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K^+ MESONS, A ROBUST PROBE TO MEASURE THE HADRONIC EQUATION OF STATE?

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We demonstrate that the K^+ mesons are sensitive to nuclear matter properties, especially to the hadronic equation of state (EoS). Once one has understood how K^+ behave in hadronic matter, we can use these mesons to study the hadronic EoS. Several observables point towards a rather soft EoS at densities around three times the normal nuclear matter density ρ_0.

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After 70 years of nuclear physics a simple question "How much energy is needed to compress hadronic matter?" has not found a definite answer yet, despite of the importance of the answer not only for a fundamental understanding of hadronic matter but also for the understanding of many astrophysical observations. This has several reasons. First of all, for our studies we have at our disposal only finite nuclei. The difference between the binding energy per nucleon in nuclear matter (-16 MeV) at ρ_0 and in finite nuclei (-8 MeV) shows the importance of surface effects. Second, in experiments we cannot compress matter without heating it up and without creating mesons and baryonic resonances. This makes the analysis of experiments, in terms of an equation of state, difficult. Last but not least, beyond densities of 1.5–2.0ρ_0 the expansion parameter of our theoretical n-body calculations, which at lower densities allows one to simplify the problem to the Brückner G-matrix calculation, becomes large, and diagrams with more hole lines have to be taken into account.

The common experimental and theoretical effort, dubbed "Quest for the hadronic equation of state" (EoS), has recently revealed a new observable which

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seems to be more promising to give an answer to this open problem. This new observable is the K^+ yield measured in heavy-ion collisions around 1–2A GeV beam energy, where densities up to $3\rho_0$ are obtained.

The most simple approach to $E(\rho)/A$, the energy/nucleon of cold matter as a function of the density, is a three-parameter approach

$$\frac{E(\rho)}{A} = E_{\mathrm{kin}} + \alpha \frac{\rho}{\rho_0} + \beta \left[\frac{\rho}{\rho_0}\right]^{\gamma}, \tag{1}$$

where two of the parameters are given by the minimum of the binding energy of -16 MeV at ρ_0. For historical reasons, the third parameter is usually expressed by the compressibility modulus

$$K = \frac{1}{\kappa} = -V\frac{dp}{dV} = 9\rho^2 \frac{d^2E(\rho)/A}{(d\rho)^2}\bigg|_{\rho=\rho_0} = R^2 \frac{d^2E(\rho)/A}{dR^2}, \tag{2}$$

κ is the compressibility.

K^+ mesons produced far below the NN threshold cannot be created in first-chance collisions between projectile and target nucleons. They do not provide sufficient energy even if one includes the Fermi motion. The necessary energy for the production of a K^+ meson in the NN center-of-mass system is 671 MeV because, in addition to the production of a kaon, a nucleon has to be converted into a Λ to conserve strangeness. Before nucleons can create a K^+ at these subthreshold energies, they have to accumulate energy. The most effective way to do this is to convert a nucleon into a Δ and to produce in a subsequent collision a K^+ meson via $\Delta N \to NK^+\Lambda$ [1, 2]. Two effects link the yield of produced K^+ with the density reached in the collision and the stiffness of the compressional energy. If less energy is needed to compress matter (i) more energy is available for the K^+ production and (ii) the density which can be reached in these reactions will be higher. Higher density means a smaller mean free path, and therefore the time between collisions becomes shorter. Thus, the Δ has an increased chance to produce a K^+ before it decays. Consequently, the K^+ yield depends on the compressional energy. Figure 1 shows the result of simulations of the heavy-ion reactions by the IQMD model. On the right-hand side we see the K^+ multiplicity in Au + Au divided by that in C + C collisions as a function of the beam energy per nucleon. We see that this ratio is quite different for a soft EoS ($K = 240$ MeV) as compared to a hard EoS ($K = 380$ MeV). We checked whether this result is robust by changing the values of several little known ingredients of the simulation program. Changes of the cross section $\sigma(N\Delta \to K^+)$ (top), of the the K^+N optical potential (middle), and of the lifetime of the Δ in matter (bottom) do not spoil the fact that only a soft EoS is compatible with data. For all the details, we refer to [2, 4]. The right-hand side shows a different observable, the centrality dependence of the K^+ yield. As

