Comparison of Chemical Freeze-Out Criteria in Heavy-Ion Collisions.

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The energy dependence of the chemical freeze-out temperature and chemical potential obtained in heavy ion collisions is discussed. Proposals for chemical freeze-out conditions are compared.

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1. Introduction

Over the past decade a striking regularity has been established in heavy ion collisions: from SIS to RHIC, particle yields are consistent with the assumption of chemical equilibrium [1]. Furthermore, the chemical freeze-out temperature, T, and the baryon chemical potential μ_B follow a strikingly regular pattern as the beam energy increases. This has led to several proposals describing the freeze-out curve in $T - \mu_B$ plane. The conditions of fixed energy per particle [2, 3], baryon+anti-baryon density [4], normalized entropy density [5, 6] as well as percolation model [7] all lead to reasonable descriptions of the freeze-out curve in the $T - \mu_B$ plane. The results have been compared with the most recent [8, 9, 10] chemical freeze-out parameters obtained in the thermal-statistical analysis of particle yields in [11] where the sensitivity and dependence of the results on parameters is analyzed and discussed. It has been shown in [11] that, within present accuracies, all chemical freeze-out criteria give a fairly good description of the particle yields, however, the low energy heavy-ion data favor the constant energy per hadron as a condition for chemical freeze-out. This condition also shows the weakest sensitivity on model assumptions and parameters. This criterion was first identified [2, 3] by comparing the thermal parameters at SIS energy with those obtained at SPS. It was shown that the average energy per particle at SIS energy reaches approximately the same value of 1 GeV as calculated at the critical temperature expected for deconfinement at $\mu_B = 0$. In addition, known results for chemical freeze-out parameters at the AGS also reproduced the same value of energy per particle. Thus, it was suggested that the condition of a fixed energy per hadron is the chemical freeze-out criterion in heavy-ion collisions. A comparison with the extracted results on T and μ_B is shown in Fig. [1]. The best estimate gives a value $\langle E \rangle / \langle N \rangle \approx 1.08$ GeV.

In addition to the fixed $\langle E \rangle / \langle N \rangle$ criterion, alternative proposals have been made to describe chemical freeze-out in heavy-ion collisions at all energies:

- a fixed value for the sum of baryon and anti-baryon densities, $n_B + n_{\bar{B}}$, of approximately $0.12/\text{fm}^3$ [4];

- a self-consistent equation for the densities based on geometric estimates using percolation theory [7];

$$n(T,\mu) = \frac{1.24}{V_h} \left[1 - \frac{n_B(T,\mu)}{n(T,\mu)} \right] + \frac{0.34}{V_h} \left[\frac{n_B(T,\mu)}{n(T,\mu)} \right]. \qquad (1.1)$$

- a fixed value of the entropy density, s/T^3, of approximately 7 [5, 6].

A comparison of these proposals is given in Fig.[2]. which shows that all proposals give a reasonable description in the region between AGS and RHIC energies. Deviations appear at the highest RHIC energy and at beam energies between AGS and SIS. It would therefore be very interesting to have good data in this energy region.

