^+ scattering amplitude by altering the effective nucleon size in the nucleus. They found that an increase of about 20% in the S11 phase shift markedly improves their agreement with the experimental data above 720 MeV/c. Such an increase has also been indicated by Close *et al*. [2] in terms of the change of confinement size of the nucleons. On the other hand, Glauber model calculations [3] also had to modify the free K^+N scattering amplitude in order to have a better description of the K^+-nucleus scattering data.

It was also suggested that the study of the K^+-nucleus total cross section in terms of the ratio $R = [\sigma_{\text{tot}}(K^+\text{-nucleus})/A]/[\sigma_{\text{tot}}(K^+\text{-deuteron})/2]$ may be more reliable than the angular distribution, as it not only reduces the systematic error appearing in the experimental setup but also cancels the inaccuracies in the K^+N phase shifts. Using the conventional nuclear reaction theories, several authors attempted to reproduce the data, but the calculations predict a value of R smaller than the measured one at higher K^+ beam momenta. Here also, Siegel *et al*. [1] have shown that the increase in nucleon size in the nucleus enhances the K^+-nucleus cross section, and the calculated values are consistent with the measured spectrum at higher energies. In other calculations by Akulinichev [4] and Jiang and Kolton [5], the additional contribution of K^+ scattering on the virtual pion present in the nucleus also lifts the cross section towards the data.

In the present work, the elastic angular distribution and the reaction and total cross sections for K^+ scattering on ^{12}C and ^{40}Ca have been calculated using the Coulomb modified Glauber model. The basic (input) K^+N amplitude is parametrized in the same form as the NN amplitude [6], and its parameters are obtained from the K^+N phase shifts [7]. Moreover, encouraged by the findings of Coker, Lumpe, and Ray [8,9] regarding the enhanced sensitivity of K^+ mesons to interior nuclear structure properties compared to that of protons, we attempt to see the suitability of the nucleon density distributions as obtained from the analyses of intermediate-energy proton scattering experiments [6,10,11] and the relativistic mean field (RMF) calculations [12]. Following Siegel *et al*. [1], the analysis also considers the nuclear medium effects, and predicts the in-medium behavior of the K^+N amplitude. In fact our aim is also to see how far the phenomenological treatment of the nuclear medium corrections affects the results of K^+-nucleus scattering.

Formalism. Following Ahmad and Auger [13], the correlation expansion for the Glauber amplitude describing the scattering of kaons from a target nucleus takes the form

$$F_{00}(\vec{q}) = F_0(\vec{q}) + \sum_{l=2}^{A} F_l(\vec{q}), \tag{1}$$

where F_0 is the uncorrelated part involving all orders of scattering [13] and F_l is the correlation term of order l [13]. Here it may be mentioned that, in this work, we restrict ourselves up to F_2 with the aim of studying the effects of two-body correlations on K^+-nucleus scattering. Moreover, it is to be noted that Eq. (1) has been modified to account for the (i) Coulomb effects [6], and (ii) deviation in the straight-line trajectory of the Glauber model because of the Coulomb field [6].

Results and discussion. We analyze the elastic angular distribution and reaction (σ_R) and total (σ_{tot}) cross sections of K^+ on ^{12}C at 635, 715, and 800 MeV/c, and of K^+ on ^{40}Ca at 800 MeV/c. The inputs needed in the theory are the elementary K^+N amplitude and the nuclear form factors. For nuclear form factors, we use the nucleon density distributions

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TABLE I. Parameter values for K^+p and K^+n amplitudes [Eq. (2), $n = 46$] using the phase shift analysis of K^+N scattering [7]. σ_t is the total cross section of K^+N scattering, and ρ is the ratio of the real to the imaginary parts of the forward K^+N amplitude.

k_{lab} (MeV/c)		σ_0 (fm^2)	β_0^2 (fm^2)	ρ_0	D_s	β_s^2 (fm^2)	ρ_s	σ_t (mb)	ρ
635	K^+p:	1.80885	0.14304	−0.37554	1.62899	0.30563	1.05181	12.95	−1.3113
	K^+n:	1.43886	0.23260	−0.48244	0.37148	0.05746	1.17706	15.71	−0.6124
715	K^+p:	1.78296	0.14141	−0.38543	1.53169	0.31029	1.21747	12.93	−1.1015
	K^+n:	1.45443	0.19881	−0.42955	0.58569	0.08472	1.01079	16.33	−0.5806
800	K^+p:	1.21219	0.09792	−0.35123	1.99992	0.25204	1.04744	13.17	−0.8854
	K^+n:	1.52145	0.23979	−0.47684	0.33027	0.05457	1.16673	16.66	−0.6105

as obtained from the analyses of intermediate-energy proton scattering experiments [6,10,11] and the relativistic mean field (RMF) calculations [12].

