Current and future experiments at SAMURAI in RIBF RIKEN

Review the SpiRIT-TPC experiment in 2016

and

ongoing and future plans.

Mizuki Kurata-Nishimura (RIKEN)
for SpiRIT-TPC collaborations

Constents

- Understanding of nuclear EOS
- Review what we have learned using SpiRIT-TPC
  - π^-/π^+ ratio, hydrogen isotope production, isoscaling, and flow
- Keys for further investigation
- Update on the ongoing day-two experiment in 2024
  - higher energy 270 MeV/u -> 320 MeV/u
- Future experiments proposed in SAMURAI for symmetry energy

slope parameter L at ρ_0

B.-A. Li, *Universe* 7, 182 (2021).

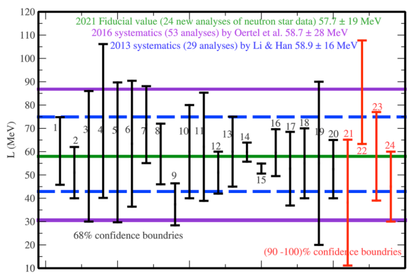


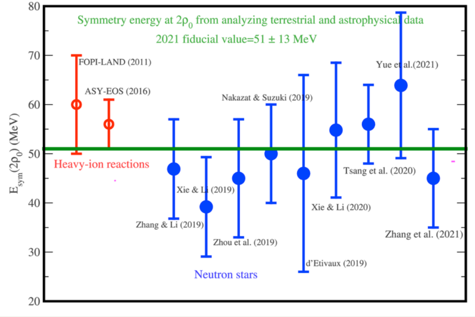
Figure 1. The slope parameter L of nuclear symmetry from the (1) 2013 survey of 29 analyses of terrestrial experiments and astrophysical observations (between the dashed blue lines) [61], (2) 2016 surveys of 53 analyses (between the violet lines) [9], and (3) 24 new analyses of neutron star observables since GW170817 (see the detailed list in the text). The green line is the average value of L from these 24 new analyses.

- Neutron star analysis
  - Before GW170817: $L = 57.7 \pm 19$ MeV
- PREX-II(2021) :L=106±37MeV
  - based on Relativistic Mean Field
- Bayesian analysis NS and PREX-II:
  - L = 69±16MeV
  - neutorn skin 208Pb with χEFT
- After GW170817: $L = 58.7 \pm 28.1$ MeV

How to reduce large error?

Symmetry $E_{sym}(2\rho_0)$

- B.-A. Li, *Universe* **7**, 182 (2021).



- It is crucial point to explain the large size of NS.
- Heavy-ion collision experiments is the only method to produce such high-density matter in lab.

- HI and NS results are consistent.
  - $E_{sym}(2\rho_0) \approx 51 \pm 13$MeV
- Error reduction is a main subject.

- In the χEFT
  - $E_{sym}(2\rho_0) \approx 45 \pm 3$MeV (Three-nucleon interaction up to 4^{th} order)
  - $E_{sym}(2\rho_0) \approx 46 \pm 4$MeV (quantum monte carlo up to next-to-next-to leading order)

Important to verify it in the HI experimental.

Review SpiRIT-TPC experiment in 2016

REVIEW SPIRIT-TPC EXPERIMENT

SpiRIT-TPC Experiment

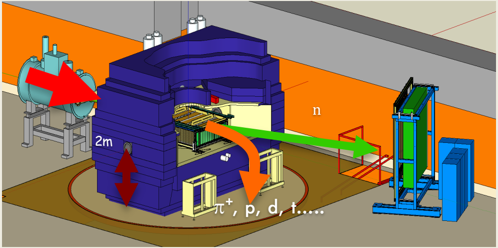
- The first SπRIT-TPC experiment at SAMURAI in RIKEN-RIBF were performed in 2016.

