Romanian Reports in Physics, Vol. 56, No 4, P. 659-666, 2004

Study of the chemical freeze-out in nucleus-nucleus collisions

Oana Ristea[*] *for the BRAHMS Collaboration*
[*]*Atomic and Nuclear Physics Department, Faculty of Physics, University of Bucharest,*
P.O.Box MG-11, R-76900 Bucureşti-Măgurele, ROMANIA

(Received July 22, 2004)

Abstract. Hadron multiplicities and their correlations are observable which can provide information on the nature, composition and size of the medium from which they are originating. To determine the parameters characterizing chemical freeze-out, we analyse particle yields in terms of temperature and baryon chemical potential. From the experimental data obtained with BRAHMS experiment, in Au-Au collisions, at 200 AGeV, we obtain the lowest value for the baryon chemical potential and a chemical freeze-out temperature of approximately 170 MeV. The net-baryon density of the central rapidity region has the lowest value, and could explain the baryon chemical potential behaviour. At the same energy, the baryon chemical potential increase from mid-rapidity to forward rapidities. This behaviour confirms that, the mid-rapidity region is almost a net-baryon free region, and in the region at forward rapidities is still a significant baryon content of the original colliding nuclei. The energy dependence of chemical parameters is also discussed. As the beam energy is increased, the values for chemical freeze-out temperature are higher and for baryon chemical potential are lower.

In high-energy heavy ion collisions is studied strongly interacting nuclear matter at high energy density and temperatures. The most important goal is to observe the possible phase transition from hadronic matter to quark-gluon plasma, in which quarks and gluons are deconfined from individual hadrons. In the early phases of the collision, when a hot, dense region is formed, there is copious production of up, down and strange quarks. As the medium expands and cools, the quarks combine to form the hadrons, which are then observed [1].

Chemical freeze-out point is the stage in the evolution of the hadronic system when inelastic collisions cease and the relative particle ratios become fixed, and is defined by the temperature, T_{ch}, and also by the chemical potential, μ_B. These parameters, T_{ch}, and μ_B determine the particle composition of the hadronic final state.

After chemical freeze-out, the particle composition inside the fireball is fixed, but elastic collisions still keep the system together until the final, thermal freeze-out. At this stage the momentum distributions of particles are no longer changes and are final. Therefore, the transverse momentum spectra determine the thermal freeze-out parameters.

Statistical interpretation of the particle production becomes an appropriate approach for the heavy ion collisions at high energies, because large multiplicities of hadrons are created. One can assumes that the nuclear matter created in these collisions form an ideal gas that can be described by a grand-canonical ensemble. Therefore, the density of particle species "i" is:

$$n_i = \frac{g_i}{2\pi^2}\int_0^\infty \frac{k^2 dk}{\exp[(E_i(k) - \mu_i)/T] \pm 1} \qquad (1)$$

where g_i is the spin degeneracy factor, $E_i = \sqrt{k^2 + m_i^2}$ is the energy, k is the momentum and chemical potential $\mu_i = \mu_B B_i + \mu_S S_i$. The quantities B_i and S_i are the baryon and strangeness quantum numbers of the particle species "i". For high temperatures, the Bose or Fermi-Dirac statistics can be replaced by the Boltzmann statistic by dropping the ± 1 in the integral. The total multiplicity, N_i, of specie "i" in the collision is $N_i = n_i V$, therefore the multiplicity ratio is [2,3]:

$$\frac{N_i}{\overline{N_i}} = \frac{n_i}{\overline{n_i}} \qquad (2)$$

and it follows that:

$$\frac{N_i}{\overline{N_i}} = \exp\frac{\mu_i - \overline{\mu_i}}{T} = \exp\frac{2\mu_i}{T} \qquad (3)$$

Ratios of particles with the same mass, but different quark content, such as $\frac{\overline{p}}{p}$ and $\frac{K^-}{K^+}$ are sensitive to the balance between matter and antimatter, characterized by the baryon chemical potential μ_B. As strange quarks are created during the collision and are not transported from the incoming nuclei, strangeness production is expected to be a good estimator of the degree of equilibration of the produced fireball.

