

Kaon squeeze-out in heavy ion reactions

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Received: 15 September 1998 / Revised version: 18 January 1999

Communicated by P. Schuck

Abstract. The squeeze-out phenomenon of K^+ and K^- mesons, i.e. the azimuthal asymmetry of K^+ and K^- mesons emitted at midrapidity in heavy ion reactions, is investigated for beam energies of 1-2 A.GeV. It is found that the squeeze-out signal is strongly affected by in-medium potentials of these mesons. The repulsive K^+ -nucleus potential gives rise to a pronounced out-of-plane emission of K^+ 's at midrapidity. With the K^+ potential we reproduce well the experimental data of the K^+ azimuthal distribution. It is found that the attractive K^- -nucleus potential cancels to a large extent the influence of rescattering and reabsorption of the K^- mesons on the projectile and target residuals (i.e. shadowing). This results in an azimuthally isotropic emission of the midrapidity K^- mesons with transverse momentum up to 0.8 GeV/c. Since it is well accepted that the shadowing alone would lead to a significant out-of-plane preference of particle emission, in particular at high transverse momenta, the disappearance of the out-of-plane preference for the K^- mesons can serve as an unambiguous signal of the attractive K^- potential. We also apply a covariant formalism of the kaon dynamics to the squeeze-out phenomenon. Discrepancies between the theory and the experiments and possible solutions are discussed.

1 Introduction

The asymmetry of particle emission with respect to the reaction plane in heavy ion reactions has attracted increasing interests of both experimentalists and theorists. It has been found recently that the azimuthal asymmetry of nucleons depends significantly on the bombarding energy [1]. If the incident energy is comparable to the Fermi energy, the attractive nuclear mean field dominates the dynamics. Projectile and target form a rotating system which preferentially emits nucleons in the reaction plane [2]. At high energies, a positive pressure develops in the overlap region of the colliding nuclei (so-called fireball) as a result of individual nucleon-nucleon collisions. The emission of the fireball nucleons can be hindered by the less disturbed matter located in the reaction plane (spectators). This shadowing leads to more nucleons emitted in the direction out of the reaction plane than in the plane [3,4]. However, at ultra-relativistic energies the shadowing by spectator matter is suppressed since the spectators depart too fast from the fireball region. Then the nucleons can escape freely from the fireball. Since the fireball has a smaller size along the impact parameter, the pressure gradient is larger in the reaction plane. This results in an in-plane preference of the nucleon emission [5,6]. The transition from an in-plane preference due to rotation to an out-of-plane one caused by shadowing was observed by the FOPI Collaboration to occur at an incident energy of 80-120 A.MeV [4]. The second transition to an in-

plane preference at high energies takes place at 4-6 A.GeV [1,7].

In this work we study the azimuthal asymmetry of K^+ and K^- mesons in heavy ion reactions at incident energies of 1-2 A.GeV. As mentioned above, shadowing dominates these reactions and leads to more nucleons out of the reaction plane. The phenomenon of an out-of-plane enhancement of particle emission at midrapidity is called "squeeze-out". E.g., pions exhibit a clear out-of-plane preference [8,9] which is due to shadowing, namely to scattering and absorption of the pions on the nucleons [10,11]. It is of high interest to see if the same mechanism still holds for kaons. Unlike a pion, which keeps the mass more or less unchanged in a nuclear environment, a kaon might vary its properties dramatically in the medium due to chiral symmetry restoration [12]. The K^+ - and K^- -nucleus potentials have observable effects in heavy ion reactions: they can change the transverse flow of kaons [13–17], the production yields [16–18], and may give rise to a collective flow, i.e. a radial flow [19].

This paper is organised as follows: In Sect. 2 we describe the kaon dynamics within the framework of the Quantum Molecular Dynamics (QMD) model. The kaon potential is based on chiral perturbation theory, however, with the space-like components of the baryon current neglected as usual. We present the azimuthal asymmetry of K^+ mesons in Sect. 3, and the corresponding results for K^- in Sect. 4. Section 5 contains a detailed discussion of

a covariant treatment of the in-medium kaon dynamics. In Sect. 6 the paper is summarised.

2 Kaon dynamics in heavy ion reactions

We adopt the QMD model to describe the dynamics of heavy ion reactions. K^+ and K^- mesons are produced from baryon-baryon collisions or pion-baryon collisions. The corresponding cross sections for the K^+ production are taken from [20,21] for the baryon-baryon channels and from [22] for the pion-baryon induced channels. The K^- production is treated as described in [17] with the corresponding elementary cross sections given there. The present QMD model describes successfully a large set of observables, such as production cross sections and collective flow patterns of nucleons, pions and kaons [23–25]. In particular, this model describes well the experimental transverse flow of protons, K^+ mesons as well as Λ hyperons [14,26].

While a K^+ meson is hardly absorbed in nuclear matter due to strangeness conservation, a K^- meson can be easily annihilated through the reaction $K^- + N \rightarrow \pi + Y$, where Y denotes a Σ or a Λ hyperon. Both K^+ and K^- mesons can scatter elastically with nucleons. The K^- absorption cross section is larger than 50 mb for K^- momenta below 0.2 GeV/c. Compared to this value the elastic K^+N cross section is relatively small ($\sigma_{K^+N} \approx 10$ mb) which results in a long mean free path of K^+ mesons in nuclear matter. In addition to scattering and absorption process, the strong interaction of K^+ and K^- mesons with a nuclear medium gives rise to a mean field which acts on the kaons when they propagate in the medium. Here both, the strong and the Coulomb potential are included [19].

The K^+ and K^- potentials are defined in the usual way as the difference of the in-medium dispersion relation and the free one

$$U_K = \omega_K - \sqrt{m_K^2 + \mathbf{p}^2}. \quad (2.1)$$

Starting from an $SU(3)_L \times SU(3)_R$ chiral Lagrangian as proposed by Kaplan and Nelson [12], one obtains the field equations for K^+ and K^- mesons in mean field approximation [13],

$$\left[\partial_\mu \partial^\mu \pm \frac{3i}{4f_\pi^2} j_\mu \partial^\mu + \left(m_K^2 - \frac{\Sigma_{KN}}{f_\pi^2} \rho_s \right) \right] \phi_{K^\pm}(x) = 0, \quad (2.2)$$

where ρ_s is the scalar baryon density and j_μ the baryon four-vector current. $f_\pi \approx 93$ MeV is the pion decay constant. According to recent lattice QCD calculations [27] the kaon-nucleon sigma term is taken to be $\Sigma_{KN} \approx 450$ MeV. The term coupling to the baryon current (so-called Weinberg-Tomozawa term) is of leading order in the chiral expansion, while the sigma term (so-called Kaplan-Nelson term) comes from the next order. The in-medium dispersion relation reads [13,28]

$$\omega^2 = m_K^2 + \mathbf{p}^2 - \frac{\Sigma_{KN}}{f_\pi^2} \rho_s \pm \frac{3}{4f_\pi^2} (\rho_B \omega - \mathbf{j} \cdot \mathbf{p}). \quad (2.3)$$

