Status Report of B01: Equation of States of the Neutron-Rich Nuclear Matter at Supra-Density

Tetsuya MURAKAMI
Department of Physics
Kyoto University
For

SπRIT Collaboration

SAMURAI Pion Reconstruction and Ion-Tracker

MSU: W. Lynch, M.B. Tsang, S. Tangwancharoen, Z. Chajecki, J. Estee, R. Shane, Jon Barney, P. Palni

TAMU: A. Mchintosh, S. Yennello, M. Capman

RIKEN : T. Isobe, H. Baba, H. Otsu, K-I Yoneda, H. Sato, Y. Nakai, S. Nishimura, A-K. Perrevoort, J. Lee, H. Sakurai, A. Taketani, He Wang, N. Fukuda, H. Takeda, D. Kameda, H. Suzuki, N. Inabe, T. Kubo

Kyoto Univ.: T. Murakami, N. Nakatsuka, M. Kaneko

Rikkyo Univ.: K. Ieki , Y. Kurita

Liverpool/ Darsbury: M. Chartier, W. Powell, J. Sampson, R.Lemmon

Korea Univ.: B. Hong, G. Jhang

WMU: M. Famiano

INFN: G. Verde, P.Russotto

SIAP CAS: Fei Lu, W.G. Ma

Tsinghau Univ.: Z. Sun

CEA: E. Pollacco

INP: J. Lukasik, P. Pawlowski

ORNL: A. Galindo-Uribarri

Tohoku Univ.: T. Kobayashi

TITech: T. Nakamura, Y. Kondo, Y. Togano

GSI: T. Aumann

Today's MENU

- Now SAMURAI acquired SπRIT
  - Kaneko-kun's poster
  - Next talk by Genie-san
- Physics
  - Our Objectives
  - Big Problems
  - From our pilot Experiment at HIMAC
- Summary (Timeline of Experiment)

Nuclear Equation of State

$$E(\rho,\delta) = E(\rho,0) + E_{sym}(\rho)\delta^2 + o(\delta^4)$$

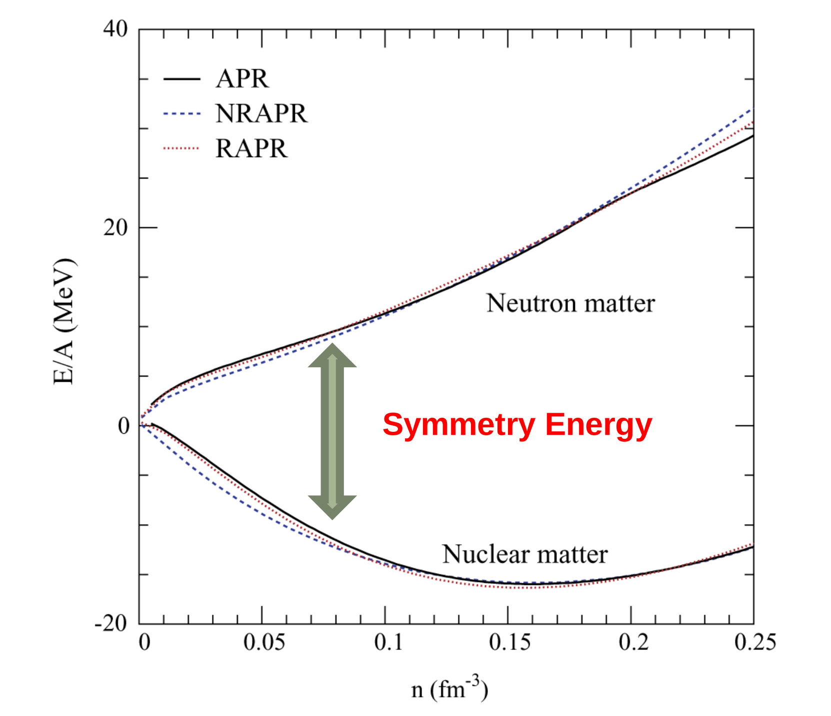
$$\delta = (\rho_n - \rho_p)/\rho$$

$$\boxed{E_{sym}(\rho) = E_{sym}(\rho_0) + L\varepsilon + \frac{K_{sym}}{2}\varepsilon^2 + o(\varepsilon^3)}$$

$$\varepsilon = (\rho - \rho_0)/3\rho_0$$

$$S_0 = E_{sym}(\rho_0) \Rightarrow J\,; sometimes$$

$$L = 3\rho_0 \left.\frac{\partial E_{sym}(\rho)}{\partial \rho}\right|_{\rho=\rho_0} = (3/\rho_0)P_0$$



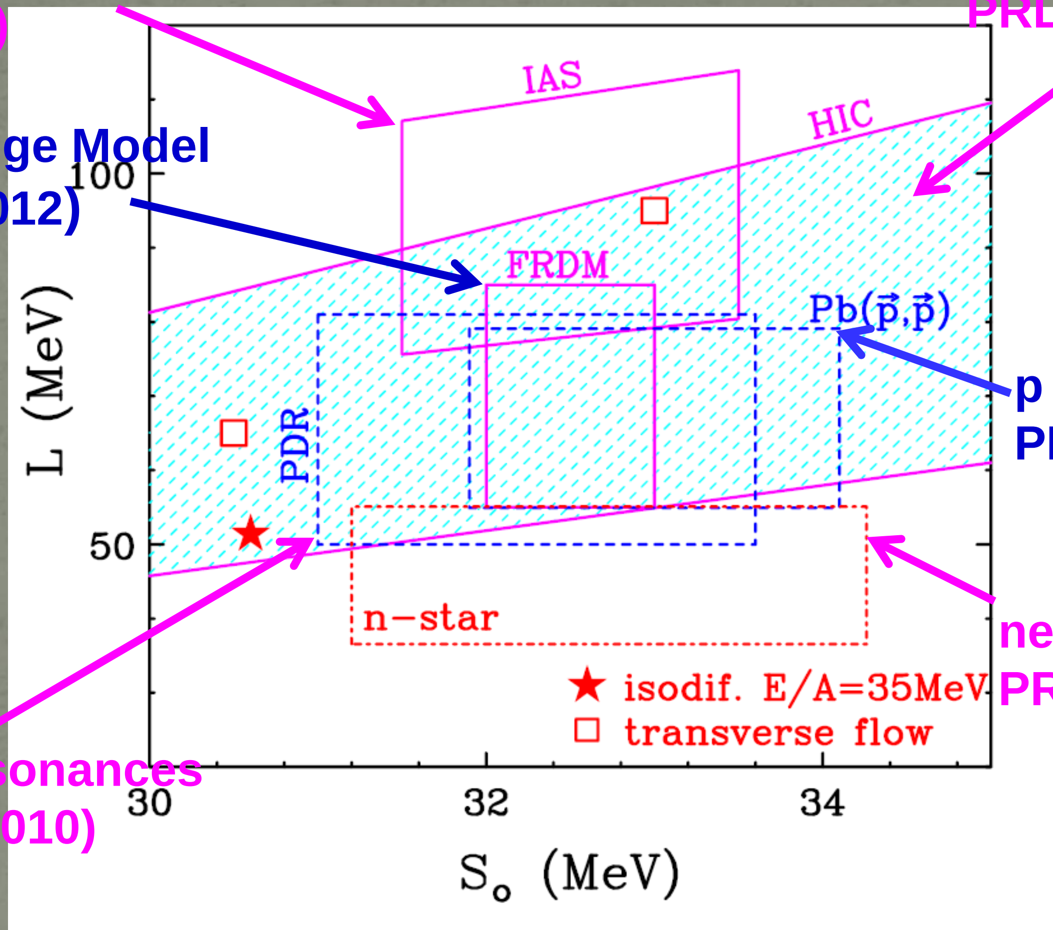
A.W. Steiner et al.,
Phys. Reports 411（2005）325

Present Constraints on Symmetry Energy from different experiments

Isobaric Analogue States
NPA 818, 36 (2009)

heavy ion collisions
PRL 102,122701(2009)

Finite Droplet Range Model
PRL108,052501(2012)

