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

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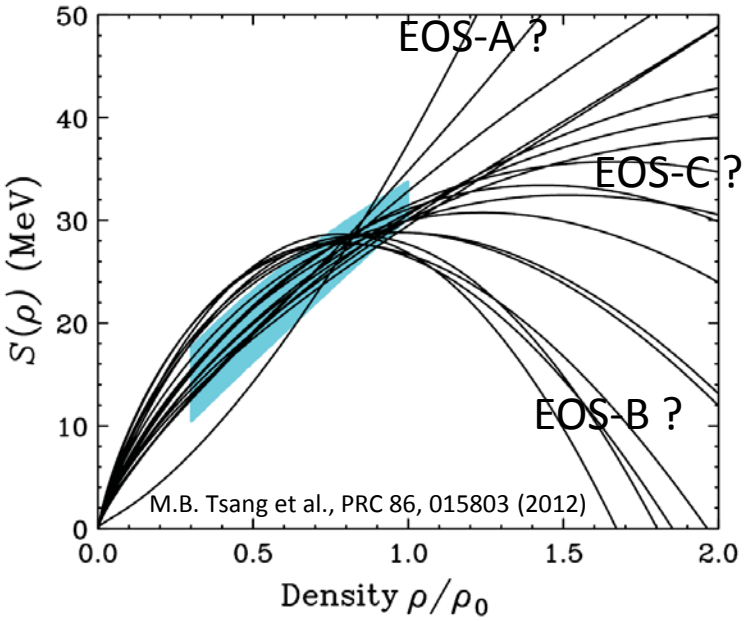
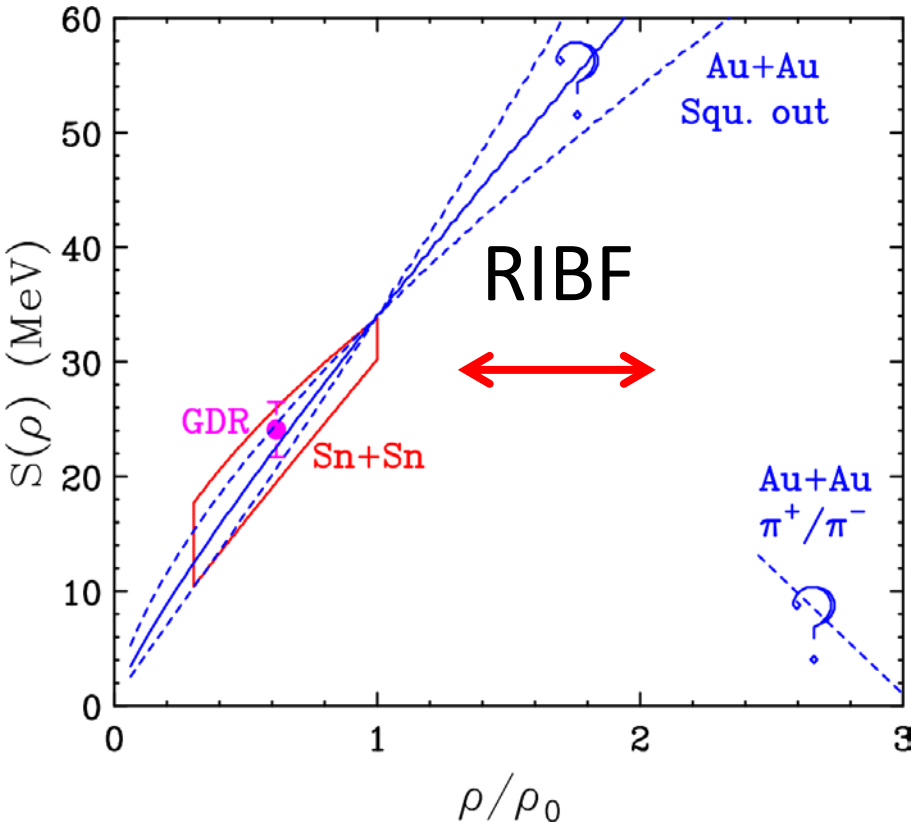
Physics introduction: constraints on the density dependence of symmetry energy



- Constraints given only for $\rho<\rho_0$.
- SAMURAI-TPC project for $\rho\sim2\rho_0$.
- Soft EoS is not realistic to explain NS data.

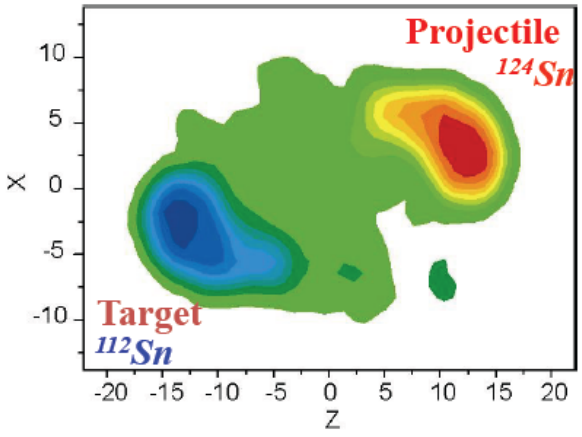
$$S = E_{sym}(\rho)$$

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

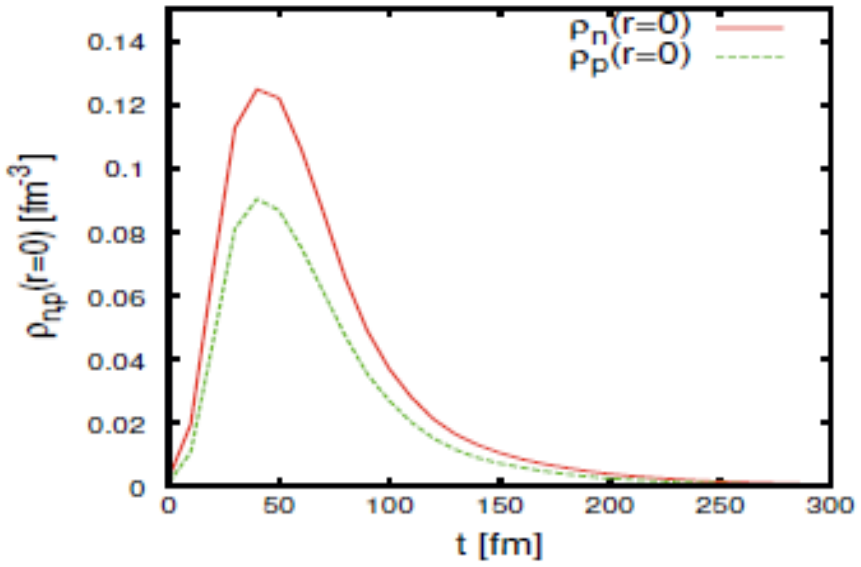


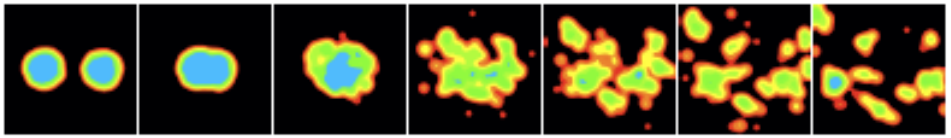
Isospin diffusion in heavy ion collision

