X(3872) Transport in High-Energy Heavy-ion Collisions

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Outline

• X(3872) in Vacuum and Heavy-Ion Collisions

• Transport Analysis
  • Rate Equation & Transport Parameters
  • Time evolution & observables (centrality & $p_T$ spectra)

• Conclusion
**X(3872) in Vacuum**

- **Mass**
  - Mass $X(3872) \approx \bar{D}^*0(2007) + D^0(1865)$

- **Total width**
  - $\Gamma(X(3872)) < 1.2$ MeV

- **Possible structures**
  - Tetraquark (Compact diquark anti-diquark)
  - Molecular (Loosely-bound)

- **Can ultra-relativistic heavy-ion collisions (URHICs) provide new structure information of $X(3872)$?**
Current Approaches to X(3872) in URHICs

- **Statistical hadronization model**
  - Yields only depend on masses
  - No internal structure information

- **Coalescence model**
  - Constituent-quark distribution functions & produced-particle Wigner functions
  - Production ratio $\frac{N_{\text{mol}}}{N_{\text{tet}}}$ up to 250

[Andronic et al.’19]

[Cho et al. ’11, Fontoura et al.’19; Cho et al. ’13, Abreu et al. ’16; …]

[Zhang et al.’20]
Transport Approach \cite{Grandchamp et al.'04, Zhao et al.'11, Du et al.'17}

- Rate equation used in calculating charmonia in URHICs

\[
\frac{dN_X}{d\tau} = -\Gamma(T) [N_X - N_X^{eq}(T, \gamma_c)]
\]

- Equilibrium limit from statistical model

\[
N_X^{eq}(T, \gamma_c) = \gamma_c^2 \int \frac{d^3 p}{(2\pi)^3} e^{-\sqrt{m_X^2 + p^2/T}}
\]

- Fugacity \(\gamma_c(T)\): charm number conservation

\[
N_{c\bar{c}} = \frac{1}{2} \gamma_c(T) n_{op} V_{FB} \frac{I_1(\gamma_c(T)n_{op}V_{FB})}{I_0(\gamma_c(T)n_{op}V_{FB})} + \gamma_c^2(T) n_{hid} V_{FB}
\]

Open-charm hadron density: \(n_{op} = \sum_\alpha n_\alpha(T; m_\alpha)\)

\(N_{c\bar{c}}\): direct \(c\bar{c}\) related to the charm cross section
Molecular vs. Tetraquark Scenario

- Reaction rate \( \Gamma \sim \Gamma_0 \left( \frac{T}{T_0} \right)^n \)

  - Molecular: Loosely-bound molecular state
    \[ \Gamma \sim 65 \text{ MeV at } T \sim 160 \text{ MeV in pion gas}, \quad \text{[Cleven et al.'19]} \]
    Scale up by total hadron density at \( T_0 = 180 \text{ MeV} \):
    \[ \Gamma_0 \sim 300-500 \text{ MeV} \]

  - Tetraquark: Compact diquark anti-diquark bound state
    Not well known, \( \Gamma_0 \sim 30-50 \text{ MeV} \)
    Little sensitivity to the power \( n \sim 0-5 \)

- Initial condition at chemical freeze-out

  - Molecular: 0
    Loosely-bound molecular state only forms later

  - Tetraquark: \( N_{eq} \)
    Compact diquark anti-diquark bound state, likely to form in the QGP phase
**X(3872) Evolution in 5 TeV Pb-Pb Collisions**

- **Tetraquark state**: small reaction rate $\Rightarrow$ mainly from the initial yield at chemical freeze-out

- **Molecular state**: large reaction rate $\Rightarrow$ affected greatly by the equilibrium limit

- **Ratio of yields at thermal freeze-out** $N_{\text{Tet}}/N_{\text{Mol}} \sim 2$
Centrality Dependence in 5 TeV Pb-Pb Collisions

- Molecular (tetraquark) state yield is close to the equilibrium limit at thermal (chemical) freeze-out for all centralities

- Ratio at thermal freeze-out $N_{\text{Tet}}/N_{\text{Mol}} \sim 2$ for all centralities
• Both scenarios in between of the blast wave $p_T$ spectra at chemical and thermal freeze-out

• Tetraquark: close to the blast wave $p_T$ at chemical freezeout

• Molecular: produced later $\Rightarrow$ has harder $p_T$ spectra
Conclusion

- We calculate the evolution of $X(3872)$ in hadronic phase in 5 TeV Pb-Pb collisions using the kinetic rate equation.
- The rate equation has been previously used in the calculation of charmonia in heavy-ion collisions.
- The $X(3872)$ structure information is encoded in the reaction rate and the initial condition.
- The molecular bound state is produced later than the tetraquark and is suppressed by a factor about 2 due to drop of the equilibrium limit as a function of temperature.
- $N_{\text{Tet}}/N_{\text{Mol}}$ is of order 2 which is quantitatively and qualitatively different from the coalescence model predictions.
- Molecular state has harder $p_T$ spectra.
Thanks for your attention!
Backup
Temperature of the Fireball

![Graph showing temperature of the fireball over time for different centrality classes (0–20%, 20–40%, 40–60%, 60–80%) with axes labeled T (MeV) vs. t (fm/c).]
Centrality Dependence with Shadowing Effect

\[
\frac{dN}{dy}/N_{\text{Coll}} \times 10^{-6}
\]

- Tetraquark
- Molecular
- Eq\text{\textsubscript{init}}
- Eq\text{\textsubscript{final}}

\(\text{N}_{\text{part}}\)

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X(3872) Evolution with Shadowing Effect

Central collisions

Semi-central collisions

T= 180 MeV
T= 110 MeV
T= 180 MeV
T= 126 MeV

Tetraquark
Molecular
Equilibrium

Tetraquark
Molecular
Equilibrium

\[ \frac{dN}{dy} \left( 10^{-3} \right) \]

\[ \frac{dN}{dy} \left( 10^{-4} \right) \]

\[ t(\text{fm/c}) \]

\[ T = 180 \text{ MeV} \]
\[ T = 110 \text{ MeV} \]
\[ T = 180 \text{ MeV} \]
\[ T = 126 \text{ MeV} \]
$X(3872) \ p_T$ Spectra with Shadowing Effect

![Graph showing $d^2N/dydp_T/p_T(GeV^{-2})$ vs $p_T(GeV)$ for Tetraquark and Molecular BW at T=180 MeV and T=110 MeV.]

- **Tetraquark**
- **Molecular**

- BW at T=180 MeV
- BW at T=110 MeV
X(3872) Evolution without Shadowing Effect

- Central collisions
  - Temperatures: T = 180 MeV, T = 110 MeV, T = 160 MeV
  - Graphs show dN/dy vs. time (t(fm/c))
  - Curves for Tetraquark, Molecular, Molecular, Equilibrium

- Semi-central collisions
  - Temperatures: T = 180 MeV, T = 126 MeV
  - Graphs show dN/dy vs. time (t(fm/c))
  - Curves for Tetraquark, Molecular, Molecular, Equilibrium