A model of anomalous production of strange baryons in nuclear collisions

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Abstract

We propose a simple model of production of strange baryons and antibaryons in nuclear collisions at the CERN SPS. The model takes into account both the increase of strangeness production in collisions of lighter ions and a possibility of the formation of anomalous, strangeness rich matter in central PbPb interactions. It is shown that ratios like $<\Omega>:<\Xi>:<\Lambda>$ depend strongly on the presence of anomalous matter and can be used to determine its phenomenological parameters. In the model we assume that particle composition of final state hadrons is essentially given by a rapid recombination of quarks and antiquarks formed in tube-on-tube interactions of incoming nucleons.

1 Introduction

Enhanced production of strange hadrons has been suggested [1, 2] as a signature of Quark-Gluon Plasma (QGP) formation in heavy ion collisions. Enhancement of strangeness production - with respect to pp interactions - has been observed [3] in pS, pAg, SS and SAg interactions, but it is in our opinion rather unlikely that QGP has been formed in these collisions. Strangeness enhancement observed in these interactions has been analysed by Werner [4], Sorge [5] and Tai An and Sa Ben-Hao [6] in models with collective string interactions and by Capella et al. [7] in the dual parton model.

When analyzing the production of strange hadrons in Pb+Pb interactions one has to disentangle that part of strangeness enhancement which is given by the extrapolation of trends observed already in collisions of lighter ions from genuine "anomalous" strangeness enhancement due to the production of new form of matter in Pb+Pb collisions.

In Refs. [4, 5, 6] the increase of strangeness due to interactions of final state hadrons has been taken into account and found insufficient to describe the observed enhancement without string-string effects. In contradistinction to these authors we use phenomenological parametrization of the production of $u\bar{u}$, $d\bar{d}$, $s\bar{s}$ pairs which will appear in final state hadrons as valence quarks and antiquarks. This parametrization is based on [8] and on the data analysis by Wroblewski [9]. We have also taken into account a possible production of anomalous strangeness rich matter in the spirit of Refs. [10, 11, 12]

In the present paper we shall study a simple model of the production of strange baryons and antibaryons in proton- nucleus (pA) and nucleus- nucleus (AB) interactions in the CERN SPS energy range. The model is based on the assumption that yields of particles of different types are roughly given by the recombination of quarks and antiquarks formed during the first stage of the nuclear collision. According to this assumption the yields of particles of different type are not strongly influenced by the stage of interacting gas of hadrons.

Models based on the idea of recombination have been intensively studied during past 15 years, see e.g. Refs.[13]-[20]. An essential ingredient of any recombination model is the number of quarks and anti- quarks (future valence quarks) just before the recombination. We shall estimate the number of recombining quarks and antiquarks of the three flavours u, d, s from the analysis of data on production of strange and non- strange hadrons in pA and AB interactions. Compilations of data can be found in Refs. [8],[21]-[28].

In what concerns the strange quarks and antiquarks we shall use the parametrization of our recent work [8], see also Refs. [9, 24], the number of created $u\bar{u}$ and $d\bar{d}$ pairs is described by a parametrization of the type used in Ref.[8] and results of Wroblewski [9].

A rapid recombination differs from models based on the assumption of a formation of a thermalized system in AB interactions, see e.g. Refs. [29], although the free parameters in models permit to obtain similar results. In particular the baryon chemical potential and parameter of partial chemical thermalization of strange hadrons have their counterparts in the ratio of quarks and antiquarks and the ratio of strange to non-strange quarks before the thermalization.

Assuming a rapid recombination implies a rather short pre-hadronic stage in heavy ion collisions, that means that hadrons are formed within about 2fm/c, which is a time interval too short to permit a transfer of quarks and antiquarks over distances in the transverse plane comparable with the dimensions of the system - about 10fm.

An indirect support of a rather short pre- hadronic stage in nuclear collisions is provided by the phenomenological success of models by Blaizot and Ollitrault [10] and by Kharzeev, Lourenco, Nardi and Satz [11, 12] in describing J/Ψ suppression, observed by NA50 collaboration [30] in Pb+Pb collisions at the CERN SPS. In models of Refs.[10, 11, 12] it is assumed that Quark- Gluon Plasma (QGP) is formed in a part of impact parameter plane, separated from the rest where only hadronic matter is present. Since the separation can hardly remain there for a time of the order of 10 fm/c the existence of the boundary indicates that the existence of QGP or, more generally, of the form of matter which is strongly absorbing J/Ψ is present only for a short time of the order of 1-2 fm/c.

The present note is structured as follows. In the Sect.2 we shall describe our parametrization of the numbers of produced pairs $u\bar{u}$, $d\bar{d}$ and $s\bar{s}$ - in addition of valence quarks present in incoming nuclei - in pA and AB interactions. In Sect.3 the rapid recombination scheme is considered. A possible modification of the rapid recombination scenario is briefly mentioned in Sect.4. In Sect.5 we discuss the modifications of the number of created quark pairs due to the presence of "anomalous", strangeness richer, matter. The last Sect.6 contains comments and conclusions.

