Novel non-equilibrium phase transition caused by non-linear hadron-quark phase structure

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Outline

Motivation

What we do

- Non-equilibrium Phase Transition
- Heat Generation of Compact Stars

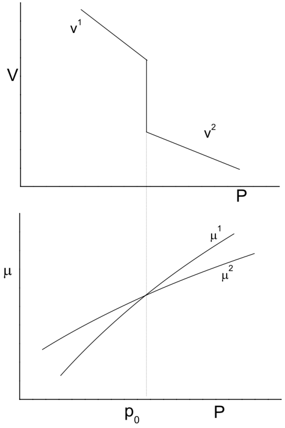
Conclusions

Phase Transition with Different Phase Structures

Maxwell construction

- local charge neutrality $\rho_H - \rho_H^e = 0, \rho_Q - \rho_Q^e = 0$
- one conserved charge, ρ_b
- the pressure keep constant during the transition from one homogeneous phase to the other.

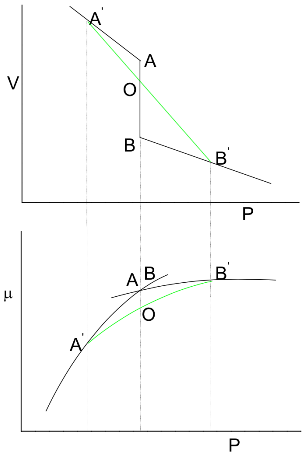
$$P_H = P_Q,$$
$$\mu_H = \mu_Q,$$
$$T_H = T_Q.$$



Phase Transition with Different Phase Structures

Gibbs construction

- global charge neutrality
  - $\rho_H^e = \rho_Q^e = \rho^e$
  - $(1-\chi)\rho_H + \chi\rho_Q - \rho_Q^e = 0$
- two conserved charge, ρ_b and q
- the pressure varies continuously with the proportion of the two phases
  - $\mu = \mu(\chi)$
  - $P_H(\mu_b, \mu_e, T) = P_Q(\mu_b, \mu_e, T)$
- The particle number density and energy density:
  - $\rho = \chi\rho_Q + (1-\chi)\rho_H$
  - $\epsilon = \chi\epsilon_Q + (1 - \chi\epsilon_H$



Phase Transition with Different Phase Structures

For convenienc, we introduce the fraction of baryon number $\eta = A_Q/A$, the energy per baryon or so-called binding energy:

$$e = \frac{\epsilon}{\rho} = \eta e_Q + (1-\eta) e_H$$

The energy density is:

$$\epsilon = \eta \rho e_Q + (1-\eta) \rho e_H$$

- the above equations illustrate the non-linear phase structure of the mixed phase. At zero temperature, the energy of the system relies on thermodynamical variable, ρ, and η
- For a system, an effective Hamiltonian or energy depends on phenomenological parameters, which are assumed to be functions of thermodynamical variables, T and μ(or ρ)
- non-linear phase structure may devote to dynamics of phase transition, and it may lead to different dynamical behaviors.

Thermodynamic Self-Consistency

The thermodynamic formula for the coexistence of two phases

$$d\epsilon = \frac{P+\epsilon}{\rho} d\rho + \sum_k \rho \mu_k d\eta_k \qquad (1)$$

If chemical balance is assumed, the formula reduces to

$$d\epsilon = \frac{P+\epsilon}{\rho} d\rho, or, P = \rho^2 \frac{d}{d\rho}\left(\frac{\epsilon}{\rho}\right) \qquad (2)$$

- eq.(2) only can hold up while η keep constant, and if η is density dependent it is no longer true.
- *To maintain the self-consistency of the system*, the standard treatment of this problem is to impose a supplement energy term(zero point energy): $\epsilon^* = \rho(e + e_0(\eta))$

Thermodynamic Self-consistency

the fundamental thermodynamical formula is

$$d\epsilon^* = \frac{P + \epsilon^*}{\rho} d\rho, or, P = \rho^2 \frac{d}{d\rho} \left(\frac{\epsilon^*}{\rho} \right) \quad (3)$$

To satify the above equation, we should use the additional conditions:

$$\frac{\partial}{\partial \eta} \left(\frac{\epsilon^*}{\rho} \right) = 0 \quad (4)$$

From the above self-consistency condition, we can obtain the equation of zero point energy

$$\frac{de_0(\eta)}{d\rho} = -\frac{\partial e}{\partial \eta} \frac{d\eta}{d\rho} - \sum \mu_k \frac{d\eta_k}{d\rho} \quad (5)$$

with eq.(5), eq.(3) return to the form $d\epsilon = \frac{P+\epsilon}{\rho} d\rho + \sum_k \rho \mu_k d\eta_k$, it can just hold if and only if two phases are chemical imbalance. Thus, we can see that the chemical imbalance during the phase transition is extremely necessary for thermodynamic self-consistency of the system.

