Updates to the p+p and A+A chemical freeze-out lines from the new experimental data

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Abstract. We show that the new data on mean multiplicities measured in p+p and A+A collisions together with the updated list of resonances lead to the significant changes of the obtained freeze-out lines. The new A+A line gives much smaller temperatures at high collision energies and agrees with the values obtained at the LHC. The newly obtained p+p line is much closer to the A+A line than previously expected, and even touches it in the region where the K^+/π^+ horn appears in the data. It indicates that the temperatures that will be obtained in the beam energy and system size scan by the NA61/SHINE Collaboration might be very close. However, our analysis shows that the chemical potentials could be very different for the same energies in A+A and p+p. It adds more puzzles to the set of surprising coincidences at the energies close to the possible onset of deconfinement.

The main motivation of these studies is the new p+p data from the NA61/SHINE and HADES Collaborations at $\sqrt{s_{NN}} = 3.2 - 17.3$ GeV [1, 2, 3, 4, 5], as well as the new A+A data from HADES, and the updated A+A data from the NA49 Collaborations at $\sqrt{s_{NN}} = 2.2 - 17.3$ GeV, see [6, 7, 8, 9, 10] and references therein. A detailed comparison between the description of the p+p and A+A data at the discussed energies is important, since the ratio of positively charged kaons to protons, K^+/π^+, has a sharp maximum at $\sqrt{s_{NN}} = 7.6$ GeV, which was predicted as one of the signals of the onset of deconfinement in Ref. [11], see also the summary of other deconfinement signals and the latest experimental outcome in [12].

The updated NA49 A+A data contain more particles, some of them are with different error bars, while others are excluded. The chemical freeze-out analysis is performed in the framework of the hadron resonance gas (HRG) model. We use the latest set of resonances from THERMUS package [13] with masses $M \leq 2.4$ GeV, while previous analyzes included only the resonances with $M \leq 1.7$ GeV, see, e.g., [14, 15]. We also exclude the σ and κ resonances from the particle list due to the reasons described in [16]. The combination of these factors alters the freeze-out line obtained within the HRG see [10] and Fig. 1. Our new line in Fig. 1 is the result of the fit to the temperatures T and baryon chemical potentials μ_B obtained by us at particular collision energies. The fit functions for the $T_{\mathrm{A+A}}(\mu_B)$ and $\mu_B(\sqrt{s_{NN}})$ are the same as in [15], however, the obtained parameters are rather different:

$$T_{\mathrm{A+A}}(\mu_B) \; = \; a \; - \; b\mu_B^2 \; - \; c\mu_B^4 \; , \qquad\qquad \mu_B(\sqrt{s_{NN}}) \; = \; \frac{d}{1 \; + \; e\,\sqrt{s_{NN}}} \; , \tag{1}$$

$$a = 0.157\,\mathrm{GeV}, \; b = 0.087\,\mathrm{GeV}^{-1}, \; c = 0.092\,\mathrm{GeV}^{-3}, \; d = 1.477\,\mathrm{GeV}, \; e = 0.343\,\mathrm{GeV}^{-1}. \tag{2}$$

They suggest that the freeze-out line goes much lower than the previous estimates from [15] at small μ_B, i.e., at large collision energies. For $\mu_B = 0$ Eqs. (1) and (2) give the temperature $T \simeq 157$ MeV, which was surprisingly obtained in HRG at the LHC, see discussion in [17]. The difference in the obtained freeze-out parameters is important for the analysis of heavy nuclei production. Our results agree well with the LHC [18], as well as with the NA49 data [19].

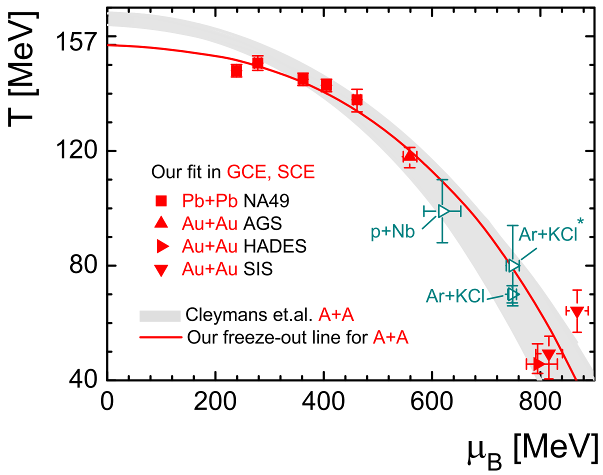

Figure 1. The freeze-out line in central A+A collisions. The grey band is the previous parametrization from [15]. The solid line is our new fit from [10], see Eqs. (1), (2). The points correspond to different collision energies. The p+Nb and Ar+KCl points are from the independent analysis [20], and were not included in the fit. The calculations are mostly done in the grand canonical ensemble (GCE). For the small energies of the old SIS and new HADES data the exact conservation of strangeness was taken into account within the strangeness canonical ensemble (SCE) [10].

The new p+p data are much more precise than the previous world data in that region. It is a difficult test for transport models, see, e.g., [10, 21]. The previous calculations of the chemical freeze-out parameters in p+p within HRG [22] were performed for larger collision energies $\sqrt{s_{NN}} \geq 17.3$ GeV. The obtained temperature had a large uncertainty due to the uncertainty in the existing data at that time. The p+p chemical freeze-out parameters for $\sqrt{s_{NN}} < 17.3$ GeV are calculated for the first time in [10].

