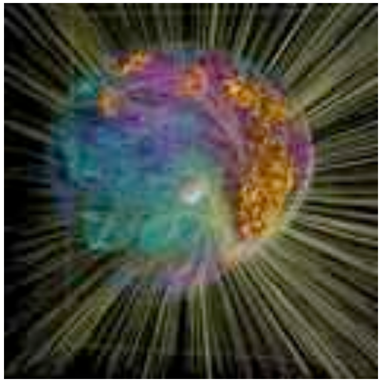
ICNT, July 15-19, 2013 NSCL/MSU



Report of Mini-WS RIKEN 2-4 July 2013

J.R.Stone

Oxford/Tennessee/Maryland

Organizers T. Inakura (Chiba Univ.),
C. Ishizuka (Tokyo Univ. of Sci.),
T. Isobe (RIKEN),
T. Maruyama (JAEA),
T. Murakami (Kyoto Univ.),
H. Nakada (Chiba Univ.),
K. Nakazato (Tokyo Univ. of Sci.)

Day 1: 2 July 2013

Tetsuya Murakami, Kyoto University,
Opening talk
Toshiki Maruyama, JAEA, Tokai
General Description of QMD
Akira Ohnishi, YITP, Kyoto University,
Particle Production and flow in hadron-string model
Tomoyuki Maruyama, Nihon Univrsity,
Density-Dependence of the Symmetry Energy and Iso-Vector Transverse Flow in Heavy-Ion Collisions"

Chair: Tsunenori Inakura (Chiba Univ.) ***Discussion 1***

DAY 2: 3 July 2013

Chikako Ishizuka (Tokyo Univ. of Sci.)

Review of Discussion 1

Hiroyuki Sagawa, University of Aizu/RIKEN

EoS, Giant resonances and Symmetry Energy

Yoritaka Iwata, CNS, University of Tokyo

TDHF calculation of the symmetry energy research

Shuichiro Ebata, VBL, Hokkaido University

Properties of finite nuclear systems and the systematics of E1 response.

Hideyuki Suzuki, Tokyo University of Science

Symmetry energy and supernovae

Day 2, continuing

Jirina R. Stone, Oxford/Tennessee-Knoxville

High density matter

Atsushi Tamii, RCNP, Osaka University

Measurement of the dipole polarizability of ^{208}Pb and constraints on the neutron skin and symmetry energy"

Tadaaki Isobe, RIKEN

H(R)IC experiment at RIBF; HIC simulation for RI collision experiment

Chair: Tetsuya Murakami (Kyoto Univ.) Discussion 2.

Day 3: 4 July 2013

Chikako Ishizuka (Tokyo University fo Science)
Review of Discussion 2
Akira Ono, Tohoku University
AMD approach to explore nuclear matter properties in HIC
Hiroshi Toki, RCNP, Osaka University
Strongly tensor correlated Hartree-Fock theory
for nuclear matter
Tetsuya Katayama, Tokyo University of Science
"Nuclear matter properties in Dirac-Brueckner-Hatree-Fock approach“
Kohsuke Tsubakihara, Osaka Electro-Comm University
Symmetry energy in an RMF model with n=3 coupling

Chair: Atsushi Tamii (RCNP) Discussion 3

DISCLAIMER

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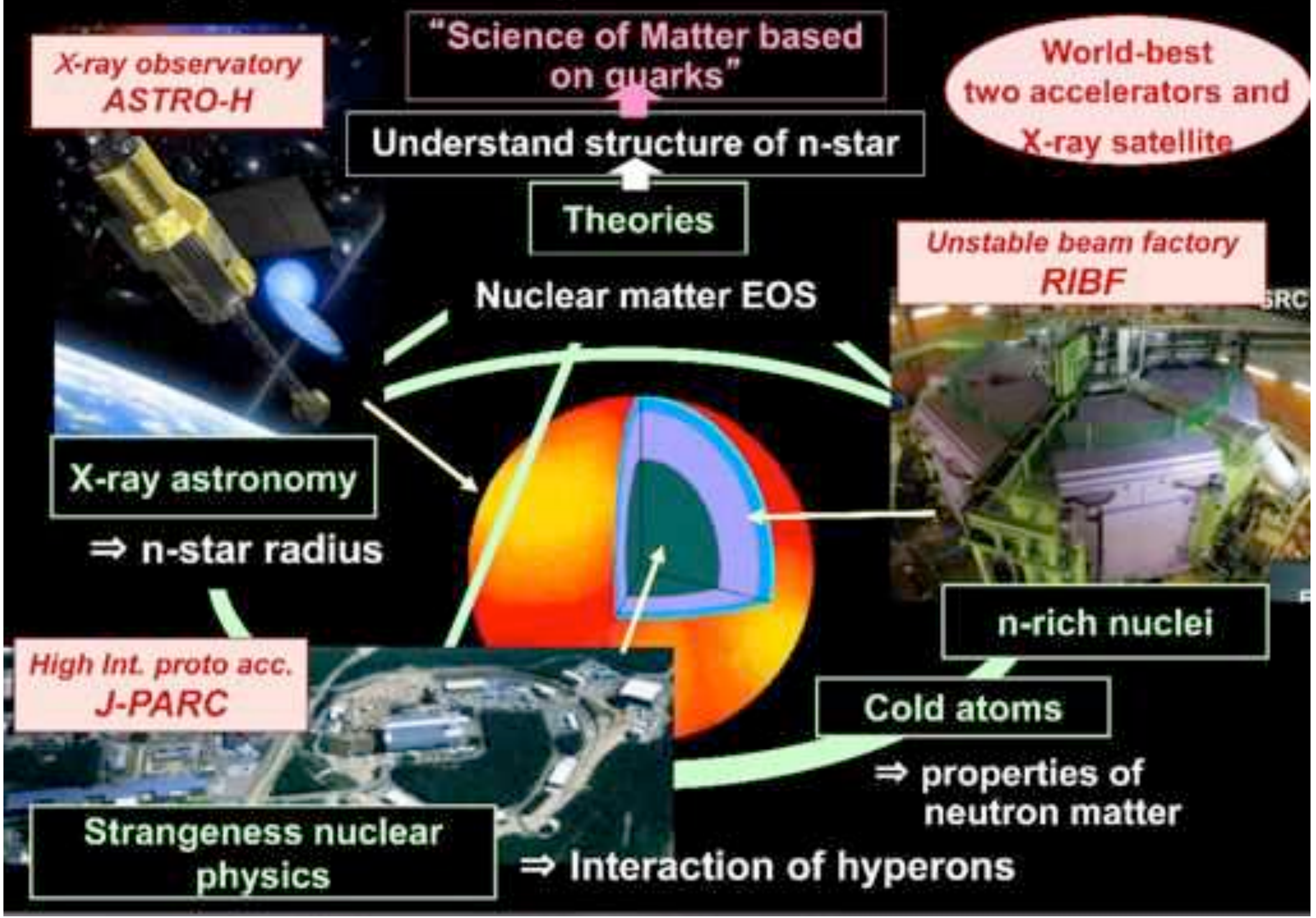
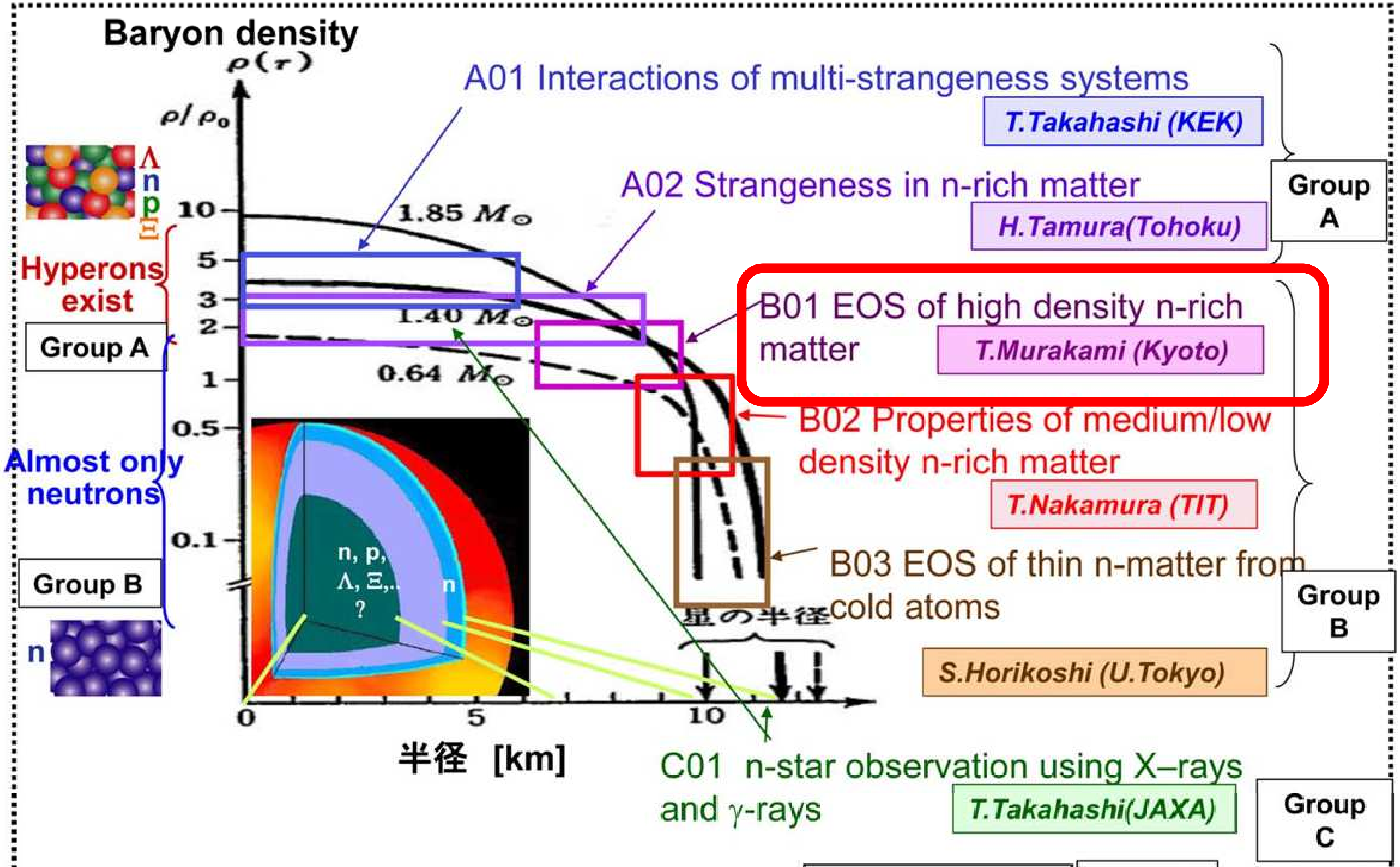
Reason: Some data shown have not been yet published and some suggestions and conclusions may be speculative and targeted only for internal discussions during the RIKEN mini-WS.


2012-2016 新学術領域
「実験と観測で解き明かす中性子星の核物質」
Grant-in-aid for innovative area:
“ Nuclear Matter in neutron Stars investigated by experiments and astronomical observations”
-- Aim of the project—
Tohoku Univ.
H. Tamura

Joint project between experiments, observations, theories



Groups and research subjects



D01 Theoretical studies on n-star matter | A.Onishi (Kyoto) | Group D

What we should discuss!!!

