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Hubble flow in relativistic heavy ion collisions

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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.

1. Introduction

Heavy-ion collisions at relativistic energies offer a unique opportunity to probe highly excited, hot and dense nuclear matter, the so-called the strongly interacting quark gluon plasma (sQGP)[1], and study its properties. 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 [2]. This new state of strongly interacting nuclear matter is similar to that existing in the early Universe, a few microseconds after the Big Bang [3].

Connections were made between the evolution of a relativistic nuclear heavy ion collision and the Universe [4], because it is believed that we can recreate a very small "early universe" in the laboratory and study it in these "little bangs" [8].

In a relativistic heavy ion collision the system expands and cools down. When the interaction among the produced particles finally ceases, during the thermal (kinetic) freeze-out stage, light nuclei like deuterons and anti-deuterons (d and \bar{d}) can be formed. This recombination process is called coalescence [9]. Due to their small binding energy it is less likely for deuterons to survive repeated collisions inside the fireball. Therefore, the light nuclei production provides a tool to measure (anti)baryon distribution and the properties of the system at thermal freeze-out. The thermal and coalescence models [5, 6, 18] describe well the particle yields and their ratios, including the light (anti)nuclei production measured in heavy ion collisions at relativistic energies.

The deuteron-to-proton ratio obtained in relativistic heavy ion collisions can be compared with the deuteron to hydrogen ratio (D/H) measurements of Big-Bang nucleosynthesis (BBN). The D/H ratio is a very sensitive probe of baryon abundance in the early Universe [10]. However, we must take into account the situations are very different, namely in the nuclear medium formed in collision, a proton and a neutron may coalesce to form a deuteron at freeze-out temperature about ~ 100 MeV, while in BBN the deuteron production takes place via $p(n, \gamma)D$ photo-production at temperatures < 1 MeV [11].

2. Results

The ratio of (anti)deuteron yield over (anti)proton yield is proportional to the (anti)baryon density [12] at kinetic freeze-out when coalescence happens. When the net baryon density is close to zero, antideuterons 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. Therefore, in this limit, the experimental results from relativistic heavy ion collisions may be compared to cosmological results.

The BRAHMS experiment [13] has measured the invariant proton and deuteron spectra versus transverse momentum, p_T , obtained in 0-20% most central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV [14]. The p_T spectra were integrated in order 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 for dN/dy are listed in Table 1:

Table 1. Rapidity, integrated yields for protons, antiprotons, deuterons and antideuterons produced in 0-20% most central Au+Au collisions at 200 GeV. Data are taken from [14].

y	$dN/dy(p)$	$dN/dy(\bar{p})$	$dN/dy(d)$	$dN/dy(\bar{d})$
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

The antiparticle-to-particle ratios can be calculated using the integrated yields listed above. At midrapidity ($y=0$) we obtain the following values: $\bar{d}/\bar{p} = 1.58 \cdot 10^{-4}$ and $\bar{p}/p = 0.75$.

In ref [15], the authors analyze the \bar{d}/\bar{p} measurements in different collision systems from γp , pp up to heavy ion collisions at various energies and found that the anti-baryon density follows a universal distribution as a function of beam energy and can be described statistically. For the nucleons and nuclei coalescence at low transverse momentum and at midrapidity it is used a simplified expression: $\frac{d^2 N_A}{2\pi p_T dp_T dy} \approx C \cdot \exp(-(m_B \pm \mu_B)A/T)$ from [16]. Therefore, the relation between the \bar{d}/\bar{p} and \bar{p}/p yield ratios is:

$$\frac{\bar{d}}{\bar{p}} = \exp\left(-\frac{m_B}{T}\right) \sqrt{\bar{p}/p} \quad (1)$$

where m_B is the nucleon mass and T is the thermal (kinetic) freeze-out temperature. It is suggested that the anti-nucleons are produced and coalesce statistically in AA, pA, pp and γp collisions at similar density and that the final state interactions in nucleus-nucleus collisions do not affect this mechanism.

Using the experimental values of the above particle ratios measured by BRAHMS experiment we obtain the following kinetic freeze-out temperature, $T = 108.3$ MeV. Our value obtained in this analysis is consistent with the thermal freeze-out temperature obtained from the blast-wave (BW) analysis [17].

