Measurement of the In-Medium K^0 Inclusive Cross Section in π^--Induced Reactions at 1.15 GeV/c

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The K^0 meson production by π^- mesons of 1.15 GeV/c momentum on C, Al, Cu, Sn, and Pb nuclear targets was measured with the FOPI spectrometer at the Schwer-Ionen-Synchrotron accelerator of GSI. Inclusive production cross sections and the momentum distributions of K^0 mesons are compared to scaled elementary production cross sections and to predictions of theoretical models describing the in-medium production of kaons. The data represent a new reference for those models, which are widely used for interpretation of the strangeness production in heavy-ion collisions. The presented results demonstrate the sensitivity of the kaon production to the reaction amplitudes inside nuclei and point to the existence of a repulsive KN potential of 20 ± 5 MeV at normal nuclear matter density.

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Modifications of hadron properties in dense baryonic matter are a subject of intensive research in hadron physics [1]. Various theoretical approaches [2] agree qualitatively on predicting, for example, modifications of masses and coupling constants for kaons and antikaons. Because of the density dependence of the $KN(\bar{K}N)$ potential, the K^- effective mass is expected to drop, whereas the mass of K^+ mesons is predicted to rise with increasing density of nuclear matter. Because of additional attractive interactions with the surrounding nucleons, a condensation of antikaons (K^-) may take place in a dense baryonic environment as encountered in the interior of neutron stars [3]. Kaons (K^+, K^0), on the other hand, have a relatively long mean free path in the nuclear matter at low momenta [4]. Therefore they are a good probe for studying the in-medium properties of hadrons produced in collisions between nuclei at energies close to the respective nucleon-nucleon production thresholds [5]. For an understanding of the strangeness production in such collisions, the knowledge of the elementary production cross sections at finite baryonic densities is essential.

As far as the production of strangeness by pions is concerned, there exist interesting predictions based on quark-meson coupling (QMC) model calculations [6], in which kaons (K^+, K^0) and hyperons (Λ, Σ) are produced via the formation of intermediate Δ and N^* resonances. Because of the in-medium modifications of the involved resonances, the reaction amplitudes of these processes are expected to be modified, thus giving rise to substantial changes of the kaon production cross sections at normal nuclear matter density ρ_0.

In this Letter, we report about measurements of the K^0 production by pions of 1.15 GeV/c momenta on various nuclear targets. The inclusive production cross sections and the K^0 phase-space distributions are compared to theoretical predictions. Evidence for the existence of a repulsive, mean-field KN potential is presented.

The experiments were performed with the FOPI spectrometer at the beam line of the Schwer-Ionen-Synchrotron (SIS) accelerator at GSI. The π^- beam had an intensity of about 3000π^-/s, a mean momentum of 1.15 GeV/c with a momentum dispersion of about 0.5%. The chosen beam momentum corresponds to an available energy $\sqrt{s}$ of about 1.75 GeV in the system of π^- mesons colliding with nucleons at rest. The identification of charged particles is achieved in FOPI [7] by the curvature of particle tracks in the magnetic field, by their specific energy loss in the drift chamber, and by the time of flight. In the present analysis the geometrical acceptance was restricted to the polar angles $25° < \theta < 150°$ covered by the central drift chamber (CDC). K^0_S mesons ($c\tau = 2.68$ cm) were reconstructed via their decays into (π^-, π^+) pairs, whereas K^0_L mesons could not be reconstructed due to their long lifetime. Five different targets were used: C, Al, Cu, Sn, and Pb, with thicknesses of 1.87, 1.56, 4.41, 2.83, and 5.76 g/cm^2, respectively. Altogether about 25×10^6 events were registered under a minimum-bias trigger condition, i.e., in case that at least a single charged particle was detected inside the CDC. The position of the primary interaction point was reconstructed with the help of two silicon microstrip detector stations, each consisting of two single-sided detectors (3.2×3.2 cm^2 area, 300 μm in thickness, and with 50 μm pitch size) and placed 94 and 224 cm upstream from the target.

