Finite temperature effects on the $\bar{K}$ optical potential

Laura Tolós, A.Polls, A.Ramos

Departament d'Estructura i Constituents de la Matèria, Universitat de Barcelona,

Diagonal 647, 08028 Barcelona, Spain

(November 2, 2018)

Abstract

By solving the Bethe-Goldstone equation, we have obtained the $\bar{K}$ optical potential from the $\bar{K}N$ effective interaction in nuclear matter at $T = 0$. We have extended the model by incorporating finite temperature effects in order to adapt our calculations to the experimental conditions in heavy-ion collisions. In the rank of densities $(0 - 2\rho_0)$, the finite temperature $\bar{K}$ optical potential shows a smooth behaviour if we compare it to the $T = 0$ outcome. Our model has also been applied to the study of the ratio between K^+ and K^- produced at GSI with T around 70 MeV. Our results point at the necessity of introducing an attractive $\bar{K}$ optical potential.

I. THE MODEL AT $T = 0$

The $\bar{K}$ optical potential in nuclear matter is computed using a $\bar{K}N$ effective interaction, G-matrix, derived microscopically from a meson-exchange potential [1]. The G-matrix is given by the solution of the Bethe-Goldstone equation

$$G(w) = V + V \frac{Q}{w - H_0 + i\eta} G(w), \tag{1}$$

which takes into account the different channels ($\bar{K}N$, $\pi\Sigma$, $\pi\Lambda$), which are coupled by the strong interaction.

At lowest order in the Brueckner-Hartree-Fock (BHF) theory, the single-particle potential for antikaons $U_{\bar{K}}$ at $T = 0$ is given by

$$U_{\bar{K}}(k, E_{\bar{K}}^{qp}) = \sum_{N \leq F} \langle \bar{K}N \mid G_{\bar{K}N \to \bar{K}N}(w = E_N^{qp} + E_{\bar{K}}^{qp}) \mid \bar{K}N \rangle, \tag{2}$$

in which $E_{\bar{K}}^{qp}$ is self-consistently determined.

In order to introduce in-medium effects on the intermediate states of the G-matrix, we have employed mean field single-particle propagators for the baryons. The single-particle potential for nucleons has been derived from a $\sigma - \omega$ model, while for Λ and Σ, we have

followed the parameterization of Ref. [2]. Finally, the pion is dressed with the momentum and energy dependent self-energy of Ref. [3], that incorporates the coupling to particle-hole, Δ-hole and two particle-two hole excitations.

Fig.1 shows the real and imaginary part of $U_{\bar{K}}$ as a function of $k_{\bar{K}}$ at $T = 0$ for $\rho = \rho_0$ including or not the dressing of pions. The long-dashed line has been calculated determining the complex $\bar{K}$ single particle energy self-consistently. However, the pion self-energy in the intermediate states is not included. This procedure is similar to the one presented in Ref. [4] with the inclusion here of a $\sigma - \omega$ model for the nucleon dressing. The presence of the $\Lambda(1405)$ resonance, dynamically generated in our model, introduces a strong energy dependence on the $\bar{K}N$ amplitude which governs, in turn, the behaviour of $U_{\bar{K}}$. The Pauli blocking on the intermediate nucleons has a repulsive effect on the resonance, produced by having moved the threshold of intermediate states to higher energies. The self-consistent incorporation of the $\bar{K}$ properties on the $\bar{K}N$ G-matrix moves the resonance back in energy, but it dilutes as the density increases. If we now include the dressing of pions (solid line), we obtain a less attractive real part, going from -84 MeV to -73 MeV at $k = 0$ MeV, and a smoother behaviour for the imaginary part. This can be understood by looking again to the $\bar{K}N$ amplitude, specially for $L = 0$. Due to the additional dressing of the pions, the resonance dissolves even faster loosing structure, although it shows a tendency to move to higher energies.

II. TEMPERATURE EFFECTS

The introduction of temperature in the calculation affects the Pauli blocking of the intermediate nucleon states in the G-matrix. In addition, the $\bar{K}$ optical potential is calculated according to

$$U_{\bar{K}}(k, E_{\bar{K}}^{qp}) = \int d^3k \; n(k,T) \; \langle \bar{K}N \mid G_{\bar{K}N \to \bar{K}N}(w,T) \mid \bar{K}N \rangle \qquad (3)$$

where $n(k,T)$ is the nucleon momentum distribution at finite temperature. By looking at Fig.2, one observes that, as the temperature increases, $U_{\bar{K}}$ is less attractive and shows a smoother behaviour in momentum. At finite T, the sum over momenta in Eq.(3) is extended over the corresponding Fermi distribution, and higher nucleon momentum translates into a weaker interaction. Moreover, the effective interaction has also changed. However, this last effect is less important. At $T = 70$ MeV, the momentum dependence is very smooth, reducing in a factor of three the difference between low and high momentum. However, $U_{\bar{K}}$ is still attractive. This fact can be used to understand the enhancement of the observed ratio K^-/K^+ in heavy-ion collisions at GSI energies.

