Investigation of the symmetry energy in EOS by isoscaling in heavy ion reactions

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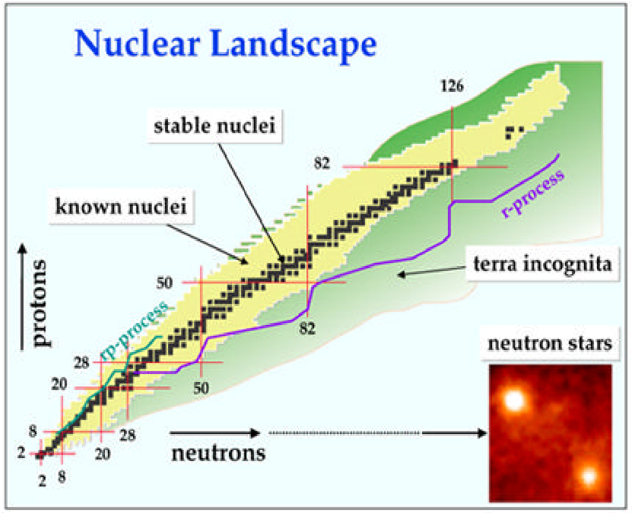
GDR study via QMD simulation for isospin asymmetry reaction

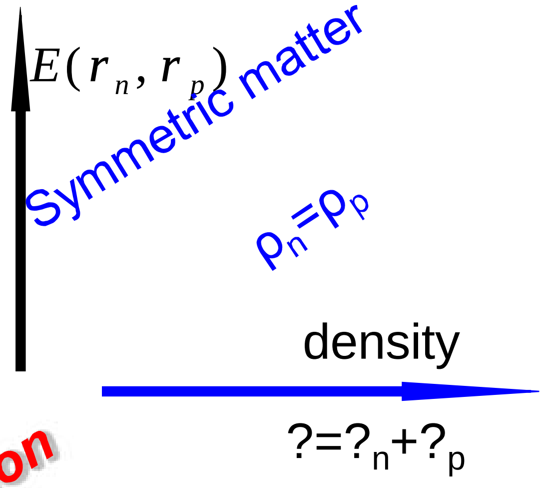
Summary

- Sequential decay effect on isoscaling and constrain of symmetry energy
- Other observables to study the isospin degree

Background and motivation

◆ Isospin and symmetry energy in nuclear EoS





A new dimension

Isospin asymmetry d=(?$_n$-?$_p$)/?

Liquid-drop model

$$a_V A - a_s A^{2/3} - a_4 \frac{(N-Z)^2}{A} - a_c \frac{Z(Z-1)}{A^{1/3}} + a_p \frac{\Delta(N,Z)}{A^{1/2}}$$

Symmetry energy term

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EOS of Isospin Asymmetric Nuclear Matter

$$E(r,d) = E(r,0) + E_{sym}(r)d^2 + O(d^4), \quad d = (r_n - r_p)/r$$

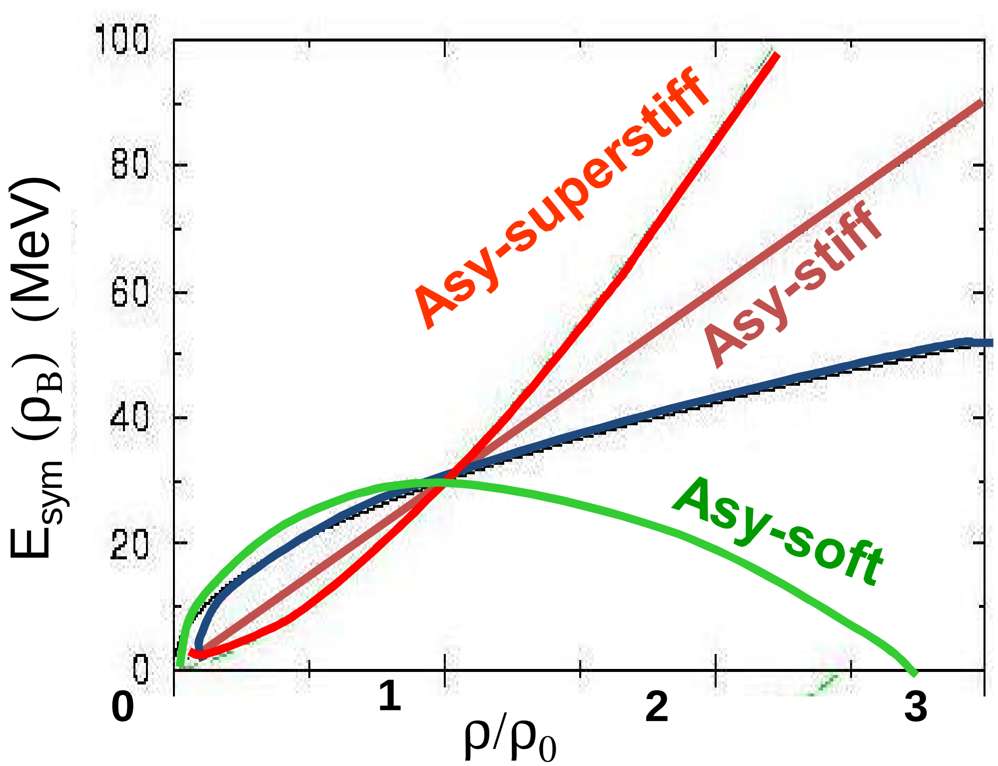
The Nuclear Symmetry Energy

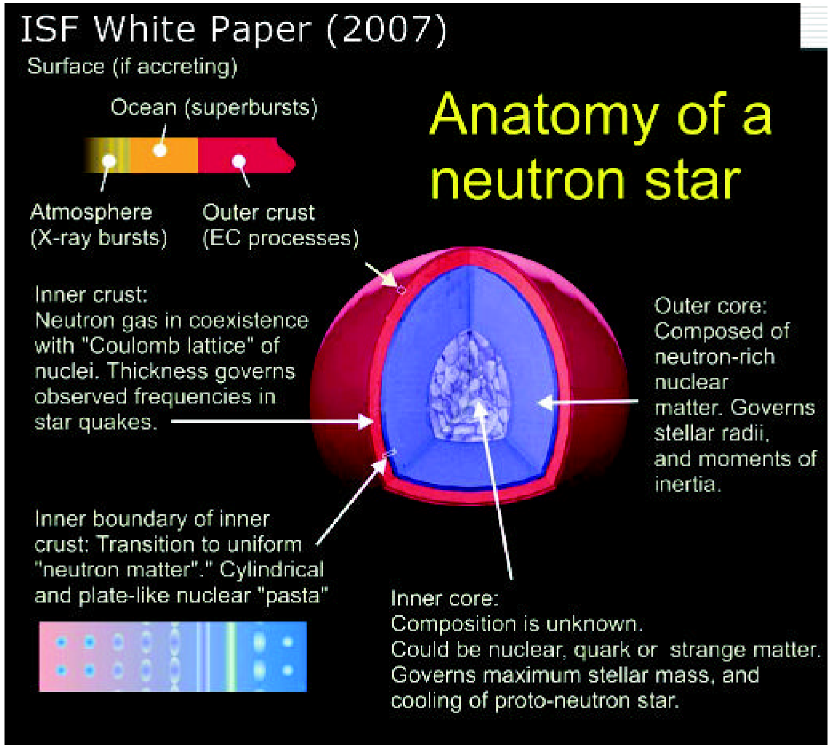
Symmetric Nuclear Matter

$$E_{sym}(r) \equiv \frac{1}{2}\frac{\partial^2 E(r,d)}{\partial d^2}$$

Symmetry energy term

Critical term for the asymmetry nuclear EOS, neutron star(mass, radius, peoperty)





