Effect of partial chiral symmetry restoration in nuclear matter to charmed meson masses based on a chiral partner structure

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Based on
• M. Harada, Y.L. Ma, D. Suenaga, Y. Takeda, arXiv:1612.03496
• Y. Motohiro, Y. Kim, M.Harada, PRC92, 025201 (2015)
1. Introduction
Phase diagram of Quark-Gluon system

High density Neutron Star

• Chiral Symmetry Restriction
• Deconfinement of Quarks

Early Universe

• Spontaneous Chiral Symmetry Breaking
• Confinement of Quarks

Hadron Phase

Normal Nuclei

100 million ton/cm³

High density

1 trillion kelvin

high temperature
Important for understanding the spontaneous chiral symmetry breaking

\[ \langle \bar{q}q \rangle \neq 0 \text{ (chiral condensate)} \]

• The spontaneous chiral symmetry breaking is expected to generate a part of hadron masses.
• It causes mass difference between chiral partners.
• Changing T and/or density will cause some change of hadron masses.
In [Y. Motohiro, Y.Kim, M.Harada, Phys. Rev. C 92, 025201 (2015)], we studied nuclear matter using a parity doublet model, and showed some relations between the chiral invariant mass of nucleon and the phase structure. We also presented a density dependence of the nucleon mass, which changes reflecting the partial chiral symmetry restoration.

What happens to the masses of other hadrons in nuclear matter?
• In this talk, I introduce our recent work [M.Harada, Y.L.Ma, D.Suenaga, Y.Takeda, arXiv:1612.03496], where we study the charmed meson masses in nuclear matter through the exchange of sigma and omega mesons.

• In this talk, I focus on the density dependence in the matter described by the parity doublet model.

Outline

1. Introduction
2. Nuclear matter from a parity doublet model
3. Density dependence of effective masses of charmed mesons
4. Summary
2. Nuclear matter from a parity doublet model

Parity Doublet model for nucleon


• An excited nucleon with negative parity such as $N^*(1535)$ is regarded as the chiral partner to the $N(939)$ which has the positive parity.

• These nucleons have a chiral invariant mass in addition to the mass generated by the spontaneous chiral symmetry breaking which is caused by the existence of the sigma condensate, $\langle \sigma \rangle \neq 0$. 
Nuclear matter in parity doublet models

• A parity doublet model including omega meson with 4-point interaction is used in a Walecka-type mean field analysis.
  — Large value of $m_0$ is needed to reproduce the incompressibility.
• Rho meson is further included with 4-point interaction.
  — $m_0 > 800$ MeV is needed to have $100 < K < 400$ MeV
• In our analysis [Y.Motohiro, Y.Kim, M.Harada, Phys. Rev. C 92, 025201 (2015)], we construct a model with a 6-point interaction of sigma, but without 4-point interaction for vector mesons.
• Our results show that $K = 240$ MeV is reproduced for $m_0 = 500 - 900$ MeV.

D.Zschiesche et al., PRC75, 055202 (2007)
V.Dexheimer et al., PRC77, 025803 (2008)
Binding Energy, Pressure, Mean fields

$m_0 = 500$ MeV

**Binding Energy**

$\langle \sigma \rangle$ (MeV)

$m_0 = 500$ MeV

$m_0 = 700$ MeV

$\langle \omega \rangle = \frac{g_{\omega NN}}{m_{\omega}^2} \rho_B$ (MeV)

$m_0 = 500, 700$ MeV

Pressure

$\rho_B$ (fm$^3$)

2017/1/9

Hadron and Nuclear Physics in 2017 @ KEK
Effective masses of nucleons

In this talk, I define effective masses of nucleons by including effects of exchanging the sigma and omega mesons in the mean field approximation, following our recent work [M.Harada, Y.L.Ma, D.Suenaga, Y.Takeda, arXiv:1612.03496].

$$m_{\pm}^{\text{(eff)}} = \frac{1}{2} \left[ \sqrt{(g_1 + g_2)^2 \langle \sigma \rangle^2 + 4m_0^2} \mp (g_2 - g_1) \langle \sigma \rangle \right] + g_{\omega NN} \langle \omega \rangle \quad \text{(nucleon)}$$

$$\overline{m}_{\pm}^{\text{(eff)}} = \frac{1}{2} \left[ \sqrt{(g_1 + g_2)^2 \langle \sigma \rangle^2 + 4m_0^2} \mp (g_2 - g_1) \langle \sigma \rangle \right] - g_{\omega NN} \langle \omega \rangle \quad \text{(anti-nucleon)}$$
Density dependence of effective masses

\[ m_{\pm}^{(\text{eff})} = \frac{1}{2} \left[ \sqrt{(g_1 + g_2)^2 \langle \sigma \rangle^2 + 4m_0^2} \mp (g_2 - g_1)\langle \sigma \rangle \right] + g_{\omega NN} \langle \omega \rangle \] (nucleon)

\[ \overline{m}_{\pm}^{(\text{eff})} = \frac{1}{2} \left[ \sqrt{(g_1 + g_2)^2 \langle \sigma \rangle^2 + 4m_0^2} \mp (g_2 - g_1)\langle \sigma \rangle \right] - g_{\omega NN} \langle \omega \rangle \] (anti-nucleon)