Usually the spatial components \mathbf{j} of the baryon current are neglected [13–18]. This means that the kaons are propagated in a static, momentum independent potential. Since the resulting kaon dynamics has been shown to agree well with experiments concerning, e.g., the transverse flow [13, 14, 18, 16] we follow this conventional treatment. However, one loses Lorentz covariance by the neglect of the spatial components of the four-vector baryon current [28]. Thus, in Section 5 we will also discuss the covariant treatment of the kaon dynamics which includes the momentum dependence of the mean field in lowest order, i.e. that part which arises from Lorentz boosts.

Brown and Rho pointed out [29] that the range term, which is of the same order in the chiral expansion as the Σ_{KN} term also contributes to the mean field. Moreover, the pion decay constant f_π can be reduced in the medium due to the decreasing quark condensate. For K^+ the range term and the medium modification of the pion decay constant are taken into account. At nuclear matter saturation density $\rho_0 = 0.16 \text{ fm}^{-3}$ this potential agrees with the empirical knowledge obtained from the impulse approximation to free K^+N scattering data [30]. The K^- potential is similar to that used in other works [13, 15, 17, 18]. It is constructed according to (1) and (3), however, with a smaller value of $\Sigma_{KN} = 350$ MeV and the f_π taken as in free space. The range term is neglected. This potential is less attractive than that extracted from kaonic atoms: the former is about -100 MeV at ρ_0 while the latter is about -185 ± 15 MeV [31]. However, such a less attractive K^- potential seems to be necessary in order to reproduce the experimental K^- yield in heavy ion reactions at 1-2 A.GeV [17, 18]. This inconsistency is so far unsolved (see also Sect. 5). In Fig. 1 we show the potentials for K^+ and K^- at zero momentum as a function of the nuclear matter density.

In addition to the influence on the propagation, the potentials can also change the production thresholds of the mesons and thus the corresponding yields. For K^- the potential has been included in the threshold throughout the present work in the same way as in [17, 18]. The influence of the K^+ in-medium potential on the yields is demonstrated in Fig. 2. The reaction considered is $C + C$ at 2.0 A.GeV under minimal bias conditions. For the comparison to the corresponding KaoS data [32] we applied a $\Theta_{\text{Lab}} = 40^\circ \pm 4^\circ$ polar angular cut. We distinguish three different cases: First a calculation without any medium effects, a calculation where the potential is only included in the propagation and finally a full calculation where the potential is included in the threshold as well as in the propagation. Without medium effects we are able to reproduce the low p_t -region of the spectrum but underpredict the high p_t part. On the other hand, the potential effect on the thresholds strongly suppresses the low energetic kaons. If the potential also acts on the propagation it makes the spectrum harder which is due to the repulsive forces. This can be clearly seen from the calculation where the potential is only included the propagation of the kaons. However, the uncertainty in the description of the cross section is still too large in order to draw definite conclusions on

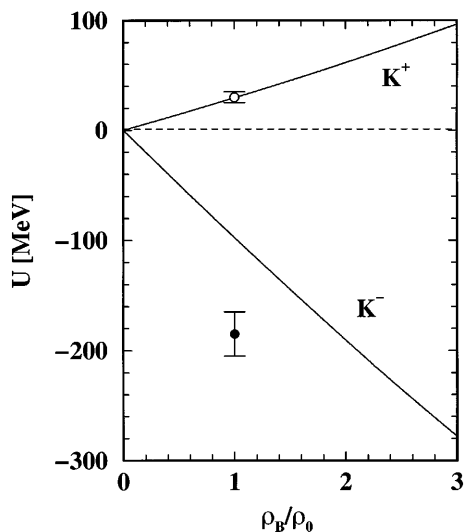


Fig. 1. The kaon potential in nuclear matter used in this work (at zero momentum). The filled circle shows the potential for K^- mesons at normal nuclear matter density ρ_0 extracted from kaonic atoms [31], while the open circle presents the potential for K^+ mesons obtained from the impulse approximation to free K^+ -nucleon scattering data [30]

the importance of medium effects. Although our calculation is in reasonable agreement with the results of other groups [18,17], there remain still discrepancies which reflect the uncertainties in the theoretical knowledge of the elementary production cross sections. Thus, for K^+ we will neglect the effect of the potential on the production thresholds in the following. This treatment is also justified since we study collective flow phenomena which do not depend sensitive on total yields.

3 K^+ squeeze-out

The strength of the azimuthal asymmetry can be quantified by the ratio of the particle multiplicity emitted perpendicular to the reaction plane over the multiplicity parallel to the plane

$$R_{out/in} = \frac{N(\phi = 90^\circ) + N(\phi = 270^\circ)}{N(\phi = 0^\circ) + N(\phi = 180^\circ)}. \quad (3.4)$$

The azimuthal angles $\phi = 0^\circ$ and 180° correspond to the positions of target and projectile in the reaction plane, while $\phi = \pm 90^\circ$ denote the directions perpendicular to the plane. A ratio $R_{out/in} > 1$ means a preference of the particle emission out of the reaction plane. An azimuthal distribution can be expressed in terms of a Fourier series [33]

$$\frac{dN}{d\phi} \sim C[1 + a_1 \cos(\phi) + a_2 \cos(2\phi) + a_3 \cos(3\phi) + \dots]. \quad (3.5)$$

The dipole term arises from a collective sideward deflection of the particles in the reaction plane ("transverse

