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Production of pentaquark states in pp collisions within the microcanonical ensemble

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Abstract

The microcanonical statistical approach is applied to study the production of pentaquark states in pp collisions. We predict the average multiplicity and the average transverse momentum of $\Theta^+(1540)$ and $\Xi(1860)$ and their antiparticles at different energies.

Recently, an exotic baryon, $\Theta^+(1540)$, with the quantum numbers of K^+n has been reported in several experiments [1–5]. The $\Theta^+(1540)$ cannot be a three quark state. Its minimal quark content is $(uudd\bar{s})$, a so-called pentaquark state.

Pentaquark states have been theoretically investigated since a long time in the context of the constituent quark model [6,7]. Also other models have been employed to construct $q^4\bar{q}$ pentaquark states, predicting different masses and quantum numbers. For example, the chiral soliton (Skyrme) model [8] predicts that the lightest member of the SU(3)-flavor $(\overline{10}_f, \frac{1}{2}^+)$-let has $m_\Theta = 1540$ MeV. The reported $\Theta^+(1540)$ agrees with the prediction remarkably well. The other members of the $(\overline{10}_f, \frac{1}{2}^+)$ antidecuplet are isospin-multiplets of N, Σ and Ξ. In an uncorrelated quark model [7], where all quarks are in the ground state of a mean field, the ground state of $q^4\bar{q}$ has negative parity. This is a striking difference to the chiral soliton model. In Jaffe and Wilczek's model [9], $\Theta^+(1540)$ is considered to be a bound state of an antiquark with two highly correlated spin-zero ud diquarks. Hence the lightest $q^4\bar{q}$ state cannot be $\Theta^+(1540)$ but belongs to the N isospin-multiplets with minimal quark

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content, i.e., $uudd\bar{u}$. Other models regard $\Theta^+(1540)$ as a member of the SU(3) flavor (27_f)-let. Missing members of the multiplet are assigned to reported particles [10].

The common members of above mentioned models are $\Theta^+(1540)$ and the multiplets of Ξ, which can be $\Xi^{--}(ddss\bar{u})$, $\Xi^-(dssq\bar{q})$, $\Xi^0(ussq\bar{q})$ or $\Xi^+(uuss\bar{d})$, where $q\bar{q}$ is a hidden quark–antiquark pair $u\bar{u}$ or $d\bar{d}$. Recently the NA49 Collaboration [11] also presented the results of a search of $\Xi^{--}(1860)$ and $\Xi^0(1860)$.

The estimation of $\Theta^+(1540)$ and $\Xi(1860)$ yields at different collision energies independent of the above-mentioned models will be helpful for the search of pentaquark states in proton–proton collisions in the ongoing experiments at SPS and RHIC. Some work has been done using the statistical hadronization approach within grandcanonical and canonical ensembles. However, the system is small in proton–proton collisions, and a microcanonical ensemble should be employed.

The dynamical model NEXUS has also been used to estimate the yields of $\Theta^+(1540)$ and $\Xi(1860)$, via employing the microcanonical ensemble to hadronize the remnants (formed by spectator quarks from the collisions) [12].

In this Letter, we use an entirely microcanonical approach to study the production of pentaquark states in pp collisions. The microcanonical parameters are well studied already in previous work via fitting the 4π yields of charged pions, proton and antiproton. We organize the Letter as followed: first we explain the model, how pentaquark states are produced in pp collisions, then we check how reliable the microcanonical parameters are, then we present our results, the yields and average transverse momentum of $\Theta^+(1540)$ and $\Xi(1860)$ and their antiparticles, and finally we compare our results to some other theoretical work and discuss our predictions on SPS and RHIC experiments.

We use the microcanonical ensemble to study the production of pentaquark states in pp collisions. In the microcanonical ensemble, we consider the final state of a proton–proton collision as a "cluster" characterized by its volume V (the sum of individual proper volumes), its energy E (the sum of all the cluster masses) and the net flavor content $Q = (N_u - N_{\bar{u}}, N_d - N_{\bar{d}}, N_s - N_{\bar{s}})$, decaying "statistically" according to phase space. More precisely, the probability of a cluster to hadronize into a configuration $K = \{h_1, p_1; \ldots; h_n, p_n\}$ of hadrons h_i with four momenta p_i is given by the micro-canonical partition function $\Omega(K)$,

$$\Omega(K) = \frac{V^n}{(2\pi\hbar)^{3n}} \times \prod_{i=1}^{n} g_i \prod_{\alpha\in\mathcal{S}} \frac{1}{n_\alpha!} \prod_{i=1}^{n} d^3p_i \times \delta(E - \Sigma\varepsilon_i)\,\delta(\Sigma\vec{p}_i)\,\delta_{Q,\Sigma q_i}, \tag{1}$$

