STAR Results on Strangeness Production at RHIC energies

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Abstract

Strangeness measurement at RHIC energies constitutes one of the favorite theme of the STAR Collaboration. Besides the fact that strangeness enhancement has been proposed as a quark gluon plasma signature, its production provides various and relevant information about the collision evolution and especially on the hadronization process. The investigation of short-lived strange particles as well as their anti-particles and resonances allows an attempt of characterization of the matter created in RHIC heavy ion collisions.

1 Foreword

RHIC physics program is devoted to the search of the quark gluon plasma (QGP) keeping in mind that despite numerous heavy ion experiments at CERN had the same goal, no unambiguous signal of its formation could be highlighted [1]. From studies performed at the AGS, SPS or RHIC facilities, one can outline that before aspiring to a clear discovery of a transition phase sign, the evolution of the fireball created in the collision has to be well understood. Although it is trivial to say that the clue resides in the characterization of hadrons because whether a QGP has been formed or not, the collision story will end with a hadron production. The aim is to describe the various phases that the created system encounters, within a characterization of the hadronization as complete as possible. Let us briefly remind the scenario commonly adopted : the pre-equilibrium phase, is related to the earlier times of the collision, during which soft hard scatterings between partons take place leading to high temperature and pressure. If the energy density exceeds the critical density predicted by lattice QCD [2], a QGP may be formed. An expansion follows, system cools down until it encounters again the deconfinement point. The hadronization process occurs, partonic degrees of freedom are thus recombined in hadrons. These later still interact (within elastic and inelastic scattering) until the chemical freeze-out : at this
point, the chemical composition of each hadron is fixed but elastic scattering continue. Finally, the system encounters the thermal (kinetic) freeze-out of the particle momenta: particles stop interacting and move freely, toward the detectors. It is still unclear nowadays if the time between freeze-outs is short or not.

The present paper aims at answer to some fundamental questions such as: what is the original environment for the particle creation, what is the nature of the production mechanisms, how much are the particles produced, what is the degree of suddenness of the hadronization process? The answers should be found through strange particle measurements, also through their anti-particles and their resonances, as described in the following section.

2 Story of the Eighties

Some twenty years ago, Jan Rafelski and Berndt Müller proposed that the quantification of strangeness produced in the collision may allow to distinguish between a hadronic gas and a quark gluon plasma. This QGP signature relies on the fact that strangeness production may be enhanced if a QGP is formed. Furthermore, the higher the strange content of the particle, the higher the enhancement.

SPS experiments suited for strangeness measurements showed the expected enhancement of the multi-strange particles, from proton-nucleus (pA) to nucleus-nucleus (AA) collisions. However, it is possible to explain this strangeness augmentation with purely hadronic scenarios, such as, notably, the interpretation in terms of canonical suppression. A. Tounsi and collaborators pointed out at the last Quark Matter conference that a transition from canonical to the asymptotic grand canonical limit is consistent with the recent NA49 results on Λ enhancement at $\sqrt{s_{NN}}=40, 80, 158$ GeV. In spite of the numerous SPS results related to strangeness, further investigations were highly required, and especially at RHIC, where the QGP is expected to be formed during a longer time offering better conditions for its discovery.

STAR made one of its priority of this strangeness study, and what will be discussed now, is the numerous interesting information which have been provided for two years of data analyses on:

- anti-baryon over baryon ratios providing knowledge ranging from the baryon density of the system to a hint on production mechanisms.
- strange over non-strange particles allowing a quantitative evaluation of strangeness production.
- ratios may also give access to an estimation of the temperature and chemical potential at the chemical freeze-out.
- transverse mass or momentum distributions informing on the partition between collective (flow velocity) and thermal effects (temperature at kinetic freeze-out).
• strange resonances serving as a probe for the duration of the hadronization process, i.e. as a chronometer of the time between the chemical and thermal freeze-outs.

3 Hadron production

3.1 Original environment

Anti-baryon over baryon ratios ($\bar{B}/B$) investigated as a function of the strangeness content of the particle species are represented on figure 1 for SPS and RHIC energies. Two observations can be made: ratios increase a) with the strange content of the particle and b) with the collision energy - due to the decreasing net baryon density. At RHIC, the tendency clearly reveals that values tend to unity but without reaching it. Probably, only the future LHC collider will offer a baryon free regime.

