Kaon Phase Space Density in Heavy Ion Collisions

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Abstract. The first measurement of kaon phase space densities are presented as a function of $m_T$, $\sqrt{s_{nn}}$ and the number of participants. The kaon phase space density increases with the number of participants from $e^+e^-$ to $Pb+Pb$ collisions. However the ratio of the kaon and pion phase space densities at low $P_T$ is independent of number of participants for $\sqrt{s_{nn}} = 17\text{GeV}$.

This paper is dedicated to Francis Riccardelli, engineer for the Port Authority, who died on September 11th 2001 while evacuating others.

1. Introduction

A particle’s phase space density is defined as

$$f(p, x) \equiv \frac{(2\pi\hbar c)^3}{(2s + 1)} \frac{d^6N}{dp^3dx^3}$$

where $s$ is the particle’s spin. A way to measure the average value of $f(p)$ over the volume of the system sampled by interferometry measurements was first suggested by Bertsch. For a system in chemical equilibrium at a temperature $T$ and chemical potential $\mu$

$$f(E) = \frac{1}{e^{(E-\mu)/T} \pm 1}$$

where $E$ is the energy and $\pm 1$ selects bosons or fermions. Since the energy $E$ may depend on the transverse flow in the system the phase space density is sensitive to both the dynamics and thermodynamics of the system. The pion phase space density was first measured, as a function of $m_T$, by Ference et al., for Pb+Pb collisions at center of mass energy $\sqrt{s_{nn}} = 17\text{GeV}$ a temperature of 120MeV was extracted as well as a measure of the average transverse flow. Later measurements of proton, antiproton and pion phase densities showed that they also depend on the number of participants and $\sqrt{s_{nn}}$. In this paper we derive phase space densities for $k^\pm$ versus $m_T$, $\sqrt{s_{nn}}$ and the number of participants and compare to $\pi^\pm$, $p$ and $\bar{p}$ densities from [3].

For a dilute system, i.e. $f \ll 1$, Eqn. 2 gives

$$f_k \approx e^{\mu - E_k/T}$$
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Since $E = m_T \cosh(y)$ we would expect $f_k$ to be exponential in $m_T$ with a slope that depends on the strength of the transverse flow. If the relevant degrees of freedom are quarks then since the $k^+$ contains both $u$ and $\bar{s}$ quarks

$$f_{k^+} \approx e^{\mu_u - \mu_s - E_k/T}$$

$$f_{k^-} \approx e^{-\mu_u + \mu_s - E_k/T}$$

This implies that

$$\frac{f_{k^-}}{f_{k^+}} = e^{-2\mu_u + 2\mu_s}$$

and so $f_{k^-}/f_{k^+}$ can give information on the light and strange quark chemical potentials.

For pions we would expect the chemical potential of $u$ and $\bar{u}$ quarks to approximately cancel and so

$$f_{\pi} \approx e^{-E_k/T}$$

and

$$f_{k^+}/f_{\pi} \approx e^{\mu_u - \mu_s}$$

Thus the ratio of phase densities $f_{k^+}/f_{\pi}$ is controlled by the balance of the light and strange quark chemical potentials.

2. Method

NA44 has measured the kaon source size in 3 dimensions with HBT, as well as single particle spectra [4, 5]. Dividing $d^3 N_k/dp^3$ by the Lorentz invariant volume, [1, 6] gives the spatially averaged phase space density.

$$\langle f_k \rangle = \frac{\pi^{\frac{3}{2}} (hc)^3}{(2s + 1)^2} \frac{d^3 N_k}{dp^3} \frac{1}{R_{\text{side}} \sqrt{R_{\text{out}}^2 R_{\text{long}}^2 - R_{\text{outlong}}^4}}$$

At $y=0$ $R_{\text{outlong}}$ should be identically zero [8] and so we ignore it in this paper since the data are close to mid-rapidity.

