重离子碰撞中K^+介子的横动能谱

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Introduction

- **One of the essential questions in nuclear physics is to study the nuclear equation of state (EOS), especially in dense matter. This is also very important in astrophysics and particle physics.**

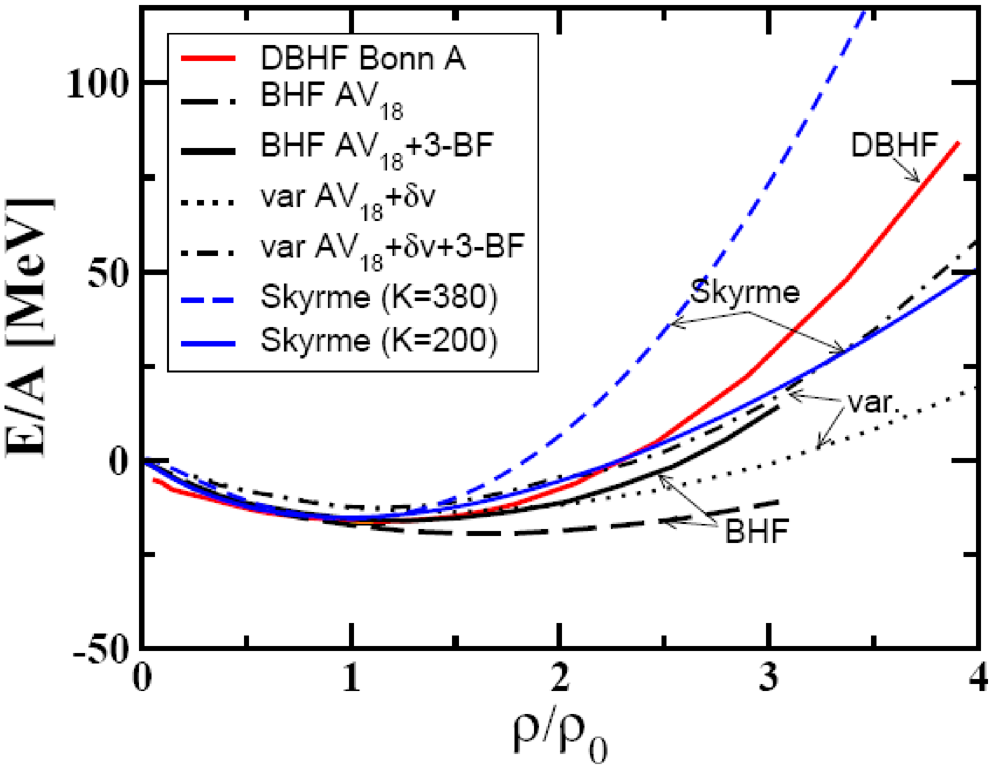


Fig. 1. The dependence of excitation energy of the nuclear matter on density.

- **The 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 and temperatures.**
- **Kaon is produced in the early stage of heavy ion collisions at which the nuclear density in the reaction zone is much higher than the saturation density ($\rho_0 = 0.16 fm^{-3}$). After its production K^+ meson escapes near-freely from the reaction zone due to the relatively low K^+N scattering cross section (10 milibarn) and the absence of the absorption channel of a K^+ meson on a nucleon in strong interaction. So, K^+ meson is proposed to be a sensitive probe to study the nuclear equation of state (EOS) in dense hadronic matter.**

- **we apply the quantum molecular dynamics (QMD) model based on the covariant kaon dynamics to simulate the ^{58}Ni + ^{58}Ni collisions at 1.93 AGeV, to analyze the transverse energy spectra of K^+ mesons, to discuss the influence of the in-medium kaon potential on the transverse energy spectra of K^+ mesons, and to make a comparison between calculated results and KaoS data.**

The model

- **Nucleons are described by the QMD model. Then, one gets the density** $\rho(\vec{r},t) = \sum_i^N \frac{1}{(2\pi L)^{3/2}} exp[-\frac{(\vec{r}-\vec{r}_{i0})^2}{2L}].$
  Thus, the local potential $U(r)$ **of a nucleon can be easily calculated.**

● **Kaons are described by the covariant kaon dynamics.**

- Chiral SU(3) Lagrangian

The chiral $SU(3)_L$ x $SU(3)_R$ Lagrangian used by Kaplan and Nelson [PLB 175 (86) 57, NPLB 192 (87) 193] reads

$$\begin{aligned}\mathcal{L} &= \frac{1}{4} f^2 \mathrm{Tr}\partial^\mu \Sigma \partial_\mu \Sigma^+ + \frac{1}{2} f^2 \Lambda [\mathrm{Tr} M_q (\Sigma - 1) + \mathrm{h.c.}] + \mathrm{Tr}\bar{B}(i\gamma^\mu \partial_\mu - m_B) B \\ &+ i\mathrm{Tr}\bar{B}\gamma^\mu [V_\mu, B] + D\mathrm{Tr}\bar{B}\gamma^\mu\gamma^5\{A_\mu, B\} + F\mathrm{Tr}\bar{B}\gamma^\mu\gamma^5[A_\mu, B] \\ &+ a_1 \mathrm{Tr}\bar{B}(\xi M_q \xi + \mathrm{h.c.})B + a_2 \mathrm{Tr}\bar{B}B(\xi M_q \xi + \mathrm{h.c.}) \\ &+ a_3 [\mathrm{Tr} M_q \Sigma + \mathrm{h.c.}]\mathrm{Tr}\bar{B}B. \end{aligned} \quad (1)$$