The upper plot in Fig. 1 shows the invariant mass distribution of (π^-, π^+) pairs registered in $\pi^- +$ Pb reactions. The combinatorial background below the K^0_S peak was reduced by imposing selection criteria on parameters of the reconstructed tracks: transverse momenta [$p_t(\pi^-, \pi^+) \geq 80$ MeV/c], assigned masses of particles [$0.05 \leq m(\pi^-, \pi^+) \leq 0.6$ GeV/c^2], distances of closest approach to the primary vertex [$|d_0(\pi^-, \pi^+)| \geq 1.5$ cm],

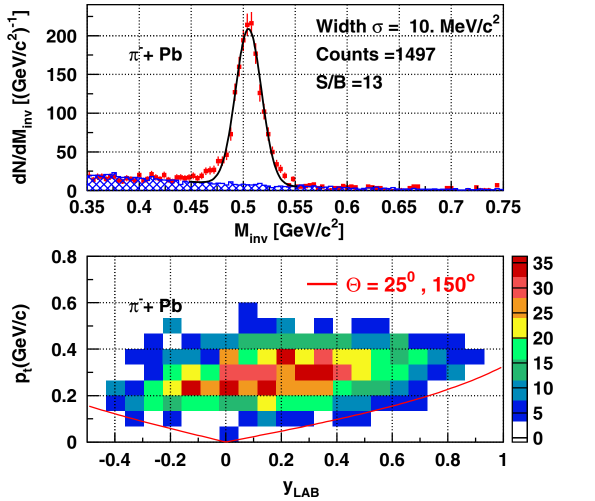

FIG. 1 (color online). Upper plot: The K^0_S invariant mass distribution in $\pi^- +$ Pb reactions. Lower plot: Geometrical acceptance of the detector in the $\pi^- +$ Pb experiment in terms of rapidity versus transverse momentum of reconstructed K^0_S mesons.

and the differences between the azimuthal angles of reconstructed secondary vertices and kaon momenta ($|\Delta\phi| < 30°$). After subtraction of the background—reconstructed by the event mixing method—the distribution is fitted with a Gaussian function. A total number of about 1500 K^0_S is identified in the interval of $\pm 2\sigma$ around the K^0_S nominal mass, where the ratio of the signal to the background is about 13. Similar statistics are available for the C target, while for each of the other targets about 300 K^0_S mesons are reconstructed.

Figure 2 shows the inclusive K^0 production cross sections as a function of the mass of the target nucleus obtained by correcting the number of reconstructed K^0_S mesons with the appropriate factors due to the geometrical acceptance of the apparatus (shown in the lower plot in Fig. 1), the reconstruction efficiency of K^0_S mesons, the normalization to the number of beam particles, the target thickness, and the branching ratio into $K^0_{S/L}$. The systematic errors (boxes in Fig. 2) are estimated to be less than 30%. As determined by extensive GEANT-based Monte Carlo simulations, about 15% of uncertainty is related to the evaluation of the reconstruction efficiency and its dependence on the reconstruction of the primary interaction point, whereas about 10% is due to the chosen selection strategy of (π^-, π^+) pairs. An additional error of about 5% is attributed to the extrapolation to the full momentum space; it was estimated from a comparison to the transport-model calculations described below, which demonstrated that 85% of the production cross section can be reconstructed in the geometrical acceptance of the experiment.

The dependence of the K^0 inclusive production cross section on the mass of the target nucleus A is fitted with a power law function: $\sigma(\pi^- + A \rightarrow K^0 + X) = \sigma_{\text{eff}} \cdot A^b$. The result of the fit yields $\sigma_{\text{eff}} = 0.87 \pm 0.13$ mb and

$b = 0.67 \pm 0.03$, with a statistical error of $\chi^2/\mathrm{ndf} = 0.9/3$. This A dependence suggests that, in the studied reactions, kaons are produced at the surface of the nucleus.