- 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<100AMeV

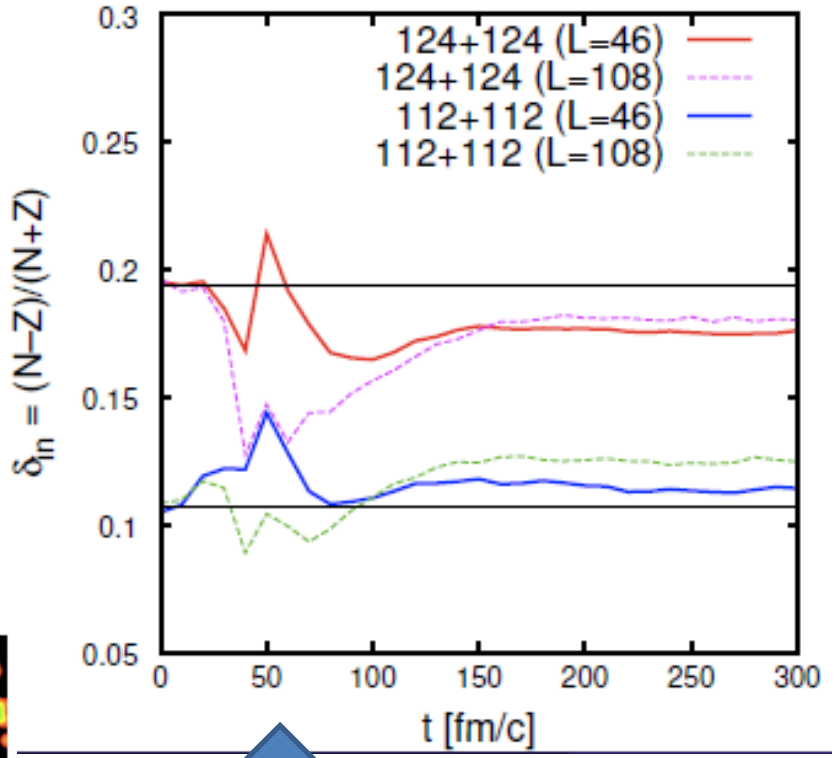


Nuclear density to be probed with isospin diffusion in HIC.





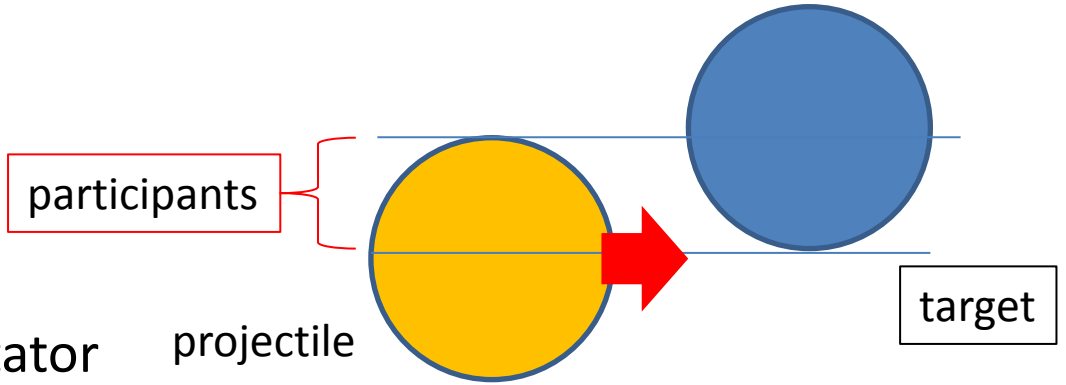
Sn + Sn central collisions at $E/A = 50$ MeV



