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исследований
дубна

E2-94-412

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PROBING THE IN-MEDIUM EFFECT IN KAON-NUCLEUS INTERACTION

Submitted to «Journal of Physics G»

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1994

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Исследование внутриядерных эффектов в каон-ядерном взаимодействии

В настоящее время широко обсуждается противоречие между отношением R, $R = \sigma (K^{+12}C) / 6\sigma (K^{+}d)$ измеренных сечений и рассчитанным по оптической модели. Это противоречие интерпретируется многими авторами как возможный сигнал новых внутриядерных эффектов в мягких ядерных реакциях при промежуточных энергиях (например, частичного деконфайнмента нуклонов в ядрах). Для новой более реалистичной оценки роли внутриядерного эффекта мы произвели расчеты по модели многократного рассеяния Глаубера. Результаты показывают, что рассмотренная модель хорошо описывает взаимодействие K^{-}-мезонов с углеродом, однако противоречит данным по взаимодействию K^{+}-мезонов. Таким образом, наши результаты подтверждают выводы других авторов, полученные в оптической модели, о проявлении внутриядерных эффектов в K-ядерных взаимодействиях при промежуточных энергиях (типа EMC).

Работа выполнена в Лаборатории теоретической физики им. Н.Н.Боголюбова ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна, 1994

Eliseev S.M., Hanna K.M. E2-94-412

Probing the in-Medium Effect in Kaon-Nucleus Interaction

The discrepancy between the experimental and the theoretical ratio R of the total cross sections, $R = \sigma (K^{+12}C) / 6\sigma (K^{+}d)$, is intensively discussed. It is interpreted as a possible signal of partial deconfinement of the nucleons in nuclei in soft nuclear reactions at intermediate energies. More realistic predictions for nuclear in-medium effects were evaluated in the framework of Glauber multiple scattering theory. Results show that a more microscopical theory rather than the old optical model, on the one hand, is suitable for describing the interaction of K^{-}-meson with carbon nucleus while, on the other hand, led to the disagreement with data for K^{+}-meson. This conclusion may be taken seriously into account as a new EMC-type effect.

The investigation has been performed at the Bogoliubov Laboratory of Theoretical Physics, JINR.

Preprint of the Joint Institute for Nuclear Research. Dubna, 1994

1. Introduction

Long time ago, and so far, the interaction of intermediate and high energy particles with nuclei considers as one of the central subjects in nuclear physics. A considerable amount of experimental data for the scattering of different strongly interacting particles from different targets at these energies have been accumulated. Theories, both phenomenological and more fundamental based on the ideas of QCD, were constructed to describe the nuclear structure and the mechanism of nuclear collisions.

From the conventional point of view of traditional nuclear physics the nucleon properties (its size, form factor, mass, magnetic moment and other internal properties) do not change either it is free or embedded in the nucleus. The success of this picture in the low energy region confirms the approximate validity of this fact.

However, some discrepancies between the calculations based on the traditional models and the experimental data measured in the interactions of different particles with nuclei at intermediate and high energies also widely discussed. These discrepancies considered as evidence for new properties of the nuclei.

Measurements in deep inelastic scattering of leptons from nuclei at high momentum transfers revealed some evidence for a break in the traditional picture. This was one of the main famous successful investigations of nuclear reactions and lead to the discovery of the EMC-effect [1] in nuclei. This effect still stimulate different theoretical explanations (see, e.g., [2,3]). On a deeper level the nucleon as a dynamic and a nonelementary entity should respond to its surroundings (see, e.g., [4]). The important questions are to what extent and how to estimate the effect of the nuclear medium.

In recent years the question of medium modification of particle properties has received so great deal of attention, that now it is possible to talk about a new direction in the study of the strong interacting matter, i. e., *"in-medium physics"*.

From an experimental point of view the probe whose strong interaction with the nucleon is relatively weak has definite advantages which express in its longer mean free path i.e., it can penetrates deeper into the nuclear interior.