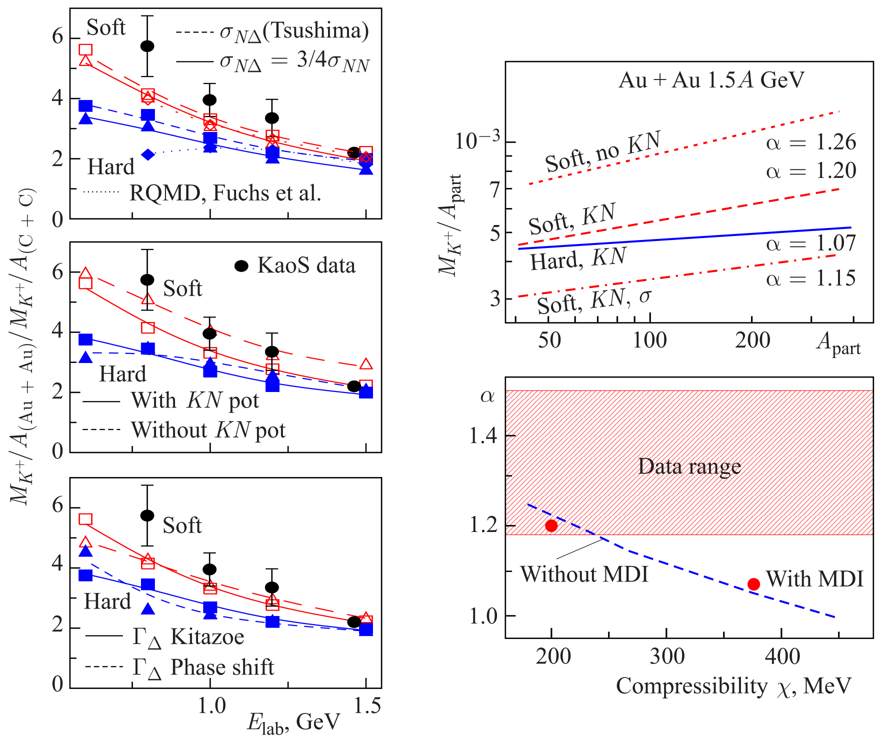

Fig. 1 (color online). Left — comparison of the measured excitation function of the ratio of the K^+ multiplicities per mass number A obtained in Au + Au and C + C reactions [3] with various assumptions on the physical input. The use of a hard EoS is denoted by thin (blue) lines; a soft EoS, by thick (red) ones. The energies of the calculations are given by the symbols, the lines are drawn to guide the eye. On top, two different versions of the $N\Delta \to K^+\Lambda N$ cross sections are used. Middle — IQMD calculations with and without KN potential are compared. Bottom — the influence of different options for the lifetime of Δ in matter. Right top — centrality dependence of the α parameter (see the text) and for different EoS. The red lines are the results for a soft EoS, with and without K^+N interaction, the blue line is that for the hard EoS with K^+N interaction. Right bottom — the α parameter as a function of the compressibility modulus for IQMD calculations with and without momentum-dependent interactions (MDI)

for the given energy the maximal density depends on centrality, the centrality dependence of the K^+ yield also depends on the hadronic EoS. We parameterize the experimental and theoretical results by $M_{K^+}(A_{\mathrm{part}}) \propto A_{\mathrm{part}}^{\alpha}$ and plot M_{K^+} as a function of A_{part}. A_{part} is the number of participating nucleons. To each curve the corresponding α value is assigned. Also this observable shows that