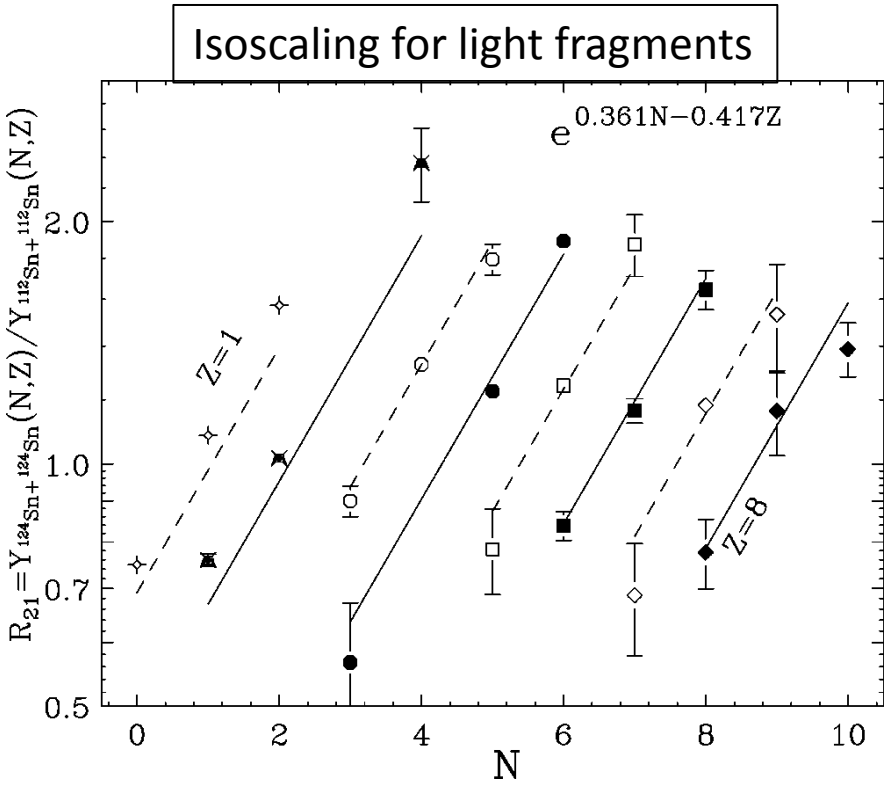
Diffusion of nucleus

Observables to study isospin diffusion in HIC

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

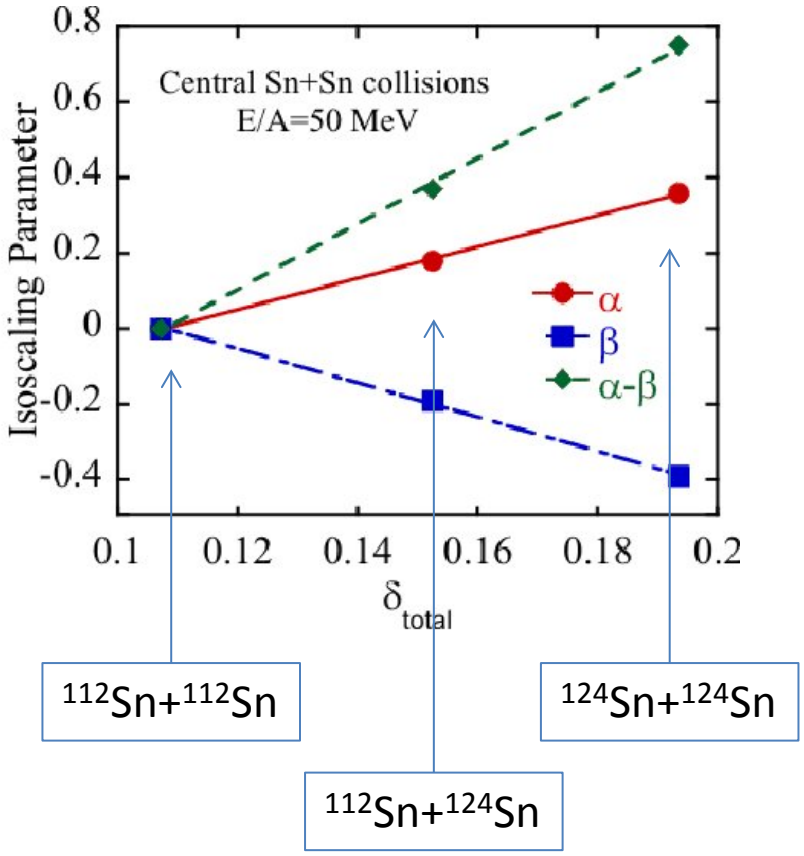


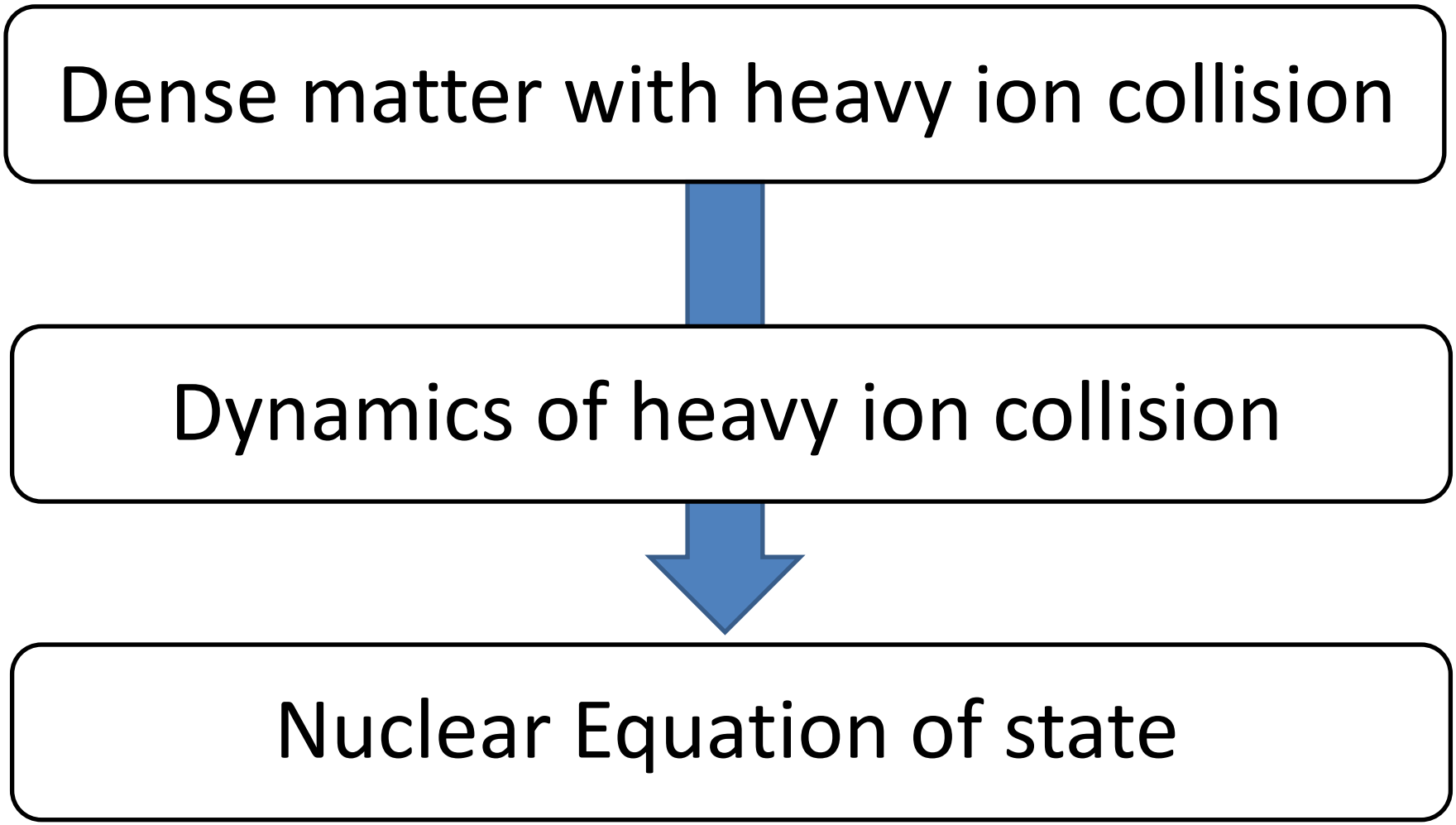
- Isoscaling parameter
  - Isotopic yields from reactions differing in their isospin composition found to satisfy:
  - $R_{21}(N,Z)=Y_2(N,Z)/Y_1(N,Z)$
    $=C_{exp}(\alpha N+\beta Z)$.



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? ρ?

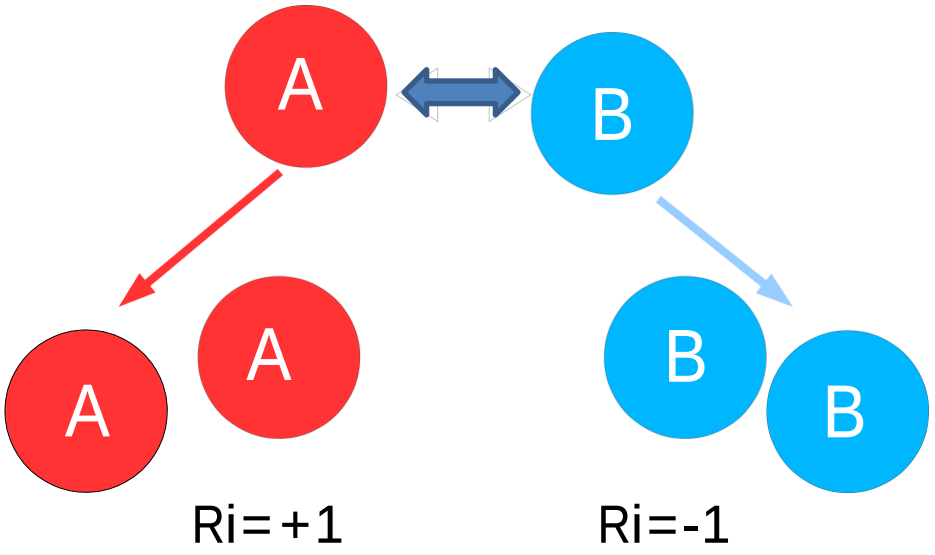
How to deal with the systematic error coming from heavy ion collision analysis?

