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Probing neutron-skin thickness with free spectator neutrons in ultracentral high-energy isobaric collisions

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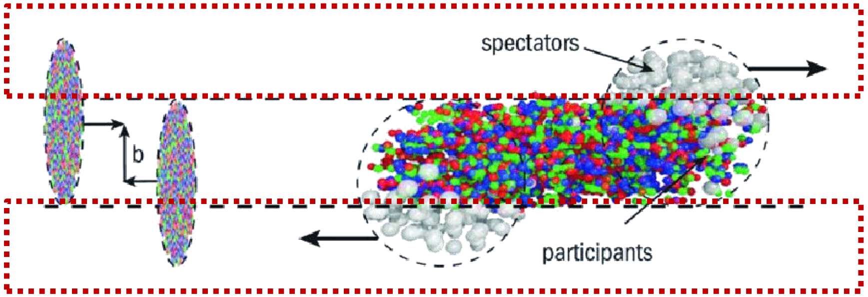


Motivation

Skyrme-Hartree-Fock (SHF) model.
L. W. Chen et al., PRC 82, 024321 (2010)

N_n: number of free spectator neutrons
N_p: number of free spectator protons
L: slope parameter of symmetry energy
$\Delta r_{\mathrm{np}} = \langle r_n^2 \rangle^{1/2} - \langle r_p^2 \rangle^{1/2}$: neutron-skin thickness

$$\frac{N_n(^{96}\mathrm{Zr})}{N_n(^{96}\mathrm{Ru})} \sim \Delta r_{np} \sim L$$

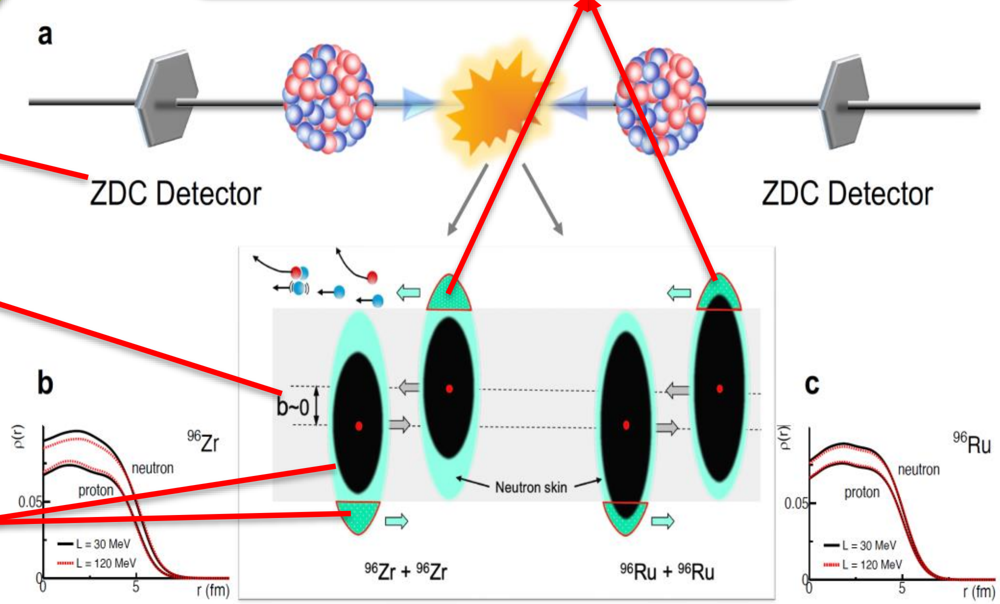
A **significant enhancement** of N_n in ^{96}Zr + ^{96}Zr collision relative to ^{96}Ru + ^{96}Ru collision.
STAR, PRC 105, 014901 (2022)

$\Delta r_{\mathrm{np}}(^{96}\mathrm{Zr}) > \Delta r_{\mathrm{np}}(^{96}\mathrm{Ru})$

N_n, easily measurable by the ZDC, is sensitive to Δr_{np}.