Using the observed A dependence, we compare in Fig. 2 the measured inclusive cross sections to reference calculations based on the assumption that the production of kaons takes place only on the surface of target nuclei with the known elementary production cross sections in vacuum. The reference values are obtained by summing the $\pi^- + p \rightarrow K^0\Sigma^0$, $\pi^- + p \rightarrow K^0\Lambda$, and $\pi^- + n \rightarrow \Sigma^- K^0$ cross sections weighted with the relative neutron and proton contents of the target nuclei and multiplying the results by $A^{2/3}$, which represents the effective number of nucleons on the nucleus surface. The results of these calculations are depicted by the hatched area in Fig. 2, which includes experimental uncertainties estimated to be about 20%. The simple scaling ansatz underpredicts the measured cross sections by about a factor of 2, which indicates that some essential part of the production process is missing. Trivial explanations, such as an enhancement of the kaon production due to the Fermi motion of the nucleons in the nuclei [8], are ruled out due to the weak dependence of the elementary production cross section on incident momentum (see [6]). Applying the same scaling procedure as for the vacuum cross sections to the results of the quark-meson coupling model, which predicts an enhancement of the inclusive kaon production at a baryon density of $\rho = \rho_0$ [6], yields the results depicted by the dashed-dotted line in Fig. 2. This type of modification has clearly the potential to describe the magnitude of the observed inclusive cross section. However, it should be noted that the densities for which the calculation is available clearly exceed the density probed by the reactions on the surface of nuclei induced by the pion beam—according to the results of the hadron-string-dynamics (HSD) transport model [9], kaons are produced on average at densities of about 0.6–0.7 for the C and the Pb target, respectively. In contrast to the QMC model predictions, available only for infinite nuclear matter, the results of the HSD calculations can be compared directly to the measured inclusive production cross sections (dashed line in Fig. 2). Here, no sensitivity to modifications of kaons can be observed; i.e., the calculations without the KN potential predicts a total production cross section that is larger by only 3% than the one shown in Fig. 2, which is due to the nonresonant K^0 production mechanism in the HSD model.

While, within the present experimental accuracy, the influence of the medium on the inclusive K^0 meson production is not identifiable when comparing the results to predictions of the HSD model, information about the mean-field KN potential can be gained by comparing the phase-space distributions of kaons produced on heavy and light targets [10,11]. In particular, kaons of low momenta, which spend considerable time inside the nuclear matter, are expected to probe the potential efficiently. The yields of K_S^0 produced on the Pb and the C targets are plotted in Fig. 3 and compared in terms of their ratio as a function of the kaon momenta. The data are corrected for the detection

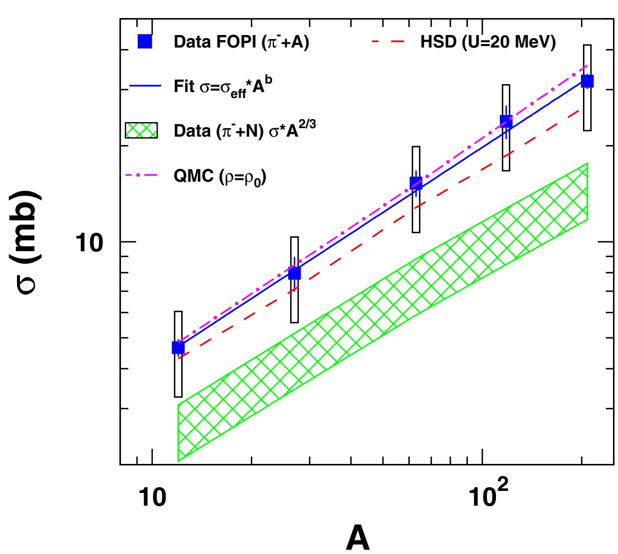

FIG. 2 (color online). The K^0 inclusive production cross section (squares) as a function of the mass number of the target nucleus. The solid line represents the fit with a power law function. The hatched area corresponds to the sum of the cross sections of the elementary processes scaled according to the transverse size of the target nuclei. QMC model predictions at $\rho = \rho_0$ [6] (dashed-dotted line) are scaled with the same prescription, whereas HSD transport-model calculations (dashed line) yield absolute predictions.

