Exotic hadrons from dynamical clustering of quarks in ultrarelativistic heavy ion collisions

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Abstract. Results from a model study on the formation of exotic quark clusters at the hadronization stage of a heavy ion collision are presented. The dynamical quark molecular dynamics (qMD) model which is used is sketched, and results for exotica made of up to six (anti-)quarks are shown. The second part focuses on pentaquarks. The rapidity distribution are shown, and the distribution of strangeness is found to yield an indicator of thermalization and homogenisation of the deconfined quark system. Relative Θ⁺ yields are found to be lower than thermal model estimates.

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In the quark model of QCD, quarks are associated with fundamental representations of the colour-gauge group SU(3). The low energy regime of QCD contains only colour singlets such as mesons and baryons, which are made up from a quark and anti-quark with colour and anti-colour, or three quarks with three different colours, respectively. However, colour neutrality can be fulfilled whenever the net number of quarks is a multiple of three, thus opening the possibility of so called exotic hadrons such as the tetraquark (or dimeson), the pentaquark, and so on. New interest in the study of exotic hadrons has been created by recent reports about the discovery of pentaquark states Θ⁺ and Ξ⁻⁻ in pA, nA, and γA collisions ([1] – see [2] for discussions of the theoretical understanding).

Here, we will discuss the formation of clusters of up to six quarks or anti-quarks in the hadronization stage of a heavy ion collision, with a focus on pentaquarks. In such an event, two nuclei collide, creating hot and dense matter, which can set free colour charges if the energy density is high enough. During the expansion of the hot system, colour charges will recombine to form colour neutral hadrons which finally can be detected. The study is motivated by the idea that the hadronization from a hot quark soup is an environment favourable to the formation of exotica [3].

In order to describe the dynamics of the collision, the hadronic model UrQMD is used to create an initial state of hot and dense matter. The particle content after complete overlap of the nuclei is converted to quarks, and the quark molecular dynamics model qMD is used to describe the subsequent dynamics and recombination.
Exotic hadrons from dynamical clustering of quarks

In the qMD model, quarks are described as classical particles with current masses subject to the Hamiltonian

$$\mathcal{H} = \sum_{i=1}^{N} \sqrt{p_i^2 + m_i^2} - \frac{1}{2} \sum_{i,j} C_{c_{ij}}^c \left( \frac{3}{4} \frac{\alpha_s}{|\mathbf{r}_i - \mathbf{r}_j|} + \kappa |\mathbf{r}_i - \mathbf{r}_j| \right).$$

All quarks carry spin and isospin which is used in the subsequent mapping to hadrons, and colour charges $\mathbf{w}_i$ represented by three vectors in the root diagram, with anti-quarks carrying the corresponding anti-colours. No colour exchange between quarks is assumed, leaving the colour of a particle unchanged throughout the complete time evolution of the system. The sign of the potential interaction between two particles depends on the scalar product of the root vectors,

$$C_{c_{ij}}^c = \mathbf{w}_i^T \mathbf{w}_j,$$

yielding repulsion for equal charges and attraction between charge and anti-charge. The shape of the potential interaction is motivated by the Cornell potential, where in all calculations the Coulomb term is omitted, and the string constant $\kappa$ is treated as a parameter of the model. The time evolution yields an expanding system where quarks form colour neutral clusters. Once a cluster is separated in space from the remaining quarks and its interaction with the system falls below a threshold, it is mapped to a hadron, taking into account the quantum numbers and energy-momentum four-vectors of the quarks in the cluster.

We investigate the formation of colour neutral clusters with quark configurations of mesons ($q\bar{q}$), baryons ($qqq$), dimesons ($qq\bar{q}$), pentaquarks ($qqqq\bar{q}$), dibaryons ($qqqq\bar{q}\bar{q}$), baryonia ($qqqq\bar{q}\bar{q}\bar{q}$), and the corresponding anti-particles. We cannot make any statement about the actual existence and physical properties of exotic hadrons from our extremely simplistic classical model, but we assume that any physical exotic hadron formed by quark coalescence at hadronization should emerge from a colour neutral cluster as described in the qMD model. The dynamical evolution of systems...
Exotic hadrons from dynamical clustering of quarks

Figure 2. Distribution over strangeness of pentaquark cluster yield (a), and normalised to the combinatorial expectation value (b). Yields of $\Theta^+$ ($S = +1$ with a $\bar{s}$ quark) and $\Xi^{-}$ ($S = -2$ with a $\bar{q}$ quark) are only half of the combinatorial value at lower SPS energies.

at upper SPS energies then yields the rapidity distribution of clusters as shown on the left part of figure 1.

Focusing on pentaquark clusters, the right part of figure 1 shows the rapidity distribution normalised to the distribution of baryons, which is relevant for the chances of identifying pentaquarks in the debris of a heavy ion collision. At least for SPS energies, this ratio is nearly twice as large at $\Delta y = \pm 1$ off midrapidity as at $y = 0$. For RHIC energies, a cylindrical quark gas, thermalised at a temperature of 250 MeV, was assumed as initial condition, so that the full dynamics of the expanding fireball is missing. The apparently high relative yield of pentaquarks is strongly reduced, of course, by the large size of the flavour multiplet,

$$3 \otimes 3 \otimes 3 \otimes 3 \otimes 3 = 3 \otimes 1 \oplus 8 \otimes 8 \oplus 4 \otimes 10 \oplus 2 \otimes 10 \oplus 3 \otimes 27 \oplus 35,$$

where, assuming SU(3) coupling, only 1 out of 243 states corresponds to the $\Theta^+$, while the clustering procedure populates the whole multiplet structure. The left part of figure 2 shows the relative distribution of pentaquark clusters over strangeness. The grey band corresponds to the fully SU(3) symmetric case. For SPS energies, there are large deviations, corresponding to the strangeness suppression. But even when normalising the relative distribution to the actual strangeness content of the quark system (right part of figure 2), deviations remain for SPS energies. In our model, this is due to the correlations carried over into the quark system from the original hadrons. However, we conclude that the relative strangeness of pentaquarks can give a measure for thermalization and homogenisation of the deconfined quark system.

Finally, we compare the relative yield of $\Theta^+ / \Lambda$ as a function of bombarding energy from our quark clustering dynamics to the results obtained from grand canonical estimates [6] and thermal models including strangeness suppression factors [7] (Figure 3). We find relative yields roughly one order of magnitude below the earlier estimates. The large downward range is due to the use of different coupling schemes, SU(2) for fixed strangeness, SU(3), and SU(6) for spin and flavour. It should be noted
that the qMD result does not include hadronic rescattering, which will both destroy \( \Theta^+ \)s formed from quark clustering and create new ones from hadronic coalescence ([3] – there are, however, much unknowns about the formation of pentaquarks, see e.

g. [8]), nor the possible population of \( \Theta^+ \) from decaying \( N^* \) pentaquarks (see e.

g. [9]). These factors shift the \( \Theta^+ / \Lambda \) and require further study.

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