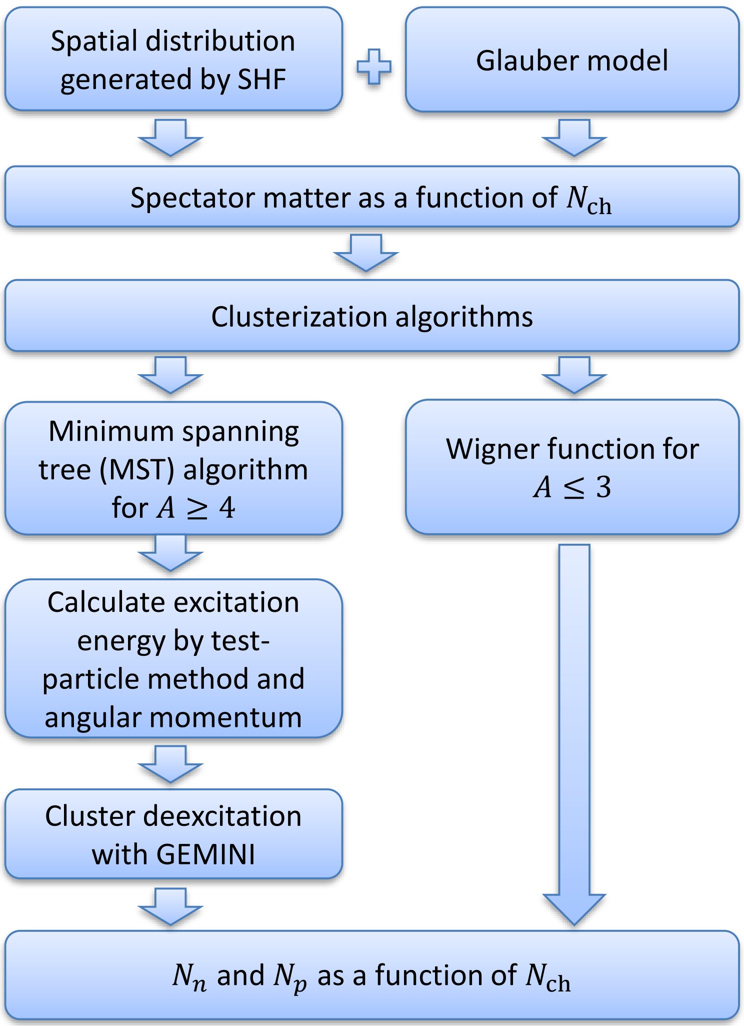
In UCC region, most spectator nucleons originate from the surface.

The spectator matter ($\nu \sim 1$) disconnected from the participant matter at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV.



Model setup: framework and Glauber model

Framework



Two-component Glauber model

Number of source

$$N_s = (1-x)\frac{N_{\text{part}}}{2} + xN_{\text{coll}}$$

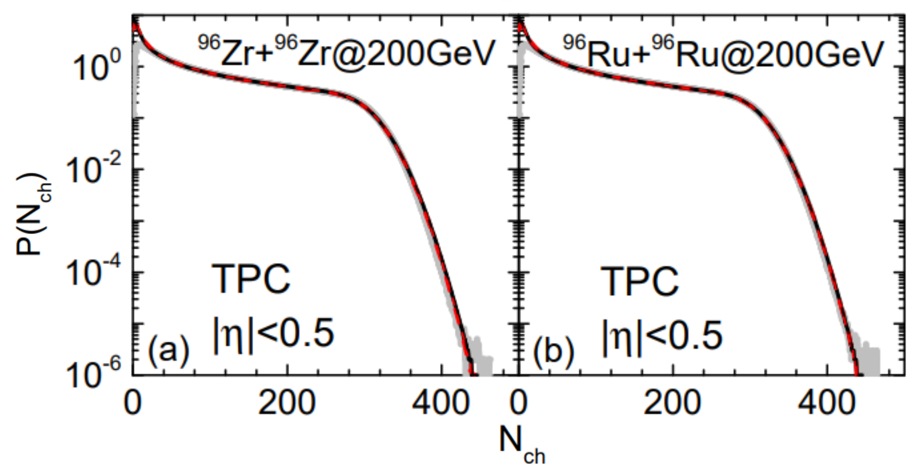
Negative binomial distribution

$$p_{\text{nbd}}(n;m,p) = \frac{(n+m-1)!}{(m-1)!n!}p^n(1-p)^m$$

NN inelastic cross section

$$\sigma_{NN} = 42 \text{ mb at } \sqrt{s_{\text{NN}}} = 200 \text{ GeV}$$

N_{ch} fitting



Observables as a function of charged-particle multiplicity N_{ch}

Model setup: initial density distribution

Skyrme-Hartree-Fock (SHF) model:

$$
\begin{aligned}
v(\vec{r}_1,\vec{r}_2) &= t_0(1+x_0P_\sigma)\delta(\vec{r}) \\
&+ \frac{1}{2}t_1(1+x_1P_\sigma)[\vec{k}'^2\delta(\vec{r})+\delta(\vec{r})\vec{k}^2] \\
&+ t_2(1+x_2P_\sigma)\vec{k}'\cdot\delta(\vec{r})\vec{k} \\
&+ \frac{1}{6}t_3(1+x_3P_\sigma)\rho^\alpha(\vec{R})\delta(\vec{r}) \\
&+ iW_0(\vec{\sigma}_1+\vec{\sigma}_2)[\vec{k}'\times\delta(\vec{r})\vec{k}].
\end{aligned}
$$

Skyrme parameters

Quantity	MSL0
t_0 (MeV fm^5)	−2118.06
t_1 (MeV fm^5)	395.196
t_2 (MeV fm^5)	−63.953 1
t_3 (MeV fm$^{3+3\sigma}$)	128 57.7
x_0	−0.070 949 6
x_1	−0.332 282
x_2	1.358 30
x_3	−0.228 181
σ	0.235 879
W_0 (MeV fm^5)	133.3

parameter space transform

macroscopic quantities

Quantity	MSL0
ρ_0 (fm^{-3})	0.16
E_0 (MeV)	−16.0
K_0 (MeV)	230.0
$m^*_{s,0}/m$	0.80
$m^*_{v,0}/m$	0.70
$E_{\rm sym}(\rho_0)$ (MeV)	30.0
L (MeV)	60.0
G_S (MeV fm^5)	132.0
G_V (MeV fm^5)	5.0
$G_0'(\rho_0)$	0.42

L. W. Chen et al., PRC 82, 024321 (2010)

Symmetry energy

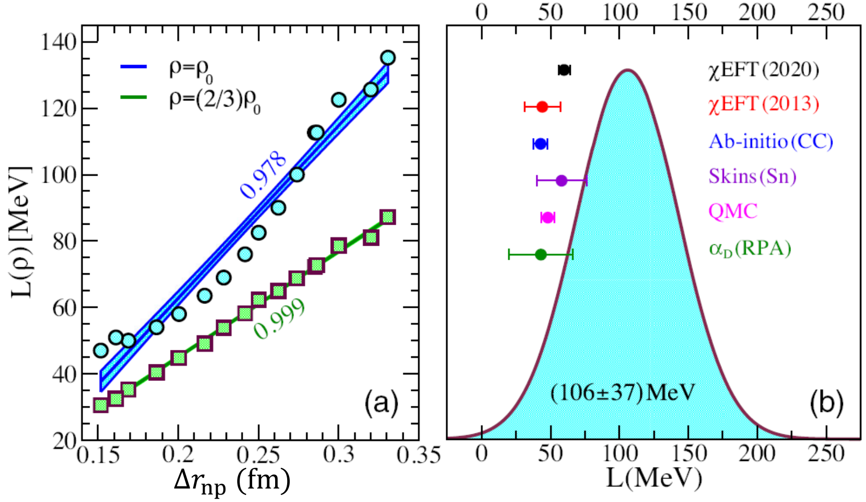
Slope parameter $L = 3\rho_0\left[\frac{\partial E_{sym}(\rho)}{\partial\rho}\right]_{\rho=\rho_0}$

Saturation density

Neutron skin $\Delta r_{\rm np} = \langle r_n^2\rangle^{1/2} - \langle r_p^2\rangle^{1/2}$

Δr_{np} increases monotonically with the increase of L, while other macroscopic quantities have only small effect.

