Statistical production of pentaquarks in high-energy nuclear collisions

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Abstract. The production yield of exotic pentaquarks in high-energy nuclear collisions is estimated on the basis of the standard statistical description of the hadronic freeze-out.

1. Introduction
An increasing number of investigators are reporting evidence for the production of pentaquarks (for recent reviews of the experimental status, see Refs. [1, 2]). The term pentaquark refers to a novel type of baryon whose simplest Fock components contain four quarks and one antiquark, thus making their combinations of baryon number, electric charge, and strangeness fall outside the familiar baryon classification scheme and hence rendering them exotic.

Because of their unique combination of attributes, the pentaquarks would be particularly useful as diagnostic tools in the exploration of the hadronization dynamics in high-energy nuclear collisions. It is therefore of interest to search for them in the data and, for such an undertaking, it would be useful to have a rough idea of their production rate.

Consequently, we present theoretical estimates of pentaquark production in high-energy nuclear collisions. For this purpose, we adopt a statistical framework which has proven to account rather well for the hadronic production yields (for a review, see Ref. [3]). On this basis, we seek to estimate the production rates of various pentaquarks of current interest.

2. Statistical model
The statistical model treats an ideal gas of hadronic species \{i\} within a volume \(V\). The partition function then factorizes, \(Z = \Pi_i Z_i\), where a hadron of specie \(i\) has mass \(m_i\), spin degeneracy \(g_i\), baryon number \(B_i\), charge \(Q_i\), and strangeness \(S_i\). Furthermore, the environment is characterized by the freeze-out temperature \(T\) and the three chemical potentials \(\{\mu_B, \mu_Q, \mu_S\}\) which enter through the corresponding fugacity, \(\lambda_i = \exp(- (B_i\mu_B + Q_i\mu_Q + S_i\mu_S)/T)\). The values used are illustrated in Fig. 1. The partition function for the specie \(i\) is then given by

\[
\ln Z_i(T, V, \{\mu\}) = \pm g_i \frac{V T^3}{2 \pi^2} \sum_{n=1}^{\infty} \left( \frac{\pm \lambda_i}{n} \right)^n \left( \frac{n m_i}{T} \right)^2 K_2 \left( \frac{n m_i}{T} \right),
\]

where we have exhibited the regular combination \(x^2 K(x) \to 2\) for \(x \to 0\). The upper sign holds for bosons (i.e. mesons), while the lower sign holds for fermions (i.e. baryons) and thus yields
an alternating series; the classical result is obtained by retaining only the first term, $n = 1$. The corresponding spatial density of a given specie, $n_i = N_i/V$, then readily follows,

$$n_i(T, \{\mu\}) = \pm g_i \frac{T^3}{2\pi^2} \sum_{n=1}^{\infty} \left( \pm \lambda_i \right)^n \left( \frac{nm_i}{T} \right)^2 K_2 \left( \frac{nm_i}{T} \right) \approx g_i \left( \frac{m_i T}{2\pi} \right)^{3/2} \lambda_i e^{-m_i/T},$$

where the last expression emerges in the large-mass limit, $m_i \gg T$. Figure 2 shows that quantum statistics is important only for pions, while the large-mass limit tends to be inadequate.

Figure 2. The average number of hadrons in a volume of $V=100 \text{ fm}^3$ as a function of the hadron mass $m$ at a temperature of $T=170 \text{ MeV}$ and vanishing chemical potentials. The quantum-statistical values are generally close to the classical result, except for pions, while the large-mass approximation is not quantitatively useful, being still about 20% too low for $\Theta^+$.  

3. Results

Most pentaquark research has focussed on the $\Theta^+(1530)$ for which quantitative predictions were made by Diakonov et al. [4]. Contrary to the familiar hyperons which have negative strangeness, $\Theta^+$ has positive strangeness, $S=+1$, as well as positive electric charge, $Q=+1$. It follows that its leading Fock component is $|\bar{u}ud\bar{s}\rangle$. Production of $\Theta^+$ in high-energy nuclear collisions was first discussed in Ref. [5] where statistical estimates suggested that there might be about one $\Theta^+$ per unit rapidity at central rapidity in a head-on Au+Au collision at the top RHIC energy (though only certain decay branches would be readily identifiable in the data analysis). More
refined studies based on microscopic transport treatment were subsequently made by Liu and Ko [6] and the statistical studies were broadened by Letessier et al. [7].

