

New method of studying slow strange meson properties in nuclear matter

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We suggest the new experimental method to explore the properties of slow strange mesons at normal nuclear matter density. We show that the K^+ and K^- mesons with extremely small momenta relative to the surrounding medium rest frame can be produced in nucleus-nucleon collisions and their production cross sections are experimentally measurable. The experiments on study of the momentum dependence of meson-nuclear potentials are discussed.

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The question about the properties of mesons in baryon matter has attracted much attention during last years [1]. In particular, the investigation of strange mesons is of special interest as it is related to a partial restoration of chiral symmetry [2] and possible existence of an antikaon condensed phase in dense interior of neutron stars [3]. According to theoretical studies based on various approaches such as effective chiral Lagrangians [4] and mean-field models [5] the in-medium antikaon mass should be substantially reduced while the kaon mass is expected to be slightly enhanced. This has triggering a considerable interest in the studying of K^- meson production in heavy-ion collisions. The dropping of the K^- mass in nuclear matter has strong impact on the antikaon yield especially in the subthreshold reactions due to in-medium shift of the elementary production threshold to lower energies. An enhanced antikaon to kaon ratio in Ni + Ni collisions in subthreshold energy regime has been observed at GSI [6, 7] and was attributed to the attractive antikaon potential of $-(100-120)$ MeV at nuclear saturation density [8]. A strong attractive optical potential of about $-(180-200)$ MeV at normal nuclear density for the K^- has been extracted from experimental data on kaonic atoms [9]. The substantial difference between the antikaon potentials mentioned above, i.e. their change in the mass, can be understood if the potential is momentum dependent. Indeed, the experiments with kaonic atoms deal with the K^- mesons of zero momentum relative to the nuclear matter rest frame while heavy-ion collisions at GSI probe the antikaons at momenta of more than 300 MeV/ c (c – velocity of light) with respect to the baryonic fireball [6]. The results of the calculations performed in the frame of

different models [10–14] show that the influence of an antikaon potential on the subthreshold production of K^- mesons increases with lowering of their momenta relative to the surrounding medium. It is thus desirable to obtain the information about the K^- and K^+ potentials at momentum less than 300 MeV/ c . In-medium modification effects are expected to be the most pronounced in nucleus-nucleus interactions in which the high density and/or temperature are accessible. However, due to a complex dynamic involved the interpretation of heavy-ion experiments is, at present, far from being unambiguous. Therefore, it is certainly useful to explore such effects under less extreme but much better controlled conditions at normal nuclear density in proton-nucleus collisions. However, slow kaons and especially antikaons are hard to investigate experimentally in pA reactions mostly due to their strong decay and small production cross sections vanishing at zero meson momentum.

We discuss the alternative method of such study. The properties of mesons with extremely small momenta with respect to the nuclear matter rest frame can be explored in the inverse kinematics, i.e. in nucleus-nucleon collisions. As it follows from the Lorentz transformation a slow particles in a projectile nucleus system appear to be fast in the laboratory i.e. in the target nucleon frame of reference. The meson which is at rest inside the incident nucleus has the same laboratory velocity as a surrounding nucleons. Using of the inverse kinematics makes possible the investigation of particle production in new kinematical range including zero momentum relative to the nuclear matter rest frame which is not accessible in pA reactions. In contrast to heavy-ion collisions the determination of the meson momenta relative to the nuclear environment in Ap reactions is model independent.

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The suggested method provides the important advantages for an experimental measurements in the low-momentum range. Large Lorentz boost with respect to the laboratory results in upward shifts of the K^+ and K^- momenta. As a consequence, their decay losses significantly decrease and the mesons become convenient for the detection. Since the invariant cross sections are the same in both systems an experimentally observed differential cross sections in the inverse and direct kinematics are related as:

$$(d^2\sigma/dpd\Omega)^{Ap} = (p^2/E)^{Ap}(E/p^2)^{pA}(d^2\sigma/dpd\Omega)^{pA}, \quad (1)$$

where p and E stand for kaon (antikaon) momentum and energy while upper indices denote the type of reaction. For the production of mesons with low momentum relative to the nuclear matter rest frame the cross section $(d^2\sigma/dpd\Omega)^{Ap}$ considerably exceeds $(d^2\sigma/dpd\Omega)^{pA}$ because of the factor $(E/p^2)^{pA}$ grows rapidly with lowering of meson momentum while the factor $(p^2/E)^{Ap}$ changes rather smoothly.

In the present Letter we shall consider some applications of the suggested method.

