Strangeness Production in STAR at RHIC

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Strangeness study is one of the major goal of the STAR experiment at RHIC. Results presented here have been obtained from analyses restricted to the mid-rapidity region of Au-Au collisions at $\sqrt{s_{NN}} = 130$ GeV. An onset of the understanding of the quark matter behavior produced at this relativistic energy can be stressed from the investigation of the relative and absolute yields of strange particle production, their transverse mass distributions and from comparisons with previous results obtained by AGS and SPS experiments

I. STRANGE PROOFS FOR A QUARK MATTER INVESTIGATION

It is well known now that studying strangeness should provide information of different nature about the quark matter which has been created during the heavy ion collision. Since several years, it is proposed that the quark gluon plasma (QGP) formation can be revealed via the observation of an enhancement in the strangeness production compared to a "normal" yield in a hadronic gas\[1\]. However, from recent results presenting by the NA49 collaboration\[2\] measuring strangeness production in proton-proton (pp), proton-nucleus (pA) and nucleus-nucleus (AA) reactions, one learns that the definition of this enhancement has to be defined very rigorously and precisely, since an enhancement is already seen in pA with respect to pp collisions. Systematical studies have to be drawn up as a function of the collision energy, the system size, the degree of centrality of the reaction and even the particle species.

Upstream from the QGP highlight, an issue is to understand how strangeness is produced. Relativistic heavy ion physics could be understood with the characterization of some fundamental points like:

- original environment (baryon density, degree of stopping) by measuring antibaryon/baryon ratios.
- production mechanisms which can be assessed from different approaches: the comparison of spectra (in terms of transverse mass or rapidity) of particles and their anti-particles can inform if species obey or not the same production mechanisms depending on similarities or discrepancies which can be seen between them; ratios can also be informative on mechanisms such as coalescence processes for example.
- relative and absolute yields of strange particle production, especially those of kaons since they carry the majority of the strangeness quark content of the reaction.
- time scale of the different phases encountered during the system evolution by the observation of the production or suppression of resonances.
- amplitude of the rescattering or collective effects by looking at the transverse momentum spectra.
- degree of suddenness of the hadronisation, depending on the coincidence or not of the chemical and thermal freeze-out parameters extracted from particles ratios.

STAR (Solenoidal Tracker At Rhic) constitutes a very well suited experiment for strangeness measurement. It includes indeed a large tracker apparatus, the Time Projection Chamber (TPC) with a large $p_T$-y acceptance and a full azimuthal coverage.

II. SOME EXPERIMENTAL CONSIDERATIONS

Results presented in the following have been obtained from analyses of events collected during the year 2000. RHIC delivered gold beams at an energy of $\sqrt{s_{NN}} = 130$ GeV. At this time, the TPC was the main detector of STAR experiment\[3\] operating with a 0.25 T field. The TPC allows for tracking of charged
particles emitted in the $|\eta|=1.8$ and $p_T \geq 0.75$ GeV/c coverage for a collision occurring at the center of the detector. The event centrality is selected according to the multiplicity distribution of the negatively charged particles $[4]$, once the event reconstruction is done. The number of events which can be used for physics analyses is equal to 460k and 330k for minimum bias and the most central events (top 5%) respectively. Minimum bias events are triggered by requiring a coincidence of signals in both Zero Degree Calorimeters which detect spectator neutrons. A high threshold in the Central Trigger Barrel is set for selecting the central events.

More specifically, several methods are used for the identification of strange particles. Strange particles ($K_0^0$, $\Lambda$, $\Xi$, $\Omega$) decaying at a certain distance from the primary vertex of the collision, are reconstructed using a topological method. The tracks of their daughters are reconstructed in the TPC, extrapolated back towards a common origin and the kinematics of the parent are calculated.

Charged kaons can be identified from their energy loss in the TPC if their momentum is lower than 0.6 GeV/c. Beyond this limit, their energy losses can not be separated unambiguously from those of the pions due to the TPC resolution. A topological method, the so-called kink method, is used for the determination of charged kaons via the $K \rightarrow \mu \nu$ channel. In this case, the charged kaon and charged daughter are used to reconstruct the kinematics of the parent. Opposite to the $dE/dx$ measurement, the kink method allows to avoid any restriction on the momentum of the kaons and thus to identify them up to 2 GeV/c.

Reconstruction of resonances ($\phi$, $K^{0*}$) is achieved by combinatorics calculating the invariant mass with all permutations of candidate decay particles. The background is obtained by the mixed-event technique. The combinatorics can be applied also for the reconstruction of the strange baryons, thus allowing an effective cross-check with the topological method.

Note that results (excepted anti-baryon over baryon ratios) presented here are corrected for tracking efficiencies, acceptance and detector effects. Besides, as a first attempt, the analyses have been restricted to the mid-rapidity region.