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 Esym



- 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

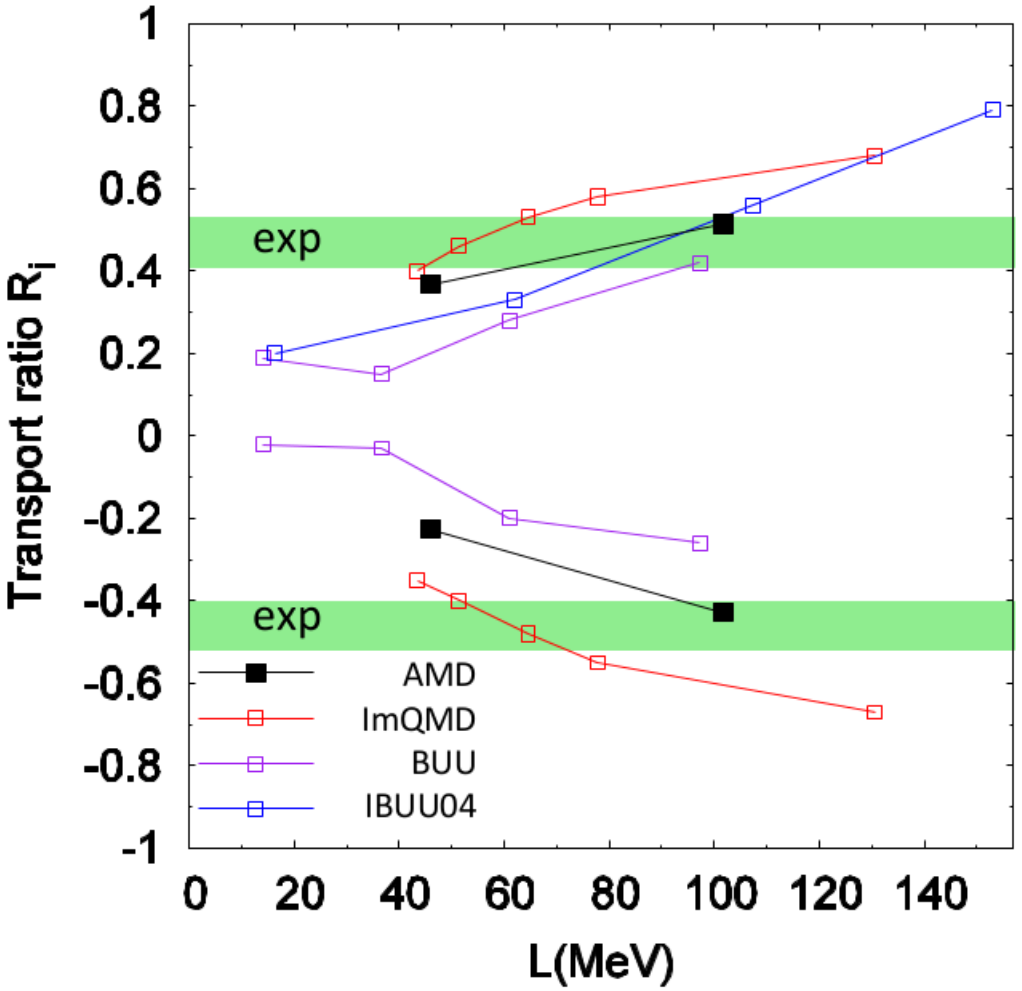
- Observable X is assumed to be liner to δ.

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

Comparison of Ri to transport theory

- X→α
  - For light fragments
  - X→ln(Y(^{7}Li)/Y(^{7}Be)) was also studied.
- Ri=+-1: no diffusion
- Ri=0: equilibration

- ImQMD: L=40~70 MeV
- AMD: L~100 MeV



Ri for HIC spectator (heavy residue)

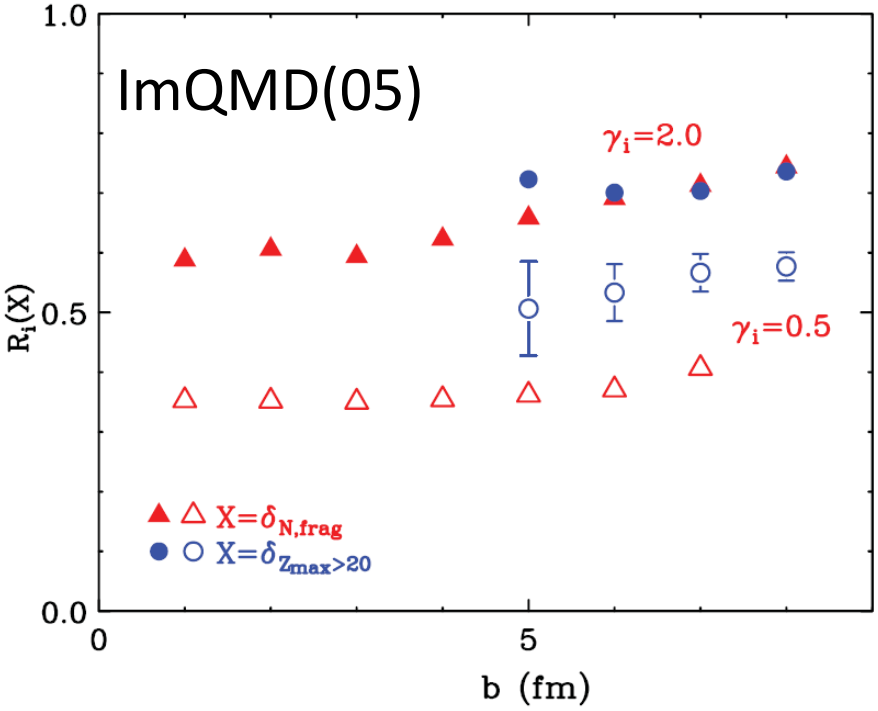
- Evaporative and multi-fragment decay theories predict:

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

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

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

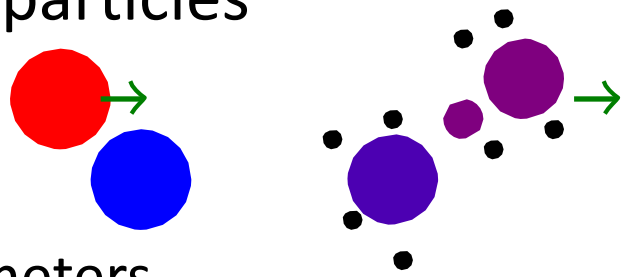
$$\overline{\delta} = (\delta_2 + \delta_1)/2$$