The degrees of freedom in Eq. (1) are the baryon octet B and the pseudoscalar meson octet ϕ

$$B = \begin{pmatrix} \frac{\Lambda}{\sqrt{6}} + \frac{\Sigma^0}{\sqrt{2}} & \Sigma^+ & p \\ \Sigma^- & \frac{\Lambda}{\sqrt{6}} - \frac{\Sigma^0}{\sqrt{2}} & n \\ \Xi^- & \Xi^0 & -\frac{2}{\sqrt{6}}\Lambda \end{pmatrix} \tag{2}$$

$$\phi = \sqrt{2} \begin{pmatrix} \frac{\eta_8}{\sqrt{6}} + \frac{\pi^0}{\sqrt{2}} & \pi^+ & K^+ \\ \pi^- & \frac{\eta_8}{\sqrt{6}} - \frac{\pi^0}{\sqrt{2}} & K^0 \\ K^- & \overline{K^0} & -\frac{2}{\sqrt{6}}\eta_8 \end{pmatrix} \tag{3}$$

The chiral pseudoscalar meson field are

$$\Sigma = \exp(2i\phi/f_\pi) \quad \text{and} \quad \xi = \sqrt{\Sigma} = \exp(i\phi/f_\pi) \quad . \tag{4}$$

$f_\pi \approx 93$ MeV.

The current quark mass matrix is given by

$$M_q = \begin{pmatrix} m_q & 0 & 0 \\ 0 & m_q & 0 \\ 0 & 0 & m_s \end{pmatrix} \tag{5}$$

where $m_u \approx m_d \equiv m_q \approx 5.5$ MeV.

The mesonic vector $V\mu$ and axial vector $A\mu$ are

$$V_\mu = \frac{1}{2}(\xi^+\partial_\mu\xi + \xi\partial_\mu\xi^+) \quad \text{and} \quad A_\mu = \frac{i}{2}(\xi^+\partial_\mu\xi - \xi\partial_\mu\xi^+) \tag{6}$$

- Effectve chiral Lagrangian

By expending the pseudoscalar meson field Σ up to $1/f_\pi^{\,2}$, and only keeping the kaon field K and explicitly only nucleon and kaon degrees of freedom, the Lagrangian (1) is reduced to the effectve chiral kaon-nucleon Lagrangian

$$\begin{aligned}\mathcal{L} \;=\; & \bar{N}(i\gamma^\mu\partial_\mu - m_N)N + \partial^\mu\bar{K}\partial_\mu K - (m_{\mathrm{K}}^2 - \frac{\Sigma_{KN}}{f_\pi^2}\bar{N}N)\bar{K}K \\ & - \frac{3i}{8f_\pi^2}\bar{N}\gamma^\mu N\bar{K}\overleftrightarrow{\partial}_\mu K \end{aligned} \qquad (7)$$

where the kaon field and the nucleon field are

$$K = \begin{pmatrix} K^+ \\ K^0 \end{pmatrix} \text{ and } \bar{K} = (K^- \;\; \bar{K}^0), \quad N = \begin{pmatrix} p \\ n \end{pmatrix} \text{ and } \bar{N} = (\bar{p} \;\; \bar{n})$$

It contains a vector interaction which is repulsive for kaons and attractive for antikaons due to g-parity. The kaon mass m_K can be related to the vacuum quark condensates

$$m_{\mathrm{K}}^2 = \frac{1}{2}(m_u + m_s)\langle \bar{u}u + \bar{s}s \rangle \quad . \qquad (8)$$

The kaon-nucleon sigma term is

$$\Sigma_{\mathrm{KN}} = \frac{1}{2}(m_u + m_s)\langle N|\bar{u}u + \bar{s}s|N \rangle \quad . \qquad (9)$$

Kaon -nucleon scattering yields values for the isospin averaged sigma term of about $\Sigma_{KN} \approx 400$ MeV whereas lattice QCD predicts values between 300 and 450 MeV. Thus Σ_{KN} can range from $2m_{\pi}$ up to 450 MeV.