As already mentioned, we parametrize the kaon-nucleon amplitude in the same form as the NN amplitude [6],

$$f_{K^+N}(\vec{q}) = \frac{ik\sigma_0}{4\pi}\sum_{n=0}^{\infty} A_{n+1}\left[\left(\frac{\sigma_0}{4\pi\beta_0^2}\right)^n \frac{(1-i\rho_0)^{n+1}}{n+1} \times \exp\left(\frac{-\beta_0^2 q^2}{2(n+1)}\right) + i(q^2/4m^2)^{1/2}\left(\frac{\sigma_0}{4\pi\beta_s^2}\right)^n \times \frac{[D_s(1-i\rho_s)]^{n+1}}{n+1}\exp\left(\frac{-\beta_s^2 q^2}{2(n+1)}\right)\vec{\sigma}\cdot\hat{n}\right], \quad (2)$$

$$A_{n+1} = \frac{A_1}{n(n+1)} + \frac{A_2}{(n-1)n} + \frac{A_3}{(n-2)(n-1)} + \cdots + \frac{A_n}{1\times 2}, \quad (3)$$

with $A_1 = 1$, and $\vec{\sigma}$ is the spin operator of the target nucleon. The amplitude (2) has six adjustable parameters, σ_0, ρ_0, β_0^2, D_s, ρ_s, and β_s^2. The values of these parameters, which reproduce simultaneously the total cross section and the angular distribution of K^+N scattering at 635, 715, and 800 MeV/c [7] are listed in Table I; the parameter values obtained in this way correspond to representation of the free K^+N scattering.

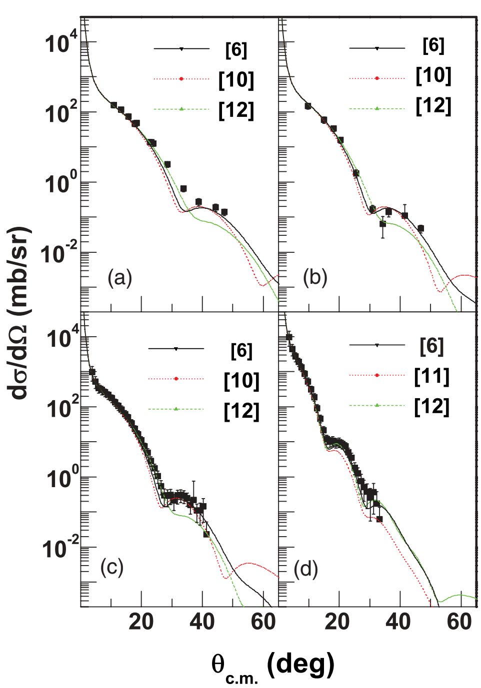

FIG. 1. (Color online) Panels (a), (b), and (c) present the elastic angular distribution of K^+-^{12}C at 635, 715, and 800 MeV/c, respectively, and panel (d) presents the elastic angular distribution of K^+-^{40}Ca at 800 MeV/c using the K^+N amplitude obtained from the phase shift analysis [7] (Table I). The calculations involve the nucleon density distributions as obtained in Refs. [6,10–12]. The data are taken from Refs. [14,15].

