Nuclear “pasta” in supernova cores

Hidetaka Sonoda
University of Tokyo

Phys. Rev. C. 75, 042801(R) (2007)
nucl-th/0712.0052 (to be published)
cond-mat/0502515

Collaborators
G. Watanabe, K.Sato, T. Takiwaki, K. Yasuoka, T. Ebisuzaki

Outline

- Introduction
- Reproduction of nuclear pasta by QMD
- Neutrino opacity of nuclear pasta
- Summary

Introduction

Supernova and nuclear pasta

Supernova Explosion **Not yet perfectly understood**

Understanding interaction between neutrino and matter

One of promising ingredient for success of SN

One of yet understood related physics is …

Nuclear shape transitions in dense matter (~10^{14}g/cc)（**Nuclear pasta**）
→**Impact on scattering cross section of neutrino and matter**
（by factor of several tens or hundreds relative to uniform matter）

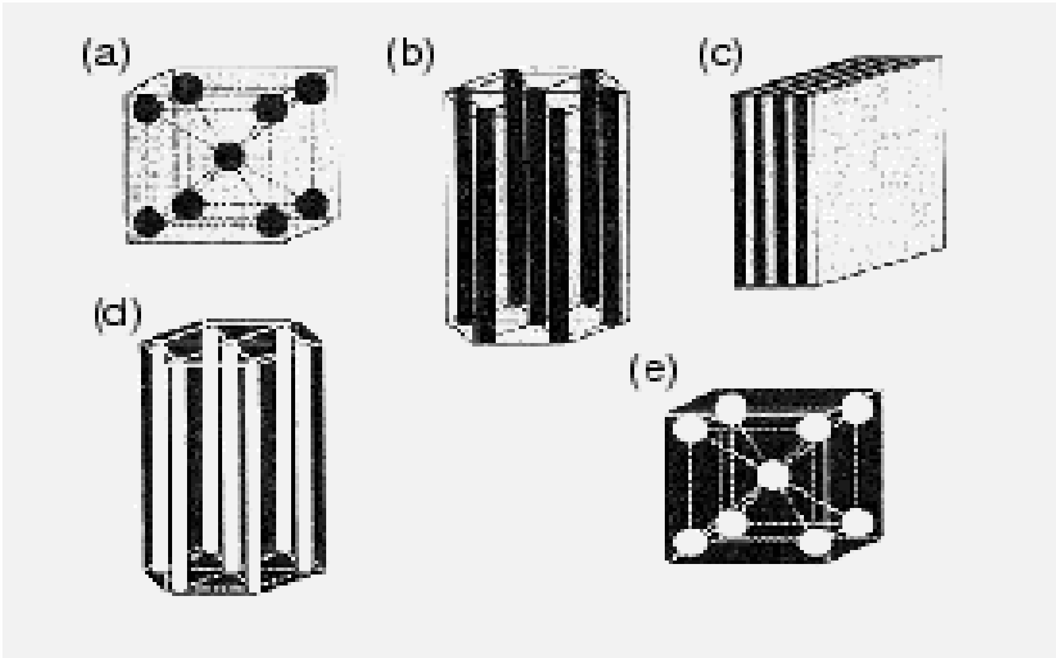
Very important for more accurate simulations of SN

What is nuclear "pasta" ?

Non-spherical nuclei in dense matter ~10^{14}g/cc
Caused by surface and Coulomb energy

Sphere→
Rod → Slab → Rod-like Bubbles → Spherical Bubbles
→Uniform Nuclear Matter

(Ravenhall et al. 1983,Hashimoto et al.1984)



(K.Oyamatsu, Nucl.Phys.**A561**,431(1993))

Meatball
Spaghetti
Lasagna
Anti-spaghetti
Cheese
→"Pasta" Phases

Estimated abundance of "pasta" in SN cores

Conditions for non-spherical nuclei
(Pethick & Ravenhall (1995))

Volume fraction of nuclei > 1/8
→spherical nuclei become unstable
(Bohr-Wheeler condition; $E_{coul} > 2E_{surf}$)

Possible region of "pasta" phases

In simulation of core-collapse SN with typical parameters
These region can occupy 10%~20% of core mass

Our study

1. Reproduction of pasta phases

Pasta phases really appear in supernova cores？

How does uncertainties of nuclear force affect？

2. Effects of “pasta” phases in supernova cores

How is neutrino opacity changed by pasta?

To approach to these problems,
we use Quantum Molecular Dynamics (QMD)

1. Reproduction of Pasta

Method

Why QMD ?

