Neutron Star Matter with In-Medium Meson Mass

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Outline

1 Introduction

★ Possible indication of hadron mass decrease in nuclear medium

♦ Theory

– Brown-Rho (BR) scaling (Brown and Rho, PRL66 (1991) 2720)

$$\frac{m_N^*}{m_N} \approx \frac{m_\sigma^*}{m_\sigma} \approx \frac{m_\omega^*}{m_\omega} \approx \frac{m_\rho^*}{m_\rho}. \tag{1}$$

– QCD-sum rule (Hatsuda and Lee, PRC46 (1992) R34)

$$\frac{m*_\rho}{m_\rho} \approx \frac{m_\omega^*}{m_\omega} \simeq 0.82. \tag{2}$$

– Quark-meson-coupling model (Saito, Tsushima and Thomas, PRC55 (1997) 4050)

$$\frac{m_N^*}{m_N} \simeq 0.79, \quad \frac{m_\rho^*}{m_\rho} \approx \frac{m_\omega^*}{m_\omega} \simeq 0.83. \tag{3}$$

- Experiment : Dilepton decay of ρ- and ω- mesons
  - KEK-PS E325 (Ozawa *et al.*, PRL86 (2001) 5019)
  - CERES/NA45 Collab. (Adamová *et al.*, PRL 91 (2003) 042301)

★ Contraints of symmetric nuclear matter at saturation density

- $E_B = 16\text{MeV}$ at $\rho_0 = 0.17\,\text{fm}^{-3}$
- $m_N^* = (0.7 \sim 0.8)m_N$
- $K = 200 \sim 300\text{MeV}$
- $a_{sym} = 32.5\text{MeV}$

★ Neutron star (NS) : Narrow mass zone (Thorsett and Chakrabarty, ApJ. 512 (1999) 288)

$$M_{NS} = (1.0 \sim 1.6)M_\odot \tag{4}$$

★ Question : Can the properties of NS be affected by meson-mass changes in matter?

Constant meson mass vs **Density-dependent meson mass**

2 Models

★ Models with constant meson mass

(1) Walecka model (QHD)

$$
\begin{aligned}
\mathcal{L}_{\rm QHD}^{\rm MF} &= \mathcal{L}_0 + U(\bar{\sigma}), \\
\mathcal{L}_0 &= \bar{\psi}_N \left[i\gamma^\mu \partial_\mu - m_N^* - g_{\omega N}\, \gamma^0\, \bar{\omega}_0 - \frac{1}{2}\, g_{\rho N}\, \gamma^0\, \bar{b}_{03}\, \tau_3 \right] \psi_N - \frac{1}{2} m_\sigma^2\, \bar{\sigma}^2 + \frac{1}{2} m_\omega^2\, \bar{\omega}_0^2 + \frac{1}{2} m_\rho^2\, \bar{b}_{03}^2, \\
m_N^* &= m_N - g_{\sigma N}\, \bar{\sigma}, \\
U(\bar{\sigma}) &= \frac{1}{3} m_N\, b\, (g_{\sigma N}\, \bar{\sigma})^3 + \frac{1}{4} c\, (g_{\sigma N}\, \bar{\sigma})^4.
\end{aligned}
$$

– $\bar{\sigma},\ \bar{\omega}_0,\ \bar{b}_{03}$: Mean field equation of motion

– $g_{\sigma N},\ g_{\omega N},\ b,\ c$: From $E_B,\ \rho_0,\ m_N^*,\ K$

– $g_{\rho N}$: From a_{sym}

(2) Modified Quark-meson coupling model (MQMC) (X. Jin and B. K. Jennings, PRC54 (1996) 1427)

