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S.M.Eliseev, T.H.Rihan*

ON THE POSSIBILITY OF OBSERVING SOME UNUSUAL PROPERTIES OF NUCLEI BY USING KAONS AS PROBES

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*Mathematics and Theoretical Physics Department,
Atomic Energy Authority, P.O. Code 13759, Cairo, Egypt

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1. Introduction

The interaction of intermediate and high energy particles with nuclei is considered as a central subject in contemporary nuclear physics. A considerable amount of experimental data for different strongly (as well as weakly) interacting particles with nuclei at those energies has been accumulated.

Many years ago, experiment and theory focused mainly on qualitative peculiarities of reaction mechanisms. Only after the experiments with 1 GeV proton beams (with a high resolution) [1], the new trends in nuclear structure investigations started to develop. Traditional mechanisms of nuclear reactions based on the idea that the nucleus is a simple collection of protons and neutrons was predominantly used for interpreting of the new data (see, e.g.,[2-4]) . From the point of view of traditional nuclear physics, the properties of a nucleon (its size, form factor, mass, magnetic moment and other internal properties) do not change from those of its free state when it is embedded into the nucleus. Success of some calculations in the low-energy region confirms the approximate validity of this picture.

However, some discrepancies between calculations of that sort and the new more sophisticated experimental data on interactions of different particles with nuclei at intermediate and high energies have been observed recently [5-12]. Those discrepancies are being currently interpreted as evidence for new properties of the nuclear medium. After the prediction and observation of cumulative processes [13,14] and the discovery of the EMC-effect [15,16], a new epoch started in the theory of nuclear reactions based on the ideas of QCD and the quark structure of nucleons and nuclei (see, e.g., review [17]).

Indeed, one of the most important subjects discussed at present, is the problem of quark confinement in hadrons and the difficulties connected with the long distances in QCD. From QCD we know that when matter is sufficiently dense, which may be obtained in high energy nucleus-nucleus collisions, color screening will lead to quark deconfinement. However, the EMC effect indicates that nucleons can significantly change their properties even in the ground state of nuclei. At present, inclusion of such unconventional EMC-type effects draw greater attention in nuclear physics.

To explore the nuclear interior, the K^+-meson was then regarded as a unique probe due to its long mean free path in the nuclear medium.

Theoretical predictions for the total cross-section based on the above conventional nuclear physics approaceches failed to reproduce the experimental data. This situation triggered the search for the role played by the medium in modifying hadronic properties. Thus, exotic mechanisms to describe the K^+ data such as nucleon *swelling* (or partial deconfinement of nucleons) [10], in-medium modification of meson properties [11], and excess of pions in nuclei [12] are still the source of considerable debate.

On the other hand, recent calculations [18] have revealed that the nucleon *swelling* in nuclear matter seems to be much less than that reported in previous works and even than that needed to explain the EMC data. We believe, a careful analysis should be performed before any conclusion can be drawn as to the necessity of introducing features that are not present in the standard nonrelativistic models. Since the Glauber multiple scattering theory [19] has been applied very successfully for various hadronic probes at intermediate energies [2-4], it may be of interest to try to apply it for the above case of K^+ scattering, as well (as no such calculations have been performed yet). We also extend such calculations by taking into account noneikonal effects as well as relativistic K^+-nucleon amplitudes. Thus far, our work serves largely to confirm other approaches based on various optical model potentials [7,8] and necessity to introduce exotic mechanisms.

2. Glauber model analysis

Although the Glauber theory was developed initially for high energy projectiles, yet it also works successfully in the intermediate-energy region. In the present work, however, we shall include as well the so-called noneikonal effects (i.e. the deviation from a simple eikonal propagation picture) into our calculations.

For the sake of clarity, we recall that following Glauber [19] the amplitude for a projectile-target elastic scattering, assumes the general form:

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

where b is the impact parameter and χ is the corresponding phase shift function.

More explicitly, for projectile-nucleus scattering Eq.(1) can be cast into the form:

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

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.