The influence of the baryon density can also be observed on the lower part of figure 2 presenting the $K^+/K^-$ excitation function sharply decreasing, as expected, with the collision energy increase. Moreover, the $K^+/\pi$ ratio peaking around 8 GeV traduces the interplay between the dropping net baryon density with $\sqrt{s_{NN}}$ and a increasing $K^+$ and $K^-$ production rate i.e. an enhanced strangeness production. This shape was predicted by thermal models.

This last statement is fully responsible of the $K^-/\pi$ steady increase. Note that for elementary collisions, the same trend is observed with a lower magnitude.
3.2 Production mechanisms

The partition between pair processes and baryon transport can be estimated from the $\bar{p}/p$ ratio (10). Pair processes mean pair creation as well as annihilation while baryon transport is related to nucleons originated from the incident nucleons. It appears that, at RHIC, pair processes are dominant, being much larger than baryon transport by a factor of 4 while at SPS, it represents only 20%.

Experimental data have been compared to coalescence model predictions (11). Their authors claim that (anti-)quark matter hadronizes suddenly via quark coalescence processes and that $\bar{B}/B$ ratios are related one to each other by a multiplicative factor $D$ given by the value of $K^+/K^-$ ratio:

$$\frac{\bar{\Lambda}}{\Lambda} = D \frac{\bar{p}}{p}, \quad \frac{\Xi}{\bar{\Xi}} = D \frac{\bar{\Lambda}}{\Lambda}, \quad \frac{\bar{\Omega}}{\Omega} = D \frac{\Xi}{\bar{\Xi}}$$

These relations can be easily demonstrated by writing explicitly the quark content of the involved particles. Hence, all ratios can be predicted via simple quark counting. The coherence of this statement can be seen in figure 3 where the measured $K^+/K^-$ ratio is found to be in line with the values obtained from other ratios, at both SPS and RHIC energies.

An alternative of this description is provided by statistical models cited in reference (12). During the last Quark Matter conference was discussed a compilation of P. Braun-Munzinger and collaborators, showing various particle ratios measured at $\sqrt{s_{NN}} = 130$ GeV by the four RHIC experiments and compared to their model pre-
dictions. The remarkable agreement allows to extract the temperature and baryon density at the chemical freeze-out, being respectively equal to 176 MeV and 41 MeV. Similar analyses have been done at different energies using other approaches. These later certainly contain some discrepancies (chemical and/or thermal equilibrium is supposed or not) but globally all approaches work well and thus lead to the question whether we are dealing with chemically equilibrated systems or not? Superimposing the various freeze-out parameters on the T-µ plane phase diagram of lattice QCD calculations (2), it appears that RHIC parameters coincide with the critical value predicted by QCD as shown by figure 4. For R. Stock (13), "This can not be a coincidence" while V. Koch (14) asks the question "Does it reflect a measurement of the phase separation line in the QCD phase diagram?" and answers "Certainly not!! Maybe it tells us about a limiting temperature."

Knowledge on chemical freeze-out appearing accessible, characterization on the thermal freeze-out can be provided with transverse mass or momentum distributions. The main result can be summarized here, namely that the flow is found to be enhanced from SPS to RHIC energy. The other point is that for both energies, the inverse slope of these spectra increases linearly for light particles and saturates for heavier masses (> 1 GeV/c²). Attempts of explanation are pointed out such as the existence of a flow at a partonic level or an earlier thermal freeze-out (decoupling) for the heavier particles. The measurement of other massive objects like D or J/ψ meson will be very instructive. During the conference, Matt Lamont has presented a review of STAR results related to the various flow analyses (15).
4 Hadronization suddenness

4.1 Motivation

Chemical and kinetic freeze-outs appear sequentially at different times which remain to be defined. A way to investigate the duration between both freeze-outs is provided by resonances of strange particles as it has been suggested by J. Rafelski and collaborators \cite{16}. The lifetime of these resonances is similar to the lifetime of the system, typically a few fm/c. Thus, their abundances could inform on the lifetime of the system and more precisely on the hadronization suddenness. Indeed, resonances are produced at the chemical freeze-out and if, after the resonance decay, the two decay products do not suffer any rescattering, the parent particle may be measured (for example, by invariant mass reconstruction). However, if one or \textit{a fortiori} all decay products rescatters, it becomes impossible to reconstruct the parent resonance. Parallel to rescattering effects, recombination of decay particles may append and reforms a resonance which has previously decayed. These scenarios are depicted on figure 5. The longer the lifetime of the system, i.e. the longer the separation in time between chemical and thermal freeze-outs, the more frequent these phenomena. According to UrQMD calculations \cite{17}, the signal loss in invariant mass reconstruction due to rescattering amounts in AuAu collisions at $\sqrt{s_{NN}} = 200$ GeV, 55\% and 33\% for K*(892)\(^0\) and Λ(1520) respectively.

