PKU-CUSTIPEN Nuclear Reaction Workshop on
"Reactions and Spectroscopy of Unstable Nuclei"

Isobaric yield ratio difference (IBD) and nuclear density determination

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Outline

* 1. Background and Motivation
* 2. IBD Method
* 3. SAA model
* 4. Results and discussion
* 5. Conclusions

1. Background and motivation

* Measurement of nuclear density and nuclear symmetry energy (NSE) is an important question in nuclear physics.
* NSE depends on nuclear density and temperature.
* Heavy-ion collisions (HIC) can produce nuclear matters from sub-saturation to supra-saturation densities, making HIC be the unique method studying NSE in lab.
* Nuclear density (and NSE) can not be measured directly. It is still an important task to find new probes to nuclear density and NSE.
    * Neutron density
    * supra-saturation nuclear matter in compressed zones of HIC.

1. Background and motivation

* An isobaric yield ratio difference (IBD) method is proven to be sensitive to the density difference between nuclei
* Isobaric yield ratio (IYR) is defined as the ratio between isobars differing two in I=N-Z
* R=y(A,I+2)/y(A,I),
  * $y(A,I) = CA^{\tau}\exp\{[F(A,I) + N\mu_n + Z\mu_p]/T\}$
* $R = \exp\{[F(A,I-2) - F(A,I) + \mu_n - \mu_p]/T\}$
* The systematic dependence of y cancels out in R.

grand-canonical ensembles theory, C. B. Das et al., PRC **64**, 044608 (2001).
Or modified Fisher model, M. Huang et al., PRC81 (2010) 044620; R. W. Minich et al., PLB 118 (1982) 458.

2. IBD method

- In IYR
- $R = \exp\{[F(A, I-2) - F(A, I) + \mu_n - \mu_p]/T\}$
- $\ln R = [\Delta F(A, I+2, I, A) + \Delta\mu_{np}]/T$

F depends on temperature

- $\Delta\mu_{np} = \mu_n - \mu_p$
- **Define the difference between IYRs in 2 reactions, namely IBD,**

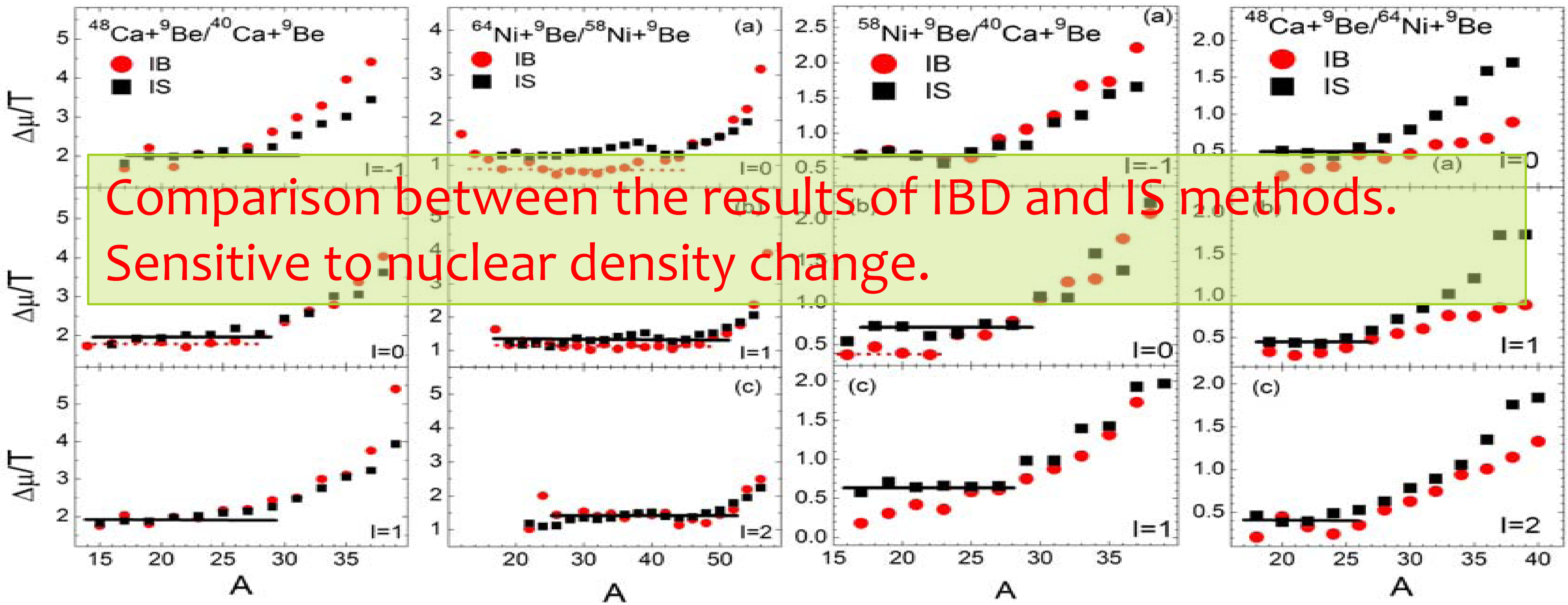
ΔF cancels out in IBD.
Assuming T is the same in reactions.

