Charmed Hadrons in Nuclei

from Few Body viewpoints

Makoto Oka
Tokyo Institute of Technology
and
Advanced Science Research Center, JAEA

Asia-Pacific Few-Body Conference
Aug. 29, 2017, Guillin, China
Key questions to be answered

What are the roles of charm (heavy) quark embedded in Atomic Nuclei?

- *As an impurity to change the properties of matter and nucleus*
  - nuclear size, density, shape, decays and transitions
  - anomalous phenomena ex. Kondo effect

- *As a probe of the properties of dense matter*
  - deconfinement and chiral symmetry restoration
  - changes in quark and/or gluon distributions

- *To study properties of heavy hadrons*
  - structure of heavy hadrons, composite nature
  - from how they are modified in medium
Hadrons in Matter

- Hadrons can probe the hadronic matter at finite $T$ and/or $\rho$.
- Interplay of *chiral symmetry* and *quark confinement* at finite $T$ and/or $\rho$ is intriguing.
Hadrons in Matter

- **D and D^\text{bar}** mesons at finite density
- QCD sum rule with the Maximum Entropy Method
- *K. Suzuki, P. Gubler, MO, PR C 93, 045209 (2016)*

**Graphs:**

- $D^-(J^P=0^-)$
  - Vacuum
  - $0.5\rho_0$
  - $1.0\rho_0$
  - $1.5\rho_0$

- $D^+(J^P=0^-)$
  - Vacuum
  - $0.5\rho_0$
  - $1.0\rho_0$
  - $1.5\rho_0$
Hadrons in Matter

- D and $D^{\text{bar}}$ mesons at finite density
- QCD sum rule with the Maximum Entropy Method
- K. Suzuki, P. Gubler, MO, PR C 93, 045209 (2016)
Hadrons in Matter

Interpretation in the constituent quark picture: The wave function will extend to feel more repulsion.


Qq potential

$m_q=324$ MeV

$m_q=160$ MeV
Hadrons in Matter

Interpretation in the constituent quark picture:
The wave function will extend to feel more repulsion.


$m_q = 324$ MeV

*confinement v.s. chiral restoration*

$m_q = 160$ MeV
Key questions to be answered

What have we learned in Strangeness Nuclear Physics?

*Hyperon does not melt in nuclei as the nucleon do not.*

<= single particle motions in nuclei

YN and YY interactions are generalized nuclear force.

=> SU(3) symmetry, meson exchange interactions

quark structure at short distances
HAL QCD Lattice calculation of the BB potentials (in SU(3) scheme) shows that the potentials have long-range meson exchange part plus short-range part consistent with the quark Pauli effects.

T. Inoue et al., (HAL QCD) PTP 124, 591 (2010)
Key questions to be answered

- Most hadrons are protected from being dissociated into multi-quark compound in medium.
  \[\Rightarrow \text{Thanks to short-range repulsion due to the quark structure of hadrons}\]

- There are exceptions, which are very interesting.
  \(K^{\text{bar}} \text{ feels a strong attraction to } N, \text{ forming a molecular bound state } \Lambda(1405).\)
  \(\text{The flavor singlet BB interaction is attractive, giving } H\text{-dibaryon } (u^2d^2s^2) \text{ which couples to } \Lambda\Lambda, N\Xi, \Sigma\Sigma \text{ channels.}\)
Key questions to be answered

- Most hadrons are protected from being dissociated into multi-quark compound in medium.
  
  \[ \Rightarrow \text{Thanks to short-range repulsion due to the quark structure of hadrons} \]

- There are exceptions, which are very interesting.
  
  \[ K^{\text{bar}} \text{ feels a strong attraction to } N, \text{ forming a molecular bound state } \Lambda(1405). \]

  \[ \text{The flavor singlet BB interaction is attrative, giving } H\text{-dibaryon} \ (u^2d^2s^2) \text{ which couples to } \Lambda\Lambda, N\Xi, \Sigma\Sigma \text{ channels.} \]

- The strange hadron physics is mature now, and why do we need heavier hadrons?
Key questions to be answered

-heart Most hadrons are protected from being dissociated into multi-quark compound in medium.
  => Thanks to short-range repulsion due to the quark structure of hadrons

-heart There are exceptions, which are very interesting.
  $K^\text{bar}$ feels a strong attraction to $N$, forming a molecular bound state $\Lambda(1405)$.
  The flavor singlet $BB$ interaction is attractive, giving $H$-dibaryon ($u^2d^2s^2$) which couples to $\Lambda\Lambda$, $N\Xi$, $\Sigma\Sigma$ channels.

