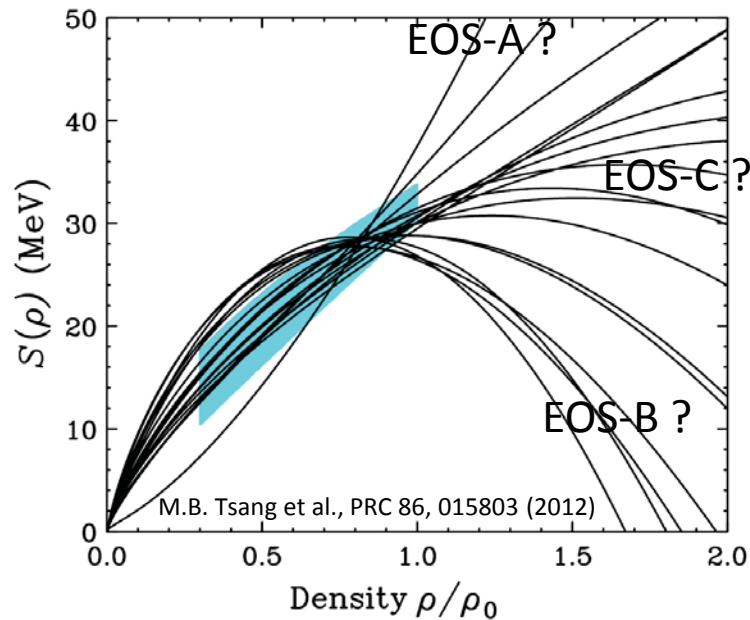


原子核衝突中における核子拡散の観測による、対称エネルギー密度依存性の測定

理研 磯部忠昭

中性子星核物質研究会@理研

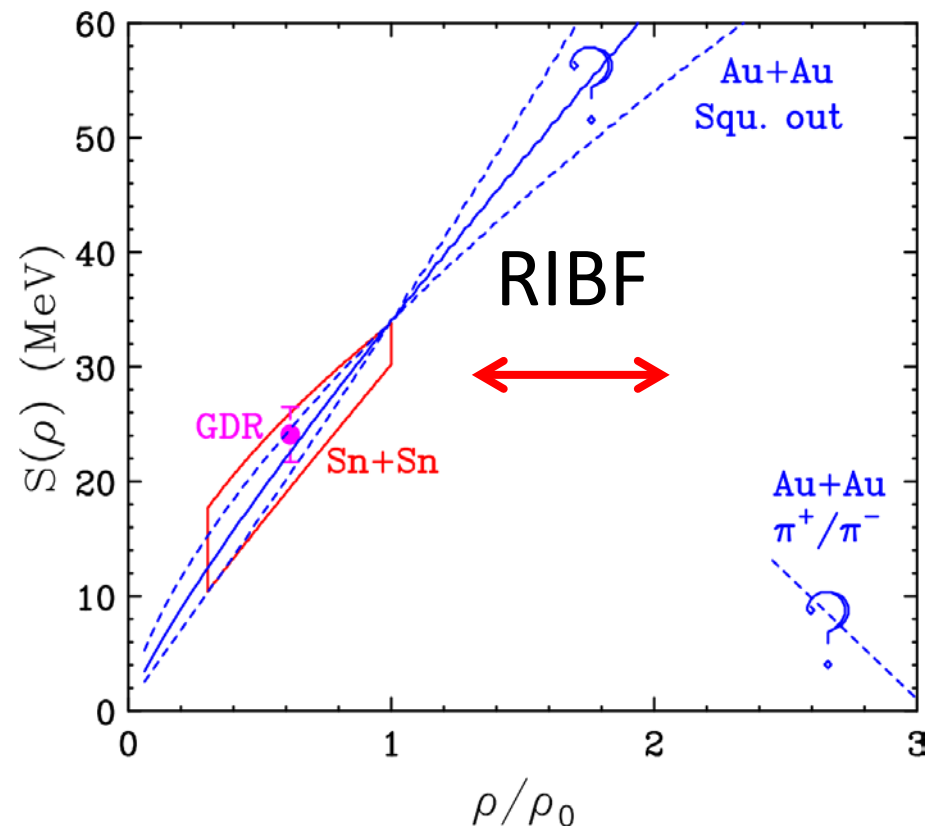
Physics introduction: constraints on the density dependence of symmetry energy



- Constraints given only for $\rho < \rho_0$.
- SAMURAI-TPC project for $\rho \sim 2\rho_0$.
- Soft EoS is not realistic to explain NS data.

$$S = E_{\text{sym}}(\rho)$$

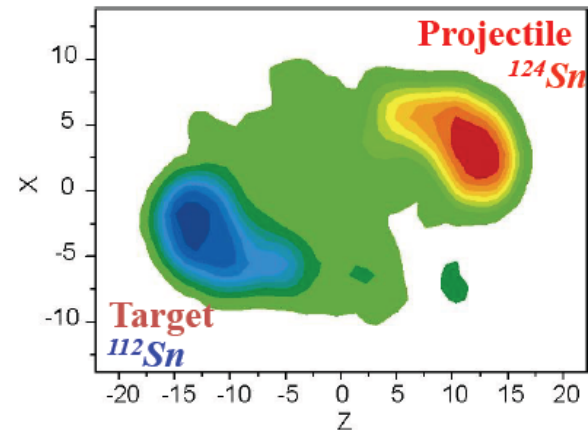
$$L = 3\rho_0 \left. \frac{\partial E_{\text{sym}}(\rho)}{\partial \rho} \right|_{\rho=\rho_0}$$