### III. WHAT RULES STRANGENESS PRODUCTION?

#### A. Production yields

Kaons carry about 70% of the strange quark content created during the collision, hence providing a good estimate of the amount of produced strangeness. The yields of kaons per unit of rapidity in the most central collisions reach for the $K^+$, $K^-$ and $K_0^*$ $35\pm3$(stat)$\pm5$(syst), $30\pm3$(stat)$\pm4$(syst) and $35.1\pm0.6$(stat) respectively $[5]$. Results are similar one to each other and when compared to the multiplicity of the negatively primary charged particles $[6]$ ($280\pm1$(stat)$\pm20$(syst)), they demonstrate the large amount of strangeness created at RHIC (more than 10 times the amount found in Pb-Pb collisions at SPS).

Analyses of the $\Phi$ mesons reveal also a large production of strangeness $[7]$. The energy dependence of the $\Phi/h^-$ ratio in heavy ion collisions from $\sqrt{s_{NN}} = 5$ up to 130 GeV indicates that this ratio increases with the collision energy hence that the $\Phi$ production increases faster than that of the $h^-$, up to RHIC energy.

The $\Lambda$ and $\overline{\Lambda}$ production at mid-rapidity is shown on figure $[8]$ as a function of the negative hadron ($h^-$) multiplicity. The hyperon production increases with the centrality of the collision reaching the values of $18.6\pm0.7$(stat) and $12.9\pm0.5$ for respectively $\Lambda$ and $\overline{\Lambda}$ in the 5% most central collisions. Moreover, this hyperon production appears to be linearly proportional to that of the $h^-$. Figure $[9]$ exhibits clearly that the $p_T$ distributions of the $\overline{\Lambda}$ and $\Lambda$ are much flatter than the $p_T$ distribution of the negatively charged particles. The hyperon production becomes very important at high $p_T$ suggesting that the baryon to meson ratio should exceed 1 at very high $p_T$ values. This surprising trend has been observed also by the PHENIX collaboration measuring $\overline{p}/\pi^-$ ratio $[8]$. The interpretation of such a behavior is still an
open question: Shuryak mentioned simple flow effects \[9\] while Vitev and Gyulassy propose a novel non-perturbative component of baryon dynamics \[10\] as an explanation.

The \( \Xi \) and \( \Xi \) yields correspond, for the 14% most central collisions in the mid-rapidity region, to \( 3.07 \pm 0.13 \text{ (stat)} \) and \( 2.63 \pm 0.12 \text{ (stat)} \), respectively.

Due to an insufficient number of events, the absolute yields of \( \Omega \) and \( \Omega \) are not yet accessible despite the signal of the \( \Omega + \Omega \) system has been extracted with a very good signal over noise ratio (S/N = 3.6). The new data of the year 2001 will allow solving this statistics issue.

\[ \] B. Initial environment

Due to the respective quark content of \( K^+ \) and \( K^- \), their ratio indicate the amplitude of the net-baryon density. Figure 3 presents the \( K^+/K^- \) ratio at mid-rapidity as a function of the centrality. It is equal to \( 1.071 \pm 0.008 \text{ (stat)} \) and is rather constant as a function of the centrality as observed at AGS and SPS energies. The decrease of this ratio as a function of the collision energy reflects the change and drop of the net-baryon density as the energy increases.

The excitation function of anti-baryon to baryon ratios (figure 4) renders the strong increase anti-baryon production going from the lower to higher energy. Even at RHIC the net-baryon density is still not equal to 1 or, differently speaking, system is still not baryon free despite the important drop of the degree of stopping going from AGS to SPS to RHIC.

Figure 5 presents ratios of antibaryons to baryons according to their strangeness content for SPS and RHIC data. As predicted \[1\] and also already seen at SPS, STAR measurements indicate the enhancement of the ratios as strangeness content increases:

\[ \overline{p}/p = 0.63 \pm 0.02 \text{ (stat)} \pm 0.06 \text{ (syst)} \quad \overline{\Lambda}/\Lambda = 0.73 \pm 0.03 \text{ (stat)} \]
\[ \Xi/\Xi = 0.83 \pm 0.03 \text{ (stat)} \pm 0.05 \text{ (syst)} \]

It is difficult to rule on the \( \overline{\Omega}/\Omega \) ratio: despite it seems to be compatible with 1, there is still large statistical errors to allow an accurate evaluation. The data collected during 2001 should allow a more precise measurement.
From these ratios, Rafelski et al. [11] have extracted the values of chemical potential and temperature at which hadronisation occurs. From $\bar{p}/p$ value [12], they estimate that the baryo-chemical potential is equal to 32(38)MeV if the temperature is fixed at 150(175)MeV, respectively. Furthermore, from $\overline{\Lambda}/\Lambda$ and $\overline{\Xi}/\Xi$ ratios, they show that the strange quark fugacity is consistent with 1 and according to their thermal model, it corresponds to the value expected for sudden hadronisation.