I. Study of the in-medium kaon potential. Let us consider K^+ meson production in the inverse kinematics by an ion beam on hydrogen target. Our estimate of the cross section for kaon production in Ap collisions is based on the data from pA reactions as well as the calculations performed in the framework of simple folding model [15] disregarding any potentials. Within this approach the inclusive K^+ production in proton-nucleus collisions at near threshold and sub-threshold energies is analyzed with respect to the one-step ($pN \rightarrow K^+YN, Y = \Lambda, \Sigma$) and two-step ($pN_1 \rightarrow \pi NN, \pi N_2 \rightarrow K^+Y$) incoherent processes. The invariant cross sections for both forward and backward kaon production in pA collisions at initial proton energies 2 GeV were found taking into account both reaction channels and then transformed into noninvariant double differential form. In Fig.1 the calculated double differential cross section for forward K^+ meson production on carbon target (dashed curve) is compared to that measured in the angular range $0-10^\circ$ at the same initial proton energy [16]. Experimental data are seen to be reproduced reasonably. The simple kinematical calculation shows that at the beam energy 2 AGeV (A – atomic mass number) the kaons produced inside a projectile nucleus with momenta from zero to 0.3 GeV/c in backward hemisphere relative to the beam direction appear in the laboratory within the longitudinal and transverse momentum ranges $0.78 \leq P_l \leq 1.47$ GeV/c and $0 \leq P_t \leq 0.3$ GeV/c, respectively. The K^+ mesons emitted in forward hemisphere with momenta up to

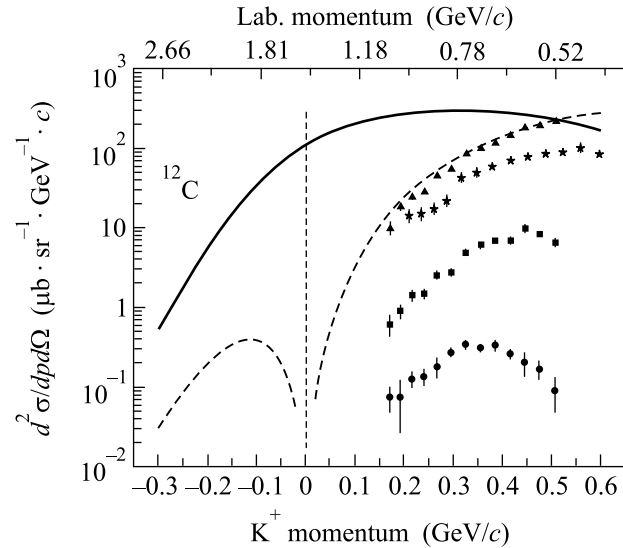


Fig.1. Double differential K^+ production cross sections. Circles denote the cross sections measured in proton-carbon collisions at $T_p = 1.0$ GeV, squares at $T_p = 1.2$ GeV, stars at $T_p = 1.5$ GeV and triangles at $T_p = 2.0$ GeV [16]. Dashed line is our calculation for $T_p = 2.0$ GeV in the direct kinematics. Solid curve represents the corresponding cross section for K^+ production in carbon-proton collisions at the ion beam energy 2 AGeV

0.3 GeV/c will be observed in the laboratory momentum range $1.47 \leq P_l \leq 2.66$ GeV/c and in the same interval of P_t . Laboratory momenta (in GeV/c) of the K^+ mesons from carbon-proton collisions corresponding to the momenta of kaons produced in forward and backward directions in $p^{12}\text{C}$ reaction are plotted on the upper axis. The solid curve in the figure depicts the double differential cross section for K^+ production in the inverse kinematics obtained from the calculated cross section (dashed curve) by using Eq. (1). Left-hand part of the figure is related to an unexplored experimental range of backward kaon production in proton-nucleus collisions. The comparison of the data [16] presented in Fig.1 with predicted cross section shows that it is definitely acceptable for measurements and significantly exceed that in traditional kinematics in the most interesting range of low K^+ momenta relative to surrounding nuclear matter. Furthermore, an upward shift of a kaon momentum in Ap collisions results in sizable decrease of a K^+ decay losses. In contrast to pA reactions large value of the cross section and its smooth behavior provide the favorable experimental conditions for the investigation of in-medium effects in the inverse kinematics in spite of the fact that the intensity of the ion beams usually smaller than that of the proton ones. The influence of kaon nuclear and Coulomb potentials should lead to the deviation of the cross section from the solid curve

calculated without above potentials. The signature of the effect will be A -dependent dip in the cross sections at laboratory kaon momentum around $1.47 \text{ GeV}/c$ corresponding to zero K^+ meson momentum relative to the projectile nucleus system.