-heart The strange hadron physics is mature now, and why do we need heavier hadrons?

They are even more exciting!
Why Heavy Quarks?

- A goal of hadron physics:
  - To clarify the relevant *effective degrees of freedom* of hadrons and hadron excitations.

- **Heavy hadrons are simpler** =>
  
  *because the QCD coupling is small and heavy quarks are non-relativistic. They are separated from light quarks dynamically.*
QCD Lagrangian is flavor independent, but the coupling constant runs. $\Lambda_{\text{QCD}}(\sim 300 \text{ MeV}) \ll m_c(\sim 1.3 \text{ GeV}) \ll m_b(\sim 4.2 \text{ GeV})$

- Light quarks are nonperturbative/relativistic.
- Heavy quarks are perturbative/non-relativistic.

$\Lambda_{\text{QCD}}$ expansion

$1$ $10$ $100$ MeV $1$ $10$ $100$ GeV

$m_q$ expansion

$u$ $d$ $s$

$1/m_Q$ expansion

$c$ $b$ $t$

Heavy quark symmetry

Chiral symmetry
Charmonium

Charmonium (1974) gave a firm evidence for quarks.

Hydrogen atom in QCD
NR quarks with an instantaneous potential
Linear + Coulomb (Cornell) potential

\[ V(r) = -\frac{e}{r} + \sigma r \]

E. Eichten, et al., PRL 34 (1975) 369

G.S. Bali, Phys. Rept. 343 (2001) 1
Why Heavy Quarks?

A goal of hadron physics:
– To clarify the relevant effective degrees of freedom of hadrons and hadron excitations.

Heavy hadrons are simpler =>
because the QCD coupling is small and heavy quarks are non-relativistic. They are separated from light quarks dynamically.

Heavy hadrons are complex =>
because many exotic multi-quark-like resonances are found.
HQ Exotic Hadrons

- X(3872) found in 2003 by Belle (KEK)
  → not reproduced by lattice QCD using only $q$-$q^{\bar{q}}$ operators.

- Z(3900), Z(4430) etc.: charged hidden charm states

**X(3872)**
- Belle

**$Z_{c^+}(4430)$**
- Belle
  - $M=4433$ MeV
  - $\Gamma = 45$ MeV

**$Z_{c^+}(3900)$**
- BES III
  - $M=3899$ MeV
  - $\Gamma = 46$ MeV

---

PRL 91 (2003) 262001

M.Oka (Tokyo Tech. and JAEA)

PRL 100 (2008) 142001

PRL 110 (2013) 252001
**HQ Exotic Hadrons**

- $P_c \rightarrow J/\psi + p (c\bar{c}uud)$
- LHCb (*PRL 115 (2015) 07201*) found two penta-quark states with hidden $c\bar{c}$.  

\[ P_c(4450) \]
\[ P_c(4380) \]
$P_c \rightarrow J/\psi + p (c\bar{c}uud)$

LHCb (PRL 115 (2015) 07201) found two penta-quark states with hidden $c\bar{c}$. Light quarks tend to stick to the $QQ\bar{Q}$ forming a new type of hadrons.
Many interesting questions in HQ hadrons