- Mean field dynamics

By applying the mean-field approximation, the field equations for the $K^{\pm}$ mesons are given as

$$\left[\partial_\mu \partial^\mu \pm \frac{3i}{4f_\pi^2} j_\mu \partial^\mu + \left(m_K^2 - \frac{\Sigma_{KN}}{f_\pi^2}\rho_s\right)\right] \phi_{K^\pm}(x) = 0 \quad . \qquad (10)$$

where ρ_s is the baryon scalar density, j_μ is the baryon

four-vector current, $f_\pi{}^*$ is the in-medium pion decay constant. Introducing the kaonic vector potential

$$V_\mu = \frac{3}{8f_\pi^2} j_\mu \qquad (11)$$

Eq. (10) can be rewritten in the form

$$\left[(\partial_\mu \pm iV_\mu)^2 + m_K^{*2}\right] \phi_{K^\pm}(x) = 0 \quad . \qquad (12)$$

The effective mass $m_K{}^*$ of the kaon is given by

$$m_{\rm K}^* = \sqrt{m_{\rm K}^2 - \frac{\Sigma_{\rm KN}}{f_\pi^2}\rho_{\rm s} + V_\mu V^\mu} \qquad (13)$$

Introducing effective momenta (k_μ * = (E*,K*)) as

$$k_\mu^* = k_\mu \mp V_\mu \qquad (14)$$

the Klein-Gordon Eqs. (10) and (12) reads in momentum space

$$\left[k^{*2} - m_{\rm K}^{*2}\right] \phi_{\rm K}(k) = 0 \quad . \qquad (15)$$

Through the in-medium dispersion relation

$$0 = k_\mu^{*2} - m_{\rm K}^{*2} = k_\mu^2 - m_{\rm K}^2 - 2m_{\rm K}U_{\rm opt} \quad . \qquad (16)$$

one gets the kaon optical potential

$$U_{\rm opt}(\rho, {\bf k}) = -\Sigma_S \pm \frac{k_\mu V^\mu}{m_{\rm K}} + \frac{\Sigma_S^2 - V_\mu^2}{2m_{\rm K}} = \pm\frac{k_\mu V^\mu}{m_{\rm K}} - \frac{\Sigma_{\rm KN}}{f_\pi^2 2m_{\rm K}}\rho_{\rm s} \quad . \qquad (17)$$

The total scalar kaon self-energy is

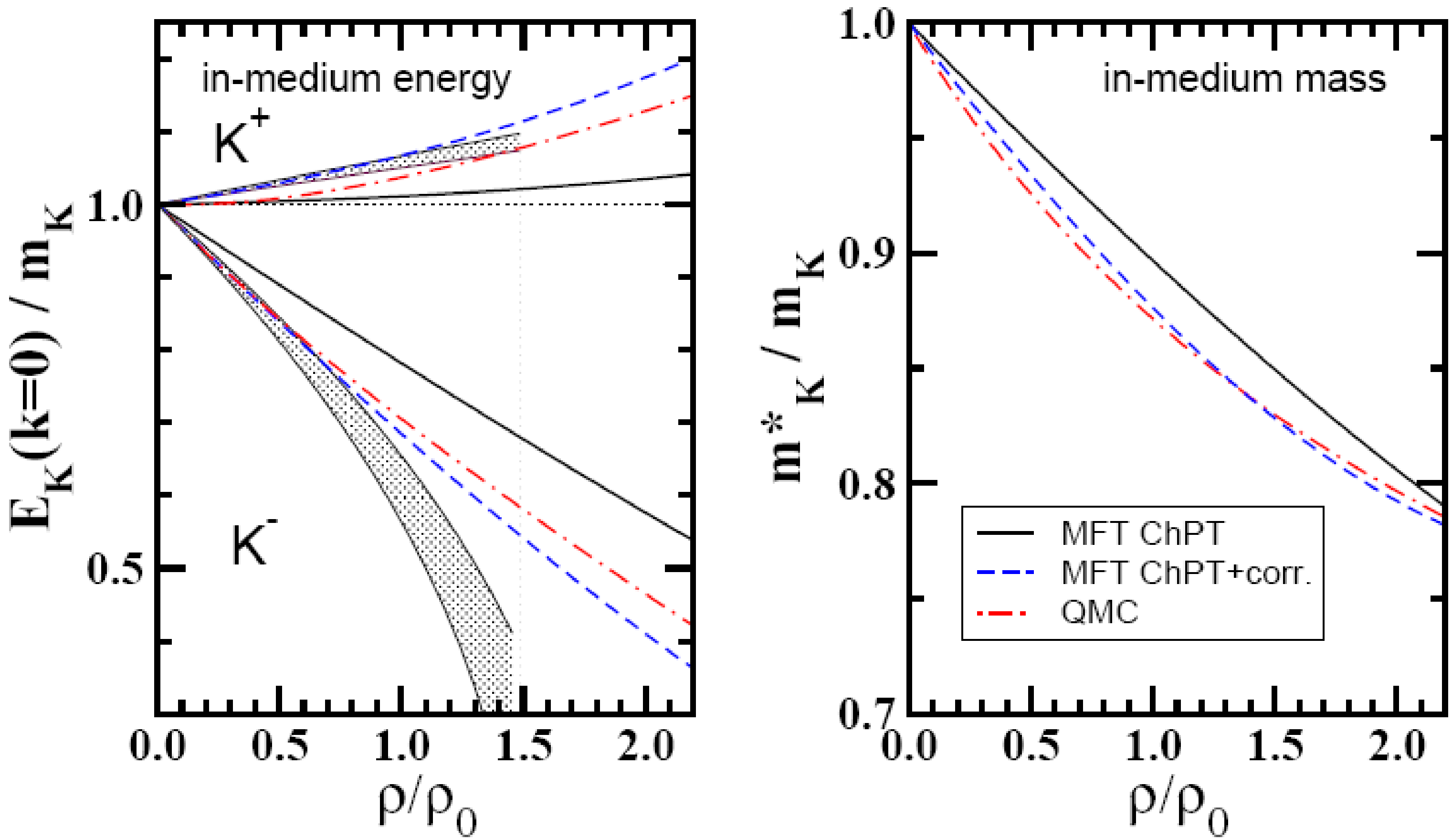
$$\Sigma_S \equiv m_{\rm K} - m_{\rm K}^* \approx \frac{1}{2m_{\rm K}}\left(\frac{\Sigma_{\rm KN}}{f_\pi^2}\rho_{\rm s} - V_\mu^2\right) \quad . \qquad (18)$$