$$\begin{aligned}
\mathcal{L}^{\rm MF}_{\rm MQMC} &= \bar{\psi}_q[i\gamma^\mu\partial_\mu - (m_q^0 - g_\sigma^q\,\bar{\sigma}) - g_\omega^q\,\gamma^0\,\bar{\omega}_0 - \frac{1}{2}g_\rho^q\,\gamma^0\,\bar{b}_{03}\,\tau_3 - B]\times\theta_V(R-r)\psi_q \\
&\quad -\frac{1}{2}m_\sigma^2\,\bar{\sigma}^2 + \frac{1}{2}m_\omega^2\,\bar{\omega}_0^2 + \frac{1}{2}m_\rho^2\,\bar{b}_{03}^2, \\
m_N^* &= \sqrt{\left(E^N_{bag}\right)^2 - 3\frac{x_q^2}{R^2}}, \\
E^N_{bag} &= 3\frac{\Omega_q}{R} - \frac{Z_N}{R} + \frac{4}{3}\pi R^3 B, \\
\Omega_q &= \sqrt{x_q^2 + R^2 m_q^{*2}}, \quad (m_q^* = m_q^0 - g_\sigma^q\bar{\sigma}), \\
B &= B_0\left(1 - g_\sigma^B\frac{4}{\delta}\frac{\bar{\sigma}}{m_N}\right)^\delta
\end{aligned}$$

– $B_0,\ Z_N$: From $m_N = 939$ MeV at $R = 0.6$ fm

– $g_\sigma^q,\ g_\omega^q,\ g_\sigma^B,\ \delta$: From $E_B,\ \rho_0,\ m_N^*,\ K$

– g_ρ^q : From a_{sym}

★ Models with density-dependent meson mass

(1) BR-scaled effective chiral Lagrangian (QHD-BR) (C. Song *et al.*, PRC56 (1997) 2244)

$$\begin{aligned}
\mathcal{L} &= \mathcal{L}_0(m_\sigma \to m_\sigma^*,\, m_V \to m_V^*,\, g_{VN} \to g_{VN}^*), \quad (V=\omega,\, \rho) \\
m_N^* &= M_N^* - g_{\sigma N}\,\bar{\sigma}, \\
\frac{M_N^*}{m_N} &= \frac{m_\sigma^*}{m_\sigma} = \frac{m_V^*}{m_V} = \left(1 + y\frac{\rho}{\rho_0}\right)^{-1}, \\
\frac{g_{VN}^*}{g_{VN}} &= \left(1 + z\frac{\rho}{\rho_0}\right)^{-1}
\end{aligned}$$

– $g_{\sigma N}$, $g_{\omega N}$, y, z : From E_B, ρ_0, m_N^*, K

(2) MQMC with scaled meson mass (SMQMC)

$$\mathcal{L} = \mathcal{L}_{\rm MQMC}^{\rm MF}(m_\sigma \to m_\sigma^*,\, m_V \to m_V^*)$$

– More parameters than the number of contraints : y fitted to BR-scaling law

(3) MQMC with meson bag (MQMC-MB)

$$\mathcal{L} = \mathcal{L}^{\rm MF}_{\rm MQMC}(m_V \to m_V^*),$$
$$m_V^* = \sqrt{\left(E^V_{bag}\right)^2 - 2\frac{x_q^2}{R^2}},$$
$$E^V_{bag} = 2\frac{\Omega_q}{R} - \frac{Z_V}{R} + \frac{4}{3}\pi R^3 B$$

