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FROM LITTLE BANGS TO BIG BANG*

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Abstract. Experiments at the RHIC and LHC can recreate quark-gluon plasma conditions similar to those when the Universe was less than a few microseconds old, and will offer the best prospects to discover how the Universe evolved in early stages. In this work we study the (anti)deuteron-to-(anti)proton ratio obtained in heavy ion collisions at relativistic energies and compare the results with the ratio obtained from Big Bang nucleosynthesis.

Key words: heavy ion collisions, quark-gluon plasma, Universe evolution, baryon production, thermal freeze-out properties.

1. INTRODUCTION

In high-energy nuclear collisions at relativistic energies, the formation of the hot and dense matter called the strongly interacting quark gluon plasma (sQGP) has been evidenced [1]. This new state of strongly interacting nuclear matter is similar to that which existed in the early Universe, a few microseconds after the Big Bang [2]. Theory has predicted several signatures of this phase transition to quark-gluon plasma. In our previous work, we analyzed experimental data obtained in various heavy ion collisions in order to investigate the high p_T suppression [3], strangeness enhancement [4] and particle correlations [5] as signals of this new state of matter. Enhanced antimatter production in central nucleus-nucleus collisions relative to p+p collisions was proposed as one of the experimental signatures for formation of the quark-gluon plasma [6].

At the late stage of the fireball evolution, when the hadronic matter is diluted enough such that the interactions between nucleons and other particles are weak, (anti)nucleon bound states are formed from (anti)nucleons that are close in momentum and configuration space. This recombination process is called

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coalescence [7]. Therefore, the light nuclei production provides a tool to measure (anti)baryon distribution and the properties of the system at thermal freeze-out.

The ratio of deuteron yield over proton yield at the same transverse momentum per nucleon, p_T/A, is proportional to the baryon density [8]. This is analogous to the deuteron to hydrogen ratio (D/H) measurements of Big-Bang nucleosynthesis (BBN), that is a very sensitive probe of baryon abundance in the early Universe [9]. Although both processes are sensitive to the baryon density, the processes themselves are very different. In the nuclear medium formed in collision, a proton and a neutron may coalesce to form a deuteron at a freeze-out temperature of ~110 MeV, while in BBN the deuteron production is through p(n,γ)D photo-production at temperatures < 1 MeV [10].

Connections were made between the evolution of a relativistic nuclear heavy ion collision and the Universe [11-13], because it is believed that we can recreate a very small "early universe" in the laboratory and study it in "little bangs" [14].

2. EXPERIMENTAL SET-UP

BRAHMS experiment [15] was located at Relativistic Heavy Ion Collider (RHIC) [16]. The BRAHMS (Broad RAnge Hadron Magnetic Spectrometer) experiment consisted of two independent spectrometer arms, the Mid-Rapidity Spectrometer (MRS) and the Forward Spectrometer (FS) and a set of global event characterization detectors. The spectrometers were made of dipole magnets, Time Projection Chambers (TPC) and Drift Chambers (DC) for tracking charged particles, and detectors for particle identification (PID). The MRS could rotate in $30^0 < \theta < 95^0$ range and the FS could rotate in $2.3^0 < \theta < 30^0$, where θ is the polar angle with respect to the beam axis. By combining different settings of angle and magnetic fields charged pions, kaons, protons and antiprotons transverse momentum spectra at different rapidities ($0 < y < 3$) were obtained. Particle identification (PID) was achieved in both spectrometers using time-of-flight walls (TOFW, TFW2 in MRS and H1, H2 in FS). In the FS a ring imaging Cherenkov detector (RICH) located at the end of the spectrometer was used for large momentum particle identification. TOFW in the MRS was capable of separating pions from Kaons up to 2 GeV/c and charged kaons from protons/ antiprotons up to 3 GeV/c, while the forward arm could identify particles up to 35-60 GeV/c by using the RICH.

3. RESULTS AND DISCUSSION

The ratio of anti-deuteron yield over antiproton yield can be taken as a measure of the anti-baryon phase space density at kinetic freeze-out when coalescence happens. When the net baryon density is close to zero, anti-deuterons can be used as a measure of deuteron production because at zero chemical potential ($\mu_B = 0$) the *d/p* ratio and $\bar{d}/\bar{p}$ ratio are identical. The experimental results from relativistic heavy ion collisions in this limit can be compared to cosmological results.

BRAHMS has measured the invariant proton and deuteron spectra *versus* transverse momentum, p_T, obtained in Au-Au collisions at $\sqrt{s_{NN}}$ = 200 GeV [17]. The p_T spectra were integrated to obtain invariant yields, dN/dy. The dN/dy values have been obtained by fitting the spectra with appropriate fit functions describing the experimental data and integrating the fit functions in the range $0 < p_T < \infty$. The obtained values are listed in Table 1.