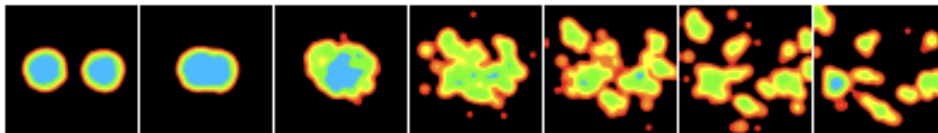
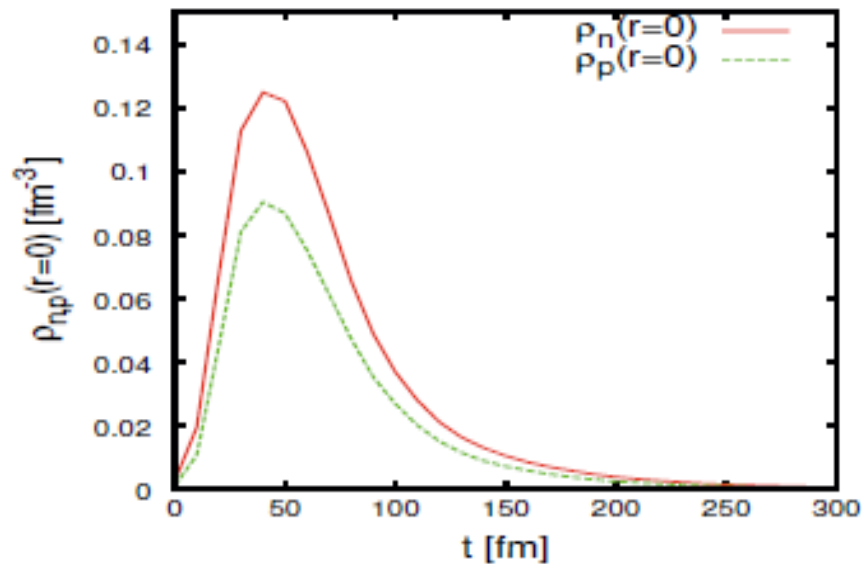
Isospin diffusion in heavy ion collision



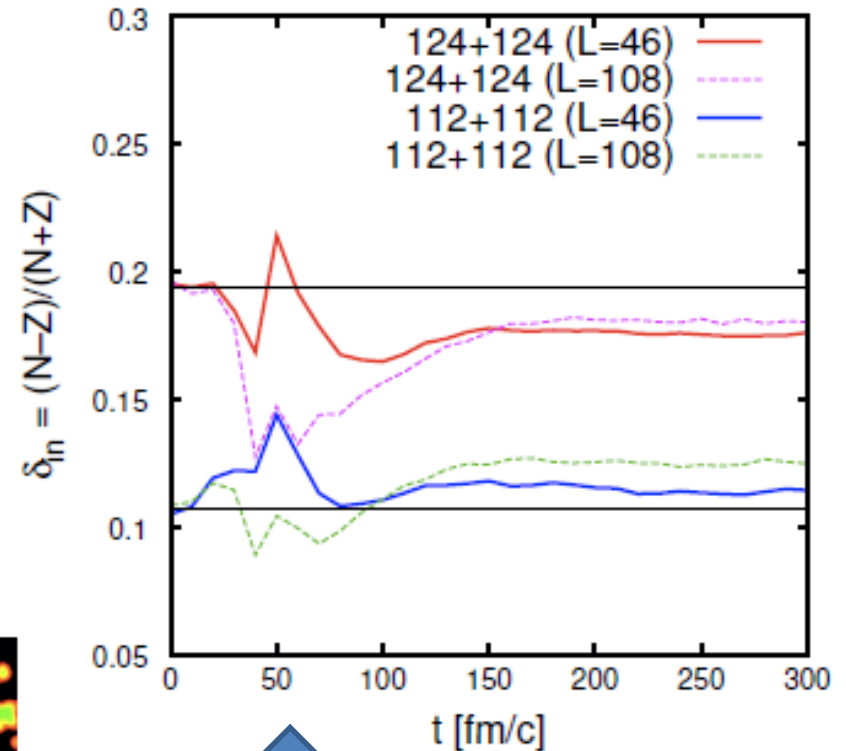
- Asymmetric systems ($A+B$) move towards isospin equilibrium under the influence of symmetry energy.
- Useful to probe the symmetry energy at subsaturation densities in peripheral $A+B$ collisions.
- i.e. $\rho < \rho_0$, $E < 100 A \text{ MeV}$



Nuclear density to be probed with isospin diffusion in HIC.



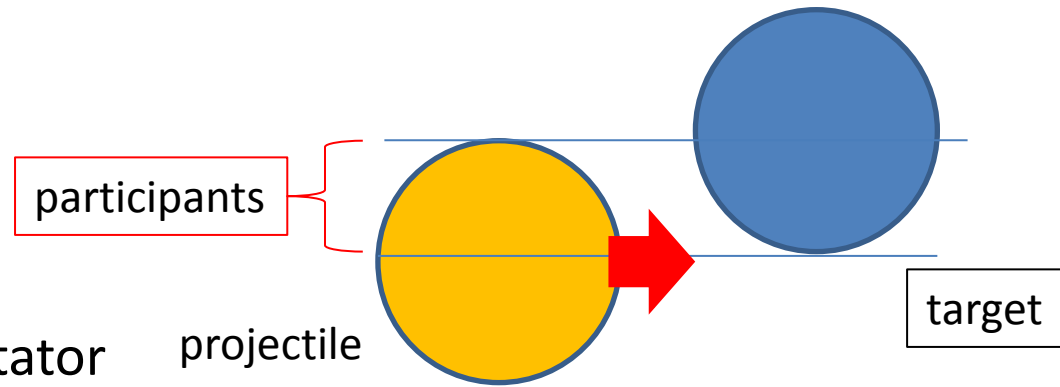
Sn + Sn central collisions at $E/A = 50$ MeV