From Eq. (15) the dispersion relation follows

$$E(\mathbf{k}) = k_0 = \sqrt{\mathbf{k}^{*2} + m_{\rm K}^{*2}} \pm V_0 \quad . \qquad (19)$$

In nuclear matter at rest where the space-like components of the vector potential vanish, i.e. V=0 and K* = K, Eq. (19) reduces to

$$E(\mathbf{k}) = \sqrt{\mathbf{k}^2 + m_{\rm K}^2 - \frac{\Sigma_{\rm KN}}{f_\pi^2}\rho_{\rm s} + V_0^2} \pm V_0 \quad . \qquad (20)$$



In-medium kaon energy (left) and quasi-particle mass (right) in the Chiral mean field theory (MFT ChPT) and including higher order corrections (MFT ChPY + corr.). Results from the mean field quark-meson-coupling (QMC) model are shown as well. The bands represent the values extracted from empirical K^+N scattering and K^- atoms [Nucl. Rep. 287 (97) 385].

Kaon production in transport model

In our transport model, the production of K^+ mesons is from baryon induced reactions

$$BB \to BYK^+, \qquad (21)$$

where B stands either for a nucleon or a Δ-resonance, Y for a Λ or a Σ hyperon, and processes induced by pion absorption

$$\pi B \to YK^+. \qquad (22)$$

For pion induced reactions the elementary cross sections of Tsushima et al [PLB337(94)245; J. Phys. G21 (95)33] have been used. The cross sections of baryons, including all baryonic resonances with masses below 2 GeV as intermediate states, are derived within the resonance model in the Born approximation.

The covariant equations of motion for kaons can be derived from Eq. (15). They are analogous to the corresponding relativistic equations for baryons and read

$$\frac{dq^\mu}{d\tau} = \frac{k^{*\mu}}{m_K^*} = u^\mu \quad , \tag{23}$$

$$\frac{dk^{*\mu}}{d\tau} = \frac{k^*_\nu}{m_K^*} F^{\mu\nu} + \partial^\mu m_K^* \quad . \tag{24}$$

Here $q^\mu = (t, \mathbf{q})$ are the coordinates in Minkowski space and $F^{\mu\nu} = \partial^\mu V^\nu - \partial^\nu V^\mu$ is the field strength tensor for K^+. For K^- where the vector field changes sign. The equation of motion are identical, however, $F^{\mu\nu}$ has to be replaced by $-F^{\mu\nu}$. The structure of Eq. (24) may become more transparent considering only the spatial components

$$\frac{d\mathbf{k}^*}{dt} = -\frac{m_K^*}{E^*}\frac{\partial m_K^*}{\partial \mathbf{q}} \mp \frac{\partial V^0}{\partial \mathbf{q}} \pm \frac{\mathbf{k}^*}{E^*} \times \left(\frac{\partial}{\partial \mathbf{q}} \times \mathbf{V}\right), \qquad (25)$$

where the upper (lower) signs refer to K^+ (K^-).

Following Brown and Rho [NPA596(96)503], we use Σ_{KN} =450 MeV, $f_\pi{}^{*2} = 0.6\, f_\pi{}^2$ for vector field and $f_\pi{}^{*2} = f_\pi{}^2$ for the scalar part given by $-\Sigma_{KN}/ f_\pi{}^{*2} \rho_s$.

This accounts for the fact that the enhancement of the Scalar part using $f_\pi{}^{*2}$ is compensated by higher-order corrections in the chiral expansion.

