Sequential Hadronization with Charm Conservation in Heavy Ion Collisions

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Different from the hadronization process in vacuum, the statistics plays an important role in hadronization of the quark-gluon plasma.

**Thermal statistical hadronization model & Coalescence model**

- Quark number scaling of the elliptic flow
- Enhancement of baryon to meson ratios

Assumption of simultaneous hadronization for all hadrons.
The charmonium/bottomonium states are described by 2-body Schroedinger equation. With increasing temperature the charmonium states "melt" sequentially.

The properties of heavy flavor mesons and baryons are studied by 2&3-body Dirac equations. The results show sequential heavy flavor hadronization in the hot medium!

Sequential Hadronization

Open charmed hadrons are “melted” at temperatures close but higher than the critical temperature in lattice QCD Simulation!


D0, $\phi$, $\Xi^-$ seem to decouple from the system earlier and gain less radial collectivity compared with light hadrons in Blast-Wave model!


Sequential Hadronization

Sequential dissociation $\approx$ sequential production

Hadrons with larger binding energy can survive at higher temperature and are earlier produced!
Charm Quark Conservation

- $m_c \sim 1.5\text{GeV} \gg T \sim (0.3 - 0.5)\text{GeV}$

  The *thermal production* of charm quarks via gluon fusion and quark and anti-quark annihilation in the QGP can be safely neglected!

- $m_c \gg \Lambda_{QCD}$

  Production can be solidly calculated through *perturbative* method!

- $\partial_\mu (n_{cc} u^\mu) = r_{\text{gain}} - r_{\text{loss}}$

  production rate \hspace{1cm} annihilation rate
Introduction II

Charm Quark Conservation

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  Production can be solidly calculated through perturbative method!

- $\partial_\mu (n_{c\bar{c}} u^\mu) = r_{gain} - r_{loss}$:
  - production rate
  - annihilation rate

Charm quark number:

- conserved at RHIC!
- almost conserved at LHC!
- considerably increased at FCC!

MODEL SETUP

( Sequential Hadronization + Charm Conservation )

&

RESULTS
Sequential Hadronization

2&3-body Dirac equations are used to study charmed bound hadrons.

Need to include the relativistic corrections: kinematics, spin.

The dissociation temperature $T_d$:

$$\epsilon(T_d) = 0 \quad <r(T_d) > \to \infty$$

Model Setup


O’Kaczmarek, EPJC 61, 811 (2009)

$T_{J/\psi} > T_{D_s} > T_{D^0} > T_{\Lambda_c} > T_{\pi,K,N}$


Sequential Hadronization

2&3-body Dirac equations are used to study charmed bound hadrons.

\[ T_{J/\psi} > T_{D_s} > T_{D^0} > T_{\Lambda_c} > T_{\pi,K,N} \]

Hydrodynamics: \[ \partial_\mu T^{\mu\nu} = 0 \]

\[ T(x, \tau_h) = T_h \quad \tau_h = \tau(x, T_h) \]

\[ \tau_{J/\psi} < \tau_{D_s} < \tau_{D^0} < \tau_{\Lambda_c} < \tau_{\pi,K,N} \]
Coalescence Mechanism

\[ \frac{dN_h}{d^2 P_T d\eta} = C \int P^\mu d\sigma_\mu \prod_{i=1}^{n} \frac{d^4x_i d^4p_i}{(2\pi)^3} f_i(x_i, p_i) \times W_h(x_1, \ldots, x_i, p_1, \ldots, p_i). \]


- The hadronization hypersurface is determined by hydrodynamics and dissociation temperature.

\[ \partial_\mu T^{\mu\nu} = 0 \quad T(x, \tau_h) = T_h \]
The hadronization hypersurface is determined by hydrodynamics and dissociation temperature.

\[ \partial_{\mu} T^{\mu\nu} = 0 \quad \text{and} \quad T(\mathbf{x}, \tau_h) = T_h \]

The Wigner function can self-consistently be determined by the wavefunction. Instead of taking a Gaussian distribution with the width as a free parameter.

\[ W(r, p) = \int d^4 y e^{-i p y} \psi(r + \frac{y}{2}) \psi(r - \frac{y}{2}) \]
Quark Distribution Function

- **Light quark:** thermal and chemical equilibrium
  \[
  f_q(x, p) = \frac{N_q}{e^{p^\mu u_\mu(x)/T(x)} + 1}, \quad q = u, d
  \]

- **Strange quark:** thermal and non-chemical equilibrium
  \[
  f_s(x, p) = \frac{N_s \gamma_s}{e^{p^\mu u_\mu(x)/T(x)} + 1}
  \]
  \[
  \gamma_s = \begin{cases} 
  0.85 & \text{at RHIC} \\
  1 & \text{at LHC}
  \end{cases}
  \]
Model Setup

