TRANSPORT MODEL STUDY OF IN-MEDIUM KAON POTENTIAL IN HEAVY ION COLLISIONS

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Abstract

The kaon production in heavy ion collisions at intermediate energies provides a sensitive probe to study the in-medium properties of hadrons. Properties of kaons in dense hadronic matter are important for a better understanding of both a possible restoration of chiral symmetry in dense hadronic matter and the properties of nuclear matter at high densities. It is known from chiral models that the kaon mean field is related to chiral symmetry breaking. The K^+ and K^- mean field potentials play a crucial role. In the lowest order approximation to the chiral Lagrangian, the kaon (antikaon) potential has an attractive scalar and a repulsive (attractive) vector part. Experimental and transport model studies on the in-medium potential of kaon produced in heavy ion collisions at intermediate energies are reviewed.

Keywords: Kaon production, heavy ion collisions, the in-medium kaon potential, transport study

Introduction

The strangeness production in heavy-ion collisions is a hot topic of theoretical and experimental studies. Because of rather high energy thresholds in NN collisions (E_{beam} = 1.58 GeV for $NN \to K\Lambda N$ and E_{beam} = 2.5 GeV for $NN \to NNKK$), the secondary processes $\Delta N \to KYN$, $\pi N \to \bar{K}Y$ and $\pi Y \to \bar{K}N$ which require high baryon density are important in the case of nucleus-nucleus collisions at 1–2 AGeV. Moreover, the relatively low K^+N scattering cross section is estimated at about 10 milibarn, and the absence of the absorption channel of a K^+ meson on a nucleon in strong interactions cause nuclear matter to be practically transparent for K^+ meson (Randrup and Ko, 1980). The analysis of sub-threshold kaon production is used to obtain information on the properties of strange mesons in dense nuclear matter. Especially the relation of the optical potential of K^+ and K^- in the nuclear medium to experimental observables such as mesonic in-plane flow and azimuthal distribution of kaons is a subject of vivid discussions.

Properties of kaons in dense hadronic matter are important for a better understanding of both a possible restoration of chiral symmetry in dense hadronic matter and the properties of nuclear matter at high densities. It is known from chiral models that the kaon mean field is related to chiral symmetry breaking (Kaplan and Nelson, 1986; Nelson and Kaplan, 1987). The K^+ and K^- mean

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field potentials play a crucial role. In the lowest order approximation to the chiral Lagrangian, the kaon (antikaon) potential has an attractive scalar and a repulsive (attractive) vector part. The calculations by Zheng *et al*. (2004) corroborated their earlier analysis (Fuchs *et al*., 1998) and have demonstrated that the new FOPI data on the kaon in-plane flow (Herrmann, 1999) are best described by using the kaon potential given by the Brown-Rho (BR) parameterization (Brown and Rho, 1996) [$U_k(\rho_0) \approx 30MeV$, where $\rho_0 = 0.16$ fm^{-3}]. At $\rho \leq \rho_0$ the kaon potential in the BR parameterization is close to the one in the impulse approximation (Li *et al*., 1995; Schaffner-Bielich *et al*., 1997). Following Zheng *et al*. (2004), similar results are also obtained by RBUU calculations (Larionov and Mosel, 2005). Recent self-consistent calculations of Korpa and Lutz (2005) and Tolos *et al*. (2006) have shown even stronger repulsive potential for K^+ meson $U_k(\rho_0) \approx 36MeV$ in Korpa and Lutz (2005) and $U_k(\rho_0) \approx 36MeV$ in Tolos *et al*. (2006).

This paper intends to give a comprehensive overview of kaon properties in dense matter formed in heavy ion reactions in the incident energy range from 0.6 to 2A GeV. Section 2 gives an overview of kaons in dense matter. Probing the in-medium kaon potential is discussed in Section 3. In Section 4, a summary is given.

Kaons in Dense Matter

The natural framework to study the interaction between pseudoscalar mesons and baryons at low energies is chiral perturbation theory (ChPT). From the chiral Lagrangian, the field equations for the $K^{\pm}$ mesons are derived from the Euler-Lagrange equations (Li *et al*., 1995; Ko, 2001).

$$\left[\partial_\mu \partial^\mu \pm \frac{3i}{4f_\pi^*} j_\mu \partial^\mu + \left(m_K^2 - \frac{\Sigma_{KN}}{f_\pi^{*2}} \rho_s\right)\right] \phi_{K^\pm}(x) = 0 \quad (1)$$