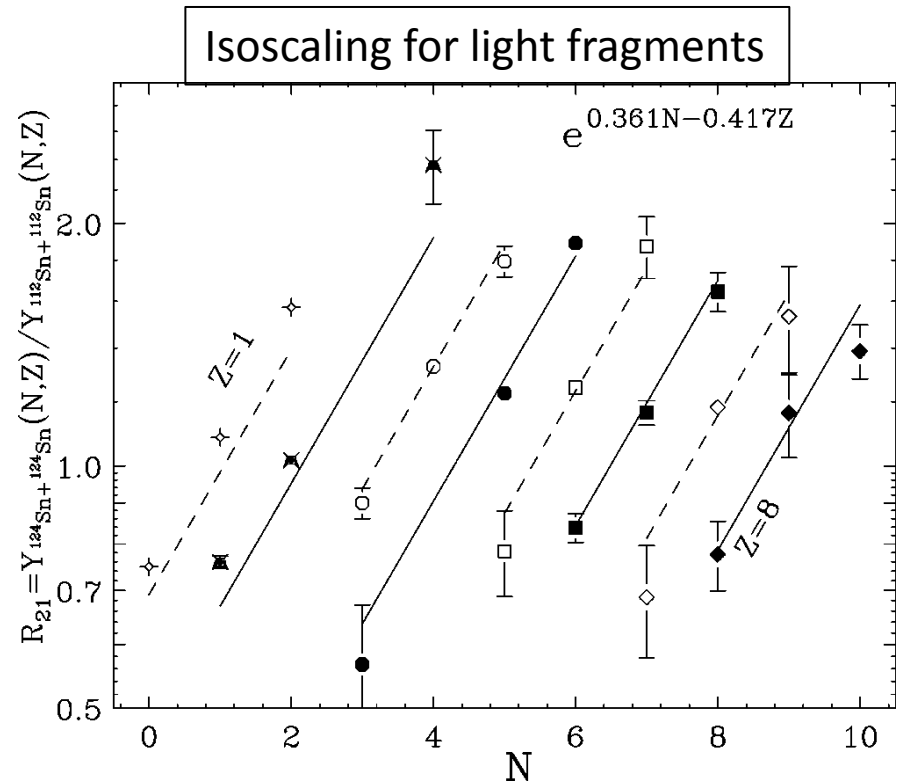
Diffusion of nucleus

Observables to study isospin diffusion in HIC

- We can see:
 - Light fragments from participants
 - Heavy residue from spectator

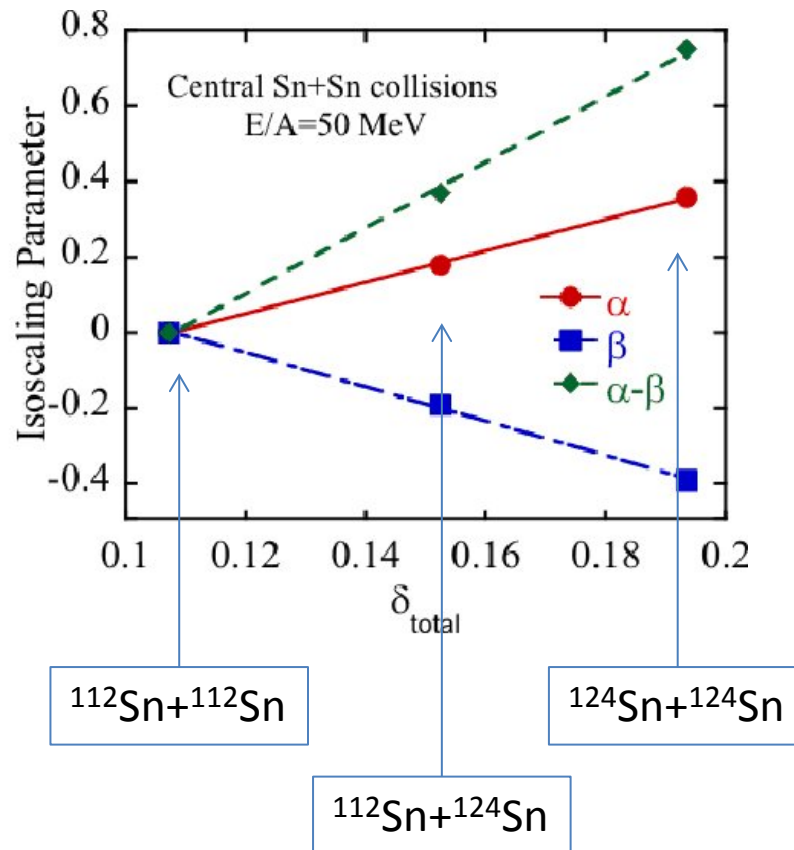


- **Isoscaling parameter**
 - Isotopic yields from reactions differing in their isospin composition found to satisfy:
 - $R_{21}(N,Z) = Y_2(N,Z)/Y_1(N,Z) = C_{exp}(\alpha N + \beta Z).$



Does isoscaling work?

- α shown to be linear in central collisions.
- Just looking light fragments from collision.
- (so far)



Dense matter with heavy ion collision



Dynamics of heavy ion collision



Nuclear Equation of state

$T?$ $\rho?$

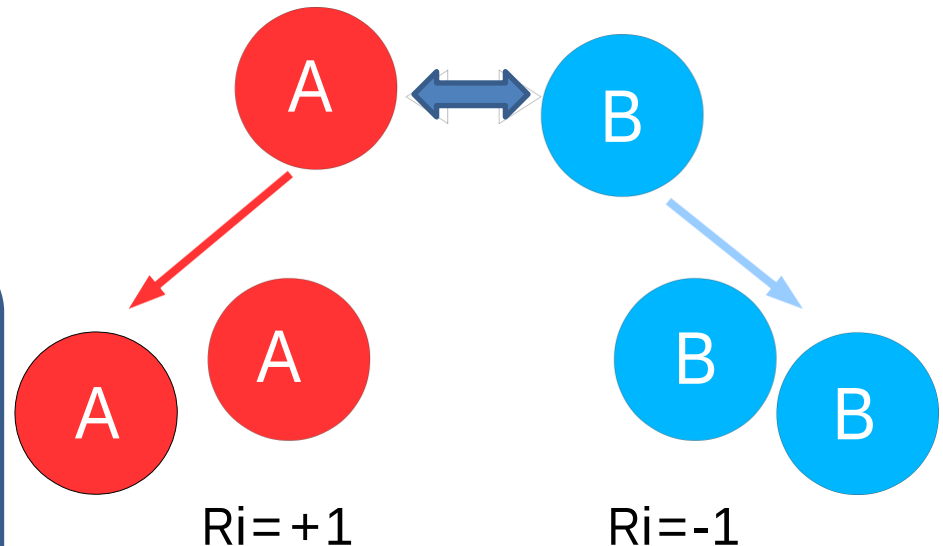
How to deal with the systematic error coming from heavy ion collision analysis?