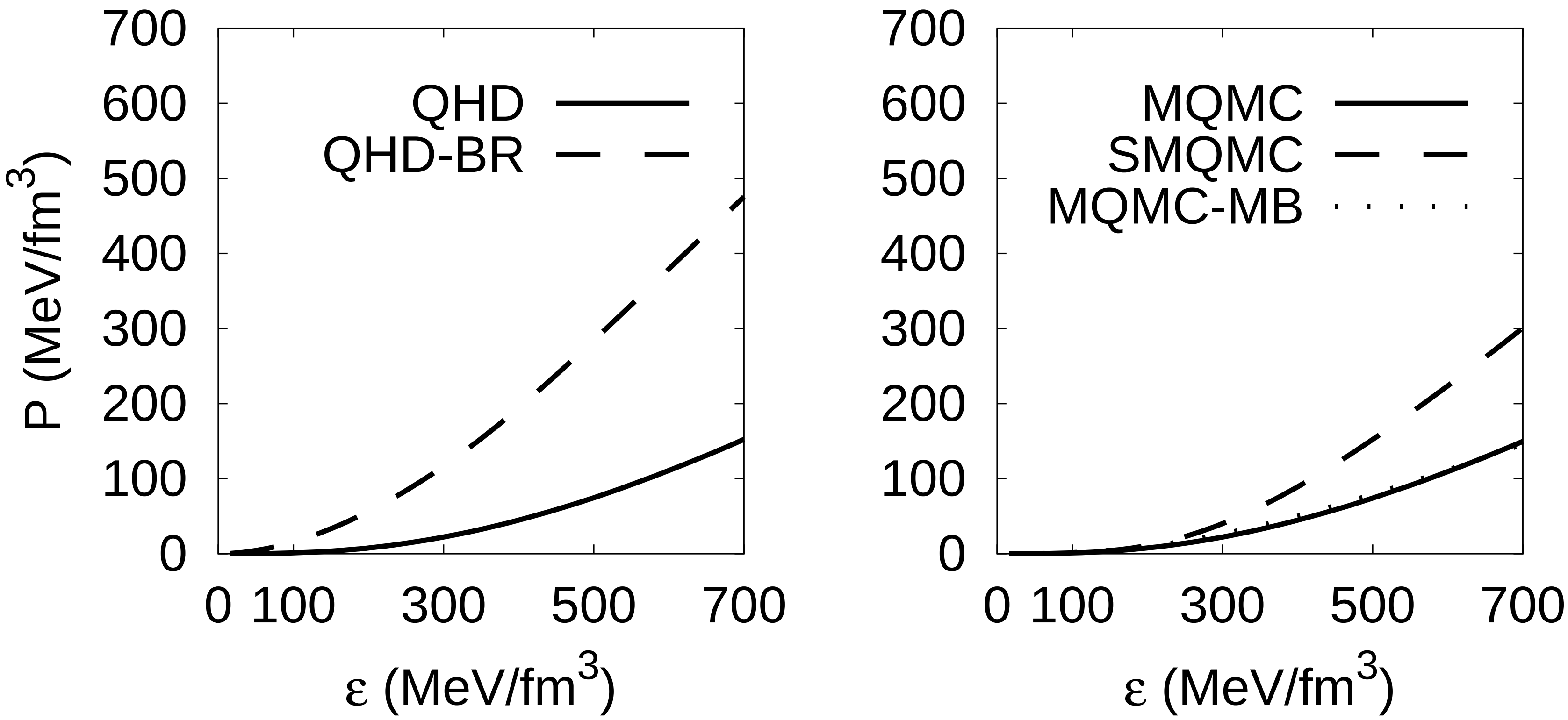
– Z_V : From m_V (770 MeV for ρ-meson and 783 MeV for ω-meson)

★ Properties at the saturation

	Constant meson mass		Density dependent meson mass		
	QHD	MQMC	QHD-BR	SMQMC	MQMC-MB
m_N^*/m_N	0.77	0.78	0.67	0.76	0.85
m_V^*/m_V	1.0	1.0	0.78	0.78	0.86
K (MeV)	311	286	265	592	324

3 Results for neutron star matter

★ Equation of state (EoS)