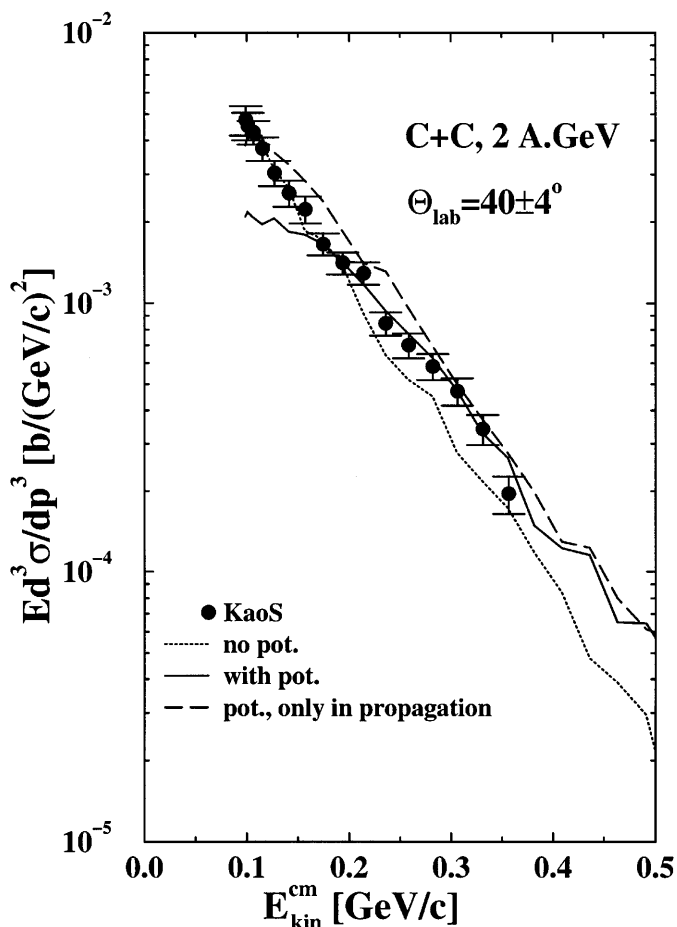


Fig. 2. Invariant cross section of the K^+ production in C+C collisions at 2 A.GeV. The calculations are performed without any medium effects (dotted), with full medium effects (solid), and including the in-medium potential only for the propagation of the kaons but neglecting it in the production thresholds (long-dashed). A $\Theta_{lab} = 40 \pm 4^\circ$ polar angular cut has been applied in order to compare to the corresponding KaoS data taken from [32]

flow") and does not contribute to the squeeze-out ratio $R_{out/in}$. In a symmetric collision, the $\cos(3\phi)$ term vanishes. The squeeze-out ratio is then determined only by the quadrupole component

$$R_{out/in} = \frac{1 - a_2}{1 + a_2}. \quad (3.6)$$

The azimuthal asymmetry of the K^+ production in heavy ion reactions has been first studied by Li et al. [34]. However, in [34] the authors focused on kaons emitted at projectile or target rapidity. In the present study we will focus on midrapidity kaons which should yield more precise information on the dense fireball.

In Fig. 3 the K^+ multiplicity as a function of azimuthal angle ϕ is shown for a semi-central ($b=6$ fm) $Au + Au$ reaction at 1 A.GeV incident energy. A transverse momentum cut of $P_T > 0.2$ GeV/c and a rapidity cut centred

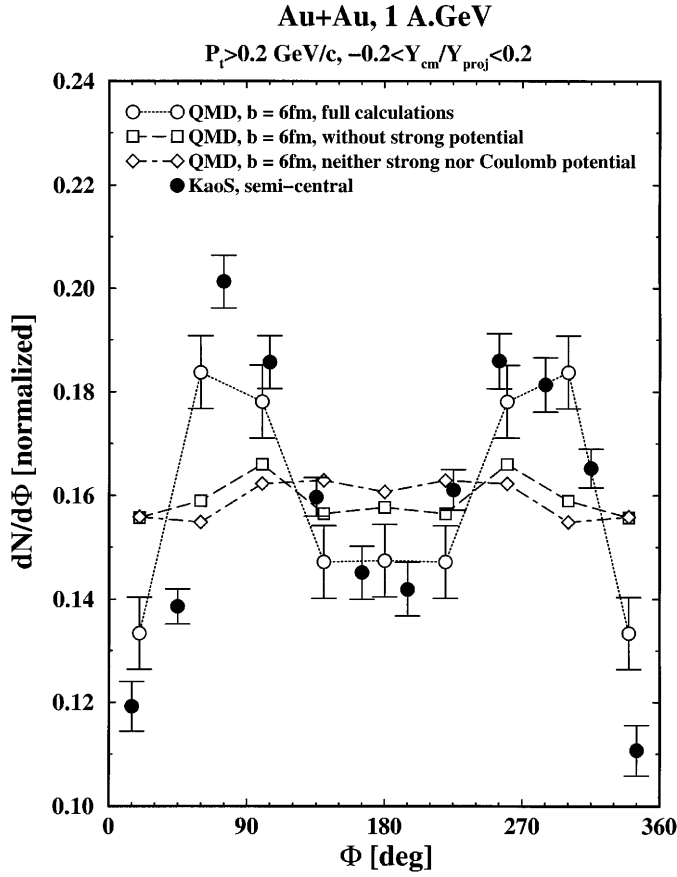


Fig. 3. The K^+ multiplicity as a function of the azimuthal angle calculated with the QMD model for the Au+Au reaction at an incident energy of 1 A.GeV and at an impact parameter of $b = 6$ fm. The dotted line shows the result of the QMD calculation with the full K^+ dynamics. The dashed line stands for the calculation where the strong K^+ potential is neglected, while the dashed-dotted line refers to the calculation where the Coulomb potential is neglected as well. The KaoS data [35] (solid line) for the same reaction at semi-central impact parameters ($5\text{fm} < b < 10\text{fm}$) are also shown

at midrapidity, i.e. $-0.2 < (Y/Y_{proj})^{cm} < 0.2$, have been applied. The same cuts have been adopted by the KaoS Collaboration. The KaoS data [35] for the same reaction at semi-central impact parameters (corresponding to $5\text{ fm} < b < 10\text{ fm}$) are also shown. We performed the QMD calculations for three different scenarios:

- with full in-medium K^+ dynamics;
- the K^+ potential due to the strong interaction is neglected;
- in addition, the Coulomb potential is neglected.

