1. Introduction

Heavy atomic nuclei at room temperatures behave as liquids. If we collide two nuclei at moderate energies in a particle accelerator, the nuclei will be compressed and heated and as a result the nuclear liquid will turn into a hadron gas – a gas of pions, protons, neutrons and other hadron species. Hadrons include baryons (such as protons and neutrons) composed of three quarks, and mesons (such as pions and kaons) composed of one quark and one antiquark. The quarks are bound inside hadrons by the strong interaction which is mediated by gluons. Under normal conditions it is impossible to knock a single quark or gluon out of a hadron - the more we pull it, the stronger is the binding force which keeps it inside. This phenomenon is called confinement.

There is, however, a special state of nuclear matter, the so-called quark-gluon plasma (QGP), in which the quarks and gluons are not confined. Quantum chromodynamics (QCD) predicts that if the nuclei are heated above the critical temperature, the density of particles becomes so high that quarks are no longer bound to particular hadrons. Thus hadrons are dissolved into individual quarks and gluons. There is no confinement and quarks as well as gluons move freely within the whole QGP volume. Simulations of QCD on the lattice predict [1] that the (deconfinement) phase transition from the hadron gas phase to the QGP phase occurs at the critical temperature around \( T_c \approx 170 \text{ MeV} \) and very high energy density. (In this paper we shall use energy units for the temperature. This should be understood as the energy equivalent which is obtained from the temperature by multiplying with the Boltzmann constant.) Such conditions are presently achieved in collisions of heavy nuclei at ultrarelativistic energies at two operating colliders: at the Relativistic Heavy Ion Collider (RHIC) of the Brookhaven National Laboratory gold nuclei are accelerated to the center of mass energies up to 200 GeV per nucleon pair, and at the Large Hadron Collider (LHC) at CERN the QGP is formed in lead-lead collisions at the energy of 2760 GeV per nucleon pair. The quark-gluon plasma is also believed to be the state of the Universe around 1μs after the Big Bang.

Properties of the QGP and of the deconfinement phase transition are under intense theoretical and experimental scrutiny. The challenge of the program is the complicated nature of heavy ion collisions. The hot nuclear matter created in the collision (the fireball) expands and cools down very quickly and the QGP phase (if present) changes back into the hadron gas phase within ~10^{-23} s. The remaining hadronic fireball then continues its rapid expansion during which hadrons interact with each other and create new hadrons until the point of chemical freeze-out when the chemical composition of hadron species is fixed. After that the hadrons keep scattering elastically until the fireball disintegrates at the point of kinetic freeze-out after ~10^{-22} s. The initial information present in the QGP phase is thus heavily distorted by the phase transition into the hadron phase, expansion and hadron interactions. Fortunately some signals of QGP remain in the bulk properties of the collisions such as particle rates, transverse flow, chemical freeze-out temperature \( T_c \) and kinetic freeze-out temperature \( T_{kin} \). These quantities can be studied via hadron spectra measured by the detectors. In this paper we will study transverse momentum \( (p_T) \) spectra of several hadron species measured by the ALICE detector at the LHC [2].
and extract the transverse flow and $T_{\text{kin}}$ by fitting the experimental spectra with the predictions based on the Blast Wave model [3] which also includes the production of final state hadrons (e.g. pions) from the decays of short-lived resonances. The model is implemented as a Monte Carlo generator published under the title DRAGON [4].

2. Transverse flow

The fireball in the QGP phase exhibits collective flow/expansion in the local thermal equilibrium which can be reasonably well described hydrodynamically. Expansion of the fireball results from strong pressure gradients in the hot nuclear matter. The fireball expands both longitudinally (along the direction of heavy ion beams, the $z$-axis) and transversely (perpendicularly to the beams).

The transverse flow is particularly interesting since it is entirely generated from the pressure of the hot matter unlike the longitudinal flow which is present also in the initial conditions (incident nucleons tend to continue in the beam direction after the collision). The transverse flow is described in terms of the transverse expansion velocity $v_t$ which depends on the radial distance $r$ from the centre of the fireball. The outer layers of the fireball move with the largest velocity while the central part is at rest in the laboratory system.