Results and discussions

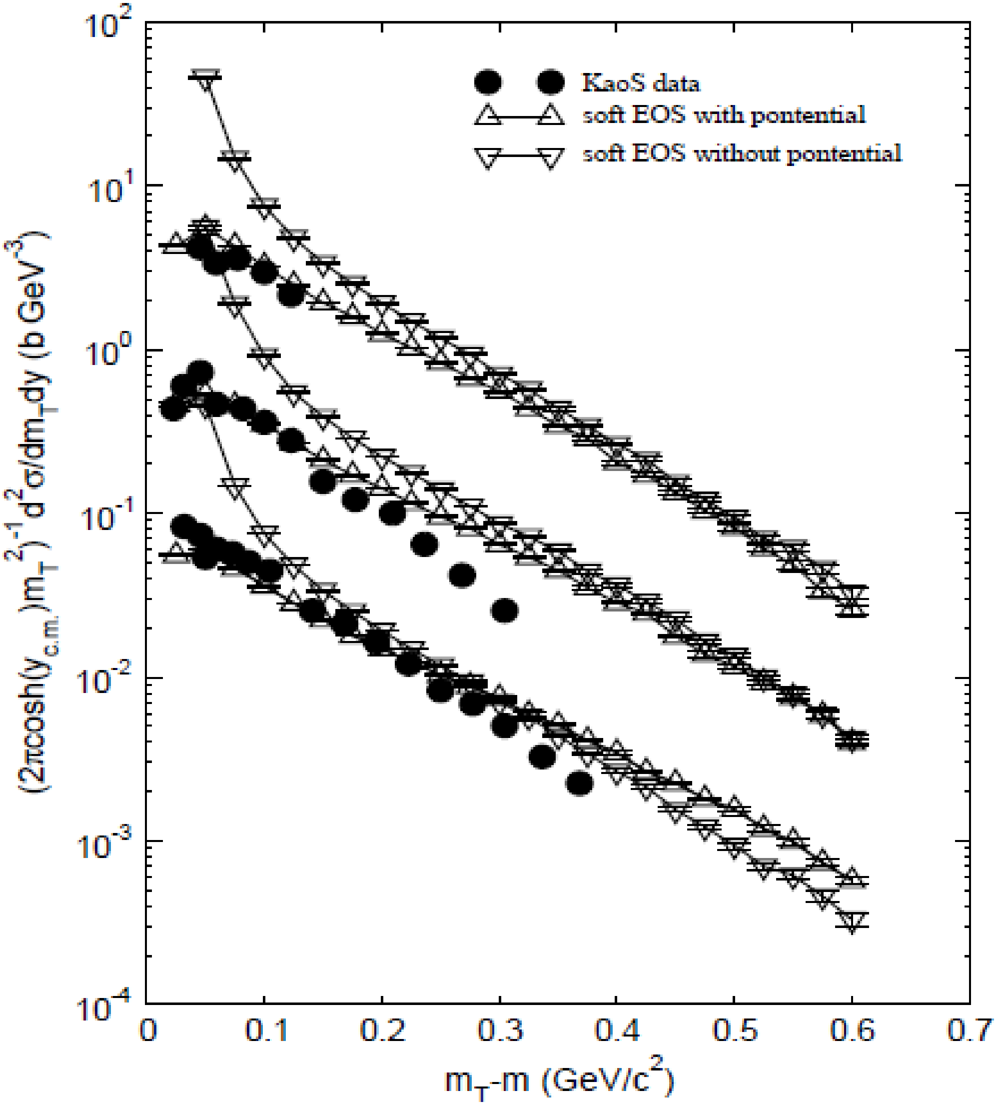


Figure 1: The transverse kinematical energy spectra of K^+ mesons as a function of the transverse kinetic energy $(m_T - m)$ from the $^{58}_{28}$Ni + $^{58}_{28}$Ni collisions at 1.93 AGeV by using the soft EOS with and without the in-medium kaon potential U_K for impact parameter $b \leq 4.5$ fm. The spectra are extracted in the following c.m. rapidity intervals (from top to bottom): -0.69 < $y_{c.m.}$ < -0.54, 0.54 < $y_{c.m.}$ < -0.39 and -0.39 < $y_{c.m.}$ < -0.24. The scaling factors 10^2, 10^1 and 10^0 are applied to the spectra from top to bottom. Data are

