SURPRISES FOR THE CHEMICAL FREEZE-OUT LINES FROM THE NEW DATA IN $p{+}p$ AND $A{+}A$ COLLISIONS*

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We summarize the surprising results obtained in the fit of the new $p{+}p$ and updated $A{+}A$ data on mean multiplicities. The available range of thermal parameters for the NA61/SHINE energy and system-size scan program is squeezed and shifted compared to expectations. The $p{+}p$ freeze-out line touches the $A{+}A$ line in the vicinity of the K^+/π^+ horn, although the touching point corresponds to different energies in $A{+}A$ and $p{+}p$. It is found that stable fit results for $p{+}p$ reactions are obtained if particles and antiparticles containing all three conserved charges are measured. It requires at least 6 particles, if strange baryons are not measured, to get the temperature and chemical potential of the freeze-out.

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For the first time, the amount of $p{+}p$ data was enough to perform the analysis of hadron production within thermal model at energies of $\sqrt{s_{NN}} <$ 20 GeV, see [1, 2]. The new $p{+}p$ data of the NA61/SHINE and HADES collaborations at $\sqrt{s_{NN}} = 3.2$–17.3 GeV [3–6], the new $A{+}A$ data of HADES,

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and the updated data of the NA49 Collaboration at $\sqrt{s_{NN}} = 2.2$–17.3 GeV were used for this purpose [1,7,8]. The result is very surprising, see Fig. 1[1].

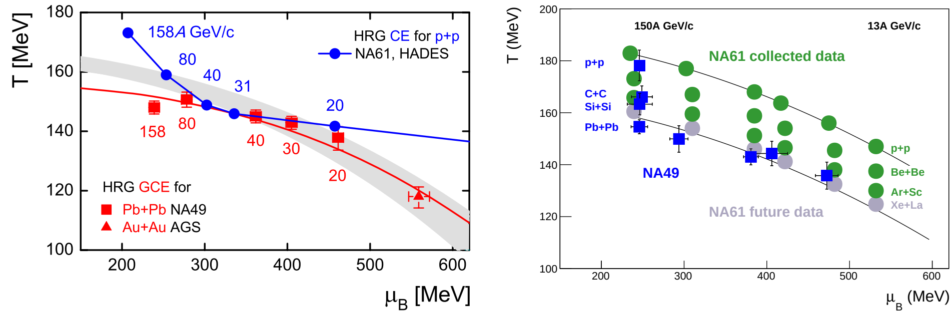

Fig. 1. The freeze-out line in $p+p$ and in central $A+A$ collisions. Left: lines — our new fit for the new $p+p$ and updated $A+A$ data [1]; the grey band — the previous parametrization from [9] and its uncertainty. The numbers correspond to the $p+p$ (upper) and $A+A$ (lower) collision energies of NA49 and NA61/SHINE in the lab frame. Right: the expectation of the NA61/SHINE [10] with the data from [11].

The available range of parameters in the NA61/SHINE scan is squeezed and shifted compared to expectations. The $p+p$ line touches the $A+A$ line in the vicinity of the K^+/π^+ horn [12]. However, the collision energies in $A+A$ and $p+p$ are different in the touching points. The difference between the expectations and the results of our calculations can be summarized as follows:

$$\begin{array}{llll}
\text{Expectation:} & & T_{p+p} > T_{A+A}\,, & \mu_B^{p+p} \simeq \mu_{\mathrm{B}}^{A+A}\,, \\
\text{Our results:} & 20\,A\text{GeV}\,, & T_{p+p} \simeq T_{A+A}\,, & \mu_{\mathrm{B}}^{p+p} \simeq \mu_{\mathrm{B}}^{A+A}\,, \\
 & (30\text{–}40)\,A\text{GeV}\,, & T_{p+p} \simeq T_{A+A}\,, & \mu_{\mathrm{B}}^{p+p} < \mu_{\mathrm{B}}^{A+A}\,, \\
 & (80\text{–}158)\,A\text{GeV}\,, & T_{p+p} > T_{A+A}\,, & \mu_{\mathrm{B}}^{p+p} < \mu_{\mathrm{B}}^{A+A}\,.
\end{array}$$

The temperature is almost the same in $p+p$ and in $A+A$ up to the highest SPS energies. The baryon chemical potentials in $p+p$ and $A+A$ are similar only at 20 AGeV. For larger energies, the chemical potential in $p+p$ is smaller than in $A+A$.

[1] The HADES point is at $\mu_B \simeq 760$ MeV, $T \simeq 132$ MeV, which does not fit into the range of the x-axis chosen at the NA61/SHINE plot shown in Fig. 1, right. However, it is very important to set the behavior of $p+p$ line at low energies, see the whole line in Ref. [1]. Note also the different scale for the y-axis. The temperature in the $p+p$ at highest SPS energy, $E_{\mathrm{lab}} = 158\,A$GeV ($\sqrt{s_{NN}} = 17.3$ GeV), is less than 180 MeV, while the prediction gave temperature higher than 180 MeV.

The updated $A+A$ data also suggest a different $A+A$ freeze-out line $T_{A+A}(\mu_{\mathrm{B}})$ that grows slower with energy, see Fig. 2, left. If one continues it to $\mu_{\mathrm{B}}=0$, then the line hits the LHC temperature, $T_{\mathrm{LHC}} = T_{A+A}(\mu_{\mathrm{B}} = 0) =$ 157 MeV [1]. This is also very interesting, since the expected temperature was much higher for the LHC [9]. The radius of the $p+p$ and $A+A$ systems is shown in Fig. 2, right, see Ref. [1]. The sizes of intermediate systems calculated by HADES [13] nicely follow the expected trend for the system radius. The $A+A$ radius is close to the size of the colliding Pb+Pb nuclei and growing with energy. The $p+p$ radius is constant within the error bars, and approximately twice larger than a proton radius[2].