In equation 1, j_μ is the baryon four-vector current, ρ_s is the baryon scalar density, f_π^* is the in-medium pion decay constant. Introducing the kaonic vector potential

$$V_\mu = \frac{3}{8f_\pi^{*2}} j_\mu \quad (2)$$

Equation 1 can be rewritten in the form (Fuchs, 2006)

$$\left[\left(\partial_\mu \pm iV_\mu\right)^2 + m_K^{*2}\right] \phi_{K\pm}(x) = 0 \quad (3)$$

Thus, the vector field is introduced by minimal coupling into the Klein-Gordon equation. The effective mass m_K^* of the kaon is then given by

$$m_K^* = \sqrt{m_K^2 - \frac{\Sigma_{kN}}{f_\pi^{*2}} \rho_s + V_\mu V^\mu} \quad (4)$$

where $m_K = 0.496$ GeV is the bare kaon mass. The parameters in equations 1 and 4 are taken as follows: the kaon-nucleon sigma term $\Sigma_{KN} = 0.450$ GeV, the in-medium pion decay constant at normal nuclear matter density (ρ_0) $n_K^* = \sqrt{m_K^2 - \frac{\Sigma_{kN}}{f_\pi^{*2}} \rho_s + V_,}$ (Brown and Rho, 1996) and the vacuum pion decay constant $f_\pi = 0.093$ GeV.

The $K^{\pm}$ single-particle energies are expressed as

$$\omega_{K^\pm}(\mathbf{k}) = \pm V^0 + \sqrt{\mathbf{k}^{*2} + m_K^{*2}} \quad (5)$$

where $k^* = k \mp V$ is the kaon effective momentum, $V^\mu = (V^0, \mathbf{V})$, the kaon vector field is introduced by minimal coupling into the Klein-Gordon with opposite signs for K^+ and K^-, and m_K^* is the kaon effective (Dirac) mass.

The kaon (antikaon) potential $U_{k\pm}$ is defined as

$$U_{K^\pm}(\mathbf{k}) = \omega_{K^\pm}(\mathbf{k}) - \sqrt{\mathbf{k}^2 + m_{\mathbf{K}}^2} \quad (6)$$

In Zheng *et al*. (2004), they use the Brown and Rho parameterization (Brown and Rho, 1996): $\Sigma_{KN} = 450$ MeV, $f_\pi^{*2} = 0.6 f_\pi^2$ for the vector field and $f_\pi^{*2} = f_\pi^2$ for the scalar part given by. $-\Sigma_{KN} / f_\pi^{*2}$ ρ_s This accounts for the fact that the enhancement of the scalar part using f_π^{*2} is compensated by higher-order corrections in the chiral expansion. In another group, a weaker potential with $\Sigma_{KN} = 350$ MeV and $f_\pi^{*2} = f_\pi^2$ is also applied. This parametrizations is called the Ko and Li parametrization (KLP) (Li and Ko, 1995; Li *et al*., 1995; Ko, 2001). For the nuclear forces, they use the standard momentum dependent Skyrme interactions corresponding to a soft (hard) equation of state (EOS) (k is compression modulus, k = 200 MeV and k = 380 MeV for soft and hard EOS, respectively). For the determination of the kaon mean field, they adopt the corresponding covariant scalar-vector description of the nonlinear σω model.

Probing In-medium Kaon Potential

The potentials given in equation 6 by the BRP and KLP are shown in Figure 1, where the KLP and BRP stand for the Ko and Li parameterization and the Brown and Rho parameterization, respectively. In this Figure 1 shows the kaon potential determined from the kaon-nucleon scattering length using the impulse approximation (IA) (Brown *et al*., 1994). In IA, the energy $\omega(\rho, \mathbf{k})$ is given as:

$$\omega(\rho,\mathbf{k}) = \sqrt{\mathbf{k}^2 + m_K^2 - 4\pi\left(1+\frac{m_K}{m_N}\right)\bar{a}_{KN}\rho} \qquad (7)$$

where m_N is the nucleon mass and $\bar{a}_{KN} \approx$ -0.255 fm is the isospin-averaged kaon-nucleon scattering length in free space (Barnes and Swanson, 1994). We can see from this figure that the potentials predicted by the BRP with the soft EOS (solid curve) and by the KLP with soft EOS (dashed line) are slightly stronger than those with the hard EOS (see the dot curve and long-dashed line, respectively). Up to saturation density, the IA and the BR potentials almost coincide [$U_k(\rho_0) \approx 30 MeV$], but at supra-normal densities the BR potential rises much steeper than the one of the IA. The KL potential [$U_k(\rho_0) \approx 5 MeV$] (dashed line and long-dashed line), on the other hand, is much weaker than those of the BR and the IA.

In order to investigate the influence of covariant dynamics on the K^+ in-plane flow, one considers the 1.93 *A*GeV ^{58}Ni + ^{58}Ni collisions at impact parameter b = 4 fm, which corresponds to the FOPI centrality cut.