- $\Delta_{21}\ln R = \frac{[(\mu_{np})_2 - (\mu_{np})_1]}{T}$

$$= \frac{[\mu_{n2} - \mu_{n1} - (\mu_{p2} - \mu_{p2})]}{T} = \frac{\Delta\mu_{n21} - \Delta\mu_{p21}}{T}$$

Ma C W, Wang S S, Zhang Y L, Wei H L, PRC87(2013)034618,JPG40(2013)125106.

2. IBD method



Comparison between the results of IBD and IS methods.
Sensitive to nuclear density change.

* Comparing to isoscaling
  * $\alpha = (\mu_{n2} - \mu_{n1})/T = \Delta\mu_{n21}/T$;
  * $\beta = (\mu_{p2} - \mu_{p1})/T = \Delta\mu_{p21}/T$;
* IBD and isoscaling
  * $\Delta_{21}\ln R = \frac{\Delta\mu_{n21} - \Delta\mu_{p21}}{T} = \alpha - \beta$

Ma C W, Wang S S, Zhang Y L, Wei H L, PRC87(2013)034618.

2. IBD method

Chemical potential and nuclear density

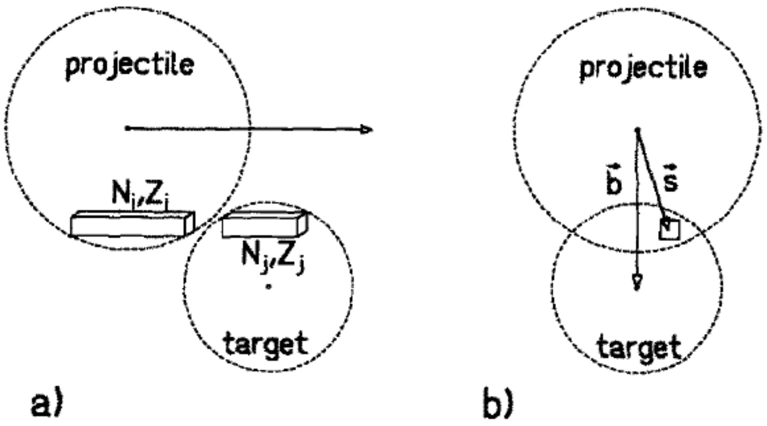
Isoscaling parameters and nuclear density.

- $\alpha = \ln\rho_{n2} - \ln\rho_{n1;}$
- $\beta = \ln\rho_{p2} - \ln\rho_{p1};$
- Denoting the density difference between the reactions.
- For IBD,
  - $$\Delta_{21}\ln R = \alpha - \beta = \ln\rho_{n2} - \ln\rho_{n1} - (\ln\rho_{p2} - \ln\rho_{p1})$$
    $$= \Delta(\ln\rho_n)_{21} - \Delta(\ln\rho_n)_{21}$$
    $$= \ln\rho_{n2} - \ln\rho_{p1} - (\ln\rho_{n1} - \ln\rho_{p1})$$
    $$= \Delta(\ln\rho_{np})_{21} - \Delta(\ln\rho_{np})_{21}$$

E. Geraci et al., Nucl. Phys. A 732, 173 (2004).

3. SAA model

- Statistical abrasion-ablation model
- Abrasion-stage (pre-fragment determination)
- evaporation-stage (final fragment determenation)



- Projectile and target nuclei are divided into independent tubes
- Neutron and proton densities discriminated (Fang et al.)
  - ρ_n, ρ_p

J. J. Gaimard and K. H. Schmidt, Nucl. Phys. A **531**, 709 (1991); T. Brohm and K. -H. Schmidt, Nucl. Phys. A **569**, 821 (1994). D. Q. Fang, W. Q. Shen, J. Feng *et al.*, Phys. Rev. C **61**, 044610 (2000).

