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REPORT

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# MULTI-HEAVY BARYONS IN ULTRARELATIVISTIC HEAVY ION COLLISIONS

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BUDAPEST

Central heavy ion collisions at ultrarelativistic energies ( $\sqrt{s} = 200$ A GeV at RHIC and $\sqrt{s} = 6.4$ A TeV at LHC) will produce large number of charmed quark-antiquark pairs because the colliding energy is far beyond the threshold of the pair production ($m_c = 1.94$ GeV). In simple nucleon-nucleon collisions these charmed quarks (antiquarks) coalesce quickly with light antiquarks (quarks) forming mostly $D$, $\overline{D}$ mesons. Charmed baryons containg only one heavy charmed quark ($\Lambda_c^+$, $\Sigma_c$, $\Xi_c^+$) were also seen[1] . However in heavy ion collisions, as it was pointed out in Ref.2., one may expect the appearence of baryons with two or three heavy quarks (e.g. $\Omega_{ccc}$, $\Xi_{cc}$, $\Omega_{cc}$). In this paper we present an estimation for the expected number of these multi-charmed baryons in the RHIC and LHC colliders. The problem of baryons with $b$ quarks will be treated separately.

A qualitative explanation of the situation can be given as follows. The charm-anticharm quark production is well established in proton-proton collisions. However in p-p collisions the production of three $c - \bar{c}$ pair with near lying momenta has practically vanishing probability. On the other hand, in an ultrarelativistic heavy ion collision many such reactions take place simultaneously, and thus the production of many $c - \bar{c}$ pairs with near lying momenta may have an observable occurrence . Furthermore, if a quark-gluon matter with high "temperature" is formed, then one can expect, that orders of magnitude more charmed quark pairs are created than in the pure hadronic scenario[3]. Similar conclusions can be reached if one assumes that in the collisions a parton cascade develops with high average relative parton momenta. On the basis of this argumentation one can conclude, that the ultrarelativistic heavy ion collisions yield a unique opportunity to produce multi-heavy baryons.

In order to calculate the multi-heavy baryon yield in heavy ion collision we shall use an extended version of combinatoric break-up model[4,5] for the description of hadron formation and for the prediction of the coalescence probability of two or three charm quarks. The combinatoric break-up model needs the quark and gluon content of the very high energy density matter before rehadronization, as an input. For the number of light quarks, $N_q$, strange quarks, $N_s$, charmed quarks, $N_c$, and gluons $N_g$ we shall use the values obtained in the parton cascade calculation of Ref.6.

The combinatoric break up model[4] describes the rehadronisation of the quark-gluon matter assuming that the light and strange quarks and antiquarks are grouped into hadrons conserving quark and antiquark number. The gluons fragment into quark-antiquark pairs[5] with $f_q$ probability to light, and with $f_s$ probability to strange quark pairs, increasing the number of quarks and antiquarks. This leads to further increase in hadron production and indirectly in entropy production. Beyond this simple gluon fragmentation, in the presence of strong QCD field the number of gluons can be modified e.g. by self-interaction, gluon absorption, brehmstrahlung, in-medium effects. As a simple approximation we will consider here a constant $\xi$ to characterise the change in the number of gluons. This constant could be extracted directly from the microscopic parton cascade calculations. The value of $\xi$ effects somewhat the final hadron number and thus it influences the entropy balance during rehadronization, too. We choose a $\xi$ value with which the final hadron number of Ref.6. is reproduced. Accordingly, our rehadronization scheme is summerized as follows. We start with the parton numbers

$$\widetilde{N}_q, \widetilde{N}_{\bar{q}}, \widetilde{N}_s, \widetilde{N}_{\bar{s}}, \widetilde{N}_c, \widetilde{N}_{\bar{c}}, \widetilde{N}_g$$

obtained from the parton cascade model.The input quark and antiquark numbers for the combinatoric break-up model are then given as follows:

$$N_i = \widetilde{N}_i + f_i \xi \widetilde{N}_g \qquad (1)$$

where $i = q, \bar{q}, s, \bar{s}, c, \bar{c}$ and $f_q = 0.85$, $f_s = 0.15$, $f_c = 0$. Here we neglect extra charm production via gluon fragmentation.