Figure 2 shows the K^+ transverse flow as a function of rapidity $Y^{(0)}$ in 1.93 *A*GeV ^{58}Ni + ^{58}Ni reactions at impact parameter b = 4 fm. It is seen from this figure that the strongly repulsive static potential tends to push the kaons dramatically

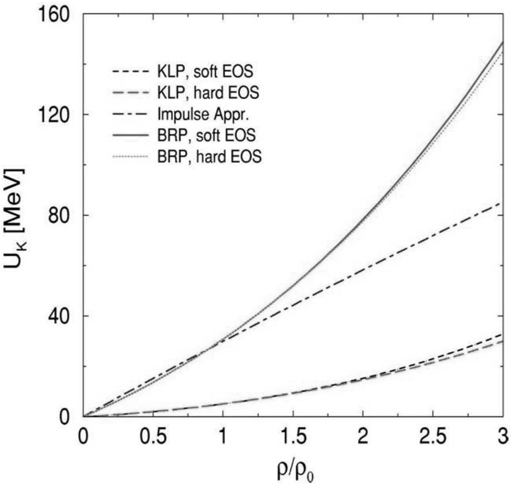

Figure 1. Density dependence of the in-medium kaon potential at zero momentum. This Figure is taken from Zheng *et al.* (2004)

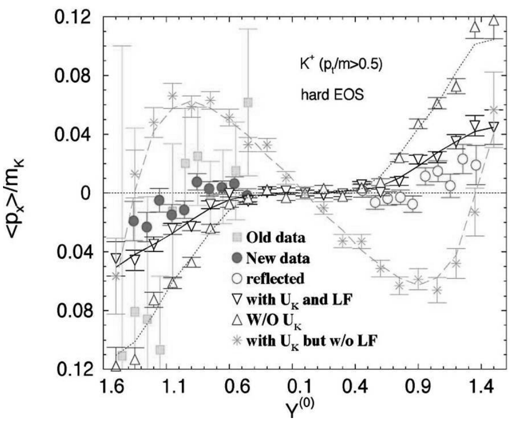

Figure 2. The K^+ transverse flow as a function of rapidity Y_0 in 1.93 *A*GeV ^{58}Ni + ^{58}Ni reactions at impact parameter b = 4 fm. The full squares represent the FOPI data from Ref. (Ritman *et al*., 1995), full circles are more recent FOPI data (Herrmann, 1999), their reflections with respect to midrapidity are shown by the open circles. The calculations are performed using the BRP K^+ in-medium potential with a soft EOS. The open down triangles denote the calculated results with U_K and the Lorentz-force (LF) contribution. The open up triangles indicate the results without U_K. The stars stand for the results with U_K but without LF. This figure is taken from Zheng *et al.* (2004)

away from the spectator matter, leading to a strong anti-flow around midrapidity (stars). The effect of the Lorentz-force (LF) contribution in the covariant kaon dynamics pulls the kaons back to the spectator matter, resulting in a finally reasonable pattern of the K^+ transverse flow, which is in good agreement with the FOPI data (See the open down triangles).

For K^+ mesons, the various transport models provide a relatively coherent picture concern the potential that has effect on kaon multiplicities. The repulsive mean field leads to a reduction of the yields by about 30-50%, depending on the potential, the system size and the energy of the reaction.

The potential effect in central ^{197}Au + ^{197}Au and ^{12}C + ^{12}C reactions as a function of beam energy is given in Figure 3. Throughout this work, the calculations which include an in-medium potential are based on the K^+ mean field. The reduction of the K^+ yield due to the repulsive potential is, as expected, slightly larger in heavy systems than in light systems and most pronounced at energies far below threshold.

Figure 4 gives the excitation functions of the K^+ production cross sections in inclusive ^{197}Au + ^{197}Au and ^{12}C + ^{12}C reactions. Calculations were performed with b_{max} = 11 fm for ^{197}Au+^{197}Au and b_{max} = 5 fm for ^{12}C + ^{12}C. The comparison to data from KaoS (Laue *et al.*, 1999) clearly supports the existence of such a repulsive K^+ potential.

The K^+ rapidity distributions dN / dY^0 ($Y^0 = Y_{lab} / Y_{cm}$ -1)for this reaction is shown in Figure 5. The description of the data requires this repulsive mean field.