Independently of any particular criterium or model for the freeze-out condition, a numerical parametrization, shown in Fig. [3], is given by.
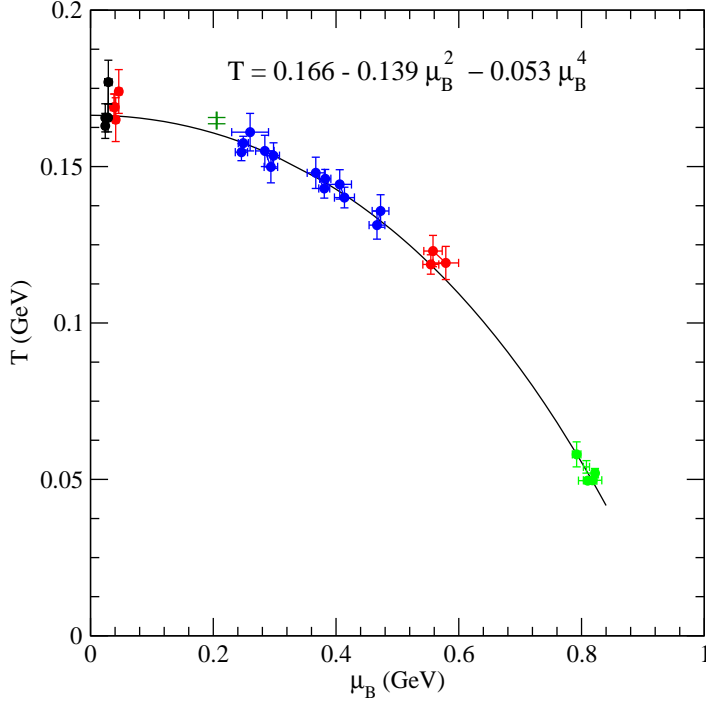
$$T = 0.166 - 0.139\mu_B^2 - 0.053\mu_B^4. \qquad (1.2)$$
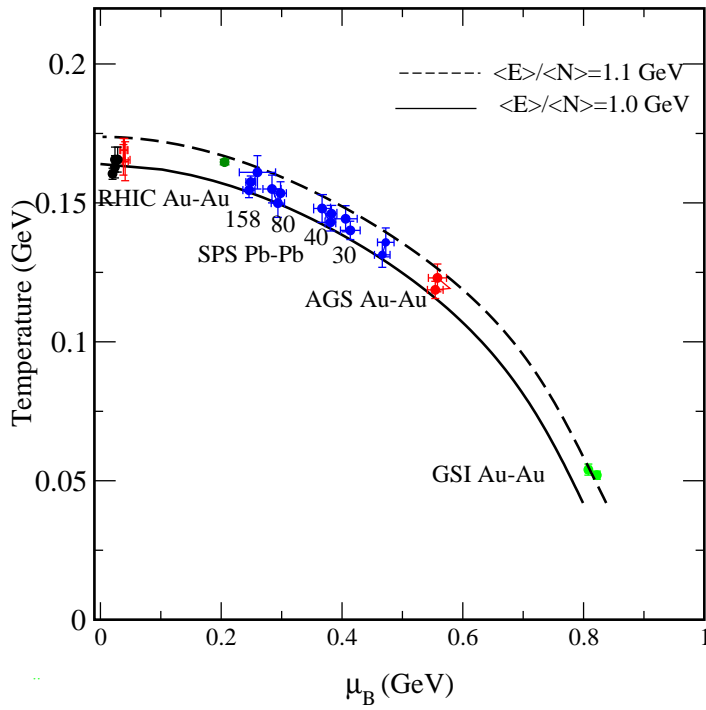
Figure 1: Values of T and μ_B deduced from particle multiplicities in heavy ion collisions for a wide range of beam energies.
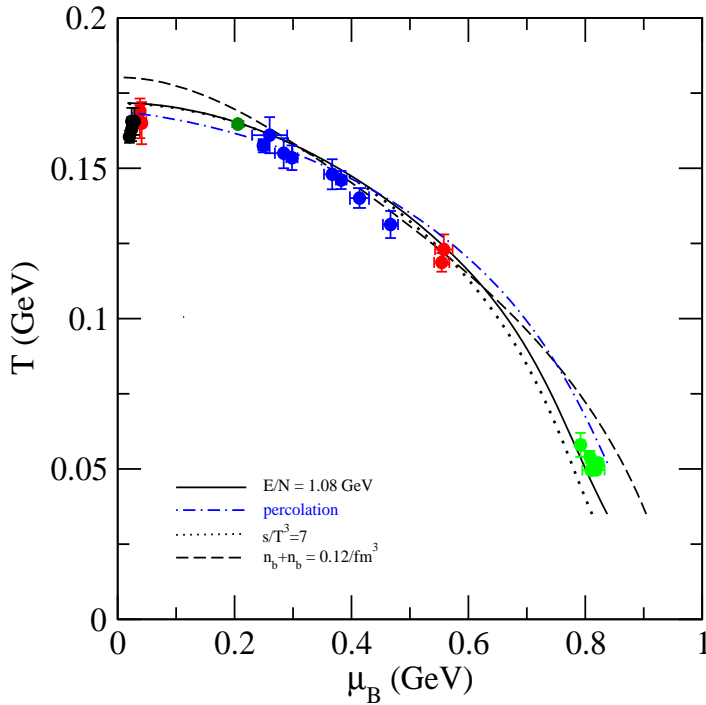
Figure 2: Comparison of various freeze-out criteria with the values of T and μ_B obtained from particle multiplicities in heavy ion collisions.