3. Results

Figure 1 shows kaon, pion and proton phase space densities versus the transverse mass $m_T$ for Au+Au and Pb+Pb collisions at $\sqrt{s_{nn}} = 5$ and 17GeV respectively. Although all phase densities drop with $m_T$ the slope is flatter for protons than for pions and kaons as might be expected from the effect of transverse flow. The kaon and pion slopes for $\sqrt{s_{nn}} = 17$GeV are equal within errors. At $\sqrt{s_{nn}} = 17$GeV around $m_T = 0.5$ the kaon phase densities lie below those of the pions. However at $\sqrt{s_{nn}} = 5$GeV this effect is reversed. Using Eqn. 8 we deduce from the drop of $\langle f_{k^+} \rangle/\langle f_{pk^+} \rangle$ with $\sqrt{s_{nn}}$ that $\mu_u$ drops more rapidly with $\sqrt{s_{nn}}$ than $\mu_s$. Extrapolating the pion slope to $m_T = 1.05$ we estimate that $\langle f_{\pi} \rangle > \langle f_k \rangle \approx \langle f_p \rangle$ at $\sqrt{s_{nn}} = 17$GeV whereas an extrapolation of the data at $\sqrt{s_{nn}} = 5$GeV would predict the opposite behavior.
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Phase Space Density $17\sqrt{s_{nn}}$ PbPb AuAu $p$ $\bar{p}$ $k$

Figure 1. $\pi^+$, proton and $k^+$ phase space densities versus $m_T$ at $\sqrt{s_{nn}} = 17$GeV, solid circles, square and diamonds. The pion point at $m_T = 0.9$ (GeV) is actually $\pi^-$. The open symbols are for $\sqrt{s_{nn}} = 5$GeV.

Figure 2 shows $\pi^\pm, k^\pm, p$ and $\bar{p}$ phase space densities from NA44 versus the number of participants. Also shown are $\pi^+$ and $k^+$ densities from $e^+e^-$ collisions at $\sqrt{s_{nn}} = 91$GeV [8]. Although all phase densities increase markedly with the number of participants their ratios are remarkably constant. A similar rise is in $\langle f_{k^+} \rangle$ is seen at the AGS where $\langle f_{k^+} \rangle$ rises from Si+Au to Au+Au. For S+Pb collisions NA44 has measured both $k^+$ and $k^-$ spectra and source sizes. We find that $\langle f_{k^-} \rangle < \langle f_{k^+} \rangle$. Therefore from Eqn. 6 we deduce that $\mu_s < \mu_u$.

4. Conclusions

The kaon phase space $\langle f_{k^+} \rangle$ density drops with $m_T$ and at a $m_T$ is somewhat lower than $\langle f_{\pi^+} \rangle$ for $m_t \approx 0.5$. This implies that $k^+$s have a larger chemical potential than pions. Near $p_t = 0$ we find

$$\langle f_{\bar{p}} \rangle \ll \langle f_p \rangle \ll \langle f_{k^-} \rangle < \langle f_{k^+} \rangle \ll \langle f_{\pi^+} \rangle < \langle f_{\pi^-} \rangle < 1$$

However because the protons have flatter slopes in $m_T$ than the pions and kaons we would expect the proton phase space density to exceed that of the pions and kaons for $m_T > 1.2$GeV/$c^2$. We find that at low $p_T$ $\langle f_{k^+} \rangle$ and $\langle f_p \rangle$ drops with $\sqrt{s_{nn}}$. This presumably is because increase flow at the higher energy overcomes the effect of extra particle production. It will be interesting to see if this trend of dropping phase space density continues up to RHIC energies. As the number of participants increases $\langle f_{k^+} \rangle$, $\langle f_{\pi} \rangle$ and $\langle f_p \rangle$ all increase but their ratios remain constant at SPS energies.
Figure 2. Kaon, pion and proton phase space densities (a) and ratios (b) versus the number of participants.

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6. References

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