The same conclusions are obtained from QMD, IQMD (Hartnack and Aichelin, 2002) and the RBUU (Stochmeier *et al.*, 2001). The RBUU calculations are based on a chiral mean field evaluated in the relativistic Hartree approximation with Σ_{KN} = 450 *MeV* and the mean field is close to that used in the QMD calculations. The IQMD calculations are based on the RMF kaon optical potential of Schaffner (Schaffner Bielich *et al.*, 1997). The kaon production by the repulsive in-medium potential is most pronounced at mid-rapidity, which is understandable from kinematical reasons. It is seen from Figure 5 that the in-medium effect shown in the IQMD calculation is slightly stronger than that given in the QMD and RBUU calculations. Both RBUU calculations use a slightly weaker in-medium potential (The RBUU Giessen is based on the

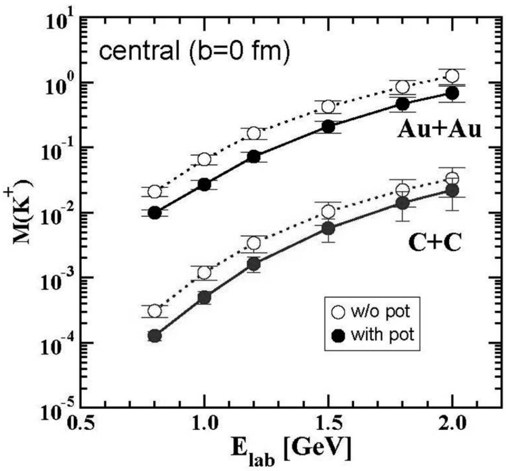

Figure 3. Influence of in-medium K^+ potential on the kaon yields for central (b=0) ^{197}Au + ^{197}Au and ^{12}C + ^{12}C reactions. This Figure is taken from Fuchs (2006)

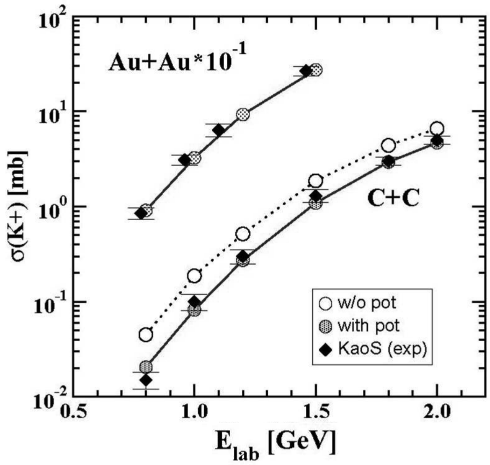

Figure 4. The K^+ excitation functions in Au + Au and C + C reactions are compared to data from KaoS (Laue *et al.*, 1999; Larionov *et al.*, 2002). This Figure is taken from Fuchs (2006)

chiral RHA potential of Mishra *et al*. (2004) and the RBUU Texas is based on the empirical potential of Chen *et al*. (2004). In the QMD calculation, the in-medium potential leads not only to suppression but also to a slight broadening of the rapidity distribution because the covariant dynamics also includes the Lorentz force. The theoretical calculations show the same results for the in-medium effect. Data support the existence of with in-medium kaon potential 1.

The situation should become clear if one considers the K^- / K^+ ratio, in particular its phase space dependence. This is done in Figure 6 where FOPI data (Wisniewski *et al*., 2000) for the K^- / K^+ ratio as a function of rapidity are compared to transport results from Li and Brown (1998) and Cassing and Bratkovskaya (1999). Without in-medium effects, the distributions are predicted to be flat, as also expected, within a statistical approach. The presence of the repulsive K^+ potential pushes the kaons outwards to higher rapidities while the attractive antikaon potential binds K^-'s at mid-rapidity. Both effects lead to an increase of the K^- / K^+ ratio around mid-*rapidity* as also seen in the data. Supplementary data from KaoS (Menzel *et al*., 2000) show that K^- / K^+ ratio reaches in Ni + Ni reactions at 1.93 *A* GeV a value of about 0.04 at mid-rapidity, which is in good agreement with the predictions from Cassing and Bratkovskaya (1999) (with pot.) but in contrast to those of Li and Brown (1998) where the in-medium effects are over estimated. However, more recent calculations which include in-medium modifications of the pion induced K^- productions cross sections $\pi Y \rightarrow NK^-$ and the corresponding absorption cross sections have not such a clear picture (Schaffner-Bielich *et al*., 2000; Tolos *et al*., 2001). The K^- chemistry and the freeze-out time depend crucially on the magnitude of the strangeness exchange cross sections, and this seems also to be reflected in the corresponding rapidity distributions.

