$K^-/K^+$ ratio at GSI in hot and dense matter

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(March 25, 2022)

Abstract

The $K^-/K^+$ ratio in heavy-ion collisions at GSI energies is studied including the properties of the participating hadrons in hot and dense matter. 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. Three approaches for the $K^-$ self-energy are considered: non-interacting $K^-$, on-shell self-energy and single-particle spectral density. With respect to the on-shell approach, the use of an energy dependent $\bar{K}$ spectral density, including both s- and p-wave components of the $\bar{K}N$ interaction, lowers considerably the freeze-out temperature and gives rise to the “broad-band equilibration” advocated by Brown, Rho and Song.

PACS: 13.75.Jz, 14.40.Ev, 25.75-q, 25.75.Dw, 24.10.Pa, 24.60.-k
Keywords: $\bar{K}N$ interaction, Finite temperature, Heavy-ion collisions

I. INTRODUCTION

Heavy-ion collisions at energies around 1-2 AGeV offer the possibility of studying hadrons under extreme conditions [1], and especially the properties of antikaons in a hot and dense medium. A considerable effort has been invested in analysing heavy-ion data implementing the modified properties of the hadrons in the medium where they are produced. In particular the multiplicity of kaons and antikaons could give information about their in-medium properties.

One first observation in C+C and Ni+Ni collisions [2,3] 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.

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 [2,3,5]. 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 [3]. A recent interpretation claims that this centrality independence is a consequence of the strong correlation between the $K^+$ and $K^-$ yields [6]. 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 [7]. However, Brown et al. introduced the concept of “broad-band equilibration” [8] according to which the independence on centrality of the $K^-/K^+$ ratio can be explained including medium effects.

This paper is devoted to study 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.

II. IN-MEDIUM EFFECTS ON THERMAL MODELS: $K^-/K^+$ 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 thermal and chemical equilibrium [7] in the final state of relativistic nucleus-nucleus collisions. One deals with an hadronic gas model which is a dilute system of hadrons that can be described by two parameters: the baryonic chemical potential $\mu_B$ and the temperature $T$.

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 [7,9]

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

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 [7].

As mentioned in the Introduction, 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 $K^+/K^-$

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

(2)
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

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

is built using a mean-field dispersion relation for the single-particle energies ($U_{\Lambda}(\rho) = -340 \rho + 1087.5 \rho^2$ of Ref. [10], where $U_{\Lambda}$ is given in MeV and $\rho$ in fm$^{-3}$, and $U_{\Sigma}(\rho) = 30 \rho / \rho_0$ MeV of Ref. [11] with $\rho_0 = 0.17$ fm$^{-3}$). The resonance $\Sigma^*(1385)$ is described by a Breit-Wigner shape

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

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 this approach the partition function reads

$$ Z_{K^-} = g_{K^-} V \int \frac{d^3p}{(2\pi)^3} e^{-\sqrt{m_{K^-}^2 + p^2 - U_{K^-}(T, \rho, E_{K^-})}} , $$

where $U_{K^-}(T, \rho, E_{K^-})$ is the $K^-$ single-particle potential in the Brueckner-Hartree-Fock approach [12, 13] (see l.h.s. of Fig. 2) based on the $\bar{K}N$ meson-exchange potential of the Jülich group [14]. The second approach incorporates the $K^-$ spectral density,

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

using the s-wave component of the Jülich interaction and adding the p-wave contributions as done in Ref. [9] (see r.h.s. of Fig. 2). This p-wave components come from the coupling of the $K^-$ meson to hyperon-hole states ($YN^{-1}$).

**III. 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 $0.031 \pm 0.005$ as reported in [3] for Ni+Ni collisions at 1.93 AGeV.

In Fig. 1 the inverse ratio, $K^+/K^-$, is shown for two 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). We note that the ratio grows.
with $e^{\mu_B/T}$ as we increase the 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 clearly seen when the s- and p-wave contributions of the $K^-$ spectral 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). A flat region as a function of the density is observed, which is in qualitative agreement with the “broad-band equilibration” advocated by Brown et al. [8]. 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 order to obtain the relation between the temperature and the chemical potential for a fixed value of the $K^+/K^-$ ratio, the l.h.s. of Fig. 3 shows the values of temperature and chemical potential compatible with a value of $K^+/K^- = 30$ for the approaches discussed above. The dot-dashed line stands for a free gas, similar to the calculations of Ref. [7]. 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 slope parameter of the pion spectra 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. One observes that the ratio should be of the order of 15 to obtain the more plausible temperature of $T \approx 70$ MeV. We 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.

**IV. 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, paying special attention to the properties of antikaons. The temperature and chemical potential compatible with a given ratio depend very strongly on the approach used for the in-medium property of the $K^-(T \approx 35$ 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. Dynamical non-equilibrium effects could explain the number of on-shell $K^-$ at freeze-out. 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 Ministerio de Educación y Cultura (Spain).
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FIG. 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. Plot taken from [9].

FIG. 2. Left: The $K^-$ optical potential at zero momentum for different densities as a function of temperature. Right: The Boltzmann factor (dotted line) and the $K^-$ spectral function, including s-wave (dashed line) or s- and p-wave (solid line) components of the $\bar{K}N$ interaction, as functions of the energy, for a momentum $q = 500$ MeV at saturation density and temperature $T = 80$ MeV. Plots taken from [9].
FIG. 3. Left: $T(\mu_B)$ for $K^+/K^- = 30$ within different approaches. Right: Different $K^+/K^-$ ratios using the full $K^-$ spectral density. Plots taken from [9].