2 Parametrization of the production of $< u\bar{u} >$, $< d\bar{d} >$ and $< s\bar{s} >$ pairs in pA and AB interactions

In our work [8] we have parametrized the production of $< s\bar{s} >$ pairs in pA and AB interactions as

$$N_s^{coll} =< s\bar{s} >=< s\bar{s} >_{nn} \sum_{i,j} (1-\beta_s)^{i-1}(1-\beta_s)^{j-1} \tag{1}$$

where the superscript "coll" indicates that $s\bar{s}$ pairs are produced in nucleon- nucleon collisions and

$$< s\bar{s} >_{nn} (1-\beta_s)^{i-1}(1-\beta_s)^{j-1}$$

is the number of $< s\bar{s} >$ pairs produced in the nucleon- nucleon collision which is i-th for the nucleon coming from the left and j-th for the nucleon coming from the right. Values of parameters $< s\bar{s} >_{nn}$ and β_s are according to data excluding those for Pb+Pb collisions [8]

$$\beta_s \approx 0.13, \qquad < s\bar{s} >_{nn} \approx 0.63 \pm 0.08$$

In Ref.[9] Wroblewski has analyzed the production of future valence quarks and antiquarks in hadron- hadron interactions, obtaining for the total number of valence quarks and antiquarks in pp interactions at 205 GeV/c the result $< N_{q\bar{q}} >= 7.4 \pm 0.6$. Subtracting from that the number of $s\bar{s}$ pairs and dividing by two to get separately $< u\bar{u} >_{nn}$ and $< d\bar{d} >_{nn}$ we obtain

$$< d\bar{d} >_{nn} \approx < u\bar{u} >_{nn} \approx 3.4 \pm 0.4$$

Making use of data on $< h^- >$ production in pA and AB interactions compiled by Gazdzicki and Röhrich [25] and assuming that the number of quark- antiquark pairs is proportional to $< h^- >$ we have obtained $\beta_u = \beta_d \approx 0.4$. In this way we have

$$N_u^{coll} =< u\bar{u} >=< d\bar{d} > \approx < u\bar{u} >_{nn} \sum_{i,j} (1-\beta_u)^{i-1}(1-\beta_u)^{j-1} \tag{2}$$

where

$$\beta_u = \beta_d \approx 0.4, \qquad < u\bar{u} >_{nn} =< d\bar{d} >_{nn} \approx 3.4 \pm 0.4$$

According to the scheme described above we can now write down formulas for the average number of quark- antiquark pairs produced in pA and AB interactions.

We shall start with pA collisions at a fixed value of the impact parameter b. The number of $s\bar{s}$ pairs denoted as $N^{coll}_{s\bar{s}}(pA;b)$ is given as

$$N^{coll}_{s\bar{s}}(pA;b) =< s\bar{s} >_{nn} \sum_{i=1}^{\mu}(1-\beta_s)^{i-1} =$$

$$=< s\bar{s} >_{nn} \frac{1-(1-\beta_s)^{\mu}}{\beta_s} \tag{3}$$

where

$$\mu = \sigma\rho 2L_A(b); \qquad L_A(b) = \sqrt{R_A^2 - b^2}$$

Here R_A is the radius of the nucleus A, b is the impact parameter of the collision, σ is the inelastic nucleon- nucleon cross- section and ρ is the nuclear density. Similarly for $u\bar{u}$ and $d\bar{d}$ pairs

$$N^{coll}_{u\bar{u}}(pA;b) = N^{coll}_{d\bar{d}}(pA;b) =< u\bar{u} >_{nn} \sum_{i=1}^{\mu}(1-\beta_u)^{i-1} =$$

$$=< u\bar{u} >_{nn} \frac{1-(1-\beta_u)^{\mu}}{\beta_u} \tag{4}$$

where the notation is the same as in Eq.(3).

In addition to quark- antiquark pairs created in the interactions there are also valence quarks of incoming nucleons. Averaging over d and u-quarks we have 1.5 of d-quark and 1.5 of u-quark for each participating nucleon. This gives

$$N^{val}_u = N^{val}_d = 1.5(\mu+1); \qquad N^{val}_s = 0 \tag{5}$$

The total number of quarks and antiquarks taking part in the recombination is given as the sum of contributions from collisions and from valence quarks

$$N_u = N^{val}_u + N^{coll}_{u\bar{u}}$$

$$N_d = N^{val}_d + N^{coll}_{d\bar{d}}; \qquad N_s = N_{\bar{s}} = N^{coll}_{s\bar{s}} \tag{6}$$

In the case of AB interactions we shall start with considering the number of quarks and antiquarks due to the collisions of nucleons present in two colliding tubes, each having cross section σ. The impact parameter of the collision is denoted as $\vec{b}$. In the transverse plain the position of the tube in nucleus A is specified by the vector $\vec{s} = \vec{s}_A$ Within the nucleus B, the transverse position of the second tube is given by the vector $\vec{s}_B = \vec{b} - \vec{s}$. The average numbers of nucleons in tubes in A and B are respectively given as

$$\nu \equiv \nu_A = \sigma\rho 2L_A(s); \qquad L_A(s) = \sqrt{R_A^2 - s^2}$$

$$\mu \equiv \mu_B = \sigma\rho 2L(\vec{b},\vec{s}); \quad 2L_B(\vec{b},\vec{s}) = \sqrt{R_B^2 - b^2 - s^2 + 2bs.cos(\theta)} \tag{7}$$