To see influence of the in-medium K^+ potential on the out-off-plane flow, the azimuthal distribution of K^+ mesons is solved in Figure 7 (Srisawad *et al*., 2011), for semi-central Au + Au collisions at 1.5 *A* Gev. In this figure, the full circles are the KaoS data (Uhlig *et al*., 2005), which are

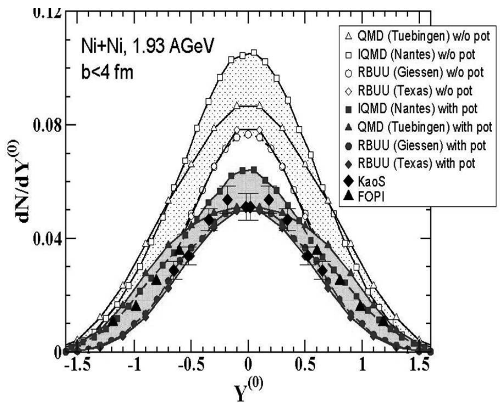

Figure 5. **K^+ rapidity distributions in 1.93 *A*GeV ^{58}Ni + ^{58}Ni reactions at impact parameter b ≤ 4 fm. The calculations are performed with and without an in-medium kaon potential using QMD, IQMD (Hartnack and Aichelin, 2002), and RBUU of Giessen (Mishra *et al*., 2004) and Texas (Chen *et al*., 2004). Calculations are compared to data from FOPI (Best *et al*., 1997) and KaoS (Menzel *et al*., 2000). This Figure is taken from Fuchs (2006)**

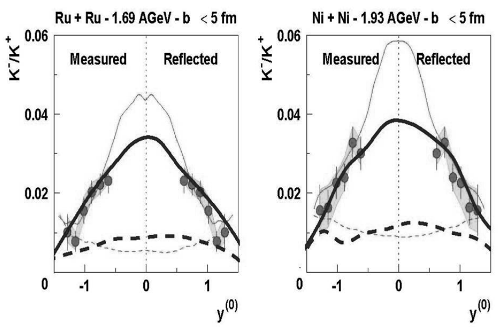

Figure 6. **K^- / K^+ ratio as a function of rapidity in Ru + Ru reactions at 1.69 *A*GeV and Ni + Ni reactions at 1.93 *A*GeV. RBUU calculations (Thick lines: (Cassing and Bratkovskaya, 1999), thin lines: (Li and Brown, 1998) are compared to FOPI data (Wisniewski *et al*., 2000). Solid lines include in-medium potential, dashed lines refer to calculations without in-medium potential. This Ffigure is taken from Wisniewski *et al*. (2000)**

corrected for the resolution of the reaction plane and refer to impact parameter of 5.9 fm < b < 10.2 fm, rapidity of $0.3 < y / y_{beam} < 0.7$, and momentum of $0.2 < p_t < 0.8$ GeV/c. The lines represent results calculated by the QMD model with covariant kaon dynamics (Zheng *et al.*, 2004). The theoretical calculations have the same conditions as the ones in experiments. The dashed line and solid line stand for the results without and with an in-medium K^+N potential, respectively. Both calculations take into account the kaon-nucleon rescattering. It is clear from this figure that the KaoS data can be reasonably reproduced by the QMD calculations if an additional repulsive in-medium K^+N potential is taken into account (solid line).

For the light collision system shown in Figure 8, the effect of the in-medium K^+ potential is also obvious. After taking into account the in-medium K^+ potential, theoretical results (solid line) are in good agreement with experimental data. Similar results are also obtained by the IQMD calculations (Uhlig *et al.*, 2005).

Conclusions

In heavy ion collisions at intermediate energies, i.e. at energies around the threshold region, strangeness is generally produced in the early and high density phase of the reaction. However, the freeze-out conditions for kaons and antikaons are completely different. Due to strangeness conservation, K^+ mesons cannot be reabsorbed by the surrounding nucleons and their chemical freeze-out takes place early. Final state interactions, i.e. elastic scattering or charge exchange reactions and the influence of the optical kaon-nucleon potential change their dynamical pattern but not the abundances. This makes K^+ mesons a suitable 'penetrating' probe to study the in-medium properties of hadrons and the dense nuclear matter created in a heavy ion reaction.

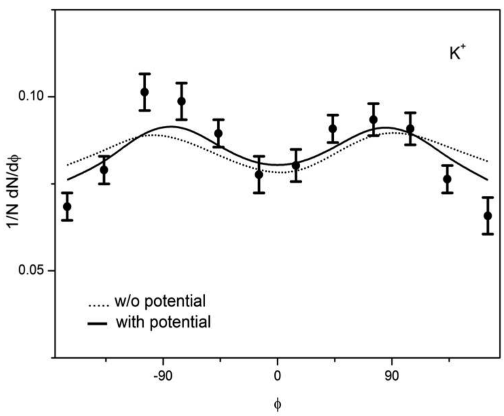

Figure 7. Azimuthal distribution of K^+ mesons for semi-central Au + Au collisions at 1.5A GeV. The full circles are the KaoS data (Unlig *et al.*, 2005), which are corrected for the resolution of the reaction plane and refer to impact parameter of 5.9 fm<*b*<10.2 fm, rapidity of $0.3<y/y_{beam}<0.7$, and momentum of $0.2<p_t<0.8$ GeV/c. The lines represent results calculated by the QMD model with covariant kaon dynamics. The dashed line and solid line stand for results without and with an in-medium K^+N potential, respectively. This Figure is taken from Srisawad *et al.* (2011)