- Does D meson melt in nuclei like $\pi$ and $K^{\text{bar}}$?
- How does the heavy quark spin symmetry emerge and the chiral symmetry disappear?
- When do the NG bosons turn into the heavy meson doublet? $\pi-\rho$, $K-K^*$ $\Rightarrow$ $D-D^*$, $B-B^*$
- Why are there many exotic resonance-like states appear in HQ sector? Are they compact states or just cusps?
- Are the interactions between $Y_{cN}$ and $Y_{cY_{c}}$ similar to hyperons? Are they described by meson exchanges plus short-range interaction?
- How does the heavy quark spin symmetry manifest in baryons? Can we study di-quark spectroscopy from the transition from strange to charm/bottom baryons?
Heavy Quark Spin Symmetry

Magnetic gluon coupling is suppressed

\[ \bar{\Psi} \gamma^\mu \frac{\lambda^a}{2} \Psi A^a_\mu \sim \Psi^\dagger \frac{\lambda^a}{2} \Psi A^a_0 \]

(Color Electric coupling) \gg (Color Magnetic coupling)

HQ spin-flip amplitudes are suppressed by \((1/m_Q)\).

\[ \Rightarrow \text{Heavy Quark Spin Symmetry} \]
M.Oka (Tokyo Tech. and JAEA)

Heavy Quark Spin Symmetry

HQ spin symmetry \( [S_Q, H] = O \left( \frac{1}{m_Q} \right) \)
\[
\begin{align*}
Q & \quad qq \\
\{ & \quad J = J_L \pm \frac{1}{2} \text{ states are degenerate in the HQ limit.}
\end{align*}
\]

\( J_L = 1 \) for 1\(^+\) diquark
\( J_L = 0 \) for 0\(^+\) diquark

\( \Sigma^* 1385 \)
\( \Sigma_{av} 1321 \)
\( \Sigma^*_{c} 2518 \)
\( \Sigma_{cav} 2496 \)
\( \Sigma 1193 \)
\( \Lambda 1116 \)
\( \Sigma_{bav} 5826 \)
\( \Sigma^*_{b} 5833 \)
\( \Sigma_{b} 5812 \)
\( \Lambda 5620 \)
Heavy Quark Spin Symmetry

Strange

\[ \Sigma^* 1385 \]
\[ \Sigma_{1193} \]
\[ \Lambda 1116 \]

Charm

\[ \Sigma_c 2453 \]
\[ \Sigma_{cav} 2496 \]
\[ \Sigma_b 5812 \]
\[ \Lambda_c 2286 \]
\[ \Lambda_b 5620 \]

\[ \Sigma_{av} 1321 \]

Bottom

\[ \Sigma^*_c 2518 \]
\[ \Sigma^*_b 5833 \]

\[ \text{vector mesons 1}^- \]
\[ \text{pseudoscalar mesons 0}^- \]

\[ K^* 892 \]
\[ K_{av} 793 \]
\[ D_{av} 1974 \]
\[ B^* 5325 \]
\[ B 5279 \]

\[ 142 \text{MeV} \]
\[ 397 \text{MeV} \]
\[ 1.4 \text{GeV} \]
\[ 46 \text{MeV} \]

\[ D' 2009 \]
\[ 142 \text{MeV} \]
\[ 323 \text{MeV} \]
\[ \sim 310 \text{MeV} \]

\[ \text{isoscalar baryon 1/2}^+ \]

\[ \text{isovector baryon 3/2}^+ \]

\[ 194 \text{MeV} \]
\[ 205 \text{MeV} \]
\[ 65 \text{MeV} \]
\[ 21 \text{MeV} \]
\[ 210 \text{MeV} \]

\[ 3 \text{MeV} \]

\[ Q-(qq)^+_1 \]
\[ Q-(qq)^-_0 \]

\[ Q-q \]
\[ Q-\bar{q} \]

\[ M_Q = 500 \text{MeV} \]
\[ K 495 \]

\[ 500 \text{MeV} \]
\[ 1.4 \text{GeV} \]
\[ 4.3 \text{GeV} \]
Heavy Hadron in Nuclei