◆ Observables to measure the symmetry energy in nuclear EoS

At sub-saturation densities

- **Sizes of n-skins of unstable nuclei from total reaction cross sections**
- **Proton-nucleus elastic scattering in inverse kinematics**
- **Parity violating electron scattering studies of the n-skin in ^{208}Pb at JLab**
- **n/p ratio of FAST, pre-equilibrium nucleons**
- **Isospin fractionation and isoscaling in nuclear multifragmentation**
- **<u>Isospin diffusion/transport</u>**
- **Neutron-proton differential flow**
- **Neutron-proton correlation functions at low relative momenta**
- **t/^{3}He ratio**

Towards high densities

- **p^-/p^+ ratio, K^+/K^0 ?**
- **Neutron-proton differential transverse flow**
- **n/p ratio of squeezed-out nucleons perpendicular to the reaction plane**
- **Nucleon elliptical flow at high transverse momenta**

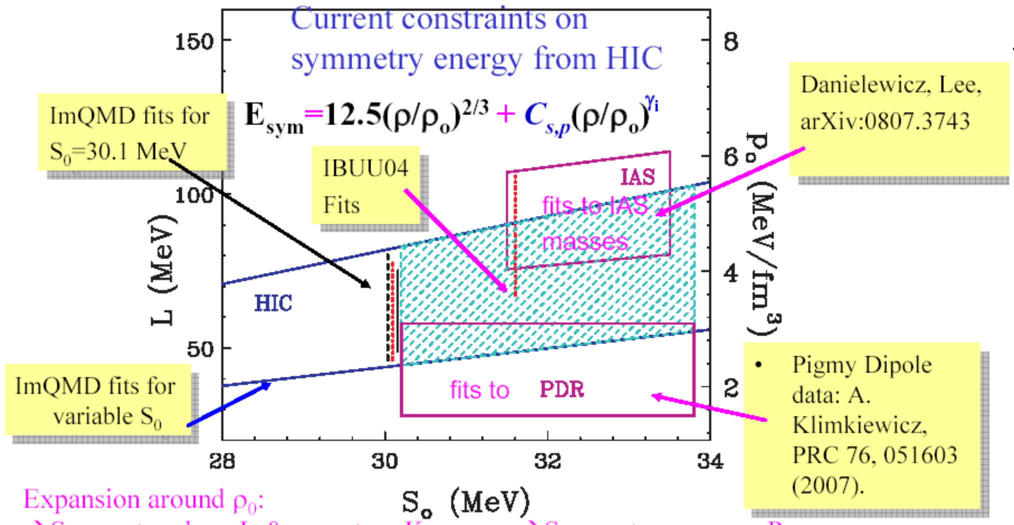
Model dependent probes or Hypothesis dependent probes

Constrain symmetry energy from experiment

Isoscaling, Isospin diffusuion,double n/p Rauio, MSU data, TAMU data at sub-saturate density

$S \sim 31.6(r/r_o)^g$ $0.69 \le \gamma \le 1.05$ **IBUU04**

$S = 12.5(r/r_o)^{2/3} + 17.6\,(r/r_o)^{g_i}$ $0.4 \le \gamma_i \le 1$ **ImQMD**

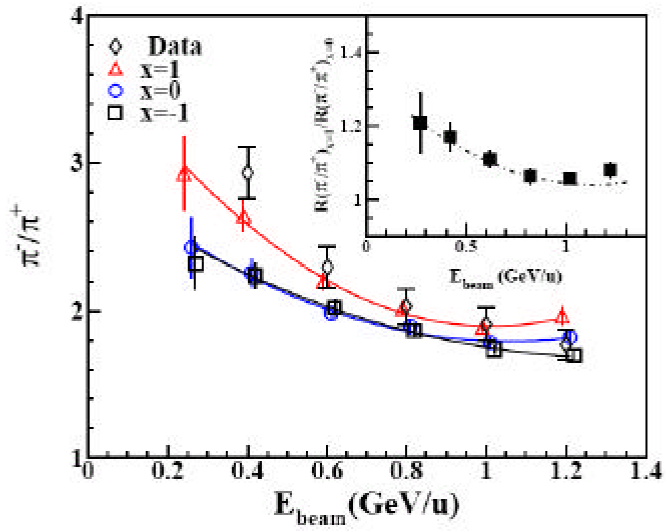


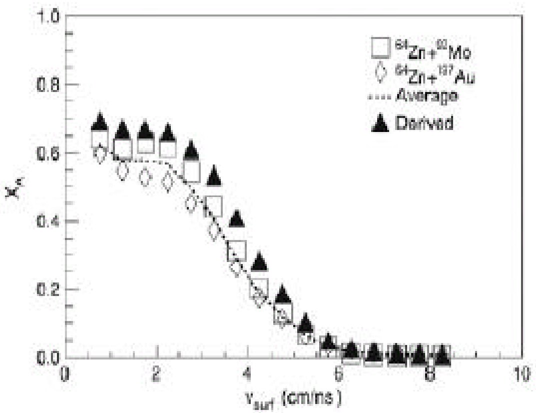
Expansion around ρ_0:
→Symmetry slope L & curvature K_{sym} →Symmetry pressure P_{sym}

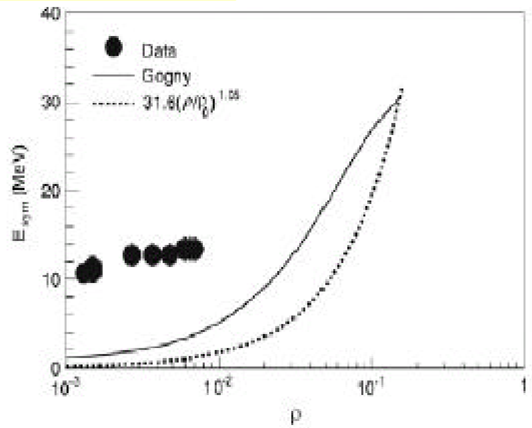
$$E_{sym} = S_o + \frac{L}{3}\left(\frac{\rho_B-\rho_0}{\rho_0}\right) + \frac{K_{sym}}{18}\left(\frac{\rho_B-\rho_0}{\rho_0}\right)^2 + \ldots$$

$$L = 3\rho_0 \frac{\partial E_{sym}}{\partial \rho_B}\bigg|_{\rho_B=\rho_0} = \frac{3}{\rho_0}P_{sym}$$

High density, FOPI data,
Xiao/Li/Chen/Yong/Zhang, PRL102, 062502(2009)







Very low density, TAMU data,
Horowitz and Schwenk, Nucl. Phys. A 776 (2006) 55
S. Kowalski, et al., PRC 75 (2007) 014601.
J. B. Natowitz et al, PRL 104, 202501 (2010)

Ideally, Isoscaling measure the hot fragments of the reaction, with the assumption of that secondary decay of the two similar reactions are same, the secondary decay so can be neglected.

But some investigation show the isoscaling difference from hot fragments and cold fragments, our purpose is to study the influence of statistical secondary sequential decay on isoscaling and constrain of the symmetry ernergy coefficient from isoscaling measurement.

A statistical sequential decay model GEMINI was selected to observave the secondary decay effect.

We simplely analyze the results from an experimental method, to compare with the experimental data.

◻Statistical sequential decay influence on isoscaling and constrain of symmetry energy

Statistical binary sequential decay model (GEMINI)

Calculates the decay of compound nuclei by sequential binary decays, all possible divisions from light-particle emission to symmetric divisions are considered. GEMINI employs a Monte Carlo technique to follow the decay chains of individual compound nuclei through sequential binary decays until the resulting products are unable to undergo further decay.