Further, given the corresponding projectile-target nucleon amplitudes,

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

where σ is the projectile-target nucleon total cross section, one can express the above projectile-target nucleus amplitude in the following parameter-free way:

$$F(Q) = ikG(Q) \int bdbJ_0(Qb) \times \left\{ 1 - \left[1 - \frac{1}{2\pi ik} \int e^{-i\vec{q}\cdot\vec{b}} f_p(q) S_p(q) d\vec{q}\right]^Z \right.$$
$$\left. \times \left[1 - \frac{1}{2\pi ik} \int e^{-i\vec{q}\cdot\vec{b}} f_n(q) S_n(q) d\vec{q}\right]^N \right\}, \tag{4}$$

here $S(q)$ is the nuclear form factor, N, Z are the numbers of neutrons and protons in the target nucleus, while $G(Q)$ is the corresponding c.m. correlation factor. Since in the present work we are interested in total cross sections, we should only calculate $F(Q)$ at $Q = 0$, and in this case $G(0) = 1$. It is then a straightforward matter to determine the total cross section for the case of K^+-target nucleus scattering according to the optical theorem. In the above equations, the parameters σ, β, and ϵ of $K^+ - N$ amplitudes at different energies will be taken from the data (see [20]) while in this work we adopt the Martin phase shifts [21] for the elementary amplitudes f(utilizing relativistic kinematics), which give very reliable results up to momenta 1 GeV/c [22]. For this purpose, we elaborated a special code for the calculation of $K^+ - N$ partial wave amplitudes (S, P, D and F states) with the corresponding isospins ($I = 0$, $I = 1$).

Having thus the amplitudes $f(I)$ for isospins $I = 0$ and $I = 1$ we can readly find the K^+ - proton amplitude ,

$$f(K^+p \to K^+p) = f(I=1), \tag{5}$$

as well as the K^+ - neutron amplitude,

$$f(K^+n \to K^+n) = \frac{1}{2}\Big[f(I=0) + f(I=1)\Big]. \tag{6}$$

For $N = Z$ nuclei (carbon and calcium) we adopted the following average $K^+ - N$ amplitude

$$f(\bar{K}^+N) = \frac{1}{2}\Big[f(K^+p) + f(K^+n)\Big]. \tag{7}$$

In a previous work [20] we have calculated the total cross sections directly from Eq.(4). We have found, however, that the same result is almost obtained with even simpler (optical-limit) form:

$$\sigma_{K+A} = 4\pi \int_0^\infty Re[1 - e^{i\chi(b)}]bdb, \tag{8}$$

where $\chi(b)$ is the nuclear phase shift function. Further, to relate the above formulation to the usual semiclassical aproaches, it is generally accepted to consider the Glauber phase shift function as the lowest order eikonal approximation of an equivalent optical model potential. For scattering in the case when the potential is spherically symmetric, an eikonal expansion has been given in a compact form by Wallace *et al.* [23] and by Waxman *et al.* [24], as follows:

$$\chi(b) = \sum_n \frac{\mu^{n+1}}{k(n+1)!}\left(\frac{b}{k^2}\frac{\partial}{\partial b} - \frac{\partial}{\partial k}\frac{1}{k}\right)^n \int_{-\infty}^{\infty} V^{n+1}(r)dz. \tag{9}$$

The zeroth order term in this expansion $\chi(b)_0$ is simply the Glauber eikonal phase, while the corrections $\chi(b)_{noneik}$ give rise to noneikonal effects. Thus, for our phase shift function $\chi(b)$ we adopted the Glauber eikonal approximation $\chi(b)_0$ as well as the first, $\chi(b)_1$, and second, $\chi(b)_2$, order noneikonal correction to this approximation, i.e.