It can be seen from Fig. 3 that the full calculation leads to an enhanced out-of-plane ($\phi = 90^\circ, 270^\circ$) K^+ emission. The corresponding ratio $R_{out/in} = 1.5$ is close to the experimental value of $R_{out/in} = 1.7$ [35]. We would like to mention that we also performed calculations for different impact parameters ranging from $b=3$ to $b=10$ fm. From the impact parameter dependence of the kaon production

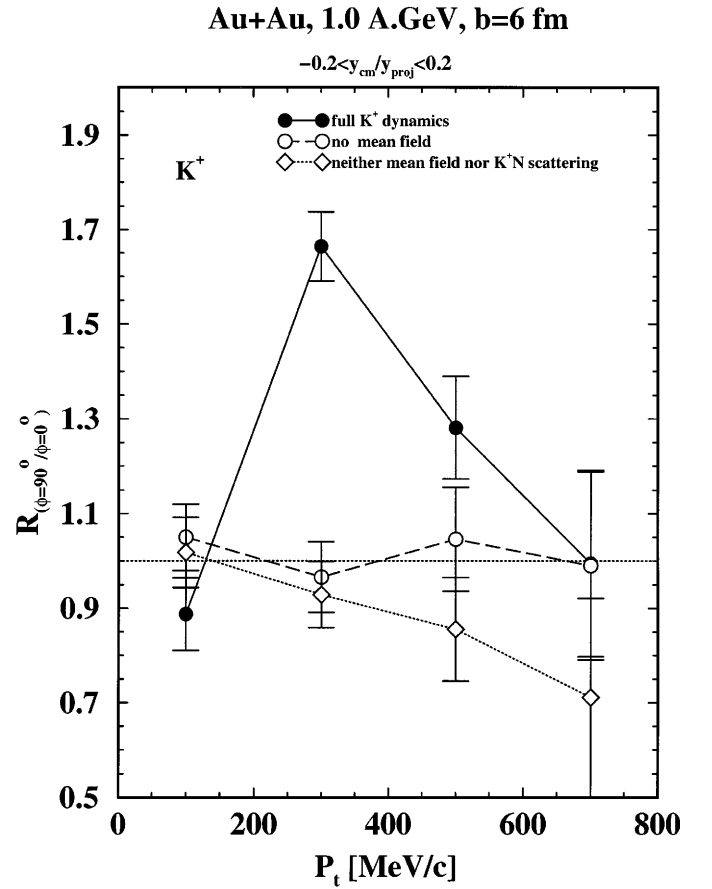


Fig. 4. The $R_{out/in}$ ratio defined in (4) for the K^+ 's as a function of transverse momentum for the same reaction as in Fig. 3. The solid line shows the result of the QMD calculation with the full K^+ dynamics as described in text. The dashed line stands for the calculation where the K^+ potentials of both the strong interaction and the Coulomb interaction are neglected, while the dashed-dotted line refers to the calculation where in addition to the potentials K^+ -nucleon scattering has been neglected

we found that it is reasonable to compare the simulation at the single impact parameter $b=6$ fm with the experimental data since the kaon multiplicity decreases very fast with decreasing centrality. (A corresponding calculation of the Stony Brook group [35] has been performed for the representative impact parameter $b=7$ fm.)

Comparing the cases (b) and (c) one clearly sees that the K^+ out-of-plane preference is mainly a result of the strong potential. The K^+ emission is nearly azimuthally isotropic in the calculation with neither the strong nor the Coulomb potential, while the Coulomb potential slightly increases the out-of-plane abundance. However, the Coulomb force has only a minor effect, and leads to an azimuthal asymmetry which is much weaker than the experimental one. Generally our results are in good agreement with those found by the Stony Brook group [35].

Figure 4 shows the K^+ $R_{out/in}$ ratio at midrapidity as a function of the transverse momentum. In this figure we also show a calculation where all final-state interactions including K^+N rescattering, have been neglected. The primordial K^+ mesons exhibit a slight in-plane preference which increases with the momentum. This behaviour reflects the primordial in-plane K^+ flow which follows the flow pattern of the production sources, i.e. the in-plane flow of the nucleons. Rescattering enhances the out-of-plane emission of the K^+ mesons and leads to a nearly isotropic azimuthal distribution. Thus we observe a clear shadowing effect by the spectator matter. However, the effect of K^+ -nucleon scattering is much less pronounced than that of the strong potential. The strong potential enhances dramatically the out-of-plane emission at transverse momentum between 0.2 GeV/c and 0.6 GeV/c. Now the azimuthal asymmetry exhibits a complex momentum dependence since the out-of-plane preference decreases again at high momenta.

This momentum dependence is, however, understandable. First of all, midrapidity K^+ mesons experience the strongest repulsion in the dense fireball. The repulsive potential gradient is larger in the direction perpendicular to the reaction plane than parallel to the plane. In the configuration where the fireball is combined with the spectators the distance from the fireball centre to free space is much shorter along the out-of-plane direction than in the reaction plane. Consequently, the K^+ mesons are driven by the potential gradient preferentially out of plane. With other words, in the reaction plane the kaons are repelled by the spectator matter. Thus, the potential acts similar as the elastic scattering and strongly enhances the shadowing effect. There occurs, however, a difference between the effect of the potential and the shadowing by simple rescattering/absorption on spectator matter. From nucleons and pions [4, 8, 9] it is known that the shadowing enhances the out-of-plane emission of high energetic particles, i.e. one observes an increasing $R_{out/in}$ ratio with increasing momentum. The same effect is observed in our calculation for K^- discussed in the next section. This is understandable since in these cases the high energetic particles stem mostly from the early phase of the reaction where the fireball and the spectators are clearly developed. However, the K^+ squeeze-out shows a different trend. Recent data [35] indicate a constant $R_{out/in}$ ratio whereas the calculation including the K^+ potential shows even a decreasing $R_{out/in}$ with increasing momentum. To understand this behaviour one has to keep in mind that the repulsive K^+ potential accelerates the particles and makes the spectrum harder (see also Fig. 2). High energetic K^+ mesons which experience the acceleration by the medium for a longer time span stem probably from the later stages of the reaction. But this means that the fireball and the spectators are washed out to more extent which results in less shadowing and a more isotropic azimuthal distribution of the particles. However, it appears that for a complete understanding of the K^+ squeeze-out phenomenon, also its momentum and impact parameter dependence, further going studies seem to be necessary.