The decay width for the evaporation of fragments with Z£2 is calculated using the Hauser-Feshbach formalism. Light particle decay width is given by

$$\Gamma_{J_2}(Z_1, A_1, Z_2, A_2) = \frac{2J_1+1}{2pr_0} \sum_{l=|J_0-J_2|}^{J_0+J_2} \int_0^{E^*-B-E_{rot}(J_2)} T_l(e) r_2(U_2, J_2) de$$

The symmetry energy term due to the neutron-proton excess is represented in calculating the binding energy for heavy systems(Z>12), For very light systems (A<=12), binding energies were calculated from the experimental masses.

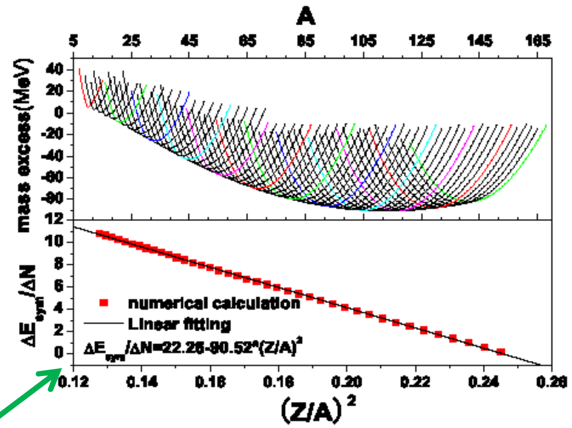
R.J. Charity et al, Nucl. Phys. A 483, 371, (1988).

R.J. Charity, computer code GEMINI, see http://wunmr.wustl.edu/pub/gemini

R. Charity et al, PRC56, (1997) 873; H. J. Krappe et al., PRC20, (1979) 992; P. Möller et al., NPA361, (1981) 117

◆Isolate from dynamical effect, at the saturate density

◆Decay from equalibrated compound nuclei(source) with different isospin asymmetry



◆Couples of group and pairs of compound nuclei(source

Different Atomic number and mass region (Z=30,50)

Different isospin asymmetry (N/Z=1.0,1.1,1.2,1.4)

Different excitation energy (E_{ex}=1, 1.4, 2, 2.4, 3MeV/u)

◆First step decay only (Well determined source and temperat

one step of decay calculated, then stop the simulation

check isoscaling and constrain of symmetry energy coefficient with determined process

◆Full step decay chains included

all decay step considered, until no particle or gamma ray emission

test the secondary decay effect on isoscaling and symmetry energy constrain

$$
\begin{aligned}
M^{(0)}_{macro} \; = \; & M_n N + M_p Z - a_v(1-k_v I^2)A + a_s(1-k_s I^2) \\
& \times \left\{ A^{2/3} - 3\left(\frac{a}{r_0}\right)^2 + \left(\frac{r_0}{a}A^{1/3}+1\right)\left[2A^{2/3} + 3\frac{a}{r_0}A^{1/3} + 3\left(\frac{a}{r_0}\right)^2\right] e^{2r_0 A^{1/3}/a} \right\} \\
& + \frac{3}{5}\frac{e^2}{r_0}\left[\frac{Z^2}{A^{1/3}} - \frac{5}{2}\left(\frac{b}{r_0}\right)^2\frac{Z^2}{A} - \frac{5}{4}\left(\frac{3}{2\pi}\right)^{2/3}\frac{Z^{4/3}}{A^{1/3}}\right] + W(|I|+d) - a_{el}Z^{2.39} + \begin{cases} \Delta - \frac{1}{2}\delta, & \text{N and Z odd} \\ \frac{1}{2}\delta, & \text{N or Z odd} \\ -(\Delta - \frac{1}{2}\delta), & \text{N and Z even} \end{cases}
\end{aligned}
$$

◆ The isoscaling behavior in first step decay and constrain of symmetry energy coefficient in GEMINI calculation

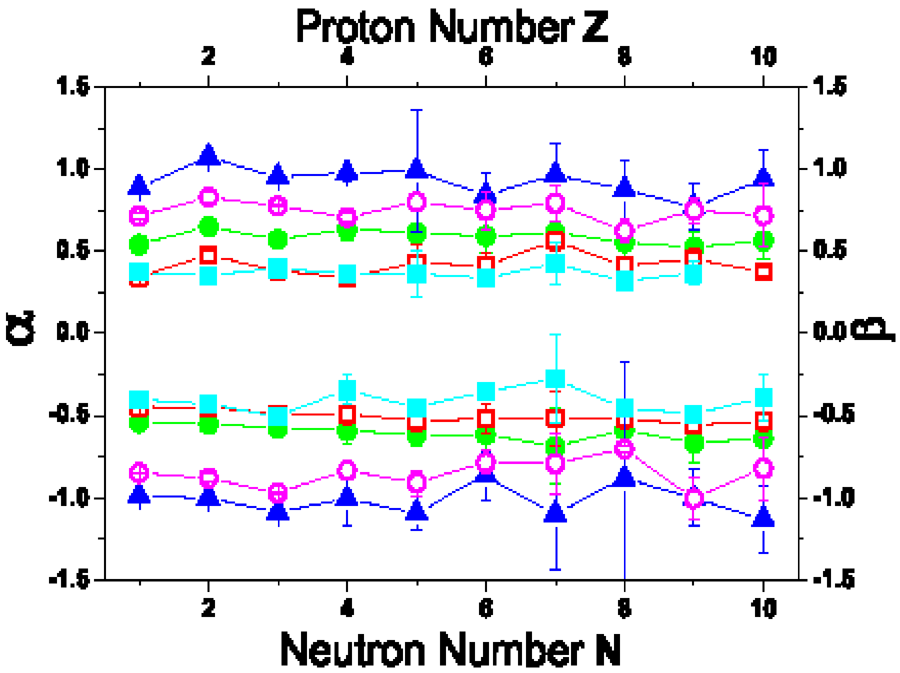


FIG. 2: (Color online) Isoscaling parameters α (positive values) and β (negative values) as a function of the fragment proton number Z or neutron number N from source pairs with the fixed proton number Z_s =50 at excitation energies E_{ex} = 2 MeV/nucleon. Symbols in figure correspond to $Y_{A_s=115}/Y_{A_s=110}$ (solid squares), $Y_{A_s=110}/Y_{A_s=105}$ (open square), $Y_{A_s=105}/Y_{A_s=100}$ (solid circles), $Y_{A_s=115}/Y_{A_s=105}$ (open circles), $Y_{A_s=110}/Y_{A_s=100}$ (solid up triangles).

