Quark model and strange baryon production
in heavy ion collisions

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August 31, 1998

Abstract

It is pointed out that the recent data on strange baryon and antibaryon production in Pb-Pb collisions at 159 GeV/c agree well with the hypothesis of an intermediate state of quasi-free and randomly distributed constituent quarks and antiquarks. Also the S-S data are consistent with this hypothesis. The p-Pb data follow a different pattern.

Recently, rather precise data on strange baryon and antibaryon production in the central rapidity region of Pb-Pb and p-Pb collisions were presented by the WA97 collaboration [1]. In this note I would like to point out that these Pb-Pb data agree rather well with a simple quark-counting rule whereas the p-Pb data follow a different pattern. This observation implies that the quark degrees of freedom are much more relevant in collisions of two heavy nuclei than in "elementary" hadronic interactions. It thus supports the interpretation of the data on strangeness production in Pb-Pb collisions as an evidence for creation of the quark-gluon plasma [2, 3].

Our argument is an application of the old idea proposed first by Rafelski [4]. Considering a system of partons in thermodynamic equilibrium (i.e. quark-gluon plasma), he observed that strange (and antistrange) particle

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abundances must satisfy a host of simple relations. Below we consider some of these relations which have a virtue of being rather general, independent of the assumption of thermal equilibrium but -on the other hand- sensitive to the quark degrees of freedom.

To explain the argument, let us formulate the quark counting rule we are talking about. We simply assume that probability of creation of a baryon (or an antibaryon) with a given quark content is proportional to the probability that three quarks (or antiquarks) with appropriate quantum numbers happen to meet at a certain region of phase-space - necessary for the binding to take place. Assuming furthermore that the quarks are uncorrelated\(^1\), we obtain the following relative probabilities:

\begin{align}
   p &= \omega_p q^3; \quad \Lambda/\Sigma^0 = \omega_\Lambda q^3 s^3; \quad \Xi = \omega_\Xi q^3 s^3; \quad \Omega = \omega_\Omega s^3 \\
   \end{align}  

(1)

where \(q\) and \(s\) are relative probabilities to find a light quark and a strange quark in the suitable phase-space region. Analogous formulae are valid for antibaryons. \(\omega_i\) are the proportionality factors taking into account the effects of resonance structure and of the binding energy in formation of various baryons. These factors, generally different for different baryons, are rather difficult to calculate and therefore the comparison of Eqs (1) with experiment is rather involved and depends on further assumptions \([2, 5]\).

One may observe, however, that these \(\omega\)-factors are identical for a baryon and the corresponding antibaryon. Consequently, if one considers only the ratios of the antibaryon to baryon rates, the \(\omega\)-factors cancel \([4, 6]\) and the discussion becomes much simpler. This is what we are going to do. We thus have

\begin{align}
   \bar{p}/p &= \bar{q}^3/q^3 \\
   \end{align}  

(2)

and

\begin{align}
   \bar{\Lambda}/\bar{\Sigma} &= \bar{p}/p D; \quad \bar{\Xi} = \bar{p}/p D^2; \quad \bar{\Omega} = \bar{p}/p D^3 \\
   \end{align}  

(3)

where

\begin{align}
   D &= \frac{q^3}{\bar{q}^3} \quad \end{align}  

(4)

\footnote{\(^1\)Both these assumptions are valid in thermal equilibrium. The inverse is not true, however.}
From these equations we see that the four ratios in (2) and (3) are expressed in terms of two parameters. Therefore we have two constraints which must be satisfied by the data.

Let us first discuss the data for Pb-Pb collisions at CERN SPS. The data of [1] give the following values for strange antibaryon/baryon ratios in the central rapidity region

\[
\begin{align*}
\frac{\bar{\Lambda}}{\Sigma} & = .133 \pm .007; \\
\frac{\Xi}{\bar{\Xi}} & = .249 \pm .019; \\
\frac{\bar{\Omega}}{\Omega} & = .383 \pm .081 
\end{align*}
\]

The data of NA44 [7] give

\[
\frac{\bar{p}}{p} = .07 \pm .01
\]

Dividing the ratios (5) by the ratio (6) and using (3) we have

\[
\begin{align*}
D_{\Lambda} & = 1.9 \pm .3; \\
D_{\Xi} & = 1.89 \pm .15; \\
D_{\Omega} & = 1.76 \pm .15 
\end{align*}
\]

and thus we see that the three values of the parameter \(D\) obtained from the data are in good agreement with each other up the experimental accuracy of about 10 percent.

From (6) we also deduce that

\[
\frac{\bar{q}}{q} = .41 \pm .02
\]

and thus employing (7)

\[
\frac{s}{\bar{s}} = .75 \pm .06
\]

where we have used the average of the three values for \(D\) given in (7), i.e. \(D = 1.83 \pm .10\). The ratios (8) and (9) are in good agreement with those obtained in [8] from a thermal fit to the data.

This completes the analysis of the Pb-Pb data. Let us now turn to the p-Pb collisions.

The data of WA97 coll. [1] give

\[
\begin{align*}
\frac{\bar{\Lambda}}{\Sigma} & = .20 \pm .03; \\
\frac{\Xi}{\bar{\Xi}} & = .33 \pm .03;
\end{align*}
\]

\[\text{Footnote: These ratios can be calculated as the inverse square of the corresponding fugacities given in [8].}\]
The $\bar{\Omega}/\Omega$ is not given in [1]. The $\bar{p}/p$ ratio was measured by NA44 collaboration [9], with the result

$$\frac{\bar{p}}{p} = .31 \pm .03$$  \hspace{1cm} (11)

Using these values and the formulae (2),(3) we thus obtain

$$D_\Lambda = .65 \pm .1; \quad D_\Xi = 1.03 \pm .07$$ \hspace{1cm} (12)
in clear disagreement. We must conclude that the quark counting rule is apparently in contradiction with p-Pb data, indicating that in this case the quark degrees of freedom do not represent a decisive factor in the production mechanism.