Quantum Molecular Dynamics (QMD)

We can observe how nuclei melts into uniform

QMD is suitable for observing structural transitions

1. No assumptions on nuclear shapes
2. Natural treatments of thermal fluctuations

Framework of QMD

Model Hamiltonian (Maruyama *et al*. Phys. Rev. **C** 57, 655 (1998))
(Chikazumi *et al* Phys. Rev. **C** 63, 024602(2001))

$$\mathcal{H} = \sum_i \frac{\boldsymbol{P}_i^2}{2m_i} + V_{\text{Pauli}} + V_{\text{Skyrme}} + V_{\text{sym}} + V_{\text{surface}} + V_{\text{MD}} + V_{\text{Coulomb}}$$

Kinetic energy | Pauli Potential | Nuclear force | Coulomb energy

Determination of parameters by reproducing …

Kinetic energy of ideal Fermi gas
Properties of symmetric nuclear matter at saturation density
Optical potential of *pN* elastic scattering
Binding energy and rms. radius of heavy stable nuclei

Time evolution calculated by solving EoM of QMD

Simulations at zero and nonzero temperatures

Simulation settings

2048 or 10976 or 16384 nucleons (n,p,e system)
Periodic boundary condition
Proton fraction x=0.3
Uniform background of electrons

Zero temperature: frictional relaxation

$$\dot{\boldsymbol{R}}_i = \frac{\partial \mathcal{H}}{\partial \boldsymbol{P}_i} - \xi_R \frac{\partial \mathcal{H}}{\partial \boldsymbol{R}_i}$$

$$\dot{\boldsymbol{P}}_i = -\frac{\partial \mathcal{H}}{\partial \boldsymbol{R}_i} - \xi_P \frac{\partial \mathcal{H}}{\partial \boldsymbol{P}_i}$$

(in timescale of~O(10^4)fm/c)

Nonzero temperature: Nose-Hoover thermostat

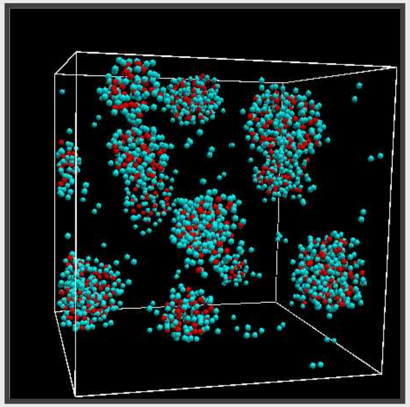
Result

Pasta phases at zero temperature

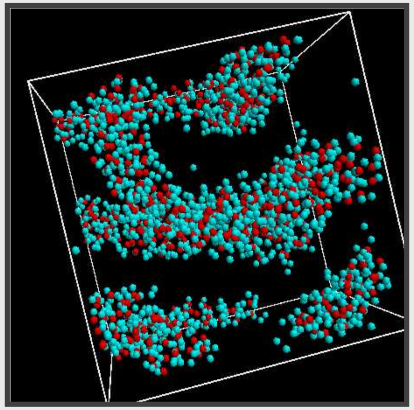
Cooling of Hot nuclear matter(~10 MeV) down to 0.1 MeV