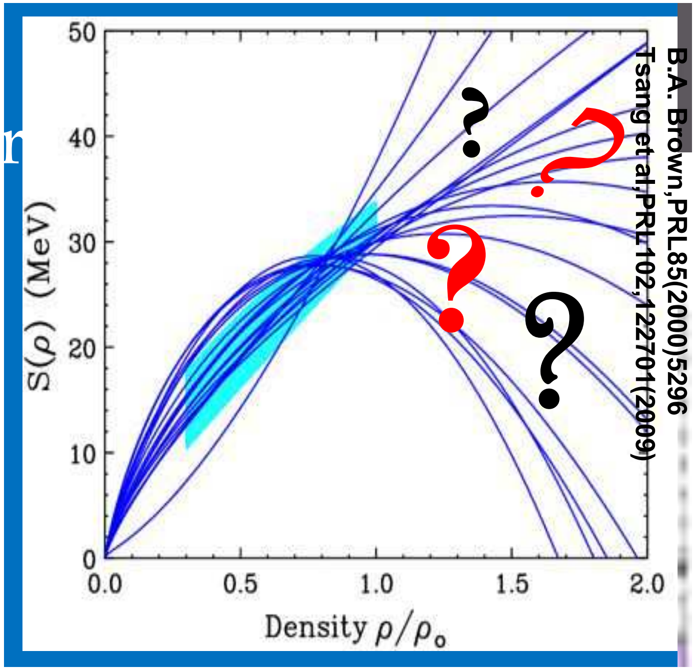
- 1. What causes the gap between neutron star observations (hard EoS) and nuclear experiments (soft EoS)?
  2. The feasibility study of theoretical assumptions and approximations in a treatment of experimental raw data.
  3. Find a new test to check the reliability of the theoretical models.
  4. Can we discuss the properties of dense matter from nuclear structures?

Overview of RIBF:

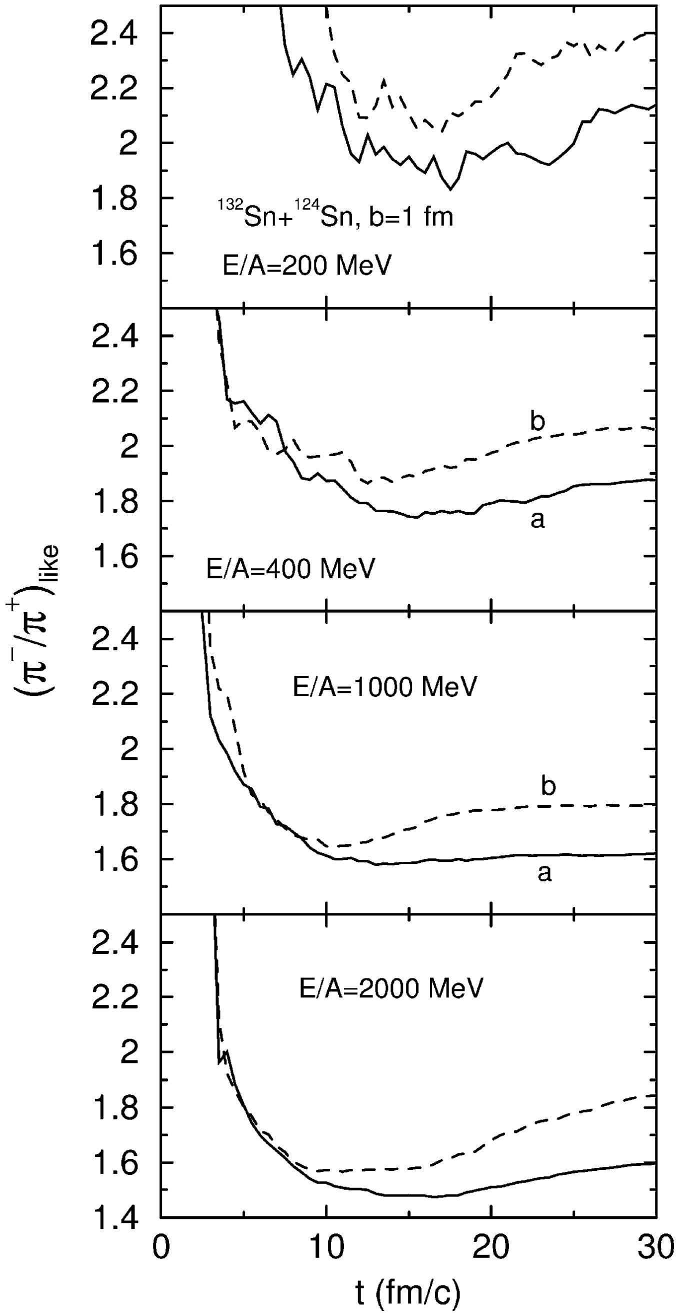
Premier Rare Isotope laboratory in the world

Energy range up to 350 MeV per nucleon

Able to create nuclear matter up to twice nuclear saturation density



- Optimal to study of the high density dependence of symmetry energy using Pion detections
- Require TPC inside a magnetic field.



Pion production in HIC
(Δ – decay pion production)

Bao-An Li, Nucl.Phys. A 708, 365 (2002)
PRL 88, 192701 (2002)

$$\pi^-/\pi^+ = \frac{5n^2 + np}{5p^2 + np} \approx (n/p)^2.$$

$$(\pi + N \rightarrow \Delta \text{ and } N + \Delta \rightarrow N + N)$$

$$(\pi^-/\pi^+)_{\text{like}} \equiv \frac{\pi^- + \Delta^- + \frac{1}{3}\Delta^0}{\pi^+ + \Delta^{++} + \frac{1}{3}\Delta^+}$$

a – stiff EoS
b – soft EoS

Simple momentum independent EoS:

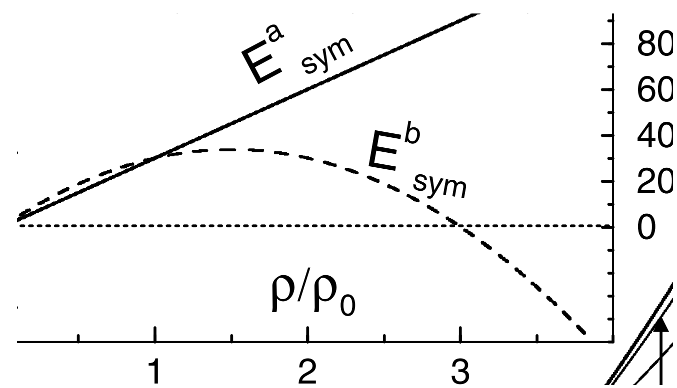
$$e(\rho,\delta) = e(\rho,0) + E_{\rm sym}(\rho)\delta^2,$$

$$e(\rho,0) = \frac{a}{2}u + \frac{b}{1+\sigma}u^{\sigma} + \frac{3}{5}e_F^0 u^{2/3},$$

$$E_{\rm sym}(\rho) \equiv e(\rho,1) - e(\rho,0) = \frac{5}{9}E_{\rm kin}(\rho,0) + V_2(\rho),$$

$$E^a_{\rm sym}(\rho) \equiv E_{\rm sym}(\rho_0)u \text{ and}$$

$$E^b_{\rm sym}(\rho) \equiv E_{\rm sym}(\rho_0)u\frac{u_c - u}{u_c - 1},$$

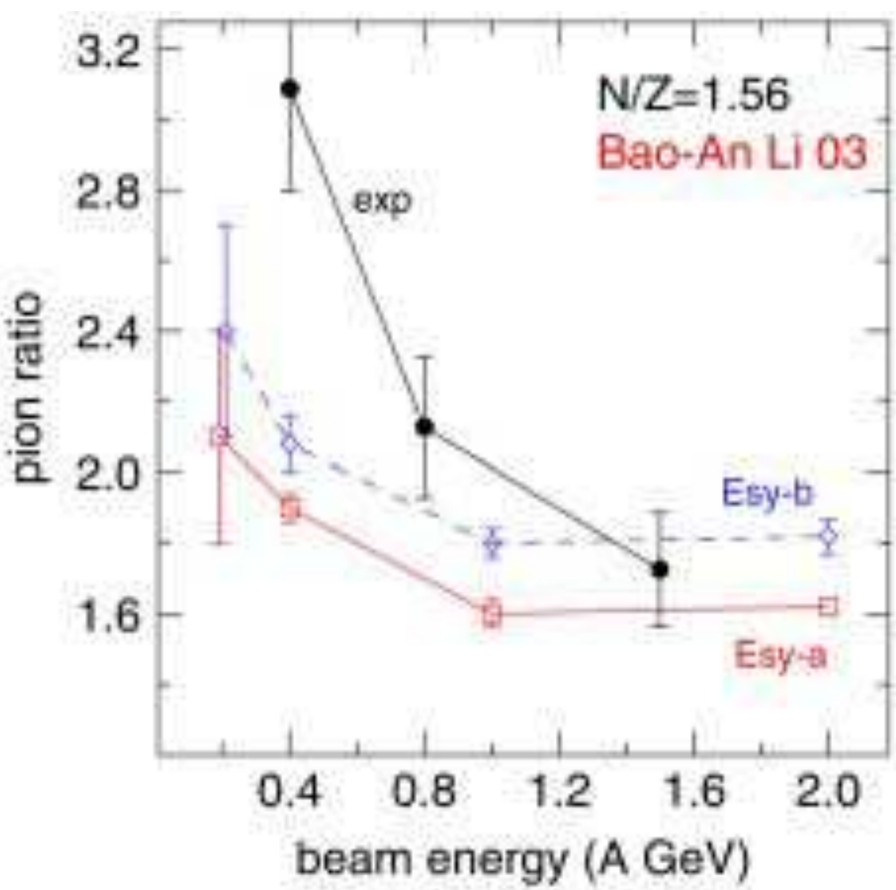


$$u = \rho / \rho_o \quad u = \rho_c / \rho_0$$

a and b fitted to saturation properties

K = 201 MeV and J = 30 MeV

FOPI data Reisdorf et al., NPA 781, 459 (2007)



Bao-An Li, PRC 67, 017601 (2003)

Statistical model of pion production
Transport model from
BAL PRC 44, 450 and 2095 (1991)

$$E^a_{sym}(\rho) \equiv E_{sym}(\rho_0) u$$

$$E^b_{sym}(\rho) \equiv E_{sym}(\rho_0) u \frac{3-u}{2},$$

Data are from Au+Au collission, linearly interpolated from N/Z=1.494 to N/Z = 1.56 (^{132}Sn + ^{124}Sn) for which the calculation was made.

PHYSICAL REVIEW C **73**, 034603 (2006)

Single and double π^-/π^+ ratios in heavy-ion reactions as probes of the high-density behavior of the nuclear symmetry energy

Gao-Chan Yong,[1,2,*] Bao-An Li,[3] Lie-Wen Chen,[4,5] and Wei Zuo[1]

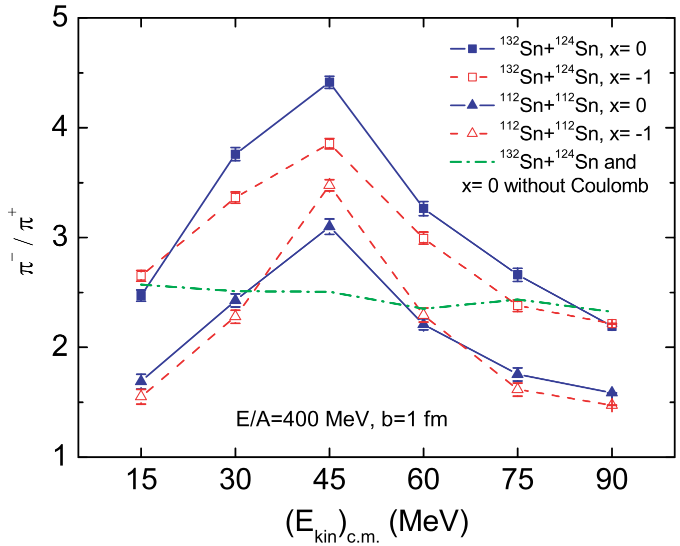


FIG. 2. (Color online) Kinetic energy distribution of the single π^-/π^+ ratio for ^{132} Sn+^{124} Sn and ^{112} Sn+^{112} Sn at a beam energy of 400 MeV/nucleon and an impact parameter of $b = 1$ fm with the stiff $(x = -1)$ and soft $(x = 0)$ symmetry energies. The dashed-dotted curve is the single π^-/π^+ ratio obtained by turning off the Coulomb potentials in the ^{132} Sn+^{124} Sn reaction.

