

# Influence of the in-medium kaon potential on kaon production in heavy ion collisions

P Srisawad<sup>1,4</sup>, A Harfield<sup>1</sup>, S Sombun<sup>1</sup>, T Katukum<sup>1</sup>, O Ketsungnoen<sup>1,4</sup>, Y M Zheng<sup>2</sup>, A Limphirat<sup>3,4</sup> and Y Yan<sup>3,4</sup>

<sup>1</sup> Faculty of Science, Naresuan University, Phitsanulok 65000, Thailand

<sup>2</sup> China Institute of Atomic Energy, P.O. Box 275(18), 102413 Beijing, China

<sup>3</sup> School of Physics, Suranaree University of Technology, Nakhon Ratchasima 30000, Thailand

<sup>4</sup> Thailand Center of Excellence in Physics (ThEP), CHE, Bangkok 10400, Thailand

E-mail: pornrads@gmail.com

## Abstract.

The inclusive cross section and polar angle distribution of  $K^+$  mesons in Ni + Ni collisions at incident energy 1.93 AGeV are studied using the Quantum Molecular Dynamics model based on the covariant kaon dynamics, and compared with experimental KaoS data from GSI. The calculated  $K^+$  yields better fit to experiment data for a soft nuclear equation of state (compression modulus  $K = 200$  MeV) when including the in-medium  $K^+$  potential (its value at saturation density is  $U_k(\rho_0) \approx 30$  MeV). The calculated results for the polar angle distribution of  $K^+$  in Ni + Ni collisions at 1.93 AGeV are slightly more forward and back direction than KaoS data.

## 1. Introduction

Kaons production in heavy ion collisions is a relevant topic for theoretical and experimental studies. Properties of kaons in dense hadronic matter are important for a better understanding of both the possible restoration of chiral symmetry in dense hadronic matter and the properties of nuclear matter at high density. Kaons are created in binary collisions of baryons and mesons ( $E_{beam} = 1.58$  GeV for  $NN \rightarrow K\Lambda N$  and  $E_{beam} = 2.5$  GeV for  $NN \rightarrow NNK\bar{K}$ , the secondary processes  $\Delta N \rightarrow KYN$ ,  $\pi N \rightarrow KY$ , and  $\pi Y \rightarrow KN$ ). 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.[1] demonstrated that the new FOPI data on the kaon in-plane flow [2] are best described by using the in-medium kaon potential given by the Brown and Rho parametrization [3] ( $U_k(\rho_0) \approx 30$  MeV, where  $\rho_0 = 0.16$  fm<sup>-3</sup>).

In this work we calculated the inclusive cross section and polar angle distribution of  $K^+$  mesons in Ni + Ni collisions at incident energies of 1.93 AGeV. Nucleons are described by the Quantum Molecular Dynamics (QMD) model. Kaons are treated within the covariant kaon dynamics [1]. For the nuclear force we use the standard momentum dependent Skyrme interactions corresponding to a soft and a hard nuclear equation of state (EOS)(compression modulus  $K = 200$  MeV and  $K = 380$  MeV respectively).



## 2. 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. [4]

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

In Eq. (1)  $j_\mu$  is the baryon four-vector current,  $\rho_s$  is the baryon scalar density,  $f_\pi^*$  is the in-medium pion decay constant. Introducing the kaonic vector potential

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

Eq. (1) can be rewritten in the form [5]

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

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  $m_K = 0.496 \text{ GeV}$  is the bare kaon mass.  
The  $K^\pm$  single-particle energies are expressed as