Quark Distribution Function

- **Light quark:** thermal and chemical equilibrium
  \[ f_q(x, p) = \frac{N_q}{e^{p\mu u_\mu(x)/T(x)} + 1}, \quad q = u, d \]

- **Strange quark:** thermal and non-chemical equilibrium
  \[ f_s(x, p) = \frac{N_s \gamma_s}{e^{p\mu u_\mu(x)/T(x)} + 1}, \quad \gamma_s = \begin{cases} 0.85 & \text{at RHIC} \\ 1 & \text{at LHC} \end{cases} \]

- **Charm quark:** non-thermal and non-chemical equilibrium
  \[ f_c(x, p) = r_h \rho_c(x) \left[ \alpha f_{th}(p) + \beta f_{pp}(p) \right] \]
  \[ \rho_c(x) = T_A(x_T)T_B(x_T - b) \frac{\cosh \eta}{\tau} \frac{d\sigma_{pp}^{cc}}{d\eta} \]

Charm Distribution Function

\[ f_c(x, p) = r_h \rho_c(x) \left[ \alpha f_{th}(p) + \beta f_{pp}(p) \right] \]

\[ r_h \text{ Charm conservation factor!} \]

- If all charmed hadrons are **simultaneously** produced, the charm conservation contributes only a normalization constant.
  
  It does not change the particles ratios!

- If charmed hadrons are **sequentially** produced, however, more charm quarks are involved in the earlier production and less in the later production.

\[ r_h = \frac{\text{involved charm quarks}}{\text{total charm quarks } N_c} = \begin{cases} 1 & \text{for } h = D_s \\ 1 - \frac{N_{D_s}}{N_c} (\sim 90\%) & \text{for } h = D^0 \\ 1 - \frac{(N_{D_s} + N_{D^0})}{N_c} (\sim 60\%) & \text{for } h = \Lambda_c \end{cases} \]

Charm conservation:

- **Enhances** the earlier produced hadrons
- **Suppresses** the later produced hadrons.

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Transverse momentum spectrum of Ds, D0 and charmed baryons

\[
d^2N/(2\pi dP_Tdy) \quad (\text{GeV}^2)\\
\]

\[
P_T (\text{GeV/c})\\
\]

Au+Au @ 200 GeV, |y|<1
Transverse momentum spectrum of $D_s$, $D_0$ and charmed baryons

Au+Au @ 200 GeV, $|y|<1$

- $\Lambda_c$ 10-60%
- $\Xi_c$ 10-60%
- $\Omega_c$ 10-60%

Transverse momentum spectrum of $D_s$, $D_0$ and charmed baryons
Transverse momentum spectrum of $D_s$, $D_0$ and charmed baryons
Transverse momentum spectrum of Ds, D0 and charmed baryons

\[ \frac{d^2N}{d^2p_T} \] (GeV$^{-2}$)

\[ \frac{dN}{dp_T} \] (GeV$^{-1}$)

\[ \frac{dN}{dp_T} \] (GeV$^{-1}$)

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\[ \frac{dN}{dp_T} \] (GeV$^{-1}$)

\[ \frac{dN}{dp_T} \] (GeV$^{-1}$)
Solid line: sequential coalescence
Dashed line: simultaneous coalescence at Tc

Strangeness enhancement + Sequential coalescence + Charm conservation

Ds enhancement —> D0 suppression —> an extra enhancement!

Ratio is sensitive to the hadronization mechanism and charm conservation law!

1. Au+Au @ 200 GeV
   STAR Preliminary |y|<1
   0-10%
   10-40%

2. Pb+Pb @ 2.76TeV
   ALICE |y|<0.5
   0-10%
   D+D, s = 7TeV

Extra enhancement!
Results

Charm conservation reduces the charmed baryon/meson ratio!

Charm conservation:

Enhances the earlier produced hadrons
Suppresses the later produced hadrons.

1. We have built a framework to realize sequential hadronization with charm conservation in HIC! Reasonable agreement between our theoretical calculation and experimental data.

2. Hadronization sequence and coalescence probability of charmed hadrons are determined by 2&3-body Dirac equation.

3. Charm conservation leads to
   an enhancement for earlier produced hadrons and
   a suppression for later produced hadrons.

   Need more exp. data to constrain the hadronization mechanism!
THANK YOU!
BACKUP
For charmed mesons we can solve Tow Body Dirac Equation to get wave functions and masses!

- $D_s^0 (1968)$
  - $T = T_c$
  - $m = 2.002$ GeV
  - $\langle r \rangle = 0.665$ fm

- $D_s^0 (2112)$
  - $T = T_c$
  - $m = 2.022$ GeV
  - $\langle r \rangle = 0.724$ fm

- $D^0 (1865)$
  - $T = T_c$
  - $m = 1.919$ GeV
  - $\langle r \rangle = 0.705$ fm

- $D^0 (2007)$
  - $T = T_c$
  - $m = 1.939$ GeV
  - $\langle r \rangle = 0.767$ fm