On the other hand, Braun-Munzinger and collaborators have performed a fit to the preliminary RHIC data [13] leading to a temperature of $175\pm7$MeV and a baryo-chemical potential of $51\pm6$MeV. According to statistical models, the fireball seems to have reached a high degree of chemical equilibration. Note however, that to be conclusive, such an approach should be investigated with data extrapolated to a $4\pi$ coverage.

C. Production mechanisms

The $\bar{p}/p$ ratio indicates that, contrarily to AGS [14] or SPS [15] trends, pair processes dominate baryon transport at RHIC, by about a factor 2 if one assumes that anti-proton production is due to pair processes (production and annihilation included) while protons come from both baryon transport and pair processes. Thus, $2/3$ of protons come from pair processes.

Furthermore, ratios seem to be consistent with simple quark coalescence model [16]. This latter assumes that quark matter hadronizes via a sudden recombination of its quark and anti-quark constituents . Within this approach, $\overline{B}/B$ ratios can be predicted from a simple quark counting:

$$\frac{\overline{\Xi}}{\Xi} = D \frac{\overline{p}}{p} \quad \text{and} \quad \frac{\overline{\Lambda}}{\Lambda} = D \frac{\overline{\Xi}}{\Xi} = D^2 \frac{\overline{p}}{p} \quad \text{... where} \quad D = \frac{N_c}{N_f}$$

Thus, the D values calculated with the various baryon ratios measured by STAR, are very close to the D value directly measured ($1.071\pm0.008$(stat)). The similarities between calculated and measured D values indicate the consistency of the coalescence model predictions with the baryon ratios at RHIC, as already seen at SPS energies.

Considering again the $K^-/K^+$ ratio (rather than $K^+/K^-$ ratio), the excitation function of the $\overline{B}/B$ can be revisited. Indeed, at energies far above the kaon production threshold, one can assume that the relative abundance of strange and anti-strange quarks do not impact the relative production of $K^-$ and...
K\(^+\) \ K\(^-\)/K\(^+\) ratio becomes similar to π/u. On the other hand, one can postulate that π/u \sim \bar{\tau}/d, which is reasonable once again at high energies for which the isospin difference at mid-rapidity is less significant. This implies the following relation: B/B \sim (\pi/u)^3 \sim (K^-/K^+)^3. The curve on figure 4 linking up the (K^-/K^+)^3 data at various \sqrt{s_{NN}} indicates that the same behavior is observed for K^-/K^+ and \bar{p}/p at the highest energies. The different behavior seen at AGS can be explained by the fact that, at this lower energy, the assumptions are less valid and also the absorption of \bar{p} in the medium is large (~20%).

D. Dynamics

Transverse mass spectra have been investigated for strange hadrons. For each couple (K\(^+\)-K\(^-\), \Lambda-\bar{\Lambda} and \Xi-\bar{\Xi}), the m_T distributions are rather identical for particles and anti-particles (same slopes), informing that they present the same final state spectra, despite the processes producing (anti-)particles may be very different.

The values of inverse slope extracted from a fit to the experimental transverse mass distributions with an exponential function are summarized on figure 6 as a function of the particle masses. It is well-known that within a hydrodynamical approach, these slopes can be interpreted as to be due to the combination of a thermal component (the corresponding parameter being the temperature at freeze-out) and a collective one (the parameter being the flow velocity). The comparison of STAR and SPS [17] data allows to highlight two facts. First, it appears clearly that there is a strong indication of radial flow at STAR. Second, strange particles follow the same behavior at SPS and RHIC energies namely that the inverse slopes decrease with increasing mass. A hydrodynamical approach [18] leads to the following parameters: T_{FO} = 130 MeV and \beta_{flow} = 0.5 c. Nevertheless, it is not trivial to obtain presently a coherent picture from the RHIC measurements (see \bar{p} or \phi points). A possible explanation is that the slopes depend strongly on the transverse momentum range where the fit is performed (more details can be found in [19]): For example, in the case of the \Lambda, a unique exponential function is not able to reproduce the distribution. Investigations have to be pursued.
IV. ATTEMPT OF ANSWERS

STAR has highlighted the important amount of strangeness produced at RHIC energy. Information has been obtained about the original environment of the particle production. Measurements of particle ratios lead to the conclusion that the net-baryon density drops with the decrease of the degree of stopping going from AGS, to SPS to RHIC but even at the higher energy, the system is still not baryon free.

Ratios appear to be consistent with a simple coalescence model. They weakly depend on the transverse momentum, suggesting that the rescattering is not significant. It has also been observed that baryon and anti-baryon present similar final state spectra however mechanisms of their production can be different and further analyses have to be done. Inverse slopes of transverse mass distributions exhibit a strong radial flow governing the fireball evolution at RHIC. And it becomes quite puzzling to observe that statistical approach is able to reproduce quite well the data.

STAR future analyses will be very promising for the strangeness investigation. RHIC is running at full energy ($\sqrt{s_{NN}} = 200$ GeV), statistics will increase and an important issue is the adding of the Silicon Vertex Detector to the TPC.

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