Numbers of future valence quarks and antiquarks created in such a tube- on -tube collision are given as

$$N^{coll}_{s\bar{s}}(AB;b,s,\theta) =< s\bar{s} >_{nn} \sum_{i=1}^{\nu}\sum_{j=1}^{\mu}(1-\beta_s)^{i-1}(1-\beta_s)^{j-1} =$$

$$=< s\bar{s} >_{nn} \frac{1-(1-\beta_s)^{\nu}}{\beta_s}\frac{1-(1-\beta_s)^{\mu}}{\beta_s}$$

$$N_{u\bar{u}}^{coll}(AB;b,s,\theta) = N_{d\bar{d}}^{coll}(AB;b,s,\theta) =$$
$$=< u\bar{u} >_{nn} \sum_{i=1}^{\nu}\sum_{j=1}^{\mu}(1-\beta_u)^{i-1}(1-\beta_u)^{j-1} =$$
$$=< u\bar{u} >_{nn} \frac{1-(1-\beta_u)^{\nu}}{\beta_u}\frac{1-(1-\beta_u)^{\mu}}{\beta_u} \quad (8)$$

The total number of future valence quarks and antiquarks produced by interaction within these tubes then becomes

$$N_u(AB;b,s,\theta) = N_d(AB;b,s,\theta) = 1.5(\mu+\nu) + N_{u\bar{u}}^{coll}(AB;b,s,\theta)$$
$$N_s(AB;b,s,\theta) = N_{\bar{s}}(AB;b,s,\theta) = N_{s\bar{s}}^{coll}(AB;b,s.\theta)$$
$$N_{\bar{u}}(AB;b,s,\theta) = N_{\bar{d}}(AB;b,s,\theta) = N_{u\bar{u}}^{coll}(AB;b,s,\theta) \quad (9)$$

In other to obtain a qualitative feeling of ratios of different flavours of quarks and antiquarks we plot in Table 1 values of N_s^{coll}, N_u^{coll}, $N_u = N_u^{coll}$, and their ratios for a set of values of μ and ν.

Table 1. Production of quarks and antiquarks in tube- on tube collision; μ and ν are numbers of nucleons in the tubes.

μ,ν	$N_s = N_s^{coll}$	N_u^{coll}	$N_u = N_u^{coll} + N_u^{val}$	N_s/N_u^{coll}	N_s/N_u
1,1	0.63	3.4	6.4	0.185	0.1
1,2	1.18	5.44	9.9	0.22	0.12
1,3	1.65	6.66	12.7	0.25	0.13
1,4	2.07	7.40	14.9	0.28	0.14
1,5	2.43	7.84	16.84	0.31	0.144
2,2	2.2	8.7	14.7	0.253	0.15
2,3	3.1	10.7	18.2	0.29	0.17
2,4	3.87	11.83	20.83	0.33	0.19
2,5	4.54	12.54	23.04	0.36	0.20
3,3	4.33	13.06	22.1	0.33	0.20
3,4	5.43	14.5	25.0	0.37	0.22
3,5	6.37	15.36	27.4	0.415	0.23
4,4	6.8	16.1	28.1	0.42	0.24
4,5	8.0	17.0	30.5	0.47	0.26
5,5	9.36	18.1	33.1	0.52	0.28

As seen in the Table 1. the ratio N_s/N_u increases by a factor of 2.8 when going from the case of $\mu = 1, \nu = 1$ to that of $\mu = 5, \nu = 5$. The increase of the production of strange to non- strange hadrons will be, of course, smaller since in the nuclear collisions one always integrates over region of nuclei overlap in the impact parameter plane and the influence of the central region is suppressed by geometry.

The NA49 Collaboration has recently presented [26] results on K^+/K^- and $\bar{\Lambda}/\Lambda$ ratios in the central Pb+Pb collisions at 158 GeV per nucleon. The resulting numbers

$$\frac{K^+}{K^-} \approx 1.8; \qquad \frac{\bar{\Lambda}}{\Lambda} \approx 0.2$$

give a hint on whether the recombination models has a chance. Since K^+ consists of $s\bar{u}$, K^- of $\bar{u}s$, Λ of s,d,u and $\bar{\Lambda}$ of $\bar{s},\bar{d},\bar{u}$ we expect in a recombination model

$$\frac{K^-}{K^+} \approx \frac{N_u}{N_{\bar{u}}}.\frac{N_{\bar{s}}}{N_s}; \quad \frac{\bar{\Lambda}}{\Lambda} \approx \frac{N_{\bar{s}}}{N_s}.\frac{N_{\bar{u}}}{N_u}.\frac{N_{\bar{d}}}{N_d} \quad (10)$$

Table 1 shows that for most of combinations of μ and ν it holds $N_u \approx 2N_{\bar{u}}$ and by assumption $N_s = N_{\bar{s}}$ so both of ratios come out roughly correct. Note that in Table 1 we include all the quarks and antiquarks just before recombination independently of their rapidity. This may be adequate for the results of NA49 with a large acceptance.

