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STRANGENESS PRODUCTION IN HEAVY ION COLLISIONS AT FINITE BARYON NUMBER DENSITY

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Abstract

We study the K^+/π^+ and K^-/π^- production rates in heavy ion collisions, using a hadron gas model which includes baryon repulsion and intermediate resonances, taking strangeness conservation into account. In such a description, the state of the system is specified by its temperature T and its baryon number density n_B . Fixing the K^+/π^+ and K^-/π^- rates then determines the freeze-out values of T and n_B . The production rates recently measured in Silicon-Gold collisions at the Brookhaven AGS energies are shown to give $93 \leq T \leq 112$ MeV and $0.02 \leq n_B \leq 0.12$ baryons/fm³.

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The K/π ratios measured in $Si - Au$ interactions^{1,2} are among the most striking results which have so far come out of high energy heavy ion collisions. For Si^{28} at 14.6 GeV/c per nucleon, incident on a gold target, the E 802 collaboration finds in the mid-rapidity region² $K^+/\pi^+ = 19.2 \pm 3\%$ and $K^-/\pi^- = 3.6 \pm 0.8\%$. For comparison, at ISR energies in the central rapidity region³, both ratios are about 11%. The $Si - Au$ measurements therefore seem to provide evidence for an appreciable nuclear effect in $Si - Au$ collisions.

Strangeness production in nuclear collisions has been discussed in the context of quark-gluon plasma formation^{4,5}; it is therefore of interest to ask whether the K^+/π^+ and K^-/π^- ratios now observed can be understood in terms of a purely hadronic model. The considerations we shall present here will show that this can indeed be done very easily and naturally, and we therefore believe that the reported results cannot provide any indication for plasma formation. They do, however, fit very nicely into a *statistical* picture of hadron production in heavy ion collisions. Without additional assumptions, the observed final particle ratios provide information only about the late stages of the nuclear reaction (freeze-out), and not about the early history of the process, when the temperature could have been high enough to have a plasma. By the same token, the agreement of the measured values with predictions of a purely hadronic model also does not rule out plasma formation at an early stage.

We shall consider a simple thermodynamic model of hadronic matter*, in which the state is specified by the temperature T and the baryon number density n_B , with zero overall strangeness. Such matter will have a certain composition of particle species, characterized by corresponding "chemical" potentials. In addition to the baryon number chemical potential μ_B , we have to impose overall strangeness conservation. This can be done by introducing a strangeness potential μ_S , since particles of a given strangeness can have different baryon numbers (e.g., $\bar{K}^0$ and Λ). The value of μ_B is fixed by giving the overall baryon number density n_B , and that of μ_S by fixing the overall strangeness, which in our case will be zero. The number densities for all hadron states are then given in terms of μ_B and T .

To keep our model as simple as possible, we include only the essential interaction features of a multi-hadron system near freeze-out: resonance production and baryon repulsion. The bulk of meson production is known to take place through intermediate resonance states, and we therefore start with an ideal gas containing all the observed non-strange and strange mesonic and baryonic resonances up to a mass of 2 GeV.⁷ To obtain the distributions of the actually observed hadrons, in particular pions and kaons, we then let these resonances decay according to the measured branching ratios. For small or vanishing baryon number, this would suffice to fix our model; at high n_B , however, a strong, short-range repulsion sets in between baryons, even if they

* A similar model is considered in ref. 6, but not applied directly to a prediction of the K/π ratios.

have different quantum numbers; this can be described in terms of a hard-sphere picture⁸. As a consequence, the baryon number density n_B becomes

$$n_B = \frac{n_B^0}{[1 + V n_B^0]}, \quad (1)$$

where n_B^0 denotes the density calculated for an ideal gas of pointlike baryons. We note that for $n_B^0 \rightarrow \infty$, $n_B \rightarrow 1/V$, i.e., we have dense packing* of hard-sphere baryons with an intrinsic volume V . In the case of several baryon species $\alpha = 1, 2, \dots, r$, eq.(1) becomes

$$n_B = \frac{n_B^0}{[1 + \sum_{\alpha=1}^r V n_{\alpha}^0]}, \quad (2)$$

using a baryon volume V_{α} proportional to the mass as suggested e.g. by the bag model. Here we take $V = 4\pi R^3/3$, with $R = 0.5$ and 0.8 as indicative radii for the nucleon. In addition, we shall also consider the case when $R=0$, to check the role baryon repulsion plays in determining particle number ratios. This completes our picture. To illustrate the resulting pattern, we note that

$$n_{K^{\pm}}^0 = (2\pi)^{-3} \int d^3p \frac{1}{[e^{(E_K \mp \mu_S)/T} - 1]} \quad (3)$$

gives the number density of *thermally produced* kaons, and

$$n_{\Lambda}^0 = (2\pi)^{-3} \int d^3p \frac{1}{[e^{(E_{\Lambda} - (\mu_B - \mu_S))/T} + 1]} \quad (4)$$

that of *thermal, pointlike* Λ 's; here $E_K = (\mathbf{p}^2 + m_K^2)^{1/2}$ and $E_{\Lambda} = (\mathbf{p}^2 + m_{\Lambda}^2)^{1/2}$. The *actual* production rates are obtained from this by including baryon repulsion according to eq.(2) and by adding to eqs.(3) and (4) the corresponding values from resonance production, such as $K^{0*} \rightarrow K^+ + \pi^-$, using the experimentally determined branching ratios. Requiring the difference between all strange particle number densities to vanish,