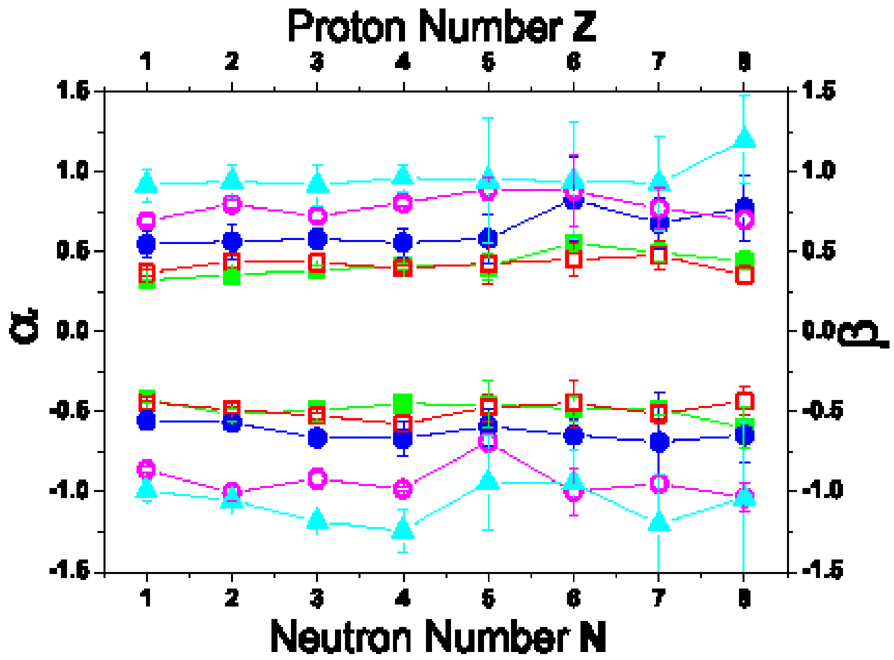
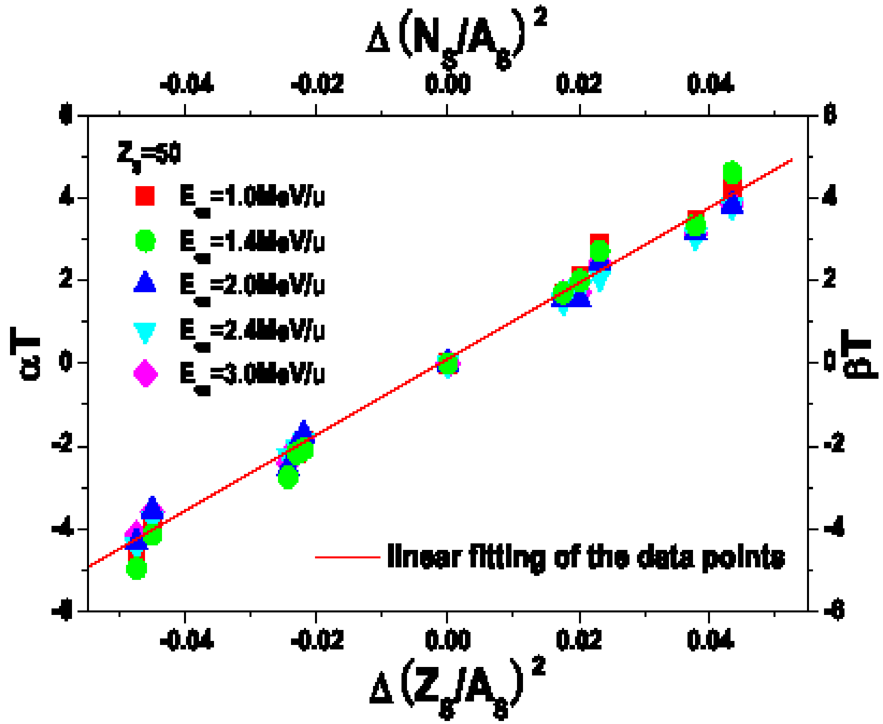


FIG. 3: (Color online) Isoscaling parameters α (positive values) and β (negative values) as a function of the fragment proton number Z or neutron number N from source pairs with the fixed proton number Z_s =30 at excitation energies E_{ex} = 2 MeV/nucleon. Symbols in figure correspond to $Y_{A_s=69}/Y_{A_s=66}$ (solid squares), $Y_{A_s=66}/Y_{A_s=63}$ (open square), $Y_{A_s=63}/Y_{A_s=60}$ (solid circles), $Y_{A_s=69}/Y_{A_s=63}$ (open circles), $Y_{A_s=66}/Y_{A_s=60}$ (solid up triangles).



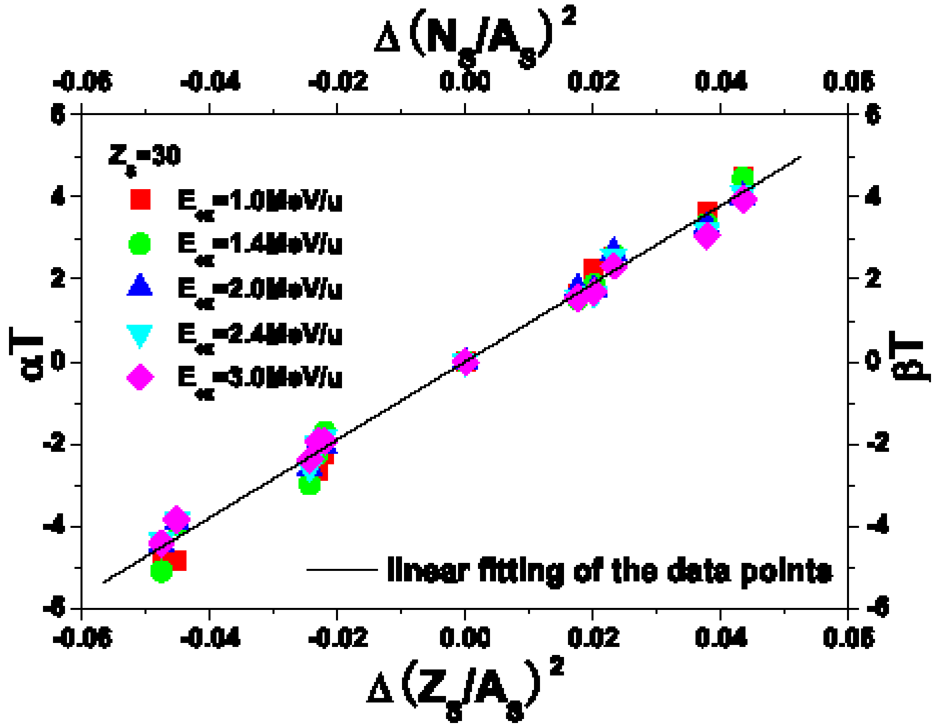


FIG. 6: (Color online) $\alpha \cdot T$ (positive parts) and $\beta \cdot T$ (negative parts) as a function of $(Z_s/A_s)_1^2 - (Z_s/A_s)_2^2$ or $(N_s/A_s)_1^2 -$ [illegible]

FIG. 7: (Color online) $\alpha \cdot T$ (positive parts) and $\beta \cdot T$ (negative parts) as a function of $(Z_s/A_s)_1^2 - (Z_s/A_s)_2^2$ or $(N_s/A_s)_1^2 -$ $(N_s/A_s)_2^2$ of the sources for various source pairs with atomic [illegible]

$$\alpha = \frac{4C_{sym}}{T}\left[\left(\frac{Z}{A}\right)_{s1}^2 - \left(\frac{Z}{A}\right)_{s2}^2\right] \equiv \frac{4C_{sym}}{T}\Delta\left(\frac{Z}{A}\right)_s^2$$

$$\beta = \frac{4C_{sym}}{T}\left[\left(\frac{N}{A}\right)_{s1}^2 - \left(\frac{N}{A}\right)_{s2}^2\right] \equiv \frac{4C_{sym}}{T}\Delta\left(\frac{N}{A}\right)_s^2$$

C_{sym}=23.0±0.7MeV (Fig. 6) 23.8±0.4MeV(Fig. 7)

W.D. Tian et al, PRC76,024607(2007)