The evidence for the action of Coulomb and nuclear potentials on soft kaon production was obtained in [17] where the ratio of forward K^+ meson yield from copper, silver and gold targets to that on carbon has been measured at proton beam energies between 1.5 and 2.3 GeV. It was found that in the momentum range from 170 till $600 \text{ MeV}/c$ the ratios exhibit similar shape rising with decreasing kaon momentum, passing a maximum and falling down at momenta less than $250 \text{ MeV}/c$. The magnitude of the K^+ – nucleus repulsive potential was found to be 20 MeV at normal nuclear density. The authors plan to extend the measurements of the ratios down to kaon momentum of about $100 \text{ MeV}/c$ what is not trivial experimental task. In the inverse kinematics both forward and backward production ranges in the nucleus rest frame can be studied simultaneously because of all produced kaons are peaked forward in the laboratory. As a consequence, the momentum dependence of the ratio of K^+ production cross section measured with heavy projectile ions to that measured with light ones should exhibit distinct two peak structure.

II. Study of the in-medium antikaon potential. Let us consider K^- meson production by an ion beam of energy 2.5 AGeV on hydrogen target. The K^- mesons produced in backward hemisphere relative to the beam direction with momenta up to $0.3 \text{ GeV}/c$ in the projectile nucleus rest frame will be observed in the laboratory momentum ranges $0.94 \leq P_l \leq 1.74 \text{ GeV}/c$ and $0 \leq P_t \leq 0.3 \text{ GeV}/c$. This process corresponds to low-momentum K^- production in forward hemisphere by protons on nuclear target. The available experimental information about subthreshold antikaons from proton-nucleus collisions is very scarce [11, 18]. Data on the production of K^- mesons with small momenta are completely missed now. Under these circumstances we have to rely upon the model calculations to evaluate the respective cross section. The forward K^- mesons production in the $p + A \rightarrow K^- + X$ reaction at the proton beam energy 2.5 GeV was studied in [10] within a coupled channel transport approach. The dashed histogram in Fig.2 shows the K^- momentum spectrum for ^{12}C target calculated in [10] with zero potentials but taking into account the antikaon absorption in its way out through the nucleus. The solid histogram in the figure depicts the double differential cross section for the K^- meson production in $^{12}\text{C}+p$ collisions obtained from the dashed histogram by using Eq. (1). The upper

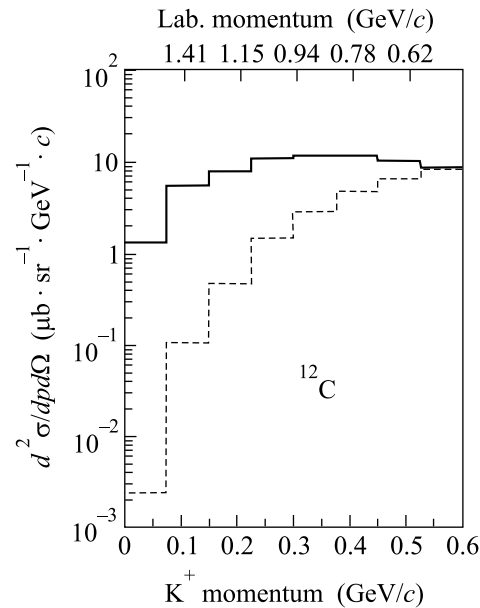


Fig.2. Double differential K^- production cross sections in the direct (dashed histogram) and inverse (solid histogram) kinematics

scale represents the corresponding laboratory momenta (in GeV/c) of the K^- mesons from carbon-proton collisions. Taking into account the values of the antikaon production cross sections and sizable decrease of their decay losses we conclude that the expected event rate in low K^- momentum range is acceptable for measurements in the Ap kinematics.

Impact of the surrounding medium on slow K^- production should differ from that on K^+ due to an attractive nature of both Coulomb and nuclear potentials. The action of Coulomb potential will populate the low-momentum range while the influence of the nuclear potential depends sensitively on its strength. One can expect that in the case of weak potential the yield of the K^- mesons will be suppressed due to their strong absorption via the $K^- + N \rightarrow \Sigma + \pi$ reaction which has very large cross section at small antikaon momentum. On the contrary, in the case of strong potential exceeded 100 MeV the K^- mesons absorption plays a minor role because of the above process is energetically almost closed [19]. This will lead to an enhanced low-momentum K^- meson yield even from heavy nuclei. The calculations [10] with attractive antikaon potential 120 MeV give a factor of about 10 enhancement in the cross sections for low momentum K^- . It is thus necessary to explore this question experimentally by measuring in the inverse kinematics the K^- spectra as a function of the projectile nucleus mass.