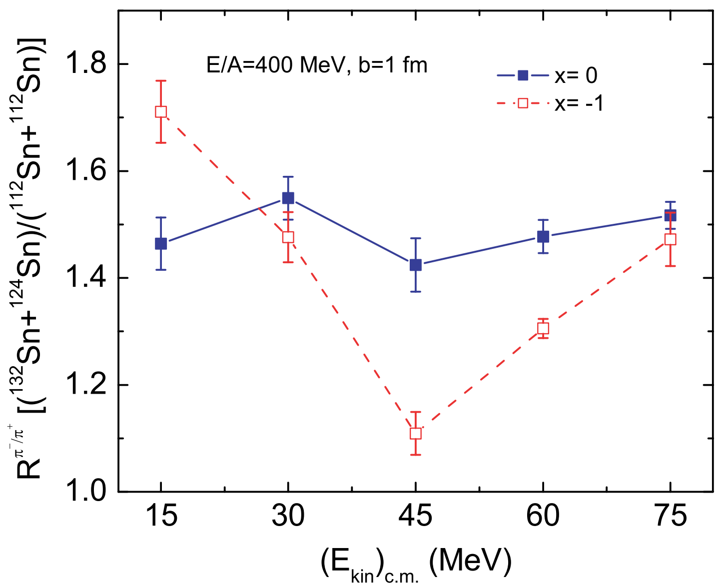


FIG. 3. (Color online) Kinetic energy dependence of the double π^-/π^+ ratio of ^{132} Sn+^{124} Sn over ^{112} Sn+^{112} Sn at a beam energy of 400 MeV/nucleon and an impact parameter $b = 1$ fm with stiff $(x = -1)$ and soft $(x = 0)$ symmetry energies.

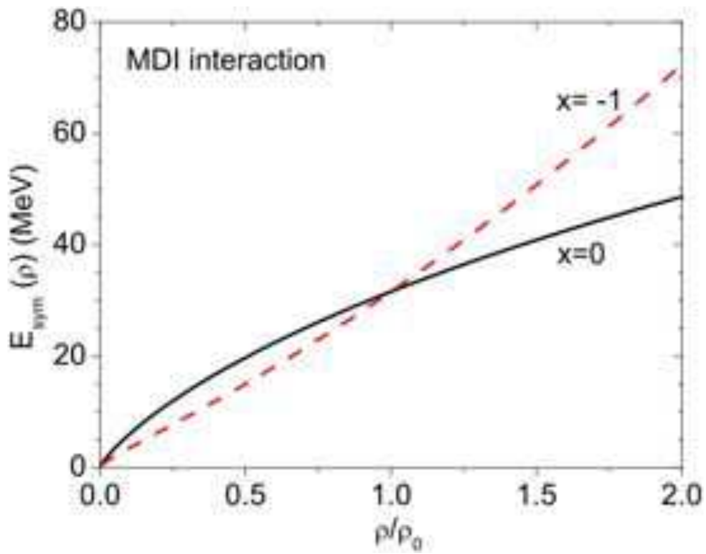
See also PLB 634, 378 (2006)

Introducing momentum dependent mean field potential (MDI) – using IBUU4 transport model

$$U(\rho, \delta, \mathbf{p}, \tau) = A_u(x)\frac{\rho_{\tau'}}{\rho_0} + A_l(x)\frac{\rho_\tau}{\rho_0} + B\left(\frac{\rho}{\rho_0}\right)^\sigma (1 - x\delta^2) - 8x\tau\frac{B}{\sigma+1}\frac{\rho^{\sigma-1}}{\rho_0^\sigma}\delta\rho_{\tau'} + \frac{2C_{\tau,\tau}}{\rho_0}\int d^3\mathbf{p}'\frac{f_\tau(\mathbf{r},\mathbf{p}')}{1+(\mathbf{p}-\mathbf{p}')^2/\Lambda^2} + \frac{2C_{\tau,\tau'}}{\rho_0}\int d^3\mathbf{p}'\frac{f_{\tau'}(\mathbf{r},\mathbf{p}')}{1+(\mathbf{p}-\mathbf{p}')^2/\Lambda^2}.$$

$$A_u(x) = -95.98 - \frac{2B}{\sigma+1}x,$$

$$A_l(x) = -120.57 + \frac{2B}{\sigma+1}x,$$



Parameters fit to Gogny Hartree-Fock and/or Brueckner Hartree Fock predictions for density dependence of the symmetry energy

K=211 MeV and J=32 MeV was used

Determination of the parameter X

The parameter x can be adjusted to mimic predictions on the density dependence of symmetry energy $E_{\rm sym}(\rho)$ by microscopic and/or phenomenological many-body theories. Shown in Fig. 1 is the density dependence of the symmetry energy for $x=0$ and -1. The recent analyzes of the MSU isospin diffusion data have allowed us to constrain the x parameter to be between these two values for densities less than about $1.2\rho_0$ [10]. The corresponding symmetry energy can be parameterized as $E_{\rm sym}(\rho)\approx 31.6(\rho/\rho_0)^{1.1}$ and $E_{\rm sym}(\rho)\approx 31.6(\rho/\rho_0)^{0.69}$ for $x=-1$ and $x=0$, respectively

Circumstantial Evidence for a Soft Nuclear Symmetry Energy at Suprasaturation Densities

Zhigang Xiao,[1] Bao-An Li,[2,*] Lie-Wen Chen,[3] Gao-Chan Yong,[4] and Ming Zhang[1]

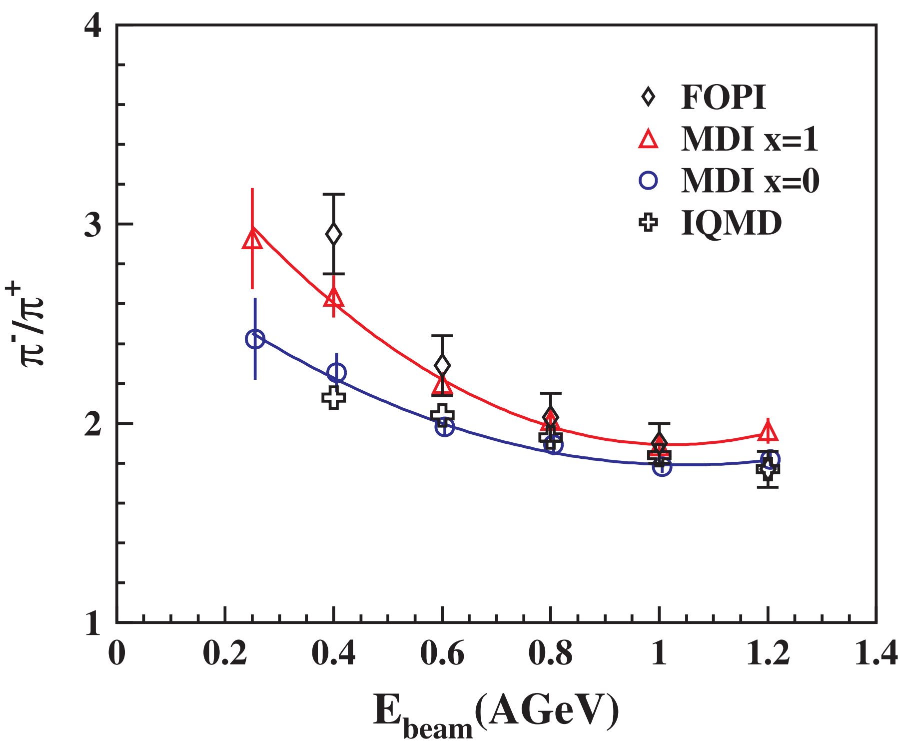
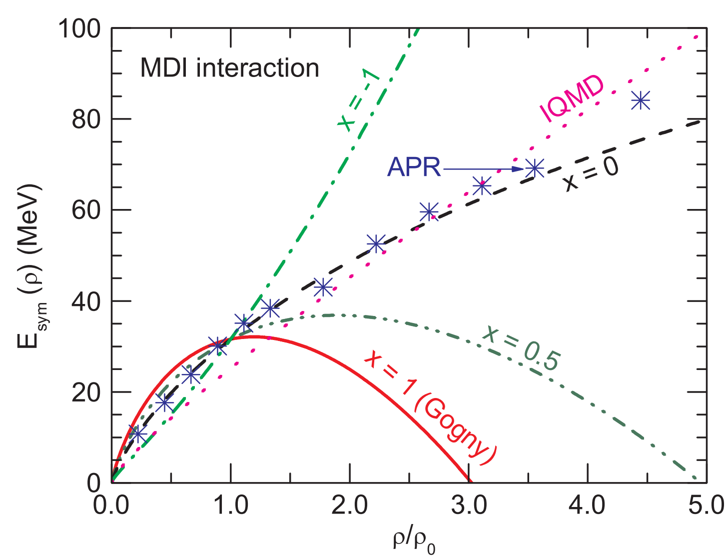


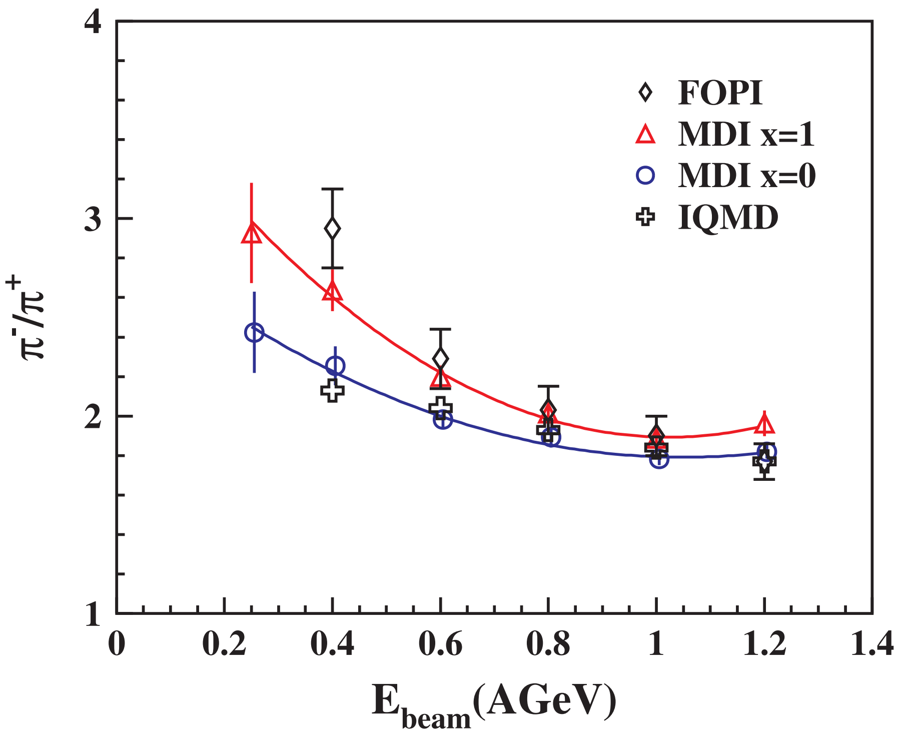
FIG. 4 (color online). Excitation function of the π^-/π^+ ratio in the most central Au + Au collisions.

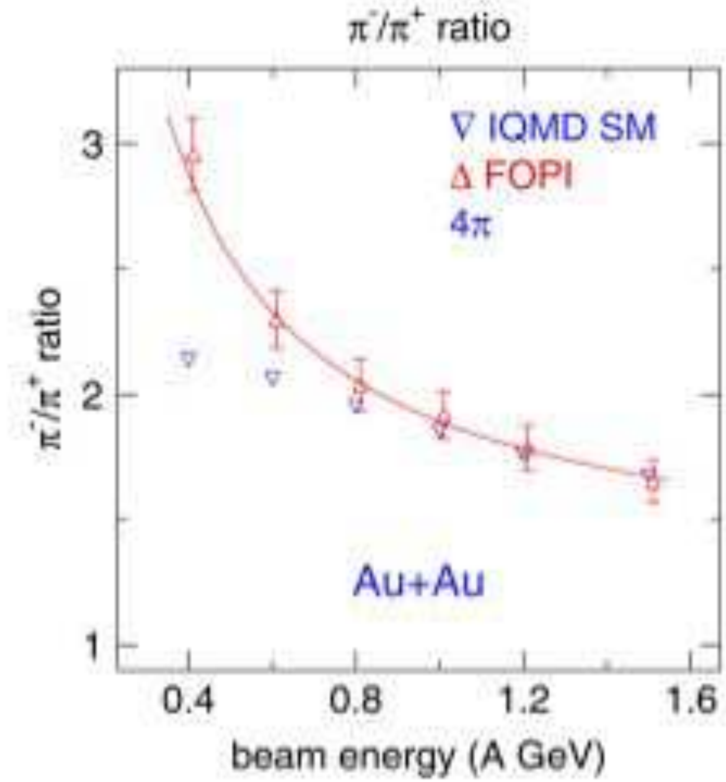
IBUU04
MDI interaction:

X=1 soft
X=0 stiff



IQMD from Reisdorf et al. Is it actually IQMD-SM?