Every step of the sequential decay, above relation work

Influence of the sequential decay

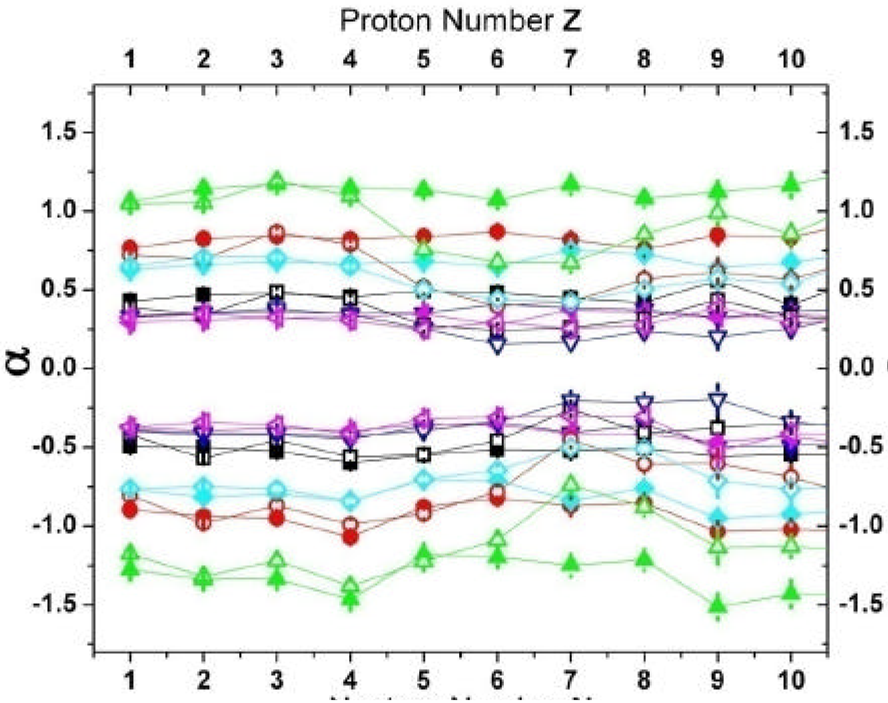


FIG. 1: (Color online) Comparison of Isoscaling parameters α (positive values) and β (negative values) as a function of the fragment proton number Z or neutron number N from source pairs of Z_s=50 at excitation energies E_{ex}=2.4MeV/nucleon, all solid symbols are only the first step secondary decay products, open symbols are full step secondary decay products, Symbols in the figure correspond to Y_{A_s}=105/Y_{A_s}=100 (squares), Y_{A_s}=110/Y_{A_s}=100 (cirlces), Y_{A_s}=115/Y_{A_s}=100 (up-triangles), Y_{A_s}=110/Y_{A_s}=105 (down-triangles), Y_{A_s}=115/Y_{A_s}=105 (Diamonds), Y_{A_s}=115/Y_{A_s}=110 (left-triangles).

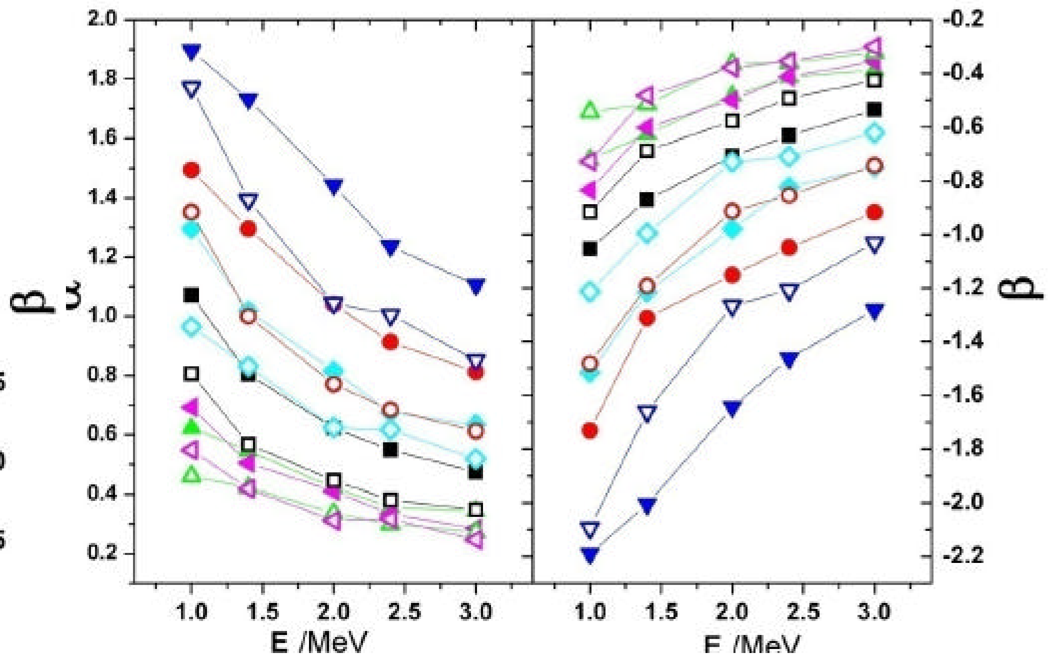


FIG. 2: (Color online) Comparison of Isoscaling parameters α (left panel) and β (right panel) as a function of the source excitation energy from source pairs of Z_s=30, all solid symbols are only the first step secondary decay products, open symbols are full steps secondary decay products, Symbols in the figure correspond to Y_{A_s}=63/Y_{A_s}=60 (squares), Y_{A_s}=66/Y_{A_s}=60 (cirlces), Y_{A_s}=66/Y_{A_s}=63 (up-triangles), Y_{A_s}=69/Y_{A_s}=60 (down-triangles), Y_{A_s}=69/Y_{A_s}=63 (Diamonds), Y_{A_s}=69/Y_{A_s}=66 (left-triangles).