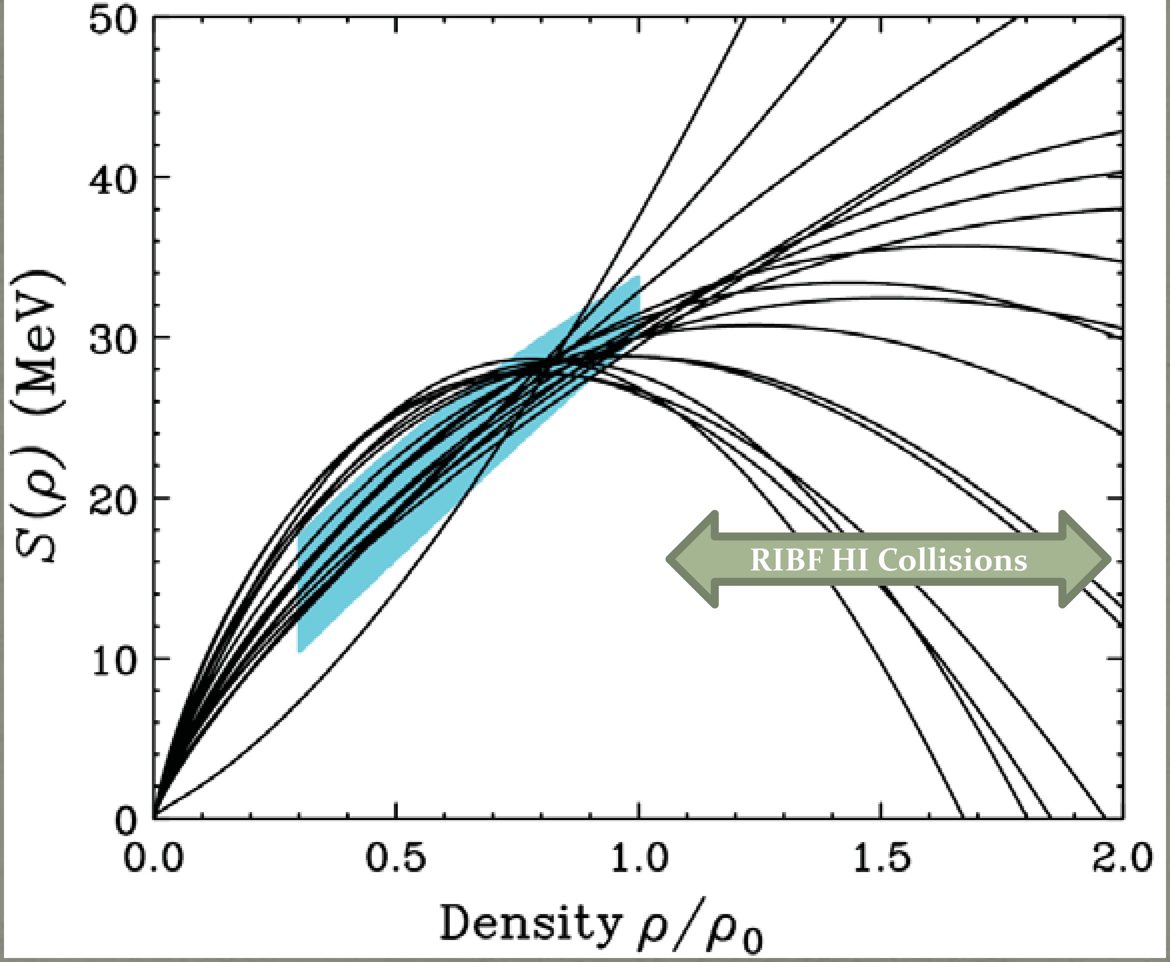


p elastic scattering
PRC82,044611(2010)

neutron-star radius
PRL108,01102(2012)

Pygmy Dipole Resonances
PRC 81, 041304 (2010)

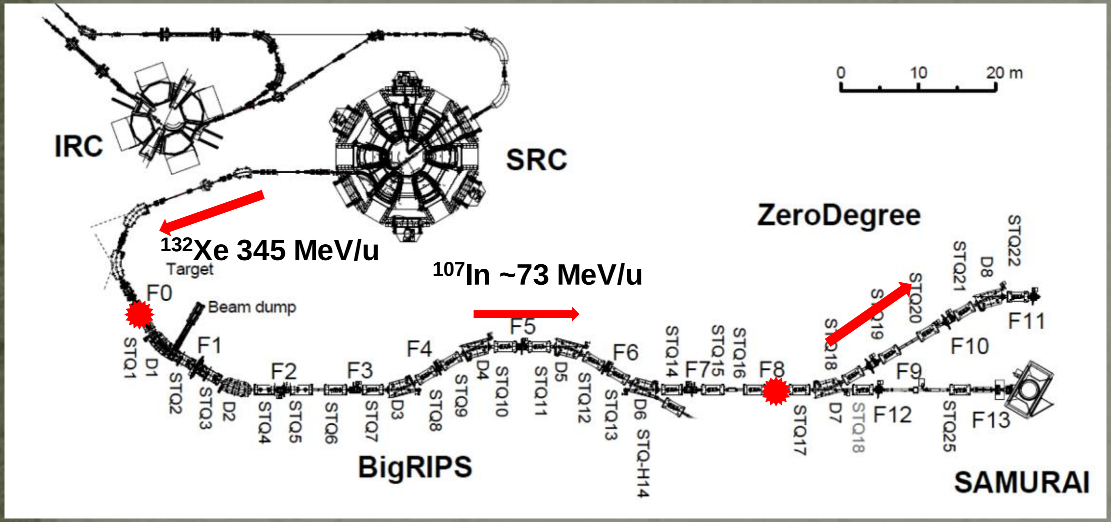
Tsang et al. Phys. Rev. C 86, 015803 (2012)

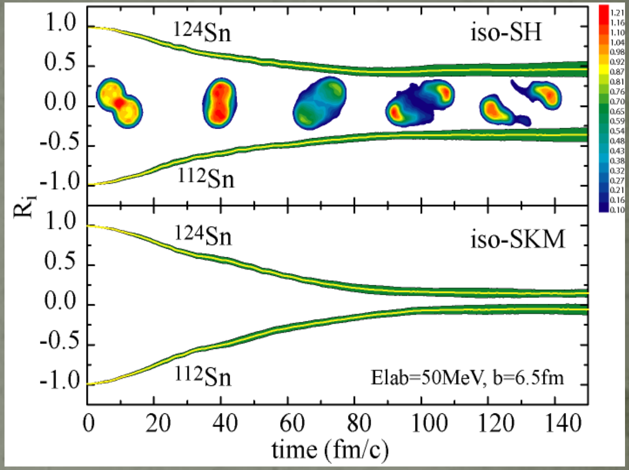


Tsang et al. Phys. Rev. C 86, 015803 (2012)