$$\chi(b) = \chi(b)_0 + \chi(b)_{noneik}, \quad \chi(b)_{noneik} = \chi(b)_1 + \chi(b)_2, \tag{10}$$

$$\chi_0(b) = \frac{\mu}{k}\int_{-\infty}^{\infty} V(r)dz, \quad V(r) = \frac{2\pi ki}{\mu}f(0)\rho(r), \tag{11}$$

where $f(0)$ is the elementary forward scattering amplitude and $\rho(r)$ is the corresponding nuclear density. Further, from Eqs.(9) and (10) we have the following expression for the phase functions:

$$\chi_1(b) = -\frac{\mu^2}{2k^3}\left(1 + b\frac{\partial}{\partial b}\right)\int_{-\infty}^{\infty} V^2(r)dz, \tag{12}$$

$$\chi_2(b) = -\frac{\mu^3}{6k^5}\left(3 + 5b\frac{\partial}{\partial b} + b^2\frac{\partial^2}{\partial b^2}\right)\int_{-\infty}^{\infty} V^3(r)dz. \tag{13}$$

In our calculations we have used (in a usual way) harmonic oscillator wave functions to obtain the carbon density with the parameters of Ref. [4], where the nucleon size has been properly taken into account i.e.

$$\rho(r) = (\alpha + \beta r^2)e^{-\gamma r^2}, \quad \alpha = \frac{4}{R^3\pi^{1.5}}, \quad \beta = \frac{2(A-4)}{3\pi^{1.5}R^5}, \quad \gamma = \frac{1}{R^2}, \tag{14}$$

where $R^2 = 2.5fm^2$ [4].

For the calcium density we have used the Dalkarov-Karmanov prescription [4] based on the following decomposition of the corresponding Woods-Saxon density $\rho(r)$:

$$\rho(r) = \sum_{j=1}^{8} C_j \exp(-jr^2/r_a^2), \quad r_a = 3.8fm, \tag{15}$$

where the parameters C_j [1] were obtained by a least square fitting based on the corresponding moments of the Woods-Saxon form and the above

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[1] $C_1 = .374093E-04, C_2 = .666504E-02, C_3 = -.125795E-01, C_4 = .333870E+00, C_5 = -.116719E+01, C_6 = .162846E+01, C_7 = -.103596E+01, C_8 = .250644E+00$.

decomposition. The accuracy of our decomposition with only eight parameters C_j was better than 1% up to $r = 8fm$.

Besides that, we have also used the following phenomenological symmetrized Fermi function to describe our calcium density [25]:

$$\rho_{sF}(r) = \rho_0 \frac{\sinh(R_{sF}/B_{sF})}{\cosh(R_{sF}/B_{sF}) + \cosh(r/B_{sF})}, \qquad (16)$$

which has some important properties and considerably simplifies the calculations , since it leads to an analytical expression for the form factors. The values of the parameters R_{sF} and B_{sF} were taken from Ref. [25]. We found, that Eqs.(14,15) and (16) lead to approximately the same cross sections.

Given the harmonic oscillator density (14), the phase shift functions $\chi(b)_0$ and $\chi(b)_1$ can be cast into the following closed form:

$$\chi(b)_0 = \frac{A\sigma_{KN}}{2}(i+\epsilon)\sqrt{\frac{\pi}{\gamma}}\left[\,(\alpha + \frac{\beta}{2\gamma}) + \beta b^2\right]\exp(-\gamma b^2) \qquad (17a)$$

$$\chi(b)_1 = -\frac{\sigma^2_{KN}}{8k}(i+\epsilon)^2\sqrt{\frac{\pi}{2\gamma}}\left[\Big(\,\alpha^2 + \frac{\alpha\beta}{2\gamma} + \frac{3\beta^2}{16\gamma}\Big) + \Big(\,4\alpha\beta\right.$$

$$\left. + \frac{3\beta^2}{4\gamma} - 4\gamma\alpha^2\Big)b^2 + \Big(\,3\beta - 8\alpha\beta\gamma\Big)b^4 - 4\gamma\beta^2 b^6\right]\exp(-2\gamma b^2). \quad (17b)$$

Moreover, a careful analytical calculations of the second order correction $\chi(b)_2$ were performed with the use of the Maple system from Waterloo Maple Software. As a result, an analytical expression for $\chi(b)_2$ was obtained. The formula for $\chi(b)_2$ is more complicated than Eq. (17b) and therefore he is not shown in the present work.