According to the combinatoric break-up model the number of a given hadron species formed from the quark matter, will be proportional to the product of the numbers of the quarks or antiquarks from which the given hadron consists. The proportionality factor depends on the number of quarks to coalesce and in the original model[4] it was denoted by $\alpha$ for mesons, while the corresponding factor for baryons (or antibaryons) was denoted by $\beta$. The conservation of the given quark and antiquark numbers in the rehadronisation leads to equations from which the $\alpha$ and $\beta$ parameters can be determined[4].

Because of the presence of the charmed quarks, the above recapitulated combinatoric break up model will be extended as follows. For the mesons and baryons containing charmed quarks or antiquarks the formation proportionality factor will be different from the $\alpha$ and $\beta$ values described above because of the heavy mass of $c, \bar{c}$. They will be denoted by $\gamma$ and $\eta$ . Further, let us observe, that the Fermi levels for the light quarks are populated very much higher up then those for the charmed quarks. As a consequence there will be a momentum mismatch between the light and heavy quarks, and thus only a fraction of the light and strange quarks will be effectively available for the coalescecnce with heavy quarks. To simulate this effect, we shall introduce a penalty factor, $p$, for forming a hadron containing one light (or strange) quark besides two charmed quarks and the square of this factor for hadrons containing two light (or strange) quarks besides one heavy charmed quark.

Here we suggest a simple qualitative argument for the estimation of the penalty factor $p$, leaving a more detailed calculation for later discussions. If we invoke the picture of coalescence model, then eqs. (2.1) and (2.14) of Ref.7. suggest, that only quarks with near lying momenta can fuse to form a hadron. In the present case the density of light quarks is much larger than the density of the charmed quarks. Thus the Fermi levels occupied by the light quarks correspond to much higher momenta, than those for the charmed quarks. Accordingly, the ratio of the number of light and strange quarks which are able to form a hadron with charmed quark to the number of those which are not able to form such a hadron because of momentum mismatch, may be guessed as the ratio of the number of charmed quarks to the number light and strange quarks . Thus, $p_R$ is then expressed as

$$p_R = \frac{\langle N_c \rangle}{\langle N_q + N_s \rangle}. \tag{2}$$

In this paper we shall use the approximation $p = p_R$ for the penalty factor, $p$.

As we shall see later at RHIC and LHC energies one obtains approximately $p_R \approx 0.01$.

According to the above argumentations the number of the different hadron species is given by the set of expressions given below.

Mesons:

$$N_\pi = \alpha N_q N_{\bar{q}} \qquad N_\Phi = \alpha N_s N_{\bar{s}} \tag{3.a}$$
$$N_K = \alpha N_q N_{\bar{s}} \qquad N_{\bar{K}} = \alpha N_{\bar{q}} N_s \tag{3.b}$$
$$N_{J/\psi} = \gamma N_c N_{\bar{c}} \tag{3.c}$$
$$N_D = p \cdot \gamma N_c N_{\bar{q}} \qquad N_{\bar{D}} = p \cdot \gamma N_{\bar{c}} N_q \tag{3.d}$$
$$N_{D_s} = p \cdot \gamma N_c N_{\bar{s}} \qquad N_{\bar{D}_s} = p \cdot \gamma N_{\bar{c}} N_s \tag{3.e}$$

Baryons:

$$N_B = \beta N_q N_q N_q / 3! \qquad N_Y = \beta N_s N_q N_q / 2! \tag{4.a}$$
$$N_\Xi = \beta N_s N_s N_q / 2! \qquad N_\Omega = \beta N_s N_s N_s / 3! \tag{4.b}$$
$$N_{Y_c} = p^2 \cdot \eta N_q N_q N_c / 2! \qquad N_{\Xi_c} = p^2 \cdot \eta N_q N_s N_c \tag{4.c}$$
$$N_{\Omega_c} = p^2 \cdot \eta N_s N_s N_c / 2! \qquad N_{\Xi_{cc}} = p \cdot \eta N_q N_c N_c / 2! \tag{4.d}$$
$$N_{\Omega_{cc}} = p \cdot \eta N_s N_c N_c / 2! \qquad N_{\Omega_{ccc}} = \eta N_c N_c N_c \tag{4.e}$$