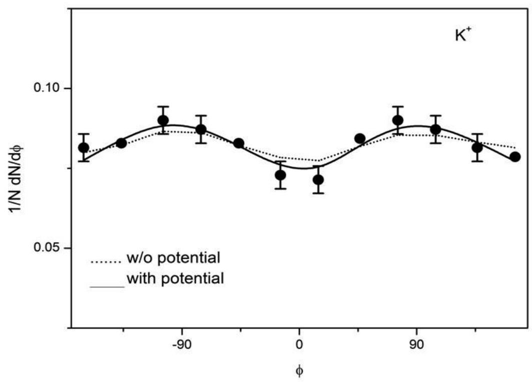

Figure 8. Azimuthal distribution of K^+ mesons from Ni + Ni reactions at 1.93 *A*GeV. The data are corrected for the resolution of the reaction plane and refer to impact parameter of 3.8 fm < *b* < 6.5 fm, rapidity of $0.3<y/y_{beam}<0.7$, and momentum of $0.2 < p_t < 0.8$GeV/c. The lines represent results of QMD calculations. The solid line and dashed line stand for the result with and without an in-medium K^+N potential, respectively. This Figure is taken from Srisawad *et al.* (2011)

Two types of in-medium potentials with different parametrization have been applied. The theoretical results show that in the kaon covariant dynamics the new FOPI data can be reasonably described by using a parametrization proposed by Brown and Rho (1996) which partially accounts for higher-order corrections in the chiral expansion. The reproduction of the more recent FOPI data, in particular at spectator rapidities, requires a relatively strong repulsive K^+ potential, which is in good agreement with those determined from the kaon-nucleon scattering length using the impulse approximation. Most transport simulations reproduce corresponding data only when in-medium K^+ potentials are included.

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References

Barnes, T. and Swanson, E.S. (1994). Kaon-nucleon scattering amplitudes and Z^* enhancements from quark Born diagrams. Phys. Rev. C., 49(2):1166-1184.

Best, D., Pelte, D., Eskef, M., Goebels6, G., Hafele, E., Herrmann, N., Korolija, M., Merlitz, H., Mohren, S., Trzaska, M., Alard, J.P., Amouroux, V., Andronic, A., Basrak, Z., Bastid, N., Belyaev, I., Best, D., Bieganský, J., Buta, A., Caplar, R., Cindro, N., Coffin, J.P., Crochet, P., Dupieux, P., Dzelalija, M., Ero, J., Fintz, P., Fodor, Z., Genoux-Lubain, A., Gobbi, A., Guillaume, G., Hildenbrand, K.D., Hong, B., Jundt, F., Kecskemeti, J., Kirejczyk, M., Koncz, P., Korchagin, Y., Kotte, R., Kuhn, C., Lambrecht, D., Lebedev, A., Legrand, I., Leifels, Y., Manko, V., Mosner, J., Moisa, D., Neubert, W., Petrovici, M., Pinkenburg, C., Pras, P., Rami, F., Ramillien, V., Reisdorf, W., Ritman, J.L., Roy, C., Schuell, D., Seres, Z., Sikora, B., Simion, V., Siwek-Wilczynska, K.V., Smolyankin, V., Sodan, V.U., Vasiliev, M.A., Wagner, P., Wang, G.S., Wienold, Wohlfarth, T.D., Zhilin, A. (1997). K^+ production in the reaction $^{58}Ni + ^{58}Ni$ at incident energies from 1 to 2 A GeV. Nucl. Phys. A., 625 (1-2):307-324.

Brown, G.E., Lee, C.H., Rho, M., and Thorsson, V. (1994). From kaon-nuclear interactions to kaon condensation. Nucl. Phys. A., 567(4): 937-956.

Brown, G.E. and Rho, M. (1996). From chiral mean field to Walecka mean field and aon condensation. Nucl. Phys. A., 596(3-4):503-514.

Cassing, W. and Bratkovskaya, E.L. (1999). Hadronic and electromagnetic probes of hot and dense nuclear matter. Phys. Rep., 308(2-3):65.

Chen, L.W., Ko, C.M., and Tzeng, Y. (2004). Cascade production in heavy-ion collisions at SIS energies. Phys. Lett. B., 584(3-4):269-275.

