Particle production in nucleus-nucleus collisions at the SPS and the QCD phase diagram.

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Abstract. The ratios of particle multiplicities determined in central collisions of heavy nuclei fit well into the concept of statistical particle production. In fact, statistical model calculations using heavy ion data on particle multiplicities converge on an approximate universal line in the \( T - \mu_B \) plane for the resulting values of temperature and baryochemical potential. We discuss whether variations of system size can lead to significant deviations from this universal interrelation. Previous analyses of data from C+C and Si+Si collisions have shown that small systems produce a higher chemical freeze-out temperature than central collisions of heavy projectiles, whereas the baryochemical potential seems to be independent of system size. These findings suggest that in small systems a departure from the universal freeze-out line towards higher temperatures is possible. Based on new data on the centrality dependence of proton and antiproton spectra from NA49, which await a dedicated statistical model analysis, we argue that in peripheral collisions both the freeze-out temperature and the baryochemical potential are lower than in central collisions, suggesting a departure from the universal freeze-out line towards the origin of the phase diagram.

1. Introduction
With the advent of ion beams, and the possibility to study nuclear collision at increasing beam energies, it became possible to compress nuclear matter to many times the density of normal nuclear matter. At some point the energy (per nucleon) deposited in these collisions is much larger than the excitation energy of the nucleons, which means that the matter consists not only of nucleons but also of newly created hadrons, as it turns from nuclear to hadronic matter. If the energy density becomes larger than the energy density in the hadrons, partonic degrees of freedom become important. The resulting partonic matter may well be the same as the QGP observed in lattice QCD calculations.

Matter can be characterized by (intensive) state variables like temperature \( (T) \), density \( (\rho) \), chemical potentials \( (\mu) \), and can be characterized by phase diagrams. In strongly interacting matter, the latter is normally the baryochemical potential \( (\mu_B) \), which is closely related to net baryon density. In these proceedings we shall deal with the interrelation between experimental observables and the phase diagram. In particular, we study the centrality dependence of (anti-)proton spectra in Pb+Pb collisions at SPS energies and their expected impact on the determination of \( T \) and \( \mu_B \).
2. The phase diagram

Nuclear collisions at ultrarelativistic energies proceed through several stages which have, in principle, specific locations in the phase diagram (see Fig. 1). When the out-of-equilibrium initial state has evolved into equilibrium, it "touch down" onto the $T$-$\mu_B$ plane, exemplified for three energies by the large red and blue circles in Fig. 1. The system then undergoes a nearly isentropic expansion with some (unknown) variation of temperature and baryochemical potential as indicated by the red and blue lines. At some point, called chemical freeze-out point, inelastic collisions cease. From then on, particle abundances will stay constant. Once also elastic interactions cease, the system reaches thermal freeze-out, and the shapes of the kinetic distributions remain constant. The chemical and thermal freeze-out points will lie somewhere on these lines. Statistical model analyses of ratios of particle multiplicities in central collisions of heavy nuclei have led to a consistent set of chemical freeze-out points which seem to define a universal interrelation in the $T$-$\mu_B$ plane. Fig. 2 shows a sample of characteristic freeze-out points together with two versions of the universal interrelation.

More differential studies have revealed that also particle ratios in intervals of rapidity are consistent with this universal interrelation. Fig. 3 shows two functional dependences of $T$ and $\mu_B$ on rapidity which are consistent with the particle ratios as function of rapidity from experiments at RHIC and SPS energies. So far all statistical model analyses have led to freeze-out points on (or close to) the seemingly universal line, raising the question of whether it is possible for freeze-out points to deviate from this line. The only control parameters accessible to experiment are the initial condition parameters $\sqrt{s_{NN}}$, phase space selection (e.g. $dn/dy$ interval), and system size. The first two parameters have been already mentioned. In the following section we discuss the system size dependence of the chemical freeze-out points.
3. The system size dependence of $T_{\text{chem}}$ and $\mu_B$ at SPS energies

The size of the fireball created in ultrarelativistic nuclear collisions can be varied either by choosing different size nuclei (and requiring central collisions) or by limiting the analysis to a

![Figure 3](image1.png)

**Figure 3.** Two functional dependences of $T$ and $\mu_B$ on rapidity, which lead to consistent particle ratios at top SPS and RHIC energies obtained from statistical model calculations [3].