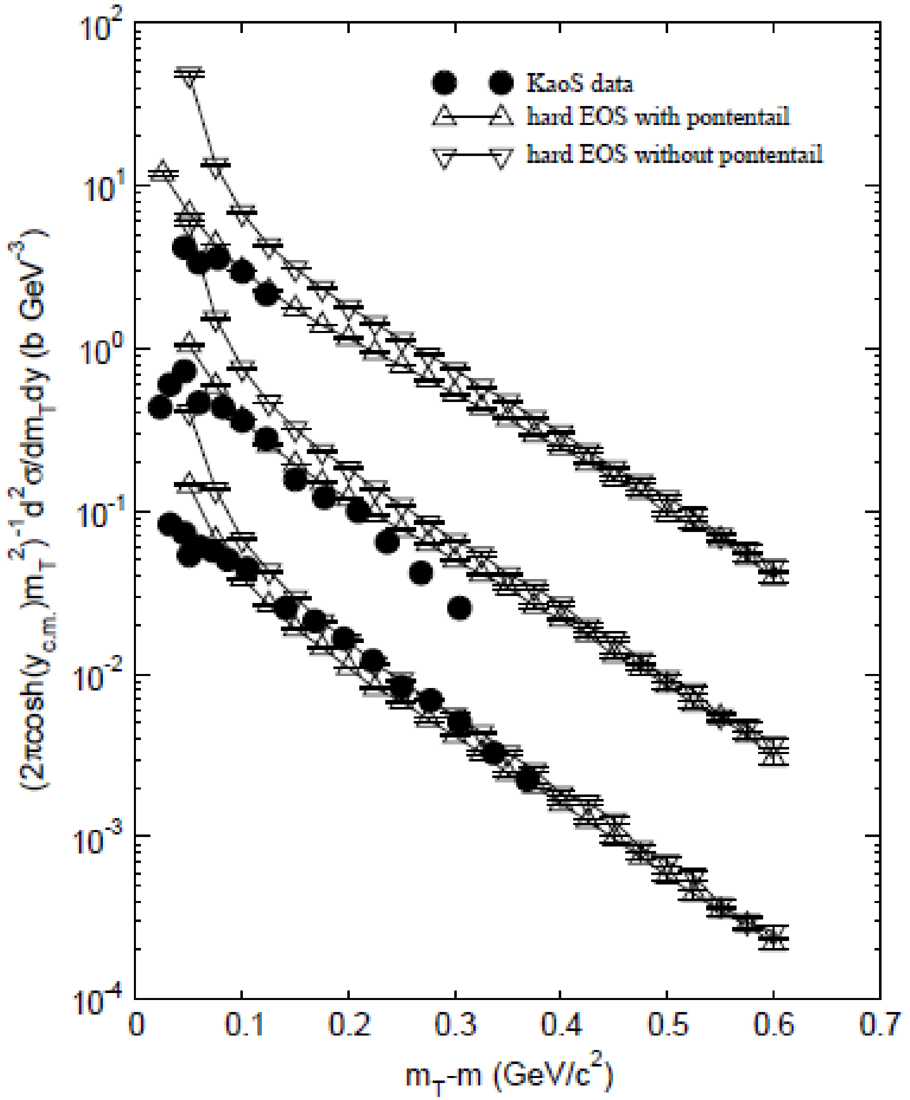
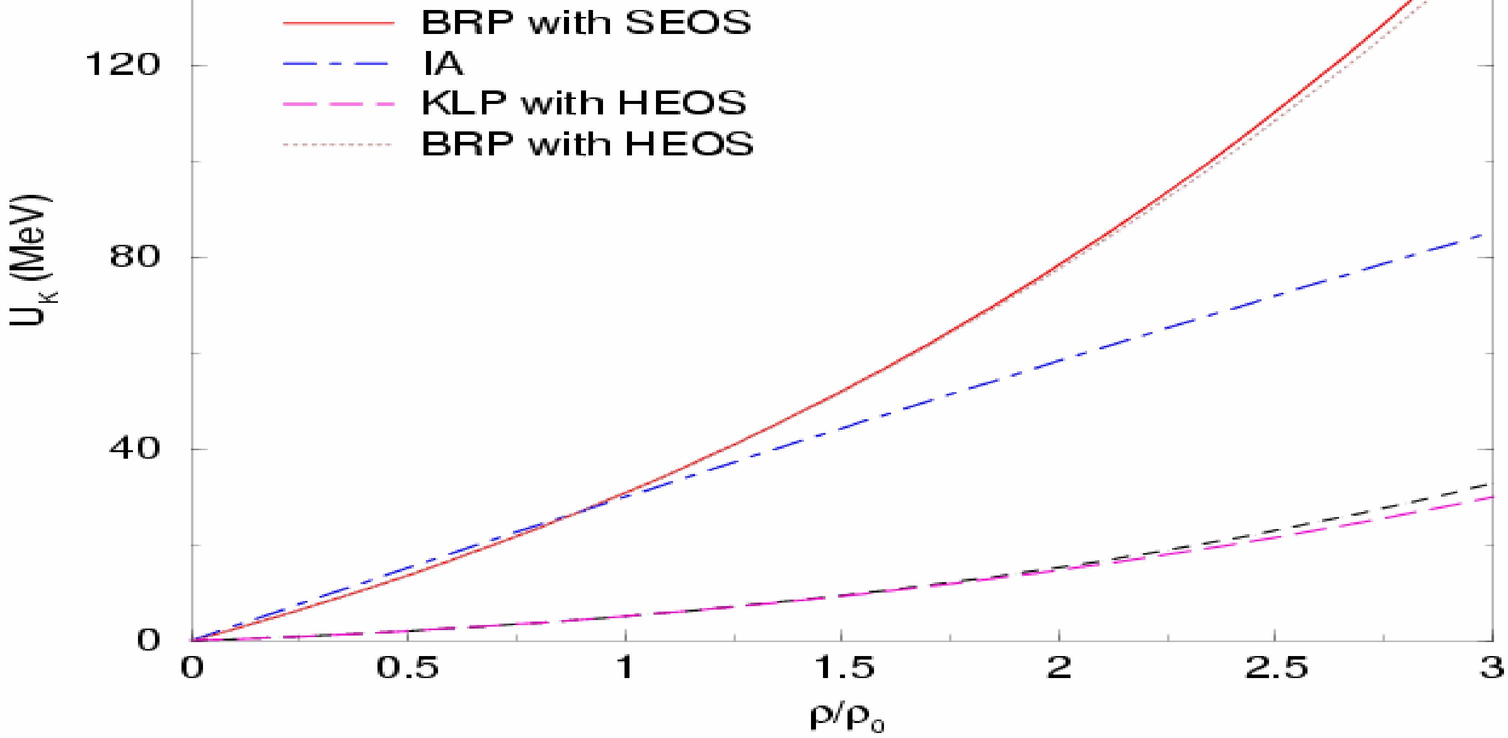


Figure 2: The same as that in Fig. 1, but by using the hard EOS.