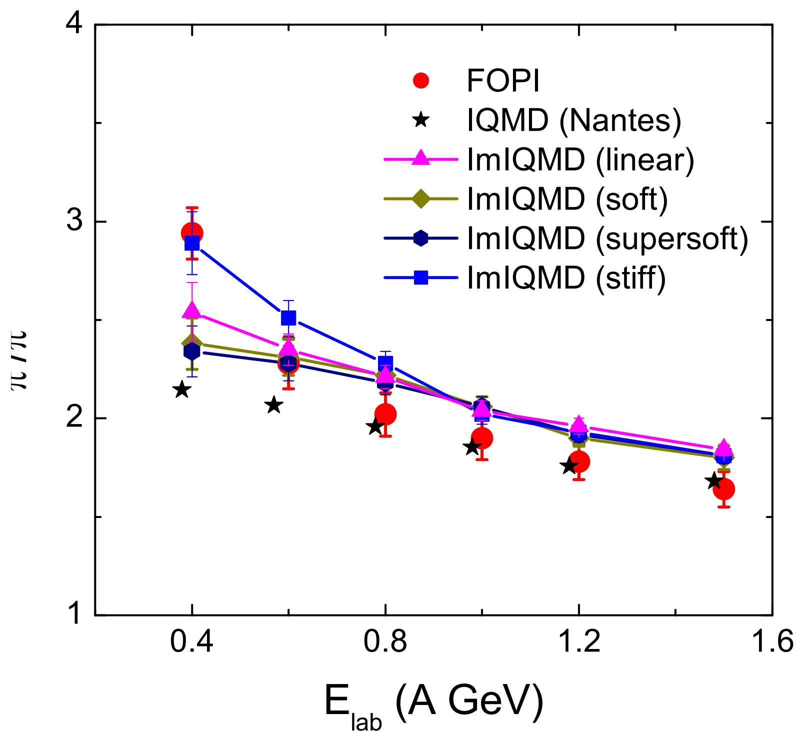
Xiao et al. PRL 102, 062502 (2009)

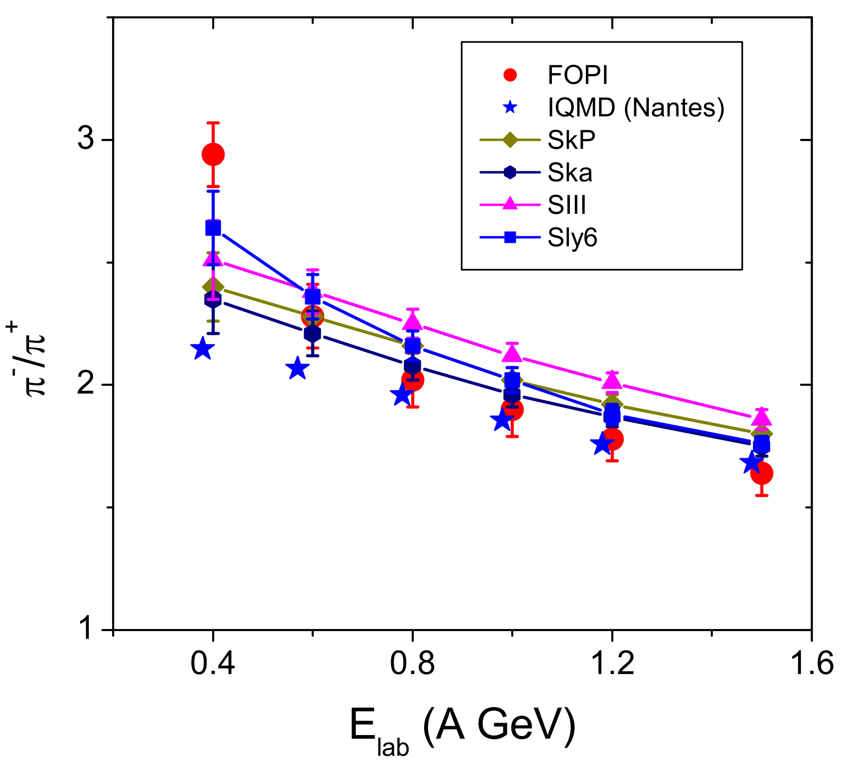
Reisdorf et al., , NPA 781, 459 (2007)

IQMD-SM K=200 MeV
IQMD-HM K=380 MeV

Zhao-Qing Feng*, Gen-Ming Jin Physics Letters B 683 (2010) 140–144

Within the framework of the improved isospin dependent quantum molecular dynamics (ImIQMD) model, the emission of pion in heavy-ion collisions in the region 1 A GeV as a probe of nuclear symmetry energy at supra-saturation densities is investigated systematically, in which the pion is considered to be mainly produced by the decay of resonances $\Delta(1232)$ and $N^*(1440)$. The total pion multiplicities and the π^-/π^+ yields are calculated for selected Skyrme parameters SkP, SLy6, Ska and SIII, and also for the cases of different stiffness of symmetry energy with the parameter SLy6. Preliminary results compared with the measured data by the FOPI Collaboration favor a hard symmetry energy of the potential term proportional to $(\rho/\rho_0)^{\gamma_s}$ with $\gamma_s = 2$.





General description of quantum molecular dynamics (QMD)

Toshiki Maruyama
JAEA, Tokai

Things to do in MD

AMD or at least **QMD with Pauli potential**

Simulation of **matter**

→ reproduce saturation, compressibility, and symmetry energy, etc

Ground states of nuclei (energy, density profile)

Density-Dependence of Symmetry Energy and Iso-Vector Transverse Flow in Heavy-Ion Collisions

Tomoyuki Maruyama, BRS, Nihon University

§1 Introduction

§2 RBUU Approach

§3 Relativistic Mean-Field with Iso-Vector Fields

§4 Heavy-Ion Collisions with Neutron-Rich Nuclei

§5 Summary

Future Problems

§ 5 Summary

(1) RBUU approach   RMF + BUU

Lorentz Covariant

Local Mean-Fields are available below a few MeV/u

(2) Different Density Dependence of Symmetry Energy

Iso-Vector Lorentz Scalar and Lorentz Vector Fields

(3) Observables

Tranverse Flow   Diractivity

Other Possible Observables

π^-/π^+ ratio   G.C.Yang et al., Phys. Rev. C 73, 034603 (06)

We must search Observables

Developing Approach RBUU + TDHF for Halo Nuclei

BUU + TDGP in Bose Fermi Atomic Gases

TM et al., PRA A72, 013609 (05), A77 063611 (08), A80 043615 (09)

Particle Production and Flow in hadron-string transport model

Akira Ohnishi (YITP, Kyoto Univ.)

RIBF miniWS: Nuclear Symmetry-energy and nucleus-nucleus collision simulation, July 2-4, 2013, RIKEN

- Introduction
- Particle production and flow at AGS and SPS energies
- Theoretical uncertainties towards symmetry energy from HIC
- Summary

Theoretical Uncertainties

- **Uncertainties for symmetric matter EOS**
  - **Density dependence & Momentum dependence of potential,**
  - **EOS effects and collision term effects,**
  - **Potential effects of hadrons other than nucleons,**
  - **Relativistic treatment of mean fields,**
  - **Code dependence, …**
- **Uncertainties for Symmetry Energy**
  → Some of the above uncertainties would cancel
  by considering the ratio or differences,
  but we may have other uncertainties.
  - **π^- / π^+ ratio: pion-nucleus potential, partial chiral restoration, …**
  - **^3H / ^3He flow: coalescence / statistical formation of fragments**
  - **n / p spectra and flow: experimental problem(?)**

AMD approach to explore nuclear matter properties in heavy-ion collisions

Akira Ono

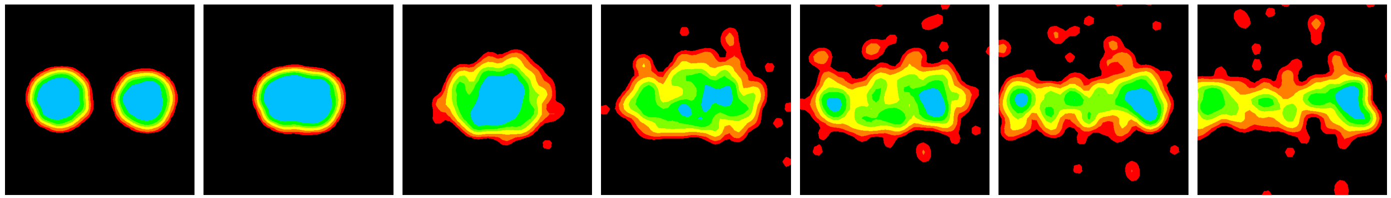
Tohoku University

RIBF-ULIC-MiniWS027: Nuclear symmetry-energy and nucleus-nucleus collision simulation, July 2 – 4, 2013.

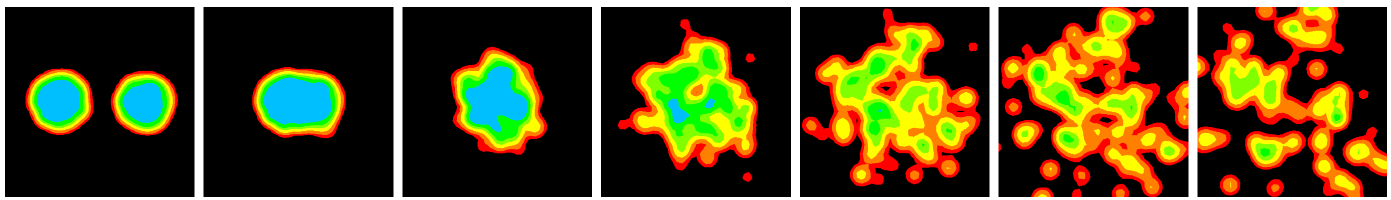
- Collision dynamics, symmetry energy, and clusters
- AMD approach (with cluster correlations)

Effect of Clusters on the Density Evolution

Without cluster correlations (AMD with NN collisions)



With cluster correlations



Bulk properties and dynamics
e.g. EOS $E(\rho)$

$\Longleftarrow\Longrightarrow$
interplay

Correlations
e.g. clusters and fragments

$\Downarrow$ $\Downarrow$

Isospin dynamics, Symmetry energy

$\rho_n - \rho_p, \quad n/p, \quad t/^3\text{He}, \ldots$

Multiplicity simulation for SAMURAI-TPC experiment

Takamasa Yoshida
Tadaaki Isobe

What is PHITS

- PHITS code
  collision pr
- In collision
  models, suc
  - JAM is a h
    model and
  - JQMD cod
    and calcul
    nucleon-n

[1] Y.Nara et.al. Phys. Rev. C61 (2000) 024901
[2] K. Niita et al. Phys. Rev. C52 (1995) 2620

We use ver. 2.150

Back up : JAM

- Jet AA Microscopic Transport
- JAM is a Hadronic Cascade Model, which explicitly treats all established hadronic states including resonances with explicit spin and isospin as well as their anti-particles. We have parameterized all Hadron-Hadron Cross Sections, based on Resonance Model and String Model by fitting the available experimental data.