Figure 3 shows the statistical yields of $\Theta^+$ relative to that of the proton, as well as the ratio between the $K^+$ and $\pi^+$ yields. The behavior of these ratios is easy to understand: as $\mu_B$ is increased the value of $\mu_S$ also goes up, see Fig. 1, thus introducing a favorable bias for positive strangeness, a trend that continues until the ultimate decrease of the temperature disfavors the larger masses. Since no special strangeness suppression has been included, the $K^+ : \pi^+$ ratio exceeds the data. Therefore, in order to reduce the sensitivity of the results to the somewhat uncertain chemical conditions, we prefer to use double yield ratios for which the various attributes counterbalance. The result is then approximately independent of the fugacities and behave as $\sim \exp(-\Delta m/T)$, where $\Delta m$ is the mismatch in masses. For the double ratio $\Theta^+ : p$ to $K^+ : \pi^+$ we have $\Delta m = 250$ MeV which thus dominates the dependence on $\mu_B$, as borne out in Fig. 4. Indeed, the double ratio is approximately constant, until the value of $\mu_B$ has become so large that the temperature has dropped significantly (see Fig. 1).

The NA49 Collaboration recently reported the observation of a somewhat heavier exotic baryon, $\Sigma^{--}(1862)$, in proton-proton collisions at the CERN SPS [8]. It has both charge and strangeness equal to minus two which thus implies a minimal composition given by $|ddss\bar{u}\rangle$.

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Figure 4 includes the statistical result for the double ratio $\Sigma^{--} : \Lambda$ to $K^- : \pi^+$ for which $\Delta m = 392$ MeV. While exhibiting a behavior that is qualitatively similar to the double ratio for $\Theta^+$, the larger value of $\Delta m$ causes a reduction in the result by a factor of about two.
The H1 Collaboration at HERA has reported evidence for an anti-charmed pentaquark, $\Theta_c(3099)$ with $C=-1$, $B=+1$ and $Q=S=0$, implying a minimal composition of $|uudd\bar{c}\rangle$ [9]. Therefore, the $\Theta_c$ abundance in a baryon-free environment is determined primarily by its mass and should thus be similar to that of the $J/\psi$, which is readily observable at both SPS and RHIC. Furthermore, in environments with $\mu_B > 0$ the $\Theta_c$ should be more abundant than the $J/\psi$, as shown in Fig. 5. The $\Theta_c$ yield may also be compared with that of the $\bar{D}^0$ which has the same charge, strangeness, and charm, as done in Fig. 6. At $\mu_B = 0$ its relative abundance is $\approx 0.3\%$, in accordance with the large-mass formula, and the ratio increases with $\mu_B$.

4. Concluding remarks

Pentaquarks are of particular interest for high-energy heavy-ion physics, because they carry exotic combinations of attributes and may therefore be utilized as probes to provide novel information about the hadronization dynamics. Elementary statistical estimates of their production yield suggest that these hadrons should be detectable in currently studied high-energy nuclear collisions. Furthermore, high-energy nuclear collisions may provide additional or novel evidence regarding pentaquarks. Thus, the observation of pentaquarks that have already been reported would add independent evidence for their existence. More importantly, nuclear collisions may permit the production of pentaquark species, such as the $\bar{\Theta}$, that cannot be reached by the available elementary reactions, thus contributing novel data.

A pentaquark search that would establish an upper limit significantly below the statistical expectation would also be valuable: Either the pentaquark production is significantly suppressed in nuclear collisions which would constrain the dynamical mechanisms. Or their absence would constitute independent evidence against their existence, which would clearly be important. In conclusion, whatever the case may turn out to be, it seems worthwhile to undertake pentaquark searches in high-energy nuclear collisions.

References

[1] Hicks K 2004, hep-ex/0412048; Hicks K 2005, hep-ex/0501018
[2] Carman D S 2005, Eur. Phys. J. A 24 S1
[3] Braun-Munzinger P, Redlich K, Stachel J 2003, Quark Gluon Plasma 3 (World Scientific); nucl-th/0304013
[4] Diakonov D, Petrov V, Polyakov M 1997, Z. Phys. A 359 305
[5] Randrup J 2003, Phys. Rev. C 68 31903
[6] Liu W and Ko C M 2003, Phys. Rev. C 68 45203
[7] Letessier J et al. 2003, Phys. Rev. C 68 61901
[8] Alt C et al. (NA49 Collaboration) 2004, Phys. Rev. Lett. 92 42003
[9] Aktas A et al. (H1 Collaboration) 2004, Phys. Lett. B 588 17