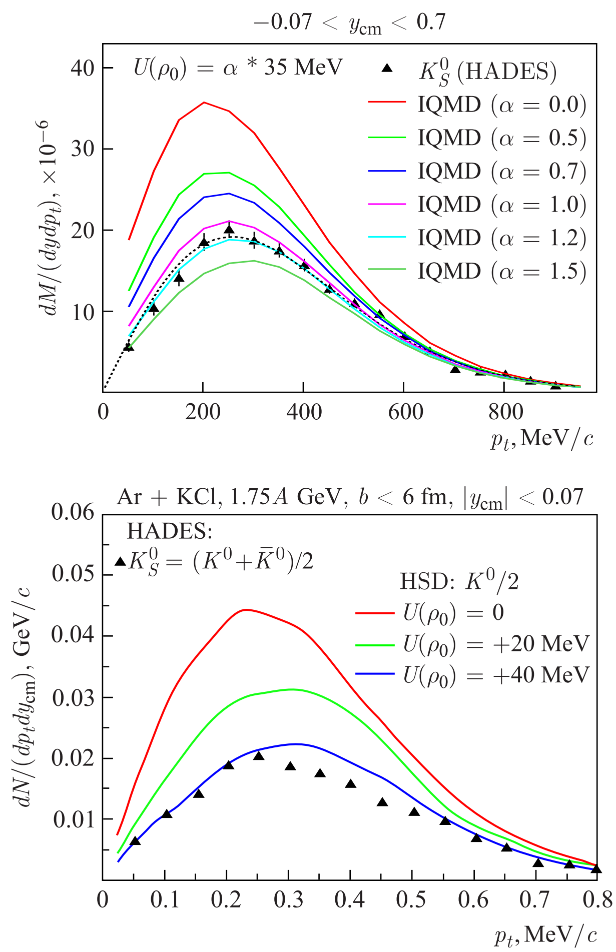

Fig. 2. K^+ transverse momentum distribution in Ar + KCl collisions at 1.93A GeV measured by the HADES collaboration. We compare the theoretical predictions for different values of the K-nucleus optical potential of two transport models with the experimental data. *a*) Results of IQMD calculations [4, 5]; *b*) results of HSD calculations [4, 6]

a hard EoS gives too low α values in comparison with the data (bottom right). Both observables are consistent with each other and demonstrate that K^+ mesons are a valuable tool to measure the nuclear EoS.

However, there is another aspect which we have to consider. K^+ in matter have other properties like in free space because they have a repulsive interaction with the nucleons. Therefore, in reality we are confronted with a double problem.

In order to test the EoS, we need K^+ mesons, but they give only the right information on the EoS if we have understood how they are modified in matter. In a heavy-ion reaction we see both aspects.

How can we measure K^+ properties in matter? When the K^+ leaves the nucleus, the repulsive K^+N optical potential accelerates the K^+. This acceleration depends on the strength of the K^+N optical potential. Therefore, the idea has been advanced to compare the transverse momentum spectrum for different K^+N optical potentials and to find out whether the experimental data are precise enough to determine this potential. The recent data of the HADES collaboration on $1.75A$ GeV Ar + KCl [7] have been sufficiently precise for such an approach. In Fig. 2, we compare the results of two of the most elaborate simulation programs for this energy domain, IQMD [4, 5] and HSD [6], with the experimental data of the HADES collaboration. In both calculations the K^+N optical potential has been varied. We see that these variations yield to quite different forms of the experimental spectra. In both calculations the experimental acceptance has been taken into account. We see that both calculations agree best with data if the linear K^+N optical potential is 40 MeV at normal nuclear matter density. These values agree with theoretical predictions [8]. So nuclei allow for measuring K^+ properties.

In conclusion, we have shown that heavy-ion reactions allow for studying K^+ properties in matter. Having the properties of the K^+ under control, we can use the kaons as a tool to study the hadronic EoS. We have shown that two independent K^+ observables point towards a rather soft EoS. The value of the compressibility modulus of the EoS measured with K^+, which are sensitive to densities of the order of $3\rho_0$, has nearly the same value than that measured by monopole resonances which are sensitive to densities around ρ_0.

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