with $\varepsilon_i = \sqrt{m_i^2 + p_i^2}$ being the energy, and $\vec{p}_i$ the 3-momentum of particle i. n_α is the number of hadrons of species α, and g_i is the degeneracy of particle i. The term $\delta_{Q,\Sigma q_i}$ ensures flavor conservation and the net flavor content $Q = (4, 2, 0)$; q_i is the flavor vector of hadron i. The symbol $\mathcal{S}$ represents the set of hadron species considered: the ordinary $\mathcal{S}$ contains the pseudoscalar and vector mesons $(\pi, K, \eta, \eta', \rho, K^*, \omega, \phi)$ and the lowest spin-$\frac{1}{2}$ and spin-$\frac{3}{2}$ baryons $(N, \Lambda, \Sigma, \Xi, \Delta, \Sigma^*, \Xi^*, \Omega)$ and the corresponding antibaryons. We generate randomly configurations K according to the probability distribution $\Omega(K)$. For the details see Ref. [13].

We add the pentaquark states $\Theta^+(1540)$, $\Xi(1860)$ and their antiparticles into $\mathcal{S}$. The Θ^+ has quark contents $(uudd\bar{s})$. The $\Xi(1860)$ can be $\Xi^{--}(ddss\bar{u})$, $\Xi^-(dssq\bar{q})$, $\Xi^0(ussq\bar{q})$ or $\Xi^+(uuss\bar{d})$. The spin of pentaquark states cannot be determined by experiments yet, and it is generally accepted they are spin-$\frac{1}{2}$ particles, so we take a degeneracy factor $g = 2$.

In our approach, because of the heavy masses of the pentaquark states, the hadron configurations containing these particles appear very rarely. Therefore, if the pentaquark states $\Theta^+(1540)$, $\Xi(1860)$ were spin-$\frac{3}{2}$ particles, then their yields would be twice as big as the results obtained for spin-$\frac{1}{2}$, according to Eq. (1), but their average transverse momenta would be the same. In the following, we report the results for spin-$\frac{1}{2}$ particles.

In case of $\Xi^-(dssq\bar{q})$ and $\Xi^0(ussq\bar{q})$, the $q\bar{q}$ can be $u\bar{u}$ or $d\bar{d}$, so these particles might be considered to be three-quark states, $\Xi^-(dss)$ and $\Xi^0(uss)$. In the microcanonical calculation, we do not need to distinguish between q^3 and $q^4\bar{q}$, the two cases give the same results, when the masses and degeneracy factors are the same, because the $q\bar{q}$ of the same flavor does not

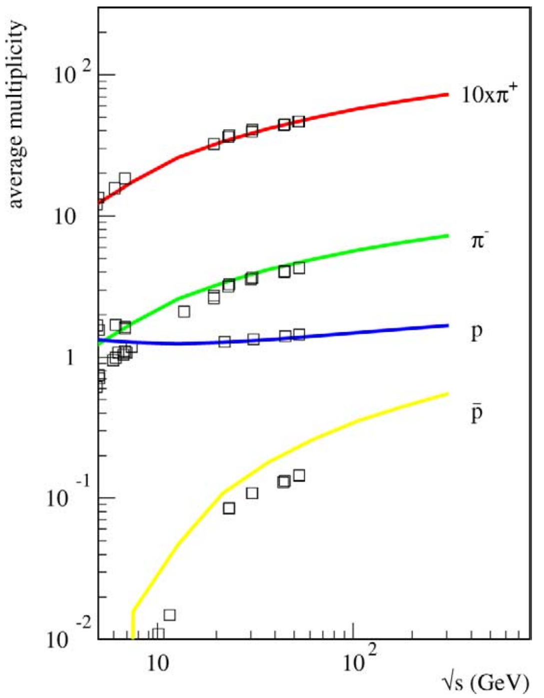

Fig. 1. $p,\ \bar{p},\ \pi^+,\ \pi^-$ excitation functions. The empty square points are experimental data [16], solid lines are microcanonical calculation after adding the pentaquark states into the hadron set.

play any role in conserving flavors or charge in the microcanonical statistical hadronization approach.