A corresponding set of expressions is valid for the antibaryons. The number of a given type of quark is assumed to be the same in the hadron side as it was on the quark matter side (this is the basic assumption of the combinatoric rehadronisation model). Therefore the following equations have to be fulfilled:

$$N_q = N_\pi + N_K + N_{\overline{D}} + 3N_B + 2N_Y + 2N_{Y_c} + N_\Xi + N_{\Xi_c} + N_{\Xi_{cc}} \tag{5.a}$$
$$N_s = N_\phi + N_{\overline{K}} + N_{\overline{D}_s} + 3N_\Omega + 2N_\Xi + 2N_{\Omega_c} + N_Y + N_{\Xi_c} + N_{\Omega_{cc}} \tag{5.b}$$
$$N_c = N_{J/\psi} + N_D + N_{D_s} + 3N_{\Omega_{ccc}} + 2N_{\Xi_{cc}} + 2N_{\Omega_{cc}} + N_{Y_c} + N_{\Xi_c} + N_{\Omega_c} \tag{5.c}$$
$$N_{\bar{c}} = N_{J/\psi} + N_{\overline{D}} + N_{\overline{D}_s} + 3N_{\overline{\Omega}_{ccc}} + 2N_{\overline{\Xi}_{cc}} + 2N_{\overline{\Omega}_{cc}} + N_{\overline{Y}_c} + N_{\overline{\Xi}_c} + N_{\overline{\Omega}_c} \tag{5.d}$$
$$N_{\bar{s}} = N_\phi + N_K + N_{D_s} + 3N_{\overline{\Omega}} + 2N_{\overline{\Xi}} + 2N_{\overline{\Omega}_c} + N_{\overline{Y}} + N_{\overline{\Xi}_c} + N_{\overline{\Omega}_{cc}} \tag{5.e}$$
$$N_{\bar{q}} = N_\pi + N_{\overline{K}} + N_D + 3N_{\overline{B}} + 2N_{\overline{Y}} + 2N_{\overline{Y}_c} + N_{\overline{\Xi}} + N_{\overline{\Xi}_c} + N_{\overline{\Xi}_{cc}} \tag{5.f}$$

Inserting into eqs. (5.a-f) the expressions (3.a-e) and (4.a-e), only four independent equations remain for the four coalescence factors $\alpha, \beta, \gamma, \eta$. The penalty factor $p$ remains a free input parameter. Thus one obtains the following solutions for these factors:

$$\gamma = \frac{2N_c + p(N_l + N_{\bar{l}})}{3N_c^2 + 3pN_c(N_l + N_{\bar{l}}) + p^2(N_l^2 + N_lN_{\bar{l}} + N_{\bar{l}}^2)} \tag{6}$$
$$\eta = \frac{2}{3N_c^2 + 3pN_c(N_l + N_{\bar{l}}) + p^2(N_l^2 + N_lN_{\bar{l}} + N_{\bar{l}}^2)} \tag{7}$$

and

$$\alpha = \frac{N_l + N_{\bar{l}}}{N_l^2 + N_lN_{\bar{l}} + N_{\bar{l}}^2}\left(1 - \left[p^2\eta N_c(N_l + N_{\bar{l}}) + p\gamma N_c + p\frac{\eta}{2}N_c^2\right]\right) \tag{8}$$
$$\beta = \frac{2}{N_l^2 + N_lN_{\bar{l}} + N_{\bar{l}}^2}\left(1 - \left[p^2\eta N_c(N_l + N_{\bar{l}}) + p\gamma N_c + p\frac{\eta}{2}N_c^2\right]\right) + p^2\eta N_c \tag{9}$$

Here we used the notation

$$N_l = N_q + N_s$$

and

$$N_{\bar{l}} = N_{\bar{q}} + N_{\bar{s}}.$$

In the final expressions (6)-(9) a charm symmetric case was considered and $N_{\bar{c}} = N_c$ was used.