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

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

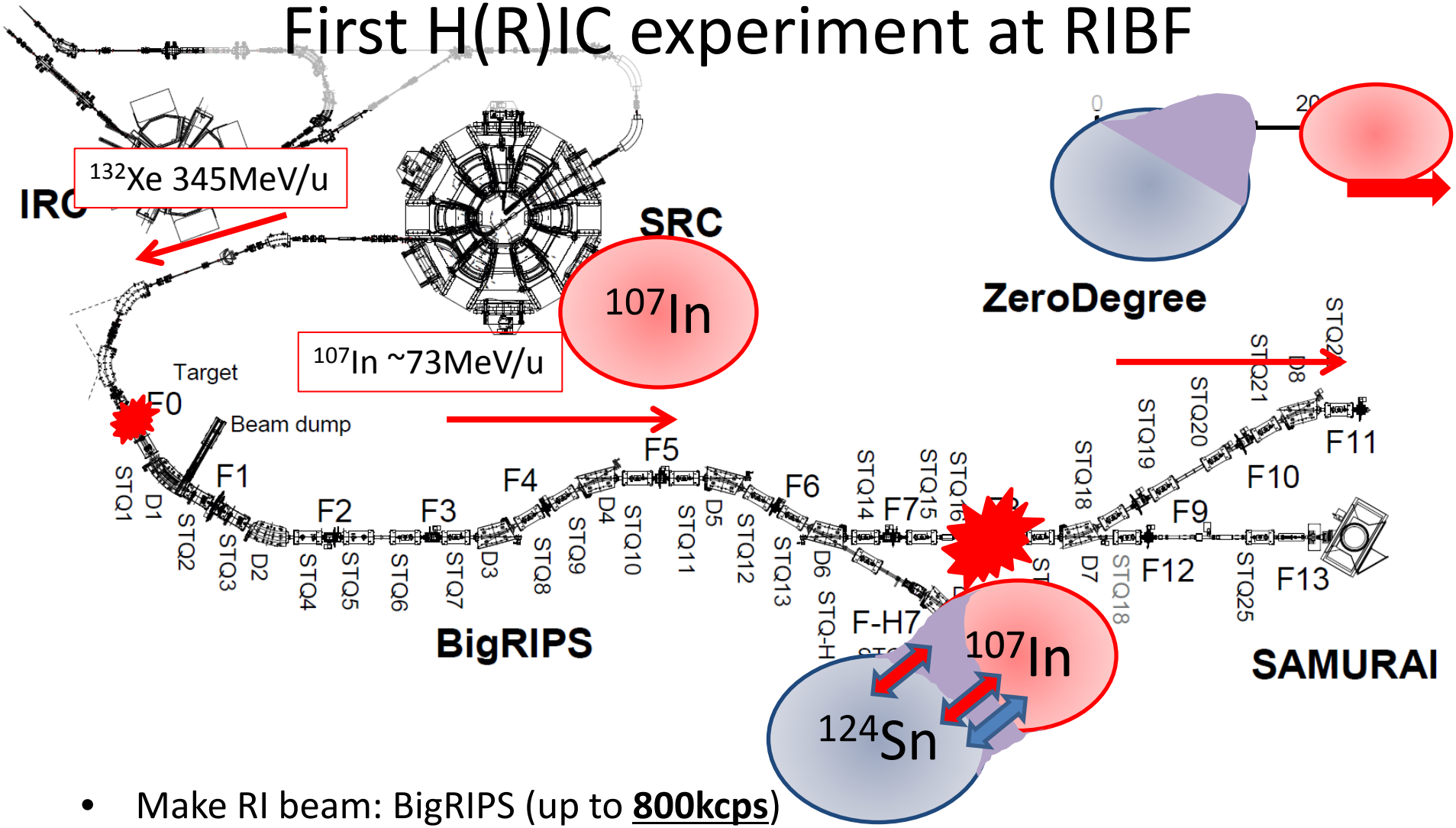
ID Increase with $\nabla\delta$ *=asymmetry gradient*