The microcanonical parameters $(E,\ V)$ for pp collisions at a given energy $\sqrt{s}/\mathrm{GeV}$ are obtained by fitting the 4π multiplicities of the most copiously produced particles $(p,\ \bar{p},\ \pi^+,\ \pi^-)$ [14,15]:

$$E/\mathrm{GeV} = -3.8 + 3.76 \ln \sqrt{s} + 6.4/\sqrt{s},$$
$$V/\mathrm{fm}^3 = -30.0376 + 14.93 \ln \sqrt{s} - 0.013\sqrt{s}.$$

After adding pentaquarks states into the hadron set, we have to verify whether the 4π multiplicities of $p,\ \bar{p},\ \pi^+,\ \pi^-$ still agree with the data, see Fig. 1. Actually, the yields of light particles are hardly changed, except for antiproton. About 10% more antiprotons are produced to compensate the net baryon numbers carried by the pentaquark states.

The microcanonical calculation has no strangeness suppression factor, so strange hadrons are overproduced [15]. However, with a global factor 1/3 per strange (anti)quark, strange hadrons yields $(K,\ \Lambda$ and $\bar{\Lambda},\ \Xi)$ agree roughly with the data, as shown in Fig. 2, where microcanonical calculations (solid lines) are compared with data [16–18] (empty squares).

In the following, we discuss the results for pentaquark hadrons. Also here we employ a strangeness suppression factor 1/3 per strange (anti)quark. The particle yields of Θ^+ (solid line) and its antiparticle (dashed line) from pp collisions at different col-

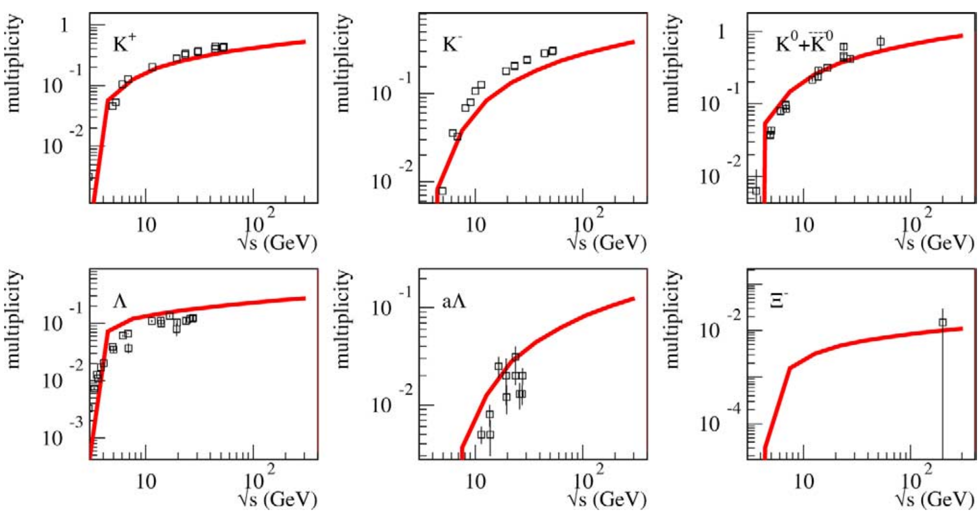

Fig. 2. With a global factor 1/3 per strange (anti)quark, the microcanonical calculation (solid lines) can reproduce the data [16–18] (empty squares) for strange hadrons such as K, Λ and $\bar{\Lambda}$, Ξ^-.

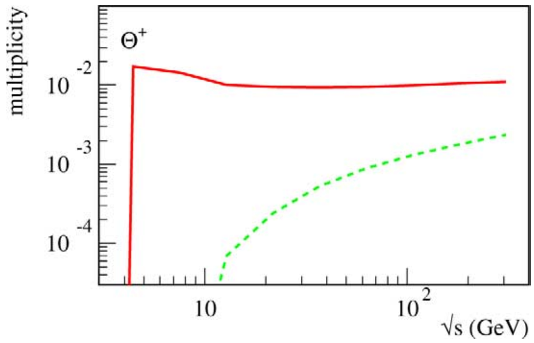

Fig. 3. The particle yields of Θ^+ (solid line) and its antiparticle (dashed line).

lision energies are shown in Fig. 3. The yields of the $\Xi(1860)$ particles (solid lines) and the corresponding antiparticles (dashed lines) are showed in Fig. 4. With the increase of collision energy, more and more pentaquarks states are produces, except Θ^+. We can see in Fig. 3, Θ^+ is favored at low energies because of the channel $p + p \to \Theta^+ + \Sigma^+$ [19].