Snapshots calculated for model 2

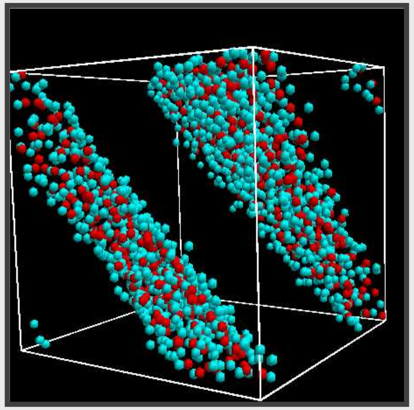
Sphere $0.100\,\rho_0$

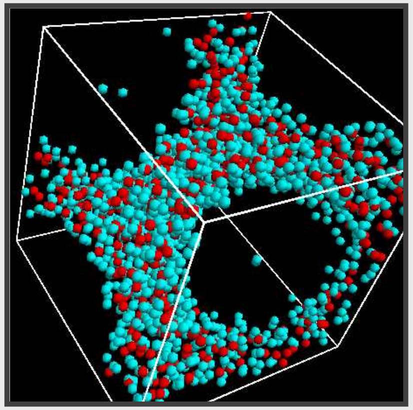


Rod $0.200\,\rho_0$

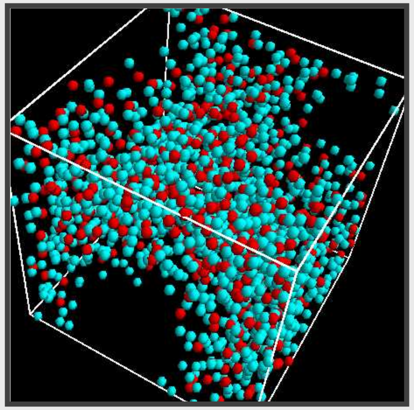


Slab $0.393\,\rho_0$





Rod-like Bubbles $0.490\,\rho_0$

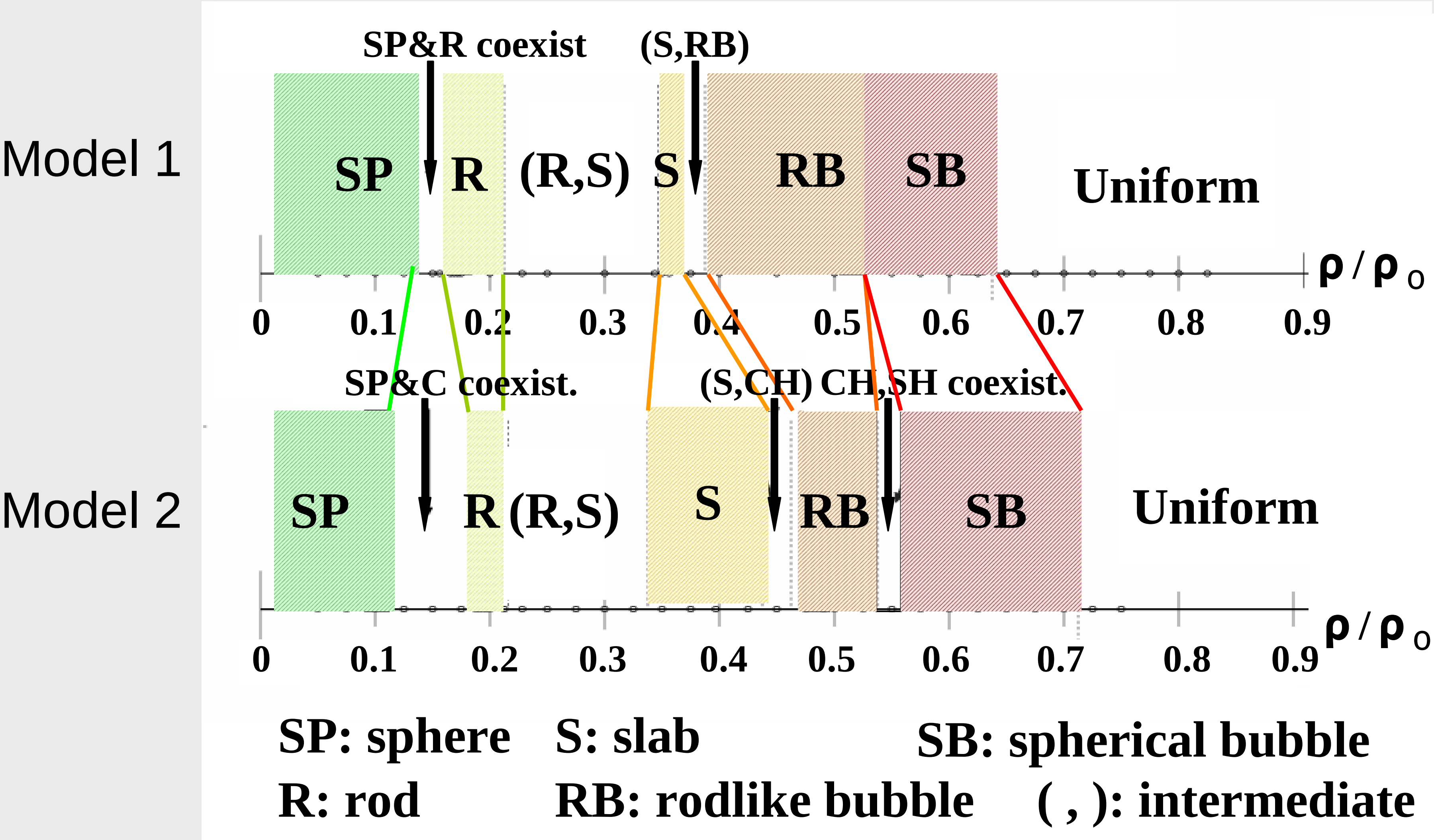


Spherical Bubbles $0.575\,\rho_0$

Red : Proton
Blue : Neutron

ρ_0 =0.168 fm^{-3}
（Nuclear density）

Phase diagram at zero-temperature



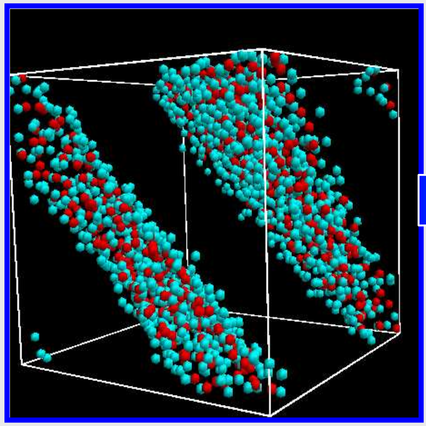
Sphere
→Rod → Slab → Rod-like bubbles → Spherical bubbles
→Uniform matter