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Figure 3: A parametrization of the freeze-out curve deduced from particle multiplicities in heavy ion collisions.

2. Energy Dependence of μ_B and T.

The values obtained for μ_B as a function of beam energy are displayed in Fig. [4]. As this shows a smooth variation with energy, it can be parametrized as

$$\mu_B(\sqrt{s}) = \frac{1.308 \text{ GeV}}{1 + 0.273 \text{ GeV}^{-1}\sqrt{s}}. \tag{2.1}$$

This leads to the expectation that $\mu_B \approx 1$ MeV at LHC energies.

Similarly, the freeze-out temperature is shown in Fig. [5].

A straightforward extrapolation leads to a value at LHC energies $T \approx 166$ MeV [12]. The energy dependence of the thermal parameters makes it possible to calculate the maximum baryon density at chemical freeze-out [13]. The hadronic freeze-out line in the $\rho_B - \varepsilon$ phase plane as obtained in the statistical model with the values of μ_B and T that have been extracted. The curves on the right have been calculated for $\mu_Q = \mu_S = 0$ using either quantal (solid) or classical (dashed) statistics, while
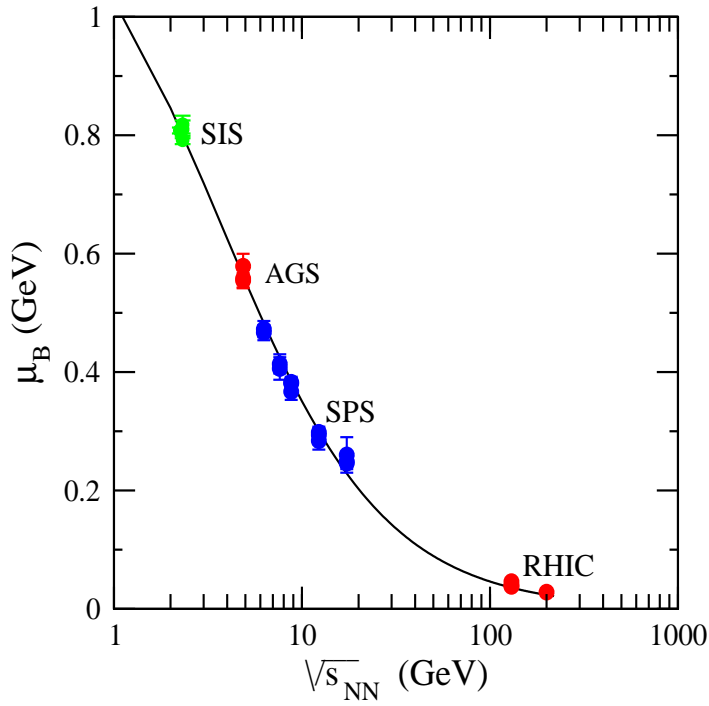
Figure 4: Variation of the baryon chemical potential as a function of energy.
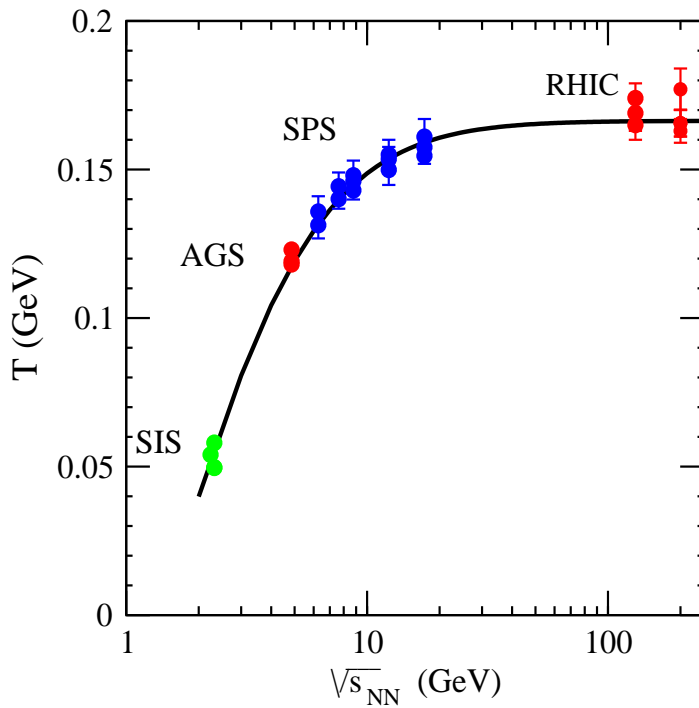
Figure 5: Variation of the baryon chemical potential as a function of energy.