3 Production of hadrons via fast recombination

In this section we shall assume that the recombination is so fast that quarks and antiquarks produced in a given tube- on - tube collision can recombine mutually and what happens in a given tube- on tube system is independent of what happens to systems produced by other tube- on- tube collisions.

We shall use the recombination model suggested by Biró and Zimányi [2, 13, 15, 20]. According to this model the number of pions N_π, kaons N_K, ϕ-mesons N_ϕ, baryons N_B, Y-hyperons N_Y, Ξ-hyperons N_Ξ, Ω's and corresponding antibaryons are given by the following relations:

$$N_\pi = \alpha(N_u + N_d)(N_{\bar{u}} + N_{\bar{d}}), \qquad N_K = \alpha(N_u + N_d)N_{\bar{s}},$$
$$N_{\bar{K}} = \alpha(N_{\bar{u}} + N_{\bar{d}}), \qquad N_\phi = \alpha N_s N_{\bar{s}},$$
$$N_B = \beta\frac{1}{3!}(N_u + N_d)^3, \qquad N_Y = \beta\frac{1}{2!}(N_u + N_d)^2 N_s,$$
$$N_\Xi = \beta\frac{1}{2!}N_s^2(N_u + N_d), \qquad N_\Omega = \beta\frac{1}{3!}N_s^3. \tag{11}$$

The constants α and β are obtained from the consistency conditions requiring that the number of quarks and antiquarks is equal to the corresponding number of valence quarks and antiquarks in hadrons formed by recombination. In this way one finds [2, 13, 15, 20]

$$\alpha = \frac{Q + \bar{Q}}{Q^2 + Q\bar{Q} + \bar{Q}^2}; \quad \beta = \frac{2}{Q^2 + Q\bar{Q} + \bar{Q}^2} \tag{12}$$

where

$$Q = N_u + N_d + N_s; \qquad \bar{Q} = N_{\bar{u}} + N_{\bar{d}} + N_{\bar{s}}$$

The yield of a certain particle is calculated in the following way. Numbers of quarks and antiquarks of all flavours in a tube- on- tube collision at given (b, s, θ) are obtained via Eqs.(8,9). This is inserted into Eqs.(11,12). In these equations we have used a short hand notation like N_π. The full notation should be $N_\pi(b, s, \theta)$. The total yield of Y-hyperons is then obtained from the expression

$$N_Y(AB; b) = \frac{1}{\sigma}\int_0^{R_A} sds \int_0^{2\pi} d\theta N_Y(AB; b, s, \theta) \tag{13}$$

We have calculated the yields $N_Y(AB, b)$ by two independent numerical methods which gave very similar results. The expression $N_Y(AB; b)$ corresponds to the sum of hyperons Λ, Σ^-, Σ^0 and Σ^-. Taking into account the decay $\Sigma^0 \to \Lambda + \gamma$ and the decay $\Xi^0 \to \Lambda\pi^0$ we have

$$< \Lambda >= \frac{1}{2}N_Y + \frac{1}{2}N_\Xi$$

Although we shall make in this paper no attempts at comparison with the data, let us point out that previous relationship corresponds to the situation in NA49 data analysis, but not to the one in WA97. Similarly the experimentally observed number of Ξ^- is given as

$$< \Xi^- >= \frac{1}{2} N_\Xi$$

The results for Pb+Pb and S+S are presented in Tables 2 and 3.

Table 2. Yields of strange baryons and antibaryons in Pb+Pb collisions as a function of the impact parameter b in the model of rapid recombination.

b	N_Y	N_Ξ	N_Ω	$N_{\bar{Y}}$	$N_{\bar{\Xi}}$	$N_{\bar{\Omega}}$
0.0	141.4	18.62	0.84	43.6	10.27	0.84
1.0	136.1	18.02	0.82	41.64	9.91	0.82
2.0	125.83	16.68	0.75	38.1	9.14	0.75
3.0	113.1	14.9	0.67	33.9	8.15	0.67
4.0	98.9	12.92	0.58	29.6	7.05	0.58
5.0	84.13	10.83	0.47	25.1	5.92	0.47
6.0	69.36	8.74	0.38	20.8	4.79	0.38
7.0	55.1	6.76	0.28	16.63	3.72	0.28
8.0	41.8	4.94	0.20	12.74	2.74	0.20
9.0	29.8	3.37	0.13	9.22	1.88	0.13
10.0	19.4	2.07	0.075	6.11	1.16	0.075
11.0	11.0	1.09	0.036	3.54	0.62	0.036
12.0	4.93	0.43	0.013	1.6	0.25	0.013

Table 3. Yields of strange baryons and antibaryons in S+S collisions as a function of the impact parameter b in the model of rapid recombination.