The ratio of particle abundances measured in BBN (D/H) and in heavy ion collisions (Au+Au) at top RHIC energy, $\sqrt{s_{NN}} = 200$ GeV, is $\Omega_{BBN/RHIC200} = 0.177$. Thus, the D/H value of $(2.8 \pm 0.2) \times 10^{-5}$ [10] 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.

Based on the statistical concepts using the Boltzmann statistics, the relation between the \bar{p}/p ratio and baryon chemical potential μ_B is: $\bar{p}/p = \exp(-2\mu_B/T_{ch})$, where T is the chemical

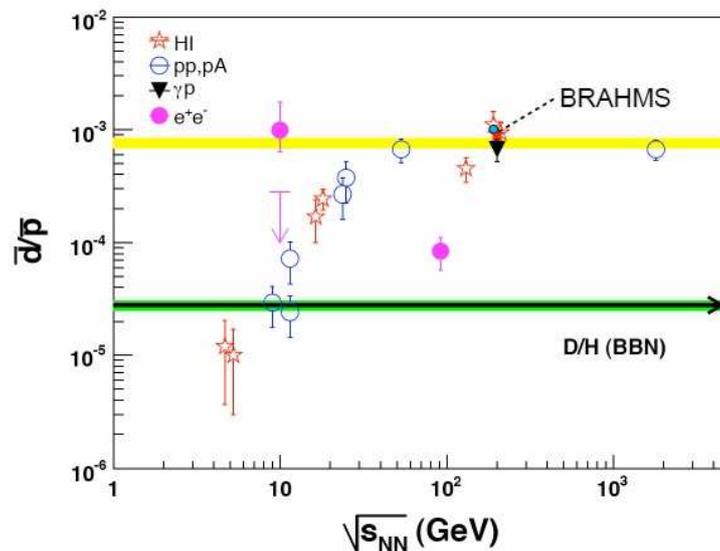


Figure 1. The antideuteron-to-antiproton ratio as a function of beam energy for different colliding species. Figure is taken from [23].

freeze-out temperature[18]. The abundances of deuterons and antideuterons follow a consistent pattern in the thermal model. The temperature remains the same as before but an extra factor of μ_B is picked up each time the baryon number is increased. Therefore, the antideuteron-to-deuteron ratio is given by

$$\frac{\bar{d}}{d} = e^{-(4\mu_B)/T_{ch}} \quad (2)$$

We can calculate the baryon chemical potential using our 200 GeV Au+Au experimental data and considering a chemical freeze-out temperature of $T_{ch}=165$ MeV [19] and we obtain $\mu_B = 42$ MeV, showing that the conditions in "little big bangs" are different from the "big bang" where due to the very high temperature in the early universe the chemical potential can be considered zero.

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. 1, the thermal freeze-out temperature is $T = 152$ MeV. This result is larger than the BRAHMS experimental value of ~ 100 MeV obtained using the blast-wave parametrization [20].

In the central 0-10% Au+Au collisions at $\sqrt{s_{NN}}= 62.4$ GeV at midrapidity ($y=0$), the antiproton-to-proton ratio is $\bar{p}/p = 0.48$ [21] and the freeze-out temperature obtained from blast-wave analysis [22] is $T = 122$ 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, 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 62.4 GeV.

Data of the \bar{d}/\bar{p} ratio from various colliding species (e^+e^- , pp, pA, AA) [24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34] as a function of beam energy is shown in Fig. 1 [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 \bar{d}/\bar{p} ratios 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 energies ≥ 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 200 GeV by STAR [11] and PHENIX [35] experiments.

3. Conclusions

In summary, we have presented measurements on the deuteron and antideuteron production in central Au-Au collisions at $\sqrt{s_{NN}}=200$ GeV. The freeze-out temperature extracted at midrapidity ($y=0$) is consistent with the blast-wave calculations. The cosmological D/H value from BBN is about 18% of what is obtained in higher energy interactions at RHIC collider.

The value of baryon chemical potential is small, but shows that in Au+Au collisions at top RHIC energy we can not yet reproduce the conditions existing in the early Universe. At the LHC, where the collision energy is over 10 times higher, the baryon chemical potential obtained in most central Pb+Pb collisions tends to zero [36], thus we are closer to the early Universe conditions than in RHIC collisions.

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