Isospin diffusion in peripheral collisions

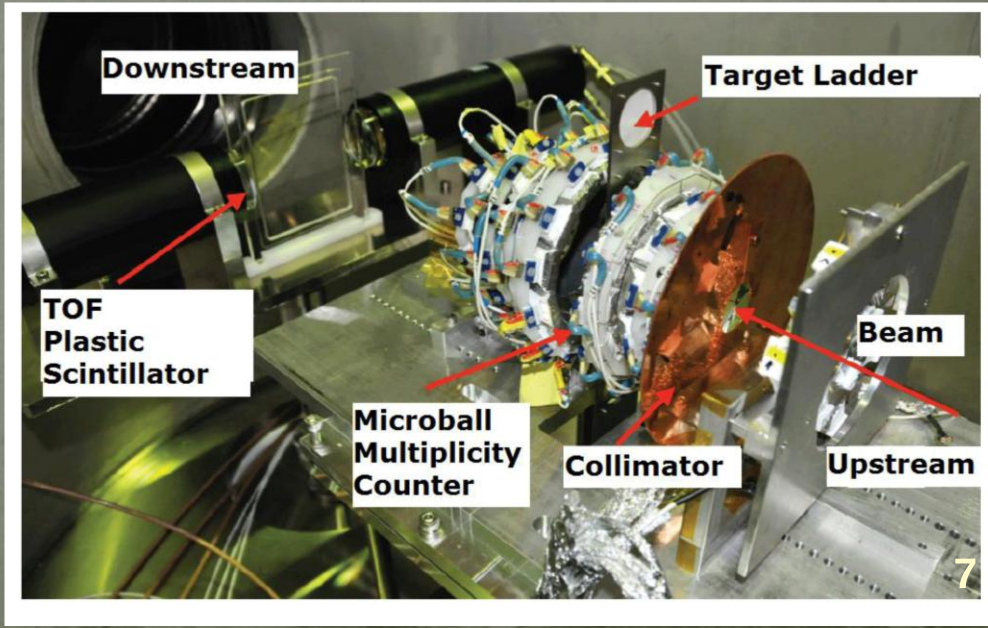
MSU/TAMU/RIKEN/Kyoto Group in June 2013



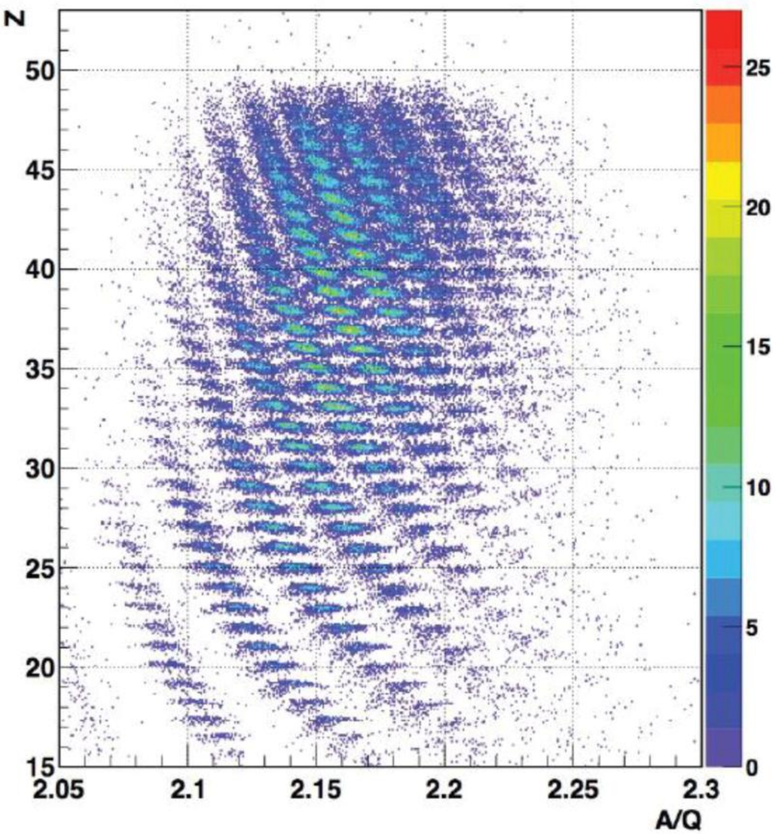


^{107}In(beam, ~73MeV/u) +^{124}Sn (Target)

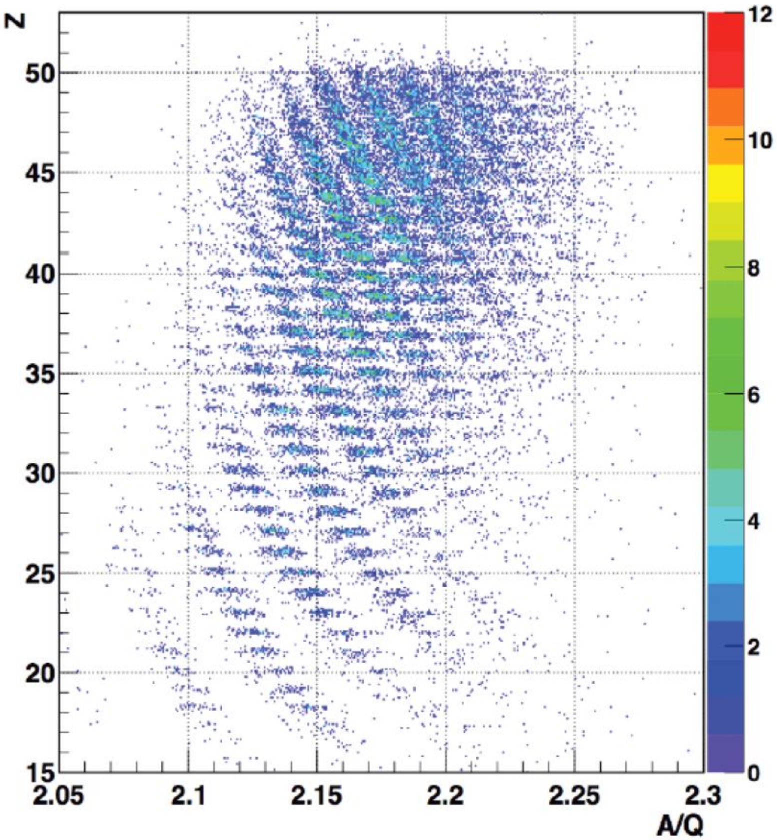
^{112}Sn(beam, ~73MeV/u) +^{112}Sn (Target)