- $D (=c\bar{q}) (\leq K\bar{q})$ bound in DNN system
- $D^{\bar{q}} (=c^{\bar{q}} q)$ in nuclear medium (Yasui, Sudoh)
- Charmonium $J/\psi, \eta_c$ in nuclei
  Charmonium bound in nuclei (Yokota et al.)
- Charmed dibaryons and nuclei
  $\Lambda_{c\bar{p}n}$ bound state (YR Liu et al., Maeda, et al.)
DN system and D in nuclei

- D (=$c\,u^{\text{bar}}, c\,d^{\text{bar}}$) in medium compared to $K^{\text{bar}} (=s\,u^{\text{bar}}, s\,d^{\text{bar}})$
  Does DN have a strong attraction and couple strongly to $\Lambda_c(1/2^-)$?
  Contact TW-type interaction is strongly attractive.
  $O\pi E$ couples D and $D^*$ strongly.

- If $\Lambda_c(2595)$ is a bound DN state, there may be a deeply bound DNN state and D-nuclei.

C. Garcia-Recio, et al. (2009), Y. Yamaguchi, et al. (2013),
M. Bayar et al. (2004)
DN system and D nuclei

- Negative-parity charmed baryon as DN $\leftrightarrow \Lambda(1405)$ as $K^{\text{bar}}N$

---

**M.Oka (Tokyo Tech. and JAEA)**
DN system and D nuclei

- A narrow DNN bound state is predicted.

* M. Bayar et al., PR C86 (2012) 044004

---

**B. E. and size of DNN (S=0)**

<table>
<thead>
<tr>
<th>Model</th>
<th>Minnesota</th>
<th>HN1 mod.</th>
<th>Av18 (C+SS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total B. E.</td>
<td>250.9 MeV</td>
<td>225.4 MeV</td>
<td>209.4 MeV</td>
</tr>
<tr>
<td>R rms (T)</td>
<td>0.5 fm</td>
<td>0.75 fm</td>
<td>1.26 fm</td>
</tr>
<tr>
<td>Λc* - N</td>
<td>42 MeV</td>
<td>16.5 MeV</td>
<td>0.5 MeV</td>
</tr>
<tr>
<td>DNN (S=0)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.0 fm</td>
<td>1.6 fm</td>
<td>2.6 fm</td>
</tr>
<tr>
<td></td>
<td>0.3 fm</td>
<td>0.4 fm</td>
<td>1.9 fm</td>
</tr>
</tbody>
</table>

---

* M. Oka (Tokyo Tech. and JAEDA)*
A narrow DNN bound state is predicted.

*M. Bayar et al.,* PR C86 (2012) 044004
DN system and D in nuclei

- D in matter shows two branches: deep bound and repulsive
  

- The strong attraction seems inconsistent with the QCD SR.
  
This is still an open problem. It is important to see how $K$ and $D$ are different from the viewpoint of chiral symmetry.

As studies of $K^{\text{bar}}NN$ system is powerful in understanding the nature of $\Lambda(1405)$ and $K^{\text{bar}}N$ interaction, $DNN$ and $D$ in nuclei should help us to understand the nature of the $DN$ interactions.
**D^{bar} (B) mesons in nuclei**


The $1/m_Q$ expansion of heavy hadron ($D^{(*)}$, $B^{(*)}$) masses in QCD

\[ M_H = m_Q + \bar{\Lambda} - \frac{\lambda_1}{2m_Q} + 4\bar{S}_Q \cdot \bar{S}_L \frac{\lambda_2(m_Q)}{2m_Q} + \mathcal{O}(1/m_Q^2), \]


\[ \frac{1}{2M_H} \left< \bar{H}_{v_r} \left| \frac{\beta(\alpha_s)}{4\alpha_s} G^2 \right| \bar{H}_{v_r} \right> = \bar{\Lambda}, \quad \text{scale anomaly} \]

\[ \left< H_{v_r} \left| \bar{Q}_{v_r} g_s \vec{x} \cdot \vec{E} Q_{v_r} \right| H_{v_r} \right> = - \frac{\lambda_1}{m_Q}, \quad \text{color electric} \]

\[ \frac{1}{2} c(\mu) \left< H_{v_r} \left| \bar{Q}_{v_r} g_s \vec{\sigma} \cdot \vec{B} Q_{v_r} \right| H_{v_r} \right> = 8 \bar{S}_Q \cdot \bar{S}_L \lambda_2(m_Q), \quad \text{color magnetic} \]