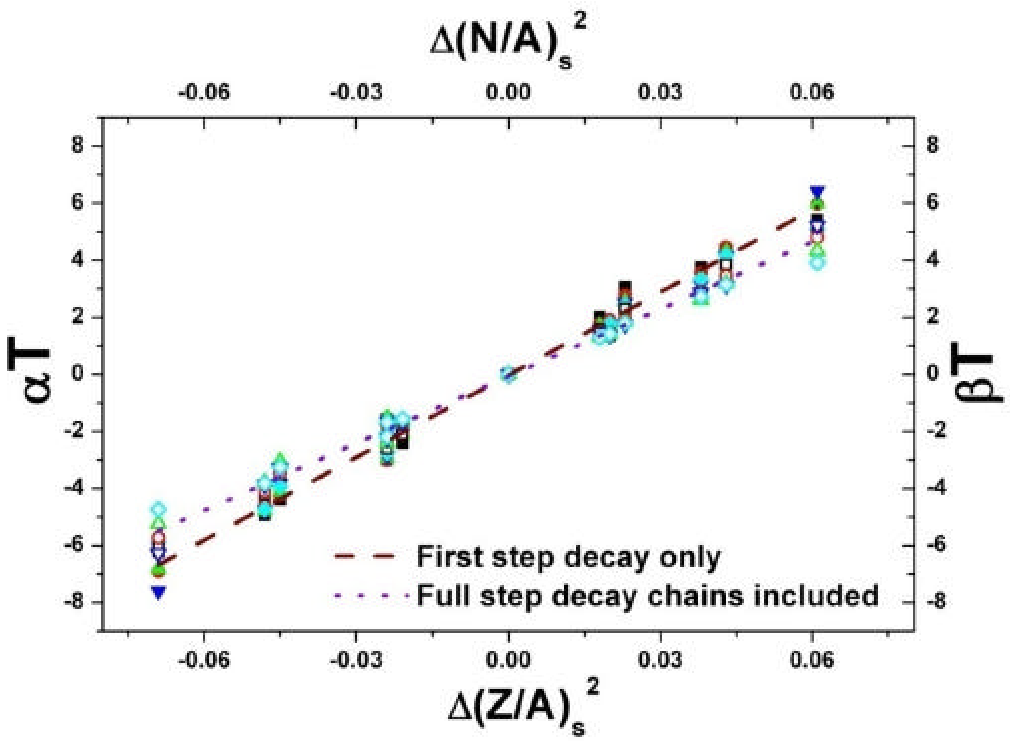


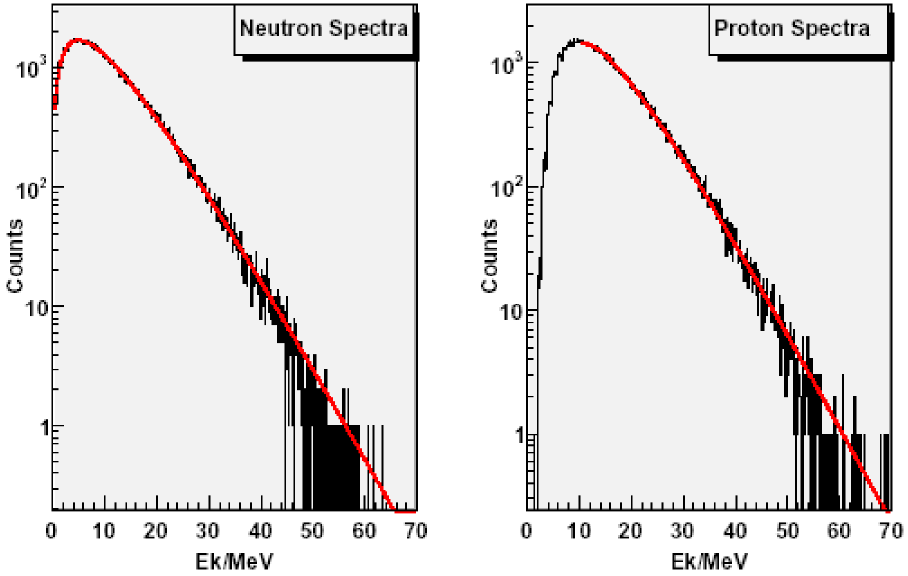
FIG. 3: (Color online) Linear fitting of Isoscaling parameters α (positive values) and β (negative values) as a function of the source isospin difference $\Delta(Z/A)_s^2$ from source pairs of Z_s=30, all solid symbols are only the first step secondary decay products, open symbols are full steps secondary decay products, Symbols in the figure correspond to Excitation energies E_{ex}=1.0 (squares), 1.4 (cirlces),2.0 (up-triangles), 2.4 (down-triangles) and 3.0 MeV (Diamonds), the dash and dot lines are the linear fitting of the first step decay only and full step decay chains included case respectively.

$$\beta = \frac{4\gamma}{T}\left[\left(\frac{Z}{A}\right)_{s1}^2 - \left(\frac{Z}{A}\right)_{s2}^2\right] \equiv \frac{4\gamma}{T}\Delta\left(\frac{Z}{A}\right)_s^2$$

$$\beta = \frac{4\gamma}{T}\left[\left(\frac{N}{A}\right)_{s1}^2 - \left(\frac{N}{A}\right)_{s2}^2\right] \equiv \frac{4\gamma}{T}\Delta\left(\frac{N}{A}\right)_s^2$$

Full step decay chains included
Intermediate sources exist tracing the decay process with different temperature and isospin asymmetry

the most probable distribution source temperature and isospin asymmetry is not the initial values.



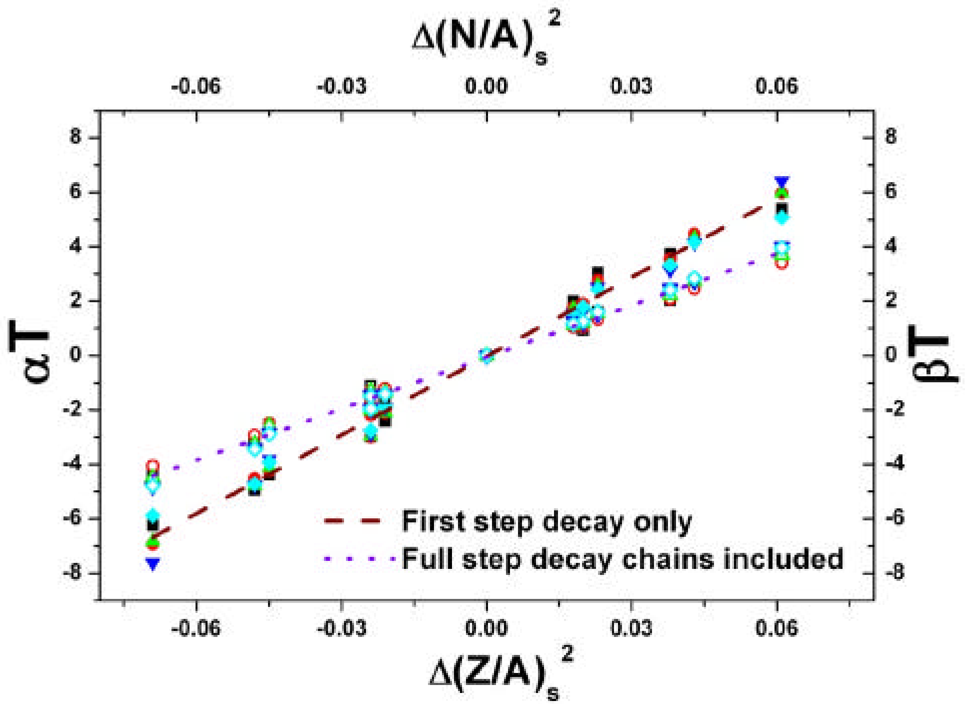


TABLE I: Source temperature extracted in different systems and by different methods.

Source Z_s	A_s	E_{ex} (MeV)	$T_i{}^a$	$T_s{}^b$ (MeV)	$T_r{}^c$ (MeV)
30	60/63	1.0	2.8/2.9	2.4/2.5	2.0/2.0
		1.4	3.4/3.5	3.0/3.1	2.3/2.4
		2.0	4.1/4.2	3.9/4.0	3.5/3.5
		2.4	4.5/4.6	4.4/4.5	4.0/4.0
		3.0	5.1/5.1	5.1/5.2	4.6/4.6
30	66/69	1.0	2.9/2.9	2.6/2.6	2.1/2.2
		1.4	3.5/3.5	3.2/3.2	2.6/2.6
		2.0	4.2/4.2	4.0/4.0	3.6/3.6
		2.4	4.6/4.7	4.6/4.6	4.0/4.0
		3.0	5.2/5.3	5.2/5.3	4.7/4.7

[a]Source initial temperature calculated directly from the GEMINI code [22].
[b]Source temperature fitted from emission neutron and proton spectra for the first step decay only.
[c]Reduced source temperature fitted from emission neutron and proton spectra for the full step decay chains included.

$$C_{sym}=24.2\pm0.3\text{MeV}$$

Sequential deday effect

$$\gamma = 15.84 \pm 0.18 \text{ MeV}.$$

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$$\alpha = \frac{4C_{sym}}{T}\left[\left(\frac{Z}{A}\right)^2_{s1} - \left(\frac{Z}{A}\right)^2_{s2}\right] \equiv \frac{4C_{sym}}{T}\Delta\left(\frac{Z}{A}\right)^2_{s}$$

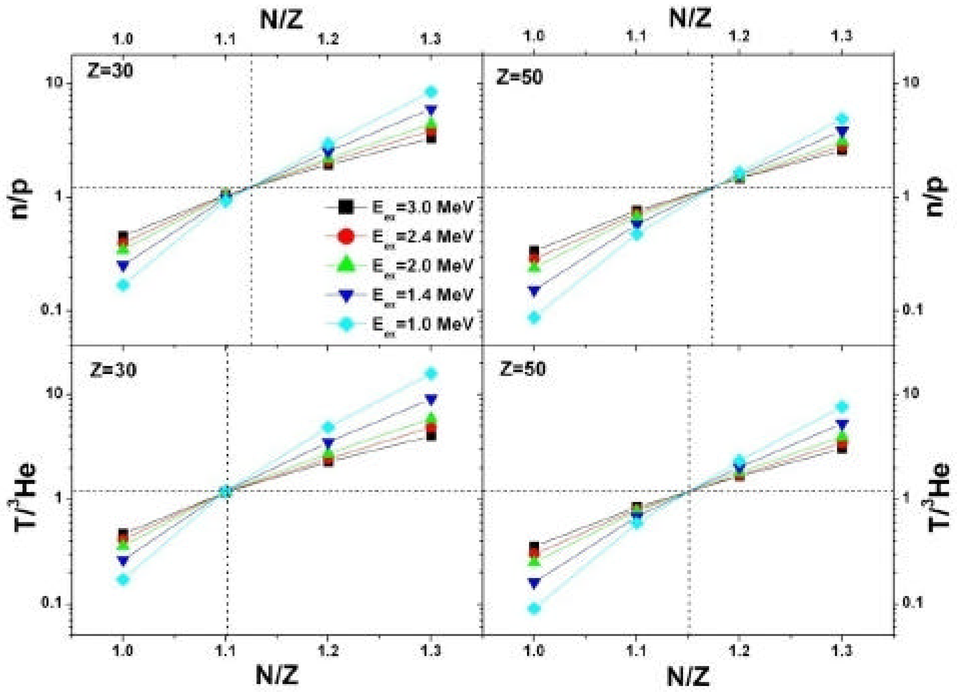
Reduced after sequential decay

Reduced after sequential decay

Should decrease after every step sequential decay, since the intermediate sources approach the stable line or the evaporation attract line,

