Strange Quark Star and Hybrid Star

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• Phase diagram including strange degrees of freedom
  – hadronization of quark–gluon plasma
• Applications:
  (1) strangelet in Heavy–ion collisions
  (2) strange quark star in the early Universe
  (3) hybrid neutron star
• Summary

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motivation

- Why strangeness in heavy-ion collisions?
  - strange enhancement as a signature for QGP
  - strangeness in quark star: introducing another quantum number lowers Fermi energy.

- EOS of QGP without s quarks is known, but including s quarks, it is unknown.

- Detailed EOS is needed to solve hydrodynamic eqs. in HI collisions, as is needed to solve TOV eq. for n–stars.

- Using different EOS for each phases, one can construct phase diagram of nuclear matter including strangeness, with condition of strange neutrality, similarly for charge neutrality in n–star.
QGP to hadron phase transition w/o strangeness

Gibbs condition for two phase equilibrium

\[ T_1 = T_2, \quad \mu_1 = \mu_2, \quad P_1 = P_2 \]

Simple pressure match as a function of chemical potential at given temperature works.

What happens if strangeness is included?
Phase diagram with strangeness

- Eg. Equilibrium between QGP and Hadron phases with a condition of strangeness neutrality: $\rho_S = 0$

- $P_Q = P_H, T_Q = T_H, \mu_Q^B = \mu_H^B$ with $\rho_{S,Q} = 0$ and $\rho_{S,H} = 0$ result in $\mu_Q^{S} \neq \mu_H^{S}$.


- What’s wrong?

  $\rho_S = f \rho_{S,Q} + (1-f) \rho_{S,H} = 0$ with $\rho_{S,Q} \neq 0, \rho_{S,H} \neq 0$
QGP volume fraction \( f = \frac{V_Q}{V_Q + V_H} \)

\( f \approx 1 \)

\[ P_Q^{f=1} = P_H^{f=1} \]

\[ \rho_s = 0 = f \rho_Q^s + (1 - f) \rho_H^s \]

\( f \approx 0.5 \)

\[ P_Q^{f=0.5} = P_H^{f=0.5} \]

\[ \mu_{Q,s}^{f=1} = \mu_{H,s}^{f=1} \]

\( f \approx 0 \)

\[ P_Q^{f=0} = P_H^{f=0} \]

\[ \mu_{Q,s}^{f=0} = \mu_{H,s}^{f=0} \]

\[ P_Q^{f=0} \neq P_Q^{f=1} \]

Lukas, Zimanyi, Balazs, PLB183 (1987) 27
QGP phase – gas of free quarks and gluons

\[ P_{\text{QGP}} = \frac{37}{90} \pi^2 T^4 + \mu_q^2 T^2 + \frac{1}{2\pi^2} \mu_q^4 + \frac{1}{\pi^2} \int_{m_s}^{\infty} d(e^2 - m_s)^{3/2} \]

\[ \times \left( \frac{1}{e^{\beta(e-\mu_q-\mu_s)/T} + 1} + \frac{1}{e^{\beta(e+\mu_q+\mu_s)/T} + 1} \right) - B \]

Hadron phase – hadron resonance gas

\[ P_{\text{Had}} = \frac{1}{1 + E^{pt} / 4B} \sum_i \frac{d_i}{6\pi^2} \int_{m_i}^{\infty} d(e^2 - m_s)^{3/2} \frac{(e^2 - m_i)^{3/2}}{e^{\beta(e-\mu_i)/T} \pm 1} \]

with \[ \mu_i = (n_i^q - \bar{n}_i^q) \mu_q + (n_i^s - \bar{n}_i^s) \mu_s \]

One can use more realistic EOS from lattice gauge calculation.
Phase diagram of quark matter with strangeness

\[ \mu_s (\text{MeV}) \]

\[ \mu_q (\text{MeV}) \]

\[ T (\text{MeV}) \]

\[ \mu_s (\text{MeV}) \]

\[ \mu_q (\text{MeV}) \]

\[ P (\text{MeV/fm}^3) \]
QGP volume fraction

\[ f = \frac{V_Q}{V_Q + V_H} \]

\[ f \approx 1 \]

\[ f \approx 0.5 \]

\[ f \approx 0 \]

\[ P_Q^{f=1} = P_H^{f=1} \]

\[ P_Q^{f=0.5} = P_H^{f=0.5} \]

\[ P_Q^{f=0} = P_H^{f=0} \]

\[ \rho_s = 0 = f \rho_s^Q + (1-f) \rho_s^H \]

\[ \mu_{Q,s}^{f=1} = \mu_{H,s}^{f=1} \]

\[ \mu_{Q,s}^{f=0} = \mu_{H,s}^{f=0} \]

\[ \rho_Q^{f=0} \gg 0 \]