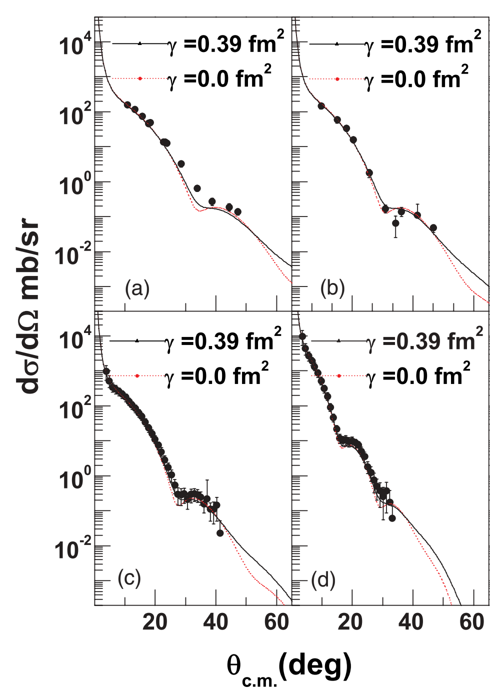

FIG. 2. (Color online) Panels (a), (b), and (c) present the elastic angular distribution of K^+-^{12}C at 635, 715, and 800 MeV/c, respectively, and panel (d) presents the elastic angular distribution of K^+-^{40}Ca at 800 MeV/c using the K^+N amplitude obtained from the phase shift analysis [7] (Table I). The calculations involve the nucleon density distributions as obtained in Ref. [6], and the results show the effect of phase variation (γ) of the K^+N amplitude. The data are taken from Refs. [14,15].

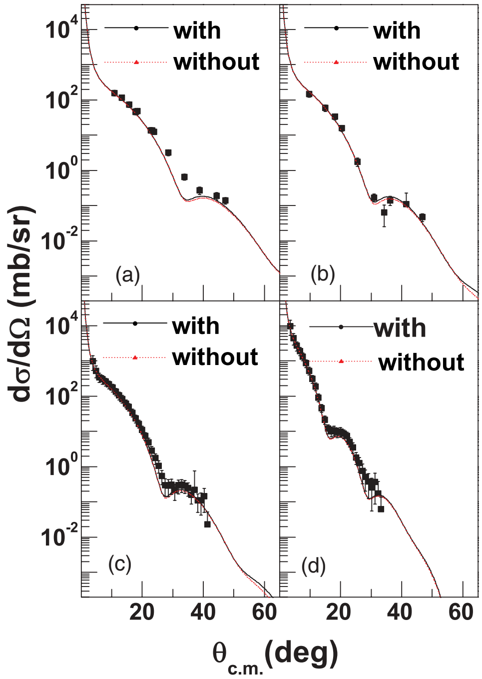

FIG. 3. (Color online) Panels (a), (b), and (c) present the elastic angular distribution of K^+-^{12}C at 635, 715, and 800 MeV/c, respectively, and panel (d) presents the elastic angular distribution of K^+-^{40}Ca at 800 MeV/c using the K^+N amplitude obtained from the phase shift analysis [7] (Table I). The calculations involve the nucleon density distributions as obtained in Ref. [6], and the results show the effect of two-body correlations. The data are taken from Refs. [14,15].

The results of the calculation for the elastic angular distribution are presented and compared with the experimental data in Fig. 1. The data also include normalization uncertainties [14,15]. It is found that the elastic angular distribution could provide a test to determine the better choice of the nucleon density distributions. For ^{12}C, we notice that the nucleon density distributions, as obtained in Ref. [6], provide an overall better description of the data as compared to those obtained in Refs. [10,12]. In the case of ^{40}Ca, the use of RMF densities [12] as well as the densities obtained in Ref. [6] provide almost similar predictions, and we have quite a satisfactory account of the data as compared to that obtained with the densities of Ref. [11].

TABLE III. Reaction cross section (in mb) for the K^+ interaction with ^{12}C and ^{40}Ca. σ_R^f uses the K^+N amplitude obtained from Ref. [7]. σ_R^{in} uses the K^+N amplitude obtained from Ref. [7], but with 15% increase in the S11 K^+N phase shift [7]. σ_R^o is taken from other works.

$k_{\rm lab}$	System	Density	Present work		Other works
(MeV/c)			σ_R^f	σ_R^{in}	σ_R^o
635	K^+-^{12}C	[6]	127.1	139.9	
		[10]	129.5	142.6	138.55 [17]; 142.25 [18]
		[12]	127.3	140.1	
715	K^+-^{12}C	[6]	128.8	138.5	
		[10]	131.4	141.6	151.31 [17]; 155.70 [18]
		[12]	129.1	138.7	
800	K^+-^{12}C	[6]	130.0	140.4	
		[10]	132.7	143.5	164.47 [17]; 168.62 [18]
		[12]	130.2	140.6	
800	K^+-^{40}Ca	[6]	368.9	393.0	
		[11]	383.3	409.4	436.26 [17]
		[12]	373.4	397.7	

It is well known that NN scattering measurements leave an overall phase of the amplitude undetermined. A similar situation may also be true in the case of K^+N scattering. Following Franco and Yin [16], the phase factor $e^{-i\gamma q^2/2}$ in Eq. (2) takes care of this fact, in which γ may be treated as an adjustable parameter. In Fig. 2, we show the effect of including the phase factor on the calculated angular distribution using the nucleon density distributions as obtained in Ref. [6]. It is seen that an arbitrary choice of $\gamma = 0.39$ fm^2 provides some improvement over the results obtained without the phase.

