The Physics Case for the $\sqrt{s_{NN}} \approx 10$ GeV Energy Region.

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To the memory of Professor Dr. Walter Greiner

There are indications that the beam energy region $\sqrt{s_{NN}} \approx 10$ GeV for heavy-ion collisions is an interesting one. The final state has the highest net baryon density at this beam energy. A transition from a baryon dominated to a meson dominated final state takes place around this beam energy. Ratios of strange particles to mesons show clear and pronounced maxima around this beam energy. The theoretical interpretation can be clarified by covering fully this energy region. In particular the strangeness content needs to be determined, data covering the full phase space ($4\pi$) would be helpful to establish the properties of this energy region.

1. Introduction

Heavy-ion collisions at high energies produce a large numbers of secondaries. At the LHC the number of charged particles produced in Pb-Pb collisions at 5.02 TeV is shown in Fig. 1, thus, including neutral particles, a total of approximately 30 000 particles is being produced on average in such a collision. It is natural to try a statistical-thermal model to analyze these. As it turns out such an analysis is useful for a very wide range of beam energies, stretching from 1 GeV all the way up to the highest energies available at the LHC. For such an analysis one has to keep in mind that a relativistic heavy-ion collision passes through several stages. At one of the later, hadronic, stages, the system is assumed to be dominated by hadronic resonances, on which the thermal model focuses. The identifying feature of the thermal model is that all the resonances as listed in are assumed to be in thermal and chemical equilibrium. This assumption drastically reduces the number of free parameters and thus this stage is determined by just a few thermodynamic variables namely, the chemical freeze-out temperature $T$, the various chemical potentials $\mu$ determined by the conserved quantum numbers and by the volume $V$ of the system.
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![Graph showing number of charged particles produced in Pb-Pb collisions as a function of beam energy.](image)

Fig. 1. Number of charged particles produced in a Pb-Pb collision as a function of beam energy as measured by the ALICE collaboration.

It has been shown that this description is also the correct one for a scaling expansion as first discussed by Bjorken.

In relativistic heavy ion collisions a new dimension was given to the model by the highly successful analysis of particle yields, leading to the notion of chemical equilibrium which is now a well-established one in the analysis of relativistic heavy ion collisions, see e.g.\cite{8-10} In view of the success of chemical freeze-out in relativistic heavy ion collisions, much effort has gone into finding models that describe this chemical freeze-out, a comparison of three parameterizations is shown in Fig. 2.

There are of course uncertainties in the thermal model, one of these is about the decays of resonances, another one is whether some resonances exist or not. Particle yields are determined from:

$$N_i = \sum_j N_j Br(j \rightarrow i).$$

Hence a lack of knowledge of branching ratios affects the quality of results obtained from the thermal model.

As an example, the final yield of $\pi^+$’s is given by

$$N_{\pi^+} = N_{\pi^+} \text{(thermal)} + N_{\pi^+} \text{(resonance decays)}$$

and, depending on the temperature, over 80% of observed pions could be due to resonance decays. Hence the crucial importance of these decays. Various theoretical uncertainties have been recently discussed in\cite{13}.
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2. What makes the beam energy $\sqrt{s_{NN}} \approx 10$ GeV special?

2.1. Maximum net baryon density

The resulting freeze-out curve in the $T-\mu_B$ plane, shown in Fig. 2, can also be drawn in the temperature $T$ vs net baryon density plane as was done in Ref. 14. The resulting curve is shown in Fig. 3. At very high beam energies the net baryon density is zero because equal numbers of particles and antiparticles are being produced while at low temperatures the net baryon density is very high. Fig. 3 shows that the a clear maximum exists just below the $\sqrt{s_{NN}} = 10$ GeV beam energy region.

2.2. Transition from a baryon dominated to a meson dominated final state

A fairly good criterium for chemical freeze-out is the constant value of the entropy density divided $s/T^3 = 7$ ratio as can be seen from Fig. 2. The components that make up the entropy density are shown in Fig. 4, the change from a baryon-dominated to a meson-dominated final state also happens around a beam energy of $\sqrt{s_{NN}} \approx 10$ GeV.
2.3. Ratios of strange hadrons to pions

Despite the smoothness in the thermal freeze-out parameters as a function of beam energy, strong changes are observed in several particle ratios, e.g. the horn in the $K^+/\pi^+$ ratio and a similar strong variation in the $\Lambda/\pi$ ratio. These are not observed in $p-p$ collisions, in Pb-Pb collisions they happen at a beam energy of around $\sqrt{s_{NN}} \approx 10$ GeV. Within the framework of thermal models this variation has been connected to a change from a baryon dominated to a meson dominated hadron gas. The values of the $K^+/\pi^+$ and $\Lambda/\pi^+$ ratios are shown in Fig. 5. From the lines of constant values for these ratios it can be seen that the maxima in the thermal model hug the chemical freeze-out line. It is also important to note that the maxima occur for different values of $T$ and $\mu_B$. 

Fig. 3. The hadronic freeze-out line in the $\rho_B - T$ phase plane as obtained from the values of $\mu_B$ and $T$ that have been extracted from the experimental data [11]. The calculation employs values of $\mu_Q$ and $\mu_S$ that ensure $\langle S \rangle = 0$ and $\langle Q \rangle = 0.4 \langle B \rangle$ for each value of $\mu_B$. Also indicated are the beam energies for which the particular freeze-out conditions are expected. The dependence on a hard-core radius is indicated.
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3. Conclusions

In the thermal model a change is expected as the hadronic gas undergoes a transition from a baryon-dominated to a meson-dominated gas. The strong variations seen in the particle ratios coincide with this transition. This transition occurs at a

- temperature $T = 151$ MeV,
- baryon chemical potential $\mu_B = 327$ MeV,
- energy $\sqrt{s_{NN}} = 11$ GeV.

There are thus several indications that the energy region around 10 GeV, covered by proposed new facilities, is an extremely interesting one. The theoretical interpretation can be clarified by covering this energy region. In particular the strangeness content needs to be determined, data covering the full phase space ($4\pi$) would be very helpful to determine the thermal parameters of a possible phase transition and the existence of a quarkyonic phase as has been discussed recently in [18].
Fig. 5. Lines of constant values of the $K^+ / \pi^+$ (left panel) and the $\Lambda / \pi^+$ (right panel) ratios in the $T - \mu_B$ plane showing a clear maximum in each ratio close to the boundary given by the chemical freeze-out line but in a different position$^{17}$.

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