Table 1

The rapidity, integrated yields for protons, antiprotons, deuterons and antideuterons. Data are taken from [17]

Y	d*N*/d*y(p)*	d*N*/d*y*($\bar{p}$)	d*N*/d*y(d)*	d*N*/d*y*($\bar{d}$)
0	27.9±0.1	20.8±0.1	0.093 ±0.008	0.033 ± 0.004
0.8	26.0±0.1	17.9±0.1	0.068±0.003	0.031±0.002
2.0	20.9±0.2	-	0.082±0.011	-

The antideuteron-to-antiproton yield ratio at midrapidity can be obtained using the integrated yields, d*N*/d*y*, namely:

$$\frac{\bar{d}}{\bar{p}} = \frac{\mathrm{d}N/\mathrm{d}y(\bar{d})}{\mathrm{d}N/\mathrm{d}y(\bar{p})} = \frac{0.033}{20.8} = 1.58 \cdot 10^{-4}, \qquad (1)$$

And the antiproton-to-proton ratio:

$$\frac{\bar{p}}{p} = \frac{\mathrm{d}N/\mathrm{d}y(\bar{p})}{\mathrm{d}N/\mathrm{d}y(p)} = \frac{20.8}{27.9} = 0.75. \qquad (2)$$

The relation between the $\bar{d}/\bar{p}$ and $\bar{p}/p$ yield ratios is:

$$\frac{\bar{d}}{\bar{p}} = \exp\left(-\frac{m_B}{T_{FO}}\right) \cdot \sqrt{\bar{p}/p}, \qquad (3)$$

where m_B is the nucleon mass and T_{FO} is the thermal (kinetic) freeze-out temperature. Using the experimental values of the above particle ratios measured by BRAHMS experiment we obtain the following kinetic freeze-out temperature, T_{FO} = 108.3 MeV.

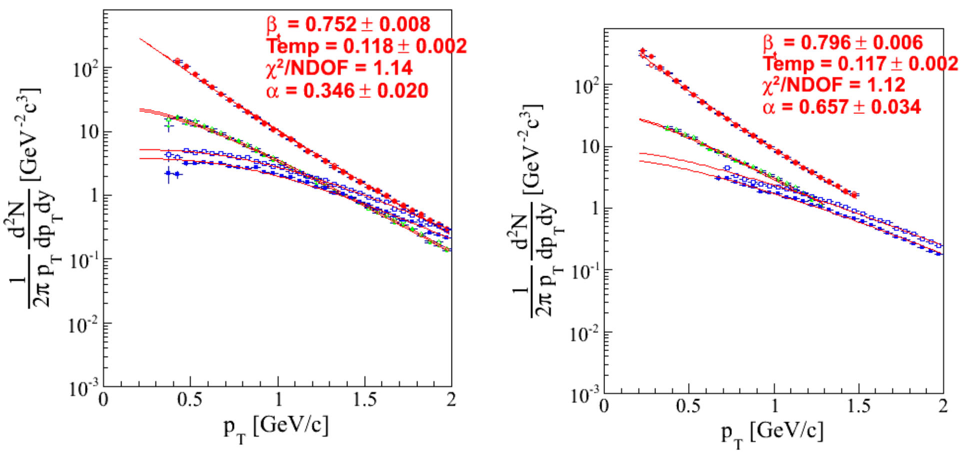

Fig. 1 – Transverse momentum spectra for identified charged particles produced in 0–10% most central Au-Au collisions at 200 GeV ($y = 0$ – left, $y \sim 1$ – right). Data taken from [20]. Red lines represent the simultaneous blast wave fits to the spectra.

The T_{FO} value obtained in this analysis is consistent with the thermal freeze-out temperature obtained from the blast-wave (BW) analysis (left part of Fig. 1). The blast-wave model is often used to describe the spectra of identified particles produced in relativistic heavy ion collisions [18, 19]. In this model, the particle spectra are written in the form

$$\frac{\mathrm{d}N}{p_T \mathrm{d}p_T} \sim \int_0^R r\mathrm{d}r m_T I_0\left(\frac{p_T \sinh\rho}{T}\right) K_1\left(\frac{m_T \cosh\rho}{T}\right), \tag{4}$$

where $\rho = \tanh^{-1} \beta_T(r)$, K_1 and I_0 are the modified Bessel functions, m_T is the transverse mass, and T is the thermal freeze-out temperature. The BW model assumes that particles decouple from a system in local thermal equilibrium with temperature T, that expands both longitudinally and in the transverse direction. The transverse expansion is defined in terms of transverse velocity field that can be parameterized according to a power law: $\beta_T(r) = \beta_S (r/R)^{\alpha}$. Here, β_S is the maximum surface flow velocity and the α exponent describes the evolution of the flow velocity (flow profile) for all radii r up to R ($r < R$), where R is the maximum radius of the expanding source at thermal freeze-out.

The BRAHMS transverse momentum distributions for identified particles produced in Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV [20] and $\sqrt{s_{NN}} = 62.4$ GeV [21, 22] were fitted simultaneously using the blast-wave model in order to obtain the thermal freeze-out temperature and the transverse collective flow velocity. The results obtained are shown in the Fig. 1 and Fig. 2.

The ratio of particle abundances measured in BBN (D/H) and in heavy ion collisions (Au-Au) at top RHIC energy, ($\bar{d}/\bar{p}$), is $\Omega_{BBN/RHIC200} = 0.177$.

