In-medium properties of antikaons at finite temperature: the $K^-/K^+$ ratio at GSI

L. Tolós$^1$, J.Schaffner-Bielich$^1$, A. Polls$^2$, A. Ramos$^2$

$^1$Institut für Theoretische Physik, J. W. Goethe-Universität
D-60054 Frankfurt am Main, Germany
$^2$Departament d’Estructura i Constituents de la Matèria,
Universitat de Barcelona, Diagonal 647, 08028 Barcelona, Spain

Abstract

The $K^-/K^+$ ratio in heavy-ion collisions at GSI is studied including the properties of the participating hadrons in hot and dense matter, paying a particular attention to the in-medium properties of antikaons at finite temperature. The determination of the temperature and chemical potential at freeze-out conditions compatible with the ratio $K^-/K^+$ is very delicate, and depends on the approach adopted for the antikaon self-energy. Different approaches for the $K^-$ self-energy have been considered: non-interacting $K^-$, on-shell self-energy and single-particle spectral density. We observe that the use of an energy dependent $\bar{K}$ spectral density lowers considerably the freeze-out temperature with respect to the on-shell approach. We also conclude that the full off-shell approach gives rise to the “broad-band equilibration” advocated by Brown, Rho and Song.

1 Introduction

The study of the properties of hadrons in hot and dense matter is receiving a lot of attention over the last years. A special effort has been invested to understand the properties of antikaons in the medium, especially after the speculation of the possible existence of an antikaon condensed phase in neutron stars [1].
Heavy-ion collisions at energies around 1-2 AGeV offer the possibility of studying hadrons under extreme conditions [2]. In particular, production and propagation of kaons and antikaons have been investigated with the kaon spectrometer (KaoS) of the SIS heavy-ion synchrotron at GSI (Darmstadt).

One first observation in C+C and Ni+Ni collisions [3, 4] is that, as a function of the energy difference $\sqrt{s} - \sqrt{s_{th}}$, where $\sqrt{s_{th}}$ is the energy for the particle production (2.5 GeV for $K^+$ via $pp \rightarrow \Lambda K^+ p$ and 2.9 GeV for $K^-$ via $pp \rightarrow ppK^- K^+$), the number of $K^-$ balanced the number of $K^+$ although in $pp$ collisions the production cross-sections close to threshold are 2-3 orders of magnitude different. This could be interpreted as an indication of an attractive $K^-$ optical potential in the medium, although a complementary explanation in terms of in-medium enhanced $\pi \Sigma \rightarrow K^- p$ production has also been suggested [5].

It has also been observed that the $K^-/K^+$ ratio remains almost constant for C+C, Ni+Ni and Au+Au collisions for 1.5 AGeV [3, 4, 6]. This could indicate that the absorption of $K^-$ via $K^- N \rightarrow Y \pi$ is suppressed and/or an enhanced $K^-$ production is obtained because of an attractive $K^-$ optical potential.

Finally, a centrality independence for the $K^-/K^+$ ratio has been noticed in Au+Au and Pb+Pb reactions at 1.5 AGeV [4]. A recent interpretation claims that this centrality independence is a consequence of the strong correlation between the $K^+$ and $K^-$ yields [7]. In fact, the centrality independence of the $K^-/K^+$ ratio has often been advocated as signalling the lack of in-medium effects in the framework of statistical models as the volume cancels out exactly in the ratio [8]. However, Brown et al. introduced the concept of “broad-band equilibration” [9] according to which the independence on centrality of the $K^-/K^+$ ratio can be explained including medium effects.

This paper is devoted to investigate the influence of dressing the antikaons on the $K^-/K^+$ ratio with particular emphasis of bringing new insight into the role of in-medium effects in heavy-ion collisions at GSI energies.

2 In-medium effects on the $K^-/K^+$ ratio

In this section we present a calculation of the $K^-/K^+$ ratio in the framework of the statistical model. The basic hypothesis is to assume that the particle ratios in relativistic heavy-ion collisions can be described by two parameters, the baryonic chemical potential $\mu_B$ and the temperature $T$ [8].