III. RATIO K^-/K^+

Heavy-ion collisions provide a unique possibility to create a dense and hot nuclear system to study the in-medium properties of hadrons, like in-medium effects on the $\bar{K}$. The measured ratio of particles K^-/K^+ gives us information about the necessity of an in-medium attractive potential for the K^-, already corroborated in the analysis of kaonic atoms.

In direct nucleon-nucleon collisions, the production of K^+ and K^- is governed by quite distinct thresholds (for $NN \rightarrow K^+ \Lambda N$, the threshold is at 1.58 GeV and for $NN \rightarrow K^+ K^- NN$ is 2.5 GeV), and the K^+ multiplicity exceeds the K^- one by 1-2 orders at a given energy above thresholds. However, this large difference disappears for nucleus-nucleus collisions ($C + C$, $Ni + Ni$ [5,6]), where the data nearly fall on the same curve. Furthermore, we observe that this ratio is approximately constant for $C + C$, $Ni + Ni$ and $Au + Au$ [5–7], although absorption of K^- via $K^- N \rightarrow Y\pi$ is supposed to be higher for heavier nuclei [8]. It turns out that both effects can be interpreted by assuming an in-medium attractive $U_{\bar{K}}$ [9,10]

Analysis of K^+/K^- in $Ni + Ni$ at GSI energies [5,6] gives a ratio around 30. In Ref. [11], it was shown that this ratio can be explained in terms of a *thermal model*, i.e., the final state can be described as a *hadronic gas* in chemical equilibrium at a given temperature. Imposing exact strangeness conservation, one obtains,

$$
\frac{K^+}{K^-} = \frac{g_{K^+} V \int \frac{d^3p}{(2\pi)^3} e^{\frac{-E_{K^+}}{T}} \left(g_{K^-} V \int \frac{d^3p}{(2\pi)^3} e^{\frac{-E_{K^-}}{T}} + g_\Lambda V \int \frac{d^3p}{(2\pi)^3} e^{\frac{-E_\Lambda}{T} + \frac{\mu_B}{T}} + g_\Sigma V \int \frac{d^3p}{(2\pi)^3} e^{\frac{-E_\Sigma}{T} + \frac{\mu_B}{T}}\right)}{g_{K^-} V \int \frac{d^3p}{(2\pi)^3} e^{\frac{-E_{K^-}}{T}} \left(g_{K^+} V \int \frac{d^3p}{(2\pi)^3} e^{\frac{-E_{K^+}}{T}}\right)}, \quad (4)
$$

where g_α are the spin-isospin degeneracies and V is the interaction volume. The above expression shows that the presence of K^+ must be compensated by Λ, Σ and K^- to conserve strangeness equal to zero, while K^- can only be compensated by K^+.

It is found that the data [12] can be explained using a $T = 70 \pm 10$ MeV and $\mu_B = 720 \pm 20$ MeV. G.Brown [13] introduced the notion of "broad-band equilibration" in heavy-ion processes at GSI energies. In this interpretation, due to the compensation between the increase in μ_B as the density increases and the density dependence of $U_{\bar{K}}$, the ratio is constant over a large range of densities, not only for $\rho \sim \frac{1}{4}\rho_0$, but also up to $2\rho_0$.

In Fig.3, we show the importance of dressing K^-. Plotting the ratio K^+/K^- as function of density, it can be seen that the effect of including $U_{\bar{K}}$ reduces the ratio that, otherwise, would increase steadily (short-dashed line). It is also seen that dressing the pions induces appreciable differences in the calculations (long-dashed line).

Once the full dressing is included, Fig.4 shows the sensitivity of the ratio to the chemical potential, and hence to density, as well as the importance of introducing the Σ in the balance equation. The "broad-band equilibration" is hardly reproduced when the Σ is taken into account, and one obtains large differences depending on the character (attractive or repulsive) of the Σ optical potential.