- Sum of masses of nucleon and anti-nucleon decreases toward \( m_0 \) reflecting the partial chiral symmetry restoration.
- Studying effective masses will give a clue for \( m_0 \).
3. Density dependence of effective masses of charmed mesons

M. Harada, Y.L. Ma, D. Suenaga, Y. Takeda, arXiv:1612.03496
Chiral partner structure for charmed mesons


- 2 heavy quark multiplets with \( J_\ell = 1/2 \) are regarded as the chiral partner:

\[
\left[ D(0^{-}), D^*(1^{-}) \right] \quad \leftrightarrow \quad \text{chiral partner} \quad \left[ D_0^*(0^+), D_1(1^+) \right]
\]

- Mass difference is generated by the chiral condensate, and the value is roughly equal to the constituent quark mass.

- Experimental value implies that the chiral partner structure seems to work:

\[
m(0^+) - m(0^-) \approx m(1^+) - m(1^-) \approx 0.43 \text{GeV}
\]
Masses of charmed mesons in nuclear matter

- Effective masses for $D(J^P=0^-)$, $D(J^P=0^+)$ in nuclear matter
  
  \[
m^{(\text{eff})}_{D(-)} = m - \frac{1}{2} \Delta M \frac{\langle \sigma \rangle}{f_\pi} + g_{\omega DD} \langle \omega_0 \rangle
  \]
  
  \[
m^{(\text{eff})}_{D(+)} = m + \frac{1}{2} \Delta M \frac{\langle \sigma \rangle}{f_\pi} + g_{\omega DD} \langle \omega_0 \rangle
  \]

- Effective masses for anti-charmed mesons
  
  \[
m^{(\text{eff})}_{\overline{D}(-)} = m - \frac{1}{2} \Delta M \frac{\langle \sigma \rangle}{f_\pi} - g_{\omega DD} \langle \omega_0 \rangle
  \]
  
  \[
m^{(\text{eff})}_{\overline{D}(+)} = m + \frac{1}{2} \Delta M \frac{\langle \sigma \rangle}{f_\pi} - g_{\omega DD} \langle \omega_0 \rangle
  \]
Charmed meson masses

\[ m^{(\text{eff})}_{D(-)} = m - \frac{1}{2} \Delta M \frac{\langle \sigma \rangle}{f_\pi} + g_{\omega DD} \langle \omega_0 \rangle \]
\[ m^{(\text{eff})}_{\bar{D}(-)} = m - \frac{1}{2} \Delta M \frac{\langle \sigma \rangle}{f_\pi} - g_{\omega DD} \langle \omega_0 \rangle \]
\[ m^{(\text{eff})}_{D(+)} = m + \frac{1}{2} \Delta M \frac{\langle \sigma \rangle}{f_\pi} + g_{\omega DD} \langle \omega_0 \rangle \]
\[ m^{(\text{eff})}_{\bar{D}(+)} = m + \frac{1}{2} \Delta M \frac{\langle \sigma \rangle}{f_\pi} - g_{\omega DD} \langle \omega_0 \rangle \]

An example \[ |g_{\omega DD}| = 3.4 \]

Increasing or decreasing of pseudo-scalar D(-) meson mass only is not enough for measuring the partial chiral symmetry restoration.

\[ g_{\omega DD} < 0 \quad g_{\omega DD} > 0 \]

\( \bar{D}(+) \)  \( D(+) \)

\( \bar{D}(-) \)  \( D(-) \)

\( D(+) \)  \( \bar{D}(+) \)

\( D(-) \)  \( \bar{D}(-) \)
Partial chiral symmetry restoration

\[ m^{(\text{eff})}_{D(\pm)} = m \pm \frac{1}{2} \Delta M \frac{\langle \sigma \rangle}{f_\pi} + g_{\omega DD} \langle \omega_0 \rangle \]

- In addition to study the mass difference of chiral partners, taking average of particle and anti-particle will give a clue for partial chiral symmetry restoration.
- Threshold energy for production of D and anti-D meson pair in medium is larger than vacuum reflecting the partial chiral symmetry restoration.
4. Summary

- We studied density dependence of charmed meson masses from the mean field contributions of sigma and omega mesons in the nuclear medium described in the parity doublet model.

- Increasing or decreasing of $D(-)$ meson mass only is not enough for measure the chiral symmetry restoration.

- In addition to study the mass difference of chiral partners, taking average of particle and anti-particle will give a clue for partial chiral symmetry restoration.

- Threshold energy for production of $D$ and anti-$D$ meson pair in medium is larger than vacuum reflecting the partial chiral symmetry restoration.
The End