The K^+ meson is a good candidate for this interaction with the nucleon since it has two important properties (both the weak energy dependence and the nature of the interaction). The total cross sections vary between 10 and 20 mb for incident momenta less than 1 GeV/c, in comparison with ≈ 40 mb for nucleon and 50-100 mb for pion-nucleon interaction in the same momentum range. The mean free path λ of K^+ in nuclear matter *vs* incident momentum P is plotted in Fig. 1.

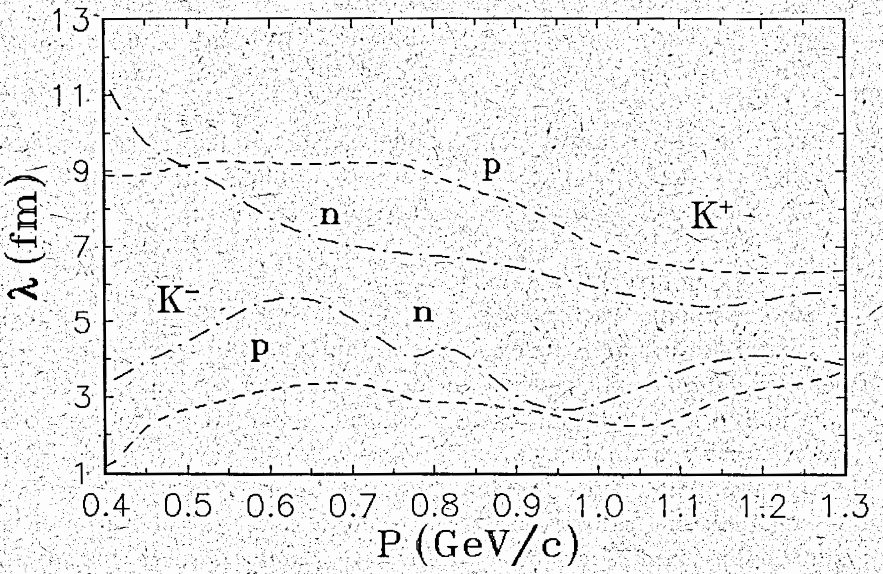

FIG. 1. Mean free path λ *vs.* momentum of K^+ and K^- mesons in protons (short-dashed line) and neutrons (dot-dashed line) nuclear matter. The cross sections of $K^\pm - p(n)$ interactions, used in our calculations, were obtained from partial wave analysis (see text).

For comparison, also it is shown the mean free path of K^- mesons. (In the calculations of mean free path the cross sections of kaon-nucleons interactions were taken from partial wave analysis, see below).

Figure 1 indicates that K^+ meson indeed capable to penetrate in the depth of the nucleus and probing entirely its volume. The K^- meson, as other hadrons, interacts with nuclei more peripheraly and can't be used to sound their inner structure.

For probes with more large cross sections like pions or protons, the mean free path becomes less or comparable to the nuclear radius and the interaction, physically, will be almost surface dominated in character. Then the increase in the projectile-nucleon interaction would expect to produce a small percentage change in the projectile-nucleus cross section.

As a matter of fact, and surprisingly, the theoretical calculations for the ratio R of the total cross section $\sigma(K^+C^{12})$ compared to $6\sigma(K^+d)$ where the deuteron d serves as a convenient isospin averaged " free " nucleon target, lie below the experimental data by about 2.5-3 standard deviations throughout the region of laboratory momentum $450MeV/c < P_L < 900MeV/c$ (moderate shadowing, i.e., $R < 1$ at least at momenta $P_L > 600MeV/c$) [5,6].

At present this discrepancy is widely discussed as a signal of unconventional phenomenon in nuclear physics in view that the standard nuclear mechanisms do not agree with the data.

The known theoretical, so far, treatments to overcome the deficit mainly can be classified into three main categories; the *swelling* models [6,7], pion-based models [8,9] and meson exchange models [10-12]. The basic idea in *swelling* models is the assumption that an increase in the nucleon radius by 10 % produces a (5-10) % increase in theS_{11}-wave phase shift [6].