H(R)IC experiment at RIBF
~HIC simulation for RI collision experiment~

Tadaaki Isobe, RIKEN Nishina Center

RIBF-ULIC-mini Workshop: Nuclear symmetry-energy and nucleus-nucleus collision simulation

2-4 July 2013

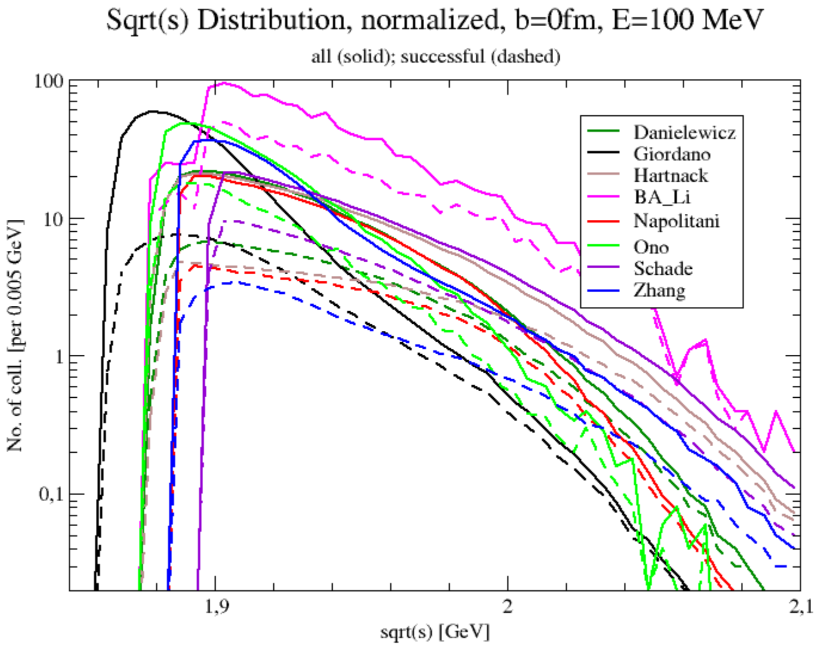
Code Comparison Project:
Workshop on Simulations of Heavy Ion Collisions at Low and Intermediate Energies, ECT*, Trento, May 11-15, 2009

→ using same reaction and physical input (not neccessarily very realistic, no symm energy))
→ included major transport codes
→ obtain estimate of „systematic errors“

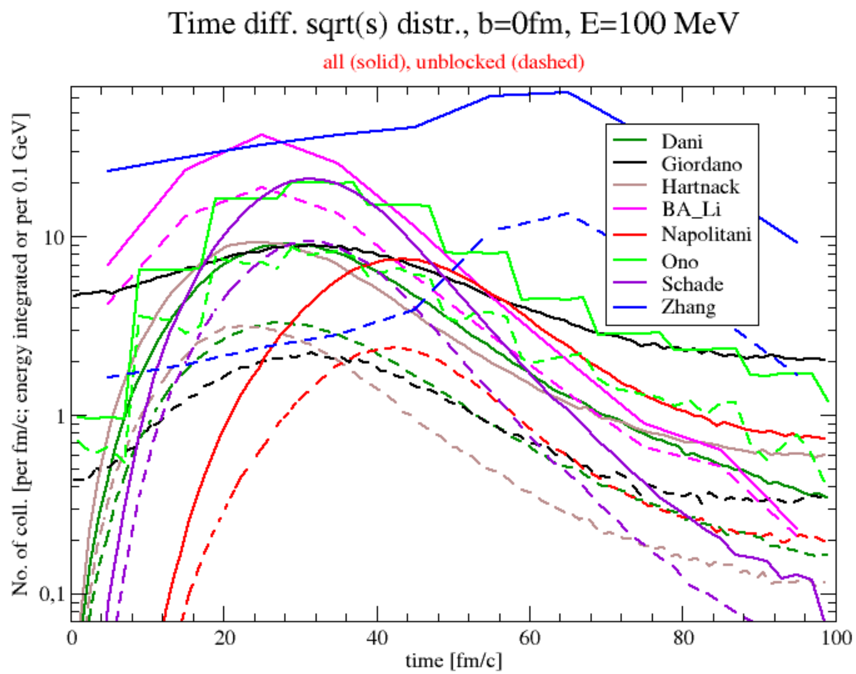
Name	**Code**	**References**	**EoS(hw1)**	**EoS (hw2)**
Ono	AMD	PR**C66**(02)014603	own EoS	own EoS
Hartnack	IQMD	EPJ**A1**(98)151	prescribed	prescribed
Napolitani	BQMD	PR**202**(91)233	prescribed	own EoS
Zhang	ImQMD	PL**B664**(08)145; PR**C71** (05)024604; PR**C74**(06)014602	prescribed	prescribed
Danielewicz	BEM	-	prescribed	prescribed
Q.-F. Li	UrQMD	PR**C73**(06)051601; JP**G32**(06)151	prescribed	prescribed
Giordano	BNV (CT)	NP**A732**(04)202; PR**C72**(05)064609	prescribed	prescribed
Pfabe	BNV	NP**A732**(04)202	prescribed	prescribed
Gaitanos	RBUU(Munich)	NP**A714**(03)643;NP**A741** (04) 209	prescribed	prescribed
GiBUU (SK)	BUU-Giessen	gibuu.physik.uni-giessen.de	prescribed	prescribed
GiBUU (RMF)	RBUU-Giessen	PL**B663**(08)197; arXiv:0904.2106v1; PR**C76**(07)044909	prescribed	prescribed
B.-A. Li, G.C.Yong	IBUU	PR**160**(88)189; PR**C44**(91)450 & 2095.	prescribed	prescribed
Schade	BUU	??	prescribed	prescribed

Distributions of collision:

Store collision energies, times, density of the environment, blocking (solid: all, dashed: unblocked)



energy of the collison (time integrated)



Time of the collision (energy integrated)

Big differences in collision histories between programs.

Effect on observables that depend on collisons, like particle production?

→ Spread of programs is still too large !!

HPCI Strategic Programs for Innovative Research (SPIRE)
Field 5 “The origin of matter and the universe”

東京大学 THE UNIVERSITY OF TOKYO

TDDFT calculations for the symmetry energy research

Yoritaka Iwata

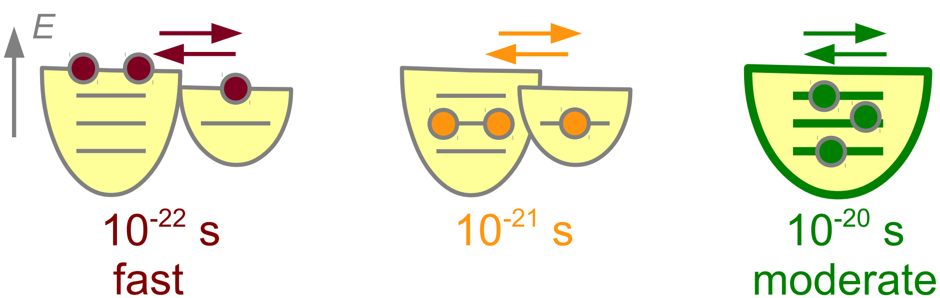
School of Science, The University of Tokyo

It's all about the motion of particles

10^{-22} s … Fermi momentum of nucleon
(features specific to Fermionic system)
= Charge equilibration

10^{-21} s … Collective oscillation of nuclear system
(larger influence of nuclear force)

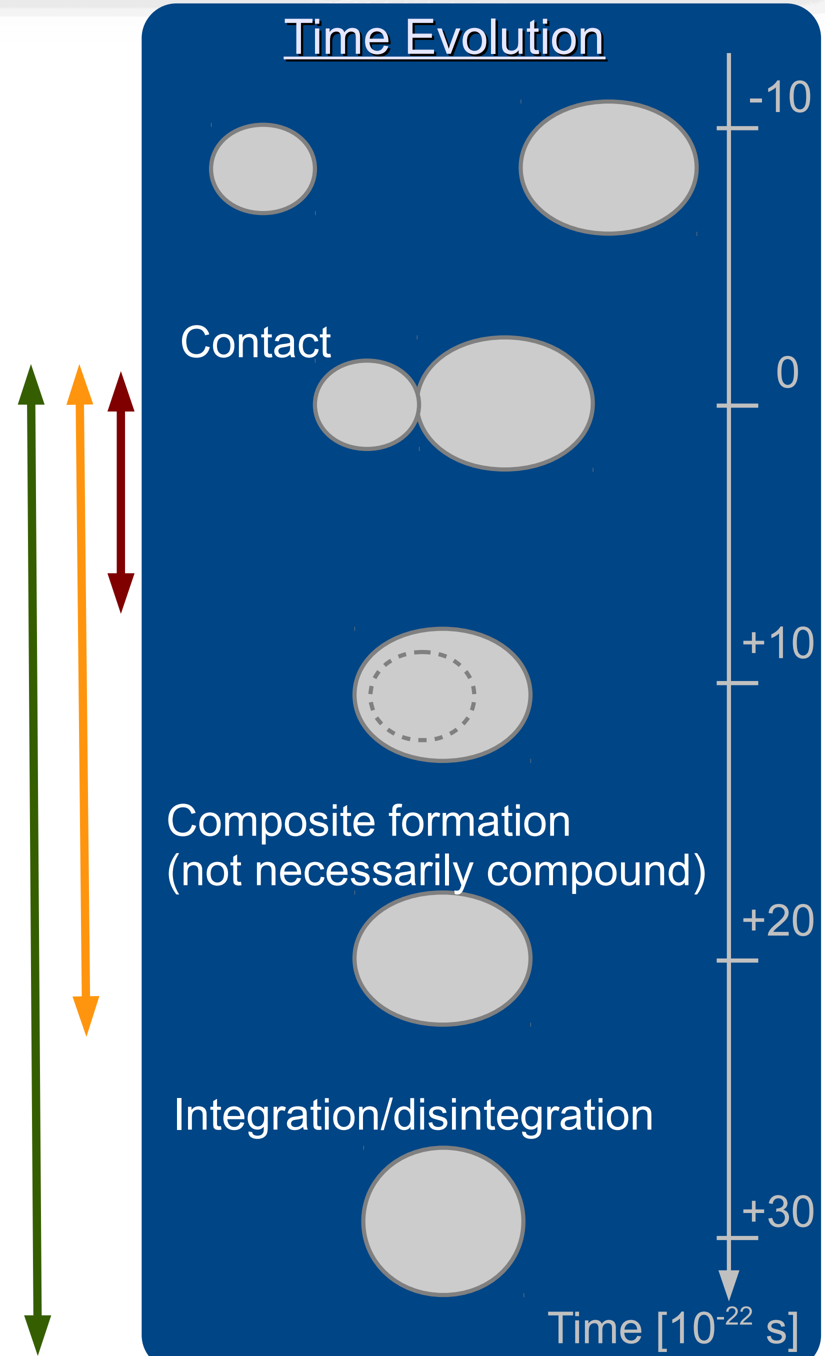
10^{-20} s … Momentum equilibration
(equilibrium of nuclear and Coulomb force)



In addition,

10^{-15} s … Thermal equilibration (~Wiener process)
(slow) fission, (slow) decays

TDDFT can investigates events < 10^{-20}s



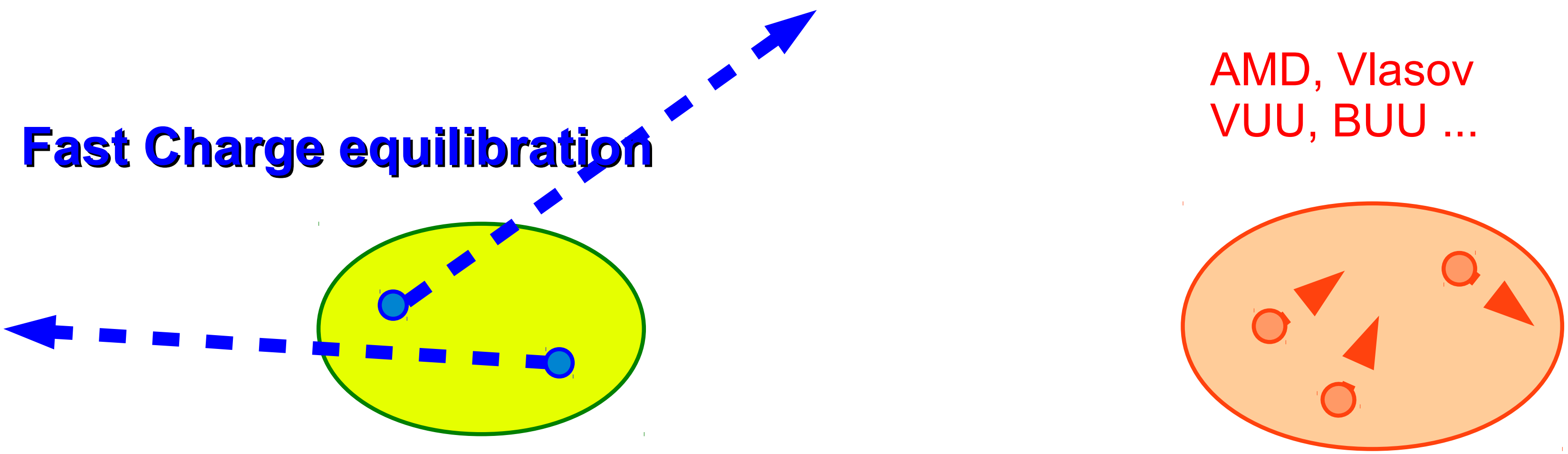
- The TDDFT is developing in order to clarify the reaction mechanism(general properties) throughout the process.
- [Very early moment] the appearance of charge equilibration is sufficiently clarified using the TDDFT.
- [Typical time scales] shape evolution will be quantitatively discussed; neck is largely formed in most cases.
- [Typical time scales] in many TDDFT research groups, fusion cross section, final products, nucleon transfer and so on are discussed (comparing with) experiments.