Pasta phase at nonzero temperatures

Transitions by increasing temperatures

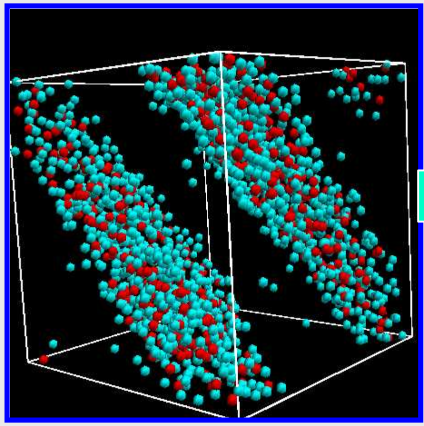
e.g. : 0.393 ρ_0 (slablike nuclei at T=0 MeV) for model 2

T= 0 MeV



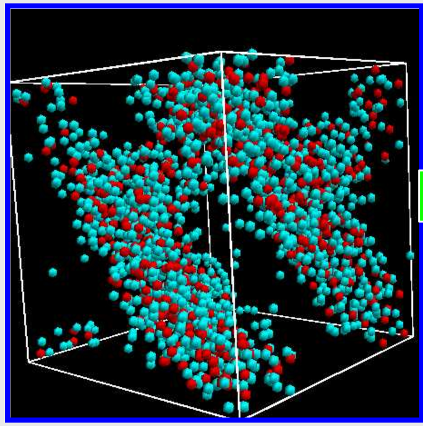
Slab-like nuclei

T= 1 MeV



Increasing dripped neutrons

T= 2 MeV



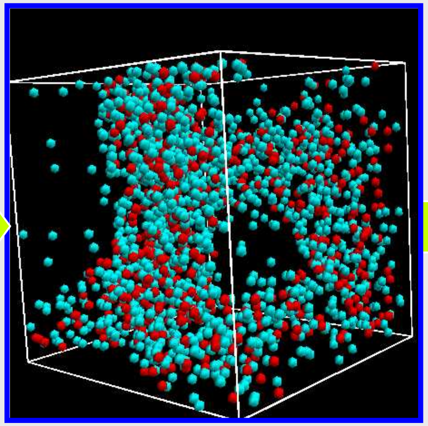
Connected slabs

Increasing dripped neutrons
Nuclear surface diffusive

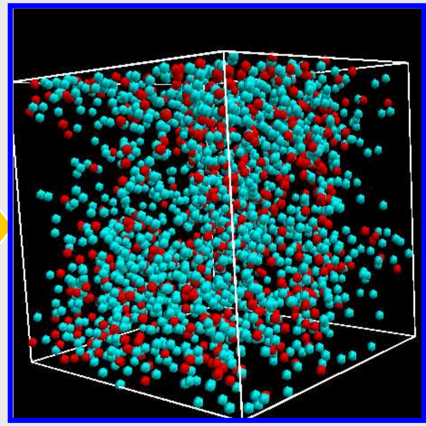
Increasing temperature

e.g : 0.393 ρ_0 (slablike nuclei at zero temperature)