The fact that the number of strange particles in the final state is small at GSI energies requires an exact treatment of strangeness conservation, while the baryonic and charge conservation laws can be satisfied on average.
Therefore, using statistical mechanics, one obtains for the $K^-/K^+$ ratio [8, 11]

$$\frac{K^-}{K^+} = \frac{Z_{K^-}^1}{Z_{K^+}^1} \frac{Z_{K^+}^1 + Z_{M,S=+1}^1}{Z_{K^-}^1 + Z_{B,S=-1}^1 + Z_{M,S=-1}^1}$$

where $Z_{K^+}^1$ ($Z_{K^-}^1$) is the one-particle partition function for $K^+$ ($K^-$), and $Z_{B,S=\pm 1}^1$ ($Z_{M,S=\pm 1}^1$) indicate the sum of one-particle partition functions for baryons (mesons) with $S = \pm 1$. It is interesting to note that the $K^-/K^+$ ratio is independent of the volume and, hence, the same in the canonical and grandcanonical scheme used for strangeness conservation in contrast to the $K^-$ and $K^+$ multiplicities alone [8].

Our objective is to study how the in-medium modifications of the properties of the hadrons at finite temperature affect the value of the $K^-/K^+$ ratio, focusing our attention on the dressing of antikaons. For consistency with previous works, we prefer to compute the inverse ratio $K^+/K^-$

$$\frac{K^+}{K^-} = \frac{Z_{K^+}^1(Z_{K^-}^1 + Z_{\Lambda}^1 + Z_{\Sigma}^1 + Z_{\Sigma^*}^1)}{Z_{K^-}^1 Z_{K^+}^1} = 1 + \frac{Z_{\Lambda}^1 + Z_{\Sigma}^1 + Z_{\Sigma^*}^1}{Z_{K^-}^1}$$

This expression is equivalent to Eq. (1) but takes into account only the most relevant contributions. For balancing the number of $K^+$, the main contribution in the $S = -1$ sector comes from $\Lambda$ and $\Sigma$ hyperons and, in a smaller proportion, from $K^-$ mesons and $\Sigma^*(1385)$ resonances. The number of $K^-$ is balanced by the presence of $K^+$ mesons.

Then, the particles involved in the calculation should be dressed according to their properties in the hot and dense medium in which they are embedded. For the $\Lambda$ and $\Sigma$, the partition function

$$Z_{\Lambda,\Sigma} = g_{\Lambda,\Sigma} V \int \frac{d^3 p}{(2\pi)^3} e^{-\sqrt{m_{\Lambda,\Sigma}^2 + p^2} - U_{\Lambda,\Sigma}(\rho) + \mu B}$$

is built using a mean-field dispersion relation for the single-particle energies (see Ref. [12] for the dressing of $\Lambda$ and Ref. [13] for $\Sigma$). The resonance $\Sigma^*(1385)$ is described by a Breit-Wigner shape

$$Z_{\Sigma^*} = g_{\Sigma^*} V \int \frac{d^3 p}{(2\pi)^3} \int_{(m_{\Sigma^*}^2 - 2\Gamma)^2}^{(m_{\Sigma^*}^2 + 2\Gamma)^2} ds e^{-\sqrt{s + m_{\Sigma^*}^2}} \frac{1}{\pi (s - m_{\Sigma^*}^2)^2 + m_{\Sigma^*}^2 \Gamma^2} e^{\mu B}$$

with $m_{\Sigma^*} = 1385$ MeV and $\Gamma = 37$ MeV.