Low-energy heavy-ion collisions

With incident energies a few MeV per nucleon

- There are **two completely different physics** related to investigate and measure nuclear symmetry energy;
  one is the zero-sound propagation region,
  and the other is usual sound propagation region.

as a result, charge equilibration (isospin equilibration) dynamics is different



Giant Resonances, EoS , Symmetry Energy

『Nucle Symmetry Energy and Nucleus-Nucleus collision simulations』

(July 2-4, 2013 at RIKEN. Japan)

H. Sagawa
University of Aizu/RIKEN, Japan

1. Incompressibility and Giant Monopole Resonances
2. Isospin dependence of GMR
3. Mass model and symmetry energy
4. Spin-Isospin instability --SAMi
5. Summary

Properties of finite nuclear system and the systematics of *E1* response

S. Ebata (江幡 修一郎),
Meme Media Laboratory, Hokkaido Univ.
Nuclear Reaction Data Center, Hokkaido Univ.

Today's contents

How do we contribute to EoS from nuclear structure ?

To analyze symmetry energy
- *N*-skin
- GDR
- PDR
- *E1* polarizability

To quantify GDR, PDR, α_D

GDR centroid
(mean or average) energy;

$$E_{\mathrm{ave}} = \frac{\int ES(E;E1)dE}{\int S(E;E1)dE}$$

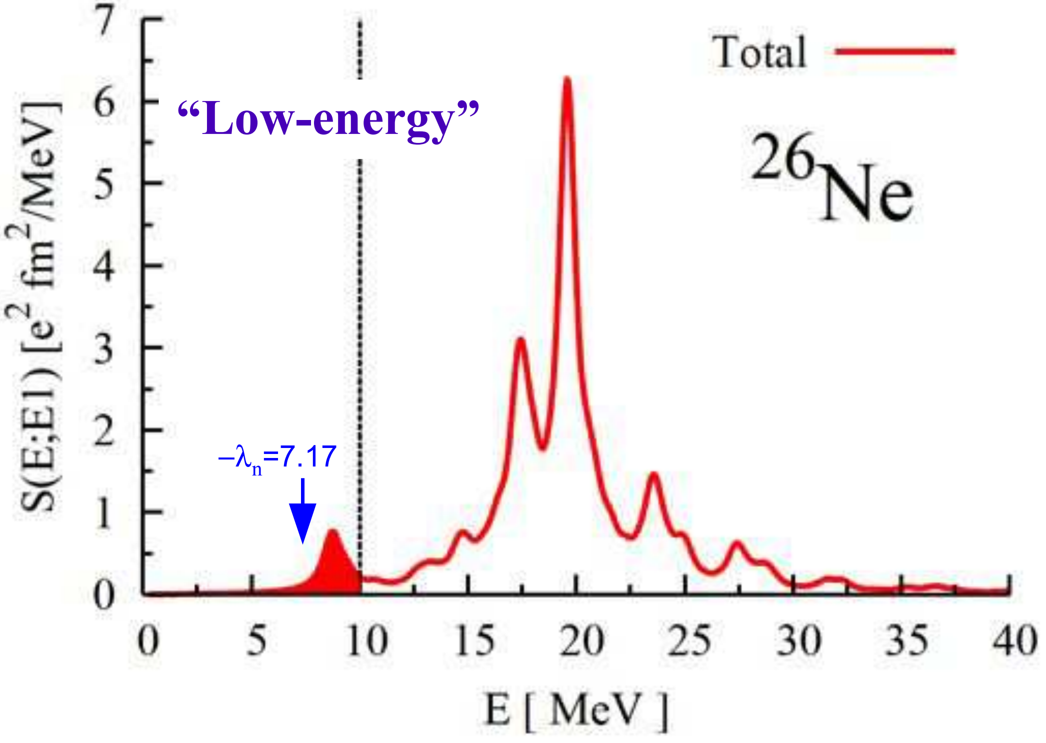
PDR ratio;

$$\frac{m_1(E_c = 10)}{m_1} \equiv \frac{\int^{10} ES(E;E1)dE}{\int ES(E;E1)dE}$$

E1 Polarizability α_D;

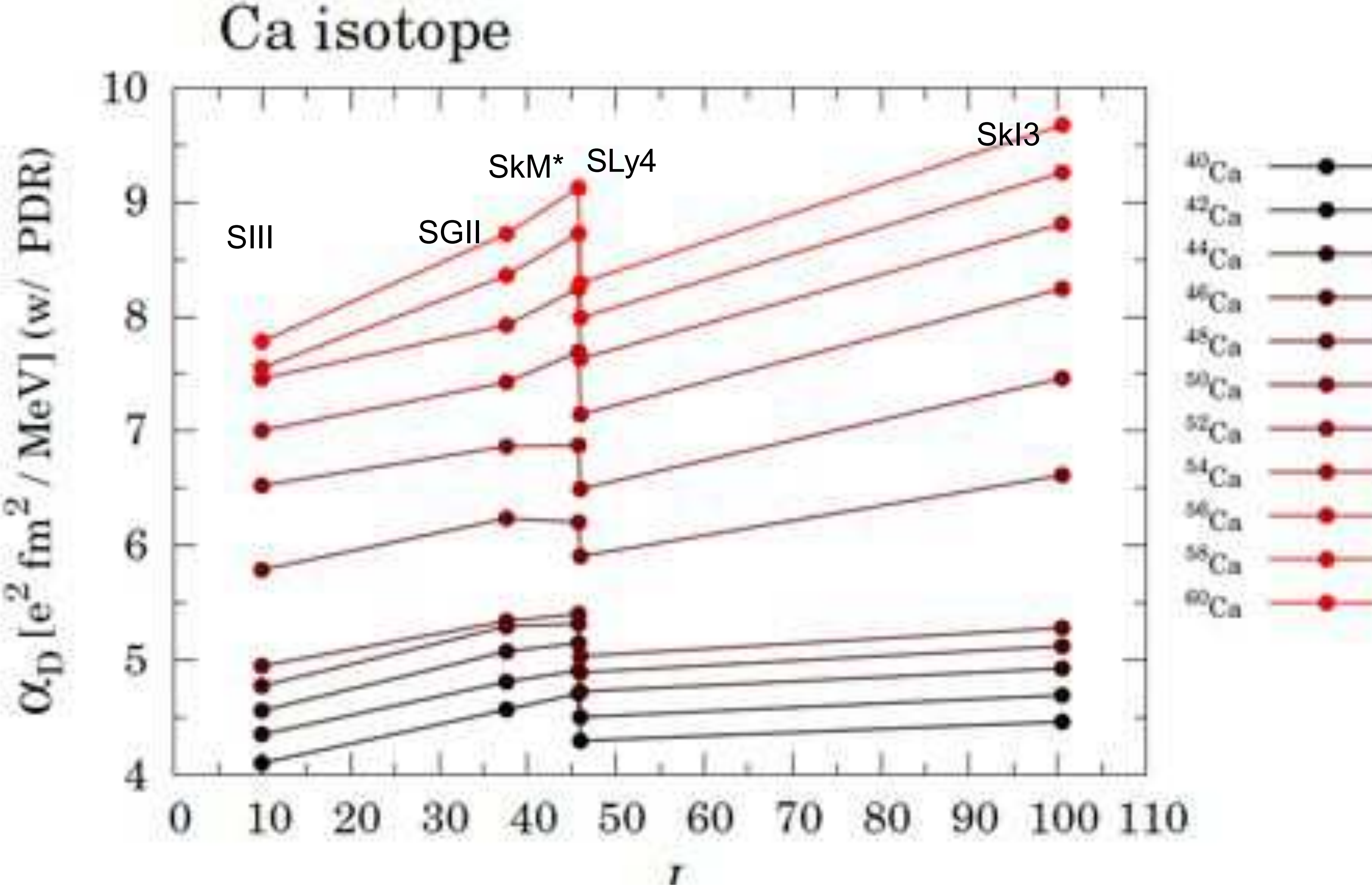
$$\alpha_D \equiv \int \frac{S(E;E1)}{E} dE$$

ex.)

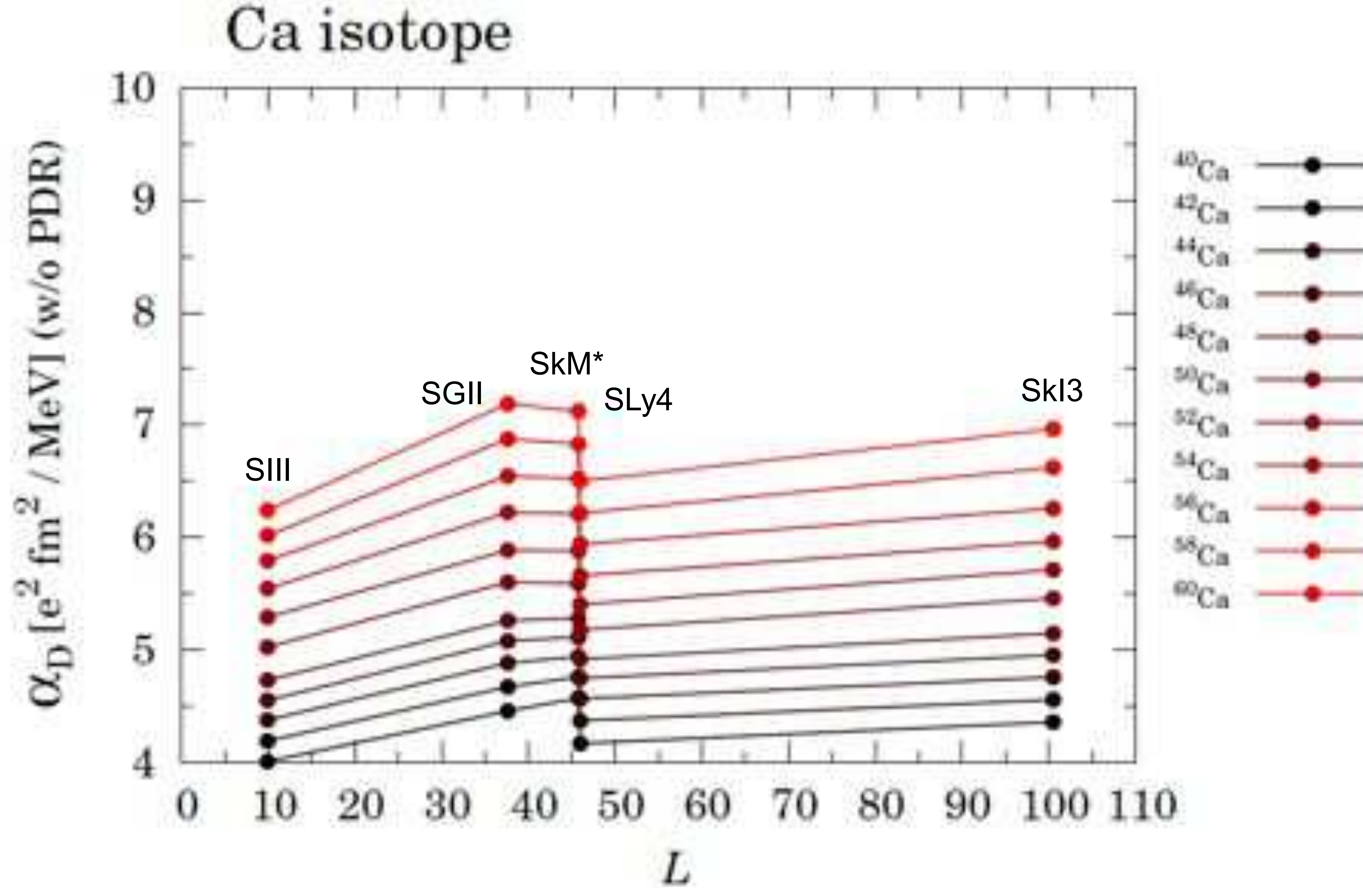


*Low-lying *E1* strength moves E_{ave} to lower region and enhances α_D , in neutron-rich region.