In Fig. 3, we show the effect of two-body correlations using the nucleon density distributions as obtained in Ref. [6]. As expected, the effect of two-body correlations is found to be only marginal. Hence one could not only ignore the two-body and also the higher-order correlations in the study of K^+-nucleus collisions, but this also gives an indication of the fact that K^+ mesons are weakly absorbed in nuclear matter.

Following Siegel *et al.* [1], we now consider an increase of 15% in the (free) S11 K^+N phase shift as one of the ways to take into account the nuclear medium effects.

TABLE II. Parameter values for K^+p and K^+n amplitudes [Eq. (2), $n = 46$] using the phase shift analysis of K^+N scattering [7], but with 15% increase in the (free) S11 K^+N phase shift [7]. σ_t is the total cross section of K^+N scattering, and ρ is the ratio of the real to the imaginary parts of the forward K^+N amplitude.

$k_{\rm lab}$ (MeV/c)		σ_0 (fm^2)	β_0^2 (fm^2)	ρ_0	D_s	β_s^2 (fm^2)	ρ_s	σ_t (mb)	ρ
635	K^+p:	1.43739	0.11249	−0.34201	1.50131	0.29796	1.64431	15.59	−1.1718
	K^+n:	1.52865	0.22925	−0.43232	0.54042	0.10858	1.57669	17.03	−0.5603
715	K^+p:	1.37787	0.10915	−0.34172	1.66301	0.27949	1.38281	15.39	−0.9814
	K^+n:	1.48041	0.16540	−0.34447	0.53699	0.11047	1.71369	17.56	−0.5232
800	K^+p:	1.22211	0.09426	−0.20355	2.00416	0.25457	1.04610	15.47	−0.7855
	K^+n:	1.56782	0.20797	−0.40485	0.32951	0.05735	1.22794	17.81	−0.5535

TABLE IV. Total cross section ratios for the K^+ interaction with ^{12}C and ^{40}Ca. R^f uses the K^+N amplitude obtained from Ref. [7]. R^{in} uses the K^+N amplitude obtained from Ref. [7], but with 15% increase in the S11 K^+N phase shift [7]. R has the same meaning as in the text.

k_{lab} (MeV/c)	System	Density	R^f	R^{in}
635	K^+-^{12}C	[6]	0.993	1.100
		[10]	0.998	1.108
		[12]	0.995	1.100
715	K^+-^{12}C	[6]	0.966	1.052
		[10]	0.973	1.062
		[12]	0.968	1.053
800	K^+-^{12}C	[6]	0.947	1.030
		[10]	0.954	1.039
		[12]	0.948	1.030
800	K^+-^{40}Ca	[6]	0.879	0.943
		[11]	0.893	0.961
		[12]	0.885	0.950

For this we repeat our calculations to first find out the so called in-medium values of the parameters of the K^+N amplitude at 635, 715, and 800 MeV/c; these parameter values reproduce simultaneously the enhanced in-medium K^+N total cross section and the corresponding angular distribution. The values of the parameters obtained in this way are reported in Table II. It is found (results not shown) that the angular distribution is almost insensitive to the inclusion of nuclear medium effects. This result goes against the findings of Siegel *et al.* [1] where it has been shown that a similar treatment of the nuclear medium effects is able to provide a better description of the experimental data.

The present analysis also predicts the reaction (σ_R) and total (σ_{tot}) cross sections, listed in Tables III and IV, respectively. Although the increase in the S11 K^+N phase shift predicts no significant contribution to the elastic angular distribution, the related analysis of σ_R and σ_{tot} provides noticeable increases in their values obtained using the (free) S11 K^+N phase shift [7]. The values of σ_R with increased S11 K^+N phase shift are found to move closer to the optical model results [17,18], whereas the corresponding results for the ratio $[\sigma_{\text{tot}}(K^+\text{-}^{12}\text{C})/12]/[\sigma_{\text{tot}}(K^+\text{-deuteron})/2]$ follow the experimental trend [19,20].

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