Finally, two different prescriptions for the single-particle energy of the antikaons have been used (see Fig. 2). First, we use the on-shell or mean-field approximation for the $K^-$ potential in which the partition function reads

$$Z_{K^-} = g_{K^-} V \int \frac{d^3 p}{(2\pi)^3} e^{-\sqrt{m_{K^-}^2 + p^2} - U_{K^-}(\rho)}$$
Figure 1: $K^+/K^-$ ratio as a function of density for $T = 50$ MeV (left panel) and $T = 80$ MeV (right panel) using different approaches to the $K^-$ optical potential: free gas (dot-dashed lines), the on-shell approach (dotted lines) and using the $K^-$ spectral density including s-waves (long-dashed lines) or both s- and p-waves (solid lines).

being $U_{K^-}(T, \rho, E_{K^-}, p)$ the $K^-$ single-particle potential in the Brueckner-Hartree-Fock approach [10, 14] (see l.h.s. of Fig. 2). The second approach incorporates the $K^-$ spectral density,

$$Z_{K^-} = g_{K^-} V \int \frac{d^3p}{(2\pi)^3} \int ds \, S_{K^-}(p, \sqrt{s}) \, e^{-s/T},$$

using the s-wave component of the Jülich interaction and adding the p-wave contributions as done in Ref. [11] (see r.h.s. of Fig. 2). This p-wave components come from the coupling of the $K^-$ meson to hyperon-hole states ($YN^{-1}$).

3 Results for the $K^-/K^+$ ratio

In this section we discuss the effects of dressing the $K^-$ mesons in hot and dense matter on the $K^-/K^+$ ratio using an experimental value of 0.031 ± 0.005 as reported in [4] for Ni+Ni collisions at 1.93 AGeV.

The inverse ratio, $K^+/K^-$, is shown in Fig. 1 as a function of density at two given temperatures ($T = 50$ MeV and $T = 80$ MeV) using different approaches for the dressing of the $K^-$ meson: free gas (dot-dashed lines), the
on-shell approach (dotted lines) and using the $K^-$ spectral density including s-waves (long-dashed lines) or both s- and p-waves (solid lines). Since the baryonic chemical potential $\mu_B$ grows with density, we note that the ratio grows with $e^{\mu_B/T}$ with increasing density. The curves representing the $K^+/K^-$ ratio tend to bend down after the initial increase when the in-medium $K^-$ properties are included. This effect is particularly notorious when the s- and p-wave contributions of the $K^-$ self-energy are taken into account in the spectral density. Actually, the low energy components of the $K^-$ spectral density related to $YN^{-1}$ excitations are responsible for this behaviour (see the overlap of the Boltzmann factor with the low energy region of the $K^-$ spectral density in Fig. 2). These results are in qualitative agreement with the “broad-band equilibration” notion introduced by Brown et al.[9]. However, this behaviour was found using a mean-field model, through a compensation of the increased attraction of the mean-field $K^-$ potential with the increase in the baryon chemical potential as density grows. In contrast, our mean-field approach does not achieve this “broad-band” behaviour.

In the framework of the statistical model, one obtains a relation between the temperature and the baryonic chemical potential by fixing the value of the
Figure 3: Left: $T(\mu_B)$ for $K^+/K^- = 30$ within different approaches. Right: $T(\mu_B)$ for different values of the $K^+/K^-$ ratio using the full $K^-$ spectral density.

$K^-/K^+$ ratio. The l.h.s of Fig. 3 shows the values of temperature and chemical potential compatible with a value of the inverse ratio $K^+/K^-$ of around 30 for the approaches discussed above. The dot-dashed line stands for a free gas, similar to the calculations of Ref. [8]. The on-shell approach (dotted line) does not represent the broad-band effect, as already mentioned. But due to the enhanced attraction felt by the $K^-$ mesons for higher densities, the chemical potential $\mu_B$ compatible with the value of the experimental ratio measured also increases for a given temperature. When the $K^-$ spectral density containing s-wave components is used (dashed line), two possible solutions that are compatible with the ratio emerge. Finally, a band of chemical potentials $\mu_B$ up to 850 MeV at a temperature of $T \approx 35$ MeV appears, when both, s- and p-wave contributions are considered (solid line). However, in the latter case, the temperature is too low to be compatible with the measured temperature and the corresponding freeze-out densities are too small (up to 0.02$\rho_0$ only), so we can hardly speak of a “broad band” feature in the sense of that of Brown et al. In the r.h.s. of Fig. 3 we represent the temperature and chemical potential for different values of the ratio when the full $K^-$ spectral density is used. We observe that the ratio is substantially lower at the more plausible temperature $T \approx 70$ MeV, being more likely around 15 for a large region of baryonic chemical potential. Note that this reduced ratio translates into an overall enhanced production of $K^-$ by a factor of 2 compared to the experimental value. This
effect is a consequence of the additional strength of the $K^-$ spectral density at low energies. The Boltzman factor amplifies the contribution of the low energy region of the spectral function so that this additional strength is becoming the main reason for the overall enhanced production of the $K^-$ in the medium.