Non-isospin diffusion effects:

- Pre-equilibrium emissions
- Sequential decays
- Coulomb effects

$$R_i = 2 \frac{X_{AB} - (X_{AA} + X_{BB}) / 2}{X_{AA} - X_{BB}}$$

X: Observable sensitive to E_{sym}

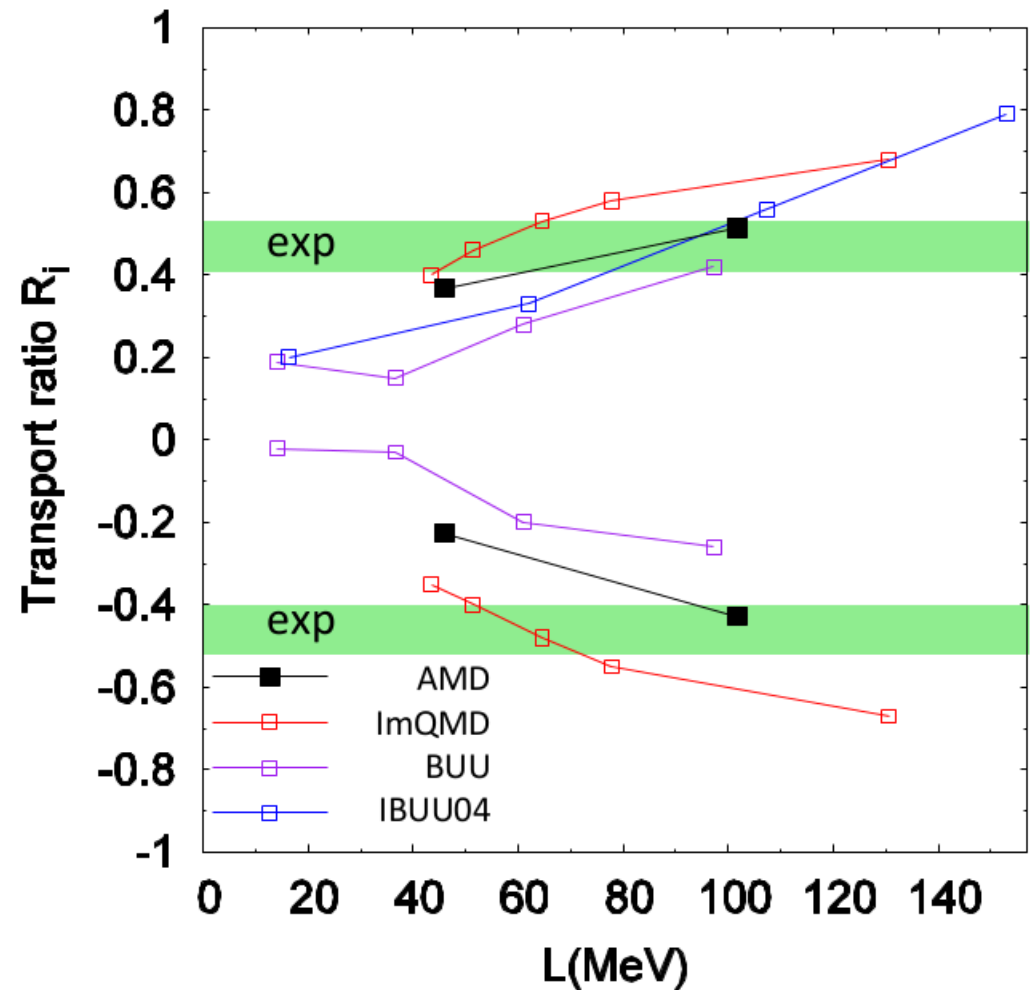


- Introduction of isospin transport ratio to cancel out above effect
 - Rami et al., PRL, 84, 1120 (2000)
- Isospin diffusion occurs only in asymmetric systems **A+B**
- No isospin diffusion between symmetric systems
- Observable X is assumed to be linear to δ .

$$\delta = \frac{\rho_n - \rho_p}{\rho}$$

Comparison of Ri to transport theory

- $X \rightarrow \alpha$
 - For light fragments
 - $X \rightarrow \ln(Y(^7\text{Li})/Y(^7\text{Be}))$ was also studied.
- $R_i = \pm 1$: no diffusion
- $R_i = 0$: equilibration
- ImQMD: $L = 40 \sim 70$ MeV
- AMD: $L \sim 100$ MeV



Ri for HIC spectator (heavy residue)

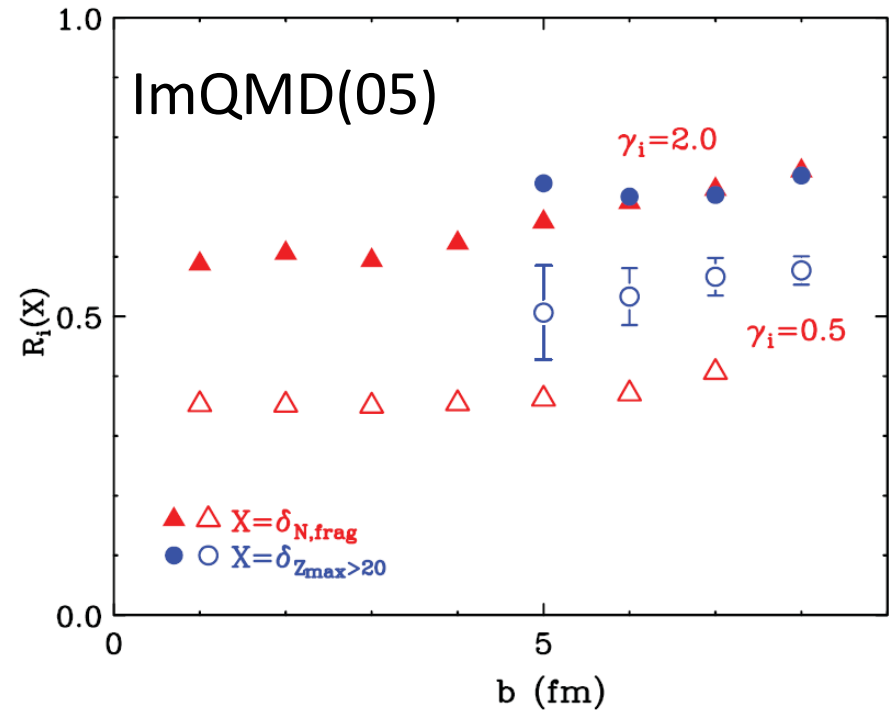
- Evaporative and multi-fragment decay theories predict:

$$\alpha = \Delta\mu_n/T = 2C_{sym}(\Delta\delta)(1-\bar{\delta})/T$$

$$\beta = \Delta\mu_p/T = -2C_{sym}(\Delta\delta)(1-\bar{\delta})/T$$

$$\Delta\delta = \delta_2 - \delta_1$$

$$\bar{\delta} = (\delta_2 + \delta_1)/2$$



PRC85 (2012) 024602

Isospin diffusion experiment at RIBF

- Measure fragments that come unambiguously from residue decay in HIC, as well as light particles