M. Neubert (1994)

M.Oka (Tokyo Tech. and JAEA)
Properties of heavy hadrons in nuclear medium will directly be connected to the QCD matrix elements of gluon fields.

\[ M_H(\rho) = m_Q + \bar{\Lambda}(\rho) - \frac{\lambda_1(\rho)}{2m_Q} + 4\bar{S} \cdot \bar{j} \frac{\lambda_2(\rho; m_Q)}{2m_Q} + \mathcal{O}(1/m_Q^2) \]
Properties of heavy hadrons in nuclear medium will directly be connected to the QCD matrix elements of gluon fields.

\[ M_H(\rho) = m_Q + \Lambda(\rho) - \frac{\lambda_1(\rho)}{2m_Q} + 4 \vec{S} \cdot \vec{j} \frac{\lambda_2(\rho; m_Q)}{2m_Q} + \mathcal{O}(1/m_Q^2) \]
Properties of heavy hadrons in nuclear medium will directly be connected to the QCD matrix elements of gluon fields.

\[ M_H(\rho) = m_Q + \bar{\Lambda}(\rho) - \frac{\lambda_1(\rho)}{2m_Q} + 4\vec{S} \cdot \vec{j} \frac{\lambda_2(\rho; m_Q)}{2m_Q} + O(1/m_Q^2) \]
Pure HQ hadrons have attractive interaction with matter.

Color-van-der-Waals force (second order perturbation) is (weakly) attractive.

Lattice QCD (quenched) calculation:
shows attractive potential with screening at large distances.
This results favors J/ψ bound states in light nuclei.
Pure HQ hadrons have attractive interaction with matter. Color-van-der-Waals force (second order perturbation) is (weakly) attractive. Lattice QCD (quenched) calculation: T. Kawanai, S. Sasaki, PRD82, 091501 (2010) shows attractive potential with screening at large distances. This results favors J/ψ bound states in light nuclei.
Charmonium in Nuclei

$J/\psi$ in $^4$He

![Graph showing the energy $E$ as a function of $a$ in fm with different values of $\mu$.](image)

$J/\psi - ^4$He bound state is made when

- $a_{J/\psi N} \leq -0.24 \text{ fm}$ ($\mu = (1.0 \text{ fm})^{-2}$)
- $a_{J/\psi N} \leq -0.23 \text{ fm}$ ($\mu = (0.8 \text{ fm})^{-2}$)
- $a_{J/\psi N} \leq -0.22 \text{ fm}$ ($\mu = (0.6 \text{ fm})^{-2}$)

If $a_{J/\psi N} = -0.3 \text{ fm}$

- $E = -0.22 \text{ MeV}$ ($\mu = (1.0 \text{ fm})^{-2}$)
- $E = -0.36 \text{ MeV}$ ($\mu = (0.8 \text{ fm})^{-2}$)
- $E = -0.44 \text{ MeV}$ ($\mu = (0.6 \text{ fm})^{-2}$)

If $a_{J/\psi N} \sim -0.4 \text{ fm}$

- $E = -1.03 \text{ MeV}$ ($\mu = (1.0 \text{ fm})^{-2}$)
- $E = -1.18 \text{ MeV}$ ($\mu = (0.8 \text{ fm})^{-2}$)
- $E = -1.29 \text{ MeV}$ ($\mu = (0.6 \text{ fm})^{-2}$)

Yokota, Hiyama, MO, PTEP (2013)
Various approaches for $\Lambda_c N$ interaction/$\Lambda_c$ in matter

- Lattice QCD T. Miyamoto (HAL-QCD) (2015)
- QCD sum rule (finite density) K. Ohtani et al. (2017)
- Chiral Effective Lagrangian approach
  Haidenbauer (2017)