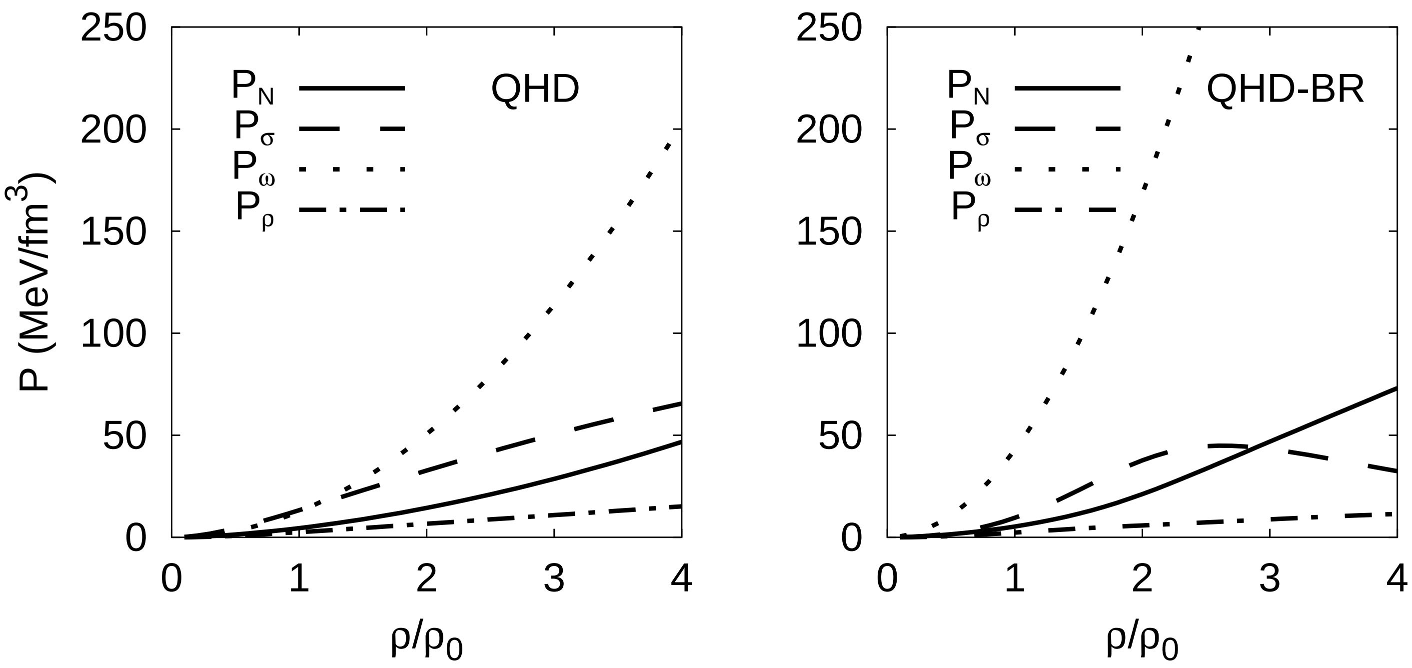
♦ Stiffer equation of state → Larger maximum mass of NS

♦ Why is the EoS so stiff?