We performed the fit of the p+p data in the HRG with the latest table of resonances and excluded σ, as discussed above. The analysis is done within the full canonical ensemble (CE) with exact conservation of electric charge, baryon number, and strangeness. Our $T_{\mathrm{p+p}}(\mu_B)$ line is obtained in two steps. The $T_{\mathrm{p+p}}(\sqrt{s_{NN}})$ dependance is the straight line fit to the points obtained within our CE HRG analysis of the new p+p data [10]. The corresponding $\mu_B(\sqrt{s_{NN}})$ are calculated from the primordial CE HRG multiplicities of neutrons and anti-neutrons using the relation between the average baryon number in GCE and the exact baryon number in CE[1], $\langle B\rangle_{\mathrm{GCE}} = B_{\mathrm{CE}}$, see Eqs. (7-11) in [24]. The neutrons and anti-neutrons are chosen, because they carry only one charge – the baryon number, and one can use the analytic formulas for the CE with one charge conservation. The combined result for the $T(\mu_B)$ in A+A and in p+p is shown in the right panel of Fig. 2.

[1] An alternative way is to fit the p+p data within the GCE, requiring that the obtained temperature is equal to that in the CE, and, additionally, demand that the average baryon number, electric charge, and strangeness, equal to the corresponding exact CE values in p+p, $\langle B\rangle_{\mathrm{GCE}} = B_{\mathrm{CE}} = 2$, $\langle Q\rangle_{\mathrm{GCE}} = Q_{\mathrm{CE}} = 2$, and $\langle S\rangle_{\mathrm{GCE}} = S_{\mathrm{CE}} = 0$. This method is applicable only in thermodynamic limit, i.e. for large enough systems, but gives practically the same $T_{\mathrm{p+p}}(\mu_B)$ line as in the exact case.

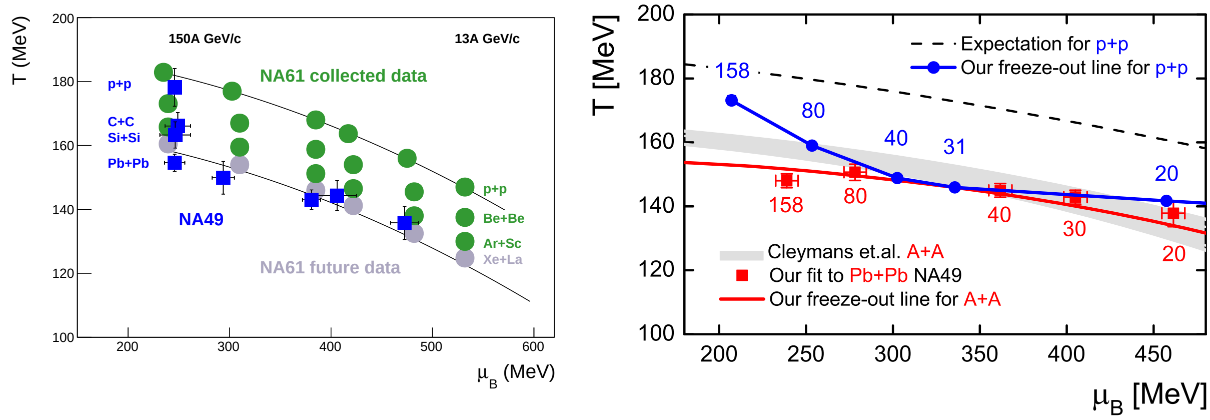

Figure 2. Left: The expectation of the NA61/SHINE Collaboration (full circles), and the $T(\mu_B)$ values obtained within the HRG with lighter resonances $M_{\text{res}} \leq 1.7$ GeV (full squares with errors) from Ref. [23]. Right: The $T(\mu_B)$ values obtained for p+p and A+A in our analysis (dots and solid lines), compared to the expectations in A+A (grey band) and in p+p (dashed line). The numbers indicate the positions of the fit results for the corresponding collision energies in the lab frame E_{lab} in the A GeV units.

One can see that the obtained $T_{\text{p+p}}(\mu_B)$ line behaves very differently, compared to the expectation of the NA61/SHINE in left panel of Fig. 2. The expected positions of the $T(\mu_B)$ points for the intermediate systems should be shifted vertically. They are also much closer to the A+A line than expected. A similar conclusion can be done looking at the p+Nb and Ar+KCl points in Fig. 1. It means that the freeze-out temperatures obtained in the energy and system size scan at the SPS [25] can be very similar[2]. The p+p and A+A lines even touch in the most interesting region $E_{lab} = 30 - 40A$ GeV ($\sqrt{s_{NN}} = 7 - 9$ GeV). However, the chemical potential is larger in A+A for 70 MeV and for 60 MeV at $E_{lab} = 30A$ and $40A$ GeV, correspondingly, which can be summarized as follows:

$$\text{Expectation} \qquad T_{\text{p+p}} \gg T_{\text{A+A}} , \qquad \mu_B^{\text{p+p}} \simeq \mu_B^{\text{A+A}} , \tag{3}$$

$$\text{Our result} \qquad T_{\text{p+p}} \simeq T_{\text{A+A}} , \qquad \mu_B^{\text{p+p}} \ll \mu_B^{\text{A+A}} . \tag{4}$$

The error bars for $T_{\text{p+p}}$ are still quite large due to the small number of measured multiplicities, see [10]. Therefore, more data are needed to make a firm conclusion. We found that the minimal set should include particles possessing all three conserved charges B, S, Q, for both p+p and A+A, for example, $\pi^{\pm}$, $K^{\pm}$ and p, $\bar{p}$ particles. If the picture seen in right panel of Fig. 2 will preserve after the new measurements, then it will add more puzzles to the strange coincidences happening at these energies.

Acknowledgments

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[2] One can still see a clear differences looking at the obtained radii of the systems [10].

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