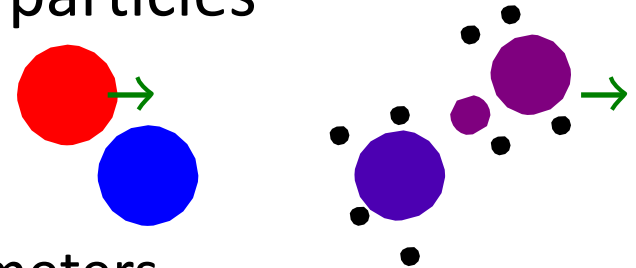
- Motivation

- Check the linearity of isoscaling parameters
- Increase sensitivity by using rare isotope beam

$$ID = j_n - j_p = -\rho D_\delta \nabla \delta$$

ID Increase with $\nabla \delta$ = asymmetry gradient

- See impact parameter dependence through the measurement of multiplicity
- Combine RIBF data with what were taken at MSU.
 - $^{124}\text{Sn} + ^{124}\text{Sn}$, $^{112}\text{Sn} + ^{112}\text{Sn}$, $^{112}\text{Sn} + ^{124}\text{Sn}$



Collaborations

- **RNC**
 - Tadaaki Isobe, Hiroyoshi Sakurai, Jenny Lee, Mizuki Nishimura, Shunji Nishimura, Yoichi Nakai, Naoki Fukuda, Naohito Inabe, Daisuke Kameda, Toshiyuki Kubo, Hiroshi Suzuki, Hiroyuki Takeda, Yoshiyuki Yanagisawa,
- **MSU/NSCL**
 - Rachel Hodges Showalter, Jack Winkelbauer, Bill Lynch, Betty Tsang, Justin Estee,
- **Kyoto University**
 - Noritsugu Nakatsuka, Tetsuya Murakami
- **Texas A&M**
 - Sherry Yennello, Alan McIntosh, Lauren Heilborn, Andrew Zarrella
- **University of Liverpool**
 - William Powell, Janet Sampson,
- **CAS**
 - Lu Fei, Guojiang Zhang,
- **GANIL**
 - Abdou Chbihi,
- **Universidad Nacional Autónoma de México**
 - Elizabeth Padilla Rodal,
- **Korea University**
 - Byungsik Hong, Genie Jhang,
- **ORNL**
 - Alfredo Galindo-Uribarri
- **Washington University**
 - Walter Reviol, Demetrios G. Sarantites, Lee G. Sobotka

The diagram illustrates the experimental setup for the first Heavy Ion (H(R)IC) experiment at the Relativistic Heavy Ion Collider (RIBF). The beam path starts at the Superconducting Ring Cyclotron (SRC) where a ^{107}In beam is produced at approximately 73 MeV/u. This beam is then accelerated by the BigRIPS (Big Relativistic Ion Spectrometer) system, which includes a series of bending magnets (F0-F13) and septa (STQ1-STQ25). The beam path is shown as a curved line with various components labeled. A red starburst indicates the collision point between the ^{107}In beam and a ^{124}Sn beam. The collision products are detected by the SAMURAI (Super-Avalanche Microcalorimeter and Ultra-Relativistic Ion Beam) detector system, which includes a ZeroDegree detector and a series of detectors (F11-F13) and septa (STQ21-STQ25). The diagram also shows the path of a ^{132}Xe beam at 345 MeV/u from the IRC (Intermediate Ring Cyclotron) to the Target area. A red arrow indicates the direction of the beam flow.

First H(R)IC experiment at RIBF

IRC ^{132}Xe 345MeV/u

SRC ^{107}In $^{107}\text{In} \sim 73\text{MeV/u}$

Target

Beam dump

BigRIPS

SAMURAI

ZeroDegree

^{107}In

^{124}Sn

- Make RI beam: BigRIPS (up to 800kcps)

-
- First H(R)IC experiment at RIBF
- IRC ^{132}Xe 345 MeV/u
- SRC ^{107}In
- Target ^{107}In ~73 MeV/u
- Beam dump
- F0 F1 F2 F3 F4 F5 F6 F7 F8 F9 F10 F11 F12 F13
- STQ1 STQ2 STQ3 STQ4 STQ5 STQ6 STQ7 STQ8 STQ9 STQ10 STQ11 STQ12 STQ13 STQ14 STQ15 STQ16 STQ17 STQ18 STQ19 STQ20 STQ21 STQ22 STQ23 STQ24 STQ25
- D1 D2 D3 D4 D5 D6 D7 D8
- BigRIPS
- ZeroDegree
- SAMURAI
- ^{107}In
- ^{124}Sn
- Make RI beam: BigRIPS (up to 800kcps)

Radiation damage on Plastic counter

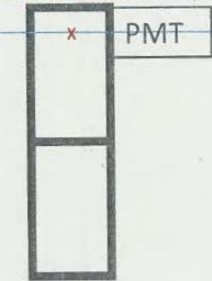
- 800kcps at F3
- 300kcps at F8
- Changing beam hit position periodically