But does this decrease compensate the change of a and T?

n/p and T/^{3}He in GEMINI calculation

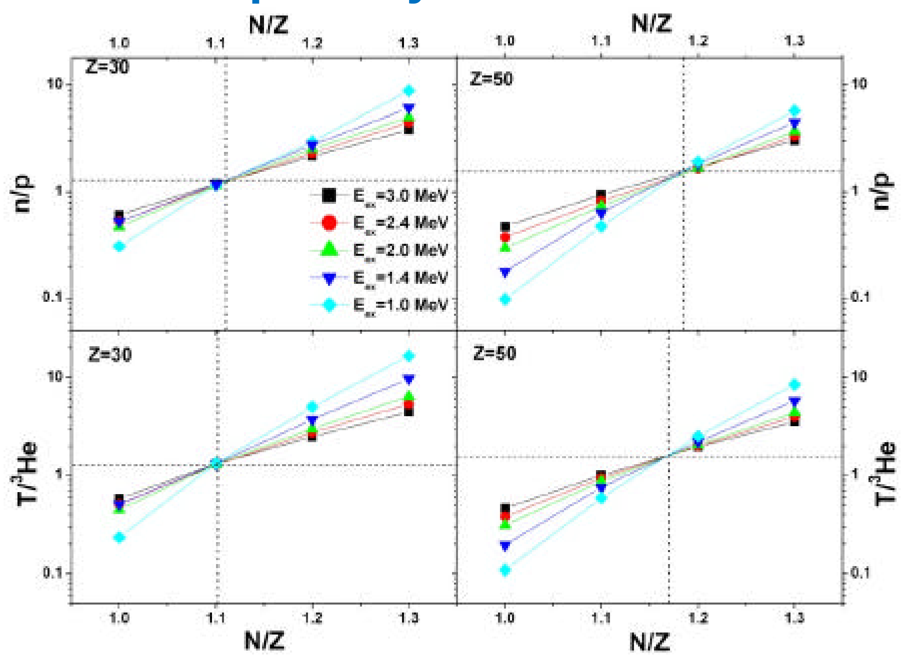


First Step decay only

Strong dependent on source isospin asymmetry N/Z, weak dependent on temperature

No large influence from sequential decay

Full Step decay chains



□ GDR study via QMD simulation for isospin asymmetry reaction

The prompt dipole ? -ray emission in GDR origin from the isospin collective dynamics

By using radioactive beams or isospin asymmetry beams,

seeking for the enhancement of the sensitivity the Iso-EoS.

Isospin dependent Quantum Molecular Dynamics model(QMD)

$$U(\rho,\tau_z)=\alpha\left(\frac{\rho}{\rho_0}\right)+\beta\left(\frac{\rho}{\rho_0}\right)^{\gamma}+\frac{1}{2}(1-\tau_z)V_c+C_{\mathrm{sym}}\frac{(\rho_n-\rho_p)}{\rho_0}\tau_z$$

the initial dipole moment

$$D(t=0)=\frac{NZ}{A}|R_Z(t=0)-R_N(t=0)|=\frac{R_P+R_T}{A}Z_PZ_T\left|\left(\frac{N}{Z}\right)_T-\left(\frac{N}{Z}\right)_P\right|,$$

prompt photon emission probability $E_g=\hbar w$

$$\frac{dP}{dE}=\frac{2}{3\pi}\frac{e^2}{E\hbar c}\left|\frac{d\overline{V_k}}{dt}(E)\right|^2,$$

$$\frac{d\overline{V_k}}{dt}(E)=\int_0^{\infty}\frac{d\overline{V_k}}{dt}(t)e^{i(Et/\hbar)}dt$$