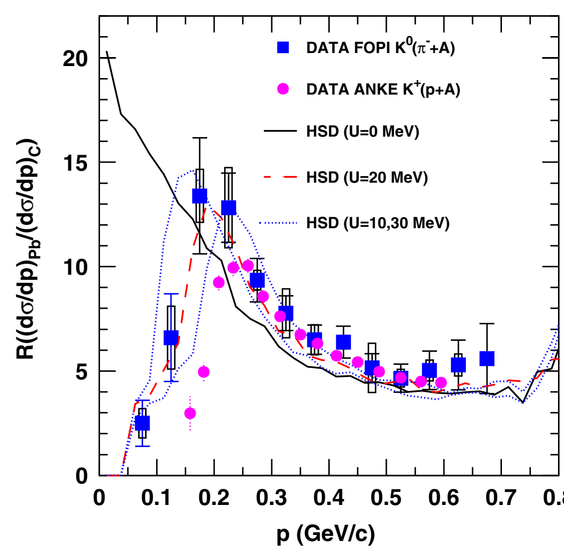

FIG. 3 (color online). The ratio of K^0 (K^+) yields produced by pions (protons) on heavy and light targets plotted as a function of the momentum p in the lab system. The full squares depict the yield ratio of K_S^0 produced on Pb and C targets in this experiment. A similar ratio of K^+ yields measured in proton-induced reactions on Au and C targets is represented by full circles [11]. The results of the HSD model with different strengths of the KN potential are depicted by solid (black), dashed (red), and dotted (blue) lines.

efficiencies, although, because of the chosen representation, these correction factors cancel out to a large extent. At low momenta ($p < 170$ MeV/c), the production of K_S^0 on the Pb target is clearly suppressed with respect to the production on the C target. This observation can be explained by a repulsive KN potential in the nuclear medium, which accelerates kaons before they escape the nucleus. The effect of the acceleration is increasing with the size of the nucleus because, in case of the Pb target, kaons stem from the medium which has a higher density on average. In order to estimate the strength of the potential, the measurements are compared to the results of the HSD transport-model calculations [9], filtered through the geometrical acceptance of the experiment. The version of the model without the K^0N potential, shown by the solid line in Fig. 3, misses the trend in the data at low momenta completely. On the contrary, the version of the model that includes a 20 MeV K^0N potential at ρ_0 (with a linear dependence of the potential on the nuclear density), depicted by the dashed line in Fig. 3, reproduces qualitatively the observed functional dependence of the K_S^0 yield ratio over the full momentum range.

A similar analysis has been performed by the ANKE Collaboration in the case of K^+ meson production by protons of 2.3 GeV energy on Au and C targets [11]. At momenta larger than 250 MeV/c, the ratios of K^+ mesons yields (full circles in Fig. 3) agree well with the results of the present work. At lower momenta, the ratios measured in both experiments exhibit a similar suppression of kaon production on heavy targets, but with a different extension of the depletion region. As in the case of the present work, the results of the K^+ production experiment were reproduced by the transport-model calculations [12] with a K^+N potential of the order of 20 MeV at ρ_0. However, in contrast to positively charged kaons, the propagation of neutral kaons is not affected by the (additional) repulsive Coulomb interaction, which in the case of Au nuclei is as large as 15 MeV. Therefore, the strength of the repulsive KN interaction can be extracted generally more directly from the results of our measurement than from previous K^+ production experiments. The accuracy for the determination of the effective K^0N potential, 20 ± 5 MeV, was inferred from the comparison of the data to HSD-model predictions with different strengths of the potential (cf. dotted lines in Fig. 3), by means of the χ^2 analysis. Experimentally, this precision is presently limited only by statistics and can be improved by an intensity upgrade of the SIS18 accelerator. A high statistics experiment would also shed light on the isospin dependence of the KN potential, a topic that is receiving a high degree of attention recently [13].

In summary, cross sections of inclusive K^0 meson production in $\pi^- + A \rightarrow K^0 + X$ reactions were measured. Comparison of the results to predictions of the QMC model demonstrates the sensitivity of the measurements to the possible changes of reaction amplitudes of the underlying elementary processes at nonzero baryon density. The momentum distributions of K_S^0 mesons produced on heavy (Pb) and light (C) nuclei have been compared by means of the yield ratio and are reproduced by HSD transport-model calculations qualitatively. At low momenta, a suppression of K_S^0 production on heavy nuclei is observed with respect to the production on the light target. The results of the HSD transport-model calculations suggest that, at $\rho = \rho_0$, a repulsive KN potential of 20 ± 5 MeV is present due to K^0 interactions with the surrounding nuclear medium.

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