b	N_Y	N_Ξ	N_Ω	$N_{\bar{\Lambda}}$	$N_{\bar{\Xi}}$	$N_{\bar{\Omega}}$
0.0	16.44	1.41	0.041	5.71	0.83	0.041
1.0	14.85	1.28	0.038	5.12	0.75	0.038
2.0	11.97	1.02	0.030	4.08	0.60	0.030
3.0	8.72	0.72	0.020	2.93	0.42	0.020
4.0	5.59	0.44	0.012	1.85	0.26	0.012
5.0	2.94	0.21	0.0053	0.96	0.12	0.0053
6.0	1.07	0.068	0.0015	0.33	0.038	0.0015

The translation from the impact parameter b to the number of nucleon- nucleon collisions $N_c(b)$ and to the number of participating (wounded) nucleons $N_p(b)$ is given by the standard relations

$$N_p(b) = \frac{1}{\sigma} \int_0^{R_A} sds \int_0^{2\pi} d\theta \Theta(R_B^2 - b^2 - s^2 + 2bs.cos\theta)$$

$$\Big(\rho_A \sigma 2L_A(s)[1 - e^{-\rho_B \sigma 2L_B(b,s,\theta)}] + \rho_B \sigma 2L_B(b,s,\theta)[1 - e^{-\rho_A \sigma 2L_A(s)}]\Big)$$

$$N_c(b) = \frac{1}{\sigma} \int_0^{R_A} sds \int_0^{2\pi} d\theta \rho_A \sigma 2L_A(s) \rho_B \sigma 2L_B(b,s,\theta)$$

where

$$L_A(s) = \sqrt{R_A^2 - s^2}, \quad L_B(b,s,\theta) = \sqrt{R_B^2 - b^2 - s^2 + 2bs.cos(\theta)}$$

The average values of strange baryons are calculated by using the relations

$$< \Lambda >= \frac{1}{2}(N_Y + N_\Xi), \quad < \Xi^- >= \frac{1}{2}N_\Xi, \quad < \Omega >= N_\Omega$$

and similarly for antibaryons. In this way we obtain results presented in Tables 4 and 5.

Table 4. Yields of strange baryons and antibaryons in Pb+Pb collisions as a function of the impact parameter b in the model of rapid recombination within the tubes.

b	$< \Lambda >$	$< \Xi^- >$	$< \Omega >=< \bar{\Omega} >$	$< \bar{\Lambda} >$	$< \bar{\Xi}^+ >$
0.0	80.01	9.31	0.84	26.95	5.13
1.0	77.07	9.01	0.82	25.78	4.95
2.0	71.26	8.34	0.75	23.97	4.57
3.0	63.99	7.46	0.67	21.04	4.07
4.0	55.90	6.46	0.58	18.3	3.53
5.0	47.48	5.42	0.47	15.53	2.96
6.0	39.05	4.37	0.38	12.79	2.40
7.0	30.92	3.38	0.28	10.18	1.86
8.0	23.23	2.97	0.20	7.74	1.37
9.0	16.57	1.68	0.129	5.55	0.94
10.0	10.73	1.033	0.075	3.64	0.582
11.0	6.054	0.542	0.036	2.08	0.308
12.0	2.68	0.216	0.013	0.926	0.124

In Fig.1 we present the dependence of the production of of $< \Lambda > + < \bar{\Lambda} >$, $< \Xi^- > + < \bar{\Xi}^+ >$ and $< \Omega > + < \bar{\Omega} >$ on the number of nucleon- nucleon collisions. All yields are normalized to 1 at the impact parameter value of b=10, corresponding to the number of nucleon- nucleon collisions $N_c(b = 10)$=104.5. In the next section these results will be compared with the situation when anomalous and strangeness richer matter is present. In order to permit a comparison with earlier work we present in Table 5. the yields of strange baryons and antibaryons in S+S collisions.

Table 5. Yields of strange baryons and antibaryons in S+S interactions as a function of the impact parameter b

b	$< \Lambda >$	$< \Xi^- >$	$< \Omega >=< \bar{\Omega} >$	$< \bar{\Lambda} >$	$< \bar{\Xi}^+ >$
0.0	8.93	0.71	0.041	3.27	0.42
1.0	8.07	0.64	0.038	2.94	0.38
2.0	6.50	0.51	0.030	2.34	0.30
3.0	4.72	0.36	0.020	1.68	0.21
4.0	3.01	0.22	0.0118	1.055	0.128
5.0	1.58	0.107	0.0053	0.54	0.062
6.0	0.567	0.034	0.0015	0.185	0.019

Results for central S+S interactions can be compared with the data [3] and with the calculations performed within the ALCOR model by Biró, Lévai and Zimányi [13]. Biró et al. obtain $< \Lambda >$=10.37, the data give $< \Lambda >= 9.4 \pm 1.0$ and our value in Table 5. is $< \Lambda >$=8.93. For $< \Xi^- >$ Biró et al. find 1.15 whereas our value is 0.73. The largest discrepancy between Ref.[13] and our results appears in Ω production where the authors of Ref.[13] find $< \Omega >$=0.14, whereas our value is 0.041.