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

Collaboratiors

- 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

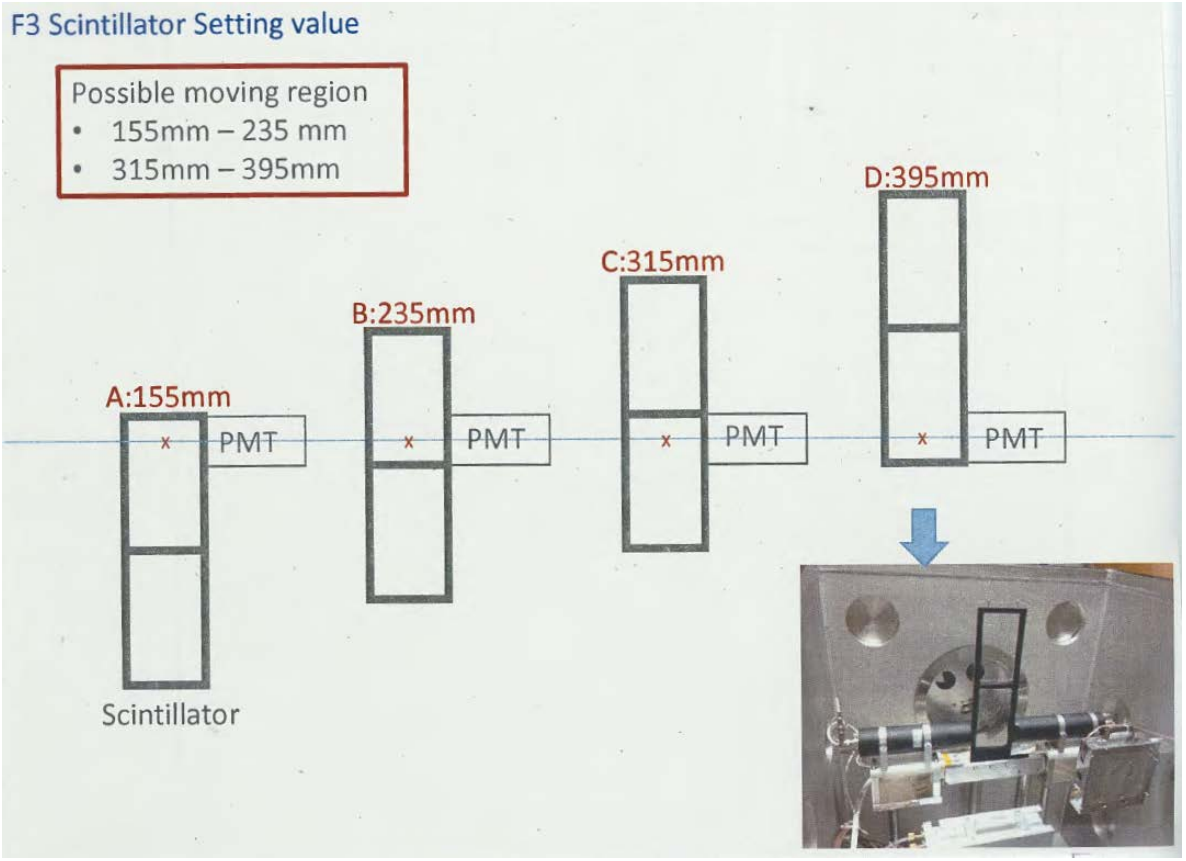
First H(R)IC experiment at RIBF

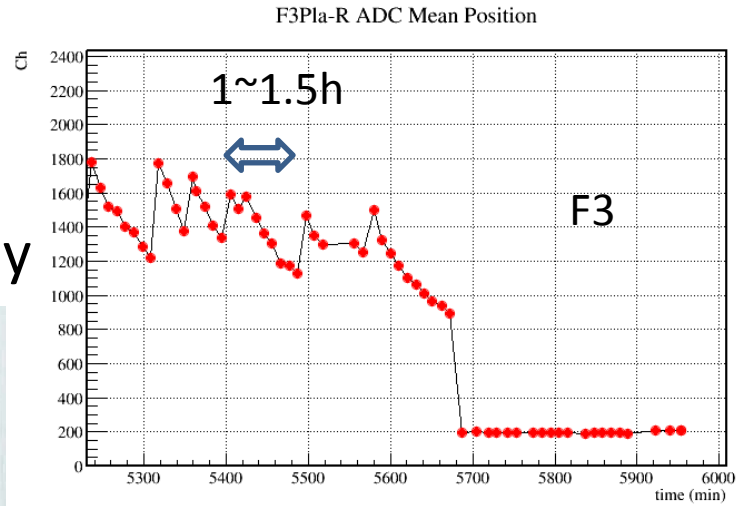


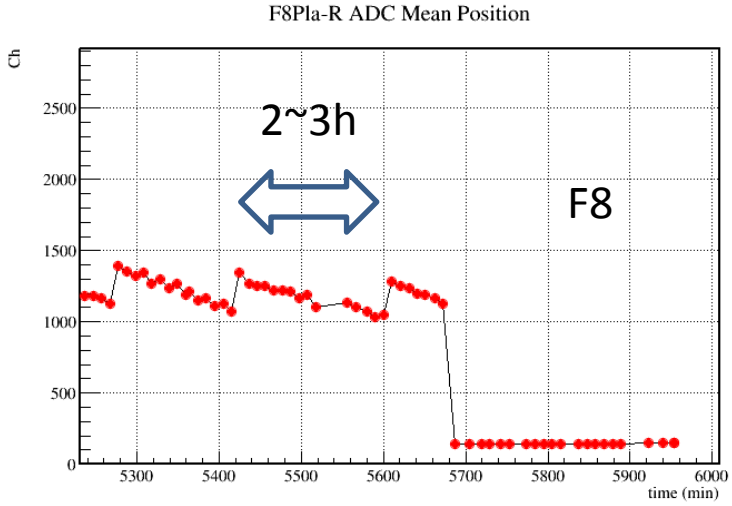
- Make RI beam: BigRIPS (up to **800kcps**)
- Let the beam collide against targets at F8
- Measure the residues produced in the collisions: ZeroDegree

Radiation damage on Plastic counter

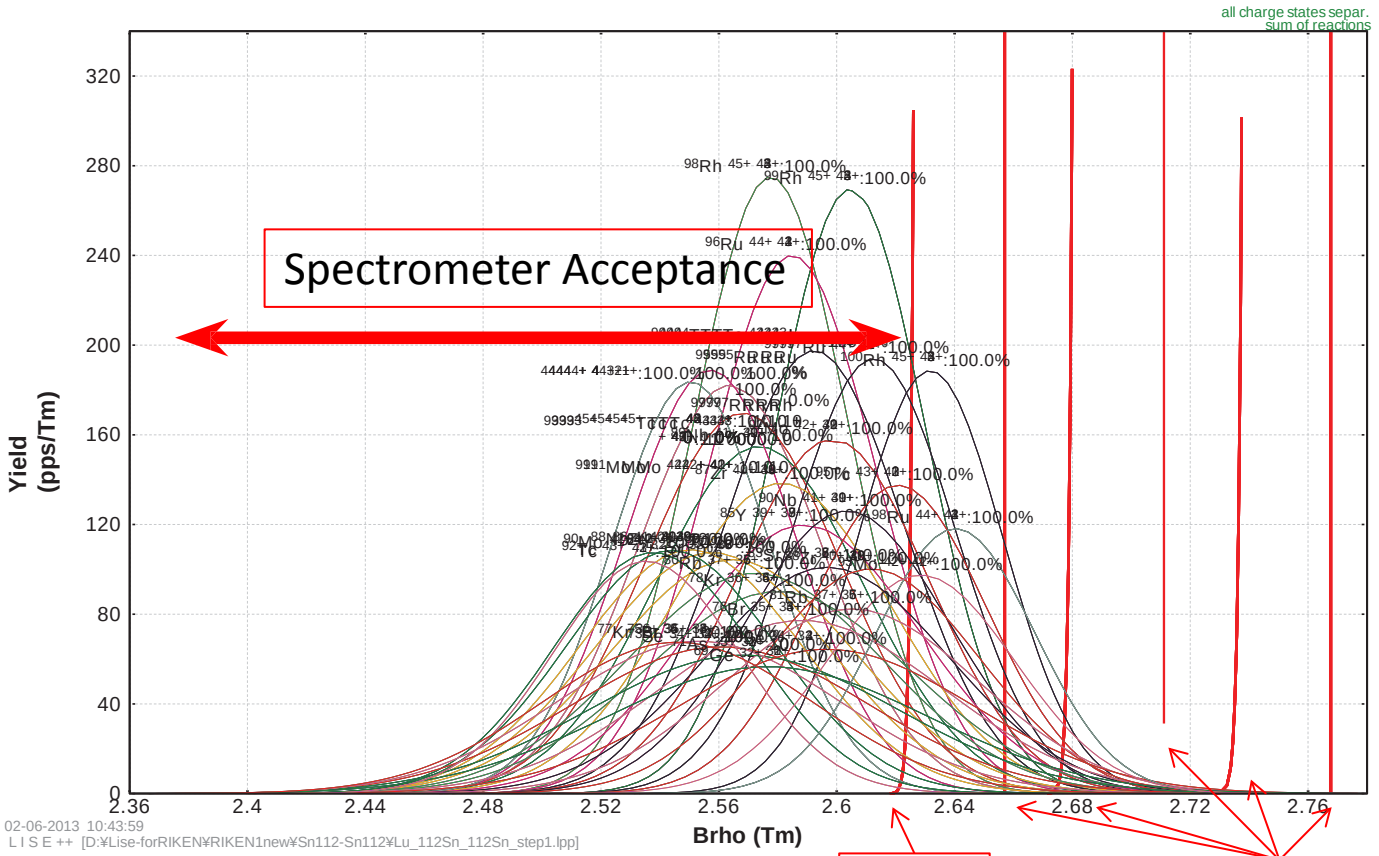
- 800kcps at F3
- 300kcps at F8
- Changing beam hit position periodically



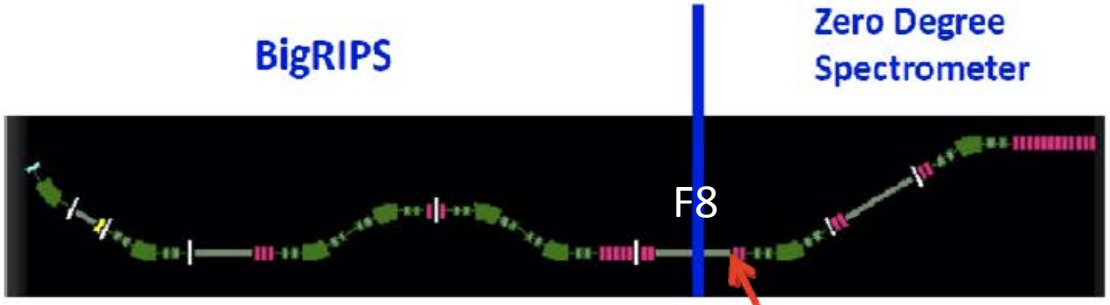




Residue Bρ distribution (LISE)