From above studies we can make conclusion that the KaoS data for the transverse energy spectra of K^+ mesons can only be described within the in-medium scenario. This means that the K^+ production can be used to probe the in-medium kaon potential, and consequently to probe an expected partial restoration of chiral symmetry at supra-normal nuclear densities.



Density dependence of the in-medium kaon potential at zero momentum. IA: the impulse approximation [NPA 567 (1994) 937], where

$$\omega(\mathbf{k},\rho) = \sqrt{\mathbf{k}^2 + m_{\mathrm{K}}^2 - 4\pi\left(1 + \frac{m_K}{m_N}\right)\bar{a}_{\mathrm{KN}}\rho}, \qquad \bar{a}_{\mathrm{KN}} \approx -0.255 \text{ fm}$$

One can see from this figure that

at $\rho / \rho_0 = 1$ U_K (BRP) $\approx$ 30 MeV $\approx$ U_K (IA), which agrees with another predictions (first mean field calculations and the ones given by p + A reactions).

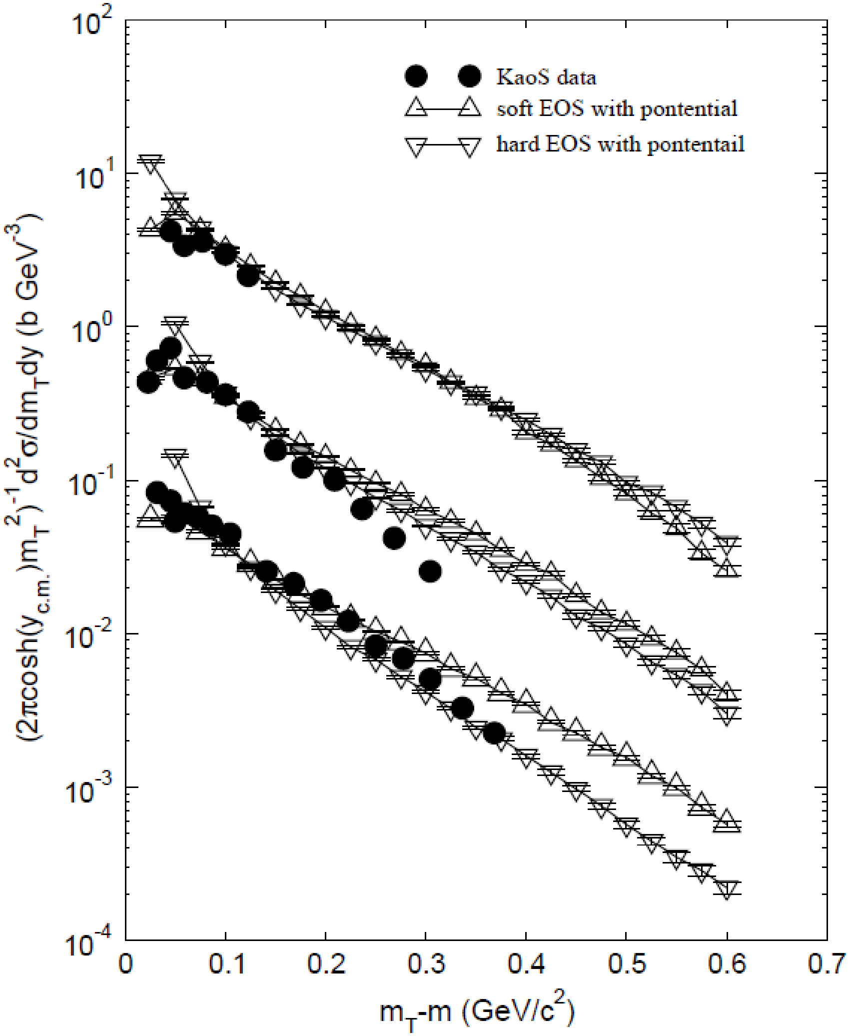
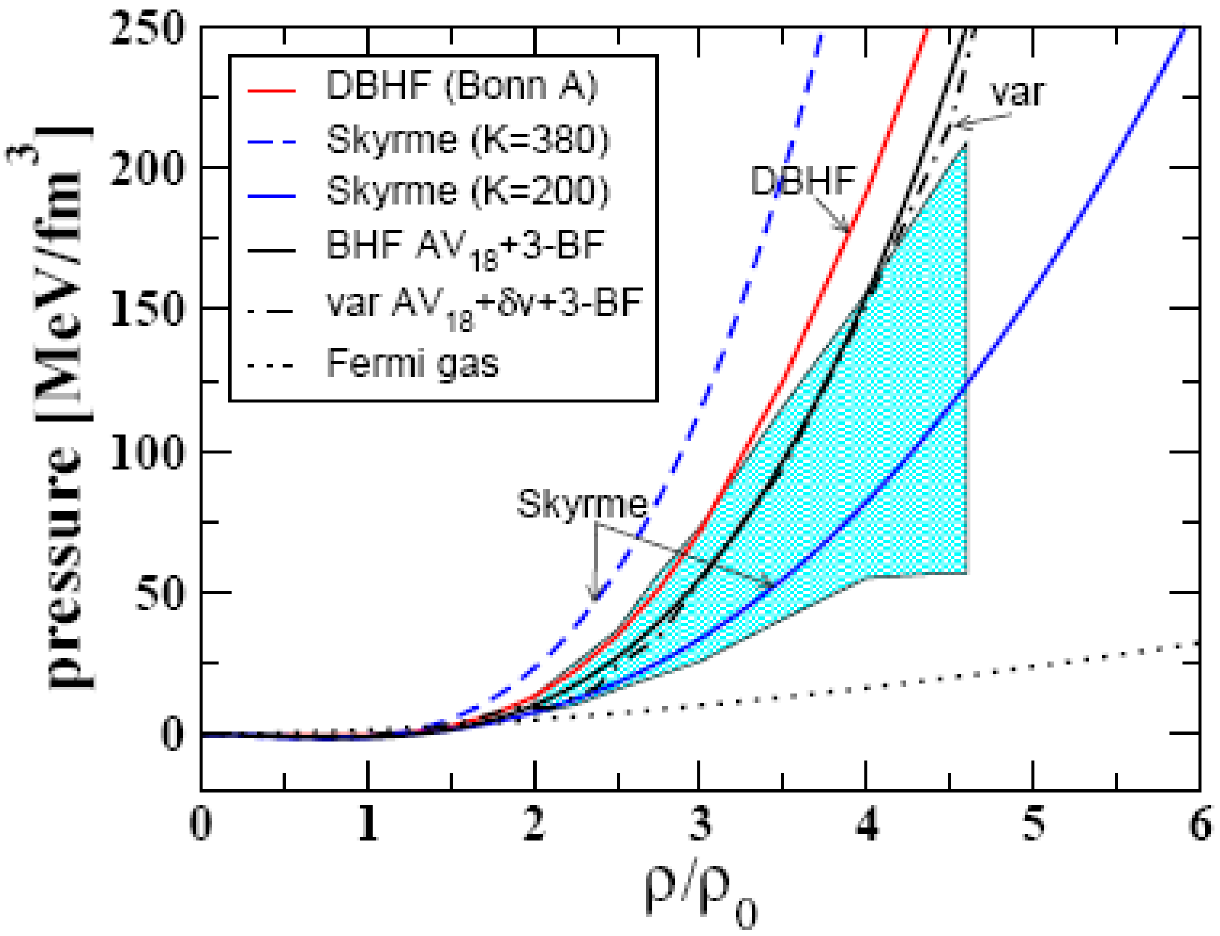