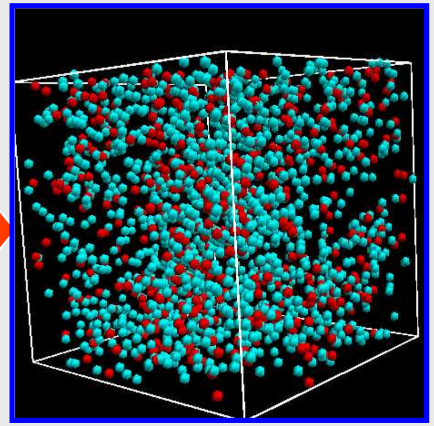
T=3MeV



T=5MeV



T=6MeV



Approaching to rod-like bubble phase

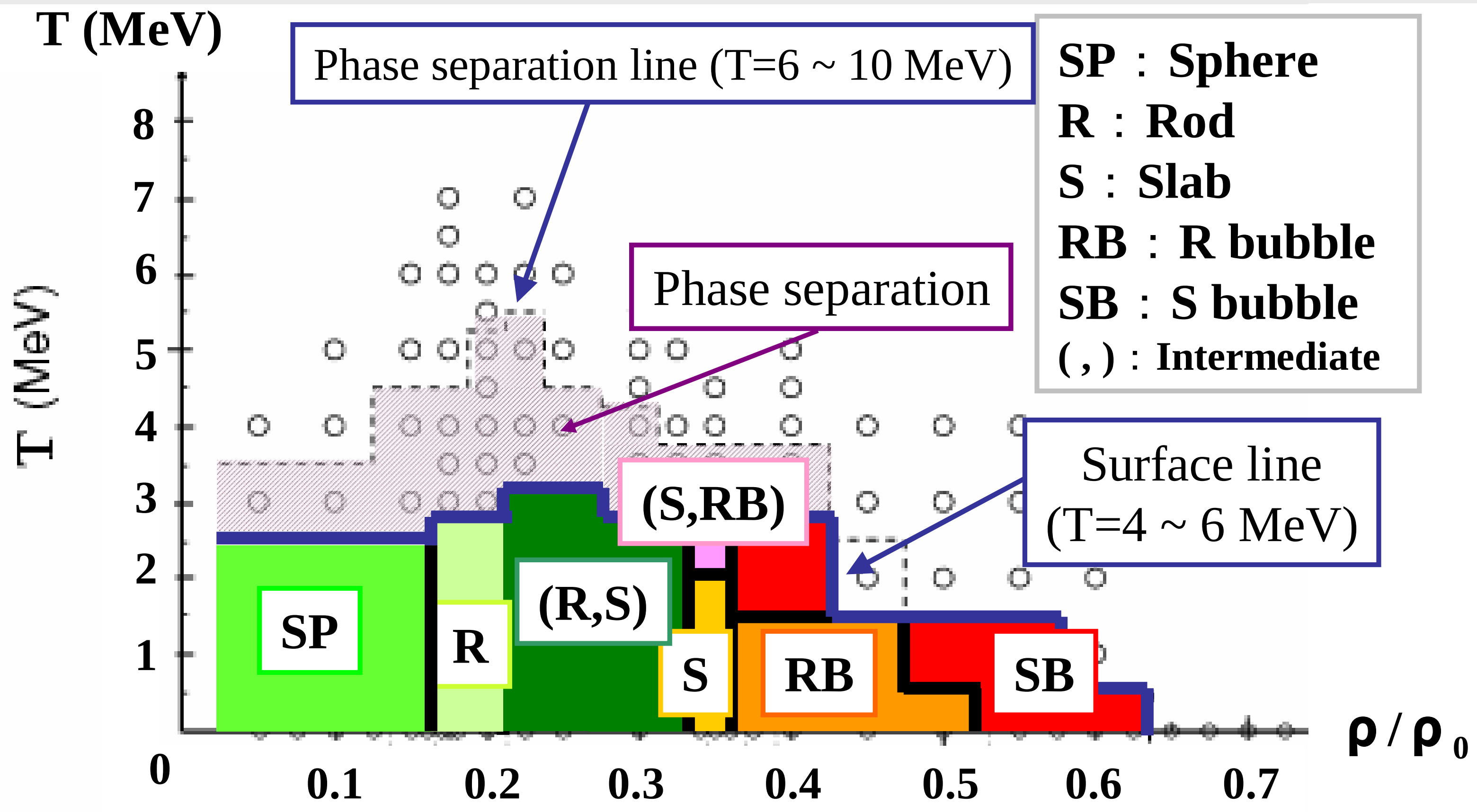
Nuclear surface cannot identified

Phase separation disappeared

Structural transition, diffusive surface, dripped protons, Disappearance of liquid-gas phase separation