- Phenomenological Meson Exchange Model
  - HQ effective theory: Y.R. Liu, MO (2012), Gal et al. (2014), Maeda et al. (2016)
  - Mean field: Tsushima, Khanna (2003)
**Heavy dibaryons**

**Couplings between $\Sigma_c N$ and $\Sigma_c^* N$ channels are strong.**

<table>
<thead>
<tr>
<th>Strange</th>
<th>Charm</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Sigma^*(1385)$</td>
<td>$\Sigma_c^*(2518)$</td>
</tr>
<tr>
<td>$(s,u,u)(s,u,d)$</td>
<td>$(c,u,u)(c,u,d)$</td>
</tr>
<tr>
<td>$(s,d,d)$</td>
<td>$(c,d,d)$</td>
</tr>
<tr>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>196 $[MeV]$</td>
<td>64 $[MeV]$</td>
</tr>
<tr>
<td>73 $[MeV]$</td>
<td>168 $[MeV]$</td>
</tr>
<tr>
<td>$\Sigma(1189)$</td>
<td>$\Sigma_c(2454)$</td>
</tr>
<tr>
<td>$(s,u,u)(s,u,d)$</td>
<td>$(c,u,u)(c,u,d)$</td>
</tr>
<tr>
<td>$(s,d,d)$</td>
<td>$(c,d,d)$</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>$\Lambda(1116)$</td>
<td>$\Lambda_c(2286)$</td>
</tr>
<tr>
<td>$(s,u,d)$</td>
<td>$(c,u,d)$</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

**Coupled channel calculation of $\Lambda_c N - \Sigma_c N - \Sigma_c^* N$ bound/resonance states:**

Charmed dibaryons

- HQ doublets
  A shallow bound state of $\Lambda_c\,N$ with $j=1/2$
  A shallow ($j=1/2$) and deep bound ($j=3/2$) state of $\Sigma_c^(*)\,N$

$\Sigma^*_c\,N - 4.8\,\text{MeV} \quad j=1/2$

$\Sigma^*_c\,N - \Sigma_c\,N$
-25 MeV ($j=3/2$)

S. Maeda et al.,

M. Oka (Tokyo Tech. and JAEA)
$\Lambda_c NN$ charm nuclei
Λ_{c}N - Σ_{c}N coupled channel: I (J^{P}) = 1 (1^{+})

Pion exchanges are still not fully included with large quark masses.
\( \Lambda_c \) in medium from QCD sum rules

QCD sum rules applied to Heavy baryons


In vacuum

\[ \alpha_s \] corrections (NLO)


dimension 8 condensates

parity projection


<table>
<thead>
<tr>
<th></th>
<th>in vacuum</th>
<th>in medium</th>
<th>in vacuum</th>
<th>in medium</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Lambda_c ) [GeV³]</td>
<td>( \lambda_{\Lambda_c} ) [GeV³]</td>
<td>( \lambda_{\Lambda_c}^* ) [GeV³]</td>
<td>( m_{\Lambda_c} ) [GeV]</td>
<td>( m_{\Lambda_c}^* ) [GeV]</td>
</tr>
<tr>
<td>K. Azizi et al.</td>
<td>0.022 ± 0.002</td>
<td>0.021 ± 0.001</td>
<td>2.284 ± 0.078</td>
<td>2.335 ± 0.045</td>
</tr>
<tr>
<td>Z. G. Wang</td>
<td>0.024 ± 0.012</td>
<td>0.023 ± 0.007</td>
<td>2.235 ± 0.244</td>
<td>1.434 ± 0.203</td>
</tr>
</tbody>
</table>

In nuclear matter
Correlation function:

\[ \Pi(q) = i \int e^{iqx} \langle \Psi_0(\rho, u^\mu) | T[J_{\Lambda_c}(x) \bar{J}_{\Lambda_c}(0)] | \Psi_0(\rho, u^\mu) \rangle d^4x \]

\[ = q\Pi_1(q_0, |q|) + \Pi_2(q_0, |q|) + \eta\Pi_3(q_0, |q|) \]

\[ \Psi_0(\rho, u^\mu) : \text{Ground state of Nuclear medium} \quad u^\mu : \text{velocity of medium} \]

\[ \Lambda_c \text{ interpolating operator:} \quad J_{\Lambda_c} = \epsilon^{abc}(u^T a c' \gamma_5 b^c d^c) \]