  $^{132}\mathrm{Sn} + {}^{124}\mathrm{Sn}(\delta \sim 0.22)$,

  $^{124,112}\mathrm{Sn} + {}^{112,124}\mathrm{Sn}(\delta \sim 0.15)$

  $^{108}\mathrm{Sn} + {}^{112}\mathrm{Sn}(\delta \sim 0.09)$

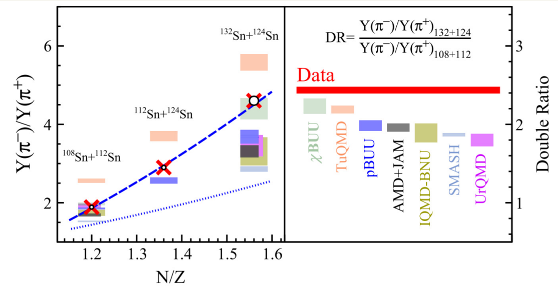
  – Incident energy: 270MeV/u



  – Not only pions but charged particles and neustron were measured.

π^-/π^+ ratio model comparison

G. Jhang, *Phys. Lett. B* **813**, 136016 (2021).



- It was proposed to measure π^-/π^+ production ratio.
- Compared with various Transport models with consistent calculation conditions.
- No consistent conclusion was derived.

Leading to improvements in the models.

π^-/π^+ ratio with [dcQMD]

J. Estee, *Phys. Rev. Lett.* **126**, 162701 (2021).

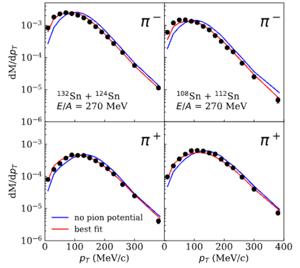
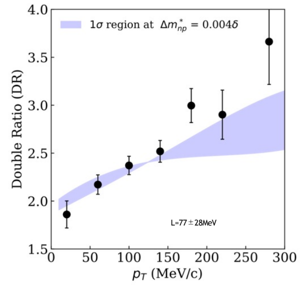


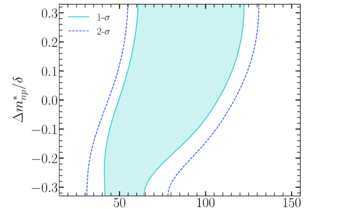
FIG. 1. Measured and calculated pion spectra. The red lines are the calculated pion spectra after adjusting the Δ potential to reproduce the pion multiplicities. The blue lines differ from the red lines in that the pion optical potential has been removed. The nucleon potentials in these simulations correspond to $L = 80$ MeV and $\Delta m^*_{np} = 0$.



- EOS was derived from the pion transverse momentum distribution using improved dcQMD.
- Reproducing the experimental data except for the small Pt region.

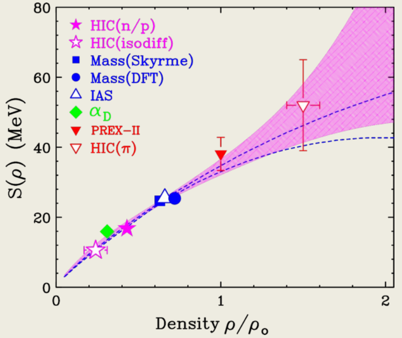
Estimated L = 77±28 MeV from the double ratio.

SE from π^-/π^+ ratio and structure



L=49~105MeV @ $\Delta m^*_{np}/\delta$=0

W.G. Lynch and M.B. Tsang PLB 830, 137098 (2022)



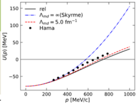
- L depends heavily on the mass shift, an analysis was performed in which the mass shift was changed in the Pt>200 MeV region, and a large range of L=49 to 105 was obtained.
- studies for 10 different observables and constraining the symmetry energy via a Bayesian analysis.
- We have continued analysis for light-charged particles

The large error remains.

How to reduce the error?