Phase diagram at nonzero temperature

Model 1

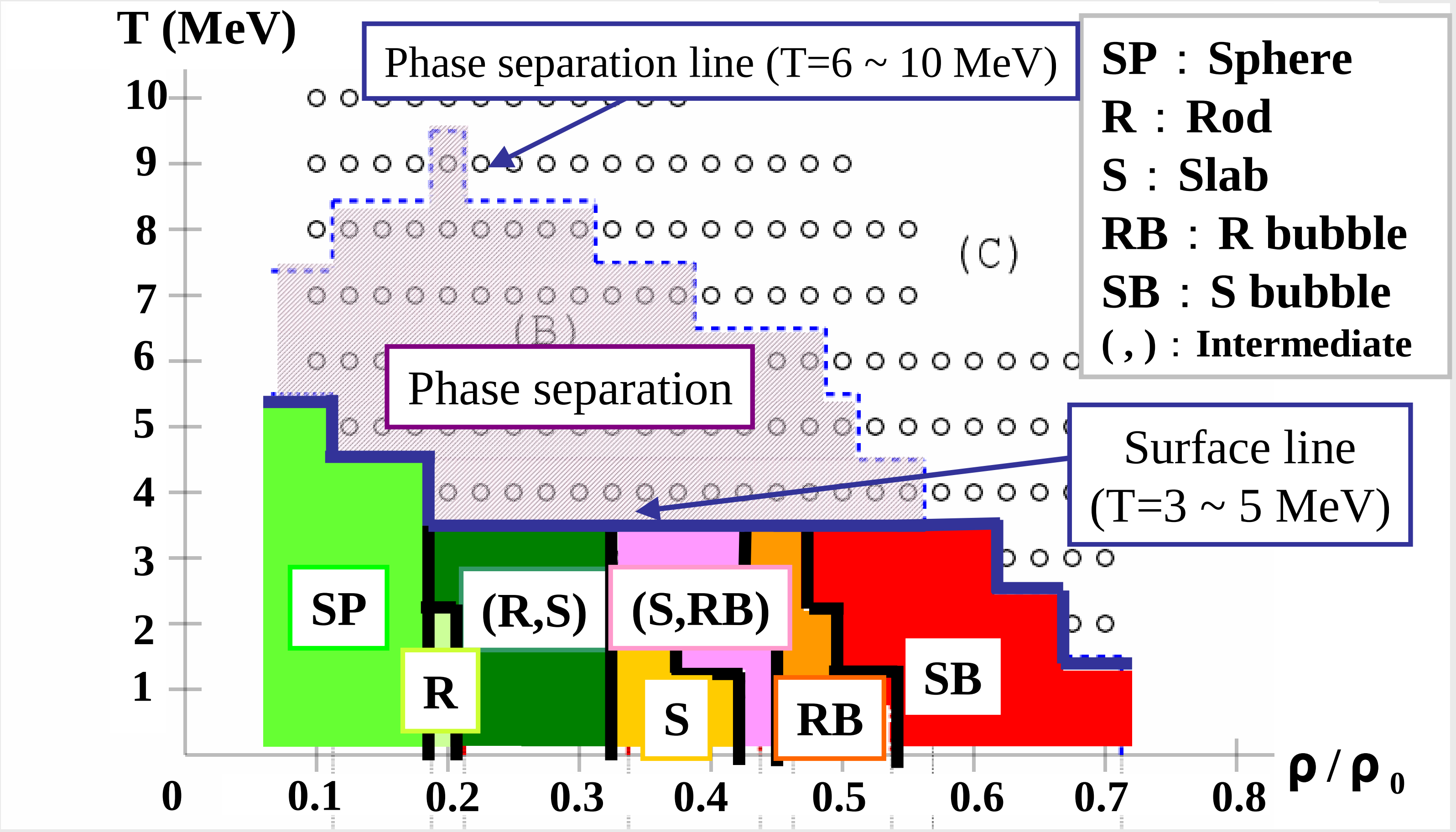


T= 2 ~ 3 MeV; nuclear surface cannot identified

T= 3 ~ 5 MeV; uniform matter appears

Phase diagram at nonzero temperature

Model 2



T= 3 ~ 5 MeV; nuclear surface cannot identified

T= 6 ~ 10 MeV; uniform matter appears

Model dependence of Phase diagram

Pasta region in **ρ** -T plane for model 2 larger than model 1

Symmetry energy parameter L is helpful for understanding uncertainty of pasta region in neutron star
(Oyamatsu and Iida (2007))

L: density derivative of energy of pure neutron matter
at normal nuclear density

L would be also helpful for pasta region in supernova

Model dependence of Phase diagram

High L = low symmetric energy at subnuclear densities
Low L = high symmetric energy at subnuclear densities

Suppose decreasing density or temperature of uniform matter, proton clustering instability occurs fast in case of low L

This extends pasta region for low L

Saturation density of asymmetric nuclear matter is high for low L

This also extends pasta region for low L

Estimated value of L is 93 MeV for model 1
80 MeV for model 2

Consistent with QMD results

(L of various nuclear forces in the range of 10~120 MeV (Oyamatsu & Iida (2007))

Summary of phase diagram

- QMD simulation of nucleon many body system at subnuclear density gives “pasta” phases
- Density dependence of symmetry energy L would be helpful for understanding phase diagram

2. Neutrino Opacity

Motivation

Neutrino transport

--- important for success of SN

Trapped when collapsing phases and effects on EOS

How does pasta phases affect neutrino opacity?

Neutrino scattering cross section

Differential scattering cross section of neutrino-nucleon systems

$$\frac{1}{N}\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}(\mathbf{q}) = \boxed{\frac{G_F^2 E_\nu^2}{4\pi^2}(1+\cos\theta)\cdot c_v^{(n)2}} \times \boxed{\overline{S}(\mathbf{q})}$$

Magnification factor
(static structure factor)

