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# Comparative study of proton and positive kaon interactions with carbon: hint of new physics like partial restoration of chiral symmetry in nuclei

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**Abstract.** Concerning the scattering of $K^+$ - mesons on nuclei, the explicit discrepancy between experimental data and optical model calculations is a longstanding problem and none of the conventional medium effect corrections improves significantly the agreement with the data. In this paper the cross sections for the reactions $K^+ + ^{12}C$ at incident momenta of the kaon $P_{lab} < 800$ MeV/c are calculated on the basis of Glauber's high-energy approximation. The noneikonal corrections, Fermi motion effect and both Pauli and dynamic short-range correlations were incorporated in the Glauber approach for nuclear collisions. The influence of all these corrections on the calculation of the cross sections for the interactions of kaon with nucleus is discussed. The full calculations is compared to available data. The corrections seem to fail in reproducing the experimental data. Our results is compared to optical model calculations. We show that both our model and optical model fails to give a satisfactory description of $K^+$-nuclei cross sections. Different attempts to remove this discrepancy with the in-medium effects taken into account are discussed.

## 1. Introduction

At present it is believe that Quantum Chromodynamics (QCD) is the most probable candidate for the fundamental theory of strong interactions. This theory have asymptotic freedom which accounts for the observed scaling behavior of strong interactions at high energies. However, the properties of hadrons at low energies are dominated by the long-distance regime of QCD, where the perturbation theory breaks down. The most important of these properties is confinement, i.e., no free quarks have been seen. But QCD predicts that quarks can be partially deconfined at high nuclear density (which may be achieved in high energy nuclei-nuclei collisions). Moreover, it has been shown by J.S. Brossky that many of the key issues in understanding quantum chromodynamics involve processes in nuclear targets at intermediate energie [1]. In addition, measurement probing nuclei in deep-inelastic scattering at high momentum transfer indicates that quark structure of free nucleons differs from that of nucleons in the nuclei (EMC effect). It is interesting to study possible signals of such effects not only in the extreme but also in usual conditions, e.g., in the intermediate energy (IE) region of interaction, E<1 GeV [2, 3].

The investigation of nuclear reactions at IE is considered as a central subject in nuclear physics. Strong evidence concerning the modification of nucleon properties in a nuclear medium (in-medium effects) has been reported from the proton electromagnetic form factors measured in polarized $(\vec{e}, e'p)$ scattering on $^{16}$O and $^{4}$He at MAMI and Jefferson Lab [4, 5].

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## 2. Glauber model of high-energy scattering

We have used the Glauber model because it is applied successfully in analyzing a large number of peculiarities of different nuclear reactions [6, 7, 8]. The breakdown of conventional Glauber model prediction (which might be a hint of new physics) has become a focus of theoretical interest [9, 10, 11].

For clarity, we recall that, following Glauber [6], the amplitude for a projectile-target elastic scattering assumes the general form as the lowest order eikonal approximation

$$f(q) = \frac{ik}{2\pi}\int e^{i\vec{q}\cdot\vec{b}}\left[1 - e^{i\chi(\vec{b})}\right]d\vec{b}, \tag{1}$$

where $\vec{b}$ is the impact parameter, and $\chi$ is the corresponding phase shift function,

$$f(\vec{q}) = \frac{ik}{2\pi}\int e^{i\vec{q}\cdot\vec{b}}\Gamma(\vec{b})d\vec{b},\ \text{with}\ \Gamma(\vec{b}) = 1 - e^{i\chi(\vec{b})} = \frac{1}{2\pi ik}\int e^{-i\vec{q}\cdot\vec{b}}f(\vec{q})d\vec{q},\ \text{and} \tag{2}$$

$$f(q) = \frac{k(i+\alpha)\sigma}{4\pi}e^{-\beta^2q^2/2}, \alpha = Ref(0)/Imf(0). \tag{3}$$

With our normalization, the optical theorem becomes $\sigma_t = \frac{4\pi}{k}\mathrm{Im}f(0)$.