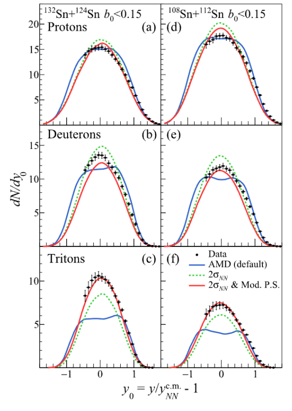
EOS from Hydrogen Rapidity Distribution [AMD]

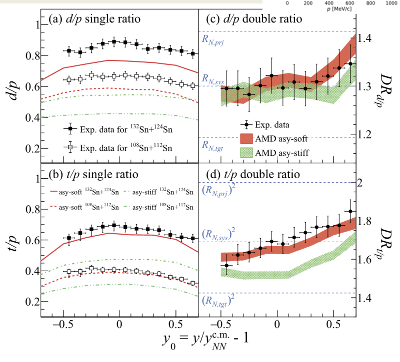
M. Kaneko *Phys. Lett. B* **822**, 136681 (2021).



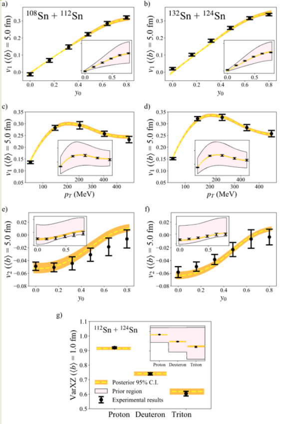
- AMD handle cluster correlations explicity
- Skrm-Sly4
  FOPI Xe+CsI reaction at 250 MeV
- Momentum dependent potential
- $2\sigma_{NN}$
- The phase space coefficient

DR(t/p) supports soft L preferably.





Flow and stopping with Bayesian analysis [ImQMD-Sky]



C. Y. Tsang, *Phys. Lett. B* **853**, 138661 (2024).

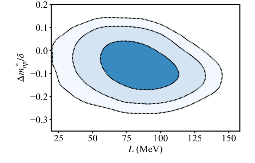
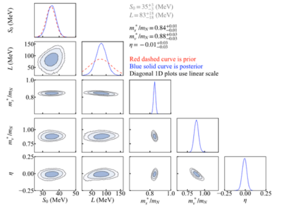


Fig. 4. Correlation between L and $\Delta m^*_{np}/\delta$. The three shades of blue, from the deepest to the lightest, correspond to 68%, 95% and 99% confidence intervals.



- $S_0 = 35^{+3}_{-3}$MeV
- L=83^{+18}_{-18}MeV
- $\Delta m^*_{np}/\delta = -0.07^{+0.07}_{-0.06}$

- It was not inconsistent with the pion results and the NS results.
- Relatively stiff EOS compared to the hydrogen isotope ratio.
- The result supports a negative mass shift.

Importance of the isospin-dependent potential.

Momentum Dependent Potential (AMD)

N. Ikeno, A. Ono, *Phys. Rev. C Nucl. Phys.* **108** (2023).

In AMD
- SLy4 : L=46MeV, L=108MeV
- Momentum dependent potential

$$U_\alpha(\mathbf{r},\mathbf{p}) = A_\alpha(\mathbf{r})\frac{[\mathbf{p}-\bar{\mathbf{p}}(\mathbf{r})]^2}{1+[\mathbf{p}-\bar{\mathbf{p}}(\mathbf{r})]^2/\Lambda_{\rm md}^2} + \tilde{C}_\alpha(\mathbf{r}),$$

  - Λ=5.0fm^{-1}, Λ=2.0fm^{-1}
- Skm*

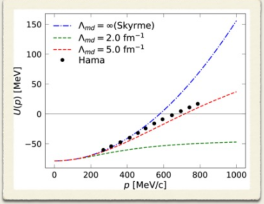
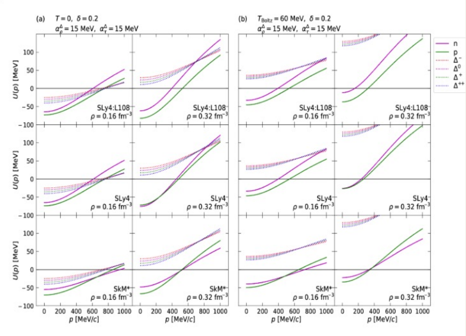
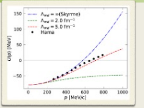


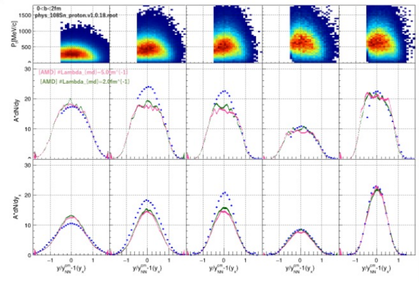
TABLE I. Nuclear matter properties for the effective interactions of Skyrme SLy4 [40], SLy4:L108 [18], and SkM* [42] (see text).

