Exploring high-density baryonic matter: Maximum freeze-out density

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Over the past decade a striking regularity has been established in heavy-ion collisions: From the lowest beam energies to the highest, the yields of various hadronic species are consistent with the assumption of chemical equilibrium \cite{1, 2, 3, 4, 5}. Analyses of the experimentally obtained hadronic yield ratios at a variety of collision energies have shown that the data can be well reproduced within the conceptually simple statistical model that describes an ideal hadron resonance gas in statistical equilibrium. Furthermore, the extracted freeze-out values of the temperature $T$ and the baryon chemical potential $\mu_B$ exhibit a smooth and monotonic dependence on the collision energy and can be simply parametrized.

The beam energy thus plays a determining role for the thermodynamic properties of the final state in relativistic heavy-ion collisions. However, there is no simple relationship between the collision energy and the freeze-out value of the (net) baryon density: At low collision energies the freeze-out density increases with the energy, whereas it decreases when the collision energy is high due to the onset of nuclear transparency. Thus there must exist a certain range of collision energies within which the freeze-out values of the net baryon density displays a maximum.

The optimal collision energy leading to this highest freeze-out density was discussed in \cite{6} on the basis of the up-to-date results on the properties of the final state. It was pointed out there that since neither $\mu_B$ nor $T$ is subject to a conservation law they may be less suitable in a dynamical context. Furthermore, when a first-order phase transition is present, they become multivalued functions of the basic mechanical variables $\rho_B$ (net baryon density) and $\varepsilon$ (energy density) inside the mixed-phase region. It is therefore of interest to reexpress the thermodynamic variables in terms of those mechanical densities. Accordingly, we considered in \cite{6} how the freeze-out line appears when represented in terms of the basic baryon and energy densities, rather than chemical potential and temperature.

In \cite{6}, we presented the freeze-out line in terms of the net baryon density $\rho_B$ and the energy density $\varepsilon$. We show below (in Fig. 1) the corresponding ($\rho_B, \varepsilon^*$) representation, where the “excitation energy density” $\varepsilon^* \equiv \varepsilon - m_N \rho_B$ is the energy density above the minimum value $m_N \rho_B$ dictated by the specified net baryon density. Thus $\varepsilon^*$ has both compressional and thermal contributions.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{freeze-out_line.png}
\caption{The hadronic freeze-out line in the $\rho_B - \varepsilon^*$ phase plane as obtained from the values of $\mu_B$ and $T$ that have been extracted from the experimental data \cite{2}. 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 (in GeV/$N$) for which the particular freeze-out conditions are expected at either a collider (red) or a fixed-target facility (blue).}
\end{figure}
The corresponding \((\rho_B, T)\) diagram, where \(T\) is the freeze-out temperature is perhaps more easily grasped and we show it in Fig. 2 below:

![Diagram showing 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 [2]. 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 (in GeV/\(N\)) for which the particular freeze-out conditions are expected at either a collider (red) or a fixed-target facility (blue).]

These novel representations of the freeze-out line bring out very clearly that there is a maximum value of the net baryon density: At the highest collision energies, freeze-out occurs for a negligible value of \(\rho_B\) and at an energy density of nearly one half GeV/fm\(^3\); then, in the range of \(\mu_B = 400 - 500\ MeV\) (and a temperature of \(T = 140 - 130\ MeV\)), the freeze-out line exhibits a backbend and approaches the origin. Thus, the net baryon density at freeze-out has a maximum value which amounts to about three quarters of the familiar nuclear saturation density of \(\rho_0 \approx 0.16\ fm^{-3}\).

The fact that the freeze-out value of the net baryon density exhibits a maximum as the collision energy is being scanned suggests that the corresponding collision energy (range) is optimal for the exploration of compressed baryonic matter. This suggested optimal beam kinetic energy is \(15 - 30\ GeV\) per nucleon for a fixed-target configuration (such as FAIR at GSI), corresponding to \(\sqrt{s_{NN}} = 5.6 - 7.8\ GeV\) for a collider (such as RHIC at BNL).

The results presented here should provide valuable guidance for establishing the desired capabilities of the contemplated NICA at JINR. In particular, our results suggest that freeze-out densities all the way up to the maximum value could be explored at a collider facility delivering beam kinetic energies of up to \(\approx 2.4\ GeV/N\).

References

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