2. Results and Discussion

We have calculated the total cross section for the K^+-deuteron scattering using the elementary K^+-nucleon amplitudes based on the Martin phase shifts [21]. Figure 1 represents the comparison of our calculations with data. In Fig. 2 we show the momentum dependence of the experimentally determined [5-6] ratio R and different theoretical pre-

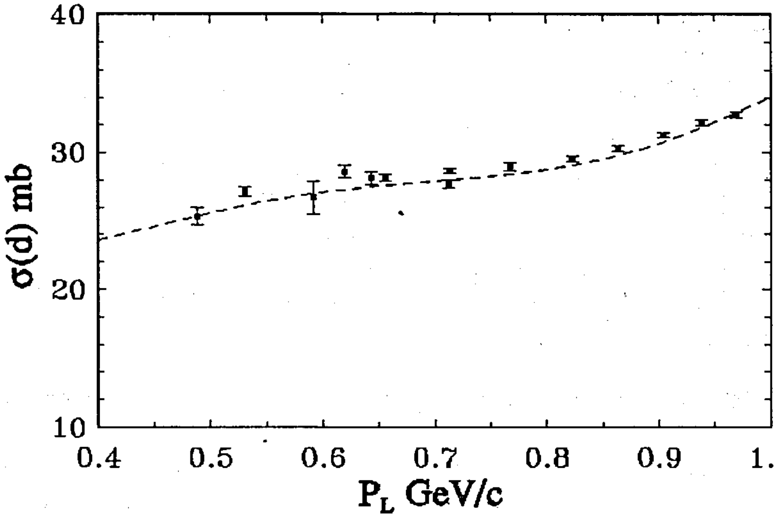

Fig. 1. Total K^+-deuteron cross section calculated as described in the text. Experimental data are taken from Ref.[26].

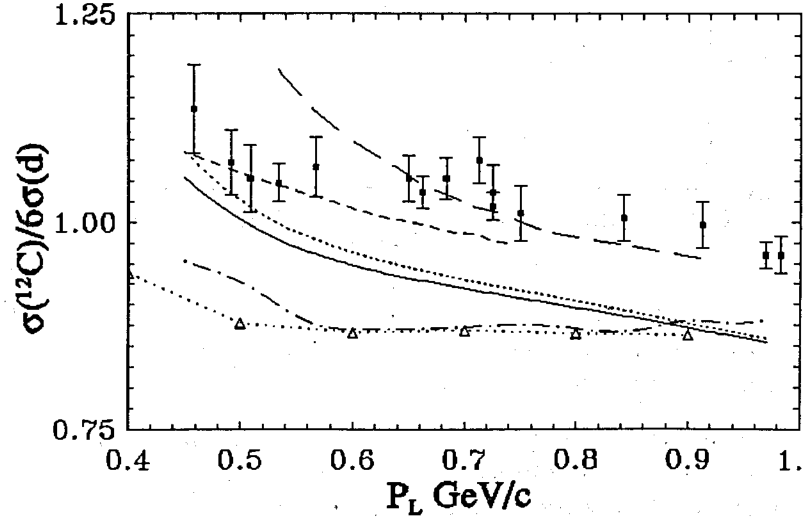

Fig. 2. Comparison of data [5,6] and different models for the ratio R (see text);dotted line - this work (eikonal approximation); solid line-this work including all noneikonal corrections; dot dash line-Glauber model from Ref. [20]; long dash line-*swelling model* [10]; short dash line-MEC model [11,12]. By triangles we show the results of the momentum-space optical model potential [26].

dictions. The dotted line represents the results of the present work obtained within the Glauber eikonal approximation (see the text).

The dot-dashed line corresponds to our previous analogous calculations [20], where for the elementary amplitudes we used the usual high-energy approximation as given by Eq.(3). It seems that there is a close agreement between the two approaches. The solid line displays our results including noneikonal corrections (see, Eq.(10)). The results of the momentum-space optical model potential of the recent work [9] (very well describing scattering of *pions* from nucleus in the same momentum interval) are represented by triangles.