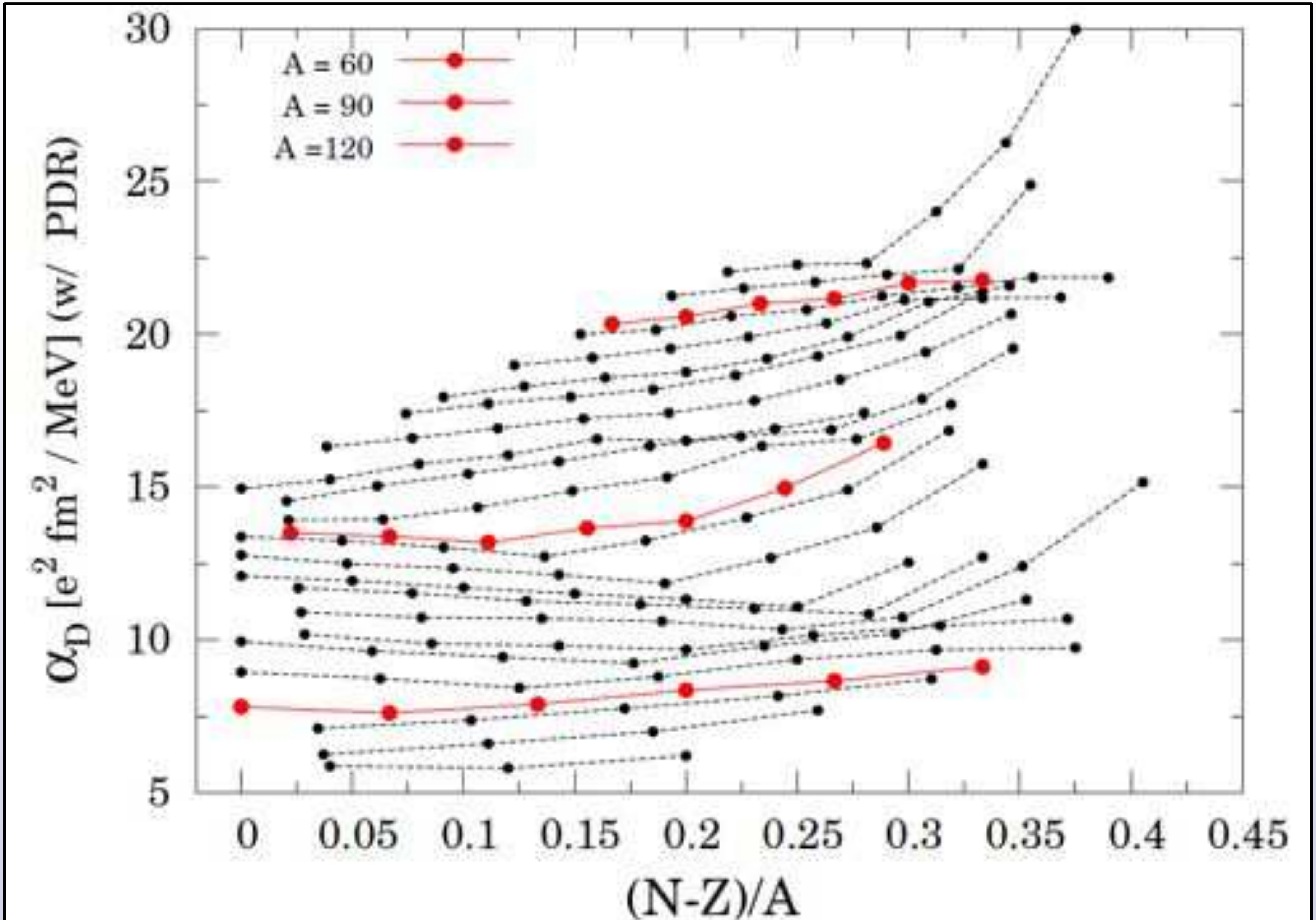
E1 polarizability vs. Slope parameter *L*



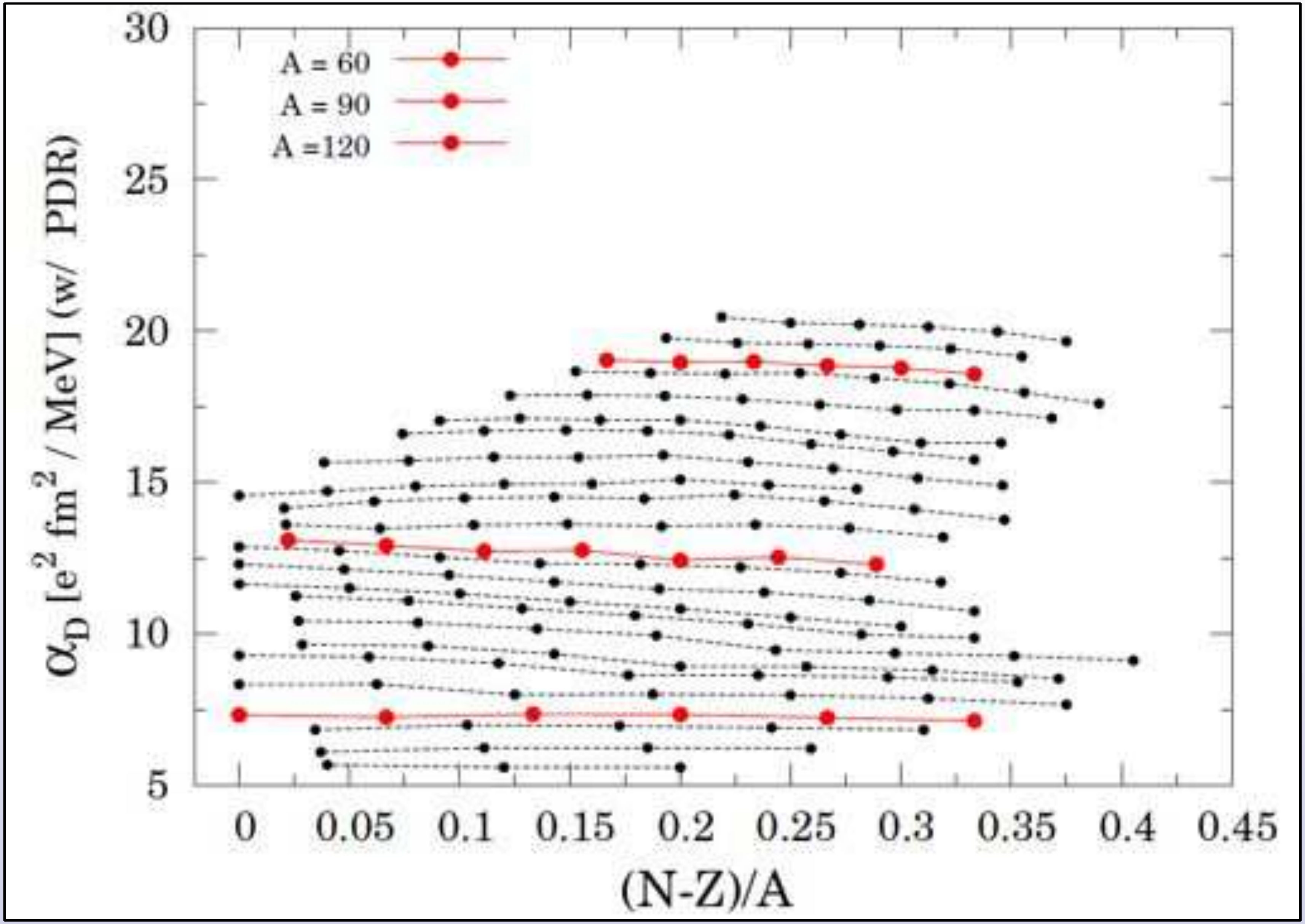
$E1$ polarizability (w/o PDR) vs. Slope parameter L



E1 polarizability vs. (*N* - *Z*)/*A*; isobar *A* =50 – 128 with SkM*



E1 polarizability (w/o PDR) vs. (*N* - *Z*)/*A*; isobar *A* =50 – 128 with SkM*



Symmetry energy and supernovae

Hideyuki Suzuki (Tokyo Univ. Sci.)

Influences of symmetry energy

1. collapsing core, initial shock energy
2. delayed explosion
3. protoneutron star cooling

collapsing core, initial shock energy

- In collapsing core, escaping ν_e's reduce the lepton fraction Y_L of the core. larger electron capture rate → more ν_e's escape → smaller Y_L
- Larger lepton fraction results in more massive inner core $M_{\rm i.c.} \sim M_{\rm Ch}(Y_L) \propto Y_L^2$
- Shock wave is launched around the boundary of bounced inner core and supersonically collapsing outer core with an initial energy ∼ gravitational binding energy of the bounced inner core $\sim \frac{GM_{\rm i.c.}^2}{R_{\rm i.c.}} \propto Y_L^{\frac{10}{3}}$
- More massive inner core is also preferable to successful shock propagation because the shock wave have only to pass through less massive outer core.
- Electron capture rate as a function of S_v is important. Bruenn demonstrated: Larger symmetry energy → more bound protons, less free proton fraction → less electron capture rate (e-cap. rate(free proton) > e-cap. rate(p in A)) → less ν_e's escape from the collapsing core → larger Y_L → larger $M_{\rm i.c.}$, larger $E_{\rm shock}$

Equation of States (EOS) for high density matter ($T \neq 0$)

- Lattimer-Swesty 1991: FORTRAN code
  Liquid Drop model: $K_s = 180, 220, 375\text{MeV}$, $S_v = 29.3\text{MeV}$
  $E/n \sim -B + K_s(1 - n/n_s)^2/18 + S_v(1 - 2Y_\mathrm{e})^2 + \cdots$

- Shen's EOS table (Shen *et al.*, 1998)
  RMF (n,p,σ, ρ, ω) with TM1 parameter set($g_\rho, \cdots$) $\Leftarrow$ Nuclear data including unstable nuclei
  ρ_B, n_B, Y_e, T, F, U, P, S, A, Z, M^*, X_n, X_p, X_α, X_A, μ_n, μ_p
  grids: wide range

grids: wide range	$T = 0, 0.1 \sim 100\text{MeV}$	$\Delta \log T = 0.1$
	$Y_e = 0, 0.01 \sim 0.56$	$\Delta \log Y_e = 0.025$
	$\rho_B = 10^{5.1} \sim 10^{15.4}\text{g/cm}^3$	$\Delta \log \rho_B = 0.1$

  Extension with hyperons (Ishizuka, Ohnishi), quarks (Nakazato)

2D/3D explosions but E_{exp} less than observed (Suwa et al., ApJ 764, 99 (2013)
Key Physics is still unclear:
Neutrino heating, Standing Accretion Shock Instability, Convection, Rotation, Magnetic field, Accoustic waves

In summary:
While K affects the core dynamics via pressure change, Sv affects composition Of the core and has influence on supernova explosions.