In the case of central Pb+Pb interactions Biró et al. have obtained $< \Lambda >$=82.4 and $< \Lambda >$=111.3 in the two versions of their model. Our result in Table 5 is $< \Lambda >$=80.0.

4 Production of hadrons by a slow recombination

In the the previous section we have considered a model in which both the formation of future valence quarks and antiquarks and their recombination to hadrons takes place within tubes of the cross- section equal to the inelastic nucleon- nucleon cross- section σ. What happens in one tube is in this model completely independent of what happens in another tube. In order to have a qualitative feeling of the effects of this assumption we shall discuss in this section a model in which all quarks and antiquarks formed in an A+B interaction at a given value of the impact parameter b can recombine with each other. The calculations proceed as above but the order is reversed. By using Eqs.(8,9) we compute numbers of future valence quarks produced in individual tube- on- tube interactions. In the next step we calculate total numbers of quarks and antiquarks formed in the A+B collision at given value of the impact parameter b according to equations like

$$N_u^T(AB;b) = \frac{1}{\sigma}\int_0^{R_A} sds \int_0^{2\pi} d\theta N_u(AB;b,s,\theta) \tag{14}$$

The obtained total numbers of quarks and antiquarks are then recombined via the Biró - Zimányi scheme as given by Eqs.(11) and (12). The results are presented in Table 6. They are very close to those shown in Table 2. This fact is easyly understood for the case of Y hyperons. Looking in Table 1. we see that with very good approximation $N_u \approx 2N_{\bar{u}} >> N_s$ and $N_u = N_d$. Then parameter β in Eq. (12) is $\beta \propto 1/N_u^2$ and $N_Y \propto N_s$ Now the number of hyperons in rapid recombination we get by calculating number of N_Y in each row and summing over all rows.

$$N_Y^{rapid} = \sum_{rows} N_Y^{row} = const. \sum_{rows} N_s^{row} = const.N_s = N_Y^{slow}$$

. Similar arguments can be done for Ξ and Ω hyperons.

Table 6. Yields of strange baryons and antibaryons in Pb+Pb collisions as a function of the impact parameter b in the model of slow recombination.

b	N_Y	N_Ξ	N_Ω	$N_{\bar{Y}}$	$N_{\bar{\Xi}}$	$N_{\bar{\Omega}}$
0.0	142.3	18.14	0.77	44.34	10.13	0.77
1.0	136.9	17.63	0.76	42.18	9.78	0.76
2.0	126.6	16.37	0.71	38.46	9.02	0.71
3.0	113.8	14.67	0.63	34.19	8.04	0.63
4.0	99.5	12.72	0.54	29.71	6.95	0.54
5.0	84.7	10.67	0.45	25.22	5.82	0.45
6.0	69.9	8.63	0.36	20.83	4.71	0.36
7.0	55.5	6.67	0.27	16.64	3.65	0.27
8.0	42.1	4.88	0.19	12.72	2.69	0.19
9.0	30.00	3.33	0.12	9.19	1.84	0.12
10.0	19.5	2.05	0.07	6.08	1.14	0.07
11.0	11.1	1.08	0.03	3.51	0.60	0.03
12.0	4.97	0.43	0.01	1.59	0.24	0.01

5 Possible presence of anomalous matter and thresholds in strange baryon and antibaryon production

Data on the multiplicity of negative secondary hadrons and on the total transverse energy in Pb+Pb interactions [31] do not indicate a presence of some thresholds connected with the formation of a new "anomalous" form of matter. It rather seems that the multiplicity of secondary hadrons in Pb+Pb and transverse energy can be obtained as the extrapolation of results obtained in collisions of lighter ions.

On the other hand recent data of the WA97 Collaboration indicate that the production of strange baryons within the acceptance region of the experiment is increased [32, 33, 34].

The WA97 experiment takes data only in a small part of the total phase- space. The accepted events cover a region near the central rapidity in the c.m.s. and transverse momenta of baryons above 0.6 GeV/c. In order to disentangle the extrapolated strangeness content one would need to use data from lighter ion collisions in the same experiment to determine the values of parameters β_u, β_s, $< u\bar{u} >_{nn}$ and $< s\bar{s} >_{nn}$ corresponding to the experimental acceptance.

Presence of a threshold in the production of strange baryons together with approximately no increase in the total multiplicity lead to the assumption that the total number of quark- antiquark pairs in tube- on- tube collisions in Pb+Pb interactions is approximately the same as calculated by the formulas given above, but starting with tube- on-tube collisions which satisfy a certain criticality condition the matter is in some sense "melted" and a part of $u\bar{u}$ and $d\bar{d}$ pairs is transformed to $s\bar{s}$ pairs.

In order to permit a comparison with the description of the anomalous J/Ψ suppression in Pb+Pb in models of Blaizot and Ollitrault [10] and of Kharzeev et al. [11] we shall use the criticality condition of Ref.[11].