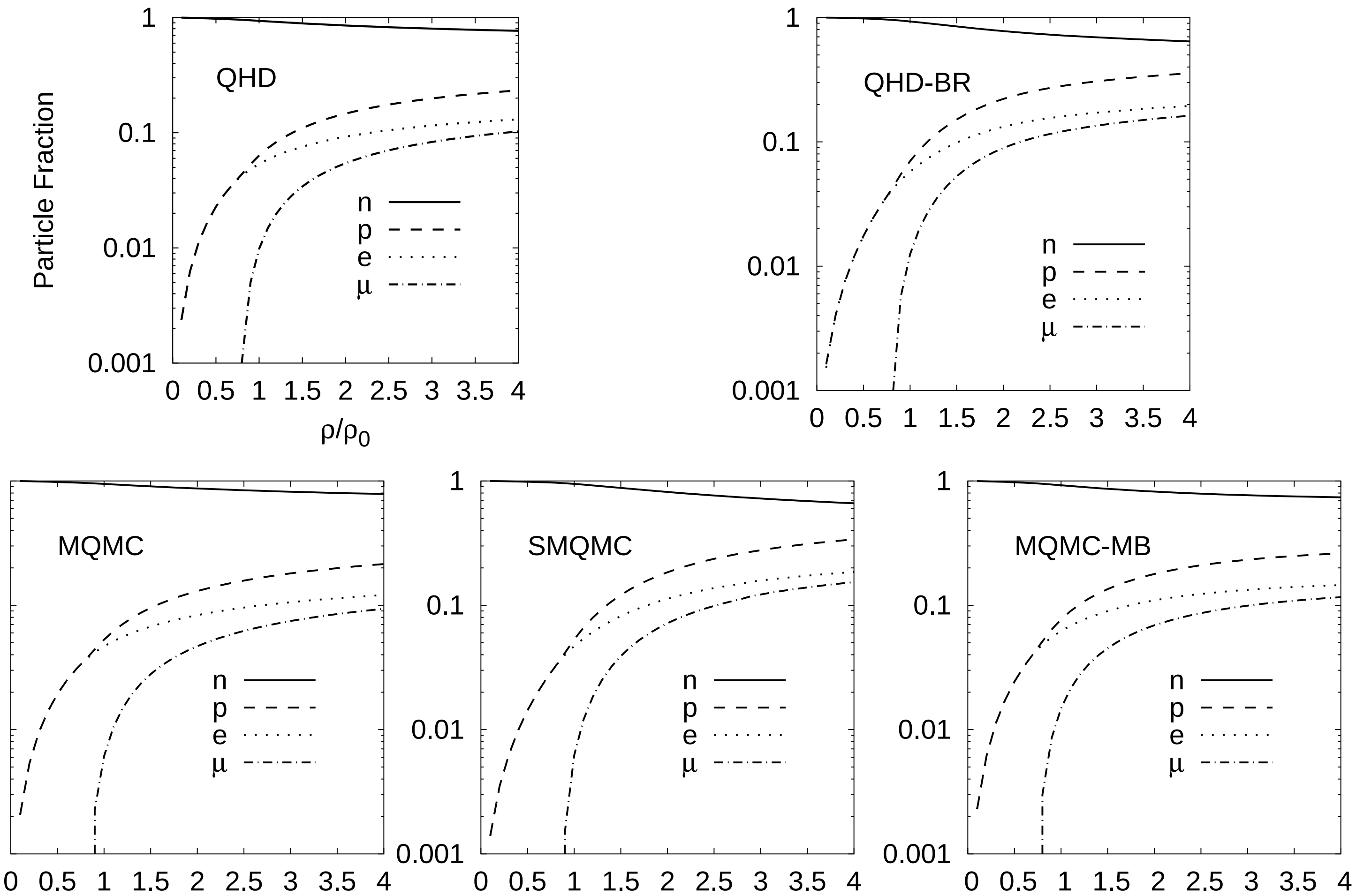
$$P \simeq -P_\sigma + P_\omega + P_\rho + P_N,$$

$$P_\sigma = \frac{1}{2} m_\sigma^{*2}\,\bar{\sigma}^2, \quad P_\omega = \frac{1}{2} m_\omega^{*2}\,\bar{\omega}_0^2, \quad P_\rho = \frac{1}{2} m_\rho^{*2}\,\bar{b}_{30}^2,$$

$$P_N = \frac{1}{3\pi^2} \sum_{N=n,p} \int_0^{k_N} \frac{k^4}{\sqrt{k^2 + m_N^{*2}}}\,dk.$$



★ Particle fraction : ρ_i/ρ $(i = n,\ p,\ e,\ \mu)$



4 Summary

★ The effect of density-dependent meson mass on the properties of NS matter was investigated.

★ EoS is sensitive to the behavior of meson mass.

★ Hyperon degrees of freedom need to be included.

★ Many possibilities are still wide open.