IV. CONCLUSIONS

Performing a microscopic calculation of the Brueckner-Hartree-Fock type , we conclude that dressing pions in the calculation of $U_{\bar{K}}$ introduces significant differences, around 13% at zero momentum. Moreover, the introduction of temperature gives rise to a smoother behaviour in momentum, being attractive even at momentum as large as 500 MeV, relevant in heavy-ion collisions. Heavy-ion collisions are the perfect scenario to test in-medium $\bar{K}$ properties, specially in understanding the ratio K^-/K^+. The attempts to reproduce this ratio require an attractive $U_{\bar{K}}$. The ratio shows a measurable density dependence. The

"broad-band equilibration" is far from being reproduced if hyperons like Σ are taken into account, showing large differences with regard to only including Λ hyperons.

ACKNOWLEDGMENTS

REFERENCES

[1] A. Müller-Groeling, K. Holinde and J. Speth, Nucl. Phys. A513 (1990) 557.

[2] S.Balberg and A.Gal Nucl. Phys. A625 (1997) 435.

[3] E. Oset and A. Ramos, Nucl. Phys. A671 (2000) 481.

[4] L.Tolós, A. Ramos, A.Polls and T.T.S.Kuo Nucl. Phys. A690 (2001) 547.

[5] R. Barth et al., Phys. Rev. Lett. 78 (1997) 4007; F. Laue et al., Phys. Rev. Lett. 82 (1999) 1640.

[6] M.Menzel et al.Phys. Lett. B (2000) 26.

[7] A.Förster, Ph.D Thesis, TU Darmstad.

[8] P.Senger , Nucl. Phys. A685 (2001) 312.

[9] W. Cassing, E.L. Bratkovskaya, U. Mosel, S. Teis and A. Sibirtsev, Nucl. Phys. A614 (1997) 415; E.L. Bratkovskaya, W. Cassing and U. Mosel, Nucl. Phys. A622 (1997) 593.

[10] G.Q. Li, C.-H. Lee and G.Brown, Nucl. Phys. A625 (1997) 372; *ibid*, Phys. Rev. Lett. 79 (1997) 5214.

[11] J.Cleymans, H.Oeschler and K.Redlich, Phys. Rev.C59 (1999) 1663

[12] J.Cleymans, D.Elliot, A.Keränen and E.Suhonen, Phys. Rev.C57 (1998) 3319

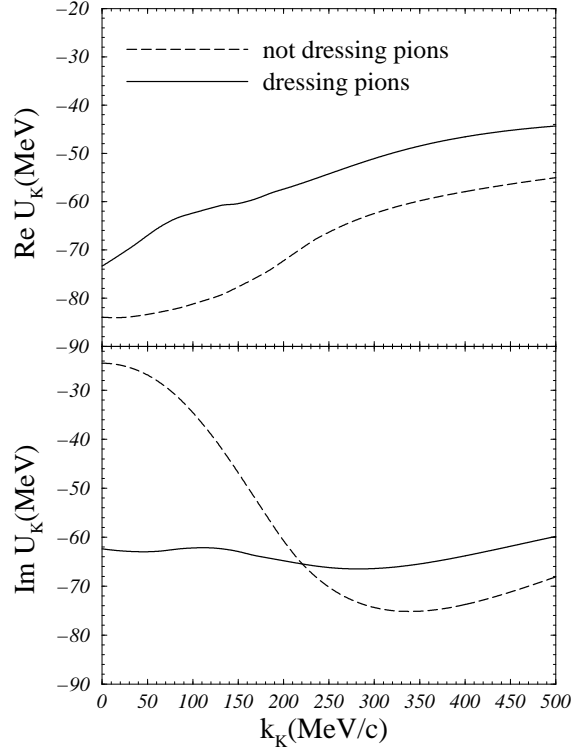[13] G.Brown, M.Rho and C.Song, Nucl. Phys.A690 (2001) 184