Strongly Tensor Correlated Hartree-Fock Theory for Nuclear Matter

Hiroshi Toki (RCNP, Osaka)

In collaboration with

Yoko Ogawa (RCNP)

Kaori Horii (RCNP)

Takayuki Myo (Osaka IT)

Kiyomi Ikeda (RIKEN)

Jinniu Hu (Peking)

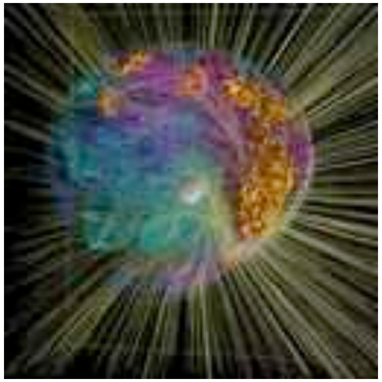
Lisheng Geng (Beihang)

Hong Shen (Tianjin)

Content

- Importance of pion in light nuclei
- Tensor optimized shell model (TOSM)
  0p0h + 2p2h states
- Strongly tensor correlated Hartree-Fock theory
- Equation of state in RMF
- Problem of RMF for EOS
- Nuclear URCA process
- Conclusion

RIKEN July 2 – 4, 2013

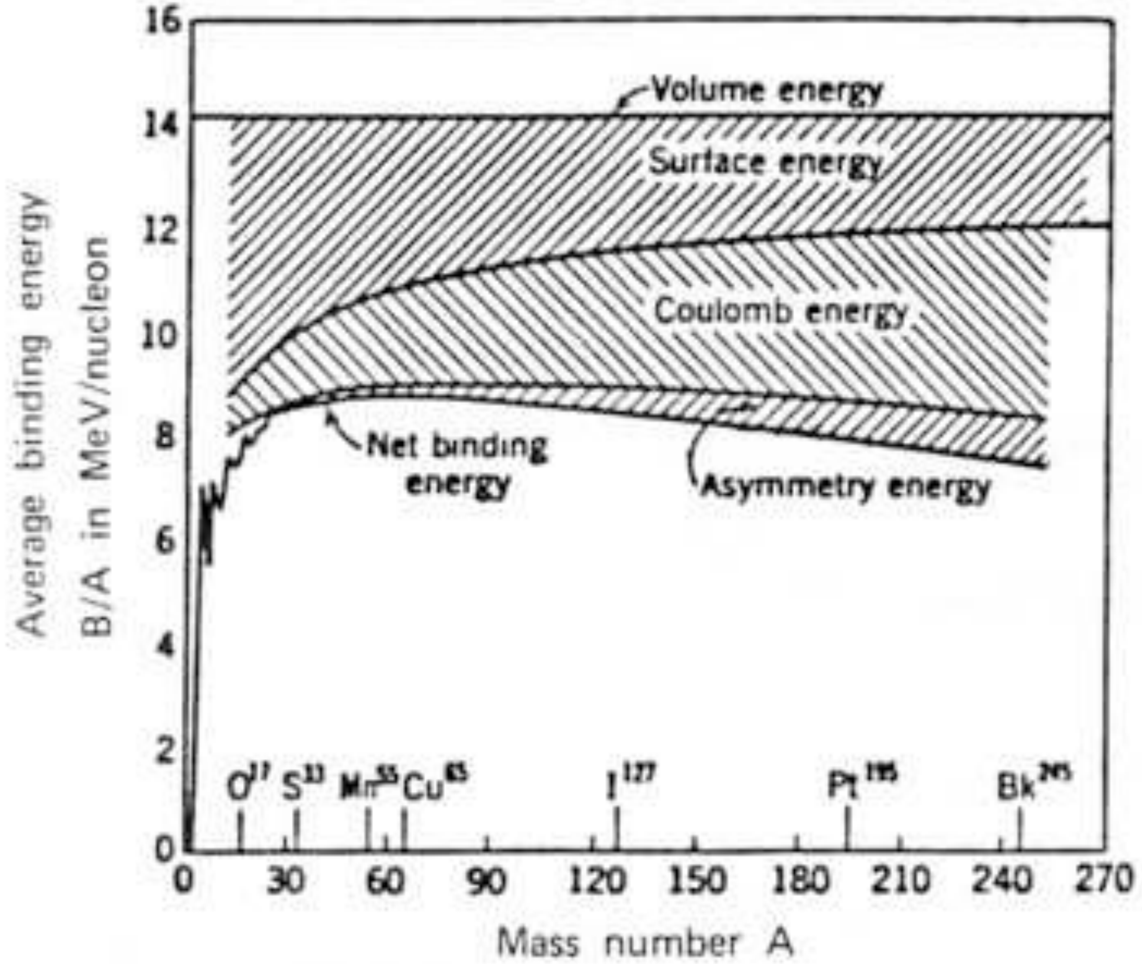


Nuclear symmetry-energy and nucleus-nucleus collision simulation

J.R.Stone

Oxford/Tennessee/Maryland

Semiclassical picture



Binding Energy per Nucleon, Explained by the Liquid Drop Model
From R. D. Evans, The Atomic Nucleus, McGraw Hill, 1955

Models of finite nuclei often are calibrated on properties of nuclear matter at saturation:

$$\rho_0,\ \ E/A\left(\rho_0\right), S(\rho_0), K_\infty$$

But, nuclear matter is an idealized medium that does not exist in nature. and is approximated by expansion A -> ∞ of expressions for energy per particle etc of finite nuclei.

Relation between quantities describing finite nuclei and nuclear matter is often model dependent (e.g. incompressibility, symmetry energy and its derivatives)

Open question remains – how valid is such a procedure

The Equation of State

Relation between pressure P, energy density ε, particle number density ρ at temperature T

$$P = \rho^2 \left(\frac{\partial(\varepsilon/\rho)}{\partial\rho} \right)_{s/\rho} \qquad \varepsilon(\rho,T) = \sum_f \varepsilon_f(\rho,T)$$

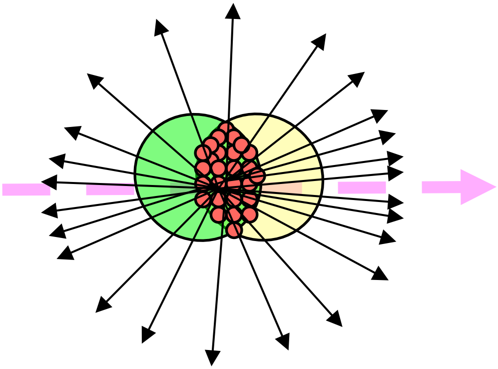
where summation over f includes all hadronic (baryons, mesons), leptonic and quark (if applicable) components present in the system at density ρ and temperature T

Two key points:

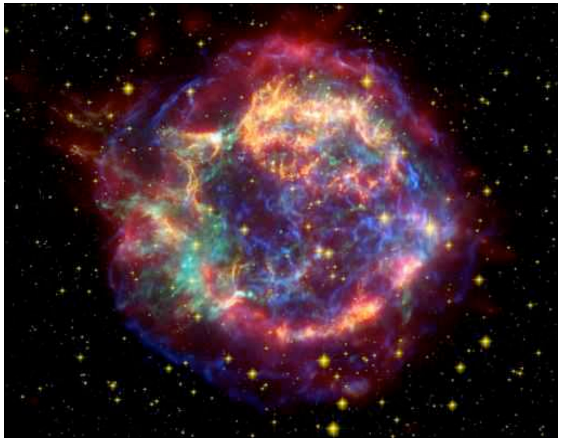
The EoS is dependent on composition
CONSTITUENTS + INTERACTIONS

ε_f and ITS DENSITY AND TEMPERATURE DEPENDENCE
must be determined by nuclear and/or particle models.

HEAVY ION COLLISIONS: Hot matter created
in dependence on beam energy
different composition
and properties

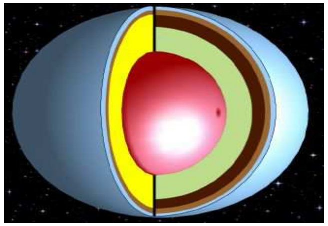


COMPACT OBJECTS: **Core-collapse supernova**



hot proto-neutron star
fast rotating neutron stars

cold non-rotating
neutron star



Figures from : D. Hofman, UIC, 2006 (top) F. Weber, talk at ORNL 2012 (bottom)

Comparison of main features of high density matter in:

Central A-A collision:
Strongly beam energy dependent
Beam energy < 1GeV/ A

Temperature: < 50 MeV
Energy density: ~ 1 -2 GeV/fm^3
Baryon density ~ 3-4 ρ_0 (transient)
(Time scale to cool-down: 10^{-22-24} s
No neutrinos

Strong Interaction: (S, B and L conserved)
Time scale 10^{-24} s

Inelastic NN scatterings,
N,N*, Δ's
LOTS of PIONS
strangeness
less important (kaons)
NO LEPTONS
? EQUILIBRIUM?

Proto-neutron star:
(progenitor mass dependent)
~ 8 – 20 solar mass

Temperature: < 50 MeV
Energy density: ~ 1 GeV/fm3
Baryon density ~ 2-3 ρ_0
Time scale to cool-down: 1 -10 s
Neutrino rich matter

Strong +Weak Interaction: (B and L con)
Time scale 10^{-10} s

Higher T: strangeness produced in
in weak processes
Lower T: freeze-out

N, strange baryons and mesons,
NO PIONS, leptons
?EQUILIBRIUM?

Discussions with Betty Tsang

Norman Glendenning: Compact Stars

"Symmetric nuclear matter and matter produced in high-energy collisions when the field equation are solved subject to the constraints of charge symmetry and strangeness (in this case zero)."

"Neutron star matter, when the field equations, supplemented by those of leptons are solved subject to the constraints of charge neutrality and generalized beta equilibrium without conservation of strangeness."

A very gentle question for discussion:

Are the EoS of HIC matter and NS matter the same?

General comment on the current situation in modeling:

Current models have very limited predictive power – they have too many parameters and it is impossible to constrain them unambiguously at present

WE KEEP REPEATING CALCULATIONS AND SOME OF THEM FIT A SELECTED CLASS OF DATA WELL BUT FAIL ELSEWHERE. SUCH MODELS CANNOT BE RIGHT AND CANNOT BE TRUSTED.

Suggested path towards a solution ?

Study basics of these models, their region of applicability and find the physics that justifies them.

STUDY SENSITIVITY TO ALL AVAILABLE DATA AND FIND THE MOST IMPORTANT SET TO FIT THE MODELS CONSISTENTLY.

Perhaps we will be able to narrow down the number of models, increase predictive power of the selected ones and move forward.

Physics may be a good tool for selection theories after all .

Extracted from conclusions of mini-WS:

ULIC-RIBF MiniWS027, 3 Jul. 2013

The information on the Symmetry Energy is indirect, depends on models.

measure the N/Z ratios of the emitted particles
(n/p ratios, isospin diffusion, t/He3, N/Z ratios of IMFs, flow, pi- /pi+, ……), and then compare with the prediction from the transport model,
in which the different symmetry potential can be used.

BUU / QMD / AMD

Current possible solutions:

QMD with Pauli blocking

AMD with relativity

PHITS for π^-/π^+

and compare ImQMD result)

Future of the Simulation models:

BUU

Bao-An Li's IBUU used for prediction of pi-production

IBUU code need very high running cost --> possible

(results a few TB; super computer; only its binary code is available in RIKEN)

How to modify BUU?

Collaboration with JAEA could help the improvements of transport models.

QMD

ImQMD@MSU cannot treat pi-production, though Beijing ImQMD can do (not apply to it)

PHITS can make a prediction of pi-production

AMD (most reliable code in Japan)

AMD CAN in principle treat pions include pions and Deltas

if pion absorption could be neglected for the following reaction

^{132}Sn + ^{124}Sn @ 300 MeV/u , ^{124}Sn + ^{124}Sn @300 MeV/u

How about relativity?

Bulk feature of HIC should be compared....

Small meeting with Bao-An on this issue at NuSYM@MSU

Mini-WS was an extremely well organised, informative and useful meeting.

Thank you!

ありがとう

Arigatō