Another proposal in the frame of these models concerns a modification in the meson clouds around the nucleons [7]. These authors found that a density-dependent decrease in the vector meson masses leads to an increase in the repulsion of the kaon and hence an increase in the cross section. It is noted that both of these proposals are belonging to the same physical concept of *swelling* in nuclear environment and the improvements mainly are similar in giving an increase in the ratio R over the whole considered range of incident momentum.

Several pion-based models have been suggested to explain the data by properly taking into account the pionic degrees of freedom in nuclei and an increase in K^+N cross sections over that in free space by $\approx$ 10-30 % [8,9].

It has been found that "pion softing" in which the effective pion mass decreases in the nucleus, accounts for many effects associated with the nuclear medium. Moreover, the results derived from the meson exchange models for the K^+-nucleon interaction which are constructed along the same guidelines of the Bonn model [13] for the NN interaction turned out to be still further improved, and led to a reasonable overall description of the data for lower energies ($P_L \leq 1$ GeV/c).

In addition, the meson exchange current (MEC) model given in [12] also gave some calculable real improvement, with some uncertainties, with the data. Both of these approaches are a good starting point to isolate possible discrepancies and to trace them back to genuine quark-gluon effects.

Since until now there is no performed calculations for the ratio R, based on Glauber theory, to be compared with the experimental one [14], it is our aim to test the validity of this theory for the interaction of K^+ and K^- mesons with carbon nucleus.

2. Glauber model analysis

Although Glauber theory was developed firstly for high energy [15], it works also successfully in the intermediate energy region [16,17].

In the Glauber multiple scattering theory the eikonal impact-parameter approximation for hadron-hadron and hadron-nucleus amplitudes was used.

The inclusion of noneikonal effects (i.e., the deviation from the eikonal straight-line propagation picture) as well as Coulomb interaction will be little change our results.

Let us assume that the elastic scattering amplitudes has either the form

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

or

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

where the profile function $\Gamma(\vec{b})$ is defined as,

$$\Gamma(\vec{b}) = 1 - e^{i\chi(\vec{b})}, \tag{3}$$

and χ is the phase shift function or the eikonal. In the formulae (1,2) $\vec{q}$ is the momentum transfer, $\vec{b}$ - impact vector which lie in the plane perpendicular to the incident momentum $\vec{k}$ and the integration is performed over a plane perpendicular to $\vec{k}$.

The basic dynamical assumption of the Glauber theory is that the phase shift of the incident wave after it passed through the nucleus is equal to the sum of the phase shifts of the individual nucleons [15],

$$\chi(\vec{b}, \vec{s}_1, \cdots, \vec{s}_A) = \sum_{j=1}^{A} \chi_j(\vec{b} - \vec{s}_j), \tag{4}$$

then the nuclear profile function gets the form

$$\Gamma(\vec{b}, \vec{s}_1, \cdots, \vec{s}_A) = 1 - \prod_{j=1}^{A}\left[1 - \Gamma_j(\vec{b} - \vec{s}_j)\right]$$

$$= \sum_{j=1}^{A}\Gamma_j(\vec{b} - \vec{s}_j) - \sum_{j\neq n}\Gamma_j\Gamma_n + \sum \Gamma\Gamma\Gamma - \cdots, \tag{5}$$

where $\vec{s_j}$ are the components of the radius-vectors $\vec{r_j}$ of intranuclear nucleons in the direction perpendicular to the incident momentum $\vec{k}$. The alternation of the signs before the sums in Eq. (5) is essentially worth noting [13]. Eqs. (4) and (5) play a fundamental role in the Glauber multiple scattering theory. The hadron-nucleus scattering amplitude then becomes

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

$$= \frac{ik}{2\pi}\int e^{i\vec{Q}\cdot\vec{b}}\Gamma(\vec{b}, \vec{s}_1, \cdots, \vec{s}_A) d\vec{b}. \tag{6}$$