The energy dependence of the chemical potential can be parameterised as:

$$\mu_B(s) \cong \frac{a}{(1+\sqrt{s}/b)} \qquad (4)$$

where $a = 0.967 \pm 0.032 GeV$ and $b = 6.138 \pm 0.399 GeV$. The full line in the figure 1 shows the result of this parametrization. [4,5]

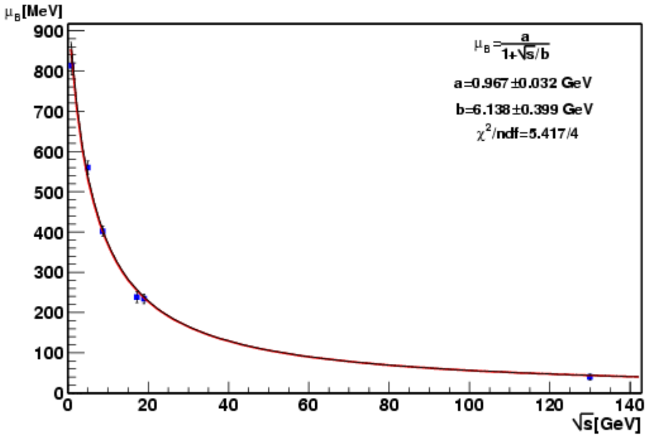


Fig.1. Variation of the baryon chemical potential at chemical freeze-out as a function on the beam energy

From this energy dependence we can obtain the values of chemical potential for the RHIC energies:

$\sqrt{s_{NN}}[GeV]$	$\mu_B[MeV]$
130	43.6 ± 3.2
200	28.8 ± 2.1

Table I: Baryonic chemical potential obtained from the above parameterisation at RHIC energies

The energy dependence of the chemical freeze-out temperature can be parameterised as:

$$T_{ch} = a - be^{-c\sqrt{s}} \qquad (5)$$

where $a = 172.3 \pm 2.8$, $b = 149.5 \pm 5.7$ and $c = 0.20 \pm 0.03$. The full line in the figure 2 shows the result of this parameterisation [5].

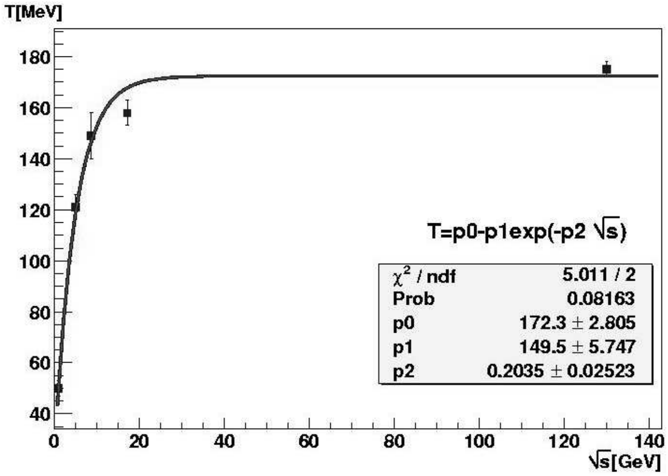


Fig. 2. Variation of the temperature at chemical freeze-out as a function on the beam energy

For the above parameterisation, the value of the chemical temperature for $\sqrt{s_{NN}} = 130 GeV$ and $\sqrt{s_{NN}} = 200 GeV$ is equal to $T_{ch} = 172.3 \pm 2.8 MeV$, value very close to the critical temperature $T_c = 170 MeV$ extracted from the lattice QCD calculation. The chemical potential and temperature resulting from this analysis place the system at chemical freeze-out very close to phase boundary between quark-gluon plasma and hadrons. Thus, the produced hadrons seem to be originating from a deconfined medium and chemical composition of the system is established during hadronization.

The chemical freeze-out temperature and chemical potential exhibit a strong variation with energy. As the beam energy is increased, the values for chemical freeze-out temperature are higher and for chemical potential are lower. Above AGS energies, the temperature exhibits only a moderate change and seems to saturate close to the critical temperature $T_c = 170 MeV$, while μ_B is strongly decreasing.