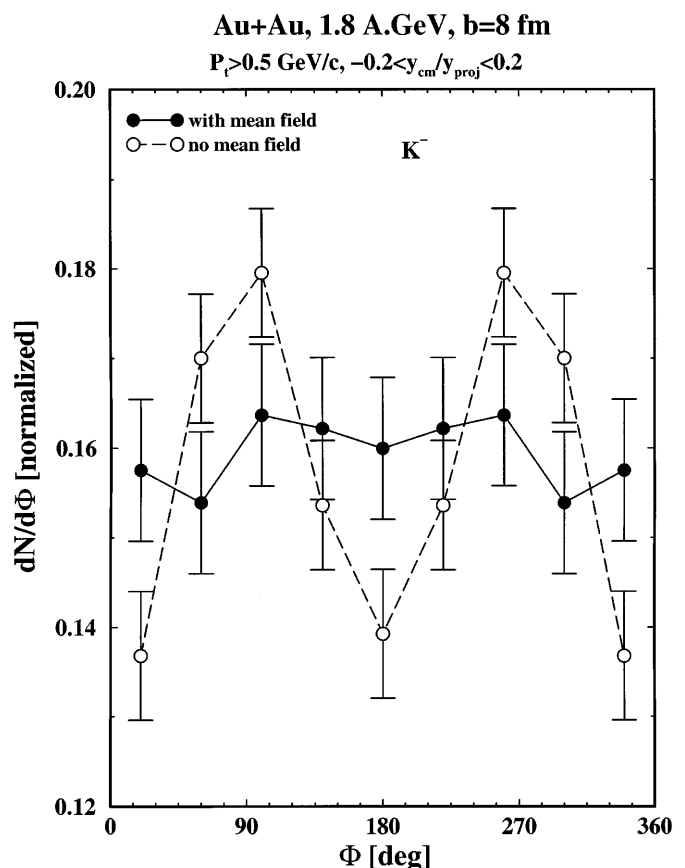


Fig. 5. The K^- multiplicity as a function of the azimuthal angle calculated with the QMD model for the Au+Au reaction at an incident energy of 1.8 A.GeV and at an impact parameter of $b = 8$ fm. The solid line shows the result of the QMD calculation with the full K^- dynamics as described in text, while the dashed line stands for the calculation where the K^- strong and Coulomb potentials are neglected

4 K^- squeeze-out

K^- mesons are strongly scattered or absorbed in the nuclear medium. In the absence of an additional in-medium potential, one expects a strong out-of-plane emission of midrapidity K^- mesons much like pions, since in both cases shadowing by the spectators plays a dominant role. In Fig. 5 we present the azimuthal distribution of the K^- mesons emitted at midrapidity ($-0.2 < (Y/Y_{proj})^{cm} < 0.2$) in the reaction of $Au + Au$ at $E/A = 1.8$ A.GeV and $b=8$ fm. A P_T cut of $P_T > 0.5$ GeV/c has been used. Figure 6 shows the corresponding $R_{out/in}$ as a function of the transverse momentum. Let us first consider the calculations where the strong and Coulomb potentials are neglected. Figs.5 and 6 show that the K^- mesons are then preferentially emitted out of the reaction plane. The $R_{out/in}$ ratio increases with transverse momentum. This P_T dependence is very similar to that observed experimentally for nucleons and pions [4, 8, 9].

In Figs. 5 and 6 the results of the full calculation are presented as well. It can be seen that the K^- in-medium potential reduces dramatically the out-of-plane abundance

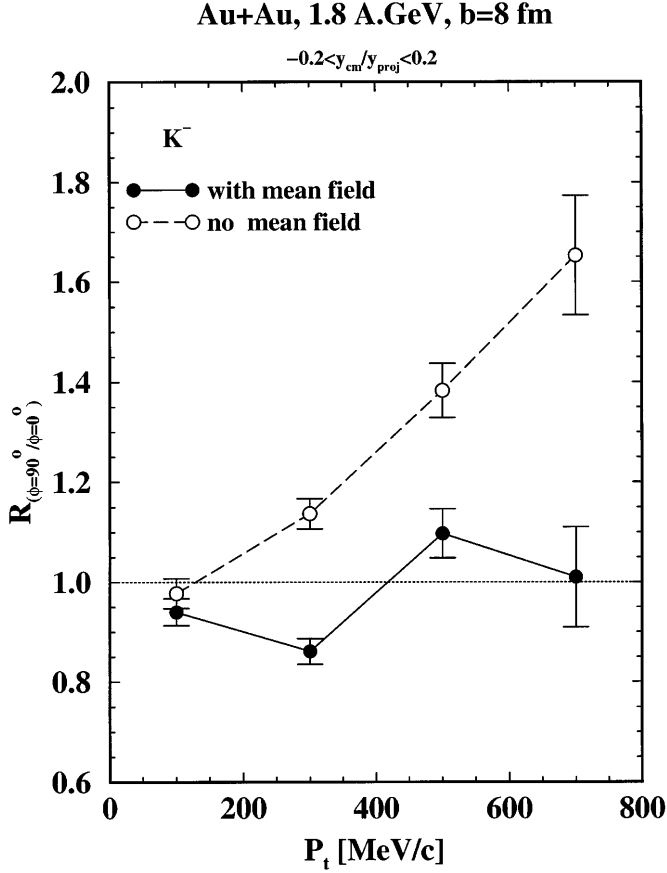


Fig. 6. The $R_{out/in}$ ratio, (4), for K^- 's as a function of transverse momentum for the same reaction as in Fig. 5. The solid line shows the result of the QMD calculation with the full K^- dynamics, while the dashed line stands for the calculation where the K^- strong and Coulomb potentials are neglected

($\phi = 90^\circ$ and 270°), and leads thereby to a nearly isotropic azimuthal emission. The $R_{out/in}$ ratio remains more or less flat as a function of the transverse momentum. We can understand the effect of the in-medium potential acting on K^- in a similar way as we have done for K^+ . The K^- potential is more attractive at higher densities. Consequently, the K^- mesons feel an attractive potential gradient as they move from the dense fireball to free space. This potential gradient is larger in the out-of-plane direction than in the in-plane direction when the fireball is still connected with the spectators. Thus the potential now favours the K^- emission in the reaction plane.

It is found in our calculations that the Coulomb potential has the same tendency but with a much smaller magnitude. From previous studies on nucleons and pions, both experimental [4,8,9] and theoretical [10,11], it is already clear that frequent rescattering and re-absorptions will lead to a pronounced out-of-plane preference of particle emission and an increasing squeeze-out ratio with increasing transverse momentum. Therefore, the disappearance of the out-of-plane preference up to transverse momentum of $P_t = 0.8$ GeV/c can serve as an unambiguous signal for the attractive K^- in-medium potential.

So far we have shown that the azimuthal asymmetry of K^+ and K^- mesons in heavy ion reactions at 1-2 A.GeV is sensitive to the in-medium potentials. The considered beam energies justify the mechanism where shadowing, namely rescattering and reabsorption by the spectators, compete with the in-medium potentials in the evolution of an kaon azimuthal asymmetry. In order to minimise the shadowing effect, one can study higher beam energies, i.e. above 6 A.GeV, where an isolated fireball elongated in the direction perpendicular to the reaction plane, rather than a combination of the fireball and the spectators, is responsible for the azimuthal asymmetry of particle emission at midrapidity. At such high beam energies, shadowing plays a minor role, and therefore, the azimuthal asymmetry of the midrapidity kaons yields a cleaner information on the in-medium potentials.