Fuchs, C. (2006). Kaon production in heavy ion reactions at intermediate energies. Prog. Part. Nucl. Phys., 56(1):1-103.

Fuchs, C., Faessler A., Zabrodin, E., and Zheng, Y.M. (2001). Probing the nuclear equation of state by K^+ production in heavy-ion collisions. Phys. Rev. Lett., 86(10):1974-1977.

Fuchs, C., Kosov, D.S., Faessler, A., Wang, Z.S., and Waindzoch, T. (1998). Consequent of covariant kaon dynamics in heavy ion collisions. Phys. Lett. B., 434(3-4):245-250.

Stochmeier, M.R., Reisdorf, W., Herrmann, N., Merschmeyer, M., Pelte, D., and Wisniewski, K. (2001) Gedellschaft fuer Schwerionenforschung (GSI). Report of GSI Scientific Report Darmstadt, p. 35.

Hartnack, C. and Aichelin, J. (2002). Analysis of kaon production around the threshold. J. Phys. G., 28(7):1649.

Herrmann, H. (1999). Strangeness production and propagation in relativistic heavy ion collisions at SIS energies. Prog. Part. Nucl. Phys., 42:187-196.

Kaplan, D.B. and Nelson A.E. (1986). Strange going on in dense nucleonic matter. Phys. Lett. B., 175(1):57-63.

Ko, C.M. (2001). Medium effects on the flow of strange particles in heavy ion collisions. J.Phys. G., 27: 327.

Korpa, C.L. and Lutz, M.F.M. (2005). Kaon and antikaon properties in cold nuclear medium. Acta Phys. Hungarica A., 22:21-28.

Larionov, A.B., Effenberger, M., Leupold, S., and Mosel, U. (2002). Resonance lifetime in Boltzmann-Uhlenbeck theory: Observable consequences. Phys. Rev. C., 66(5):054604.

Larionov, A.B. and Mosel, U. (2005). Kaon production and propagation at intermediate relativistic energies. Phys. Rev. C., 72(1):014901.

Laue, F., Sturm, C., Bottcher, I., Debowski, M., Forster, A., Grosse, E., Koczon, P., Kohlmeyer, B., Mang, M., Naumann, L., Oeschler, H., Puhlhofer, F., Schwab, E., Senger, P., Shin, Y., Speer, J., Strobele, H., Surowka, G., Uhlig, F., Wagner, A., and Walus, A. (1999). Medium effects in kaon and antikaon production in nuclear collisions at subthreshold beam energies. Phys. Rev. Lett.., 82(8):1640-1643.

Li, G.Q. and Brown, G.E. (1998). K^-/K^+ ratios in relativistic heavy-ion collisions. Phys. Rev. C., 58(3):1698-1705.

Li, G.Q. and Ko, C.M. (1995). Kaon flow in heavy-ion collisions. Nucl. Phys. A., 594(4):460-482.

Li, G.Q., Ko, C.M., and Li, B.-A. (1995). Kaon flow as a probe of the Kaon potential in nuclear medium. Phys. Rev. Lett., 74(2):235-238.

Menzel, M., Böttcher, I., Dębowski, M., Dohrmann, F., Förster, A., Grosse, E., Koczoń, P., Kohlmeyer, B., Laue, F., Naumann, L., Oeschler, H., Pülhofer, F., Schwab, E., Senger, P., Shin, Y., Ströbele, H., Sturm, C., Surówka, G., and Uhlig, F. (2000). First measurement of antikaon phase- space distributions in nucleus-njcleus collisions at subthreshold energies. Phys. Lett. B., 495(1-2)26-32.

Mishra, A., Bratkovskaya, E.L., Schaffner-Bielich, J., Schramm, S., and Stocker, H. (2004). Kaons and antikaons in hot and dese hadronic matter. Phys. Rev. C., 70(4):044904.

Nelson, A.E. and Kaplan, D.B. (1987). Strange condensate realignment in relativistic heavy ion collisions. Phys. Lett. B., 192(1-2):193-197.

Randrup, J. and Ko, C.M. (1980). Kaon production in relativistic nuclear collisions. Nucl. Phys. A., 343:519-544.