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

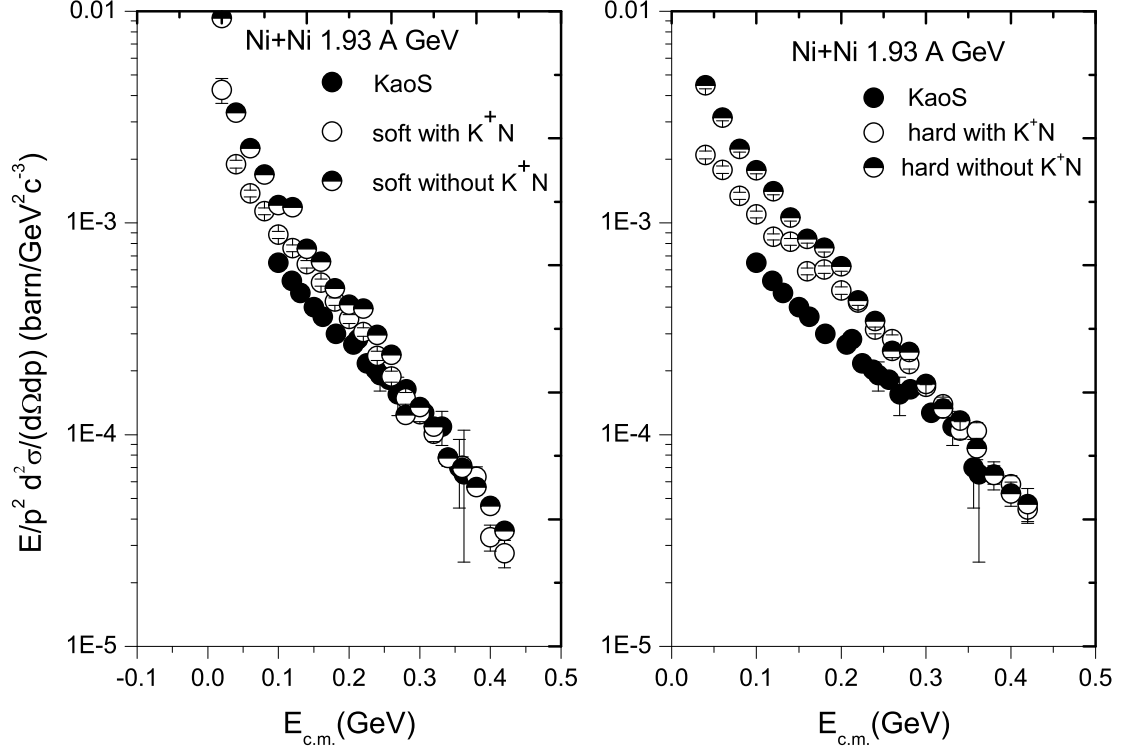
where  $\mathbf{k}^* = \mathbf{k} \mp V$  is the kaon effective momentum,  $V^\mu = (V^0, \mathbf{V})$ , the kaon vector field is introduced by minimal coupling into the Klein-Gordon with opposite signs for  $K^+$  and  $K^-$ , and  $m_K^*$  is the kaon effective (Dirac) mass. The kaon (antikaon) potential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

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

Following Ref.[1], we use the Brown and Rho parameterization  $\Sigma_{KN} = 450 \text{ MeV}$ ,  $f_\pi^{*2} = 0.6f_\pi^2$  for the 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. For the nuclear forces we use the standard momentum dependent Skyrme interactions corresponding to a soft (hard) equation of state (EOS) (the compression modulus  $K = 200 \text{ MeV}$  for a soft and  $K = 380 \text{ MeV}$  for hard EOS). For the determination of the kaon mean field we adopt the corresponding covariant scalar-vector description of the nonlinear  $\sigma\omega$  model. Up to saturation density the BR potential is ( $U_k(\rho_0) \approx 30 \text{ MeV}$ ).

## 3. Results and discussions

The inclusive invariant cross sections of  $K^+$  mesons as a function of the kaon energy for  $^{58}_{28}\text{Ni} + ^{58}_{28}\text{Ni}$  at incident energy of 1.93 AGeV are given in Fig.1. In this figure full circles are KaoS data [6], empty and half empty circles are calculated results with and without the in-medium kaon potential, the left (right) panel shows the results calculated by using the soft (hard) EOS. We can see clearly from this figure that calculated results with the in-medium kaon potential and by using the soft EOS better fit to experimental data.