Strangeness enrichment in Q phase near \( f=0 \) – strangeness distillation


Possible strangelet formation

C. Greiner, prl58(1987)1825
Phase diagram with different strangeness
Phase Structure of strange matter at $T=0$

KSLee, Heinz, PRD47, 2068 (1993)

$$\rho_s \neq 0$$
Applications

- Heavy–ion collisions: strangelets?
- Strange quark star in the early Universe
- Hybrid neutron stars
### Quark star

- quark star  
  *Witten PRD 30, 272(1984)*
- strange quark star – early Universe or from n–star

### Neutron star

- hybrid star: neutron star with QGP core or mixed phase core including straneness  
  *Glendenning, prd46, 1274(1992)*  
  *Heiselber, pethick, Staubo, prl70, 1355(1993)*
- Structure of mixed phase including surface tension: rods, pastas, and slabs depending on density  
  *Baym*
Strange matter lump with hadronic crust in the early universe

Strange matter lumps are stable only in the region of positive slope.

Central energy density

Hybrid Neutron Star

Strange quark matter

1995年 2月
I. 강입자 상(hadron phase)의 상태 방정식


\[
L = \sum_B \left\{ \left(1 + \frac{g_\omega \sigma}{2m} \right) \bar{\phi}_B \left[ i\gamma_\mu \partial^\mu - g_\omega B \gamma_\mu \omega^\mu - \frac{1}{2} g_\rho B \gamma_\mu \tau \cdot \rho^\mu \right] \phi_B \right. \\
- \bar{\phi}_B m\phi_B \right\} + \frac{1}{2} \left( \partial_\mu \sigma \partial_\nu \sigma - m_\sigma^2 \sigma^2 \right) - \frac{1}{4} \omega_\mu \omega_\nu \nu + \frac{1}{2} m_\omega^2 \omega_\mu \omega_\nu \nu \\
- \frac{1}{4} \rho_\mu \rho_\nu + \frac{1}{2} m_\rho^2 \rho_\mu \rho_\nu + \sum_\lambda \bar{\phi}_\lambda (i\gamma_\mu \partial^\mu - m_\lambda)
\]

여기서 B는 중입자의 종류로 중성자, 양성자와 여러 가지 hyperon들이다 [표 1]. \(\lambda\)는 전자(\(e^-\))와 뮤온(\(\mu^-\))에 대한 것이다. meson으로는 Sclar, vector, 와 isovector meson 인데 각각 \(\sigma, \omega, \rho\)로 표기 되었다.
II. QGP phase—gas of free quarks and gluons

\[ P_{QGP} = \frac{37}{90} \pi^2 T^4 + \mu_q^2 T^2 + \frac{1}{2\pi^2} \mu_q^4 + \frac{1}{\pi^2} \int_{m_s}^{\infty} de \left( e^2 - m_s \right)^{3/2} \]

\[ \times \left( \frac{1}{e^{\beta(e-\mu_q-\mu_s)/T} + 1} + \frac{1}{e^{\beta(e+\mu_q+\mu_s)/T} + 1} \right) - B \]
[그림 7-2] Baryon density of a strange matter lumps for $B = 150 MeV/fm^3$ and S/A=2 as a function of radial distance from the core.
[그림 7-3] Pressure of a strange matter lumps for 

\[ B = 150 \text{MeV/fm}^3 \] and \( S/A = 2 \) as a function of radial distance from the core.
Summary

• Construction of phase boundary from Gibbs condition in case of more than two chemical potentials need careful treatment, and the result is different from the simple Maxell’s construction, which is right only with one constraint.

• Three applications of the phase construction has been discussed.
• Conditions for the existence of strange quark matter, arXiv:1612.0075
  : Bodmer–Witten hypothesis
• Hybrid stars in the framework of different NJL models, arXiv:1612.09485

The transition from hadronic to quark matter is constructed by considering either a soft phase transition (Gibbs construction) or a sharp phase transition (Maxwell construction). We find that high-mass neutron stars with masses up to 2.1 – 2.4M☉ may contain a mixed phase with hadrons and quarks in their core, …
Hybrid stars in the framework of different NJL models, arXiv:1612.09485
The transition from hadronic to quark matter is constructed by considering either a soft phase transition (Gibbs construction) or a sharp phase transition (Maxwell construction). We find that high-mass neutron stars with masses up to $2.1 - 2.4M_\odot$ may contain a mixed phase with hadrons and quarks in their core,

![Diagram](image)

Fig. 1. (Color online) Schematic illustration of the interior structure of a hybrid star for the Maxwell construction (a) and the Gibbs construction (b). Regions of quark-hadron matter are only obtained for the latter.