Ritman, J.L., Herrmann, N., Best, D., Alard, J.P., Amouroux, V., Bastid, N., Belyaev, I., Berger, L., Bieganský, J., Buta, A., Caplar, R., Cindro, N., Coffin, J.P., Crochet, P., Dona, R., Dupieux, P., Dzelalija, M., Fintz, P., Fodor, Z., Genoux-Lubain, A., Gobbi, A., Goebels, G., Guillaume, G., Grigorian, Y., Höafele, E., Hildenbrand, K.D., Höolbling, S.H., Jundt, F., Kecskemeti, J., Kirejczyk, M., Korchagin, Y., Kotte, R., Kuhn, C., Lambrecht, D., Lebedev, A., Lebedev, A., Legrand, A., Leifels, Y., Maazouzi, C., Manko, V., Matulewicz, T., Möosner, J., Mohren, S., Moisa, D., Neubert, W., Pelte, D., Petrovici, M., Pinkenburg, C., Rami, F., Ramillien, V., Reisdorf, W., Roy, C., Schuell, D., Seres, Z., Sikora, B., Simion, V., Siwek-Wilczyhska, K., Smolyankin, V., Sodan, U., Tizniti, L., Trzaska, M., Vasiliev, M.A., Wagner, P., Wang, G.S., Wienold, T., Wohlfarth, D., and Zhilin, A. (1995). On the transverse momentum distribution of strange hadrons produced in relativistic heavy ion collisions. Zeitschrift főr Physik A Hadrons and Nuclei., 352(4):355-357.

Schaffner-Bielich, J., Koch, V., and Effenberger, M. (2000). Medium modified cross sections, temperature and finite momentum effects for antikaon production in heavy ion collisions. Nucl. Phys. A., 669(1-2):153-172.

Schaffner-Bielich, J., Mishustin, I.N., and Bondorf, J. (1997). In-medium kaon production at the mean-field level. Nucl. Phys. A., 625(1-2):325-346.

Srisawad, P., Zheng, Y.M., Katsungnoen, O., Limpirat, A., and Yan, Y. (2011). Azimuthal distributions of strange mesons in heavy-ion collisions. Few-body Systems." In press.,"

Tolos, L., Cabrera, D., Ramos, A., and Polls, A. (2006). The effect of the in-medium pentaquark on the kaon optical potential. Phys. Lett. B., 632 (2-3):219-225.

Tolos, L., Ramos, A., Polls, A., and Kuo, T.T.S. (2001). Partial wave contributions to the antikaon potential at finite momentum. Nucl. Phys. A., 690(4):547-566.

Uhlig, F., Főrster, A., Böttcher, I., Debowski, M., Dohrmann, F., Grosse, E., Koczon, P., Kohlmeyer, B., Laue, F., Menzel, M., Naumann, L., Oeschler, H., Scheinast, W., Schwab, E., Senger, P., Shin, Y., Stroöbele, H., Sturm, C., Suroówka, G., Wagner, A., and Walus, W. (2005) Observation of different azimuthal emission patterns of K^+ and of K^- mesons in heavy-ion collisions at 1-2 A GeV. Phys. Rev. Lett., 95(1):012301.

Wisniewski, K., Crochet, P., Herrmann, N., Andronic, A., Averbeck, R., Devismes, A., Finck, C., Gobbi1, A., Hartmann, O., Hildenbrand, K.D., Koczon1, P., Kress, T., Kutsche, R., Leifels1, Y., Reisdorf, W., Schüll, D., Alard, J.P., Barret, V., Basrak, Z., Bastid, N., Belyaev, I., Bendarag, A., Berek, G., Caplar, R., Cindro, N., Dupieux, P., Dzelalija, M., Eskef, M., Fodor, Z., Grishkin, Y., Hong, B., Kecskemeti, J, .Kim, Y.J., Kirejczyk, M., Korolija, M., Kotte, R., Kowalczyk, M., Lebedev, A., Lee, K.S., Manko, V., Merlitz, H., Mohren, S., Moisa, D., Neubert, W., Nianine, A., Pelte, D., Petrovici, M., Plettner, C., Rami, F., de Schauenburg, B., Seres, Z., Sikora, B., Sim,K. S., Simion, V., Siwek-Wilczýnska, K., Smolyankin, V., Somov, A., Stockmeier, M., Stoicea, G., Vasiliev, M., Wagner, P., Wohlfarth, D., Yang, J.T., Yushmanov, I., Zhilin, A. (2000). Direct comparison of phase-space distributions of K^- and K^+ mesons in heavy-ion collisions at SIS energies- evidence for in-medium modifications of kaons Euro. Phys. J. A., 9(4):515-519.

Zheng, Y.M., Chu, Z.L., Fuchs, C., Faessler, A., Xiao, W., Hua, D.P., and Yan, Y.P. (2002). Transverse flow of kaon in heavy-ion collisions. Chinese Phys. Lett., 19(7):926.

Zheng, Y.M., Fuchs, C., Faessler, A., Shekhter, K., Yan, Y.P., and Kobdaj, C. (2004). Covariant kaon dynamics and kaon flow in heavy ion collisions. Phys. Rev. C., 69(3):034907.