4 Conclusions

The influence of a hot and dense medium on the properties of the hadrons involved in the determination of the $K^-/K^+$ ratio has been studied. We have focused our attention on incorporating the effects of the antikaon properties in the medium at finite temperature.

It is found that the temperature and chemical potential compatible with a given ratio depend very strongly on the approach used for the in-medium properties of the $K^-$ meson ($T \approx 35$ MeV and $\mu_B$ up to 850 MeV for $K^+/K^- = 30$ with the full $K^-$ spectral density).

The “broad-band equilibration” advocated by Brown, Rho and Song is not achieved in the on-shell approach. This behaviour is only observed when $K^-$ is described by the full spectral density due to the coupling of the $K^-$ meson to $YN^{-1}$ states. However, the $K^-/K^+$ ratio is in excess by a factor of 2 with respect to the experimental one. What needs to be clarified is how the particles get on-shell at the freeze-out and this has to be addressed in dynamical non-equilibrium effects. However, this study is left for forthcoming work.

Acknowledgments

This work is partially supported by DGICYT project BFM2001-01868, by the Generalitat de Catalunya project 2001SGR00064 and by NSF grant PHY-03-11859. L.T. also wishes to acknowledge support from the Alexander von Humboldt-Foundation.

References

[1] D. B. Kaplan and A. E. Nelson, Phys. Lett. B 175, 57 (1986); ibid. B 179, 409(E) (1986).

[2] H. Oeschler, J. Phys. G 28, 1787 (2002); P. Senger, Acta Phys. Polon. B 31, 2313 (2000); P. Senger, Nucl. Phys. A 685, 312 (2001); C. Sturm et al., J. Phys. G 28, 1895 (2002).
[3] R. Barth et al., Phys. Rev. Lett. 78, 4007 (1997); F. Laue et al., Phys. Rev. Lett. 82, 1640 (1999).

[4] M. Menzel et al., Phys. Lett. B 495, 26 (2000).

[5] J. Schaffner-Bielich, V. Koch, and M. Effenberger, Nucl. Phys. A 669, 153 (2000).

[6] A. Förster, PhD Thesis, TU Darmstadt (2002).

[7] Ch. Hartnack, H. Oeschler, and J. Aichelin, Phys. Rev. Lett. 90, 102302 (2003).

[8] J. Cleymans, D. Elliot, A. Keränänen, and E. Suhonen, Phys. Rev. C 57, 3319 (1998); J. Cleymans, H. Oeschler, and K. Redlich, Phys. Rev. C 59, 1663 (1999); J. Cleymans, and K. Redlich, Phys. Rev. C 60, 054908 (1999).

[9] G. E. Brown, M. Rho and C. Song, Nucl. Phys. A 690, 184c (2001); G. E. Brown, M. Rho and C. Song, Nucl. Phys. A 698, 483c (2002)

[10] L. Tolós, A. Ramos, and A. Polls, Phys. Rev. C 65, 054907 (2002).

[11] L. Tolós, A. Polls, A. Ramos, and J. Schaffner-Bielich, Phys. Rev. C 68, 024903 (2003).

[12] S. Balberg, and A. Gal, Nucl. Phys. A 625, 435 (1997).

[13] J. Mares, E. Friedman, A. Gal, and B. K. Jennings, Nucl. Phys. A 594, 311 (1995); J. Dabrowski, Phys. Rev. C 60, 025205 (1999).

[14] L. Tolós, A. Ramos, A. Polls, and T. T. S. Kuo, Nucl. Phys. A 690, 547 (2001).