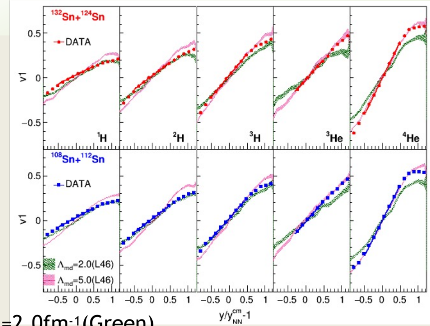
	SLy4	SLy4:L108	SkM*
ρ_0 (fm^{-3})	0.160	0.160	0.160
E/A (MeV)	−15.97	−15.97	−15.77
K (MeV)	230	230	217
m^*/m_N	0.70	0.70	0.79
S_0 (MeV)	32.0	32.0	30.0
L (MeV)	46	108	46
$\Delta m^*_{np}/(m_N\delta)$	−0.18	−0.18	+0.33
in n-rich	$m^*_n < m^*_p$	$m^*_n < m^*_p$	$m^*_n > m^*_p$



dN/dy and flow [AMD: Λ=5.0fm⁻¹ vs 2.0fm⁻¹]



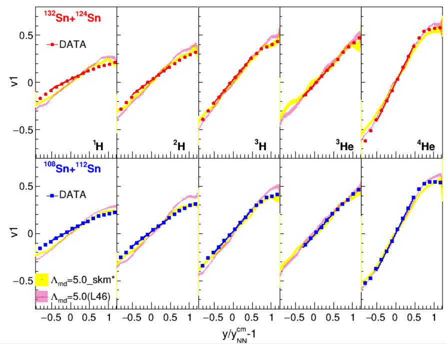


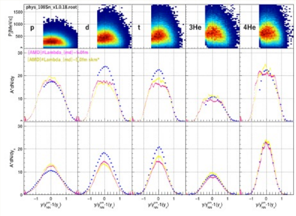


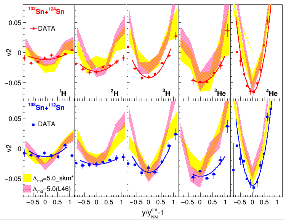
- Compare dN/dy and flow (v1) with Λ=5.0fm^{-1}(Magenta), Λ=2.0fm^{-1}(Green)
- Integrated multiplicity is underestimated for deuteron and triton, but the width is reasonably well reproduced.
- v1 is larger when weakened moderately (Λ=5.0fm^{-1}).
- It is reproduced for t, 3He, and 4He.
- Strongly weakened dependence(Λ=2.0fm^{-1}) is more accurate for proton and deuteron..

Momentum-dependent potential effect on v1

Individual Flow [AMD: Λ=5.0fm^{-1} vs skm*]



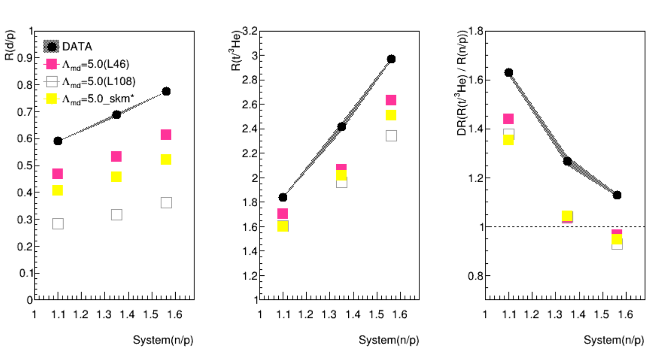




- Compare Λ=5.0fm^{-1} and skm* (M*n > M*p at high density)
- v1 for p, d, and t is stronger for skm*(Yellow) and closer to the data
- A little enhancement of triton multiplicity is seen.

v1 reflects mass shift but stopping doesn't.

n/p dependence of production ratio R(d/p) and R(t/3He) [AMD:L=46, 108MeV, skm*]



- AMD reproduces the trend of data
- But underestimates the data.
- L dependence is seen in R(d/p)
- The difference is reduced in DR.