3. SAA model

* pre-fragment determination
* Nucleons abraded from the overlapping tubes

$$< \Delta A(b) >= \int d^2 s \rho_n^P(\boldsymbol{s})[1 - t_n(\boldsymbol{s} - \boldsymbol{b})] + \int d^2 s \rho_p^P(\boldsymbol{s})[1 - t_p(\boldsymbol{s} - \boldsymbol{b})],$$

* $t_n(\boldsymbol{s}\text{-}\boldsymbol{b})$, $t_p(\boldsymbol{s}\text{-}\boldsymbol{b})$: transmission probability for neutrons and protons at ***b***,

$$t_k(\boldsymbol{s} - \boldsymbol{b}) = \exp\{-[\rho_n^T(\boldsymbol{s} - \boldsymbol{b})\sigma_{nk} + \rho_p^T(\boldsymbol{s} - \boldsymbol{b})\sigma_{pk}]\},$$

* Cross sections of a prefragment with N neutrons and Z protons abraded,

$$\sigma(\Delta N, \Delta Z) = \int d^2 b P(\Delta N, b) P(\Delta Z, b),$$

Cross section of prefragment is mainly determined by density and nucleus-nucleus reaction cross sections.

3. SAA model

* Fermi-type density distributions of nucleus

$$\rho_k(r) = \frac{\rho_k^0}{1+\exp(\frac{r-C_k}{t_k f_k/4.4})}, \quad k = n, p$$

* t_k diffuseness, f_k introduced to adjust t_k. The increase of f_k will push nucleons from core to surface of nucleus.

A. Fermi-type density distribution, Ozawa, T. Suzuki, I. Tanihata, Nucl. Phys. A **693**, 32 (2001);
B. f_n is introduced in C. W. Ma, Y. Fu, D. Q. Fang, Chin. Phys. B 17 (2008) 1216.

3. SAA model

* Evaporation process—decay of hot prefragment
* Excitation energy (E^*) of prefragment