The aim will be hence to compare the resonance yields in AA collisions for which a separation in time is expected to yields obtained in elementary reactions.

4.2 Sign of a resonance suppression ?

Various resonances have been measured in STAR \cite{18}. In particular, K*(892)\(^0\) and Λ(1520) resonances have been investigated in pp and AuAu collisions via combinatorial of particles for invariant mass reconstruction.

K*(892)\(^0\)/K ratio measurements have been studied as a function of the beam energy and presented on figure 6. The interest of this observable resides in the fact that these particles have the same quark content but differ by their mass and spin. K*(892)\(^0\)/K ratio appears to be lower in $\sqrt{s_{NN}}=200$ GeV AuAu collisions than in pp at the same energy, by a factor of 2. If one assume that this difference is due to the K*(892)\(^0\) survival probability, this measurement is compatible with a short time between the chemical and thermal freeze-outs and no K*(892)\(^0\) regeneration. A long time unless significant K*(892)\(^0\) regeneration seems to be ruled out.
Considering now the $K^*(892)^0$ absolute yields, a suppression of 45% is observed from pp collisions ($dN/dy=0.058\pm0.02$) to the yield scaled to the number of participants obtained for the 20% most central AuAu collisions ($dN/dy=8.35\pm0.99$). This result can be compared to the 55% of signal loss predicted by UrQMD. Nevertheless, two precautions have to be stressed before concluding on the rescattering magnitude: firstly, inverse slopes of transverse mass spectra are quite different in UrQMD and data, and secondly, the partition between rescattering and regeneration remains to be investigated within the model.

$\Lambda(1520)/\Lambda$ ratio has been similarly analyzed. Preliminary results are summarized on figure 7 which was recently presented at the Breckenridge workshop \cite{19}. Although STAR measurements suffer a lack of statistics, the ratio is equal to 0.09$\pm0.028$ in pp and 0.034$\pm0.011$(stat) in AuAu collisions. Thus, the signal of suppression amounts about 65% (with large error bars) being in line with UrQMD predictions as it was already in agreement with the NA49 analysis.

Note the unexpected larger signal loss for $\Lambda(1520)$ than for $K^*(892)^0$ whose lifetime is 3 times shorter than that of the lambda resonances and hence should be in principle more suppressed. More precise measurements are of course needed. This requirement appears even more crucially looking at figure 8 where Rafelski statistical model predictions on the lifetime and temperature of the system are reported. $K^*(892)^0/K$ and $\Lambda(1520)/\Lambda$ experimental values are also indicated. The constraint on the model are obviously not sufficiently severe but here, the interest of such a measurement can be realized.

From these resonances, one learned that there is an observed suppression of resonances from pp to AuAu collisions and it will be very interesting to pursue these analyses.
In particular, $\Sigma(1385)$ (width $\Gamma_{\Sigma(1385)} = 35$ MeV) currently under investigation is a resonance of high interest since it is produced an order of magnitude more abundantly than is $\Lambda(1520)$ due to an high degeneracy factor and smaller mass. Its signal is more strongly influenced by final state interactions than that of $\Lambda(1520)$ but not as strong as $K^*(892)^0$.

5 Summary

Strangeness measurement with STAR experiment has been fully informative for the description of the hot and dense fireball. The original environment which has been characterized corresponds to a low baryon density but not to a baryon free regime. The various studies related to the strange particle production indicate that coalescence process can describe the particle creation mechanism. From the preliminary strange resonance measurements, information on the hadronization suddenness tends to support a very short time between chemical and thermal freeze-outs.

The capability of statistical models for reproducing the various particle yields with a very nice agreement is very remarkable. It leads to the puzzle why so “simple” statistical models can described so complex relativistic heavy ion collision. STAR continues its physics program and the new data collection related to d-Au collisions will allow an even more complete understanding of the collision evolution.

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