Reproducing light-charged particle multiplicity would help to constrain L.

Iso scaling broken at Pt>280MeV/c

J. W. Lee, *Eur. Phys. J. A* **58** (2022).

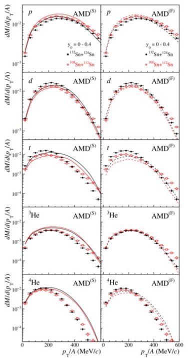


Fig. 3 Differential multiplicity as a function of p_T/A for $p, d, t, {}^3$He, and ^{4}He from top to bottom panels. Data points are compared to the AMD$^{(S)}$ (solid lines) on the left panels and AMD$^{(F)}$ (dotted lines) on the right panels for ^{132}Sn + ^{124}Sn (black) and ^{108}Sn + ^{112}Sn (red) reactions

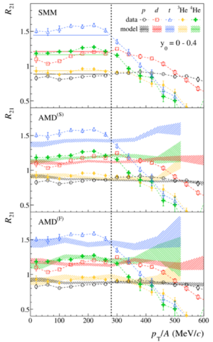


Fig. 6 Isotope yield ratios compared with the models: SMM (top), AMD$^{(S)}$ (middle) and AMD$^{(F)}$ (bottom). The data are the same in all panels. The break line at p_T/A = 280 MeV/*c* show different trend of isoscaling for particles with low (left side of the line) and high (right side of the line) p_T/A

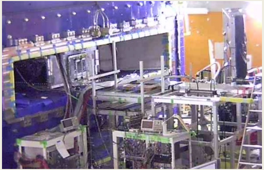
- Isoscaling is broken at Pt > 280MeV.
- It is not explained by AMD.

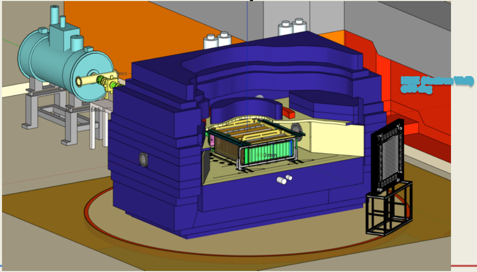
Effective mass shift may explain?

ONGOING AND FUTURE PLAN

Day-two SpiRIT experiment

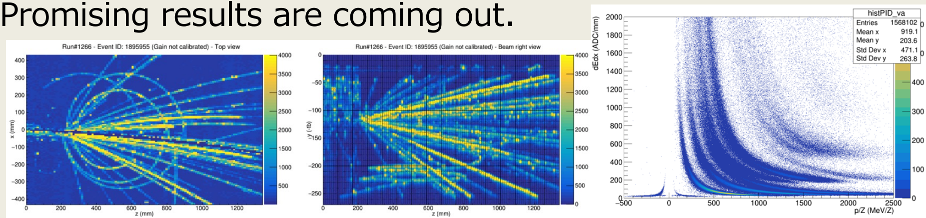
- $^{124}Xe + ^{112}Sn$ (320MeV/u)
  - We performed an experiment from 27 June to 1 July.
  - HIME (neutron wall from GSI) is installed at 30 deg.





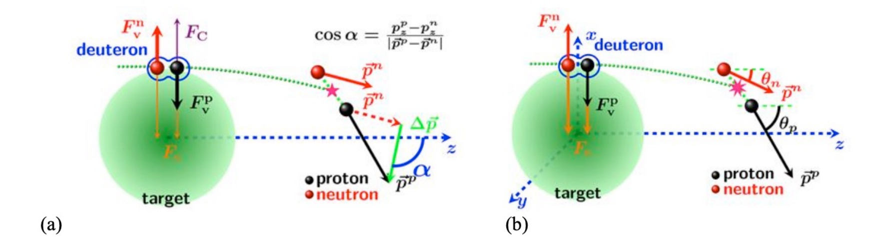
SpiRIT experiment in 2024

- PID is clear and many pions were detected.
- Promising results are coming out.