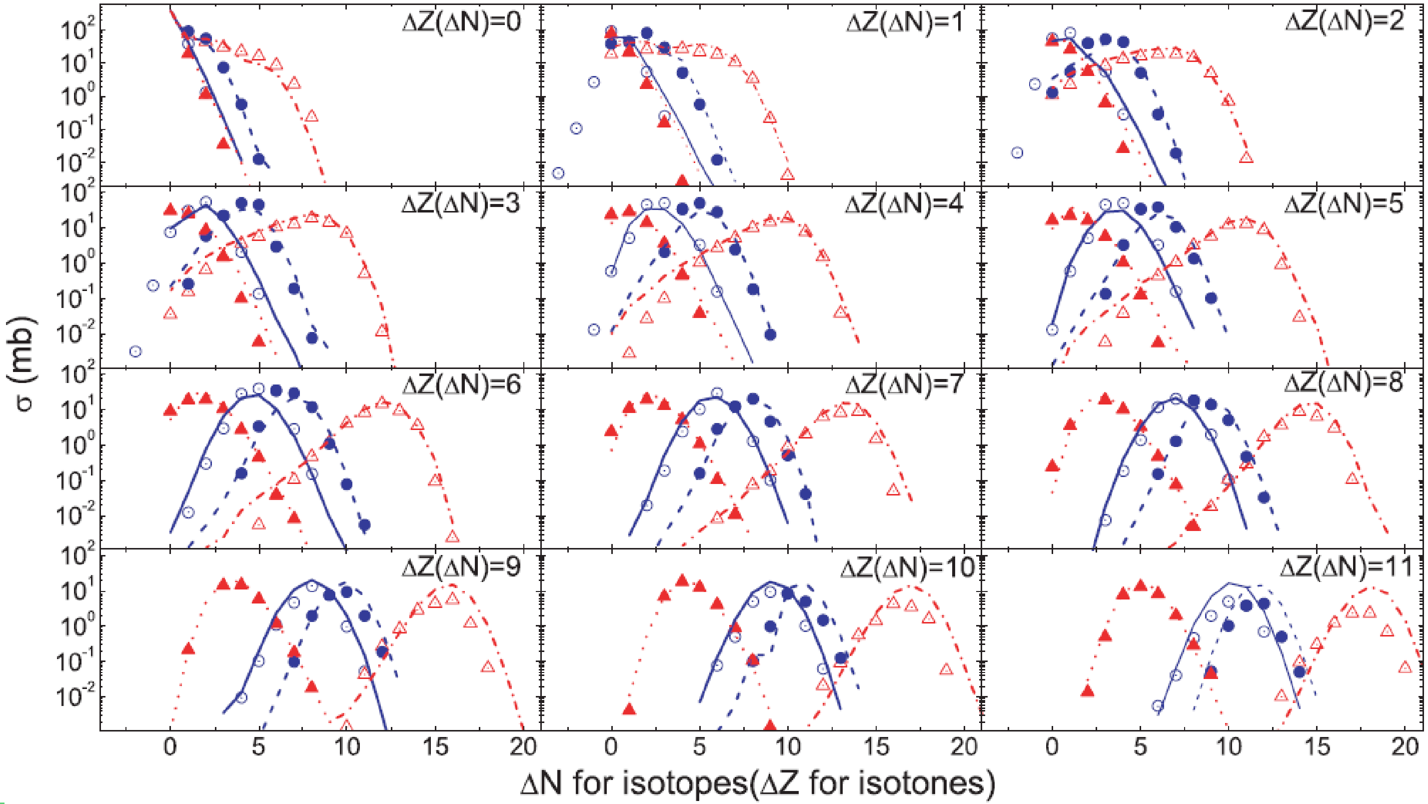
$$E^* = 13.3 < A(b) > \mathrm{MeV}$$

  * Excitation energy for per abraded nucleon 13.3MeV.
  * <A(*b*)> abraded nucleons from projectile at *b*.
* Prefragment (N,Z) decays by emitting n, p or α, until the residue is stable.
* The emitting particle is selected according to min(s_n, s_p, s_α) of prefragment (N,Z).

Comparing with GEMINI and SMM, the decay method of SAA is an simple way to determine the final fragment.

3. SAA model

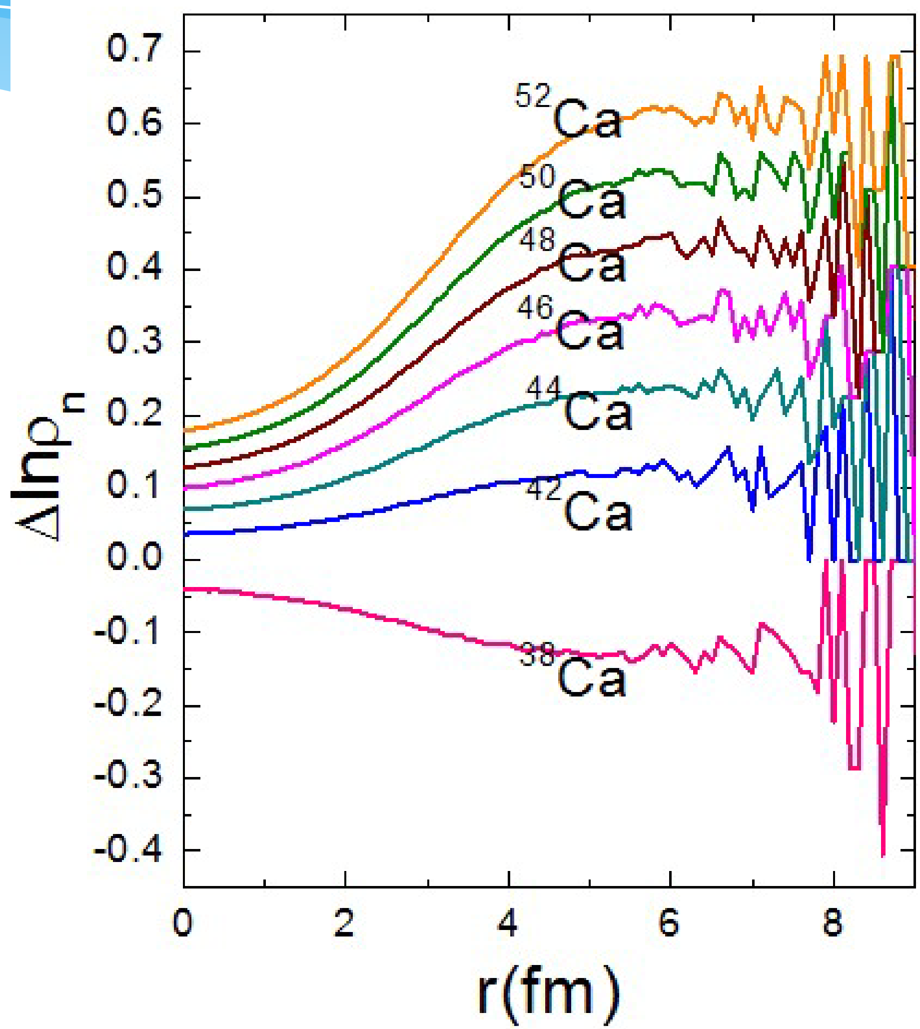
* **SAA (lines) can well reproduce the measured data (symbols)**



C W Ma et al., PRC **79**, 034606 (2009); M. Mocko et al., PRC **74**, 054612 (2006).