Using these values for $\alpha, \beta, \gamma$ and $\eta$ one obtains the number of different hadrons produced in the process of the rehadronisation. We note here, that the above described model has the following reasonable property: if all quark numbers are multiplied by a constant then all hadron numbers will also increase to this constant times their original value. Thus, if the rapidity distribution is uniform, then the number of heavy hadrons in a unit rapidity interval can be obtained from the values shown in Figs.1. and 2. by dividing with the corresponding total rapidity length of the produced particle distribution (i.e. about 16 for LHC and 10 for RHIC data).

| | $\mathcal{RHIC}$ | $\mathcal{RHIC}$ | $\mathcal{LHC}$ | $\mathcal{LHC}$ |
|---|---|---|---|---|
| FINAL PARTONS | Parton cascade[5] | Combinatoric model | Parton cascade[5] | Combinatoric model |
| $\langle N_g\rangle$ | 14813 | — | 38335 | — |
| $\langle N_q + N_{\bar{q}}\rangle$ | 3282 | 21413 | 8604 | 66932 |
| $\langle N_s + N_{\bar{s}}\rangle$ | 1006 | 4207 | 2454 | 12747 |
| $\langle N_c + N_{\bar{c}}\rangle$ | 222 | 222 | 652 | 652 |
| FINAL HADRONS $\langle N_{hadrons}\rangle$ | 11482 | 11485 ($\xi = 0.720$) ($p_R = 0.00866$) | 35700 | 35702 ($\xi = 0.895$) ($p_R = 0.00818$) |

**Table I:** Number of partons calculated in the parton cascade model[5] and the modified parton numbers obtained with the gluon decay at RHIC and LHC energies for $Au + Au$ collisions. The latter numbers are used in the combinatoric break up model. The gluon fragmentation parameter, $\xi$ and the penalty factor corresponding to eq.2. are also displayed.

To carry out a calculation for multi-heavy baryon production one needs the different quark numbers appearing in the above expressions. For this purpose we shall borrow the parton number values from a recently published parton cascade model[6]. We recapitulate these numbers in Table I. at RHIC and LHC energies for $Au + Au$ collisions. We modify the quark numbers with the contribution from the gluon fragmentation. The thus obtained quark numbers are then used as input for the combinatoric break up model. These numbers are also displayed in Table I.

Using these numbers, we obtain from the combinatoric break up model the number of different hadrons produced in the heavy ion collisions. The number of multi-heavy baryons and other charmed hadrons are displayed in Fig.1. and Fig.2. at the RHIC and at the LHC energy, respectively, as a function of the penalty factor, $p$. Since the number of hadrons containing only light and strange quarks are order of magnitude larger then hadrons containing charm, their number will not be sensitive to the penalty factor, $p$. Their number is displayed in Table II.

| | $N_N$ | $N_Y$ | $N_\Xi$ | $N_\Omega$ | $N_\pi$ | $N_K$ | $N_{\bar{K}}$ | $N_\phi$ |
|---|---|---|---|---|---|---|---|---|
| $\mathcal{RHIC}$ | 817 | 481 | 94.6 | 6.2 | 5915 | 1162 | 1162 | 228 |
| $\mathcal{LHC}$ | 2582 | 1474 | 280 | 17.8 | 18500 | 3540 | 3540 | 674 |

**Table II:** Number of hadrons not containing charm quarks obtained in the present combinatoric break up model ($N_{\bar{B}} \approx N_B$). The detected particle ratios may deviate from these values due to possible final state hadrochemical process.