F3 Scintillator Setting value

Possible moving region

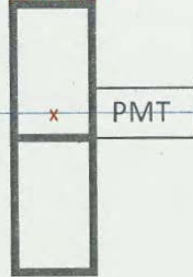
- 155mm – 235 mm
- 315mm – 395mm

A:155mm

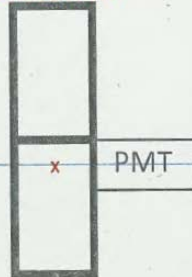


Scintillator

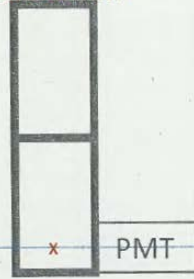
B:235mm



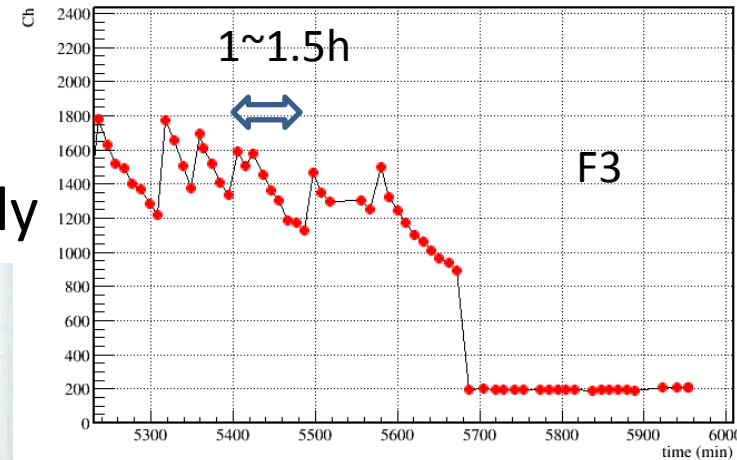
C:315mm



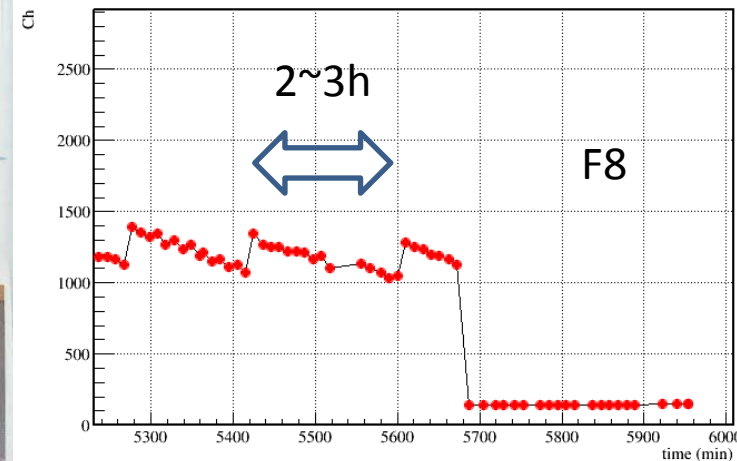
D:395mm



F3Pla-R ADC Mean Position



F8Pla-R ADC Mean Position



02-06-2013 10:43:59
L I S E ++ [D:\Lise-forRIKEN\RIKEN1new\Sn112-Sn112\Lu_112Sn_112Sn_step1.lpp]