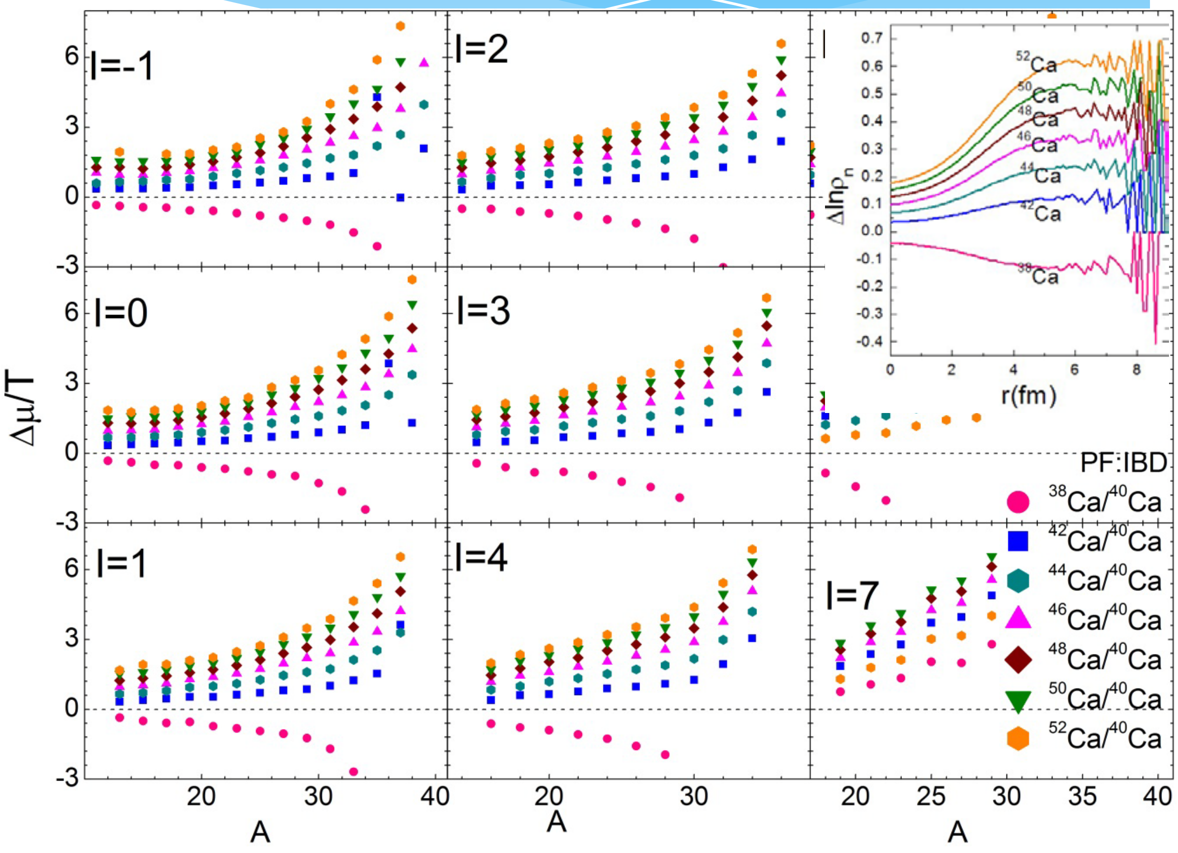
4. Results and discussion

* The calculated 80*A* MeV Ca + ^{12}C reactions by using a modified statistical abrasion ablation model
* $^{38, 40, 42, 44, 46, 48, 50, 52}$Ca as projectiles
* Neutron density difference
* $\Delta_{21}\ln R = \Delta(\ln\rho_n)_{21}$