With the 4π yields of charged pions, protons and antiprotons as input, the microcanonical calculation can predict reliably the average transverse momenta of both non-strange and strange hadrons [15]. In Fig. 5, we also show the average transverse momentum of $\Theta^+(1540)$ and $\Xi(1860)$ (solid lines) and their antiparticles (dashed lines). The difference between the aver-

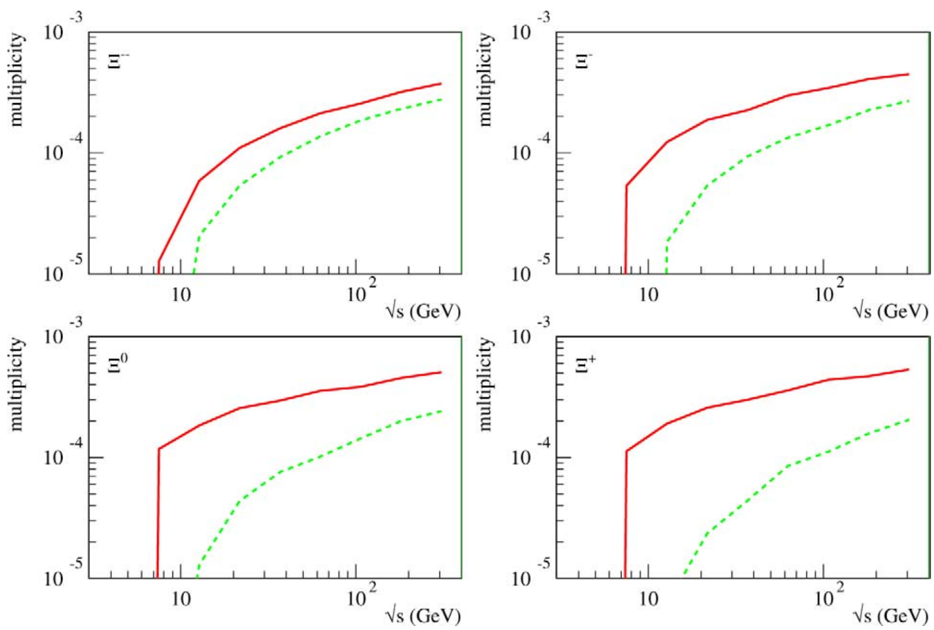

Fig. 4. The particle yields of the $\Xi(1860)$ particles (solid lines) and their antiparticles (dashed lines).

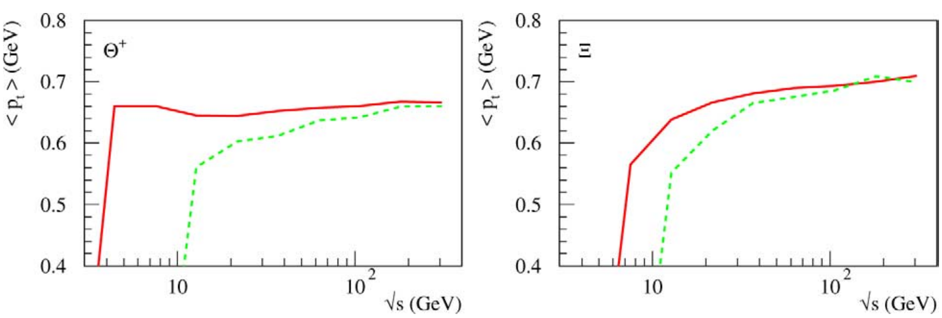

Fig. 5. The average transverse momentum of $\Theta^+(1540)$ and $\Xi(1860)$ (solid lines) and their antiparticles (dashed lines).

age transverse momentum of $\Xi^{--}(ddss\bar{u})$, $\Xi^{-}(dss)$, $\Xi^{0}(uss)$ and $\Xi^{+}(uuss\bar{d})$ from the microcanonical calculation is very small antiparticles.

Now we compare our results to previous research results at SPS and RHIC energies. It is expected that the yields of pentaquark states should be higher as compared to NEXUS calculations [12]. Indeed we find 2–3 times more Θ^{+} and $\Xi(1860)$. We also compare the particle ratio with the results from other models even though these models are meant to describe heavy ion collisions, corresponding to the large-system limit of our microcanonical treatment. Our microcanonical particle ratio Θ/p is about 0.7%, which agrees surprisingly well with the prediction from a quark molecular dynamics model prediction (0.6% [20]), while the grandcanonical ensemble [21] gives about 6%. The particle ratio $\Xi^{--}(1860)/\Xi^{-}$ is 2% at SPS and 3% at RHIC, which is 3–4 times bigger than the grandcanonical results [22].

The inclusive cross section $\sigma_{pp\to\Theta^{+}}$ near the production threshold, estimated with empirical coupling constants and form factor, is 20 μb [19], which is about ten times smaller than our results.

In conclusion, we presented a calculation of the yields of different pentaquark states in pp collisions, using the microcanonical approach. We obtain roughly 10^{-2} (almost independent of energy) for the Θ^{+}, whereas the Ξ yields increase strongly with energy, reaching 4×10^{-4} at RHIC.

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