Neutrino-one neutron cross section

Angle averaged total transport cross section

$$\sigma_t = \langle \overline{S}(E_\nu)\rangle \sigma_t^0$$

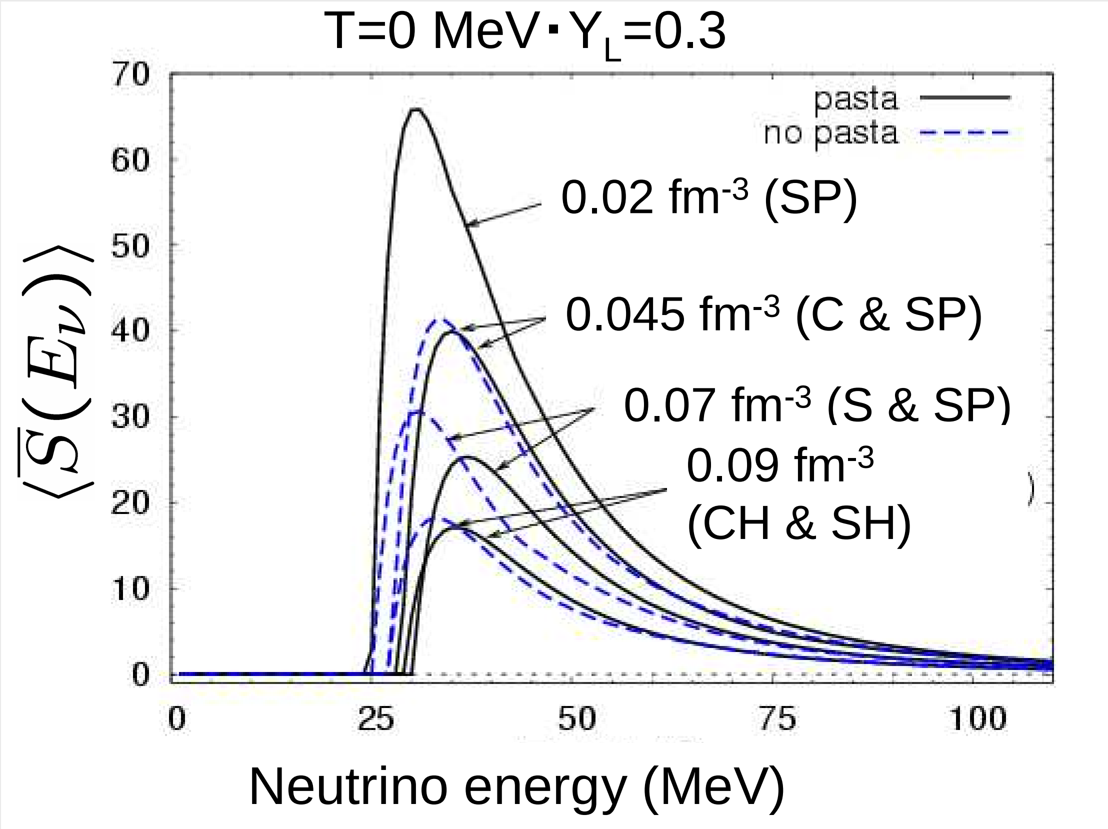
$\langle \overline{S}(E_\nu)\rangle$→magnification of total transport cross section

Results

- Understanding effects of pasta phases on neutrino opacity by liquid drop model
- Calculation of cross section by results of QMD

Scattering by pasta phases

Comparison of cases with and without pasta by BBP liquid drop model



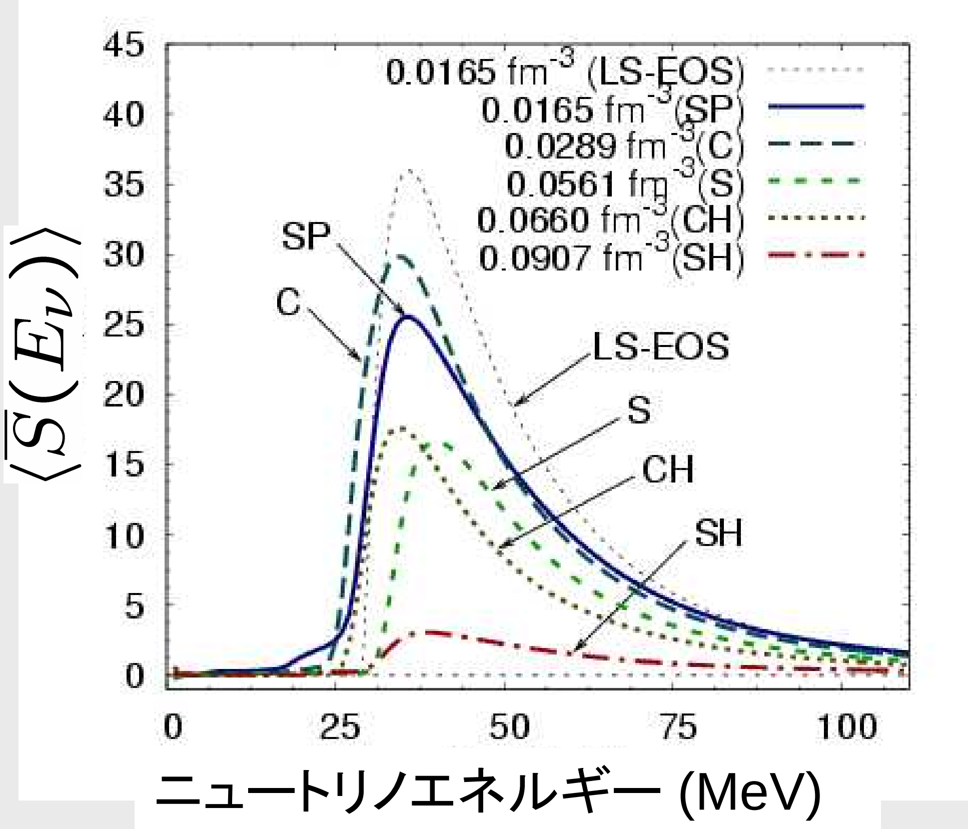
Black: Pasta phases
Blue: spherical nuclei