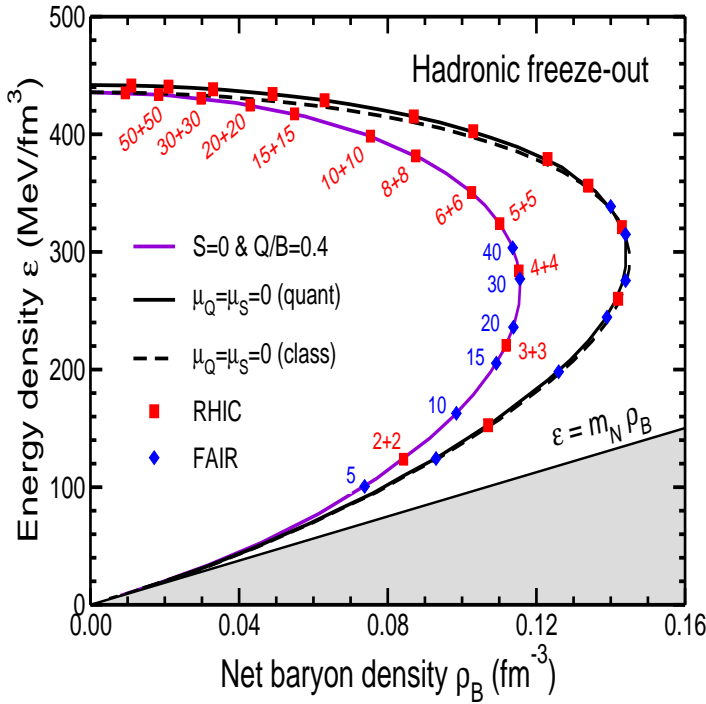
Figure 6: Chemical freeze-out line showing the maximum baryon density.

the curve on the left employs values of μ_Q and μ_S that have been adjusted to ensure $\langle S \rangle = 0$ and $\langle Q \rangle = 0.4\langle B \rangle$ for each value of μ_B. Also indicated are the beam energies (in GeV/*A*) for which the particular freeze-out conditions are expected at either RHIC (total energy in each beam), starting at 100+100 and going down to 2+2, or FAIR (kinetic energy of the beam for a stationary target), starting at 5 and going up to 40. as based on fits to existing data. The triangular area corresponds to energy densities below the minimum required at the given net baryon density, $\varepsilon = m_N \rho_B$ (ignoring binding and compression), and is thus inaccessible.

3. Conclusions

There is by now a long history of measurements of particle abundances in heavy ion collisions covering a wide range of beam energies. The case for chemical equilibrium has become stronger over the years with every new analysis confirming and reinforcing conclusions reached previously. To distinguish between the various proposals which have been made in the literature, the lower energy range at the AGS acquires a special significance as it will make it possible to discriminate between them.

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