In Glauber theory there is another basic approximation: the hadron traverses the nucleus in such a short time that the nucleons cannot rearrange themselves until the projectile has left the nucleus. This mean that we can calculate the amplitude as if the target nucleons are "frozen". The amplitude calculated by averaging over the nucleons distribution applying the nuclear wave functions ψ_i and ψ_f takes the form [15,16],

$$F_{fi}(\vec{Q}) = \frac{ik}{2\pi}\int e^{i\vec{Q}\cdot\vec{b}}d\vec{b}\int \psi_f^*(\vec{r}_1,\cdots,\vec{r}_A)\Gamma(\vec{b},\vec{s}_1,\cdots,\vec{s}_A)$$

$$\psi_i(\vec{r}_1,\cdots,\vec{r}_A)\delta\left(A^{-1}\sum_{j=1}^{A} r_j\right)\prod_{j=1}^{A} d\vec{r}_j. \tag{7}$$

Therefore, we can express the hadron-nucleus scattering amplitude F with no free parameters, given the hadron-nucleon amplitudes f_j, in the form,

$$F_{fi}(\vec{Q}) = \frac{ik}{2\pi}\int e^{i\vec{Q}\cdot\vec{b}}d\vec{b}\int \psi_f^*(\vec{r}_1,\cdots,\vec{r}_A)\left\{1-\prod_{j=1}^{A}\left[1-\frac{1}{2\pi ik}\int e^{-i\vec{q}_j\cdot(\vec{b}-\vec{s}_j)}\right.\right.$$

$$\left.\left.\times f_j(q_j)d\vec{q}_j\right]\right\}\psi_i(\vec{r}_1,\cdots,\vec{r}_A)\delta\left(A^{-1}\sum_{j=1}^{A} r_j\right)\prod_{j=1}^{A} d\vec{r}_j. \tag{8}$$

Here ψ_i, ψ_f are the wave functions of the initial and the final states of the nucleus and $\vec{Q}$ is the momentum transfer in the hadron-nucleus interaction. The δ-function ensures the conservation of total angular momentum of the system [16].

For elastic scattering, we need only the density distribution of the ground state of the nucleus,

$$\rho(\vec{r}_1,\cdots,\vec{r}_A) = \psi_G^*(\vec{r}_1,\cdots,\vec{r}_A)\psi_G(\vec{r}_1,\cdots,\vec{r}_A) \tag{9}$$

We assume that the protons and the neutrons inside the nucleus are all uncorrelated, so the density function factorizes to the product of A terms,

$$\rho(\vec{r}_1,\cdots,\vec{r}_A) = \rho(\vec{r}_1)\times\cdots\times\rho(\vec{r}_A) \tag{10}$$

Using Eqs.(9,10) and removing, by the help of Gartenhaus and Schwartz transformation [18] the δ-function, Eq.(8) gets the form,

$$F_{ii}(\vec{Q}) = \frac{ikG(Q)}{2\pi}\int e^{i\vec{Q}\cdot\vec{b}}d\vec{b}\left\{1-\left[1-\frac{1}{2\pi ik}\int e^{-i\vec{q}\cdot\vec{b}}f_p(q)S_p(q)d\vec{q}\right]^Z\right.$$

$$\left.\times\left[1-\frac{1}{2\pi ik}\int e^{-i\vec{q}\cdot\vec{b}}f_n(q)S_n(q)d\vec{q}\right]^N\right\}, \tag{11}$$

where $G(Q)$-Gartenhaus-Schwartz factor, $G(0) = 1$ [18] and the form factors S are defined as follows,

$$S_{p,n}(q) = \int_0^\infty \rho_{p,n}(r)e^{i\vec{q}\cdot\vec{r}}dr, \qquad \int \rho_{p,n}(r)d\vec{r} = 1 \tag{12}$$

If we assume that the nucleus is spherical then the integration will be carried only over the impact parameter b, so the amplitude gets the form,

$$F_{ii}(Q) = ikG(Q)\int bdbJ_0(Qb)\left\{1-\left[1-\frac{1}{2\pi ik}\int e^{-i\vec{q}\cdot\vec{b}}f_p(q)S_p(q)d\vec{q}\right]^Z\right.$$

$$\left.\times\left[1-\frac{1}{2\pi ik}\int e^{-i\vec{q}\cdot\vec{b}}f_n(q)S_n(q)d\vec{q}\right]^N\right\}. \tag{13}$$