![Figure 4](image2.png)

**Figure 4.** $T$ and $\mu_B$ as function of atomic number $A$ for different systems at $158A$ GeV obtained from fits to $4\pi$ multiplicities [4](left column). The right column shows $T$ and $\mu_B$ as function of the mean number of participant nucleons [5]. The circles in the latter are obtained from fits to midrapidity yields.
single heavy collision system, but selecting different impact parameter (centrality) ranges. The former approach has been pursued in Reference [4]. Central collisions of Pb+Pb, Si+Si and C+C at 158 A GeV were analyzed in terms of statistical model calculations. Fig. 4 (left column) shows the results for $T_{\text{chem}}$ and $\mu_B$ as function of $A$ (= atomic number of the projectiles). A systematic variation of $T_{\text{chem}}$ with $A$ is observed (8 %) when comparing central Pb+Pb with C+C collisions. An even stronger $A$-dependence (here quantified by the number of participating nucleons $N_{\text{part}}$) was obtained by the authors of Reference [5] (see Fig. 4 right diagram) in which a variation of 16% was observed. The differences between both analyses are most pronounced in the light collision systems (especially in p+p interactions). Both analyses find no variation of $\mu_B$ with $A$.

Figure 5. Mean $m_T$ of protons (left) and antiprotons (right) at midrapidity as function of the number of wounded nucleons ($N_w$) in centrality selected Pb+Pb collisions at 158 A GeV. Also shown are the results from p+p interactions in the same energy [6].

New data on (anti-) proton spectra from the NA49 collaboration in centrality selected Pb+Pb collisions at 40 A GeV and 158 A GeV [7] may provide more information on the system size dependence of $T_{\text{chem}}$ and $\mu_B$. Fig. 5 shows the centrality dependence of mean $m_T$ ($m_T^2 = m^2 + p_T^2$) at midrapidity of protons (left) and antiprotons (right). Also shown are the values from p+p collisions [6]. We observe that $m_T$, which reflects both the kinetic freeze-out temperature and flow, increases significantly with centrality for both particles. This suggests that the temperature of the source of these particles (however at kinetic and not necessarily at chemical freeze-out) increases with centrality in contrast to the behavior noted for the analysis of small systems in the previous paragraph.

Additional insight may be gained from the rapidity distributions of protons and antiprotons. Fig. 6 shows the rapidity distribution of protons at 40 A GeV (top row), of net protons (middle row), and antiprotons (bottom row) at 158 A GeV for different centrality ranges. Since the antiprotons are rarely produced at 40 A GeV, we consider the corresponding proton distribution to be equivalent to the net proton distribution. All distributions are normalized to the inverse of the number of participant nucleons. We first address the dependence of the midrapidity densities on centrality. We find a slight increase with centrality for net protons at 158 A GeV which is accompanied by a significant reduction of the antiproton yields. The increase of net protons
is more pronounced at 40A GeV. These findings suggest a larger baryochemical potential in central collisions (C0 sample) than in peripheral collisions (C4 sample). For this change to be consistent with the universal freeze-out line, the temperature would have to go do down with centrality, which is counterintuitive and at odds with the $m_T$ dependence on centrality. Thus, the expectation is that peripheral collisions lead to chemical freeze-out points in the phase diagram below the universal line in contrast to what was found for the difference between heavy and light collision systems. A statistical model analysis of centrality selected event samples is needed to tell whether this is indeed so.

Shape variations of the net proton distributions would also be indicative of changes of $\mu_B$. Such variations are obvious at 40A GeV (upper row). A differential (in rapidity) analysis of particle ratios at 40A GeV would yield different rapidity dependences in central and peripheral collisions, because the maximum of the net proton distributions is below $|y| = 1$ in central but above $|y| = 1$ in peripheral collisions. A closer look, however, reveals a normalisation problem. Since all distributions are normalized, their integrals over the whole rapidity gap should be independent of centrality (within the experimental uncertainties). This is not the case, as is most obvious in the 40A GeV distribution. The variation of the midrapidity values is less than 20%, whereas the yields nearest to beam-line rapidity go up by almost a factor of two. The protons making up this excess are quantitatively reproduced in the UrQMD and HSD transport models (not shown). We attribute them to interactions of produced particles with spectator matter. These move spectator nucleons into the participant phase space. This finding puts into question any stopping and statistical model analysis of protons in peripheral collision of heavy colliding systems.
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