PREXII data of ^{208}Pb favors a large $L(\rho_0) = (106 \pm 37)$ MeV



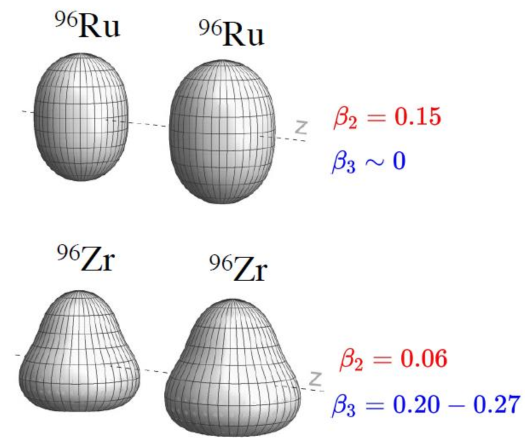
$\Delta r_{\rm np}^{\rm Pb} = (0.284 \pm 0.071)$ fm

B. T. Reed et al., PRL 126, 172503 (2021)

Deformed nucleus

Skyrme-Hartree–Fock–Bogoliubov (HFB) method using the cylindrical transformed deformed harmonic oscillator basis.

M. V. Stoitsov et al., CPC (2013)



multipole moments

$$\beta_{\lambda,\tau} = \frac{4\pi Q_{\lambda,\tau}}{3N_\tau R^\lambda}$$

C. Zhang and J. Jia, PRL 128, 022301 (2022)
J. Jia, PRC 105, 014905 (2022)

Model setup: clusterization and deexcitation

A. Heavy clusters with $A\geq 4$ handled by the minimum spanning tree (MST) algorithm

coalescence parameter (fitted by the Au + Au data)

$$\begin{cases}\Delta r_{\max} = 3\ \text{fm (empirical nucleon interaction range)}\\ \Delta p_{\max} = 300\ \text{MeV/c (empirical Fermi momentum at } \rho_0)\end{cases}$$

Formed clusters

Excitation energy

$$E = \frac{1}{N_{TP}}\sum_i\left(\sqrt{m^2+p_i^2}-m\right)$$

Simplified SHF EDF (test-particle method for parallel events with similar collision configuration)

$$+\int d^3r\left[\frac{a}{2}\left(\frac{\rho}{\rho_0}\right)^2+\frac{b}{\sigma+1}\left(\frac{\rho}{\rho_0}\right)^{\sigma+1}\right]$$

$$+\int d^3r E_{\text{sym}}^{\text{pot}}\left(\frac{\rho}{\rho_0}\right)^{\gamma}\frac{(\rho_n-\rho_p)^2}{\rho}$$

$$+\int d^3r\left\{\frac{G_S}{2}(\nabla\rho)^2-\frac{G_V}{2}[\nabla(\rho_n-\rho_p)]^2\right\}$$

$$+\frac{e^2}{2}\int d^3rd^3r'\frac{\rho_p(\vec{r})\rho_p(\vec{r}\,')}{|\vec{r}-\vec{r}\,'|}-\frac{3e^2}{4}\int d^3r\left[\frac{3\rho_p}{\pi}\right]^{4/3}-E_{GS}$$

Angular momentum

$$\vec{L}=\sum_i\vec{r}_i\times\vec{p}_i$$

A and B are two sources of free spectator nucleons

Heavy cluster deexcitation with GEMINI model with the input parameters of mass number A, proton number Z, excitation energy and angular momentum.