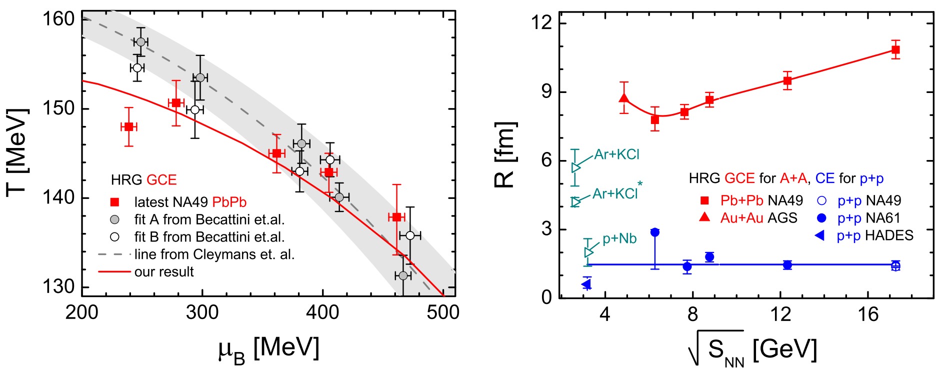

Fig. 2. Left: The $A+A$ freeze-out line in the SPS energy range $\sqrt{s_{NN}} = 6.3$–17.3 GeV. The solid line and the full dots are the results of our new fit [1]. The open points show the old fits from Ref. [11]. The dashed line and the grey band is the old fit with the error bars from Ref. [9]. Right: the radius of the system in $A+A$ and in $p+p$, calculated in GCE and CE, correspondingly [1].

The calculations are done within grand-canonical statistical ensemble (GCE) for $A+A$, and in the canonical ensemble (CE) for $p+p$. It means that in $A+A$ we assumed that the baryon number, strangeness, and electric charge are conserved on average, while in $p+p$ they are conserve exactly for each micro-state of the system, see [1] for more details. The baryon chemical potential in CE is calculated from the primordial multiplicities of neutrons and antineutrons in our thermal model. They carry only one conserved charge, therefore, one can apply analytic formulas that relate CE and GCE baryon number, $\langle B\rangle_{\mathrm{GCE}} = B_{\mathrm{CE}}$, see, *e.g.*, Eqs. (7)–(11) in [14] and in [15].

[2] The considered thermal model assumes that hadrons are point-like. The inclusion of a non-zero hard-core eigenvolume for them may not change the obtained temperatures and chemical potentials, but changes all the densities, due to the change of the total system volume [16]. However, many new degrees of freedom appear, since every particle may have different eigenvolume, and one needs to restrict this freedom, see [17, 18] for the latest developments on this topic.

The chemical freeze-out line in $p+p$ at SPS energies is obtained for the first time. The obtained results fall within the wide error bars obtained in [2] for higher energies. The change of the $A+A$ line is a combination of extended list of measured resonances, and the changes in the experimentally measured particle set. We found that by imposing the cut on the maximal resonance mass, M_{cut}, included in the table of particles that is used for the analysis, we can reproduce the results of the old fits. A change of the parameters of the famous σ meson cannot help, because it is excluded from thermal model, see [19].

The new $p+p$ data are much more precise than the 'world' data in that region. They require corresponding re-calibration of many existing models, like UrQMD and HSD. In spite of the fact that the $p+p$ data are the input parameters in these models, they fail to reproduce energy dependence of pions, kaons, protons and antiprotons in $p+p$ at SPS [1]. However, the uncertainty for temperature obtained in the CE thermal model fit of the $p+p$ data is still too large [1]. The $p+p$ and $A+A$ have the same temperature within two standard deviations, except for the largest energy, $\sqrt{s_{NN}} = 17.3$ GeV. It means that a large set of temperatures and chemical potentials may describe the data well, and more data are needed to constrain them.

The point $\sqrt{s_{NN}} = 17.3$ GeV is special, because it is the only one, where the NA49 has the data for $p+p$. Currently, they have even more measured multiplicities than the newer NA61/SHINE Collaboration — 18 *versus* 5, correspondingly. Therefore, we had a chance to check what happens, if we use different particle sets in the analysis. This is important, because making experimental measurements for a new particle consumes a lot of resources. We analyzed different particle sets, and found that the stable fit results are obtained, if particles and antiparticles containing all three conserved charges are measured. It gives at least 6 multiplicities for the minimal set, for example $\pi^{\pm}$, $K^{\pm}$, p and $\bar{p}$. The NA61/SHINE Collaboration has measured only 4 yields (no protons and anti-protons) at lowest energy, and only 5 yields (no protons) at other energies. Therefore, their measurement at all energies is necessary to obtain $p+p$ freeze-out line that would not change after adding more particles to the set. The measurement of Λ baryon can be very helpful to constrain thermal parameters, since Λ contains both baryon number and strangeness.

We conclude, that the new data added even more interesting questions to the set of puzzles happening in the vicinity of the K^+/π^+ horn. Many new measurements and investigations are necessary to answer them.

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