Beam charge state

Cut with slits

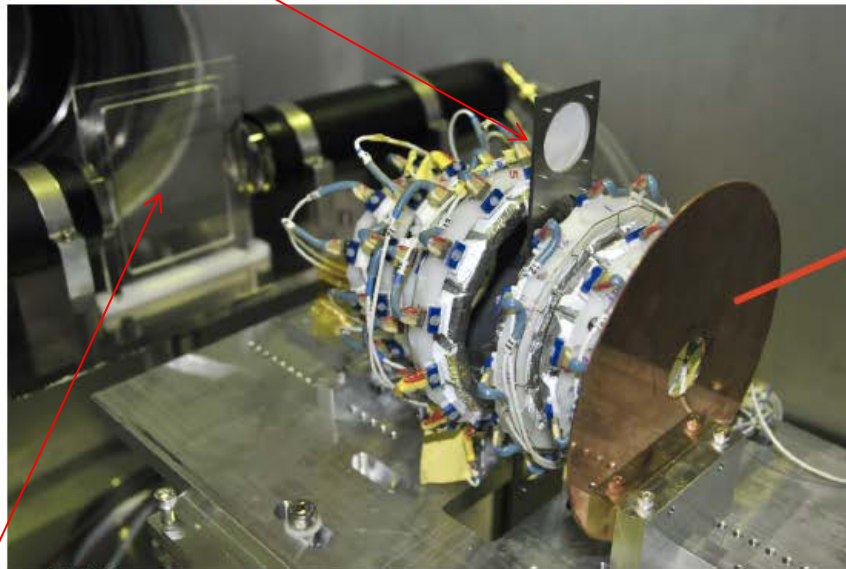
Reaction Chamber at F8

Target is surrounded by CsI(Tl) array

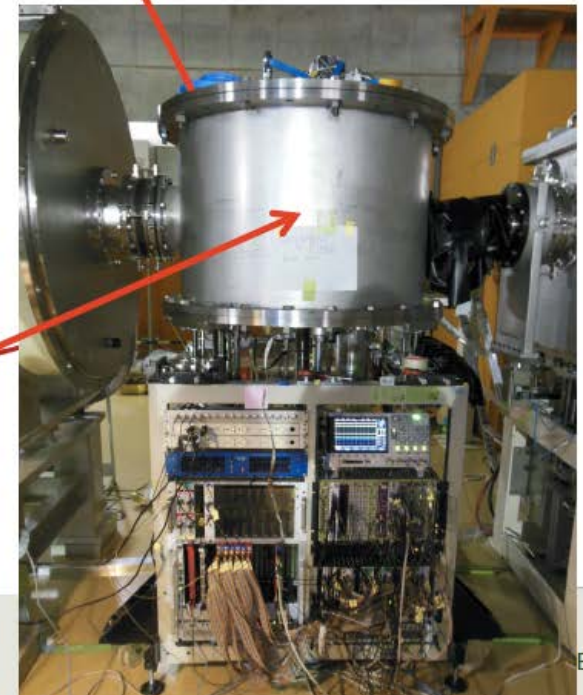


Movable HI target

Washington University microball

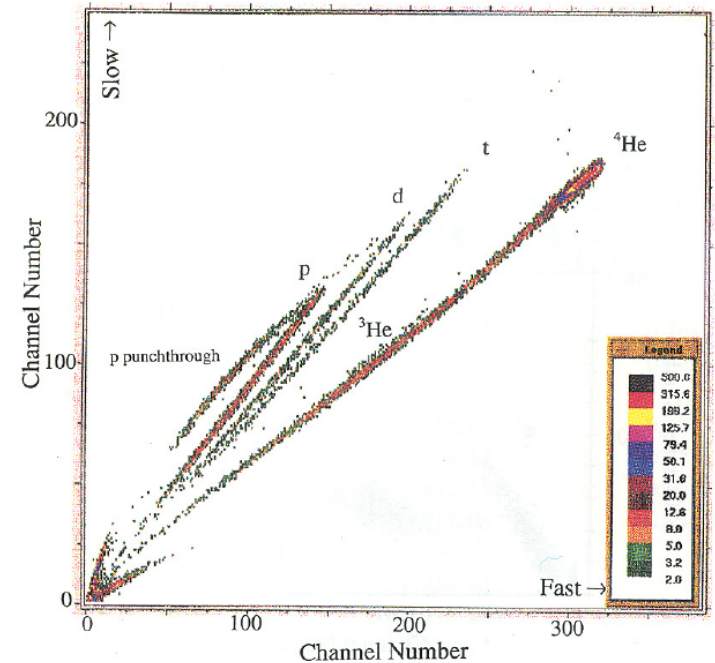
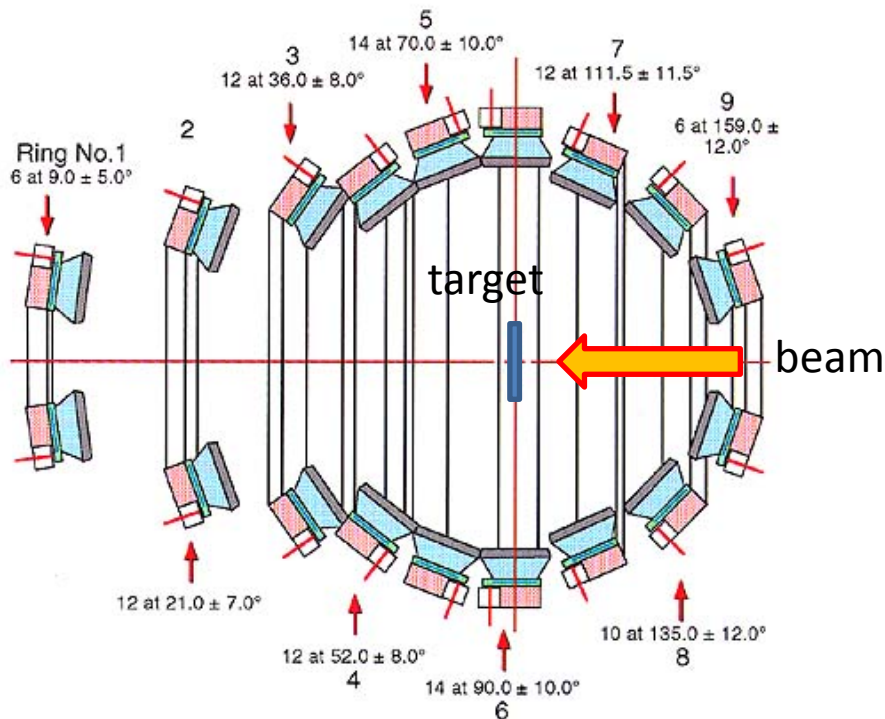
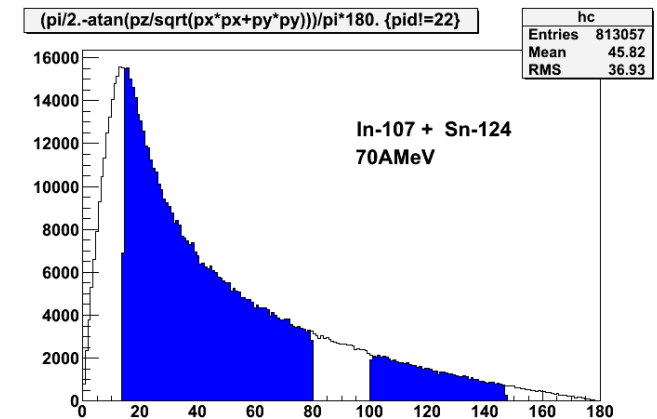


ZD start counter



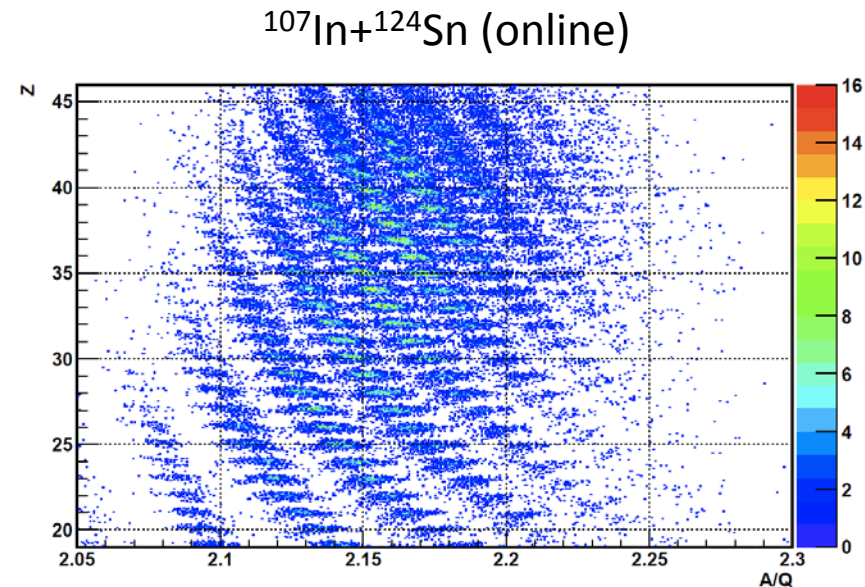
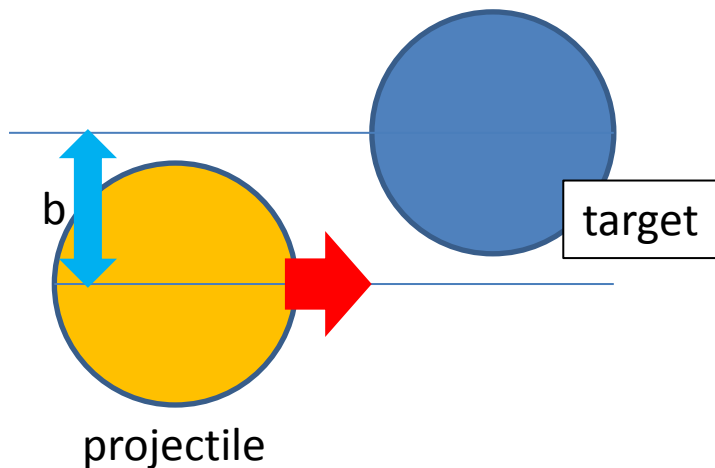
More about μ -ball