In the table II are presented the values for baryonic chemical potential and chemical freeze-out temperature for different collisions and energies [6-8]. The trend for chemical potential shows less baryon stopping with increased energy. At lower energies (AGS and SPS), the original baryons are stopped in the collision and the midrapidity region contains most of the net-baryons. Therefore, the chemical potential has a greater value than at higher energies, when the collisions are more transparent and the midrapidity region is almost a baryon free region. Net-baryon density decreases with increasing collision energies, but still differs from zero, and therefore the pair production is dominant at midrapidity even if baryon transport from the beam exists.

$\sqrt{s_{NN}}[GeV]$	$T_{ch}[MeV]$	$\mu_B[MeV]$	μ_B/T	*Collisions*
1	50 ± 3	813 ± 23	16.26 ± 0.99	*Au-Au*
5	121 ± 5	560 ± 16	4.62 ± 0.19	*Au-Au*
8.7	149 ± 9	402 ± 12	2.69 ± 0.17	*Pb-Pb*
17.2	158 ± 3	238 ± 13	1.51 ± 0.08	*Pb-Pb*
130	172.3 ± 2.8	43.6 ± 3.2	0.25 ± 0.02	*Au-Au*
200	172.3 ± 2.8	28.8 ± 2.1	0.17 ± 0.01	*Au-Au*

Table II: Baryonic chemical potential and chemical freeze-out temperature at different beam energies

The chemical temperature obtained at RHIC energies ($\sqrt{s_{NN}}=130GeV$ and $\sqrt{s_{NN}}=200GeV$) is very close to the chemical temperature obtained at CERN energy ($\sqrt{s_{NN}}=17GeV$). The increase of the energy of colliding nuclei does not produce a hotter system. As the beam energy is increased, the available energy is used to produce more particles, but not to increase the system temperature.

Considering the two values of chemical potential from table I and the value of the chemical temperature $T_{ch}=172.3\pm2.8MeV$, from the next relation [2,9]:

$$\frac{\overline{p}}{p}=\exp(\frac{-2\mu_B}{T}) \qquad (6)$$

we obtain the value for the antiproton-proton ratio $\frac{\overline{p}}{p}$. The calculated values are very close to the values of $\frac{\overline{p}}{p}$ obtained with BRAHMS experiment for these energies [10,11].

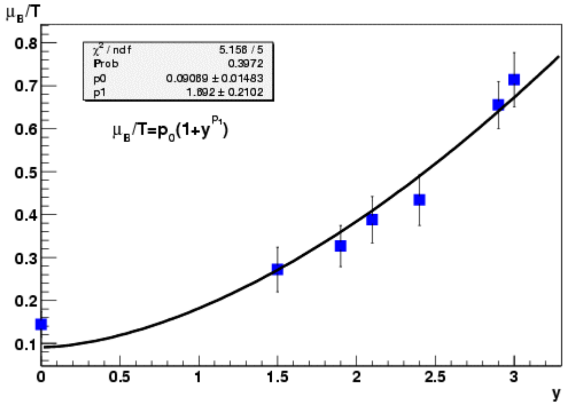
$\sqrt{s_{NN}}[GeV]$	$\frac{\overline{p}}{p}\|_{BRAHMS}$	$\frac{\overline{p}}{p}$
130	0.64 ± 0.04*(stat)* ±0.06*(syst)*	0.603
200	0.75 ± 0.03*(stat)* ±0.05*(syst)*	0.716

Table III: The experimental ratios obtained with BRAHMS experimental set-up (left) and the values obtained with $T_{ch}=172.3\pm2.8MeV$ and the two values of chemical potential from the Table I.

In the figure 4 is presented the μ_B/T ratio as a function of rapidity. The rapidity dependence of the chemical freeze-out parameters, μ_B/T, can be parameterised with the next relation:

$$\mu_B/T=a(1+y^b) \qquad (7)$$

where $a = 0.09 \pm 0.01$ and $b = 1.69 \pm 0.21$.