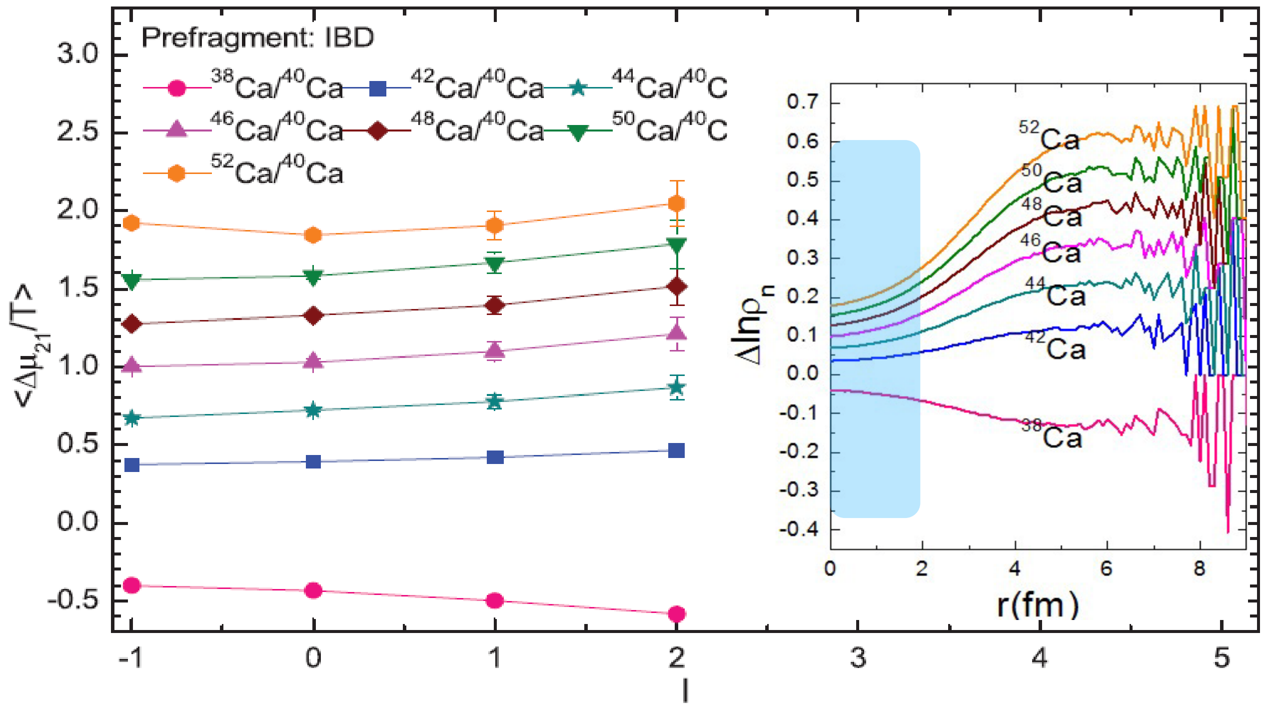
4. Results and discussion

- prefragments
- IBD-plateaus
- Height increases with n/z of projectile
- $\Delta_{21}\ln R = \Delta(\ln\rho_n)_{21} - \Delta(\ln\rho_n)_{21}$
- Assuming the proton density distributions of ^{X}Ca are the same
- $\Delta_{21}\ln R = \Delta(\ln\rho_n)_{21}$
- H of Plateau sensitive to $\Delta(\ln\rho_n)_{21}$