Parity Projection + Gaussian sum rule

\[ G_{OPE}(\tau) = \int_0^\infty \frac{1}{\sqrt{4\pi \tau}} \exp \left( -\frac{(q_0^2 - m_c^2)^2}{4\tau} \right) \rho(q_0) dq_0 \]
\( \Lambda_c \) in medium from QCD sum rules

**Operator Product Expansion**

\[
G_{OPE}(\tau) = Q + \langle \bar{q}q \rangle + \frac{\alpha_s}{\pi} G^2 + \cdots
\]

Quark, Gluon Condensates contain non-perturbative (long-distance) contribution

\[
\langle \bar{q}q \rangle_0 \langle \frac{\alpha_s}{\pi} G^2 \rangle_0 \langle \bar{q}q\bar{q}q \rangle_0 \cdots \quad \text{in vacuum}
\]

Effects of the medium are taken into account as density dependences of the condensates.

\[
\langle \bar{q}q \rangle_m \langle \frac{\alpha_s}{\pi} G^2 \rangle_m \langle \bar{q}q\bar{q}q \rangle_m \cdots \quad \text{in medium}
\]

Linear density dependence

\[
\langle \bar{q}q \rangle_m = \langle \bar{q}q \rangle_0 + \rho \frac{\sigma_N}{2m_q} \\
\langle q^\dagger q \rangle_m = \rho \frac{3}{2}
\]

\[
\cdots
\]
Density dependence of the four-quark condensate

Factorization (F-type)

\[
\langle \bar{q}q\bar{q}q \rangle_m = -\frac{1}{6} \left( \langle \bar{q}q \rangle_m^2 + \langle q^\dagger q \rangle_m^2 \right)
\]

\[
= -\frac{1}{6} \left( \langle \bar{q}q \rangle_0^2 + \rho \left( \frac{\sigma_N}{m_q} \right) \langle \bar{q}q \rangle_0 + \left( \frac{\sigma_N^2}{4m_q^2} + \frac{9}{4} \right) \rho^2 \right)
\]

\[
\sim 10
\]

**Factorization predicts a strong density dependence.**

Model calculation in Perturbative chiral quark model (QM-type)


\[
\langle \bar{q}q\bar{q}q \rangle_m = -\frac{1}{6} \langle \bar{q}q \rangle_0^2 - \rho \frac{1}{4} \left( 0.935 \langle \bar{q}q \rangle_0 + \mathcal{O}(\rho^2) \right)
\]

**The coefficient of the linear-density term is much smaller.**
Density dependence of the 4-quark condensate in the factorization scheme seems too strong.

The perturbative chiral quark model gives milder dependence. At the normal nuclear density $\Delta E_{\Lambda_c} \approx -20\text{MeV}$
Summary

- We are in the era of new discoveries and development of heavy hadron spectroscopy in vacuum and also in matter.
- New forms of atomic nuclei with heavy flavor hadrons are very interesting. Heavy hadrons can probe the properties of hadronic matter.
- Heavy hadrons in matter provide us with information of the heavy hadron structure.
Sincere thanks to Qiang Zhao, Wei-Hong Liang, and All the members of LOC for wonderful hospitality.

As a member of IAC, I am honored to announce
APFB2020
in Kanazawa, Japan

Chair: Emiko Hiyama (RIKEN/Kyushu Univ.)
Vice-Chair: Atsushi Tamii (RCNP, Osaka Univ.)
Nishi Chayamachi Street
Kaga Yuzen Dyeing of Fabric
Tea Ceremony
Gold Leaf Crafts & Arts
See you in Kanazawa, in 2020
Kenrokuen Garden