For the wave functions of carbon we have used harmonic oscillator wave functions with 4 nucleons in s-and 8 in p- states with parameters from Refs. [16,17] where is taken properly into account the nucleon size. Then the density function ρ becomes,

$$\rho(\vec{r}_1,\cdots,\vec{r}_A) = \prod_{j=1}^{4}\rho_s(\vec{r}_j)\prod_{j=5}^{A}\rho_p(\vec{r}_j), \tag{14}$$

where s- and p- waves densities were calculated by use of the harmonic oscillator wave functions,

$$\rho_s(\vec{r}) = (\alpha^2/\pi)^{3/2} e^{-\alpha^2 r^2}, \qquad (15)$$

$$\rho_p(\vec{r}) = (2\alpha^5/3\pi^{3/2}) r^2 e^{-\alpha^2 r^2}. \qquad (16)$$

We have also used the phenomenological symmetrized Fermi function,

$$\rho_{sym}(r) = \rho_0 \frac{\sinh(R/B)}{\cosh(R/B) + \cosh(r/B)}, \qquad (17)$$

which has some important properties and simplify calculations because it leads to analytical expression for form factors,

$$S_{sym}(q) = -\frac{4\pi^2 BR\rho_0}{q \sinh \pi Bq} \left(\cosh qR - \frac{\pi B}{R} \sinh qR \coth \pi Bq \right). \qquad (18)$$

The parameters α, R and B describing experimental elastic electron form factors were used from [19].

The elementary scattering amplitude was parametrized as in other Glauber theory calculations,

$$f(q) = \frac{k(i+\gamma)\sigma}{4\pi} e^{-\beta^2 q^2/2}, \gamma = \Re e f(0)/\Im m f(0). \qquad (19)$$

The parameters σ, β, and γ of $K^{\pm} - p(n)$ amplitudes at different energies were taken from partial wave analysis and dispersion relations calculation [20-24].

3. Results, Discussion and Conclusion

To verify our approach, firstly we have calculated the total cross sections of K^--carbon interaction where, as expected, the theory agrees with data.

Figure 2 illustrates comparison of our results with experiment [14,25] at incident momenta 0.6-2.6 GeV/c and shows very encouraging agreement between the theory and the measured cross sections. A remarkably good description of the K^--carbon data makes us hope that the considered approach can be applied for investigating the peculiarities of other nuclear reactions of such type using K^+ meson as projectile.

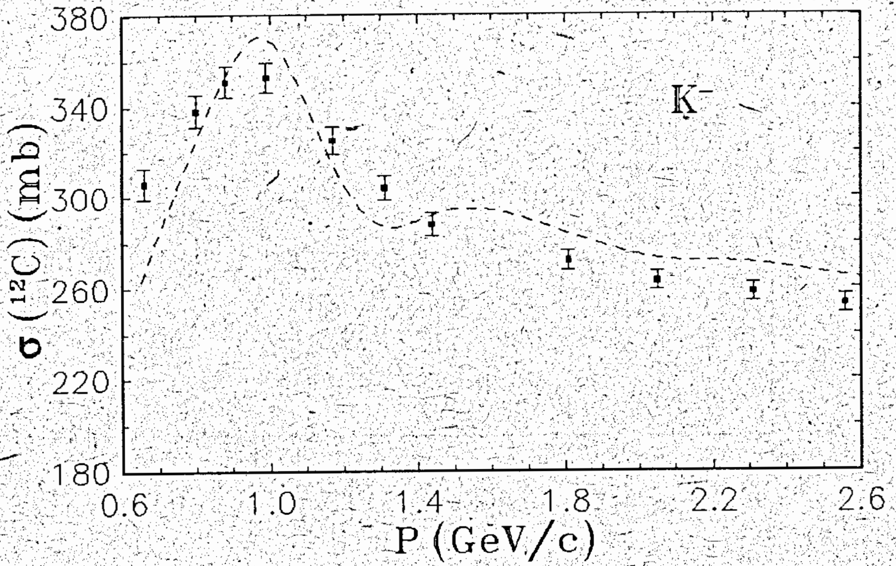

FIG. 2. Comparison between experimental cross sections, Refs. [14,25], and as calculated in the Glauber model (short-dashed line) *vs.* kaon momentum.