In their description of J/Ψ suppression Kharzeev et al. [11, 12] assume that QGP is formed only in a limited region of the transverse plane. Taking that view we shall introduce the parameter

$$\kappa(b,s,\theta) = \frac{\sigma_{nn}\rho_A 2L_A(s).\sigma_{nn}\rho_B 2L_B(b,s,\theta)}{\sigma_{nn}\rho_A 2L_A(s) + \sigma_{nn}\rho_B 2L_B(b,s,\theta)} \tag{15}$$

The parameter $\kappa(b,s,\theta)$ is roughly proportional in the "tube- on -tube picture" to the ratio of the number of nucleon- nucleon collisions to the longitudinal dimension of the system formed by the two colliding tubes. It is further assumed that for

$$\kappa(b,s,\theta) \geq \kappa_{crit} \tag{16}$$

QGP is formed, whereas in the opposite case the system remains in the normal state.

In Ref.[11] the authors introduce two values of κ_{crit}. Above κ_{crit} ≈2.3 QGP is formed and the χ meson responsible for about 40% of J/Ψ production is dissolved. For κ_{crit} above 2.9 also J/Ψ is completely dissolved.

In the present work we shall use a single threshold, corresponding to the onset of a "new" or "anomalous" form of matter. According to Refs.[11, 12] we expect this threshold at about κ_{crit}=2.3. We assume that above this threshold the matter goes into a new form characterized by a higher value of the strangeness abundance, that means that above κ_{crit} a part of $u\bar{u}$ and $d\bar{d}$ pairs is transformed to $s\bar{s}$ ones.

To simulate this effect, we go back to the Eqs.(8,9) and for $\kappa \geq \kappa_{crit}$ make the replacement

$$N_{s\bar{s}}^{coll} \rightarrow N_{s\bar{s}}^{coll}[1 + (\xi - 1)\Theta(\kappa - \kappa_{crit})]$$

$$N_{u\bar{u}}^{coll} \to N_{u\bar{u}}^{coll} - 0.5(\xi - 1)N_{s\bar{s}}^{coll}\Theta(\kappa - \kappa_{crit})$$
$$N_{d\bar{d}}^{coll} \to N_{s\bar{s}}^{coll} - 0.5(\xi - 1)N_{s\bar{s}}^{coll}\Theta(\kappa - \kappa_{crit}) \quad (17)$$

and then continue as within the scheme of the rapid recombination model in Sect.3. In this way we obtain for the two cases considered the results presented in Tables 7 and 8. In order to see the effects caused by the presence of the anomalous matter these results should be compared with those given in Table 2.

Table 7. Yields of strange baryons and antibaryons in Pb+Pb collisions as a function of the impact parameter b within the model of rapid recombination. Anomalous matter present: $\xi = 2.0$, κ_c =2.1.

b	N_Y	N_Ξ	N_Ω	$N_{\bar{Y}}$	$N_{\bar{\Xi}}$	$N_{\bar{\Omega}}$
0.0	186.8	52.6	5.59	45.95	24.96	5.59
1.0	179.8	50.7	5.40	43.85	24.08	5.40
2.0	166.6	47.2	5.00	40.17	22.30	5.00
3.0	149.6	42.00	4.41	35.88	19.87	4.41
4.0	130.3	35.9	3.72	31.35	17.04	3.72
5.0	110.1	29.4	2.98	26.77	14.05	2.98
6.0	89.6	22.8	2.24	22.23	11.04	2.24
7.0	69.5	16.5	1.55	17.82	8.12	1.55
8.0	50.7	10.8	0.94	13.6	5.42	0.94
9.0	33.9	5.9	0.44	9.68	3.07	0.44
10.0	19.4	2.07	0.08	6.11	1.16	0.08
11.0	11.0	1.09	0.04	3.54	0.62	0.04
12.0	4.93	0.43	0.01	1.6	0.25	0.01

Table 8. Yields of strange baryons and antibaryons in Pb+Pb collisions as a function of the impact parameter b within the model of rapid recombination. Anomalous matter present: ξ=2.0; κ_c=2.5.

b	N_Y	N_Ξ	N_Ω	$N_{\bar{Y}}$	$N_{\bar{\Xi}}$	$N_{\bar{\Omega}}$
0.0	167.7	40.04	3.99	44.13	19.17	3.99
1.0	161.8	38.89	3.88	42.16	18.59	3.88
2.0	149.4	35.71	3.53	38.59	17.06	3.53
3.0	133.4	31.20	3.03	34.44	14.96	3.03
4.0	115.1	25.77	2.42	30.03	12.46	2.42
5.0	95.91	19.98	1.78	25.55	9.80	1.78
6.0	76.30	14.02	1.11	21.20	7.06	1.11
7.0	57.21	8.33	0.50	16.75	4.41	0.50
8.0	41.8	4.94	0.2	12.74	2.74	0.2
9.0	29.8	3.37	0.13	9.22	1.88	0.13
10.0	19.4	2.07	0.08	6.11	1.16	0.08
11.0	11.0	1.09	0.04	3.54	0.62	0.04
12.0	4.93	0.43	0.01	1.6	0.25	0.01

Proceeding as below the Table 2, we obtain the yields of $< \Lambda > + < \bar{\Lambda} >$, $< \Xi_- >$ $+ < \bar{\Xi}^+ >$ and $< \Omega > + < \bar{\Omega} >$ normalized to 1 at b = 10 that means N_c=104,5 as presented in Figs.2 and 3.