PID plot of 107In+124Sn

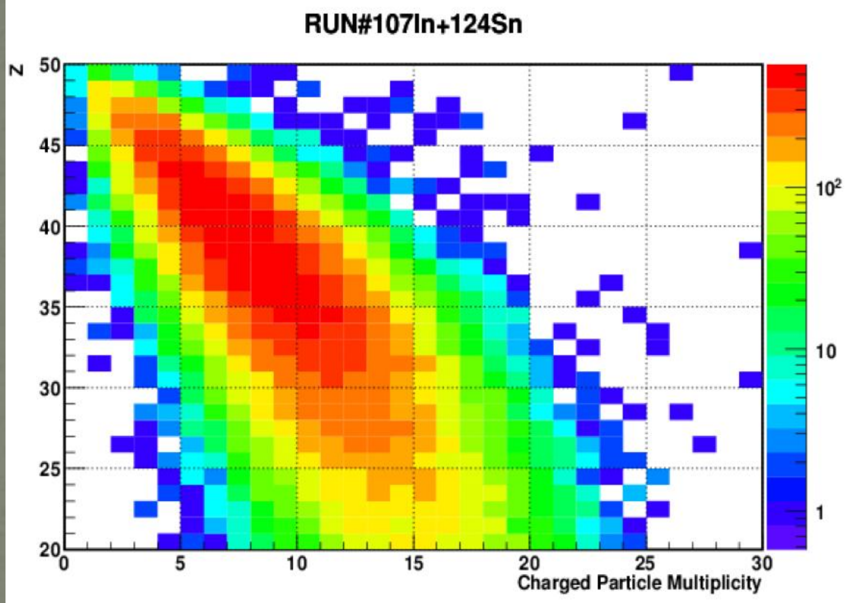


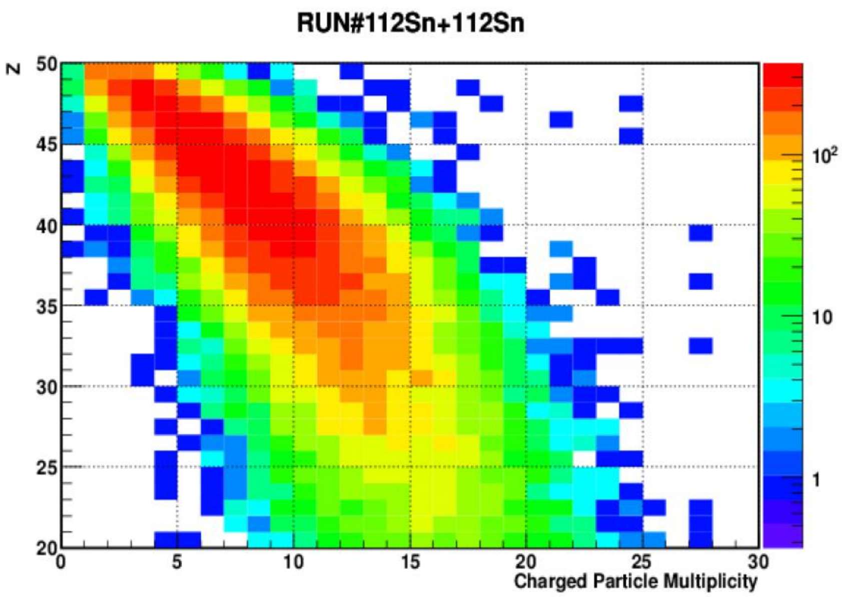
PID plot of 112Sn+112Sn



Multiplicity vs Z of projectile fragment correlation from

107In+124Sn reaction 112Sn+112Sn reaction





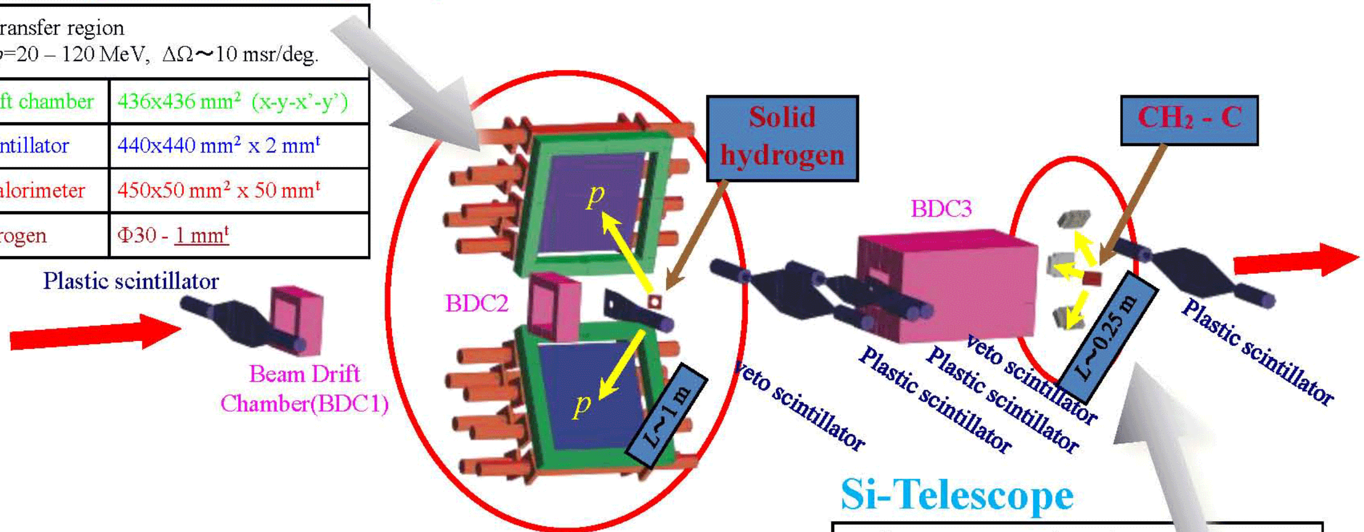
Future Direction of p elastic scattring

ESPRI Group (J. Zenihiro et al.)

Recoil Proton Spectrometer (RPS)

Large momentum transfer region
θ_{lab} = 66 - 80°, Ep=20 – 120 MeV, $\Delta\Omega\sim$10 msr/deg.

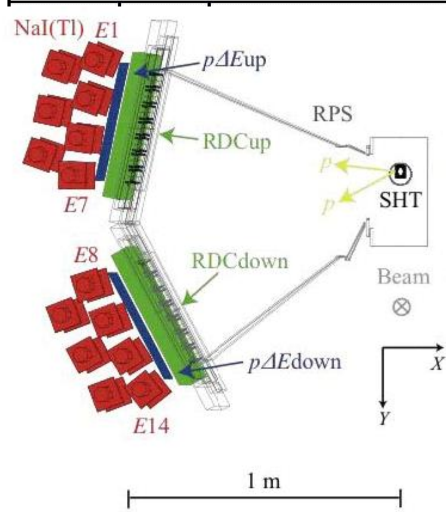
RPS	Recoil drift chamber	436x436 mm^2 (x-y-x'-y')
	plastic scintillator	440x440 mm^2 x 2 mm^t
	NaI(Tl) calorimeter	450x50 mm^2 x 50 mm^t
Target	Solid hydrogen	Φ30 - 1 mm^t



Si-Telescope

Small momentum transfer region
θ_{lab} = 75 - 85°, Ep=5 – 50 MeV $\Delta\Omega\sim$14 msr/deg.

- Missing mass spectrometer : $P^{\mu}_{beam} + P^{\mu}_{p} \Rightarrow E_x$ ($\Delta Ex\sim$400 keV)
- Cover extensive momentum transfer region : up to ~2.5 fm^{-1}

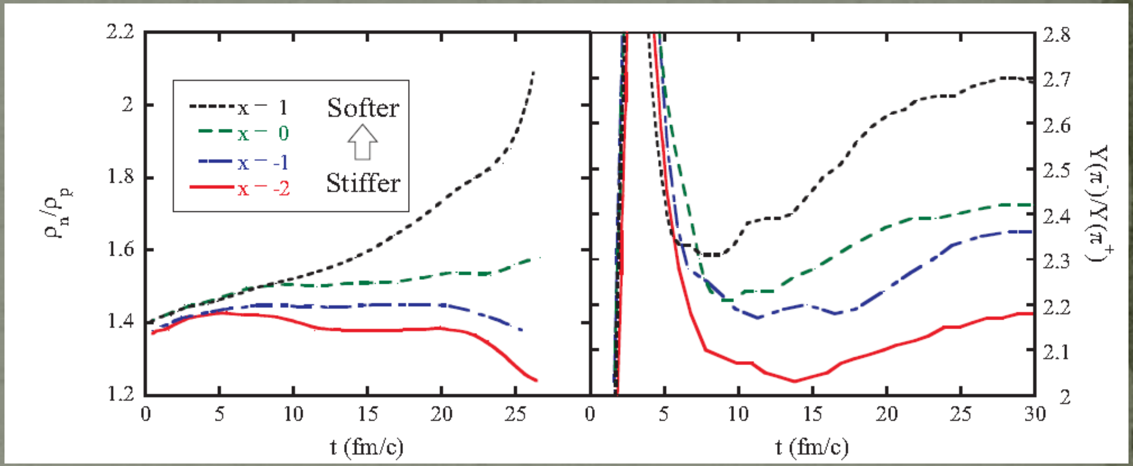


Elastic Scattering of Protons with RI beam

^{132}Sn : flag-ship nuclei as a next step from ^{208}Pb (NP1112-RIBF79)

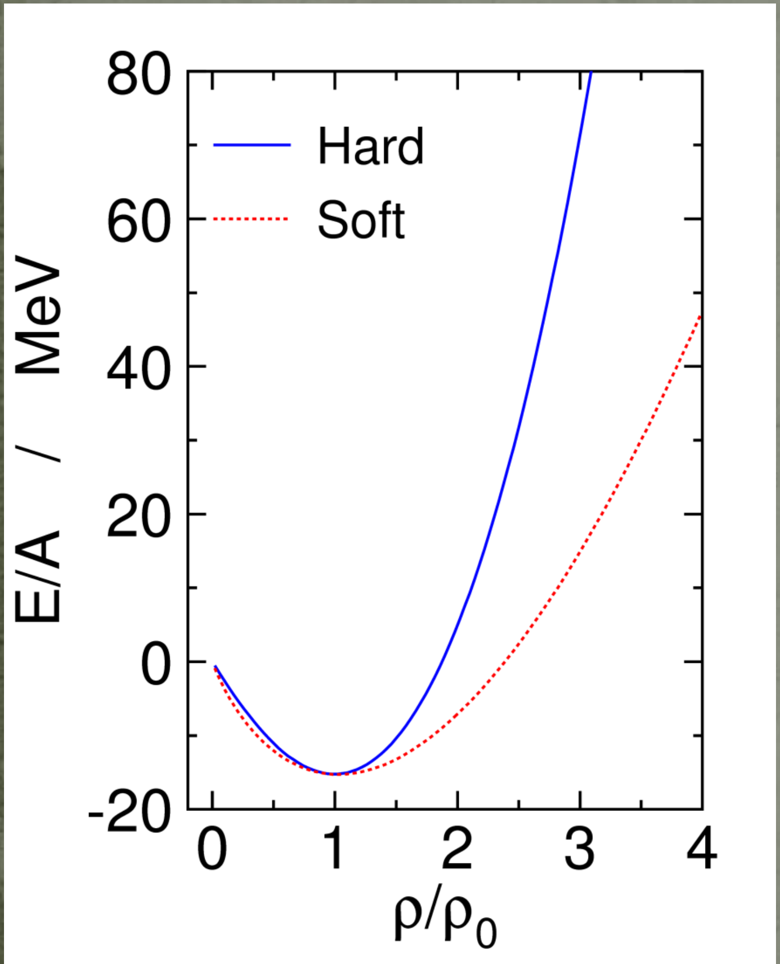
Influence of symmetry pressure; Possible Probe

The symmetry pressure expels neutrons from and attracts protons to high density region of neutron-rich system. This suppresses Y(n)/Y(p), Y(π^-)/Y(π^+), etc.