$$\sum_i n_i^{(S)} - \sum_i n_i^{(B)} = 0, \quad (5)$$

fixes μ_S and thus gives us all particle densities in terms of T and μ_B . Summing at fixed μ_B over all baryon contributions,

$$\sum_i n_i^{(B)} - \sum_i n_i^{(B)} = n_B, \quad (6)$$

* Actually $1/V$ is the limiting value for incompressible but deformable baryons; a true hard-sphere system yields $1/cV$, with $c \geq 1$.⁹

determines the overall baryon number density n_B . Note that in eq.(6) we sum over the *physical* baryon densities as defined by eq.(2).

Before we turn to the numerical K/π ratios resulting from this model, let us discuss qualitatively the expected behaviour. At $n_B = 0$, we have complete particle-antiparticle symmetry and hence $K^+/K^- = \pi^+/\pi^- = 1$. With increasing n_B , Fermi repulsion forces baryons of a given species to acquire higher momenta and thus eventually makes e.g. $p \rightarrow \Lambda$ K^+ energetically favourable. At low temperatures, this results in an increase of K^+/π^+ with n_B . Since processes such as $n \rightarrow \Delta^0$, with the subsequent decay $\Delta^0 \rightarrow p \pi^-$, enhance π^- production, but no similar effect exists for antikaons, the K^-/π^- ratio decreases with increasing n_B . For higher temperatures and hence more available kinetic energy, the role of Fermi repulsion and thus also the variation of K^+/π^+ and K^-/π^- with n_B is reduced.

When the baryon density is increased still further, more and more higher mass baryon states come into play. These – although some also lead to further kaon production – on the whole enhance pion more than kaon rates. This means that eventually the initial K^+/π^+ gain is overcome and also this ratio starts falling with n_B . On the other hand, strange baryon resonances now lead to further antikaon production, so that the decrease of the K^-/π^- ratio slows down. At still higher densities one eventually reaches the dense packing limit.

We now discuss our actual calculations. In figure 1 we show the dependence of the K/π ratios on the hard-core radius R as a function of baryon density. As one can see the K^+/π^+ ratio initially rises with increasing baryon density; it then reaches a plateau and starts decreasing. For moderate densities the K^+/π^+ ratio is almost independent of the hard-core radius and after reaching a maximum the ratio becomes very strongly dependent on this radius. The K^-/π^- ratio always decreases for increasing baryon densities.

Figure 2 shows the K/π ratios in their T and n_B dependence for the range of relevance for the BNL data. As seen, the data fall into the region of $93 \leq T \leq 112$ MeV and $0.02 \leq n_B \leq 0.12$ fm $^{-3}$; a fit gives $T \simeq 105$ MeV and $n_B \simeq 0.1$ baryons/fm 3 as freeze-out parameters for a baryon radius of $R = 0.8$ fm. To test for the dependence of these results on the finite volume corrections we show these results again in figure 3 together with different choices for volume corrections. These include the purely geometric volume correction, a volume correction depending only on the overall baryon density of the gas and one which depends on the energy density¹⁰ of the gas. We also include the case of no volume corrections at all. As can be seen from figure 3, the influence of the different volume corrections is minimal in the low baryon density region (corresponding to the freeze-out value). This is consistent with the assumptions of the model. If the baryon density were extremely high, the gas would still continue to exist and only freeze out much later. – The corresponding values for the entropy per baryon are shown in figure 4.

Our results thus lead to a temperature which is about ten per cent lower than the

value deduced from the transverse momenta spectra as presented in reference 1. As our model is crude, this could be due to a variety of factors, such as non-equilibrium effects, hydrodynamic expansion, or interactions between hadrons. In view of all this, it is perhaps even surprising that an ideal hadron gas leads to such close agreement with the results obtained from the transverse momenta spectra.

How do the results for heavy ion collision results compare to those from $p-p$ collisions? The K/π ratio is generally quite sensitive to kinematic factors such as transverse momentum or rapidity. One reliable point seems to be the ISR measurement in the central region since this corresponds best to zero baryon number density and also remains constant over the whole central rapidity region. The ratio measured is 11% for both K/π ratios. This is in fact reproduced quite well by our results. One should keep in mind, however, that finite size effects could be appreciable in $p-p$ collisions¹¹; this aspect is presently being investigated using the canonical ensemble.

A somewhat similar calculation has been performed recently¹² using a smaller number of hadrons and without considering their decay products. The K/π ratios have also been analysed¹³ in a covariant microscopic approach.

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Figure Captions

Figure 1: Dependence of the K/π ratios on the baryon density for different values of the nucleon radius at $T = 105$ MeV.

Figure 2: Dependence of the K/π ratios on the baryon density for different values of the temperature at $R = 0.8$ fm.

Figure 3: Influence of volume corrections on the K/π ratios.

- 1: no volume correction;
- 2: volume correction using the energy density of the gas¹⁰;
- 3: geometric volume correction;
- 4: volume correction using the baryon density⁸.

Figure 4: The K/π ratios as function of the entropy per baryon for $R = 0.8$ fm, at two different temperatures.

Figure 3

Figure 4