- 136Xe + 124Sn (345MeV/u)
  - It is scheduled from 24 Oct. ~28 Oct. in this Autumn.

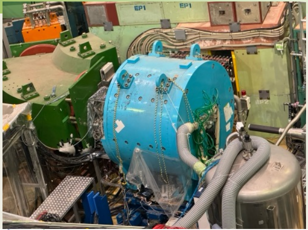
Isovector reorientation by Z. Xiao

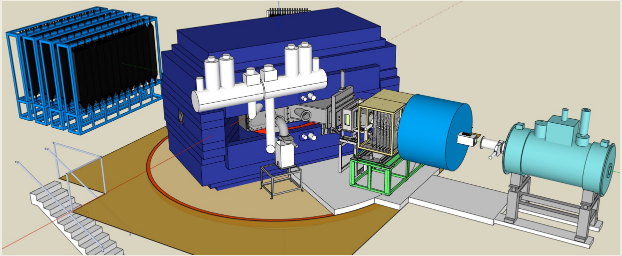


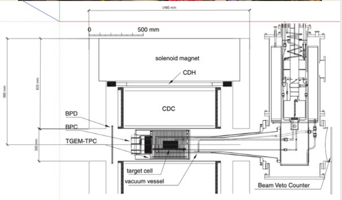
Measurement of isovector reorientation effect using polarized deutron induced scattering.
A neutron and proton relative momentum w.r.t. the beam would differ depending on the deuteron polarization axis.

It is a very challenging experiment, but it would provide a direct measurement of the isovector potential.

Draemon Solenoid Spectrometer







High-intensity experiments are possible.

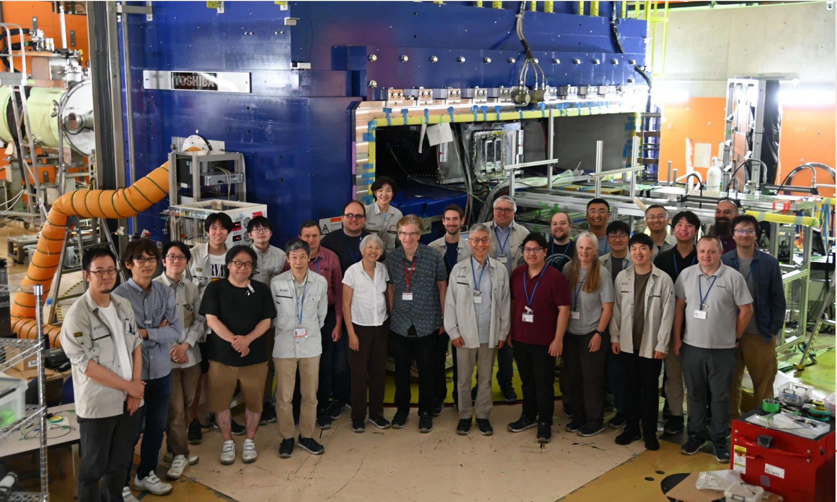
Summary

- We have reviewed SpiRIT-TPC experimental results related to the symmetry energy study.
- Pion and light-charged particles were analyzed and compared with dcQMD, ImQMD-skm and AMD with several parameter settings to constrain symmetry energy.
- Pion ratio shows relatively stiff EOS and hydrogen production is preferable to soft EOS.
- To reduce the error, multiple observables should be explained at the same time.

- The requirement for improving models.
  - Cluster formation to explain multiplicity of light-charged particles.
  - Momentum-dependent and isospin dependent potential
  - Comparison among models preciously.