The D/H value of $(2.8 \pm 0.2) \times 10^{-5}$ obtained from Big Bang nucleosynthesis in the evolution of the Universe is about 18% of what is obtained in higher energy Au-Au interactions at present RHIC collider.

At rapidity $y = 0.8$, using the yields from Table 1, we obtain the following values for the studied ratios: $\bar{p}/p = 0.688$, $\bar{d}/\bar{p} = 0.0017$. From Eq. 3, the thermal freeze-out temperature is $T_{F0} = 152$ MeV. This value is higher than the thermal freeze-out temperature obtained from the blast-wave analysis: $T_{F0} = 117 \pm 2$ MeV (right part of Fig. 1). This could be due to the fact that the p_T coverage of the transverse momentum spectra at $y \sim 1$ is not sufficient for a reliable hydrodynamic blast-wave fit.

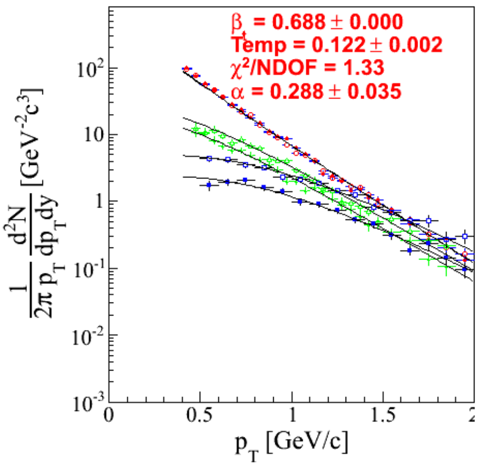

Fig. 2 – Transverse momentum spectra for identified charged particles produced in 0-10% most central Au-Au collisions at 62.4 GeV ($y = 0$). Data taken from [21, 22]. Red lines represent the simultaneous blast wave fits to the spectra.

In the most central 0–10% Au-Au collisions at $\sqrt{s_{NN}} = 62.4$ GeV (y=0), the antiproton-to-proton ratio is $\bar{p}/p = 0.48$ [21] and the freeze-out temperature obtained from blast-wave analysis (Fig. 2) is $T_{F0} = 122 \pm 2$ MeV. Using the above values we obtain the following value for the antideuteron-to-antiproton yield ratio: $\bar{d}/\bar{p} = 3.16 \cdot 10^{-4}$. The ratio of particle abundances measured in BBN (D/H) and in 62.4 GeV Au-Au collisions, ($\bar{d}/\bar{p}$), is $\Omega_{BBN/RHIC62} = 0.089$.

Comparing to the 62.4 GeV Au-Au value, the cosmological D/H value of $(2.8 \pm 0.2) \times 10^{-5}$ obtained from BBN is about 9% of what is obtained in the most central 0–10% Au-Au collisions at $\sqrt{s_{NN}} = 62.4$ GeV.

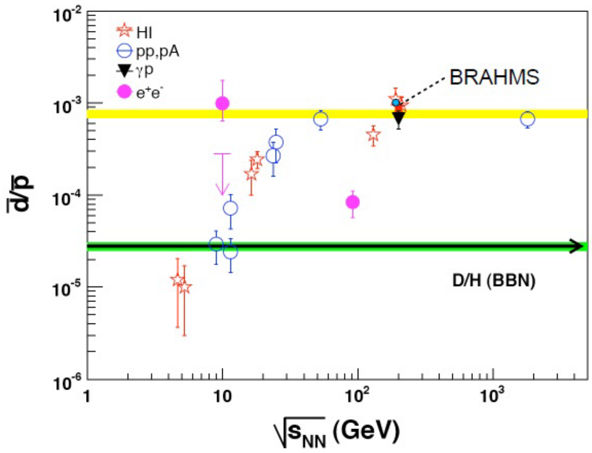

Fig. 3 – The antideuteron-to-antiproton ratio as a function of beam energy for different colliding species. The figure is taken from [23].

Data of the $\overline{d}/\overline{p}$ ratio from various colliding species (e^+e^-, pp, pA, AA) as a function of beam energy is shown in Fig. 3 [23]. The green band is the *D*/*H* (deuteron to hydrogen ratio) measurements of Big-Bang nucleosynthesis (BBN), $D/H = (2.8 \pm 0.2) \times 10^{-5}$. The yellow band is the average of $\overline{d}/\overline{p}$ from collider data at near zero chemical potential (the data that are closest to the $\mu_B = 0$ condition). The ratio increases monotonically with beam energies and reaches a plateau above ~50 GeV regardless of the beam species (pp, pA, AA). BRAHMS Au-Au point at midrapidity is added to this plot, and is consistent with measurements obtained in Au-Au at $\sqrt{s_{NN}}$ = 200 GeV by STAR [10] and PHENIX [24] experiments.

4. CONCLUSIONS

In summary, we have presented measurements on the deuteron and antideuteron production in central Au-Au collisions at 200 GeV. The freeze-out temperature extracted at midrapidity is consistent with blast-wave calculations. The cosmological *D*/*H* value from BBN is about 18% of what is obtained in higher energy interactions at present colliders.

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