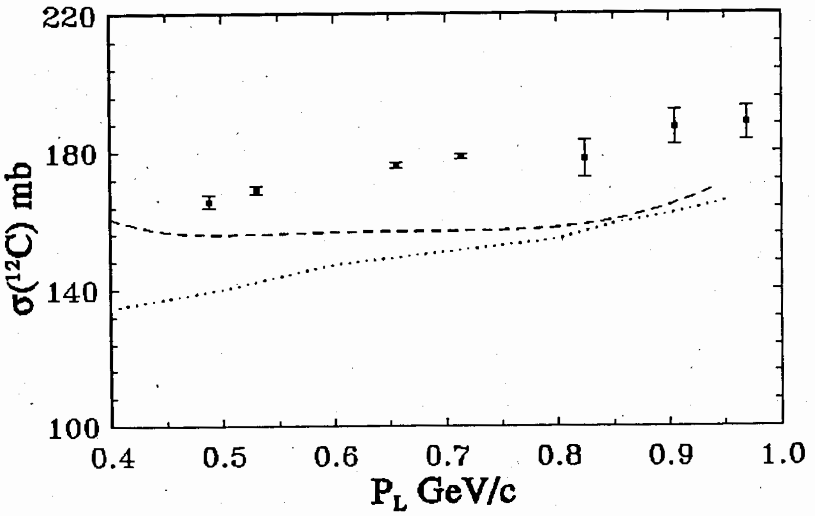

Fig. 3. Total $K^+ - {}^{12}C$ cross section: our result (dashed line), relativistic optical model of Ref.[9] (dotted line). Experimental data are taken from Ref.[26].

It is interesting to note here that the first-order noneikonal correction lowers the cross section ratios in the considered range of projectile momenta, while the second-order correction results in bringing that ratio closer to the Glauber result. This seems to be extremely interesting as those corrections are intended to improve the eikonal result bringing it closer to its exact quantum-mechanical counterpart. Thus, we feel that care should be taken when dealing with noneikonal corrections.

Figure 3 demonstrates recent experimental data [26] for the total cross section of $K^+ - {}^{12}C$ interaction together with theoretical predictions. The dashed line is the result of the present work, and the dotted line represents the results of Ref. [9].

In Fig.4, the momentum dependence of the ratio R (see the caption for Figs. 2) for calcium and deutron cross sections is also shown. The dashed line represents the results of the present work, while the dotted line is the results of Ref. [9].

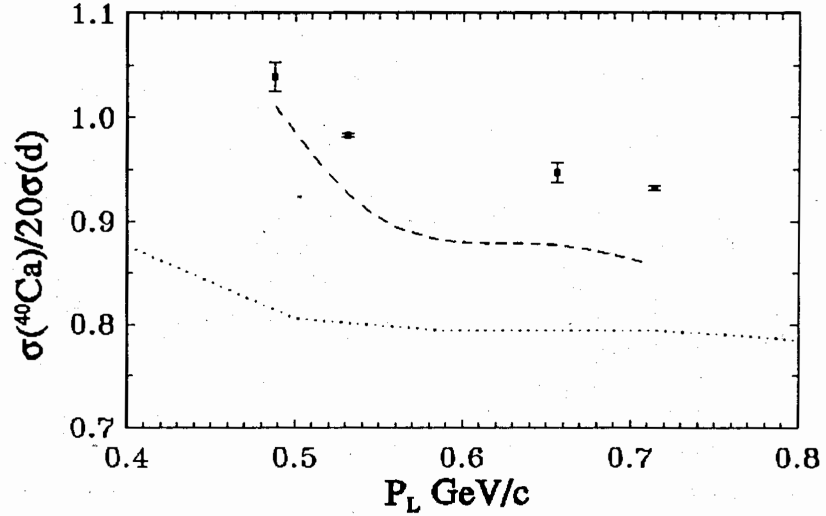

Fig. 4. Total cross-section ratio for K^+-nucleus scattering. Result of our calculations (dashed line) and relativistic optical model of Ref.[9] (dotted line). Experimental data are taken from Ref.[26].