For projectile-nucleus scattering Eq.(1) in the Glauber model can be recorded into the form:

$$F(Q) = \frac{ik}{2\pi}\int e^{i\vec{Q}\cdot\vec{b}} < [1 - e^{i\chi(\vec{b},\vec{s}_1,\cdots,\vec{s}_A)}] > d\vec{b}, \tag{4}$$

where $\vec{s_j}$ is the component of the radius-vector $\vec{r_j}$ of the $j^{th}$ target-nucleon in the direction perpendicular to the incident momentum $\vec{k}$, while the brackets $<\ >$ denote the target ground-state average.

The total and reaction cross sections in the eikonal model may then be approximated by

$$\sigma_t = 4\pi\int_0^\infty \mathrm{Re}[1 - e^{i\chi(b)}]bdb, \quad \sigma_r = 2\pi\int_0^\infty [1 - e^{-2\mathrm{Im}\chi(b)}]bdb. \tag{5}$$

For potential scattering the eikonal expansion has been derived by Wallace [12],

$$\chi(b) = \sum_n -\frac{\mu^{n+1}}{k(n+1)!}\left(\frac{b}{k^2}\frac{\partial}{\partial b} - \frac{\partial}{\partial k}\frac{1}{k}\right)^n \int_{-\infty}^{\infty} V^{n+1}(r)dz, \tag{6}$$

where $\mu$ is the reduced mass, and $k$ is the momentum in the c.m system ($\hbar = c = 1$). The zeroth-order term in the above expansion represents the Glauber eikonal phase shift function while the higher-order terms correspond to the noneikonal effects. In this work we truncate the tedious expansion of eqs. (6) and include in our calculations till the the second-order noneikonal corrections.

For local potentials the first and second order corrections are given, respectively, by

$$\chi_1(b) = -\frac{\mu^2}{2k^3}\left(1 + b\frac{\partial}{\partial b}\right)\int_{-\infty}^{\infty} V^2(r)dz, \quad \chi_2(b) = -\frac{\mu^3}{6k^5}\left(3 + 5b\frac{\partial}{\partial b} + b^2\frac{\partial^2}{\partial b^2}\right)\int_{-\infty}^{\infty} V^3(r)dz. \tag{7}$$

The zero order term in (6) gives the eikonal phase

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$$\chi_0(b) = -\frac{2\pi}{k}\int_{-\infty}^{\infty} f(0)\rho(b,z)dz, \ \ \chi_0(b) = -\frac{\mu}{k}\int_{-\infty}^{\infty} V(b,z)dz, \ \ V(r) = \frac{2\pi}{\mu}f(0)\rho(r), \tag{8}$$

where f(0) is the elementary forward scattering amplitude, $\rho(r)$ is the corresponding nuclear density. The elementary scattering amplitudes for K-nucleon scattering were taken from Martin phase shifts analysis [13].

In our calculations we have used (in a usual way) harmonic oscillator wave functions to obtain the carbon density with the parameters of Ref. [8]:

$$\rho(r) = (\alpha+\beta r^2)\exp(-\gamma r^2), \ \ \alpha = \frac{4}{R^3\pi^{1.5}}, \ \ \beta = \frac{2(A-4)}{3\pi^{1.5}R^5}, \ \ \gamma = \frac{1}{R^2}, \ \ R^2 = 2.5fm^2 \tag{9}$$

Correlation effects have also been incorporated into the Glauber approach [14]. These will lead to the correction $\chi_{corr}$ in the nuclear phase, which can be given by,

$$i\chi(\mathbf{b})_{corr} = \frac{(A-1)^2}{2}\int d\mathbf{r}_1 d\mathbf{r}_2 \rho(\mathbf{r}_1)\rho(\mathbf{r}_2)\gamma(\mathbf{b}-\mathbf{b}_1)\gamma(\mathbf{b}-\mathbf{b}_2)g(\mathbf{r}_1,\mathbf{r}_2) \tag{10}$$

where $g(\mathbf{r}_1,\mathbf{r}_2)$ is a two–body correlation function, whereas the profile function $\gamma(b)$ is given in terms of the projectile target–nucleon amplitude [14]. It has been shown, that $g(\mathbf{r}_1,\mathbf{r}_2)$ is a sum of contributions due to the Pauli correlations $g_p$ and short–range dynamic correlations $g_s$. Both the functions $g_p$ and $g_s$ can be well approximated [14] by

$$g_p = g_1 e^{-a_1|\mathbf{r}_1-\mathbf{r}_2|^2}, \qquad g_s = g_2 e^{-a_2|\mathbf{r}_1-\mathbf{r}_2|^2} \tag{11}$$

where the parameters $g_1$, $g_2$, $a_1$, $a_2$ are given in [15].