5 Covariant kaon dynamics

We have mentioned that the kaon dynamics is described in the present study in a non-covariant way since the spatial components of the baryon current are neglected. Such a description is correct in nuclear matter at rest but generally not in energetic heavy ion collisions. Keeping the four-vector baryon current in the kaon field equation, (2), one can construct a covariant description of the kaon dynamics in the nuclear medium [28]. In order to do this, it is convenient to write the kaonic vector potential as

$$V_\mu = \frac{3}{8f_\pi^2} j_\mu \quad , \quad (5.7)$$

The effective mass of the kaons is defined by

$$m_k^* = \sqrt{m_k^2 - \frac{\Sigma_{KN}}{f_\pi^2} \rho_s + V_\mu V^\mu} \quad . \quad (5.8)$$

The kaon field equation is then rewritten as

$$[(\partial_\mu + iV_\mu)^2 + m_k^*] \phi_{K^+}(x) = 0, \quad (5.9)$$

$$[(\partial_\mu - iV_\mu)^2 + m_k^*] \phi_{K^-}(x) = 0. \quad (5.10)$$

Thus the vector field is introduced by minimal coupling into the Klein-Gordon equation. The effective mass defined by (8) is a Lorentz scalar and is equal for K^+ and K^- mesons [28]. We should note that this definition of kaon effective mass is different from that conventionally used in the non-covariant description of the kaon dynamics. In the latter case the effective mass of the kaons is defined as kaon in-medium energy at zero momentum. Introducing an effective kinetic momentum

$$p_\mu^* = p_\mu \mp V_\mu \quad (5.11)$$

for K^+ (K^-) mesons, the Klein-Gordon equations ((9) and (10)) reads in momentum space

$$[p^{*2} - m^{*2}] \phi_{K^\pm}(p) = 0. \quad (5.12)$$

This is just the mass-shell condition for the quasi-particles carrying the effective mass and kinetic momentum, i.e. the effective energy is on-shell $E^* = p_0^* = \sqrt{\mathbf{p}^{*2} + m^{*2}}$. These quasi-particles can be treated like free particles. This yields in the test-particle limit the covariant equations of motion for the kaons [28]

$$\frac{d\mathbf{q}}{dt} = \frac{\mathbf{p}^*}{E^*} \quad (5.13)$$

$$\begin{aligned} \frac{d\mathbf{p}^*}{dt} = & -\frac{m_k^*}{E^*} \frac{\partial m_k^*}{\partial \mathbf{q}} \mp \frac{\partial V^0}{\partial \mathbf{q}} \mp \partial_t \mathbf{V} \\ & \pm \frac{\mathbf{p}^*}{E^*} \times \left(\frac{\partial}{\partial \mathbf{q}} \times \mathbf{V} \right) \end{aligned} \quad (5.14)$$

where the upper (lower) signs refer to K^+ (K^-) mesons. The last term of (14) provides a momentum dependent force which is missing in the non-covariant description of the kaon dynamics. Such a force is analogous to the Lorentz force in electrodynamics, and is a genuine feature of relativistic dynamics as soon as a vector field is involved. Since in the QMD approach the equations of motion are formulated in terms of canonical momenta \mathbf{p} rather than kinetic momenta \mathbf{p}^* , it is instructive to rewrite (14)

$$\begin{aligned} \frac{d\mathbf{p}}{dt} = & -\frac{m_k^*}{E^*} \frac{\partial m_k^*}{\partial \mathbf{q}} \mp \frac{\partial V^0}{\partial \mathbf{q}} \pm \boldsymbol{\beta} \cdot \frac{\partial \mathbf{V}}{\partial \mathbf{q}} \\ = & -\frac{\partial}{\partial \mathbf{q}} U_K \pm \boldsymbol{\beta} \cdot \frac{\partial \mathbf{V}}{\partial \mathbf{q}}, \end{aligned} \quad (5.15)$$

with $\boldsymbol{\beta} = \mathbf{p}^*/E^*$ the kaon velocity and the potential U_K given by (1). (15) is the equation which we have solved in the present work. A study with use of a relativistic version of the QMD model (RQMD) has shown that the inclusion of the Lorentz-like force leads for the reaction Ni+Ni at 1.93 A.GeV ($b \leq 4$ fm) to a K^+ transverse flow which essentially follows the nucleon flow [28]. This result contradicts the experimental data [36], since the latter show clearly different flow patterns for nucleons and K^+ . The QMD model used in the present work yields a result similar to that of the covariant RQMD model after the Lorentz-like force is included. However, as shown in our previous work, the same QMD model but in absence of the Lorentz-force enabled us to reproduce very well the FOPI data [36] of the in-plane K^+ flow. Other groups also got agreement with the data using conventional kaon dynamics [13,15].

In Fig. 7 we show the azimuthal K^+ distribution for the same reaction as in Fig. 3, however, now including the Lorentz-force like momentum dependence. One finds again that this force destroys the agreement with experiments: the calculation with the momentum dependent force yields an isotropic K^+ emission with respect to the azimuthal angle ϕ , while the KaoS data show a remarkable out-of-plane preference.

Both, the in-plane flow and the azimuthal asymmetry are predominately determined by the interactions of the kaons with the spectators. Due to the non trivial relative motion between the kaons and the spectators, the momentum dependent Lorentz-force plays a role in cancelling the