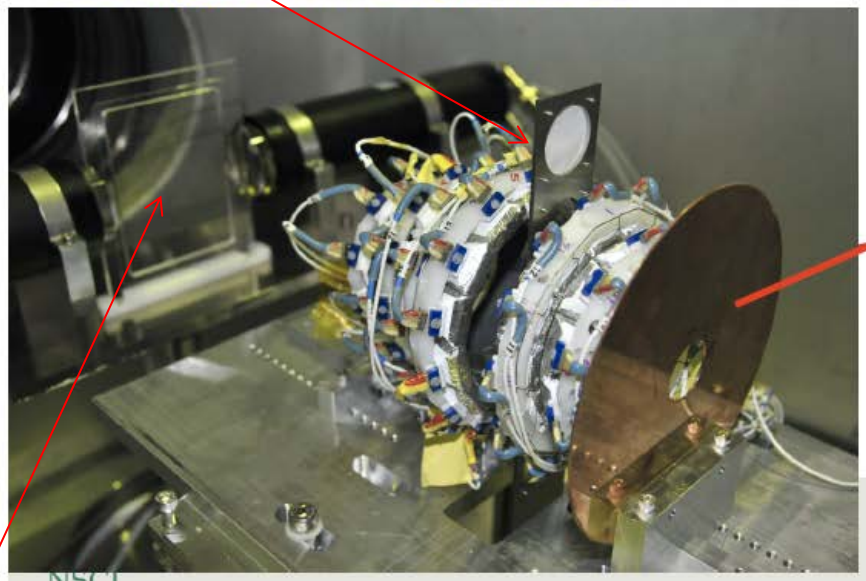


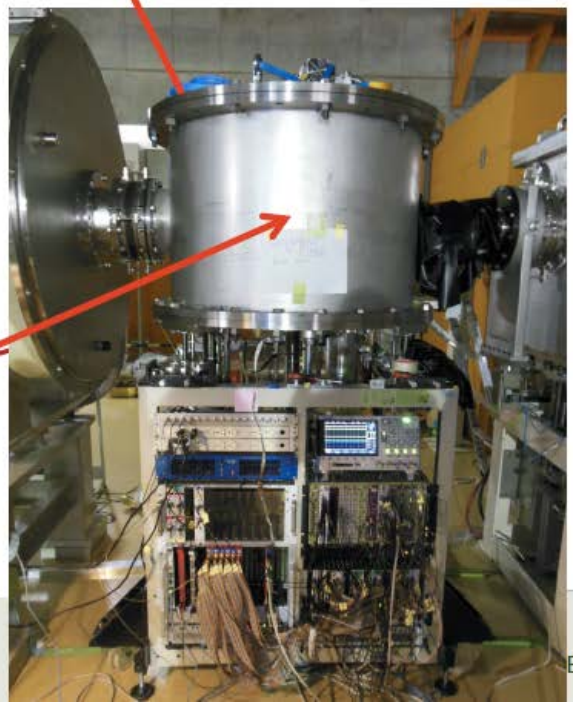
Reaction Chamber at F8
Target is surrounded by CsI(Tl) array



Movable HI target

Washington University microball

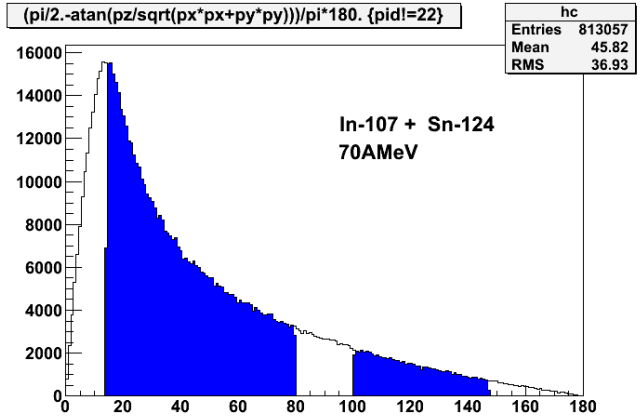


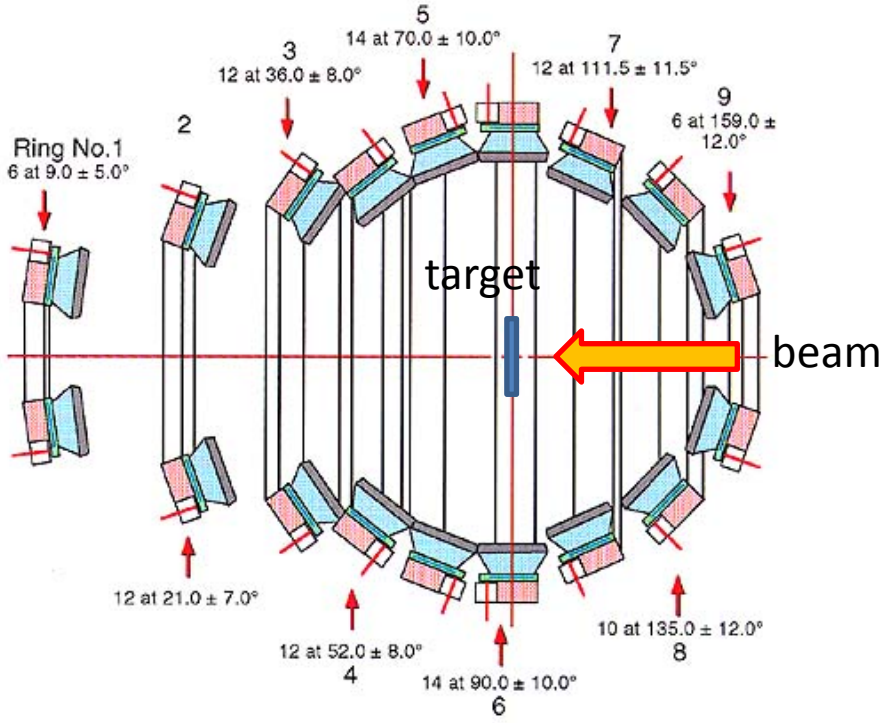


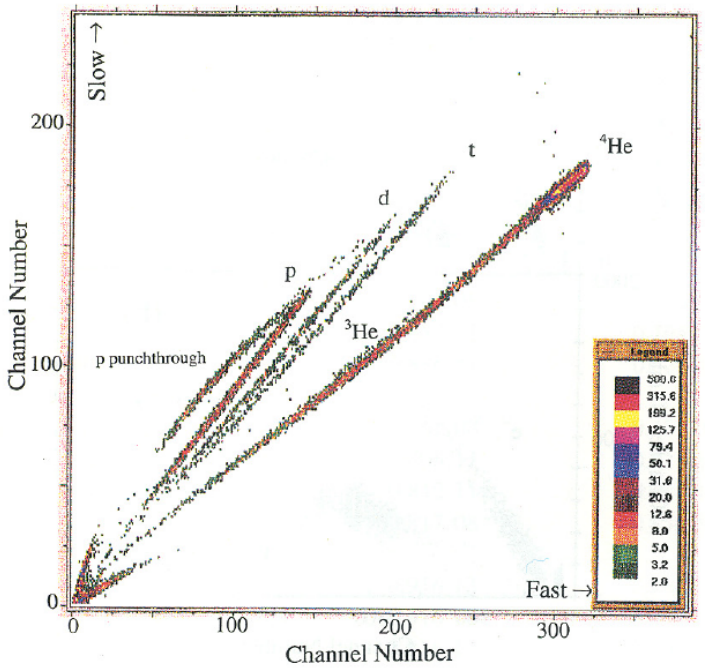
ZD start counter

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~1,2 by using pulse shape analysis (fast and slow).
- Used for characterization of event: impact parameter.