- π^+–π^- ratio
- Proton-neutron ratio
- Light ion ratio (t-^{3}He)
- Particle flow of pions, protons, neutrons and light ions

In Theoretical Model like IQMD……



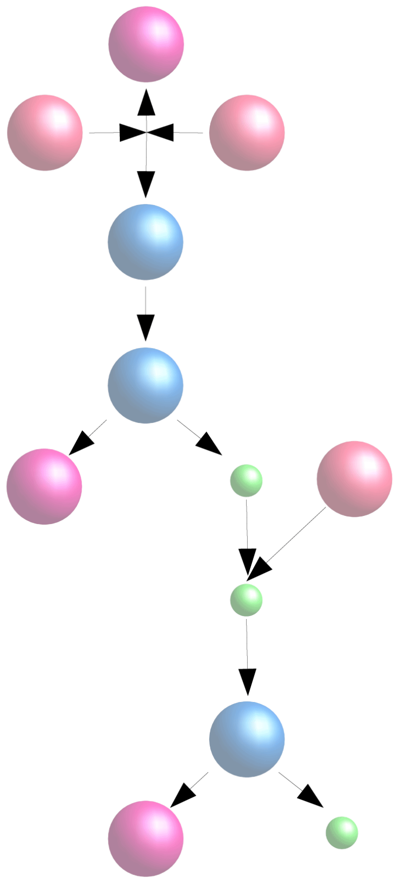
Following Four Slides are from Y.Leifels' presentation at ICNT2013

$$U_{skyrme} = \alpha \cdot \left(\frac{\rho}{\rho_0}\right) + \beta \cdot \left(\frac{\rho}{\rho_0}\right)^{\gamma} + \delta \ln^2\left(\epsilon(\Delta\vec{p})^2 + 1\right) \cdot \left(\frac{\rho}{\rho_0}\right)$$

IQMD	α MeV	β MeV	γ	δ MeV	ε c^2/GeV^2	κ MeV
S	-356	303	1.17	-	-	200
SM	-390	320	1.14	1.57	500	200
H	-124	71	2.00	-	-	376
HM	-130	59	2.09	1.57	500	376

Just for a reminder

Inelastic cross sections



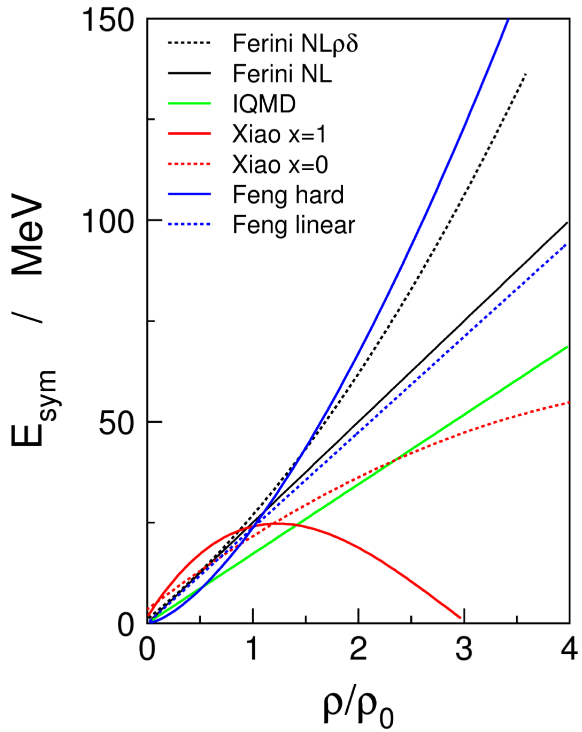
- pion production most dominant channel
- threshold energy in fixed target pp collisions 0.29 GeV
- pp and np cross sections differ
- production via resonances (Δ, N*)
- pion production sensitive to N/Z
- in case predominantly via Δ

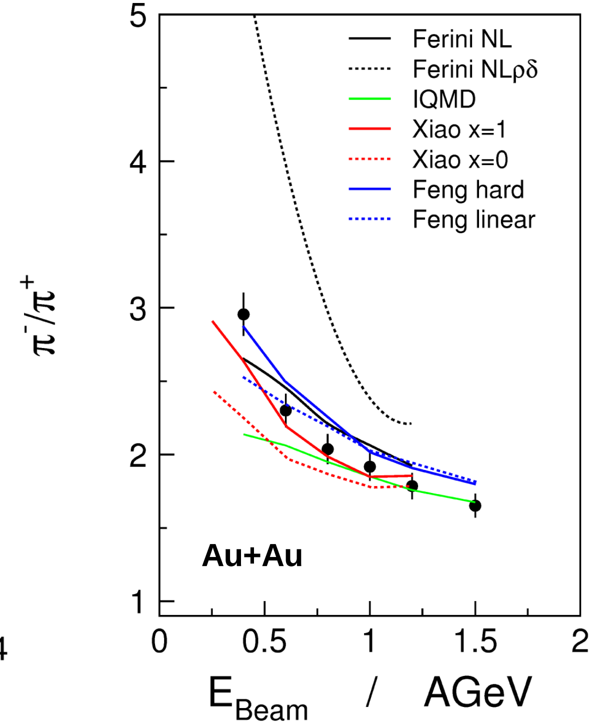
$$\frac{\pi^-}{\pi^+} = \frac{5N^2 + NZ}{5Z^2 + NZ} \approx \left(\frac{N}{Z}\right)^2$$

- pion recreation cycle

$$NN \rightarrow NN \qquad NN \rightarrow N\Delta$$
$$N\Delta \rightarrow NN \qquad \Delta \rightarrow N\pi$$
$$N\pi \rightarrow \Delta$$

Big Problem on Theoretical Prediction





Z. Xiao et al. PRL 102 (2009) 625
J. Xie et al, PLB 718 (2013)
J. Xu et al., nucl-the 1305.0099
G. Ferini et al. PRL 97 (2006) 202301
Feng et al, nucl-th 0907.2990
C. Hartnack, J. Aichelin (2013)
J. Hong, P. Danielewicz (2013)

Possible answer to this mess

M.Di Toro et al., J. Phys. G: Nucl. Part. Phys. **37 083101**

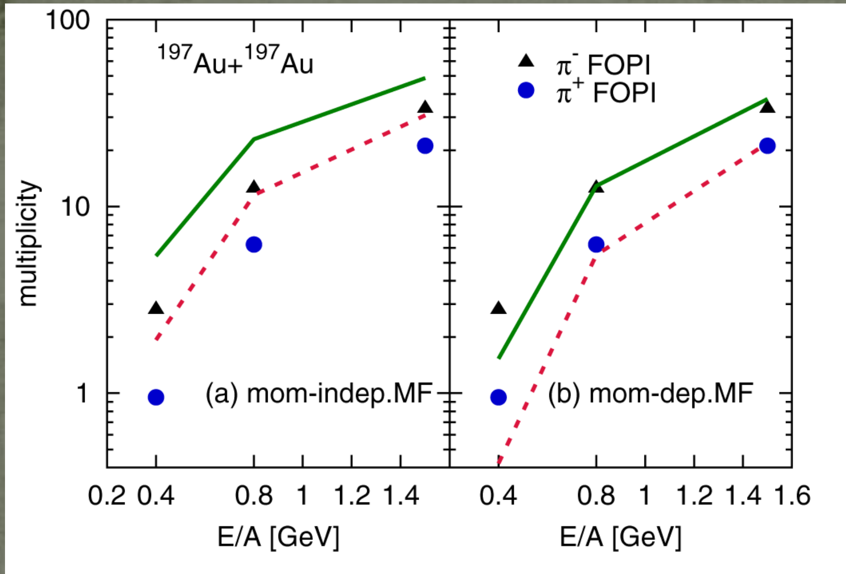
- symmetry energy $\rightarrow$ n/p ratio, number of nn, np, pp collisions

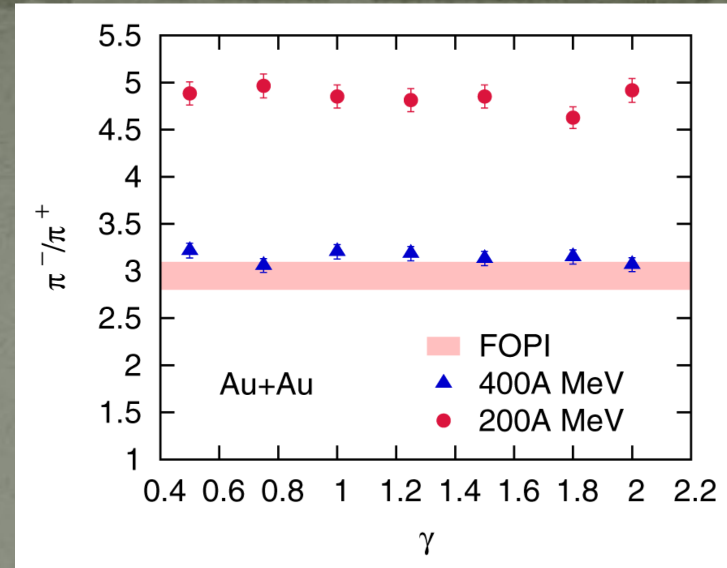
  asy stiff $\frac{n}{p}\downarrow \Rightarrow \frac{Y\left(\Delta^{0,-}\right)}{Y\left(\Delta^{+,++}\right)}\downarrow \Rightarrow \frac{\pi^-}{\pi^+}\downarrow$