Peak around 30~40 MeV
Peak declines with density
Incoherent E<25MeV

Existence of pasta phases
increases peak energy up to E= 30-40 MeV
slightly increases **σ** for E > 40MeV

QMD results (Density dependence)

Y_e=0.3, T=1 MeV



Compared with LD

- lower peak height
- broad peak width
- tail at low energy

Due to thermal fluctuations

Height reverse

SP⇔C

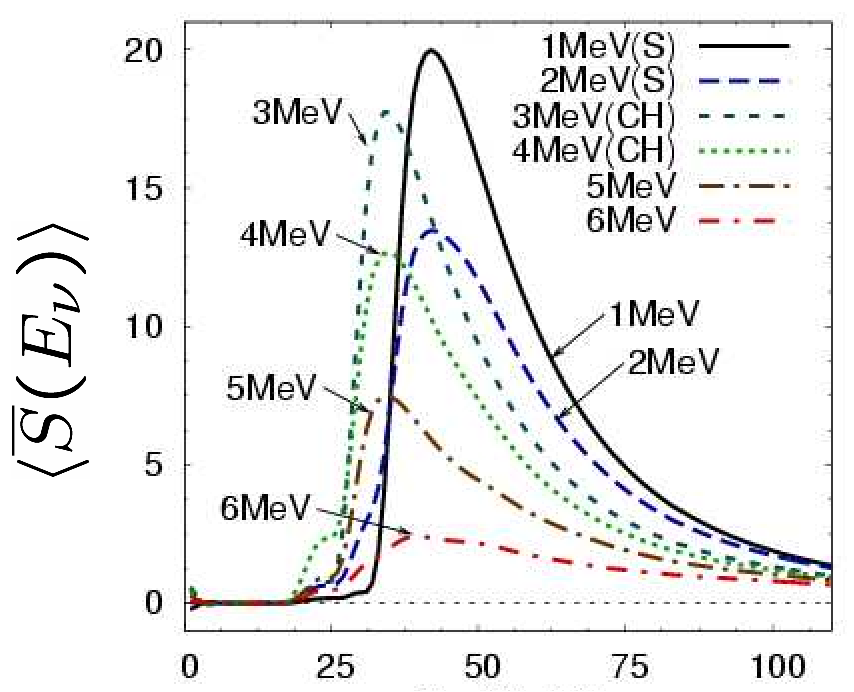
Thermal fluctuations ?

S⇔CH

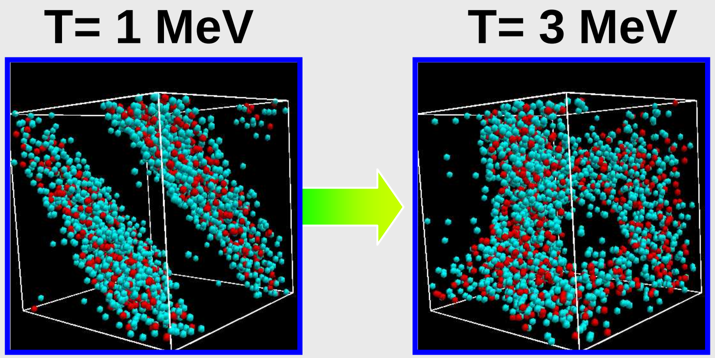
number of reciprocal lattice vectors ?

QMD results (temperature dependence)

Y_e=0.3, **ρ** =0.0660fm^{-3} (Slab at T=0)



Neutrino energy (MeV)



- Peak decline with temperature

- Phase transition triggers
  peak energy transition
  reverse of peak height

Phase transitions highly complicate cross section for intermediate energy neutrinos (E ~25-50 MeV)

Summary of neutrino opacity

- Pasta phases increases peak energy (30-40 MeV)
- Increasing temperature basically lowers neutrino opacity
- Phase transitions complicate neutrino opacity for intermediate energy

Summary

- Pasta phases are reproduced in the framework of QMD
- Pasta region in **ρ** -T plane is understood in terms of symmetry energy parameter L; low L enlarges pasta region
- Neutrino opacity is greatly affected by pasta phases, especially for intermediate energy neutrinos (25-50 MeV)