Thermodynamic Self-consistency

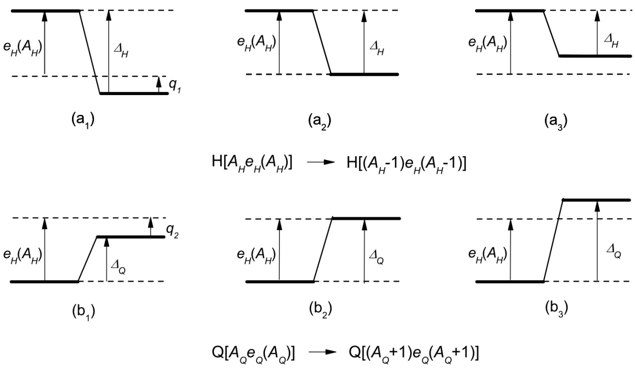
zero point energy

$$\frac{de_0(\eta)}{d\rho} = -\frac{\partial e}{\partial \eta}\frac{d\eta}{d\rho} - \sum \mu_k \frac{d\eta_k}{d\rho}$$

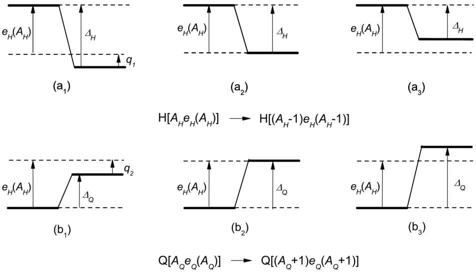
- the zero point energy means a Gibbs free enthalpy difference(imbalance of two phases).
- During transitions, η a parameter describing non-equilibrium status

Microphysics

- apparently certain energy-level structures are hidden behind the hadronic and quark matter in mixed phase.
- the surplus binding energy is possible to release when hadronic cluster losses nucleons and received by quark phase
- the behaviors are analogous to neutron emission and absorption through nuclei

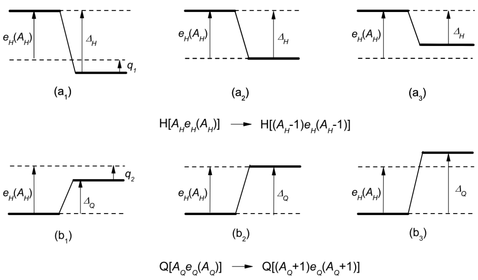


Microphysics



- The panel (a1) shows that a nucleon emission lowers the energy state of hadronic matter from $A_H e_H$ to $(A_H - 1)e_H(A_H - 1)$
- the excess of energy $q_1 = \Delta_H - e_H(A_H) = A_H \frac{\partial e_H}{\partial A_H}$

Microphysics



- The panel (b1) shows a nucleon is captured by quark matter in the mixed phase and then dissolves into quarks to excite to a higher state(from $A_Q e_Q(A_Q)$ to $(A_Q+1)e_Q(A_Q+1)$).
- The nucleon energy is in excess of the threshold for a nucleon absorption $q_2 = e_H(A_H) - \Delta_Q = e_H - e_Q - A_Q \frac{\partial e_Q}{\partial A_Q}$
- The conversion of a hadron into quarks can therefore **liberate total energy** $q = q1 + q2 = e_H - e_Q - \eta \frac{\partial e_Q}{\partial \eta} - (1-\eta)\frac{\partial e_H}{\partial \eta}$

Microphysics

The total liberated energy from conversion of a hadron into quarks

$$q = e_H - e_Q - \eta \frac{\partial e_Q}{\partial \eta} - (1-\eta)\frac{\partial e_H}{\partial \eta}, with, \delta\mu = -\frac{\partial e}{\partial \eta}$$