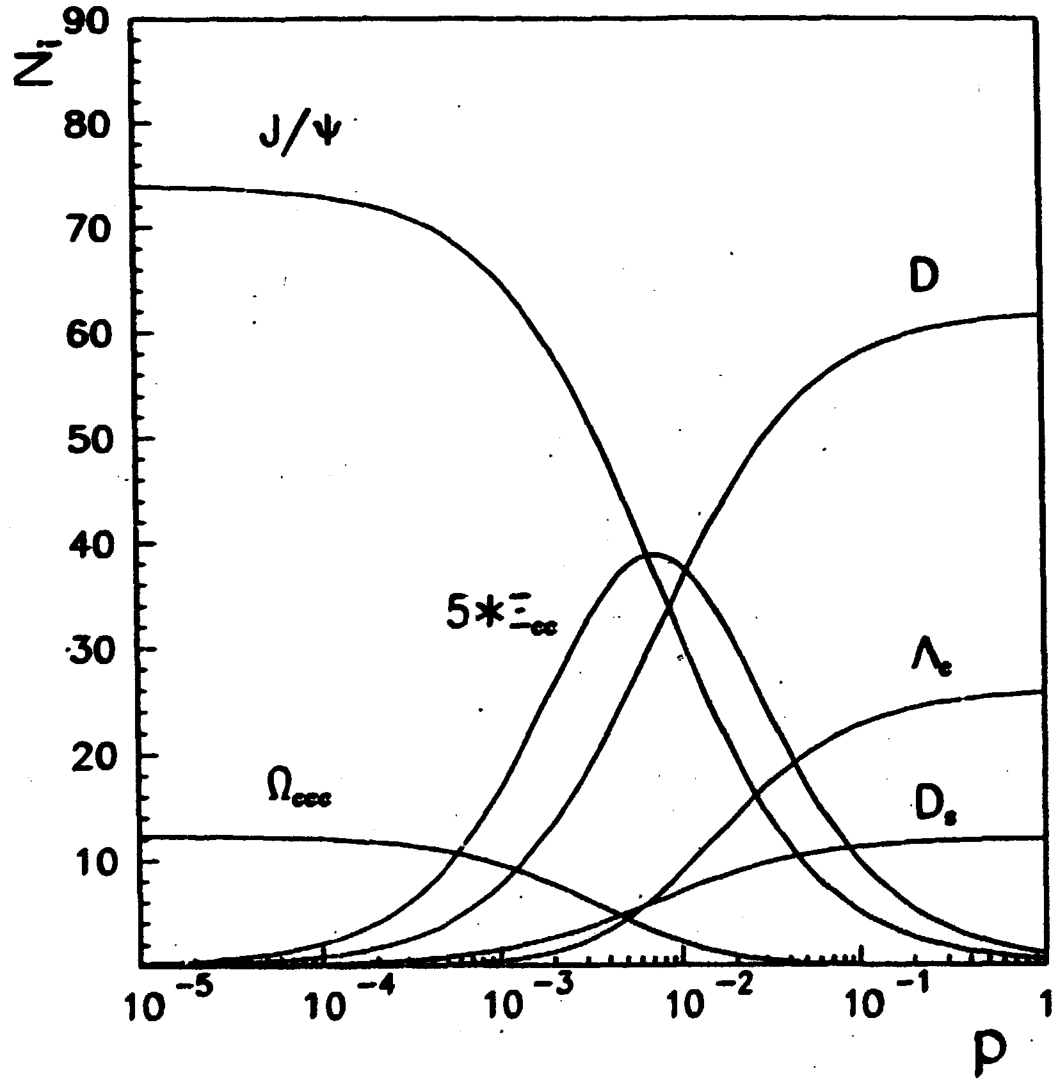


**Fig. 1:** Number of hadrons containing charmed quarks ($\Omega_{ccc}$, $\Xi_{cc}$, $\Lambda_c$, $J/\psi$, $D$, $D_s$) as a function of penalty parameter, $p$, obtained in the present combinatoric break up model for $Au+Au$ collision at RHIC energy.

Fig.1. shows that if the penalty factor is very small, then the charm and anticharm quarks mix among each other only. As the penalty factor is less prohibiting for making groups with light and heavy quarks, ( *i.e.* $p$ is increased toward 1), than the light and strange quarks begin to have a chance to stick to the heavy quarks: first the number of $\Xi_{cc}$ increases, and after that the number of $\Lambda_c$ and that of $D$ mesons. Finally, as the penalty factor reaches the value 1 (no prohibition), then practically all $c$ and $\bar{c}$ is attached to light and strange quarks, since they are in overwhelming majority. Thus in this case the expected number of multi-heavy baryons vanishes.

