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Production of charmed mesons, baryons and tetraquarks in heavy-ion collisions at the LHC

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We investigate the production of mesons, baryons and exotic tetraquarks containing heavy flavors, b and c, in the framework of coalescence quark model. The Wigner function for the produced cluster is defined in terms of wave functions calculated from exact solutions of the few-body problem using a realistic constituent quark model. It contains a chromoelectric part made of a Coulomb-plus-linear interaction together with a chromomagnetic spin-spin term described by a regularized Breit-Fermi interaction with a smearing parameter that depends on the reduced mass of the interacting quarks. We take into account effects of temperature on the masses of the light quarks that enter in the constituent quark model. The temperature dependence of those quantities are taken from the Nambu–Jona-Lasinio model. We use such formulas to calculate the yields for $\bar{D}^0$, Λ_c^+, Ξ_{cc}^{++}, T_{cc} and T_{bc}. We find an enhancement in the number of all clusters produced when temperature effects are taken into account. We also find that the color component $6\bar{6}$ of the overlap between the Wigner function of the produced hadron with the phase-space distribution of the constituents at finite temperatures is strongly suppressed for T_{cc} and T_{bc} tetraquarks.

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1. Introduction

In recent years there has been an impressive experimental progress in the spectroscopy of heavy hadrons, mainly in the charm sector. The LHCb Collaboration at the Large Hadron Collider (LHC), in particular, is engaged in an extensive program aimed at analyses of charmed hadrons produced in the hot and dense environment of relativistic heavy-ion collisions [1] and has already reported the observation various new kinds of heavy-flavor structures, e.g., X [2], Ω_c [3], Ξ_{cc}^{++} [4] and T_{cc} [5, 6].

Along with the large array of applications offered by relativistic heavy-ion collisions, the search of hadronic states in the quark-gluon plasma (QGP) is an exciting new direction in our quest to understand the structure of the new heavy-flavor states. In the heavy quark sector, there has been a general consensus on the key role of the hadronization process by coalescence on the hadron production [7].

Within this perspective, in the present work we study the production by coalescence of charmed hadrons ($\bar{D}^0$, Λ_c^+, Ξ_{cc}^{++}) and exotic tetraquarks (T_{cc}, T_{bc}) in central Pb + Pb collisions at the LHC at $\sqrt{s_{NN}} = 2.76$ TeV and $\sqrt{s_{NN}} = 5.02$ TeV. We employ the dynamical coalescence model extensively used in hadron production reviewed recently in Ref. [7]. We calculate the Wigner function of the tetraquark employing the two-, three- and four-body wave function obtained from constituent models that correctly reproduce the low-lying meson and baryon spectra [8]. We also address the important question of how a partial restoration of chiral symmetry affects the coalescence process [9].

2. Coalescence quark model

In the nonrelativistic coalescence model, the probability of producing hadrons from quarks in the medium formed in a QGP is given by

$$N_h = g_h \frac{\prod_{i=1}^{n}\left(\frac{N_i}{g_i}\right)}{\prod_{j=1}^{n-1}\left[\, V\,(2\pi T\mu_j)\,\right]}\,\mathcal{F}_h(T), \tag{1}$$

where n is the number of constituent quarks, V is the volume of the of the source, g_h is a degeneracy factor, and the overlap $\mathcal{F}_h(T)$ is defined as

$$\mathcal{F}_h(T) = \int \Big(\prod_{j=1}^{n-1} d\boldsymbol{k}_{j\perp}\, d\boldsymbol{r}_j\, e^{-\frac{\boldsymbol{k}_{j\perp}^2}{2T\mu_j}}\Big)\rho_h^W(\boldsymbol{r}_1,\cdots,\boldsymbol{r}_{n-1};\boldsymbol{k}_1,\cdots,\boldsymbol{k}_{n-1}). \tag{2}$$

The Wigner function, ρ_h^W, is given in terms of the hadron wave function

$$\begin{aligned}\rho_h^W(\boldsymbol{r}_1,\cdots,\boldsymbol{r}_{n-1};\boldsymbol{k}_1\cdots,\boldsymbol{k}_{n-1}) &= \int \Big(\prod_{j=1}^{n-1} d\boldsymbol{r}'_j e^{-i\boldsymbol{k}_j\cdot \boldsymbol{r}'_j}\Big) \\ &\times\ \psi\Big(\boldsymbol{r}_1+\frac{\boldsymbol{r}'_1}{2},\dots,\boldsymbol{r}_{n-1}+\frac{\boldsymbol{r}'_{n-1}}{2}\Big)\psi^*\Big(\boldsymbol{r}_1-\frac{\boldsymbol{r}'_1}{2},\dots,\boldsymbol{r}_{n-1}-\frac{\boldsymbol{r}'_{n-1}}{2}\Big).\end{aligned}$$