Figure 3: The transverse kinematical energy spectra of K^+ mesons as a function of the transverse kinetic energy $(m_T - m)$ from the $^{58}_{28}$Ni + $^{58}_{28}$Ni collisions at 1.93 AGeV by using the soft and hard EOS with the in-medium kaon potential U_K for impact parameter $b \leq 4.5$ fm. The spectra are extracted in the following c.m. rapidity intervals (from top to bottom): -0.69 < $y_{c.m.}$ < -0.54, 0.54 < $y_{c.m.}$ < -0.39 and -0.39 < $y_{c.m.}$ < -0.24. The scaling factors 10^2, 10^1 and 10^0 are applied to the spectra from top to bottom. Data are taken from Ref. [18].

It is known from figure 3 that the theoretical results given by the soft EOS are in better agreement with data. This means that the dense matter created in this reaction has the property with the soft EOS.

The present status



gure 51: Constraints on the nuclear EOS from heavy ion flow data. The shaded are
essure-density which is compatible with heavy ion flow data according the analysis o
uations-of-state from the models shown in Fig. 40 are displayed.

Summary

1. We have investigated the transverse energy spectra of K^+ mesons as a function of the transverse kinetic energy (m_T - m) from the ^{58}Ni + ^{58}Ni collisions at 1.93 AGeV within the QMD model based on the covariant kaon dynamics.
2. We observe that the KaoS data can only be reasonably described by calculated results with a repulsive K^+ in-medium potential. This indicates that one can extract the information on the K^+ in-medium potential in a nuclear medium from the analysis of the transverse energy spectra of K^+ mesons.
3. We find that the transverse energy spectra of K^+ mesons is also a sensitive observable to probe the nuclear equation of state (EOS) in dense nuclear matter.

Thank you!