Similar trends of $\Delta\mu_{n21}/T$ and $\Delta\ln\rho_n$ r<6fm

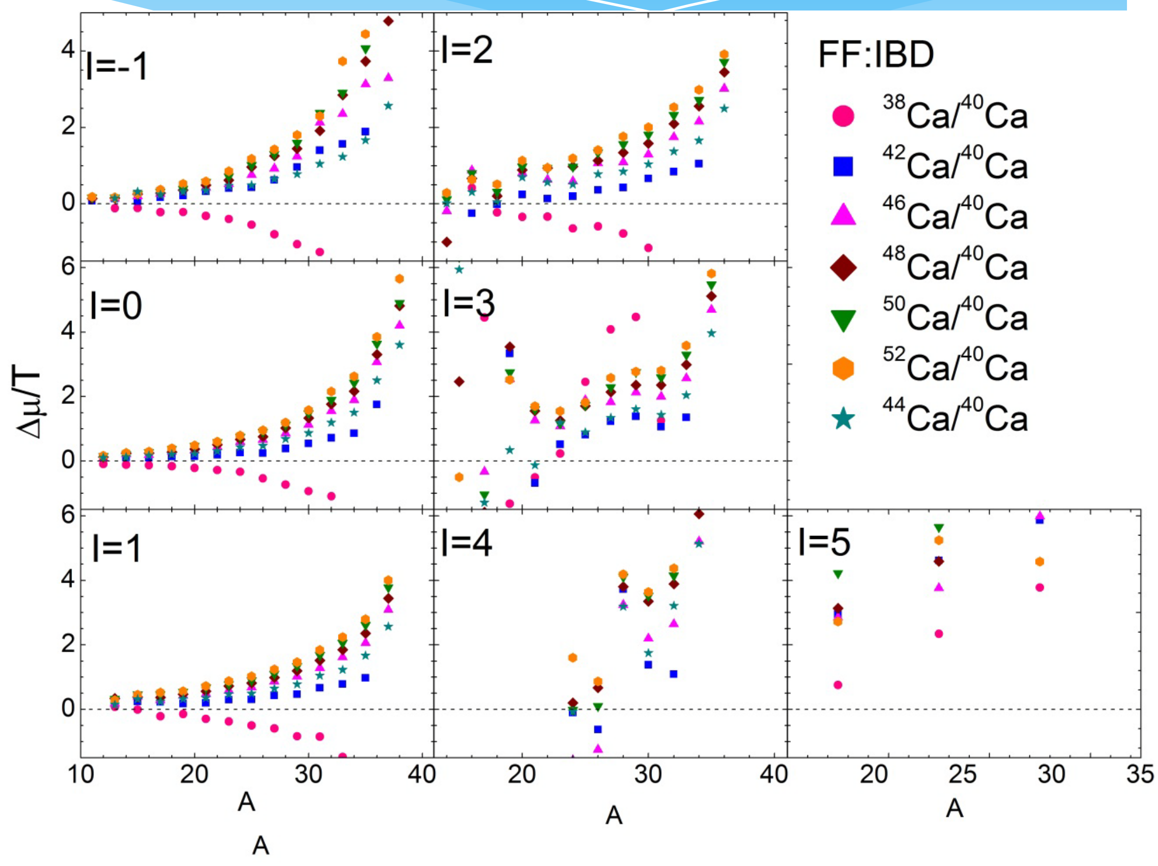
4. Results and discussion



* Averaged values of plateaus <$\Delta\mu_{n21}/T$> vs. I of fragments
* <$\Delta\mu_{n21}/T$> changes little with I

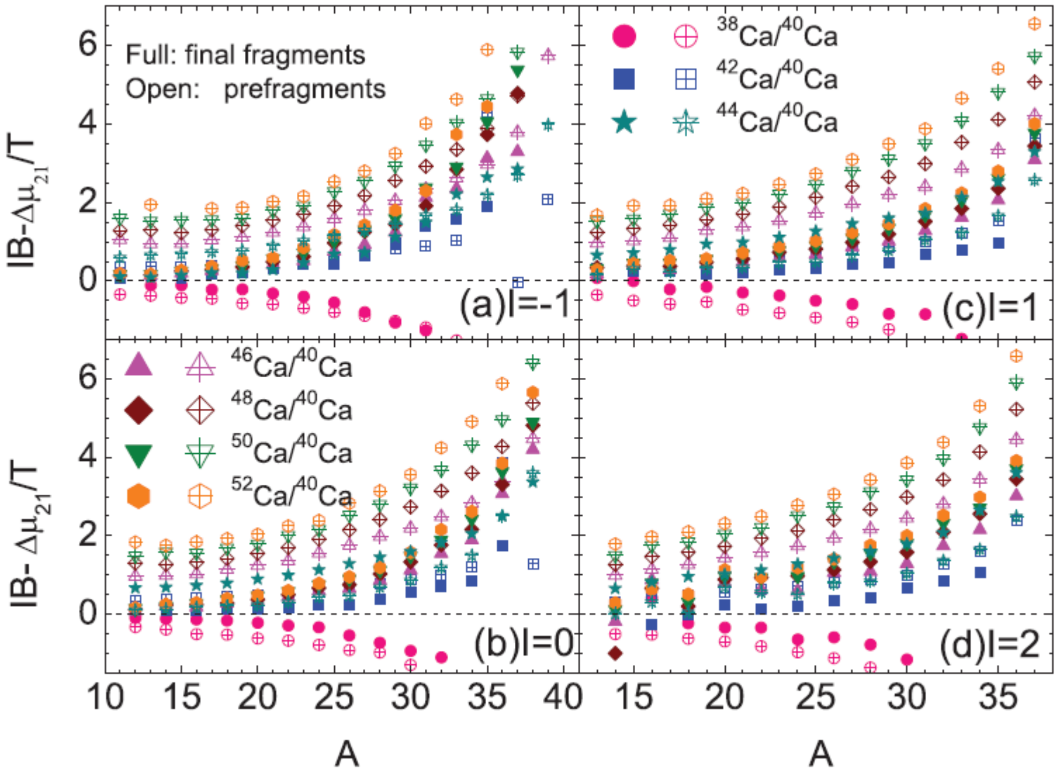
4. Results and discussion

- Final fragments
- IBD-plateaus
- Height also increases with n/z of projectile
- H of Plateau less sensitive to $\Delta(\ln\rho_n)_{21}$
- Plateau disappears in neutron-rich fragments