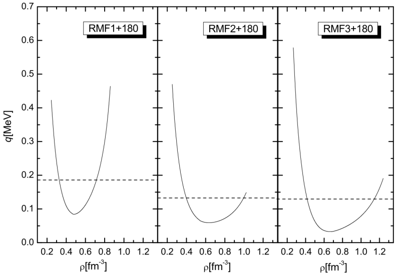
$$\boxed{q \equiv \delta\mu}$$

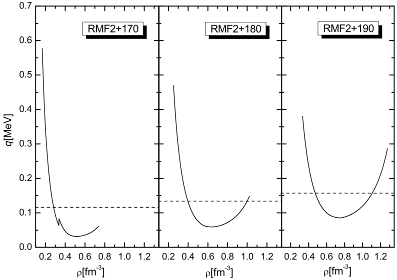
It means that the **two phases are imbalance** even if an infinitesimal conversion takes place, which fully coincides with the requirement of self-consistent condition of thermodynamics.

Heat Generation

Energy release per baryon: $q \equiv \delta\mu = \left(\left(\frac{\partial e}{\partial \rho} \right)_\eta - \frac{de}{d\rho} \right) \left(\frac{d\eta}{d\rho} \right)^{-1}$

Using the above formula, we can numerically calculate q for specific EoS





relativistic mean-field theory(RMF) + MIT bag model

- mean value of heat per baryon $\bar{q}$ is order of 0.1MeV

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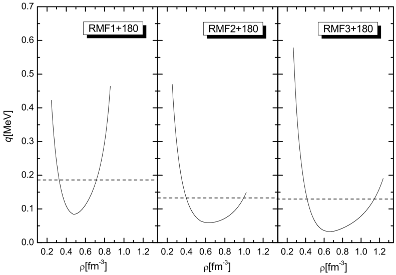

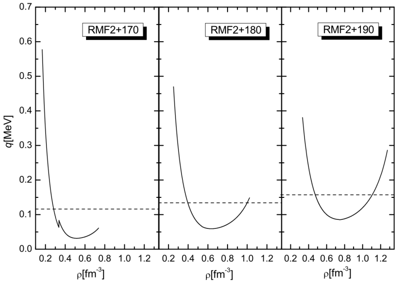

relativistic mean-field theory(RMF) + MIT bag model

- mean value of heat per baryon $\bar{q}$ is order of 0.1MeV
- rotochemical heating mechanism, the heat per baryon is order of 0.01 MeV.

Heat Generation

The spin-down causes the continuing conversion of hadrons into quarks in the core of compact stars

$$H = 2\Omega\dot{\Omega}\int_c dN_q \frac{d\eta}{dP}\left(\frac{\partial P}{\partial \Omega^2}\right)_N = -N_c \bar{q}\frac{2\Omega\dot{\Omega}}{\Omega_K^2}$$

For a dipole magnetic field and the baryon number of 10^{56},

$$H \sim 10^{33}\left(\frac{\bar{q}}{0.1MeV}\right)\left(\frac{\bar{B}}{10^8 G}\right)^2\left(\frac{\Omega}{6000 rad\ s^{-1}}\right)^4 erg\ s^{-1}$$

This is to be higher than, at least be compared with, the neutrino and photon luminosities in the absence of pairing phenomena.

Heat Generation

1. the energy release could **significantly change the thermal properties of the neutron stars** containing deconfinement matter in which the fast cooling process dominates.
2. **astrophysical and experimental physical problems:**
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   - the delayed cooling of isolated neutron stars and the old neutron stars with high thermal luminosity(PSR J0437-4715, is inferred as high thermal luminosity, $\sim 10^{29} erg\ s^{-1}$, or the upper limits 10^{31} for PSR J2124-3358, 10^{32} for PSR J0030+0451).

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   - the cooling of X-ray transients. The fluxes coming from deep crust and core contribute or influence the quiescent X-ray evolution.

Conclusions

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- The non-linear phase structure leads to the imbalance of the two phases during the phase transition.
- applying to the neutron star containing mixed phase, we found that the released energy might strongly change the thermal evolution behavior of the star.
- the constraint of the equation of state with X-ray data of neutron stars and hence present the signal of deconfinement phase transition in the core of neutron stars.