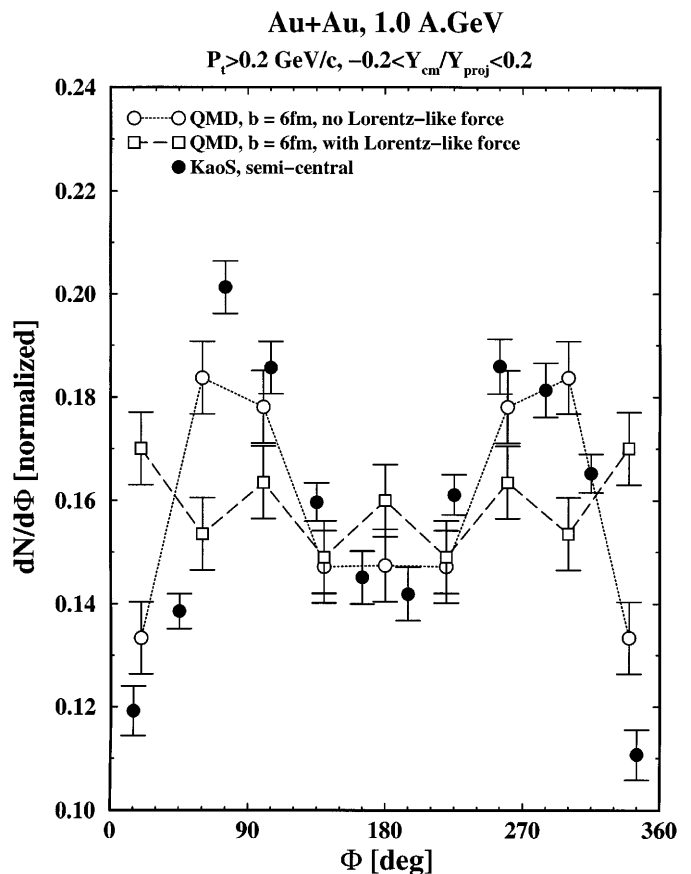


Fig. 7. The K^+ multiplicity as a function of the azimuthal angle for the same reaction as in Fig. 3. The dotted line shows the result of the QMD calculation with the K^+ dynamics using the conventional static potential, while the dashed line stands for the calculation where the Lorentz-like force due to the space-like components of the baryon current is included

effect from the time-like component of the vector potential which is the major source of the repulsion acting on the K^+ mesons. Therefore we observe a K^+ in-plane flow similar to the nucleon flow and an azimuthal isotropy of the midrapidity K^+ mesons. In a recent publication [19] we demonstrated that, in heavy ion reactions at a beam energy below the kaon production threshold in free space (1.58 A.GeV for K^+ and 2.5 A.GeV for K^- mesons), the in-medium potentials lead to new collective motion in the radial direction of midrapidity K^+ and K^- mesons. This collective flow results in a "shoulder-arm" or a "concave" structure in the transverse mass spectrum of the K^+ or K^- mesons, respectively. Such "shoulder-arm" or "concave" structure obviously differentiates the kaon spectrum from the standard Boltzmann distribution. We called this collective motion kaon radial flow. The kaon radial flow is primarily a consequence of the interactions of the midrapidity kaons with the fireball. Since the relative motion between the kaons and the fireball is small, the radial flow has been found to keep more or less unchanged after the Lorentz-like force is included [37].

It is surprising that the conventional description of the in-medium kaon dynamics, rather than the more consistent one including the full four-vector baryon current, turns out to agree with the phenomenology of kaon production in heavy ion reactions. To understand this fact it is important to realize that the kaon field equation, (2), which is the same starting point for the two treatments, consists only of the two lowest-order contributions from the chiral expansion, namely the Weinberg-Tomozawa and Kaplan-Nelson term. At that level the mean field approximation gives rise to only density dependent scalar and vector potentials for the kaons. Although the consistent treatment is based on the same level, it accounts for the additional momentum dependence which arises by Lorentz covariance and thus addresses the momentum dependence of the interaction of the kaons in the nuclear medium at lowest order. The success of the conventional treatment where the momentum dependence is neglected seems to imply that higher order contributions in the chiral expansion might lead to cancellation effects. Thus, one probably needs to take into account in a covariant formalism not only the lowest-order terms but also higher-order contributions, e.g. P-wave contributions of the kaon-nucleon interaction arising from nucleon hole-hyperon excitations. Such a P-wave interaction goes beyond the Weinberg-Tomozawa and Kaplan-Nelson terms and leads to a non trivial momentum dependence of the kaon potential [38–40].

Furthermore, the mean field approximation which is used to obtain the field equations (2) is justified at low nuclear matter densities, but might be questionable at high densities. The kaon-nucleon and nucleon-nucleon correlations will start to play a more important role [41]. The effect of the correlations can be illustrated considering the low and high density limits. At very low densities a kaon interacts many times with the same nucleon before it encounters another one. Thus, the impulse approximation is justified and the energy of a kaon interacting with nucleons is given in terms of the kaon-nucleon scattering length a_{KN} [39],

$$\omega_{\text{Lenz}} = m_K - \frac{2\pi}{m_K} \left(1 + \frac{m_K}{m_N} \right) a_{KN} \rho_B . \quad (5.16)$$

This is the so-called Lenz potential. At high densities, however, the K-N interaction has to be summed over many nucleons which results in a potential of a Hartree type. According to an estimation given in [41], the Hartree potential is reduced compared to the Lenz potential by a factor of 1.63 for K^- 's in nuclear matter. The correlation effect for K^+ 's should be smaller than for K^- 's, since the K^+ -nucleon interaction is relatively weak compared to other hadron-nucleon interactions. However, the onset of short-range correlations is a general feature of the dynamics of dense matter. Such effects have, e.g., been discussed concerning particle production in heavy ion reactions [43]. In [42] the transition from the Lenz to the Hartree potential was investigated for K^- mesons in neutron matter. There it is found that correlations reduce the K^- potential already significantly at densities below $3\rho_0$ which could also

provide a solution of the disagreement between the K^- potential extracted from kaonic atoms (at $\rho \leq \rho_0$) and the less attractive potential which has to be used to obtain a reasonable description of the experimental K^- yields in heavy ion reactions at 1-2 A.GeV [16] (at $\rho \leq 3\rho_0$).

6 Conclusions

In the present paper we investigated the azimuthal asymmetry of midrapidity K^+ and K^- mesons in heavy ion reactions at beam energies of 1-2 A.GeV. The in-medium kaon potential is constructed from the lowest-order terms of the chiral expansion. The kaon dynamics are described in a conventional way with a quasi-potential formalism where the space-like components of the baryon current are neglected. This description turned out to be rather successful in reproducing the current experimental data on K^+ and K^- production.

The present study finds that the in-medium potentials of the K^+ and K^- mesons play an important role in the evolution of an azimuthal asymmetry. Due to the long mean free path of the K^+ mesons in nuclear matter, K^+ -nucleon scattering processes are insufficient to understand the pronounced out-of-plane emission of midrapidity K^+ mesons observed by the KaoS Collaboration. The K^+ potential drives the kaons out of the reaction plane by a repulsive potential gradient. These kaons are repelled by the spectators which leads to an additional shadowing. The repulsive potential is necessary in order to understand the KaoS data. The momentum dependence of the K^+ squeeze-out signal is, however, more complex. We observe a decreasing squeeze-out signal with increasing transverse momentum. For a complete understanding of the p_t dependence of the K^+ squeeze-out further-going theoretical and experimental investigations seem to be necessary.