Note that in addition to the explicit T dependence due to the presence of the Boltzmann distribution in Eq. (2), $\mathcal{F}_h(T)$ might also acquire an implicit T dependence through the parameters of the constituent model when chiral symmetry restoration effects are taken into account.

The normalized wave function for mesons is defined as

$$\psi(\boldsymbol{r}) = \frac{\chi^{csf}}{4\pi}\sum_{i=1}^{n_g}\alpha_i\, e^{-\frac{\boldsymbol{r}^2}{2s_i^2}}, \tag{3}$$

where χ_κ^{csf} are orthonormalized color-spin-flavor vectors and the radial part of the wave function is expanded in terms of n_g single Gaussians with variational parameter s_i.

The baryon wave function are taken to be a sum over all allowed channels with well-defined symmetry properties

$$\psi(\boldsymbol{r}_1,\boldsymbol{r}_2) = \sum_{\kappa=1}^{n}\sum_{i=1}^{n_g}\chi_\kappa^{csf}\;\alpha_i^\kappa\, e^{-a_\kappa^i\boldsymbol{r}_1^2-b_\kappa^i\boldsymbol{r}_2^2-c_\kappa^i\boldsymbol{r}_1\cdot\boldsymbol{r}_2}, \tag{4}$$

where n is the number of channels, χ_κ^{csf} are orthonormalized color-spin-flavor vectors of the $\kappa-$th channel and the radial part of the wave function expanded in terms of n_g generalized Gaussians with $a_\kappa^i,\cdots,c_\kappa^i$ variational parameters.

The tetraquark wave function is taken to be a sum over all allowed channels with well-defined symmetry properties [10, 11]:

$$\psi(\boldsymbol{r}_1,\boldsymbol{r}_2,\boldsymbol{r}_3) = \sum_{\kappa=1}^{6}\sum_{r=1}^{4}\sum_{i=1}^{n}\chi_\kappa^{csf}\;w(\kappa,r)\,\alpha_i^\kappa\, e^{-a_\kappa^i\boldsymbol{r}_1^2-b_\kappa^i\boldsymbol{r}_2^2-c_\kappa^i\boldsymbol{r}_3^2}e^{-d_\kappa^i s_1(r)\boldsymbol{r}_1\cdot\boldsymbol{r}_2-e_\kappa^i s_2(r)\boldsymbol{r}_1\cdot\boldsymbol{r}_3-f_\kappa^i s_3(r)\boldsymbol{r}_2\cdot\boldsymbol{r}_3}, \tag{5}$$

where χ_κ^{csf} are orthonormalized color-spin-flavor vectors of the $\kappa-$th channel and $a_\kappa^i,\cdots,f_\kappa^i$ are variational parameters. In order to get the appropriate symmetry properties in configuration space, the radial part of the wave function is expanded in a single Gaussian basis expressed as the sum of four components where $s_1(r),\cdots,s_3(r)$ are equal to ±1.

3. Solving the few-body problem with realistic interaction

The few-body problem will be addressed by means of the variational method, specially suited for studying low-lying states—see Ref. [11] for further details about the minimization procedure. The nonrelativistic Hamiltonian used is given by

$$H = \sum_i\left(m_i+\frac{p_i^2}{2m_i}\right)+\sum_{i<j}V(r_{ij}), \tag{6}$$

where V_{ij} is taken to be the AL1 potential [8],

$$V_{ij}(r) = -\frac{\kappa}{r}+\lambda\, r-\Lambda+\frac{2\pi\alpha}{3\,m_i\,m_j}\frac{e^{-\frac{r^2}{r_0^2}}}{\pi^{\frac{3}{2}}\,r_0^3}\,\vec{\sigma}_i.\vec{\sigma}_j\;. \tag{7}$$

suitably modified by the $1/2$ rule for quark-antiquark pairs. The parameters of the AL1 model are given in Ref. [11] and it fits rather well the ground-state charmed mesons and baryons, and in particular the spin multiplets of interest in the study of doubly-flavored tetraquarks. Finite temperature effects are incorporated in those parameters of the model related to the dynamical breaking of chiral symmetry, namely the masses of the light constituent quarks–see Refs. [12, 13]. In Table. 1 we present the explicit values of the temperature dependence of the light quark and also for the meson, baryon and tetraquark masses predicted by the AL1 model.