In the Blast Wave model [3] one parametrizes the final freeze-out state of the fireball. It is motivated by the assumption that the hydrodynamic relativistic expansion continues up to the point when the temperature of the fluid falls below $T_{\text{kin}}$ and the freeze-out from a thermalized fluid into non-interacting free-streaming hadrons occurs suddenly. Within the model this happens at the same longitudinal proper time $\tau = \sqrt{r^2 - z^2}$ for each part of the fireball. Further assumptions include parametrization of $v_t$ as

$$v_t = \tanh \left( \sqrt{2} \eta_f \frac{r}{R} \right)$$

where $\eta_f$ is the transverse flow parameter and $R$ is the radius of the cylindrical fireball at the freeze-out. Hadron number density is assumed to be constant within the cylinder and zero for $r > R$. The Blast Wave model gives a prescription to calculate transverse momentum ($p_T$) spectra of different species of hadrons as a function of $T_{\text{kin}}$, $\eta_f$, hadron masses and several other parameters. For more details about the model we refer the reader to the original works [3]. The calculated spectra can then be used to fit the experimental data and extract $T_{\text{kin}}$ and $\eta_f$ [2].

3. DRAGON calculations and results

We calculate the $p_T$ spectra with the DRAGON tool based on the Blast Wave model to which a careful treatment of all 277

\[\text{Fig. 1 \  } \chi^2 \ \text{DRAGON fit to the 0-5% of the most central ALICE data. The size of the boxes is proportional to the } \chi^2 \ \text{value. The color of the boxes indicates the statistical size of the calculated spectra: green is based on 140 simulated events (collisions), blue on 1400 and red on 14 000 events}\]
The resulting $\chi^2$ divided by the number of degrees of freedom ($N_{\text{ dof}} = 232$) from 0-5% most central Pb+Pb collisions (a central collision is one with the zero impact parameter between the two nuclei) are shown in Fig. 1 as a function of $T_{\text{ kin}}$ and $\eta_f$. The area of the boxes is proportional to the $\chi^2$ value, the color of the boxes indicates the statistical size of the calculated spectra: green is based on 140 simulated events (collisions), blue on 1400 and red on 14 000 events. The minimum $\chi^2/N_{\text{ dof}}$ value, 0.62, lies at $T_{\text{ kin}} = 0.095$ GeV and $\eta_f = 1.0$.

The transverse momentum ($p_T$) spectra for the six hadron species simulated with DRAGON at the minimum and compared to 0-5% most central Pb+Pb experimental data are shown in Fig. 2. Fit results also for other centralities are summarized in Table 1.

Freeze-out temperatures and transverse expansion parameters from the fits to transverse momentum ($p_T$) spectra at different centralities based on 1400 simulated events Table 1

| Centrality | $T_{\text{ kin}}$ [MeV] | $\eta_f$ | $\chi^2/N_{\text{ dof}}$ |
|------------|--------------------------|---------|--------------------------|
| 0-5%       | 95                       | 1       | 0.673                    |
| 5-10%      | 95                       | 1       | 0.764                    |
| 10-20%     | 105                      | 0.975   | 0.733                    |
| 20-30%     | 120                      | 0.925   | 0.881                    |
| 30-40%     | 125                      | 0.9     | 1.044                    |
| 40-50%     | 145                      | 0.825   | 1.411                    |
| 50-60%     | 155                      | 0.775   | 1.900                    |

Fig. 2 The transverse momentum ($p_T$) spectra from central collisions for six hadron species calculated with DRAGON at the $\chi^2$ minimum (solid line) and compared to 0-5% most central Pb+Pb experimental data from ALICE (red triangles)
To make a comparison with lower energy data from RHIC we repeated the fit with the 0-5% of the most central STAR data at the energy 62.4 GeV per nucleon pair [5] and found the minimum $\chi^2$ value at $T_{\text{kin}} = 0.085$ GeV and $\eta_f = 0.825$. We observe that going from RHIC to the LHC energy both the freeze-out temperature and the transverse flow go up. This can be understood as a result of higher pressure which builds up at the LHC heavy ion collisions. Higher pressure leads to stronger transverse flow and stronger expansion also means that the interaction rate of hadrons in the fireball drops below the expansion rate earlier, at higher freeze-out temperature. ALICE has published similar results [2], however, our study properly accounts for all hadron species including resonance decays.

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