The Fermi motion in nuclei was included in our model since the nucleon motion is crucial for the particle production in backward semisphere, the Cronin effect etc. The fact that Fermi motion is important induced us to include his in our calculations by an more accurate method. In contrast with diferent analytical approximations used in others Refs. (see, e.g., [16]) we utilized Monte Carlo statistical modulation of interactions of kaons in nuclei. The internal momentum distribution in nuclei was approximated by

$$\rho(p) = \frac{A}{\alpha^3}exp\Big(-\frac{p^2}{2\alpha^2}\Big) + \frac{B}{\beta^3}exp\Big(-\frac{p^2}{2\beta^2}\Big) \tag{12}$$

where the parameter $\alpha$ is related to the nuclear Fermi momentum and $\beta$ corresponds to the high momentum component. The parameters were obtained from the analysis of the experimental data on backward proton production in pA and AA collisions [17]. It was found that for the carbon target the inclusive distribution of the protons is described by the function (12) with the parameters (Y = 75 MeV/c , p = 190 MeV/c , B/A = 0.06.

## 3. Results of calculation and summary

The total cross section is the most fundamental characteristic of nuclear reaction. The $K^+$-meson has a long mean fee path and can penetrate into the interior of a nucleus, thus probing the nucleus in a region where the density is high. (Other hadrons can probe only nuclear surface.) Total cross section measurements of $K^+$-nuclei interaction show a significant discrepancy when compared to theory of the optical potential model [2, 3]. We used Glauber model because she is utilised successful in analysing of different nuclear reactions. In the framework of our Glauber

Monte Carlo model, we calculated cross sections of $K^+$ and proton interactions with nuclei (see Table 1).

Table 1. $K^+$ - $^{12}C$ and P - $^{12}C$ total cross-sections in mb. In column "Theory" is demonstrated results of this work. Here, the column G denotes the results on conventional Glauber model, the column GF denotes the results as in column G including Fermi motion, column GF+CO denotes the results as in column GF including corelations, column GF+CO+NE denotes the results as in column GF+CO including noneikonal corrections. In parenthesis is shown experimental data [18, 19]. For comparison, we represent the optical models results of Ref. [20].

| $P_{lab}$ (GeV/c) | Theory $\sigma_{tot}$(mb) | | | | Relativistic optical potential model |
|---|---|---|---|---|---|
| | G | GF | GF+CO | GF+CO+NE | |
| 0.488 ($K^+$ - $^{12}C$) | 155.98 | 156.72 | 152.05 | 152.78 | 137.8 (165.60±1.40) |
| 0.531 ($K^+$ - $^{12}C$) | 157.36 | 158.10 | 153.44 | 154.18 | 140.5 (169.16±1.05) |
| 0.656 ($K^+$ - $^{12}C$) | 157.11 | 158.00 | 153.82 | 154.71 | 146.9 (176.09±0.62) |
| 0.714 ($K^+$ - $^{12}C$) | 156.96 | 158.11 | 154.71 | 155.86 | 148.8 (178.66±0.57) |
| 1.000 (P - $^{12}C$) | 365.74 | 367.08 | 363.88 | 365.23 | (370±9) |

As can be seen from Table 1. our approach for $K^+$ - $^{12}C$ intraction gives the results more close to the experiment. Nevertheless, a universal discrepancy is observed between predictions of our model and data. In conclusion, our model describes well the data on the scattering of proton with carbon [8, 19] as well demonstrate the opportunity of observing some unusual phenomena in $K^+$-nucleus interaction (e.g. partial restoration of chiral symmetry in ground state nuclei) [1, 2, 3, 21, 22].

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