The rapid increase of the yields of $<\Lambda> + <\bar{\Lambda}>$, $<\Xi^-> + <\bar{\Xi}^+>$ and in particular of $<\Omega> + <\bar{\Omega}>$ seen in Figs.2 and 3. in comparison with Fig.1 shows that the presence of anomalous matter increases the yields of strange hyperons significantly. The two parameters κ_c and ξ regulate the position of the onset of the increase as a function of the impact parameter or alternatively as a function on the number of nucleon-nucleon collisions or the number of participating nucleons. These two parameters should be determined by the comparison of model predictions with the data. We shall not attempt to make this comparison here.

Let us remark that a similar calculation was done also for slow recombination scenario. Comparison of the results obtained in both recombination schemes shows greater differences between them for the case of the anomalous enhanced strangeness production. This behaviour is natural since the difference in final hyperon multiplicities between slow and fast recombination depends mainly on the ratio of strange to nonstrange quarks. We shall not discuss this issue in more detail since we consider the rapid recombination scheme as a more realistic model.

6 Summary, comments and conclusions

We have presented here a recombination model of hadron formation in nuclear collisions, which permits to calculate hadron yields as a function of the impact parameter. The model is based on the phenomenological parametrization of the number of quarks and antiquarks just before the hadronization. A few parameters are determined by comparison with data on hadron production in interactions of lighter ions and extrapolated to the case of Pb+Pb collisions. The second ingredient is the Biró - Zimányi recombination scheme.

The model contains several simplifications. In its present form it does not contain fluctuations in the number of produced quarks and antiquarks which may be important in estimating yields of multistrange baryons in pA interactions and in collisions of lighter ions. For this reason we have not normalized the strange baryon yields to pA interactions.

The model does not analyse rapidity and p_T distributions of quarks and antiquarks before the recombination and therefore gives only predictions for the total numbers of final state hadrons. Because of that, when comparing model predictions with the data in a small part of the phase space, one should rather determine the values of input parameters by data on hadron production in the corresponding acceptance region.

The model neglects modifications of the chemical composition of final state hadrons due to interactions in the hadronic stage of the nuclear collisions. The changes in the chemical composition in the hadronic phase are known to be slow, and we do not expect that they will modify substantially the yields of strange baryons.

On the other hand, the model includes a phenomenological description of the influence of the presence of anomalous, strangeness rich, matter. The parametrization of the effects due to the anomalous matter (perhaps QGP) is similar to models used by Blaizot and Ollitrault, and Kharzeev and Satz to describe the anomalous J/Ψ suppression in Pb+Pb interactions. The analysis of data on strange baryon production within this model can thus contribute to the understanding of the anomalous J/Ψ suppression as observed by the NA 50 collaboration.

We have made here no attempt to compare our results with the data of the WA97 collaboration covering the midrapidity region. This would require a specification of what fraction of valence quarks participate in the recombination to strange baryons in this region. We shall return to this question in the near future.

Acknowledgements We are indebted to W.Geist, R.C.Hwa, I.Králik, M.Mojžiš, E.Quercigh, L.Šándor and other members of the WA97 Collaboration for numerous useful discussions. One of the authors (J.P.) would like to thank G.Roche and B.Michel for the hospitality at the Laboratoire de Physique Corpusculaire at the Blaise Pascal University at Clermont- Ferrand, where a part of this work has been done. This work was supported in part by the US- Slovak Science and Technology Joint Fund under grant No. 003-95 and by the Slovak Grant Agency under grants No. V2F13-G and V2F18-G.

Figure Captions

Fig.1.

Yields of $< \Lambda > + < \bar{\Lambda} >$, $< \Xi^- > + < \bar{\Xi}^+ >$ and $< \Omega > + < \bar{\Omega} >$ as a function of the number of nucleon- nucleon collisions N_c in the case when no anomalous matter is present. All yields normalized to 1 at $b = 10$ that means at N_c=104,5.

Fig.2.

Yields of $< \Lambda > + < \bar{\Lambda} >$, $< \Xi^- > + < \bar{\Xi}^+ >$ and $< \Omega > + < \bar{\Omega} >$ as a function of the number of nucleon- nucleon collisions N_c in the case when anomalous matter characterized by parameters $\kappa_c = 2.5, \xi = 2.0$ is present. All yields normalized to 1 at $b = 10$, that means at N_c=104.5.

Fig.3.

Yields of $< \Lambda > + < \bar{\Lambda} >$, $< \Xi^- > + < \bar{\Xi}^+ >$ and $< \Omega > + < \bar{\Omega} >$ as a function of the number of nucleon- nucleon collisions N_c in the case when anomalous matter characterized by parameters $\kappa_c = 2.0, \xi = 2.0$ is present. All yields normalized to 1 at $b = 10$, that means at N_c=104.5.

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