Thank you for your attention

Pre-run participants Photo (not everyone is in the picture, sorry)



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S_0 (MeV)	32.0	32.0	30.0
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$\Delta m^*_{np}/(m_N\delta)$	−0.18	−0.18	+0.33
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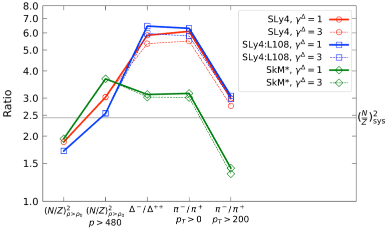
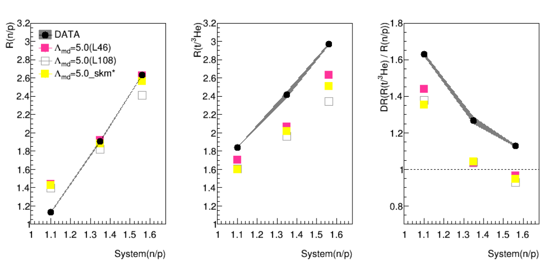
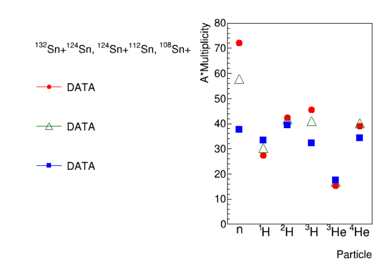


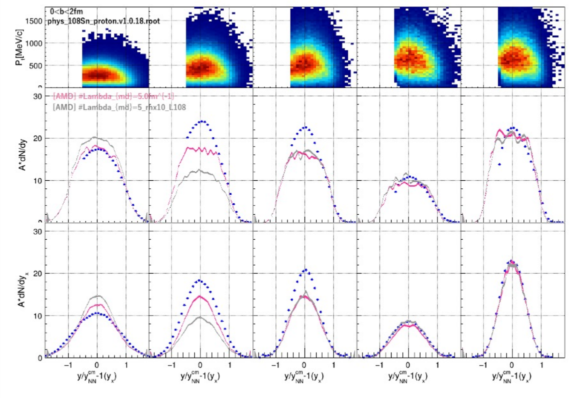
FIG. 9. From left to right, the representative nucleon ratios of $(N/Z)^2_{\rho>\rho_0}$ and $(N/Z)^2_{\rho>\rho_0,\mathrm{HM}}$ in the high density region without and with imposing the high momentum condition, respectively, the Δ^-/Δ^{++} production ratio, the π^-/π^+ ratio from all pions ($p_T > 0$), and the π^-/π^+ ratio of high-momentum pions ($p_T > 200$ MeV/c). The results are shown for the three cases of nucleon interaction based on SLy4, SLy4:L108, and SkM*. As for the isovector part of the Δ potential, two cases are shown for $\gamma^\Delta = 1$ (solid line) and $\gamma^\Delta = 3$ (thin dashed line). The horizontal line represents the $(N/Z)^2_{\rm sys}$ ratio of the total system.



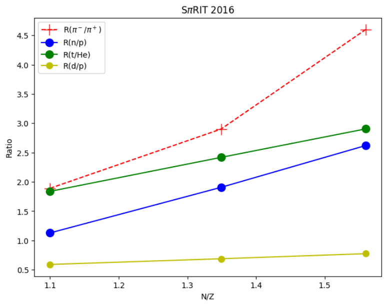
DATA
Λmd=5.0(L46)
Λmd=5.0(L108)
Λmd=5.0_skm*
R(n/p)
System(n/p)
R(t/3He)
System(n/p)
DR(R(t/3He) / R(n/p))
System(n/p)



132Sn+124Sn, 124Sn+112Sn, 108Sn+
DATA
DATA
DATA
A*Multiplicity
n
1H
2H
3H
3He
4He
Particle



0<b<2fm
phys_108Sn_proton.v1.0.18.root
P_t[MeV/c]
[AMD] #Lambda_{md}=5.0fm^{-1}
[AMD] #Lambda_{md}=5_mx10_L108
A*dN/dy
A*dN/dy_x
y/y_NN^cm-1(y_x)


SπRIT 2016
R(π⁻/π⁺)
R(n/p)
R(t/He)
R(d/p)
Ratio
N/Z
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
1.1
1.2
1.3
1.4
1.5