High temperature Bose-Einstein condensation

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in collaboration with

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Bose-Einstein condensation

- 1924 - Bose statistics discovered
- 1925 - Bose-Einstein condensation predicted
- 1995 - two experimental groups created BEC
- 2001 - leaders of the groups, Cornell, Wieman, and Ketterle, won the Nobel Prize

The density of bosons is calculated from

$$\rho = \int \frac{d^3p}{(2\pi)^3} \frac{1}{\exp[(\sqrt{p^2 + m^2} - \mu)/T] - 1}$$

The BEC temperature for $T/m \ll 1$ is $T_C \sim m^{-1} \rho^{2/3}$. The density depends on the proper particle radius as $\rho \sim r^{-3}$. Then the ratio of the BEC temperature in the atomic gases, $T_C(A)$, to that in the pion gas, $T_C(\pi)$, in non-relativistic approximation

$$\frac{T_C(\pi)}{T_C(A)} \approx \frac{m_A}{m_\pi} \left(\frac{r_A}{r_\pi}\right)^2 \approx \frac{m_A}{m_\pi} 10^{10}$$

- The BEC of atoms is achieved at temperatures $T_C \sim 10^{-8} K$
- The BEC of pions would have $10^{12}$ higher temperature and very different properties due to different interaction forces involved, much smaller volumes, and higher densities
The LHC Puzzle

- Thermal model gives the freeze-out curve
- The prediction was too high for ratios to pions, especially proton to pion ratio
- The best fit of the LHC data still gives three standard deviations for protons
- The low-transverse-momentum pion spectra show up to 50% enhancement compared to hydrodynamic models
- The fit of the LHC data gives the parameters that fall out to the "wrong" side

Possible explanations:

- hadronization and freeze-out in chemical non-equilibrium (Rafelski et al., PRC (2013))
- hadronic rescattering in the final stage (Becattini, Stock et al., PRL (2013))
- incomplete list of hadrons (Noronha-Hostler, Greiner, 1405.7298; NPA (2014))

Reasons for the non-equilibrium:

- overcooling of the QGP (Shuryak, 1412.8393)
- gluon condensation in Color Glass Condensate (Gelis, NPA (2014))
The phase-space distribution of the primordial particles has the form:

$$f_i = g_i \int \frac{d^3p}{(2\pi)^3} \frac{1}{\gamma_i^{-1} \exp(\sqrt{p^2 + m^2}/T) \pm 1},$$

where

$$\gamma_i = \gamma_q^{N_q^i + N_{\bar{q}}^i} \gamma_s^{N_s^i + N_{\bar{s}}^i} \exp\left(\frac{\mu_B B_i + \mu_S S_i}{T}\right),$$

and $N_q^i, N_s^i$ are the numbers of light $(u, d)$ and strange $(s)$ quarks in the $i$th hadron. It includes all well established resonances from PDG. Resonance decay according to their branching ratios.

**Single-freeze out model** (Broniowski, Florkowski, PRL (2001))


The spectra are calculated from the Cooper-Frye formula at the freeze-out hyper surface

$$\frac{dN}{dyd^2p_T} = \int d\Sigma_\mu p^\mu f(p \cdot u), \quad t^2 = \tau_f^2 + x^2 + y^2 + z^2, \quad x^2 + y^2 \leq r_{max}^2,$$

assuming the Hubble-like flow: $u^\mu = x^\mu/\tau_f$.

There is only one additional parameter in the model, because the product $\pi \tau_f r_{max}^2$ is equal to the volume (per unit rapidity), while the ratio $r_{max}/\tau_f$ determines the slope of the spectra.
Spectra of pions kaons and protons in Cracow model at the LHC

The fits to the ratios of hadron abundances (Rafelski et al., PRC (2013)) yield $\gamma_q$ which is very close to the critical pion chemical potential: $\mu_\pi = 2T \ln \gamma_q \approx 134$ MeV $\approx m_{\pi^0} \approx 134.98$ MeV

The spectra favor the non-equilibrium model. It may suggest that a substantial part of $\pi^0$ mesons form the condensate (V.B., Florkowski, Rybczynski, PRC (2014))
The fit done initially for $\pi^+ + \pi^-$ and $K^+ + K^-$ only appears also very good for $p + \bar{p}$, $K_S^0$, $K^*(892)^0$ and $\phi(1020)$! (V.B., Florkowski, Rybczyński, PRC (2014) 054912)
Explicit treatment of hadronic ground states