Table 1: Predicted masses of the AL1 model for charmed mesons, baryons and exotic tetraquarks as function of temperature. All values are listed in MeV.

	Vacuum	In-medium			
	$T = 0$	$T = 100$	$T = 120$	$T = 140$	$T = 156$
$M_{\bar{D}^0}$	1862	1862	1863	1867	1880
$M_{\Lambda_c^+}$	2281	2270	2243	2217	2176
$M_{\Xi_c^{++}}$	3607	3607	3607	3611	3623
$M_{T_{cc}}$	3877	3870	3864	3846	3824
$M_{T_{bc}}$	7131	7127	7118	7111	7096
$M_{u,d}$	328	313	300	267	230

4. Numerical Results

We present numerical results for the yields of mesons, baryons and tetraquarks in the quark coalescence model in Table 2. We also present results for the temperatures effects on the color component of the overlap $\mathcal{F}_h(T)$ of T_{cc} and T^0_{bc} in Figure 1 and Figure 2.

Table 2: Heavy hadron yields at mid-rapidity in the coalescence model expected at LHC in $\sqrt{s_{NN}} = 2.76$ TeV and 5.02 TeV Pb+Pb collisions. All results are calculated using the AL1 quark model to obtain the hadronic wave functions. We use the notation: T^0_{bc} for $J^p = 0^+$.

	LHC (2.76 TeV)		LHC (5.02 TeV)	
	$T = 0$	$T = 156$	$T = 0$	$T = 156$
$N_{\bar{D}^0}$	1.5×10^{-1}	2.3×10^{-1}	2.0×10^{-1}	3.0×10^{-1}
$N_{\Lambda_c^+}$	6.4×10^{-2}	1.0×10^{-1}	8.1×10^{-2}	1.3×10^{-1}
$N_{\Xi_{cc}^{++}}$	1.3×10^{-4}	1.5×10^{-4}	2.2×10^{-4}	2.5×10^{-4}
$N_{T_{cc}}$	5.8×10^{-5}	6.4×10^{-5}	9.4×10^{-5}	1.0×10^{-4}
$N_{T^0_{bc}}$	3.4×10^{-7}	4.5×10^{-7}	7.0×10^{-7}	9.2×10^{-7}

5. Conclusions

In this work we present results for the production of mesons, baryons and tetraquarks containing heavy flavors, c and b, in the coalescence quark model. In the calculation of the Wigner function for all hadrons we use wave function derived from the constituent quark model AL1. We take into account effects of temperature on the masses of the light quarks that enter in the AL1 model. We find an enhancement in the number of all clusters produced when temperature effects are taken into account. We also find a strong suppression of the color component $6\bar{6}$ of the overlap function $\mathcal{F}_h(T)$ for the T_{cc} and T_{bc} tetraquarks at finite temperatures.

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Figure 1: The overlap function decomposition for the T_{cc} tetraquark in terms of the color vectors $|\bar{\mathbf{3}}\mathbf{3}\rangle$ and $|\bar{\mathbf{6}}\mathbf{6}\rangle$ at $T = 0$ MeV (left panel) and $T = 156$ MeV (right panel).

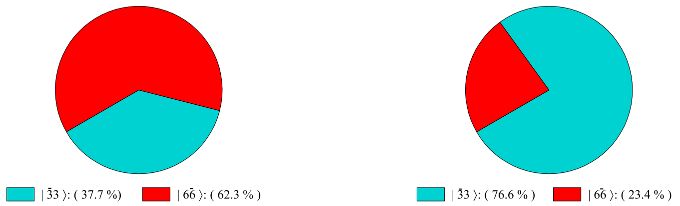

Figure 2: The overlap function decomposition for the T^0_{bc} tetraquark in terms of the color vectors $|\bar{\mathbf{3}}\mathbf{3}\rangle$ and $|\bar{\mathbf{6}}\mathbf{6}\rangle$ at $T = 0$ MeV (left panel) and $T = 156$ MeV (right panel).

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