We observe a rapidity dependence of the chemical freeze-out parameters. The chemical potential increases from midrapidity to forward rapidities, because at midrapidity, the net-baryon density is much reduced than what was observed at forward rapidities.

y	$\mu_B[MeV]$
0	28.8 ± 2.1
1.5	46.7 ± 8.9
2.1	66.8 ± 9.4
3.1	123.1 ± 10.9

Table IV: Baryonic chemical potential as a function of rapidity

If we have a system of quarks in chemical and thermal equilibrium, then ratios of particles and antiparticles can be described by the ratios of the chemical potential of the constituent quarks to the chemical freeze-out temperature. Considering the quark content of proton, uud, and for charged kaons: $K^+ = u\overline{s}$, $K^- = \overline{u}s$, then the ratio K^- / K^+ can be written as [12]:

$$K^+ / K^- = \exp(2\mu_B / 3T - 2\mu_s / T) = (p / \overline{p})^{1/3} \exp(-2\mu_s / T) \qquad (8)$$

At $\sqrt{s_{NN}} = 200GeV$, the value is $K^- / K^+ = 0.95 \pm 0.05$, ([5]), and using the above relation the chemical potential of strange quarks is very small $\mu_s = 3.8MeV$. Using the antiparticle to particle ratios obtained with PHOBOS experimental set-up at $\sqrt{s_{NN}} = 130GeV$, $K^- / K^+ = 0.91 \pm 0.07(stat) \pm 0.06(syst)$ and $\overline{p} / p = 0.60 \pm 0.04(stat) \pm 0.06(syst)$ [13], the strange chemical potential is $\mu_s = 6.5MeV$. These values are very small comparing with the values obtained at lower energies:

$\sqrt{s_{NN}}[GeV]$	$\mu_s[MeV]$	*Collisions*
5	51	*Au-Au*
8.7	35	*Pb-Pb*
17.2	22	*Pb-Pb*
130	6.5	*Au-Au*
200	3.8	*Au-Au*

Table V: Strange quark chemical potential for different collisions and energies

The value for strange chemical potential, μ_s, should be zero in an equilibrated quark-gluon plasma and on the phase boundary of a hadron gas. Therefore, the small value obtained may suggest that the freeze-out takes place near the phase transition.

In d-Au collisions, at $\sqrt{s_{NN}} = 200GeV$, the particle ratios measured with PHOBOS experiment are $K^- / K^+ = 0.97 \pm 0.03(stat) \pm 0.03(syst)$ $\overline{p} / p = 0.86 \pm 0.02(stat) \pm 0.03(syst)$, for the most central events (0-10\% centrality) [14]. Considering a chemical freeze-out temperature of $T_{ch} = 170MeV$, the value for baryonic chemical potential is: $\mu_B = 12.8MeV$. This value of baryonic chemical potential is around half of the value of chemical potential obtained in Au-Au collisions at the same energy. For the same energy, the baryonic chemical potential increases with the size of the collision system.

The small baryon and strange chemical potential imply that antiparticle to particle ratios are close to 1 but still smaller than 1 (the values near the baryon free limit). There is an excess of quarks over their antiquarks favouring the production of particles over antiparticles.

Bibliography:

[1]. H. Satz – Nucl. Phys. A715 (2003) 3-19
[2]. D. Ouerdane - Ph.D. Thesis, University of Copenhagen, 2003
[3]. R. Stock - hep-ph/0212287
[4]. P. Braun-Munzinger, K. Redlich, J. Stachel - nucl-th/0304013
[5]. Al. Jipa for BRAHMS Collaboration – “Overview of the results from the BRAHMS experiment” – 3rd RHIC Winter School, 8-11.XII.2003, Budapest, Hungary, (nucl-exp/0404011)
[6]. F. Becattini - hep-ph/0202071
[7]. A. Panagiotou, P. Katsas - hep-ph/0212082
[8]. F. Becattini, J. Cleymans, A. Keranen, E. Suhonen, K. Redlich - hep-ph/0002267

[9]. R. Rapp, E. V. Shuryak - hep-ph/0104006
[10]. BRAHMS Collaboration - Phys. Rev. Lett.87, 112305 (2001)
[11]. BRAHMS Collaboration - Phys. Rev. Lett.88, 202301 (2002)
[12]. NA44 Collaboration - nucl-ex/9808002
[13]. PHOBOS Collaboration - Phys. Rev. Lett.87 (10), 102301 (2001)
[14]. PHOBOS Collaboration - nucl-ex/0309013