The Table I displays the numerical values of total cross sections for K^+–nucleus scattering together with the corresponding theoretical predictions.

From figures and table I it is clear that in comparison whith recent Ref. [9] the model of the present work improves the agreement between theory and experiment. All the eikonal as well as the optical-models results fail to quantitatively reproduce the cross sections for calcium and carbon as well as the corresponding ratio R.

At the same time it should be stressed, that the model of Ref. [9] very well describes the scattering of *pions* from the same nuclei in the same momentum interval. Also, our model [20] seems to account pretty well for the data of K^--nucleus scattering.

Table I. $K^+ + {}^{12}$C and $K^+ + {}^{40}$Ca total cross-sections data. In column "Theory" the result is shown of this work and in parenthesis-theoretical results of Ref. [9]. Data are taken from Ref. [26].

P	^{12}C		^{40}Ca	
MeV/c	Theory	Experiment	Theory	Experiment
400	154.89		546.94	
	(134.2)		(420.3)	
488	152.28	165.60±1.77	508.59	526.37 ±7.65
500	152.41		506.18	
	(138.4)		(425.3)	
531	152.91	169.16±1.20	501.52	533.57 ±4.22
600	154.23		495.62	
	(145.3)		(444.4)	
656	154.86	176.09±0.76	491.94	533.38 ±4.20
700	155.14		489.14	
	(148.2)		(453.4)	
714	155.23	178.66±0.72	488.32	534.00 ±2.82

We thus see that there is a universal discrepancy between the theoretical models and data for particles (K^+-mesons) interacting in deeper regions of the nucleus. At the same time traditional models [2-4,20] give an adequate description of collisions of projectiles with targets in the case of more peripheral interactions . This situation then led many authors to assume some exotic phenomena ranging from the nucleon *swelling* to pion excess in nuclei [11,12]. However, the results based on such phenomena do not still provide to a satisfactory agreement with the experimental data as can be seen from the figures below.

We conclude that our results, the results calculated in the framework of the optical models and also suggestions about nucleon *swelling* [10] as well as pion excess in nuclei [11,12] show the possibility of observing some unusual phenomena in K^+ - nucleus interaction. On the other hand, recent calculations [18] have revealed that nucleon nucleon *swelling* in nuclear matter seems to be much less than that reported in previous works, and even that required to explain the EMC data. The investigation of such in-medium effects in the theory of nuclear reactions is still in its early stage and it needs much more time to clarify and

exactly isolate the role played by the nuclear medium for phenomena as that described above.

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Елисеев С.М., Рихан Т.Х. E4-96-64

О возможности наблюдения необычных свойств ядер,
используя каоны в качестве пробников

Исследуется возможность проявления необычных эффектов типа ЕМС в мезон-ядерных взаимодействиях при промежуточных энергиях. Обсуждаются противоречия между экспериментальными и теоретическими значениями отношений сечений, $R = \sigma(K^+ - {}^{12}C)/6\sigma(K^+ - d)$, вычисленных по теории многократного рассеяния Глаубера. После введения неэйкональных поправок и использования релятивистских $K^+ - N$ амплитуд не удается получить согласия с данными. Обсуждаются последние попытки уменьшения этого противоречия посредством введения внутриядерных эффектов.

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

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Eliseev S.M., Rihan T.H. E4-96-64

On the Possibility of Observing Some Unusual Properties
of Nuclei by Using Kaons as Probes

We investigated the possibility of observing some unusual effects such as the EMC-effect but for meson-nucleus interactions at intermediate energies. The discrepancy between the experimental and theoretical ratio R of the total cross sections $R = \sigma(K^+ - {}^{12}C)/6\sigma(K^+ - d)$ is discussed, in the framework of the Glauber multiple scattering approach. Various corrections like noneikonal effects and/or adopting relativistic $K^+ - N$ amplitudes seem to fail in reproducing the experimental data. Different recent attempts to remove this discrepancy with the in-medium effects taken into account are discussed.

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

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