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

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The in-medium modifications on the $K^-/K^+$ ratio produced at GSI are studied. Particular attention is paid to the properties of antikaons, which determine the chemical potential and temperature at freeze-out conditions. Different approaches have been considered: non-interacting $K^-$, on-shell self-energy and single-particle spectral density. We observe that the full off-shell approach to the spectral density reproduces the Brown et al. ‘broad-band equilibration’ which is crucial to explain an enhanced $K^-/K^+$ ratio.

1. Introduction

The medium modifications of mesons with strangeness such as kaons and antikaons can be studied in connection to heavy-ion experiments for energies around 1-2 AGeV [1]. One surprising observation in C+C and Ni+Ni collisions [2] is that the $K^-$ multiplicity and that of $K^+$ are of the same order of magnitude although in $pp$ collisions the $K^+$ multiplicity exceeds the $K^-$ one by 1-2 orders of magnitude at the same energy above threshold. Another interesting observation is that the $K^-/K^+$ ratio stays almost constant for C+C, Ni+Ni and Au+Au collisions for 1.5 AGeV [2]. Both observations could be interpreted to be a manifestation of an attractive $K^-$ optical potential. On the other hand, equal centrality dependence for the $K^+$ and $K^-$ mesons has also been observed in Au+Au and Pb+Pb reactions at 1.5 AGeV [2]. Actually, the independence of centrality of the $K^-/K^+$ ratio was claimed to indicate that no in-medium effects were needed in order to explain the experimental ratio [3]. However, the concept of “broad-band equilibration” was introduced by Brown et al. [4] in order to explain the centrality independence but including medium modifications of antikaons.

In this work we study the implications of introducing the $K^-$ spectral density for the $K^-/K^+$ ratio in order to address the above mentioned issues.

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

We present a brief description of the statistical models which are applied for the calculation of the $K^-/K^+$ ratio. Statistical models are based on the assumption that the

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particle ratios in relativistic heavy-ion collisions can be described by two parameters, the baryonic chemical potential $\mu_B$ and the temperature $T$ [3].

Therefore, by using canonical strangeness conservation and taking into account the most relevant contributions in the $S = 0, \pm 1$ sectors, the inverse ratio $K^+/K^-$ is given by [3,5]

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

where $Z$s indicate the different one-particle partition functions for $K^+, K^-, \Sigma, \Lambda, \Sigma^*$. In order to balance 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. On the other hand, the number of $K^-$ is balanced by the presence of $K^+$ mesons. We finally observe that the ratio is determined by the relative abundance of $\Lambda, \Sigma, \Sigma^*$ baryons with respect to that of $K^-$ mesons.

In order to introduce in-medium and temperature effects, the particles involved in the calculation should be dressed accordingly. For $\Lambda$ and $\Sigma$, the partition function reads

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

which is built using a mean-field dispersion relation for the single-particle energies (see Refs. [5,6]), while the resonance $\Sigma^*(1385)$ is described by a Breit-Wigner shape.

With regards to the $K^-$ meson, two different prescriptions for the $K^-$ single-particle energy have been used. First, we use the mean-field approximation for the $K^-$ potential

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

where $U_{K^-}(T, \rho, E_{K^-}, p)$ is the $K^-$ single-particle potential in the Brueckner-Hartree-Fock approach [7]. The second approach incorporates the $K^-$ spectral density (see Ref. [5])

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

3. Results

In Fig. 1 the inverse ratio $K^+/K^-$ is shown for two temperatures 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). The ratio grows with $e^{\mu_B/T}$ as we increase the density although it tends to bend down after the initial increase when the in-medium $K^-$ properties are considered. Actually, when the full spectral density is used (solid lines), a flat region as a function of the density is observed. This is due to the increased attraction produced by the $YN$ excitations present in the low-energy region of the $K^-$ spectral density. This result is in qualitative agreement with the “broad-band equilibration” advocated by Brown et al.[4]. However, this behaviour was found in Ref. [4] using a mean-field model through a compensation of the increased attractive mean-field $K^-$ potential with
the increase in the baryonic chemical potential as density grows, which is not observed in our mean-field approach.

In the framework of statistical models, one obtains the relation between the temperature and the chemical potential by fixing the $K^+/K^−$ ratio. In the l.h.s. of Fig. 2 we show, for the previous approaches, the values of temperature and chemical potential compatible with a value of $K^+/K^− = 30$, close to the experimental one for Ni+Ni collisions at 1.93 AGeV. Similar to the calculations of Refs. [3], the dot-dashed lines gives the free gas case. While the on-shell approach (dotted line) does not show the broad-band effect, a band of chemical potentials $\mu_B$ up to 850 MeV for $T \approx 35$ MeV appears to be in accordance with the given ratio when both $s$- and $p$-wave contributions are taken into account (solid line). However, in this case, the temperature is too low to be compatible with the experimental one and the corresponding freeze-out densities are too small. 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. 2 we display the temperature and chemical potential for different values of the ratio when the full $K^−$ spectral density is used. A ratio of the order of 15 seems to be the solution for a more plausible experimental temperature of $T \approx 70$ MeV. We therefore conclude that the strength of the low-energy region of the $K^−$ spectral density gives an enhanced production of $K^−$ compared to the experimental results.

4. Concluding remarks

We have analyzed the $K^−/K^+$ ratio in the framework of statistical models considering the medium properties of antikaons. It is found that the determination of the temperature and baryonic chemical potential for a given ratio is very delicate depending on the approximation adopted for the $K^−$ self-energy. On the other hand, the “broad-band equilibration” advocated by Brown, Rho and Song is not accomplished in the on-shell
approach. Only when $K^-$ is described by the full spectral density we observe this broadband. This is 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 value. Only further studies on non-equilibrium evolution of $K^-$ in the medium could give some indications about the reduced number of $K^-$ that are observed experimentally.

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