If an attractive antikaon-nucleus potential turns out to be large it will be a strong argument for existing

of narrow discrete nuclear antikaon bound states (see [19] and references therein). The using of the inverse kinematics can be the promising way to produce such a states.

It should be noticed that slow pions inside nuclei can also be explored in the inverse kinematics. Such a measurements may help to disentangle the effects of the Coulomb and nuclear potentials on kaon and antikaon production.

III. Study of the subthreshold reaction mechanism. As it was mentioned above the kaon and antikaon production in proton-nucleus interactions below the free NN threshold is reduced to the one-step and two-step processes due to the lack of collision energy. It is commonly believed that the reaction mechanism can be identified from the target atomic mass dependence of the cross sections. The A -dependence for the one-step process is determined by the total inelastic cross section and scales as $\approx A^{2/3}$ provided weak final state absorption of the produced mesons. The stronger dependence $\approx A^1$ is expected for the two-step kaon creation process since the respective cross section includes the additional probability of the second collision of an intermediate pion with another target nucleon which is proportional to $\approx A^{1/3}$. The total K^+ production cross section on different nuclei have been measured in [20] at the proton energy 1 GeV which is far below the free NN threshold ($T_{NN} = 1.58$ GeV). Note that low-momentum kaons give the main contribution to the total cross section. By fitting to the cross sections with an A^α function the exponent α was found to be 1.04 ± 0.03 . The strong A -dependence has been interpreted in [20, 21] as an evidence for the dominance of the two-step reaction mechanism. Recently ANKE Collaboration obtained the data on double differential cross sections for low-momentum K^+ production on nuclear targets from carbon to gold at the same proton energy 1 GeV [22]. The extracted value of $\alpha = 0.74 \pm 0.05$ is in reasonable agreement with A -dependence expected for the one-step mechanism. This discrepancy does not allow one to draw unambiguous conclusion about the underlying reaction mechanism of slow K^+ production in pA collisions [23].

Investigation of low momentum kaon in the inverse kinematics seems the most promising way to clarify the situation. Using of different ion beams provides the possibility to explore the atomic mass dependence. At projectile energy 1 AGeV the K^+ meson emission in backward hemisphere relative to the ion beam direction within the momentum range 0–0.3 GeV/ c in the projectile nucleus rest frame looks like forward kaon production in the laboratory momentum intervals $0.43 \leq P_l \leq 0.89$ GeV/ c and $0 \leq P_t \leq 0.3$ GeV/ c . This makes the

measurements in the inverse kinematics more favorable than those in the direct kinematics. For instance, since the K^+ meson momentum 0.1 GeV/ c relative to projectile nucleus corresponds to the laboratory momentum 0.7 GeV/ c , the differential cross section in Ap collisions is enhanced by a factor of 30 (Eq. (1)). Furthermore, at the distance between the production target and the detectors of about 2.5 meters corresponding to the actual experimental situation, the loss of the kaons due to their decay in flight is decreased by more than an order of magnitude. Therefore, the K^+ event rate would exceed that in traditional kinematics by about a factor of 400. The corresponding enhancement in the event rate of the K^- mesons with the same momentum is equal to be 800 at ion beam energy 2 AGeV which is far enough below the free NN threshold ($T_{NN} = 2.50$ GeV). Due to the Lorentz boost all kaons and antikaons produced in full solid angle with momenta < 300 MeV/ c relative to the projectile nucleus rest frame will be concentrated in the laboratory inside rather narrow cone 10 – 20° what corresponds to the solid angle of 1–3% of 4π . Note that the multiple scattering effect on the detected particles is significantly decreased in the Ap kinematics due to upward shift of both kaon momentum and velocity. Thus, the inverse kinematics is well suited for the experimental study of the mechanisms of deep subthreshold low-momentum strange meson production.

The feasibility of the experiments discussed above depends on backgrounds. Subthreshold K^+ and K^- meson production is accompanied by the background of secondary pions and protons which is much more intense. Note that the modern magnetic spectrometers provide reliable K/π and K/p separation up to values of these ratios $10^{-6} - 10^{-7}$ [15, 22]. Another source of background is a particle production from an envelops of hydrogen target. Usually “target full-target empty” measurements have to be carried out to obtain the cross sections on hydrogen. However, this background can be totally removed by using the windowless target consisting of frozen hydrogen pellets [24].

It is worth notice that the method discussed opens the new way to explore the properties of low-momentum η , η' , ω , ρ and ϕ mesons in nuclear matter, the topic extensively discussed over the last years [25]. The experiments in the inverse kinematics may be carried out at GSI-SIS using an ion beams in 1–2 AGeV region and at ITEP where an ion beams of energy up to 4.3 AGeV are expected to be available in the near future.

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