V. Baran *et al., Nucl. Phys. A* ***679, 373 (2001).***

M. Papa *et al., Phys. Rev. C* ***68, 034606 (2003).***

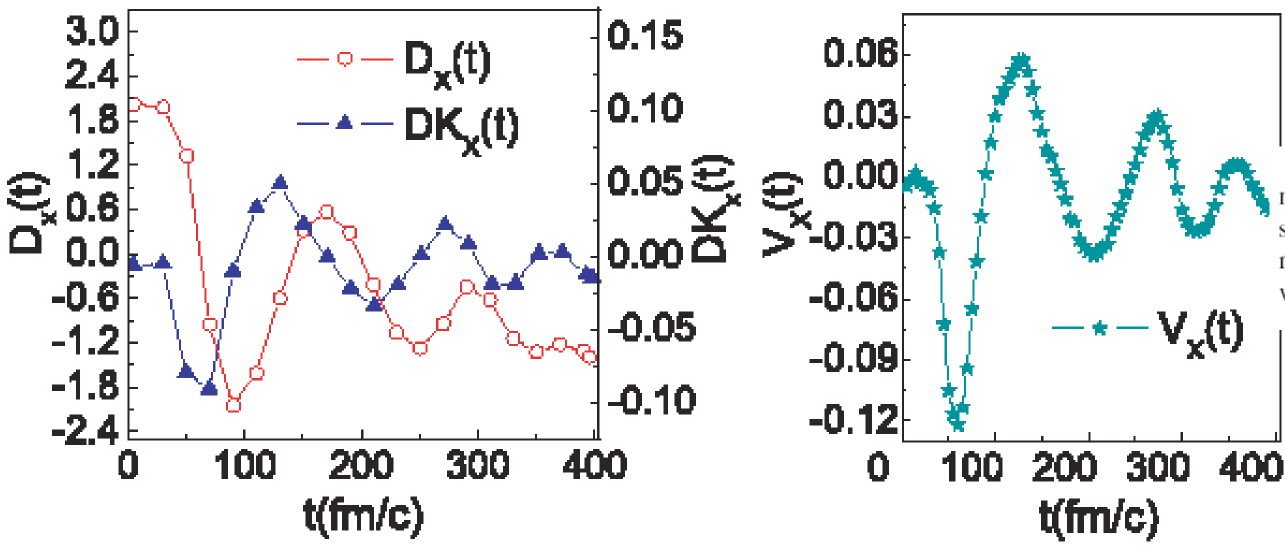
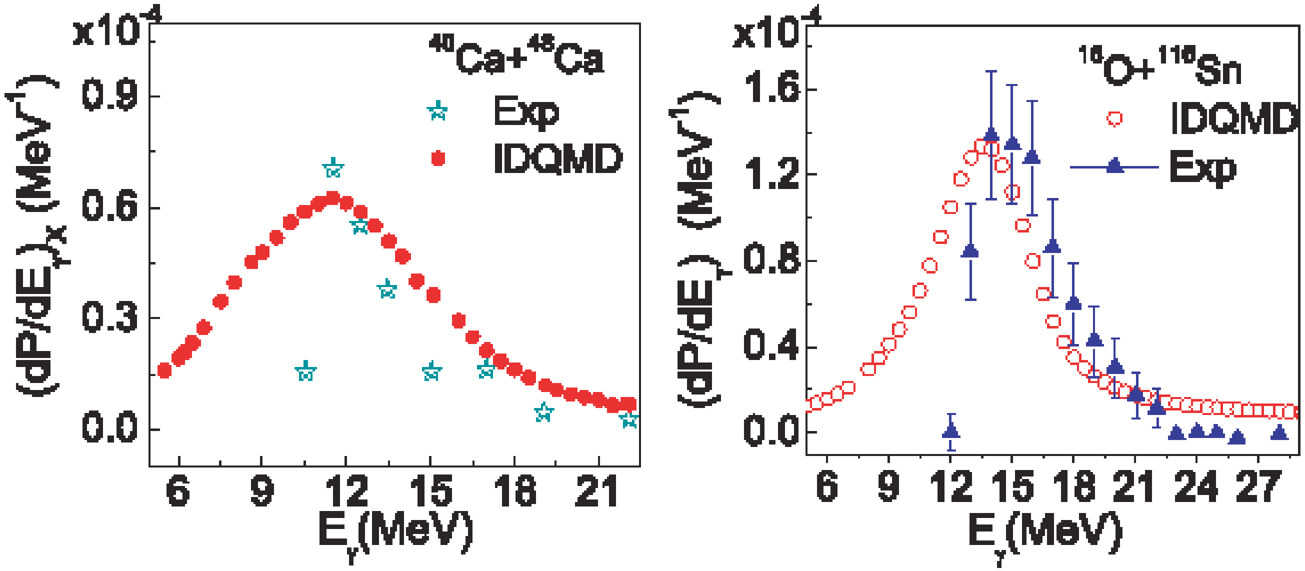
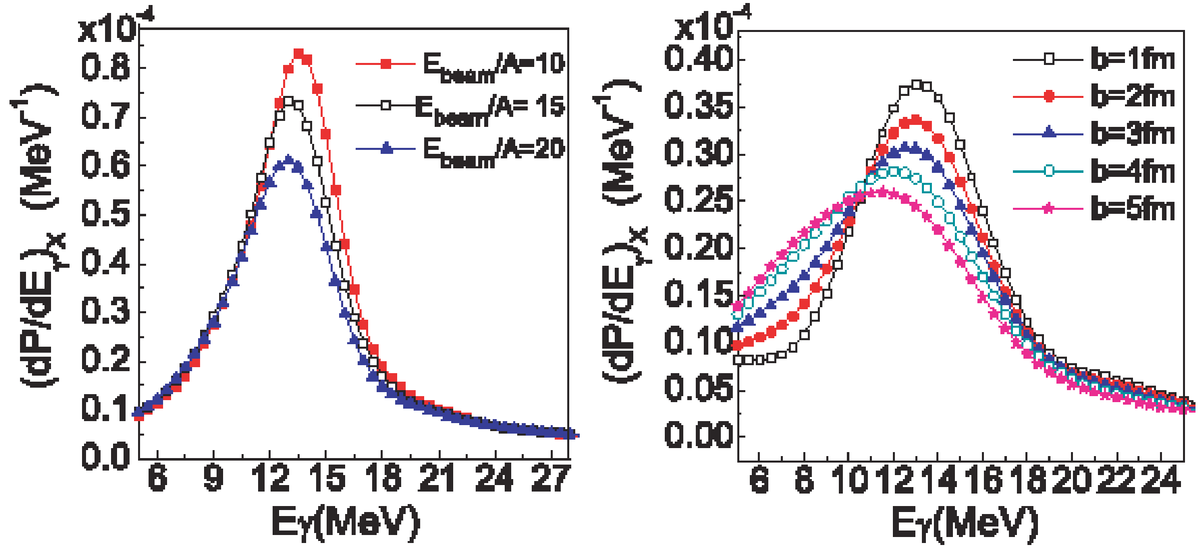


FIG. 1. (Color online) Left: Evolution of the giant dipole moment with time in coordinate space [$D_x(t)$] and momentum space [$DK_x(t)$]. Right: Dynamical dipole mode [$V_x(t)$]. The reaction system is ^{40}Ca + ^{48}Ca collision at 10 MeV/nucleon with $b = 1$ fm and soft EOS parameters.

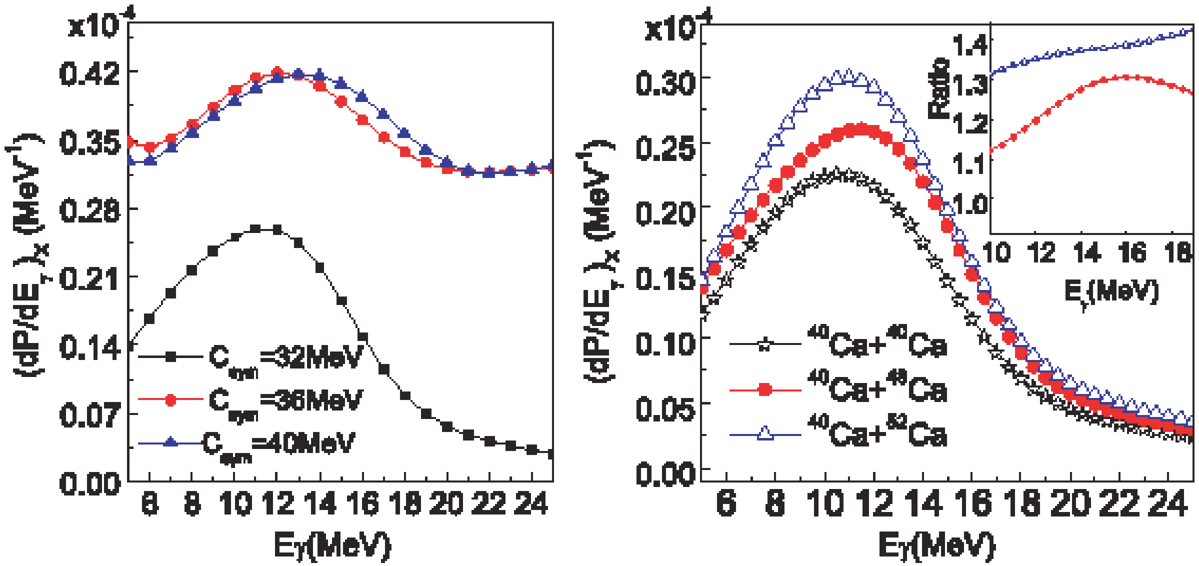
Comparison with experimental data



Corsi *et al.*, *Phys. Lett. B* ***679, 197 (2009).***
M. Papa *et al.*, *Phys. Rev. C* ***72, 064608 (2005).***



Dipole dynamical emission spectra of the $^{40}Ca+^{48}Ca$ system at different incident energies and impact parameter b



Dipole dynamical emission spectra of the $^{40}Ca+^{48}Ca$ system with different symmetry energy strongth and isospin asymmetry N/Z

H. L. Wu et al, Phys.Rev. C 81, 047602 (2010)

Summary

Sequential decay was investigated, It was found that isoscaling still can be observaed, secondary sequential decrease the isoscaling parameters.

1) If the initial source parameters are used to constrain the symmetry energy coefficient, C_{sym} extracted from cold fragments is different from the hot fragments.
2) Use an experiemental method to extract the source temperature, that C_{sym} constrain from cold fragment is reduced further.
3) The isospin difference from the sources was also changed in the secondary decay procedure, which will affect C_{sym}.

Secondary sequential effect affect the constraint of symmetry energy coefficient C_{sym}, which need to be corrected for the cold fragments.

n/p and T/^{3}He show strong dependence on source isospin N/Z.

γ rays of the dynamical dipole resonance is sensitive to the isospin freedom and symmetry energy, it can be a signal to measure the symmetry energy.

Thanks