The K^- potential, in contrast, suppresses the K^- emission out of the reaction plane by an attractive potential. The effect is found to counterbalance to a large extent the strong shadowing by scattering and absorption. This results in a nearly isotropic azimuthal K^- emission. Since it is clear from both experimental and theoretical studies that frequent scattering and absorption give rise to a remarkable out-of-plane preference of the particle emissions, the disappearance of the squeeze-out can serve as a signal of the K^- in-medium potential.

In a covariant treatment, in particular with respect to the vector potential which is proportional to the four-vector baryon current, one finds that the agreement with experiments concerning both, the azimuthal asymmetry and the in-plane flow is destroyed. Since the corresponding fields originate from the lowest-order terms of the kaon-nucleon interaction we suggest to include in future also higher-order contributions, in particular to treat the momentum dependence of the kaon-nucleon interaction more carefully.

The authors would like to thank M. Lutz for valuable discussions.

References

1. For a recent review, see J.-Y. Ollitrault, Nucl. Phys. A **638**, 195c (1998)
2. M.B. Tsang et al., Phys. Lett. B **148**, 265 (1984); C.B. Chitwood et al., Phys. Rev. C **34**, 858 (1986); W.K. Wilson et al., Phys. Rev. C **41**, R1881 (1990)
3. H.H. Gutbrod, K.H. Kampert, B.W. Kolb, A.M. Poskanzer, H.G. Ritter and H.R. Schmidt, Phys. Lett. B **216**, 267 (1989)
4. N. Bastid and the FOPI Collaboration, Nucl. Phys. A **622**, 573 (1997)
5. J. Barrette and the E877 Collaboration, Phys. Rev. Lett. **73**, 2523 (1994); Phys. Rev. C **55**, 1420 (1997) and Phys. Rev. C **56**, 2336 (1997)
6. H. Sorge, Phys. Rev. Lett. **78**, 2309 (1997)
7. P. Danielewicz, R.A. Lacey, P.-B. Gossiaux, C. Pinkenburg, P. Chung, J.M. Alexander and R.L. McGrath, Phys. Rev. Lett. **81**, 2438 (1998)
8. D. Brill and the KaoS Collaboration, Phys. Rev. Lett. **71**, 336 (1993)
9. L.B. Venema and the TAPS Collaboration, Phys. Rev. Lett. **71**, 835 (1993)
10. B.A. Li, Nucl. Phys. A **570**, 707 (1994)
11. S.A. Bass, C. Hartnack, H. Stöcker and W. Greiner, Phys. Rev. C **51**, 3343 (1995)
12. D.B. Kaplan and A.E. Nelson, Phys. Lett. B **175**, 57 (1986)
13. G.Q. Li, C. M. Ko and B.A. Li, Phys. Rev. Lett. **74**, 235 (1995)
14. Z.S. Wang, Amand Faessler, C. Fuchs, V.S. Uma Maheswari and D. Kosov, Nucl. Phys. A **628**, 151 (1998)
15. E.L. Bratkovskaya, W. Cassing and U. Mosel, Nucl. Phys. A **622**, 593 (1997)
16. G.Q. Li and G.E. Brown, Nucl. Phys. A **636**, 487 (1999)
17. E.L. Bratkovskaya and W. Cassing, Phys. Reports **308**, 65 (1999)
18. G.Q. Li, C.-H. Lee and G.E. Brown, Nucl. Phys. A **625**, 372 (1997)
19. Z.S. Wang, Amand Faessler, C. Fuchs, V.S. Uma Maheswari and T. Waindzoeh, Phys. Rev. C **57**, 3284 (1998)
20. A. Sibirtsev, Phys. Lett. B **359**, 29 (1995)
21. K. Tsushima, A. Sibirtsev, A.W. Thomas, G.Q. Li, Phys. Rev. C **59**, 369 (1999)
22. K. Tsushima, S.W. Huang, A. Faessler, Phys. Lett. B **337**, 245 (1994); J. Phys. G **21**, 33 (1995)
23. V.S. Uma Maheswari, C. Fuchs, Amand Faessler, Z.S. Wang and D. Kosov, Phys. Rev. C **57**, 922 (1998)
24. C. Fuchs, Z.S. Wang, L. Sehn, Amand Faessler, V.S. Uma Maheswari and D. Kosov, Phys. Rev. C **56**, R606 (1997)
25. Z.S. Wang, Amand Faessler, C. Fuchs, V.S. Uma Maheswari and D. Kosov, Phys. Rev. Lett. **79**, 4096 (1997)
26. Z.S. Wang, Amand Faessler, C. Fuchs and T. Waindzoeh, Nucl. Phys. A **645**, 177 (1999)
27. G.E. Brown and M. Rho, Phys. Reports **269**, 333 (1996)
28. C. Fuchs, D. Kosov, Amand Faessler, Z.S. Wang and T. Waindzoeh, Phys. Lett. B **434** (1998) 254
29. G.E. Brown and M. Rho, Nucl. Phys. A **596**, 503 (1996)
30. T. Barnes and E.S. Swanson, Phys. Rev. C **49**, 1166 (1994)
31. E. Friedman, A. Gal and J. Mares, nucl-th/9804072; B.F. Gibson and E.V. Hungerford III, Phys. Reports **257**, 349 (1995)
32. F. Laue and the KaoS Collaboration, GSI-Preprint-99-03, Phys. Rev. Lett. in press
33. S.A. Voloshin, Phys. Rev. C **55**, R1630 (1997)
34. G.Q. Li, C.M. Ko and G.E. Brown, Phys. Lett. B **381**, 17 (1996)
35. Y. Shin and the KaoS Collaboration, Phys. Rev. Lett. **81**, 1576 (1998)
36. J.L. Ritman and the FOPI Collaboration, Z. Phys. A **352**, 355 (1995)
37. Z.S. Wang, thesis, Tuebingen, 1998, unpublished
38. E.E. Kolomeitsev, D.N. Voskresensky and B. Kämpfer, Nucl. Phys. A **588**, 889 (1995)
39. M. Lutz, Phys. Lett. B **426**, 12 (1998)
40. A. Sibirtsev and W. Cassing, Nucl. Phys. A **641**, 476 (1999)
41. V.R. Pandharipande, C.J. Pethick and V. Thorsson, Phys. Rev. Lett. **75**, 4567 (1995)
42. H. Heiselberg, in *Proceedings of the International Workshop XXVI on Gross Properties of Nuclei and Nuclear excitations, Hirschegg, Austria*, 1998, edited by Buballa, Nörenberg, Wambach and Wirzba
43. Z.S. Wang and Y.K. Ho, Phys. Rev. C **51**, 182 (1995); Z.S. Wang, Y.K. Ho and Z.Y. Pan, Phys. Rev. C **49**, 2104 (1994)