- NIM A381 (1996) 418-432
- Up to 96 CsI(Tl) array for the measurement of light fragments.
- PID capability for $Z \sim 1, 2$ by using pulse shape analysis (fast and slow).
- Used for characterization of event: impact parameter.



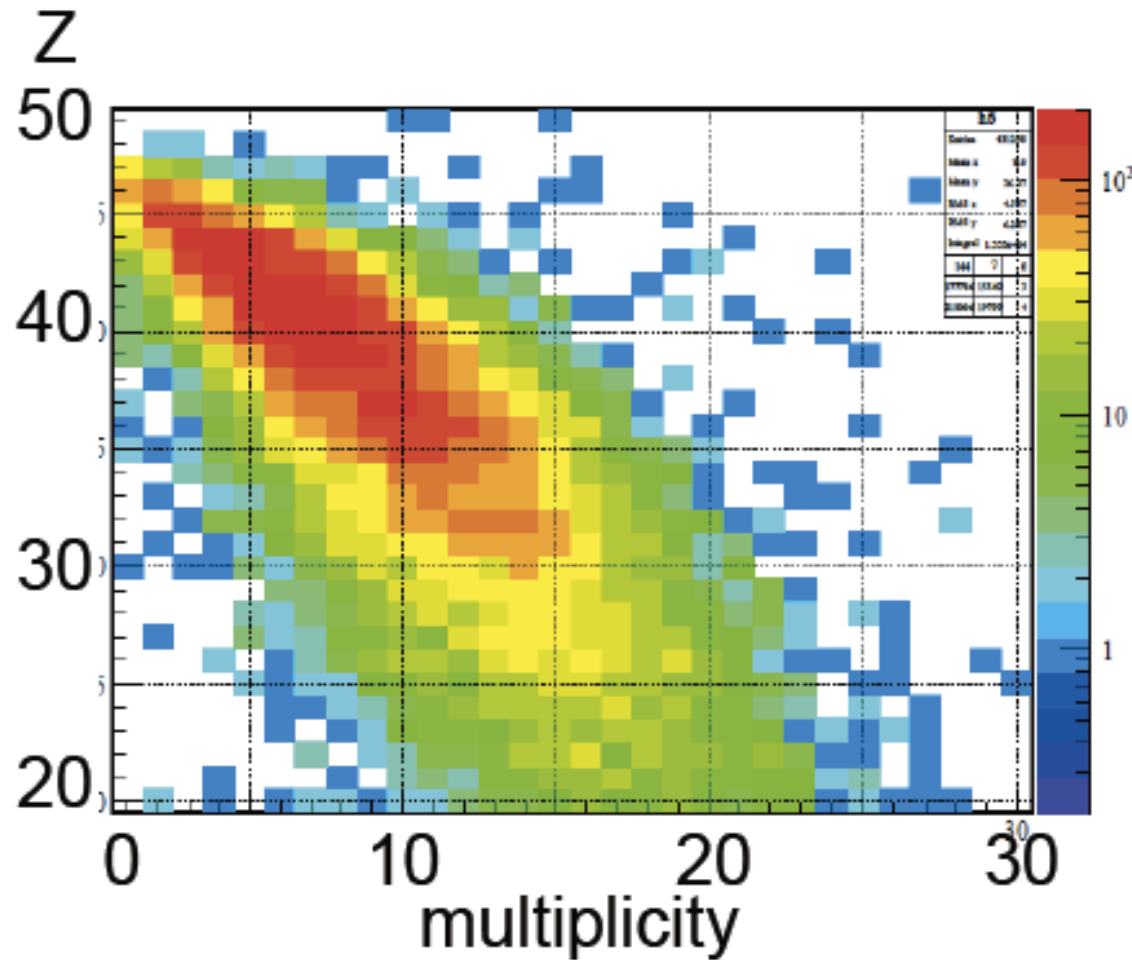
Data sets taken at experiment

- $^{107}\text{In}(\text{beam}, \sim 73\text{MeV/u}) + ^{124}\text{Sn}(\text{Target})$
- $^{112}\text{Sn}(\text{beam}, \sim 73\text{MeV/u}) + ^{112}\text{Sn}(\text{Target})$
- In addition:
 - $^{106}\text{Cd}(\text{beam}, \sim 71\text{MeV/u}) + ^{124}\text{Sn}(\text{Target})$
 - $^{108}\text{Sn}(\text{beam}, \sim 74.5\text{MeV/u}) + ^{124}\text{Sn}(\text{Target})$
 - $^{111}\text{In}(\text{beam}, \sim 71\text{MeV/u}) + ^{112}\text{Sn}(\text{Target})$
 - $^{113}\text{Sb}(\text{beam}, \sim 74.5\text{MeV/u}) + ^{112}\text{Sn}(\text{Target})$



- We will get impact parameter (b) dependence of momentum spectra of heavy residues produced in HIC.

Does centrality detector work well?: YES!



Summary

- Isospin diffusion is one of the important phenomena in HIC which is useful for the study of symmetry energy.
 - Subsaturation density region.
- Isospin diffusion experiment was performed at RIBF to give more strong constraint on symmetry energy.
 - $^{107}\text{In}+^{124}\text{Sn}$, $^{112}\text{Sn}+^{112}\text{Sn}$
 - Combining with MSU data, $R_i(\delta_{\text{residue}})$ will be given to discuss symmetry energy.