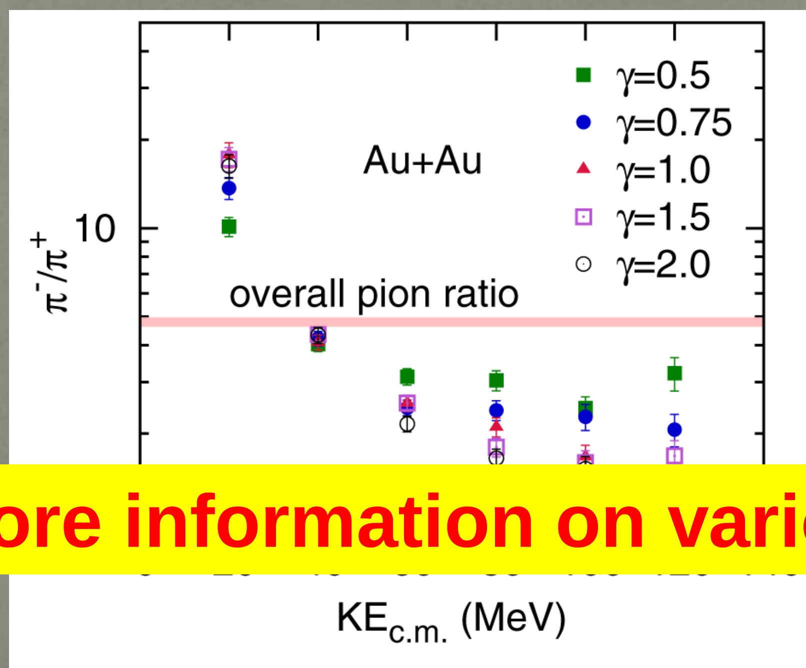
- medium $\rightarrow$ effective masses (N, π, Δ), cross sections

  $\rightarrow$ thresholds

  asy stiff $\Rightarrow \frac{\pi^-}{\pi^+}\uparrow$





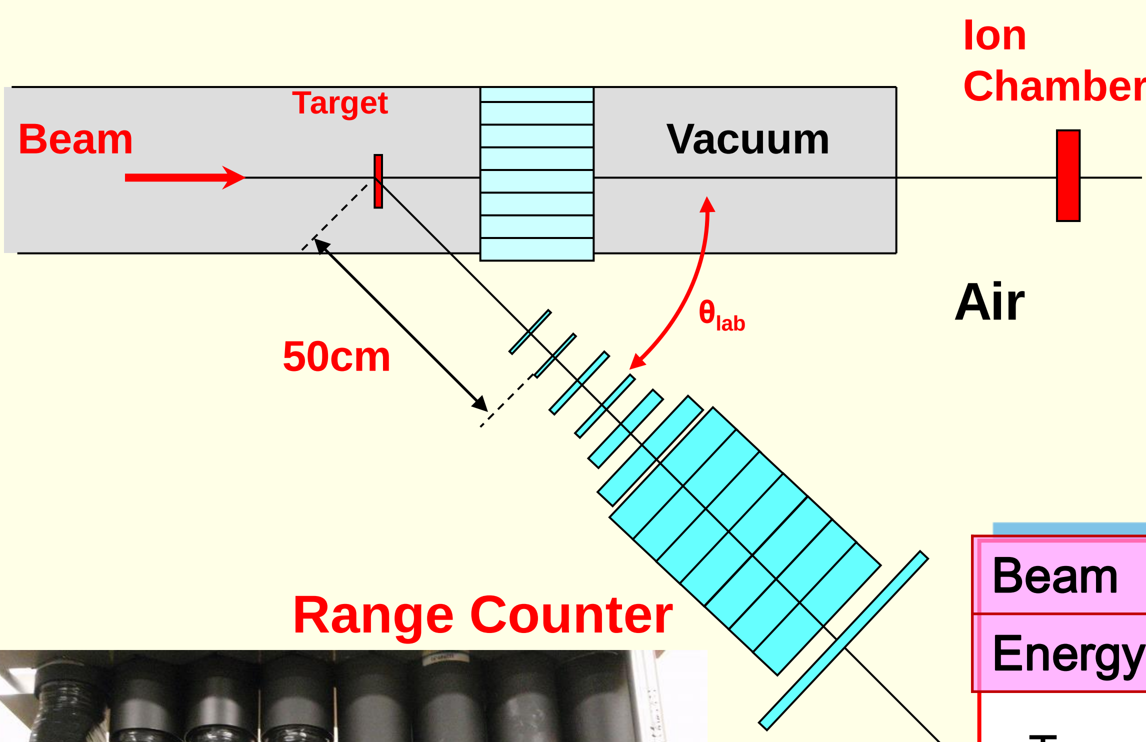


Hong and Danielewicz
Phys. Rev.C 90 (2014)
024605.

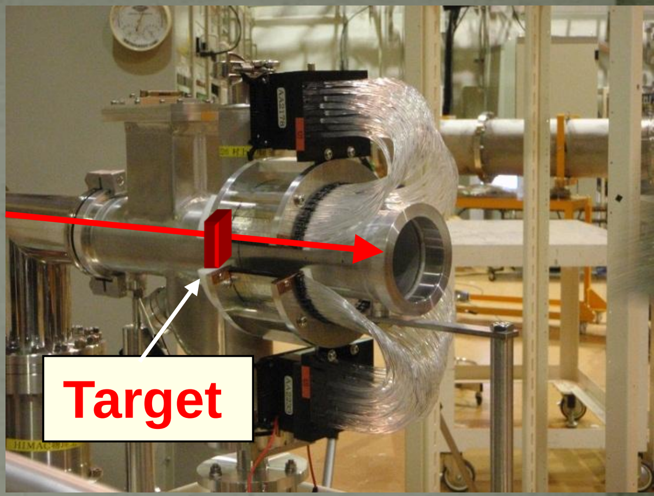
Need more information on various ejectiles