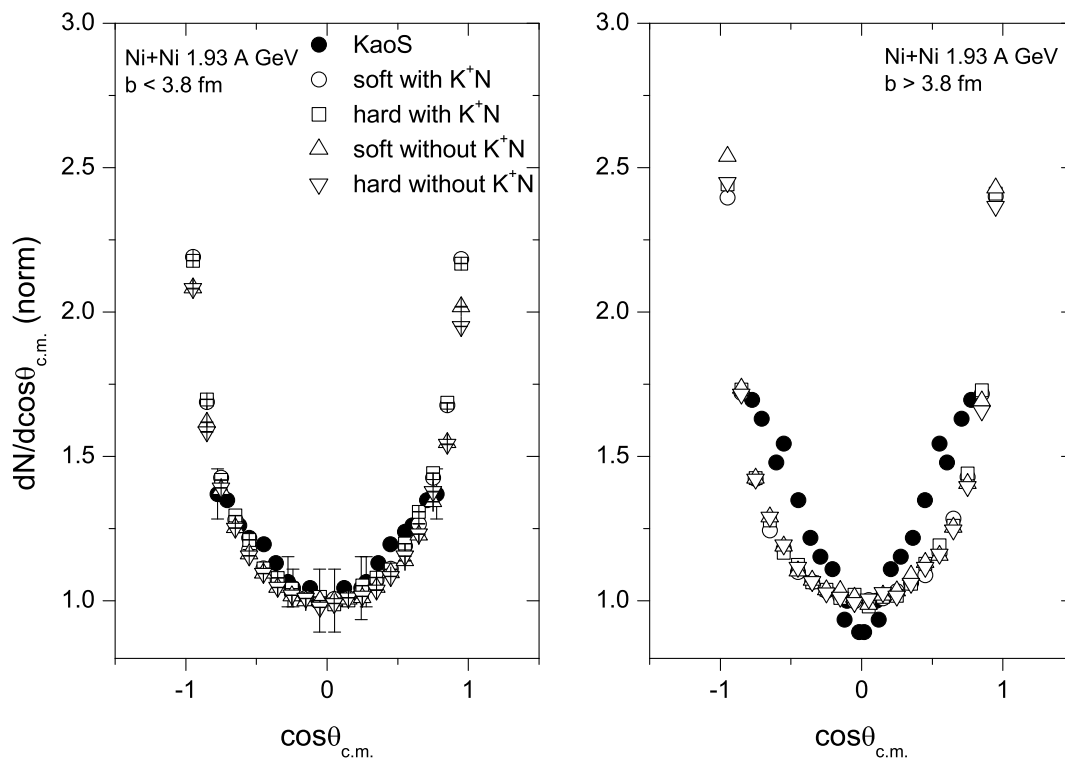
**Figure 1.** The inclusive invariant cross sections of  $K^+$  mesons as a function of the kaon energy for  $^{58}\text{Ni} + ^{58}\text{Ni}$  at 1.93 A GeV, in which full circles are the KaoS data [6], empty and half empty circles are calculated results with and without the in-medium kaon potential. The left (right) panel shows the results calculated by using the soft (hard) EOS.

Figure 2 shows the polar angle distribution of  $K^+$  for  $^{58}\text{Ni} + ^{58}\text{Ni}$  collisions at 1.93 A GeV. The distributions are normalized to 1 for  $\cos\theta_{c.m.} = 0$ . The data are taken from Ref. [6]. It is seen from this figure that the calculated distributions are rather flat. The polar angle distribution is not affected by the in-medium kaon potential. Because the effects of rescattering and  $K^+$  nucleus potential do not add linearly for the polar angle distribution of  $K^+$ . It is also shown that the polar angle distribution is not affected by the nuclear EOS.

#### 4. Conclusions

The inclusive invariant cross sections and the polar angle distribution of  $K^+$  in reactions  $^{58}\text{Ni} + ^{58}\text{Ni}$  at 1.93 A GeV are analyzed within the QMD model based on the covariant kaon dynamics, and compared to the KaoS data. Our calculated results with a repulsive in-medium  $K^+N$  potential (Its value at saturation density  $\rho_0$  is  $U_k(\rho_0) \approx 30\text{MeV}$ ) better fit to experimental data. This means that in order to describe reasonably data the medium effect of  $K^+$  mesons should be included in the kaon dynamics. On the other hand, The inclusive invariant cross sections of  $K^+$  meson turn out to be sensitive to the nuclear equation of state and to be preferred to the soft equation of state. However, the polar angle distribution of  $K^+$  mesons is not sensitive to the equation of state.

We can conclude that the physics of kaon production close to threshold in A + A collisions is quantitatively understood for most of the observables of kaon production. To make progress in



**Figure 2.** The polar angle distribution of  $K^+$ 's for  $^{58}_{28}\text{Ni} + ^{58}_{28}\text{Ni}$  collisions at 1.93 A GeV. Full circles are the experimental data. Empty symbols are calculated results. Left and right part show the calculated results for impact parameter  $b < 3.8\text{ fm}$  and  $b > 3.8\text{ fm}$  respectively. Data are taken from KaoS Collaborations [6].

understanding the strength of the  $K^+$  nucleon interaction in the nuclear medium it is necessary to reach a consistent description of all sensitive observables in a heavy ion reactions.

### Acknowledgments

This work was supported in part by Faculty of Science, Naresuan University. The computing resources have been provided by the National e-Science Infrastructure Consortium of Thailand.

### 5. References

- [1] Zheng Y M, Fuchs C, Faessler A, Shekhter K, Yan Y and Kobdaj C 2004 *Phys. Rev. C* **69** 034907
- [2] Herrmann H 1999 *Prog. Part. Nucl. Phys.* **42** 187
- [3] Brown G E and Rho M 1996 *Nucl. Phys. A* **596** 503
- [4] Li G Q and Ko C M 1995 *Nucl. Phys. A* **594** 460
- [5] Fuchs C 2006 *Prog. Part. Nucl. Phys.* **56** 1
- [6] Forster A et al., 2007 *Phys. Rev. C* **75** 024906