Taken together, Eqs (7) and (12) show that the result obtained for Pb-Pb collisions is likely not accidental but indeed indicates existence of an intermediate step in baryon (antibaryon) production process: a system of quasi-free constituent quarks and antiquarks\(^3\) distributed randomly in phase-space. A natural interpretation seems to be that this intermediate $q - \bar{q}$ system is the first step of the chiral symmetry breaking transition from the earlier quark-gluon plasma phase.

Another interesting issue is: which pattern is followed in collisions of lighter nuclei. Answering this question could bring new arguments to the controversy as to where the transition to the quark-gluon plasma phase takes place.

The data of [9] and [12] on $S - S$ collisions give:

$$\frac{\bar{p}}{p} = .12 \pm .01; \quad \frac{\bar{\Lambda}/\Sigma}{\Lambda/\Sigma} = .22 \pm .01; \quad \frac{\bar{\Xi}}{\Xi} = .55 \pm .07.$$ \hspace{1cm} (13)

So that we obtain

$$D_\Lambda = 1.83 \pm .17; \quad D_\Xi = 2.14 \pm .16$$ \hspace{1cm} (14)

Thus the agreement with Eqs (2) and (3) is not bad, although not as good as in the case of Pb-Pb collisions.

Using the average value $D = 1.99 \pm .12$ and $\bar{q}/q = .49 \pm .02$ we obtain $\bar{s}/s = .98 \pm .07$ in good agreement with the analysis of [13] where the data on

\(^3\)Dynamical models which explicitly introduce the $q - \bar{q}$ intermediate system are being developed since some time by the groups in Budapest [10] and in Bratislava [11].
central rapidity region in $S - S$ collisions were discussed using the thermal model. It is also interesting to note that the obtained value of the parameter $D$ is not inconsistent with that found from the Pb-Pb data. This certainly supports the idea that already in $S - S$ collisions the baryon and antibaryon production process proceeds through an intermediate random $q - \bar{q}$ system. This observation, in turn, strengthens the evidence for quark-gluon plasma phase present already in collisions of light nuclei.

We would like to close this paper with the following comments.

(i) Although we consider only baryon and antibaryon production, it is tempting to extend the argument also to $K$ and $\bar{K}$ production. Taking into account (4), we obtain

$$\frac{K}{\bar{K}} = \frac{q\bar{s}}{s\bar{q}} \equiv D.$$  \hspace{1cm} (15)

The data [12] and [14] give

$$\left(\frac{K}{\bar{K}}\right)_{S-S} = 1.91 \pm 0.37; \quad \left(\frac{K}{\bar{K}}\right)_{P_p - P_b} \approx 1.8 \text{ (no error given)}$$  \hspace{1cm} (16)

We see that these results are not in disagreement with the values of $D$ found from baryon-antibaryon data in $S - S$ and $Pb - Pb$ collisions$^4$.

(ii) The advantage of our argument is that the Eqs (2) - (4) can be applied to any phase space region (of course the specific parameters may depend on the region). When the appropriate data are available, it shall be thus possible to test the relevance of the quark degrees of freedom also outside the central rapidity region considered here. One may hope in this way to determine the kinematic domain where the particles are dominantly produced by the intermediate step of quark-gluon plasma. Furthermore, this should allow to determine the rapidity dependence of the basic ratio $\bar{s}/s$. This last point is particularly interesting in view of the recent suggestion by Letessier and Rafelski [15] that the observed deviation of $\bar{s}/s$ from unity is a reflection of the Coulomb interactions.

(iii) Our argument assumes that the production of all baryons and antibaryons in the central rapidity region of heavy ion collisions proceeds by a common mechanism, i.e. "coalescence" of the independently distributed quarks and antiquarks. Recent analysis of the thermal model by Letessier

$^4$ I could not find the data for $p - Pb$ collisions. The $p - S$ data [12] give $K^+/K^- = 2.02 \pm 0.14$ is strong disagreement both values of $D$ in (12)
and Rafelski [15], based on the Pb–Pb data extrapolated to full phase-space, (and including Coulomb corrections which modify somewhat the relations (2)-(4)), indicates that the conditions for production of Ω and ¯Ω may differ from those of other baryons. This is certainly a serious possibility. The present experimental accuracy does not yet allow, however, to draw definite conclusions about this problem.

(iv) We would like to repeat that the relations (2)-(4) are independent of the assumption of thermal equilibrium. When thermal equilibrium is additionally assumed, one may produce many more specific predictions, as discussed in detail in [6, 13]. In particular, it is possible to calculate the ratios of the rates of particles with different strangeness content, a task which is clearly beyond the scope of the present investigation. We feel, however, that our simple argument can still serve a useful purpose of convincing a layman that the quark degrees of freedom are essential for a correct description of particle production in heavy ion collisions.

Acknowledgements

I would like to thank B. Muller for raising my interest in the subject. The discussions with F. Beccatini, R. Calandro, R. Lietava, E. Quercigh, J. Rafelski and K. Zalewski are highly appreciated. Thanks are also due to M. Morando and E. Quercigh for a very kind hospitality at the Padova meeting on Strangeness in Quark Matter, where part of this work was done. This investigation was supported in part by the KBN Grant No 2 P03B 086 14.

References