Pilot Experiments at HIMAC

arXiv:1409.3322



Multiplicity Array

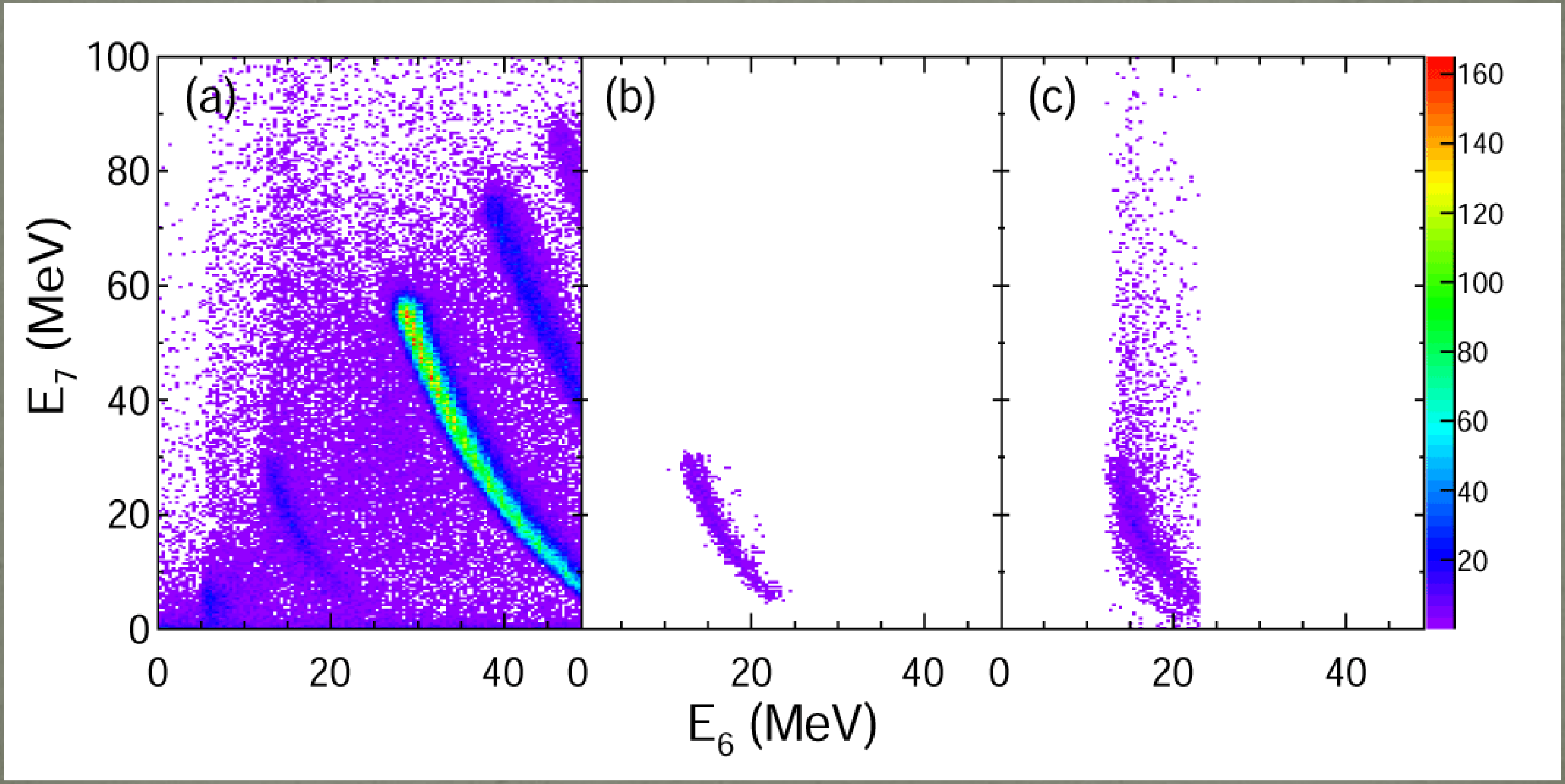


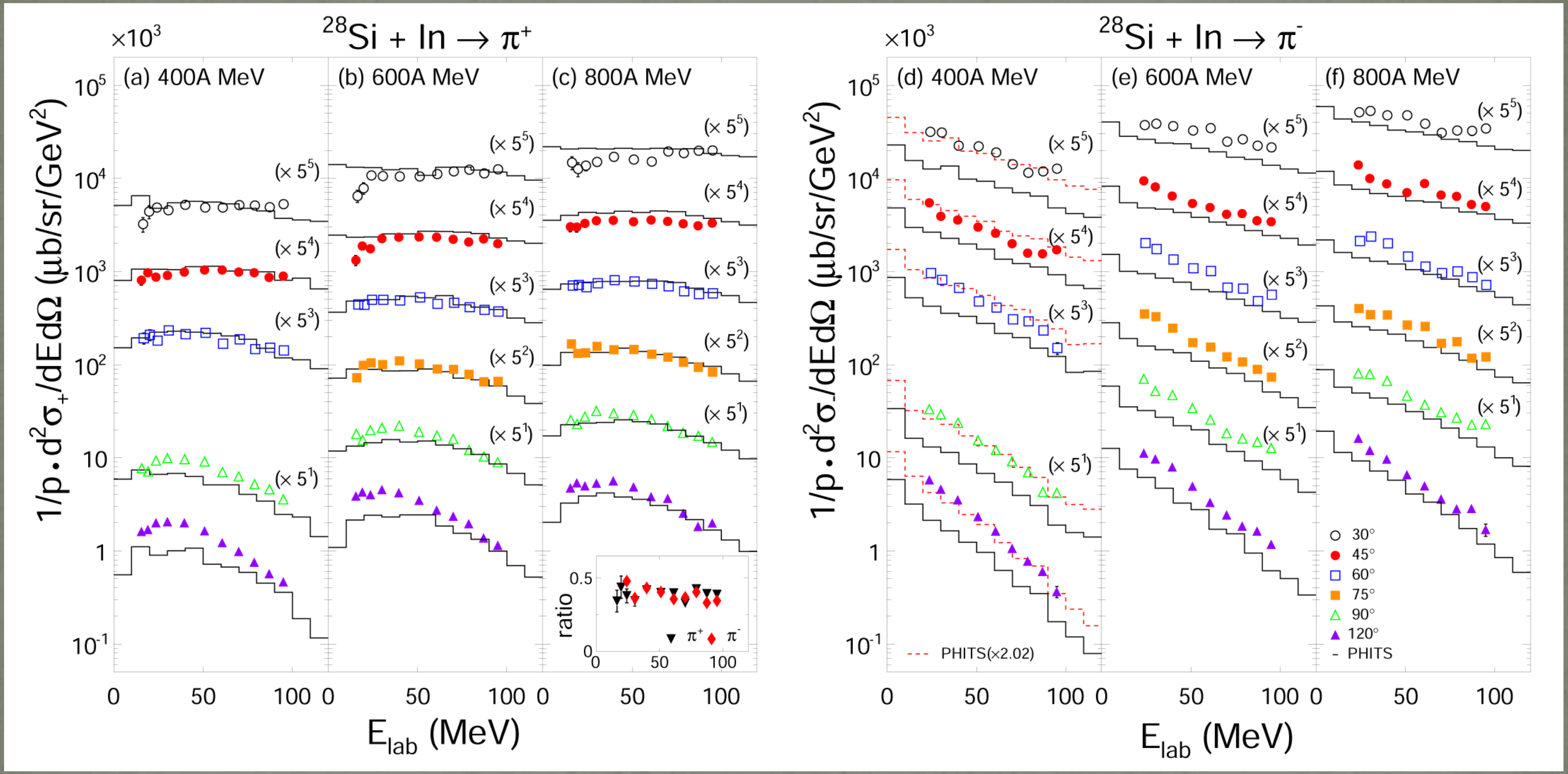
Beam	^{28}Si	^{132}Xe
Energy(AMeV)	400, 600, 800	400

- Target : In ~ 390 mg/cm^2
- Typical Intensity : ~ 10^7 ppp
- Range Counter : 14 layers (+2) of Sci.
- measured angle (θlab)
  : 30, 45, 60, 75, 90, 120 degree
- solid angle : 10 msr