FIGURES

FIG. 1. $U_{\bar{K}}$ as a function of $k_{\bar{K}}$ for $T = 0$, including or not the dressing of pions at $\rho = 0.17 fm^{-3}$
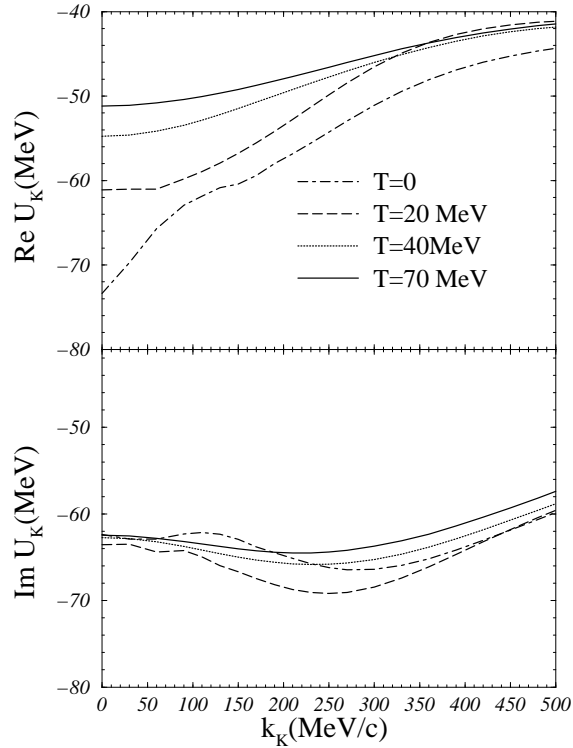

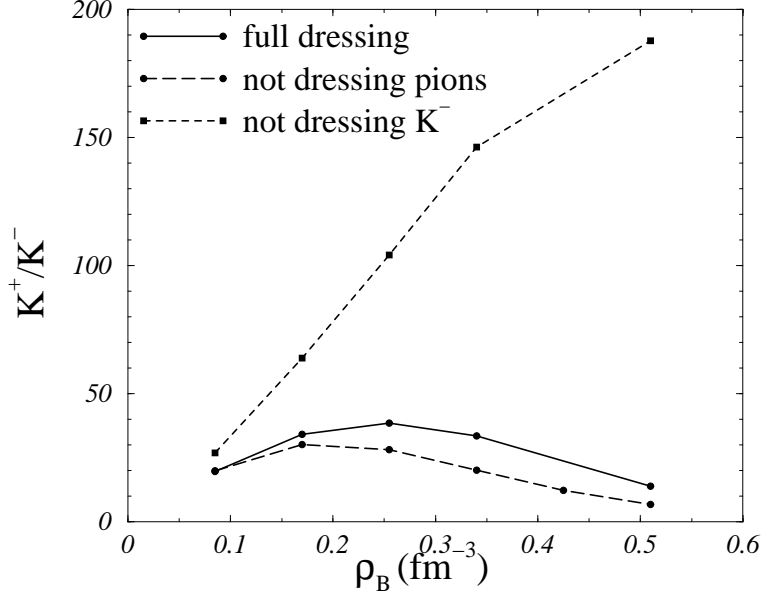FIG. 2. $U_{\bar{K}}$ as a function of $k_{\bar{K}}$ for different T, at $\rho = 0.17 fm^{-3}$

FIG. 3. K^+/K^- as a function of density at $T = 70 MeV$, including or not $U_{\bar{K}}$
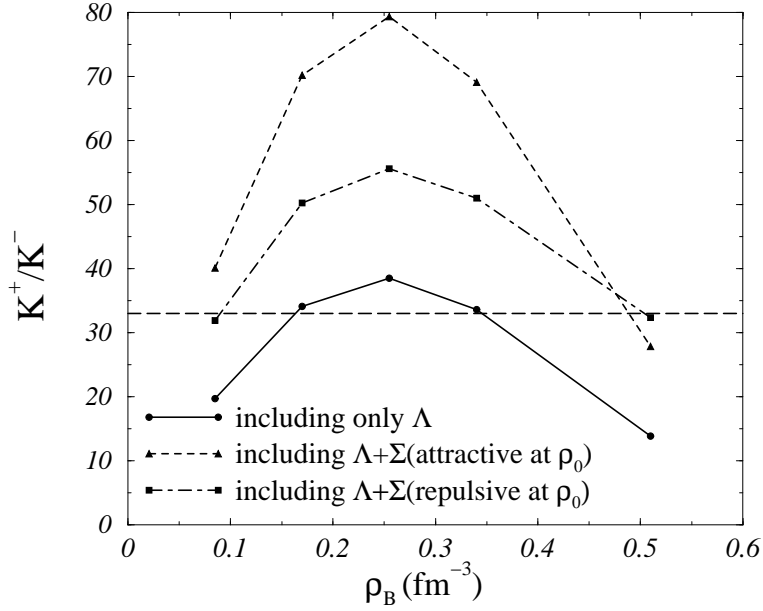

FIG. 4. K^+/K^- as a function of density at $T = 70 MeV$, included $U_{\bar{K}}$, including or not Σ