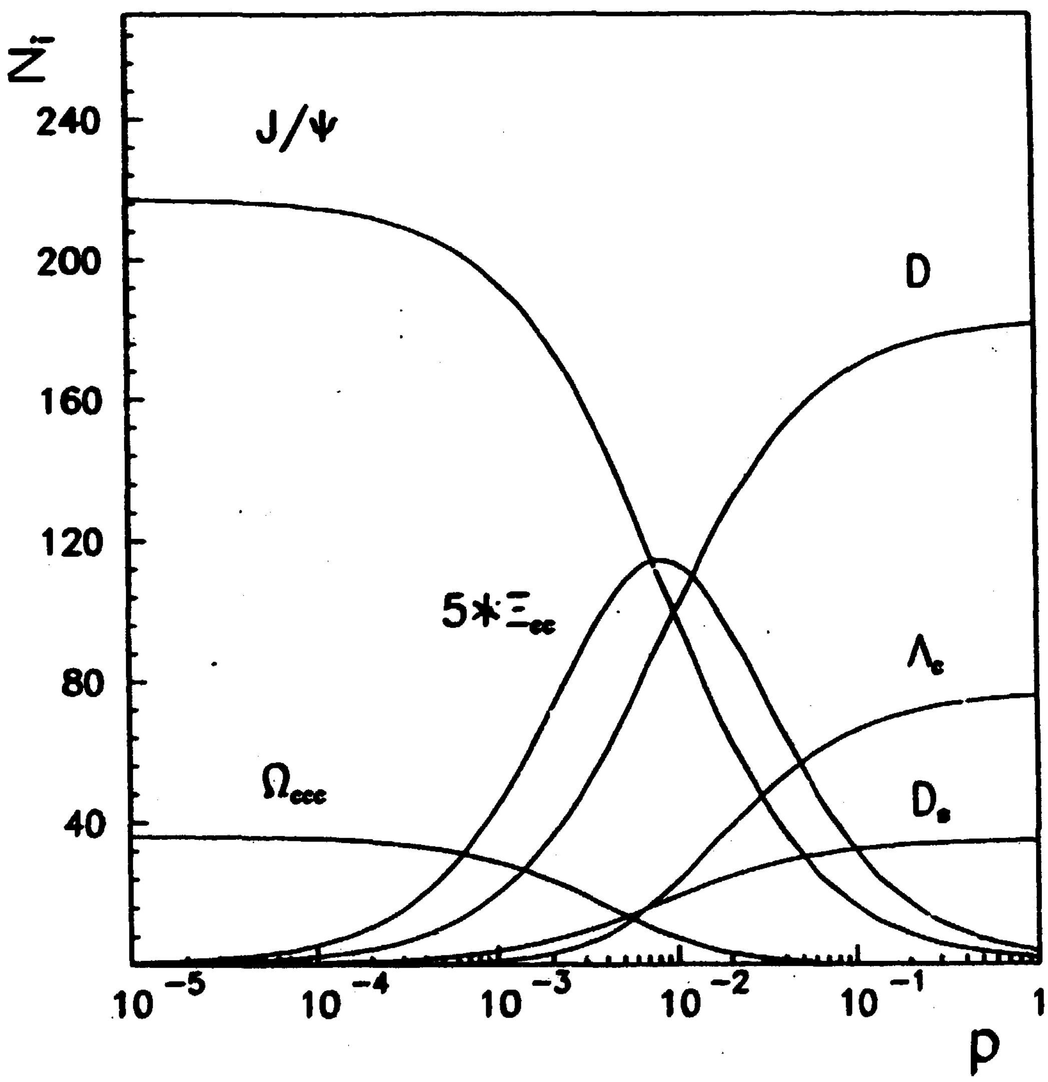


**Fig. 2:** Number of hadrons containing charmed quarks ($\Omega_{ccc}$, $\Xi_{cc}$, $\Lambda_c$, $J/\psi$, $D$, $D_s$) as a function of penalty parameter, $p$, obtained in the present combinatoric break up model for $Au+Au$ collision at LHC energy.

In Fig.2. one can see the same tendencies as in Fig.1. The number of multi-heavy baryons is approximately 3 times more as that at RHIC energy, which corresponds to the increase in the number of produced charm quarks.

Additionally, we point out a mechanism, which may have an effect on the number of multi-heavy hadrons. Namely, the heavy quarks will move much slower in the expansion period than the light and strange quarks. Therefore there is a possibility, that the light quarks will run away leaving behind a piece of matter enriched strongly in heavy quarks and antiquarks. Due to the large difference in their masses, the dragging of the heavy quarks by the light ones is very ineffective. This effect also tends to increase the number of multi-heavy baryons with respect to the single heavy ones.

Finally we summarise the argumentations given in this paper as follows. i) The ultrarelativistic heavy ion collisions provide unique possibility for producing multi-heavy baryons. ii) If in the heavy ion collision quark matter is formed containing as many charmed quarks as predicted in Ref.6. then our extended combinatoric break up model predicts a remarkable large number of multi-heavy baryons . iii) In the expansion phase of the reaction a piece of matter may be formed, which is enriched in heavy quarks and antiquarks.

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