If chemical potential approaches the mass of a particle, $\mu \rightarrow m$, the zero momentum level, $p_0 = 0$ becomes important (V.B., Gorenstein, PRC (2008), V.B. EPJ (2015)):

$$\sum_i \frac{1}{\exp[(\sqrt{p_i^2 + m^2} - \mu)/T] - 1} \approx \frac{1}{\exp[(m - \mu)/T] - 1} + V \int_0^\infty \frac{d^3p}{(2\pi)^3} \frac{1}{\exp[(\sqrt{p^2 + m^2} - \mu)/T] - 1}$$

Inclusion of the ground state makes equilibrium and non-equilibrium models closer.
The momentum distribution is given by
\[
\frac{dN}{dy d\phi d\mathbf{p}_T d\mathbf{p}_T} = \frac{N_{\text{cond}}}{V} \frac{r_t^3}{m^2} \theta \left( r_{\text{max}} - p_T \tau_f / m \right)
\]

- The inclusion of several more levels would lead to finer steps
- The gray area shows the 10% deviation from the best fit
- The EQ fit for pions over-predicts protons at low \( p_T \) (V.B., EPJ (2015)).
- The combined data on multiplicities and spectra are compatible with 5% of pions in the condensate (V.B., Florkowski, PRC (2015)).
Can the LHC data be explained by the updated sigma?

- The recent PDG reviews report much **lower mass** and width of the $f_0(500)$ or the **sigma** meson

- The lower mass of the $\sigma$ would result in its **higher multiplicity**. It decays into pions, therefore it **could add** some of the missing pions

The derivative of the experimental $\pi\pi$ phase shift has attractive isospin-spin channel $(0, 0)$ that is responsible for the emergence of the $f_0(500)$. However, the channel $(2, 0)$ is repulsive and cancels $f_0(500)$ until $f_0(980)$ takes over above $M \sim 0.85$ GeV.

V.B., Broniowski, Giacosa, arXiv:1506.01260, accepted in PRC

The cancellation occurs at the level of the distribution functions, therefore it persists in all isospin-averaged observables. The $\sigma$ implemented as a Breit-Winger pole with $M_\sigma = 484$ and $\Gamma_\sigma / 2 = 255$ MeV produces up to $5\%$ of pions, while the truth contribution is $-0.3\%$. The famous $K/\pi$ horn is affected, as well as all ratios to pions.
The contribution of the **sigma** meson ($f_0(500)$ resonance) to isospin-averaged observables is cancelled by the repulsion from the isotensor-scalar channel.

The cancellation enhances the $K/\pi$ horn at the SPS and the proton-pion puzzle at the LHC.

The **non-equilibrium** thermal model combined with the single freeze-out scenario explains very well the spectra of $\pi, K, p, K^0_s, K^*(892)^0$ and $\phi(1020)$ particles at the LHC.

The introduction of the **ground state** makes a link between equilibrium and non-equilibrium thermal models.

The **enhancement** of the pion spectra may be interpreted as a signature of the onset of pion condensation at the LHC.
The prediction of thermal models gave too high ratios to pions, especially proton to pion ratio.

The best fit of the LHC data gives three standard deviations for protons.
Problems of hydrodynamic models with the pion spectra at the LHC

IP - Glasma + MUSIC:

$\frac{1}{2} \frac{dN}{dy} p_T \frac{d\phi}{p} \approx 10^{-1}$

$10^0 \quad 10^1 \quad 10^2 \quad 10^3 \quad 10^4 \quad 10^5$


**pion enhancement**

AdS + hydro + cascade:

(1/2) $dN/dY/dp_T$

$0-5\%$

$10^{-1}$

$10^0 \quad 10^1 \quad 10^2 \quad 10^3 \quad 10^4 \quad 10^5$

$0.001 \quad 0.01 \quad 0.1 \quad 1 \quad 10 \quad 100 \quad 1000$


**pion enhancement**

Hydro with dynamical freeze-out:

$\pi^+, \pi^-, K^+, K^-$

$\rho + \bar{\rho}$

$0-5\%$

$10^{-6} \quad 10^{-5} \quad 10^{-4} \quad 10^{-3} \quad 10^{-2} \quad 10^{-1} \quad 10^0 \quad 10^1 \quad 10^2 \quad 10^3$

$0 \quad 0.5 \quad 1 \quad 1.5 \quad 2 \quad 2.5$


**pion enhancement**

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