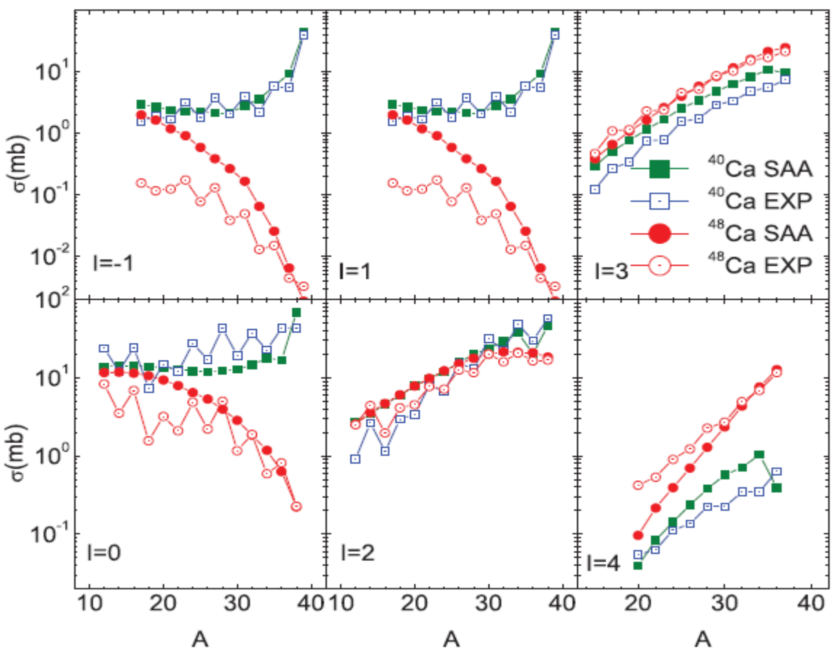
4. Results and discussion

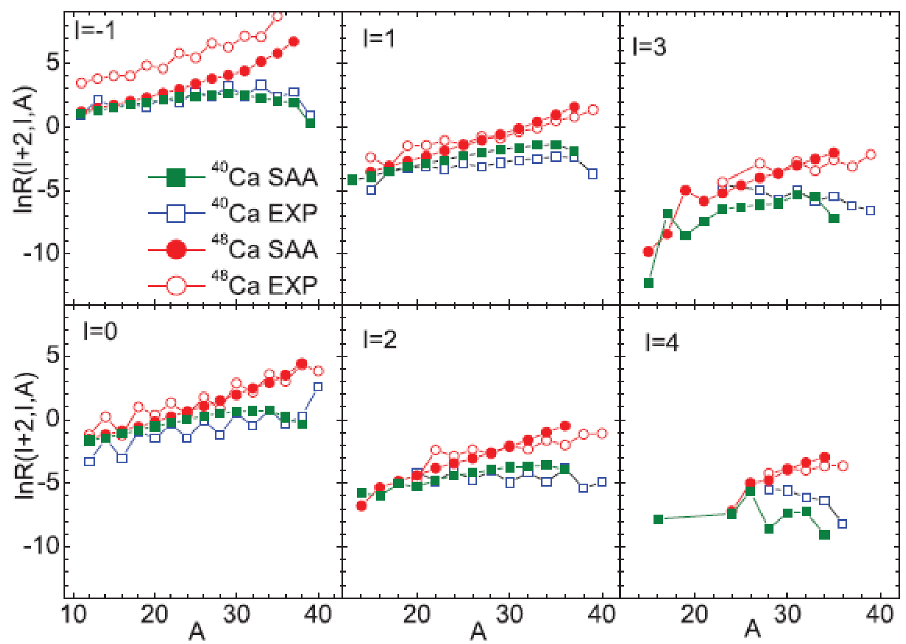
- Decay effects in IBD
- H of final fragments is suppressed, make H less sensitive to the density changes of Ca isotopes
- Prefrags. IBD
- SAA~1.75
  - Final frags. IBD
  - SAA ~0.5, exp. ~2



4. Results and discussion

- SAA well reproduces yields of frag. in ^{40}Ca reaction, but overestimates yields of frags with small A in the I=-1, 0 and 1 chains in the ^{48}Ca+C reaction.
- SAA underestimate IYR for I=-1 frags in the ^{48}Ca+C reaction.
- The decay calculations should account for the difference between IYRs for reactions of neutron-rich projectile nucleus.





5. Conclusions

* Experimentally, IBD is sensitive to density difference between projectiles.
* IBD from SAA prefrags is sensitive to the density difference between projectiles. While IBD from SAA final frags is suppressed and is less sensitive to the density difference between projectiles.
* The decay calculation for small A fragments should be modified.
* More works should be carried out on the IBD probes both theoretically and experimentally.

More discussion on the IBD method, please refer to:
Ma C W, Wang S S, Zhang Y L, Wei H L, PRC87, 034618 (2013); JPG 40 (2013) 125106;
C. W. Ma, J. Yu, X. M. Bai, Y. L. Zhang, H. L. Wei, S. S. Wang, PRC 89, 057602 (2014).

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* Wang Shan-Shan, Zhang Yan-Li, Qiao Chun-Yuan, Zhang Hui-Ping, Bai Xiao-Man, Yu Jiao

Thanks for your attention!