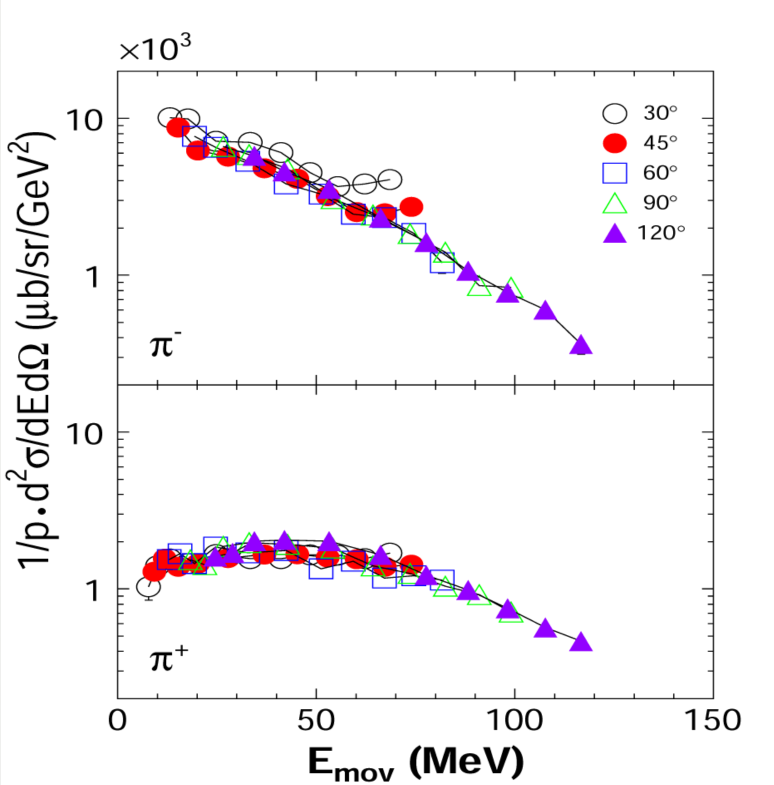
- ～400MeV/u
  Pion's are rare

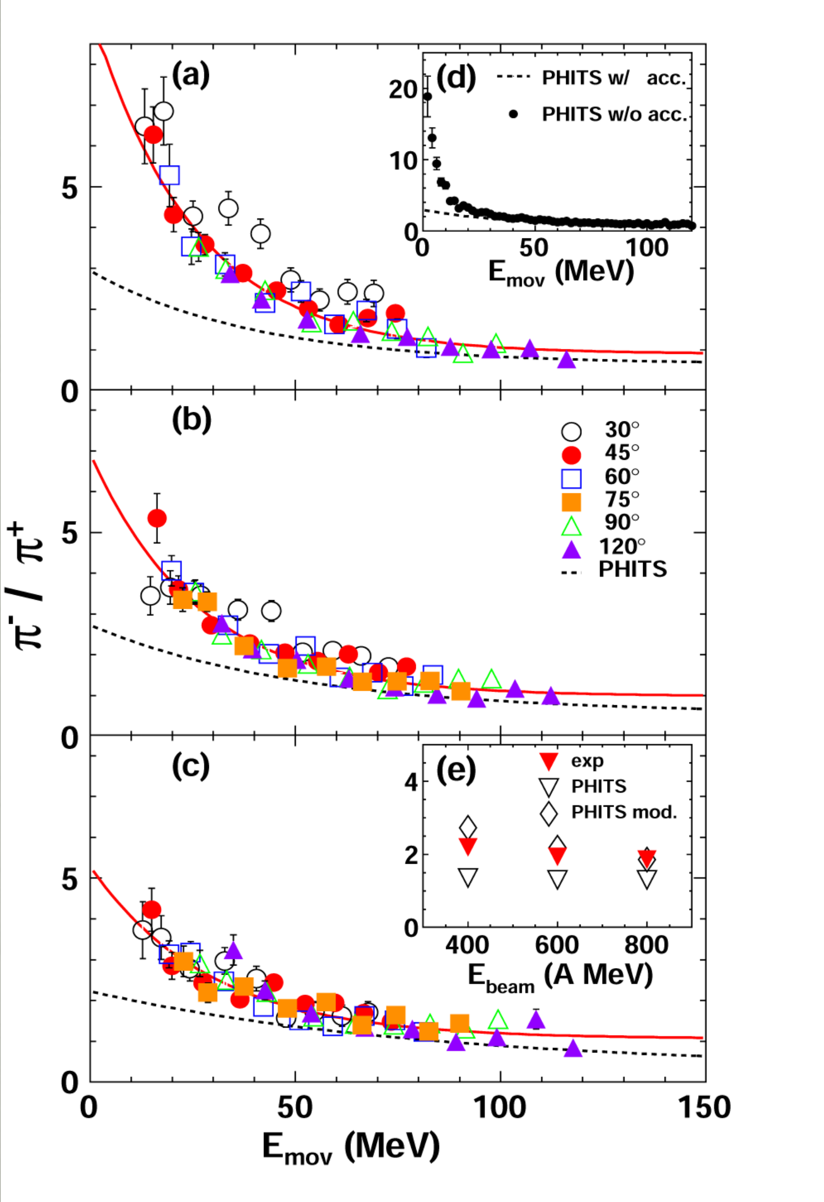
  less than 1/100 of protons





Normalization constant: 2.02, 1.68, and 1.43





Source velocities:
0.18c, 0.15c, and 0.19c for 400, 600, and 800 MeV/nucleon, respectively.

What we found

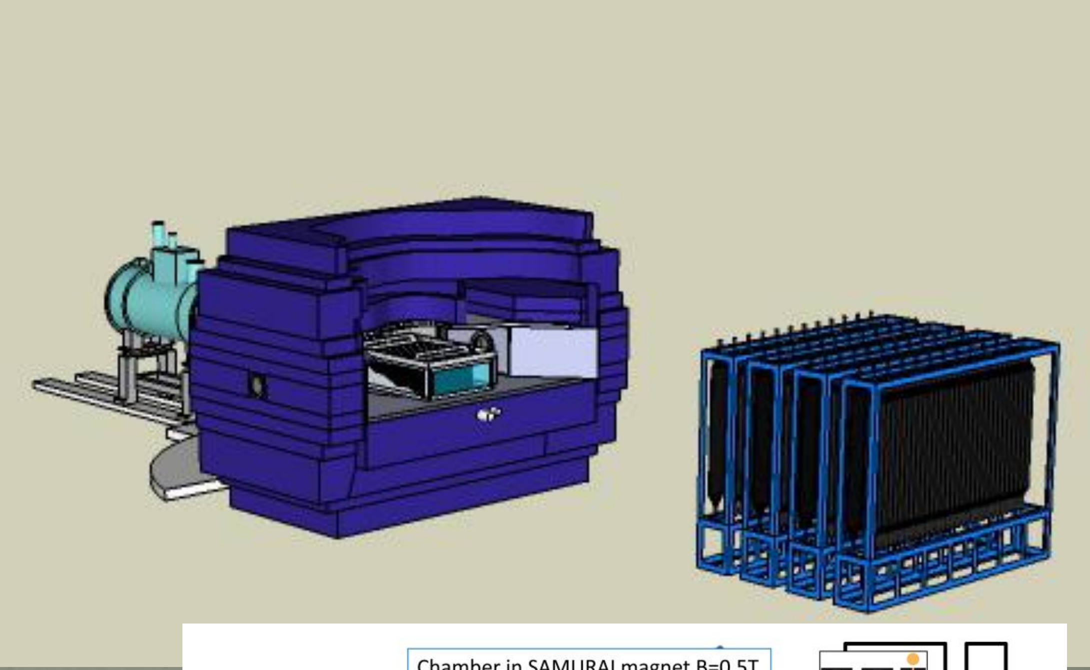
- Double differential cross sections of π^+ and π^- for the ^{28}Si + In reactions at 400, 600 and 800 MeV/nucleons.
- They are emitted isotropically from the single moving source, whose velocity is quite slower than the mid rapidity.
- The differential pion ratios represented in such moving frames overlap each other at each incident energy.
- PHITS fails to reproduce the observed absolute cross section, the angular dependence of the cross sections and the charged pion ratio.
- With the enhanced normalization factor for the π^- yield, the incident energy dependence of the total pion ratio may be reproduced within the experimental acceptance, indicating at least a part of the enhancement might be due to the symmetry energy.

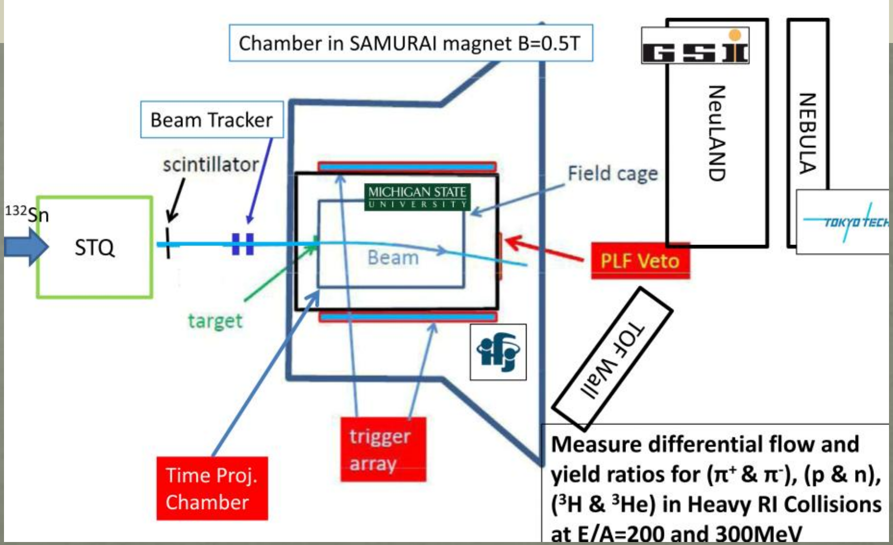
Our Main Experiment

Experimental Setup at RIBF

Equipment

- TPC - measures:
  - π^+ , π^- , p, d, t, ^{3}He, ^{4}He, IMF's
  - The SAMURAI chamber is at air
- Trigger scint. array:
  - selects central collisions and suppresses peripheral collisions.
- NEBULA:
  - provides neutron information





One day in February 2014

SYSTEM GET
Conceptuel Design

To be continued……..

Summary

- We will be ready to measure pion and light fragment flow from $^{132}Sn+^{124}Sn$, $^{124}Sn+^{112}Sn$, $^{112}Sn+^{124}Sn$, and $^{108}Sn+^{112}Sn$ collisions at 300 MeV/u using the TPCs at RIKEN RIBF to constraint the symmetry energy above saturation densities by spring of 2015.

Primary	Beam	Target	E_{beam}/A	δ_{sys}	Goal	Days
^{238}U	^{132}Sn	^{124}Sn	300	0.22	Probe maximum δ	3
	^{124}Sn	^{112}Sn	300	0.15	Probe intermed. δ, σ_{nn}, σ_{np}	3
^{124}Xe	^{108}Sn	^{112}Sn	300	0.09	Probe minimum δ	3
	^{108}Sn	^{124}Sn	300	0.15	Probe intermed. δ, σ_{nn}, σ_{np}	3