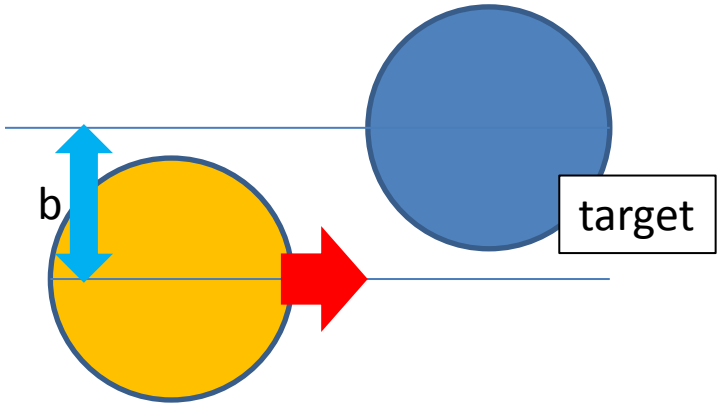




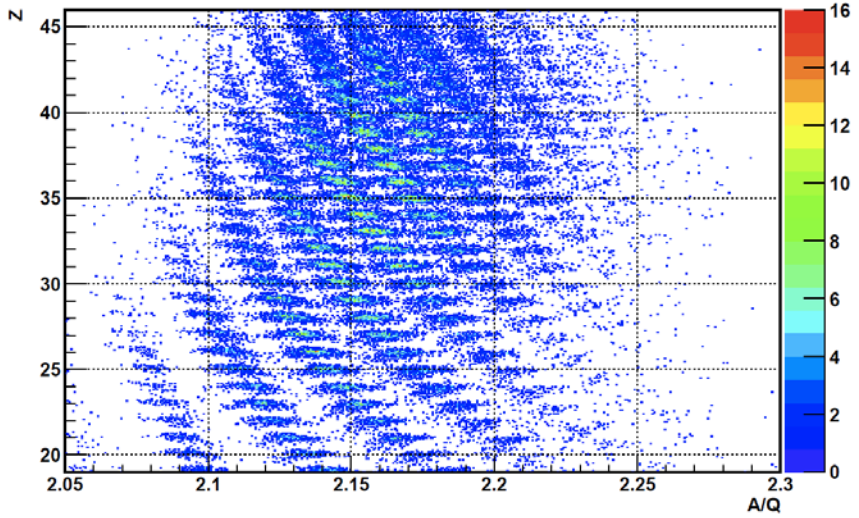


Data sets taken at experiment

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

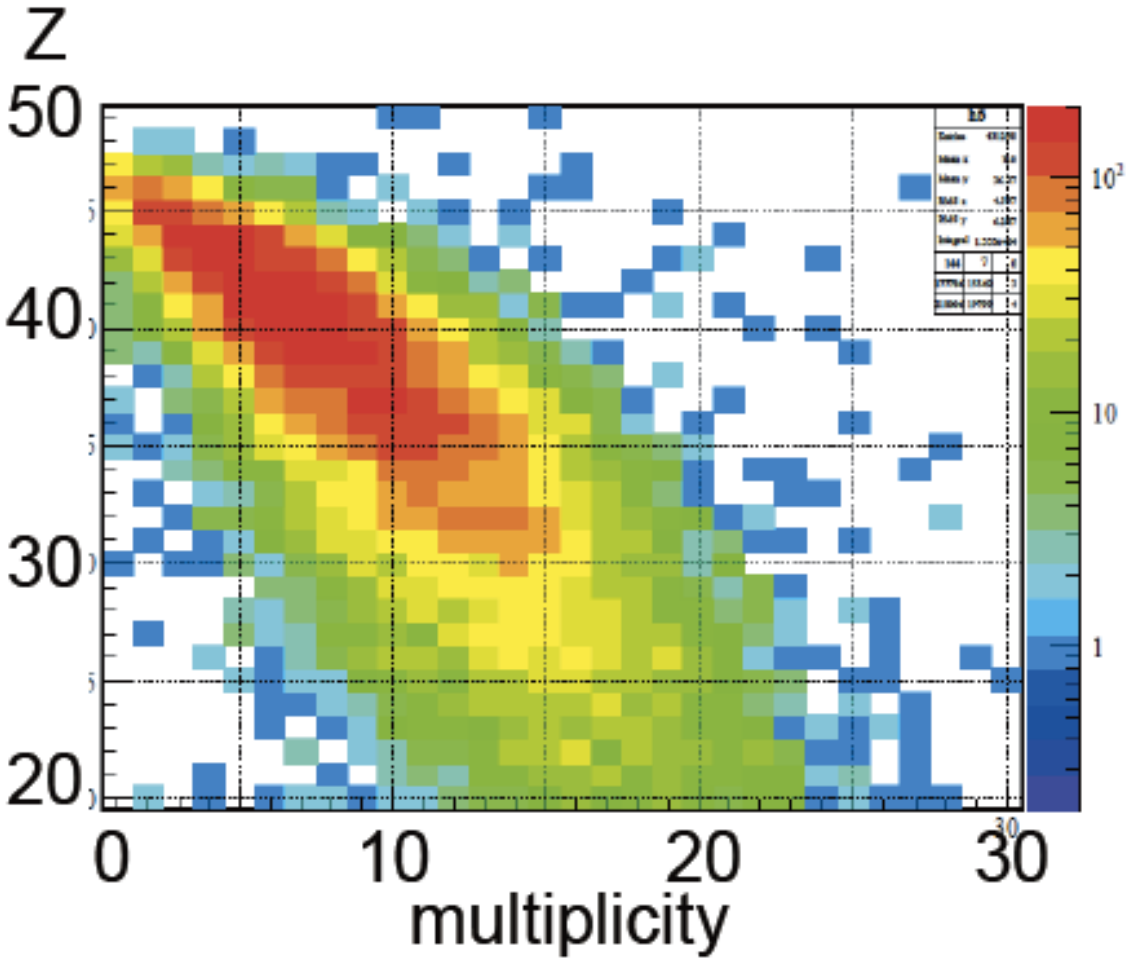


^{107}In+^{124}Sn (online)



- 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}In+^{124}Sn, ^{112}Sn+^{112}Sn
  - Combining with MSU data, Ri($\delta_{residue}$) will be given to discuss symmetry energy.