Towards this aim and to give a more realistic evaluation for the role of the nuclear medium effects in the discrepancy which was found in the K^+-nucleus scattering we performed calculations for the above mentioned ratio R in the framework of the multiple scattering theory of Glauber which considers a more microscopical theory than the old optical model calculations. The result of this calculations is shown by a short-dashed line in Fig. 3. It is evident, that a serious disagreement with the data was received.

Figs. 2,3 show that a more refined theory, on the one hand, is suitable for K^--meson interactions but, on the other hand, has led to the disagreement with data for the K^+-meson.

May we add that the unconventional medium phenomena in nuclear physics, e.g., partial deconfinement, nucleon swelling, EMC-effect, ... so far were discussed only in reactions with large momentum transfer, while the scattering process discussed in the present work ($K^+ -^{12}C$) is a soft intermediate energy interaction.

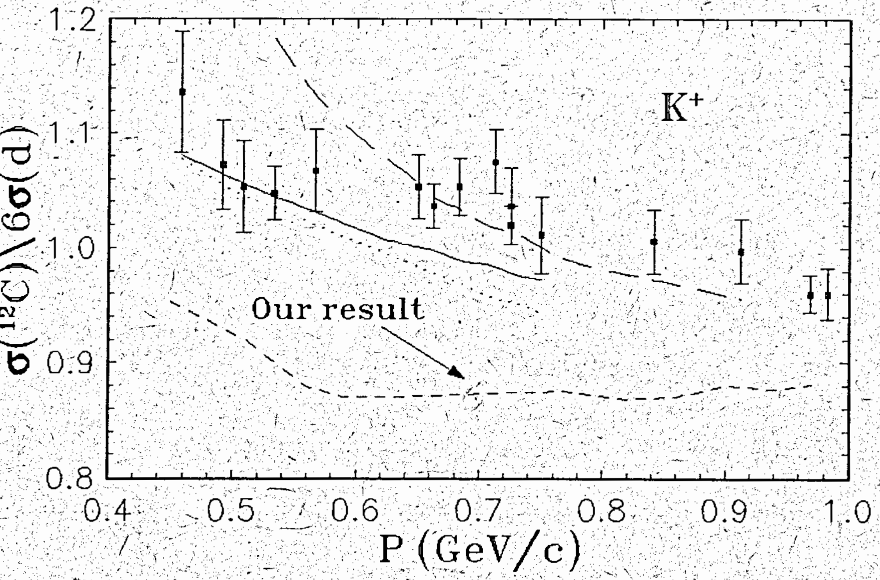

FIG. 3. The ratio of K^+-^{12}C and K^+-deuteron total cross sections. Data from [14,25]; short-dashed line - this work; dotted line - optical model calculation of Ref. 6; solid line - MEC model, Ref. 12; long-dashed line - *swelling models* [7].

In fact the discrepancy between the experimental total cross sections ratio R and the predicted one in $K^+ -^{12}C$ scattering, at momenta less than 1 GeV/c, attracts much attention as one of these unconventional EMC-type problems. So far, all the theoretical attempts to overcome the deficit using "conventional" nuclear corrections [6] were led to lower this ratio in the opposite direction of the experimental data. We mean by "conventional" such corrections, e.g., Pauli blocking, nucleon binding, virtual excitations, nucleon-nucleon correlations, *etc.*

Our main conclusion is summarized in the following: our calculations based on a more refined and microscopical multiple scattering theory of Glauber which, on the one hand, was suitable for describing

the experimental data for the scattering of K^--^{12}C but has led, on the other hand, to the disagreement with data for the K^+-meson case. This fact should be taken seriously into account. Moreover, these calculations give a more realistic evaluation for the possible nuclear medium effects. In addition, our results, the previous calculations performed in the framework of the old optical model and also the suggestions of the authors [6-9,12,26] show the possibility of observing some unconventional EMC-type phenomena in K^+-nucleus interaction.

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Received by Publishing Department
on October 25, 1994.