The free spectator nucleons from the deexcitation

B. Other spectator nucleons coalesce into light clusters with $A \leq 3$ according Wigner functions

$$f_d = 8g_d\exp\left(-\frac{\rho^2}{\sigma_d^2}-p_\rho^2\sigma_d^2\right),$$

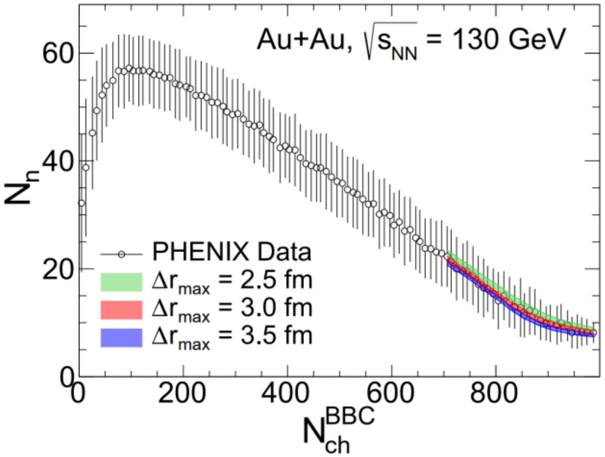
$$f_{t/^3He} = 8^2g_{t/^3\text{He}}\exp\left[-\left(\frac{\rho^2+\lambda^2}{\sigma_{t/^3\text{He}}^2}\right)-(p_\rho^2+p_\lambda^2)\sigma_{t/^3\text{He}}^2\right],$$

The residue nucleons that have not coalesced into light clusters

Total free spectator neutrons N_n and protons N_p

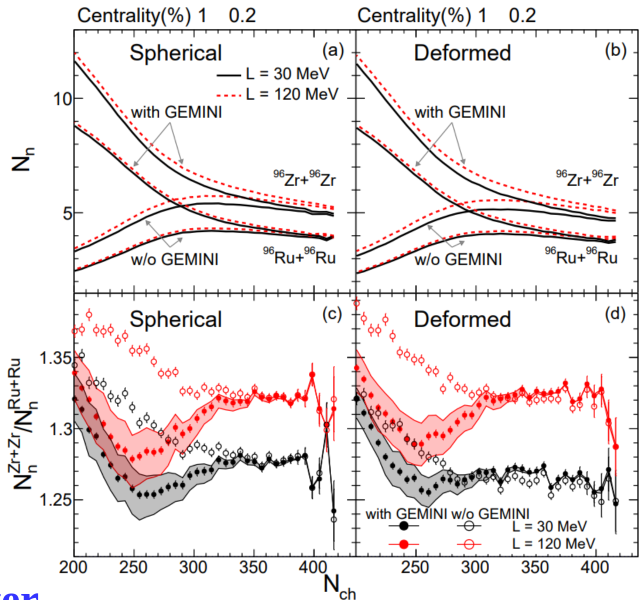
Results and discussions

1. Validation with experimental data



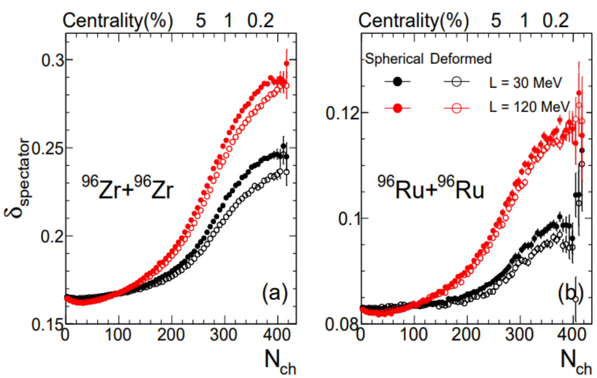
The value of $\Delta r_{max} = 3$ fm achieves the best description

3. Predictions for the isobar systems



- Large L leads to a large N_n
- Taking ratios of N_n large cancels the theoretical and experimental uncertainties
- Large L leads to a large ratio of N_n
- The ratio in the UCC region is insensitive to the excitation energy ± 1 MeV (the shaded bands)
- Deformation leads a subleading effect

2. Bulk properties of spectator matter



- More neutron-rich spectator matter in more neutron-rich system
- More neutron-rich spectator matter in more central collisions
- More neutron-rich spectator matter with a larger L or Δr_{np}

Summary and outlook

The yield ratio of free spectator neutrons $\frac{N_n(^{96}\mathrm{Zr})}{N_n(^{96}\mathrm{Ru})}$ is a robust probe of Δr_{np} and L

- Spectator neutrons: not suffer from the complex dynamics for observables at midrapidities and easily measurable
- SHF: self-consistent spherical and deformed calculations
- Ultracentral HIC: free from deexcitations
- Ratio of neutron-rich to neutron-poor system: reduce uncertainties
- Extension: any two colliding systems with similar mass number but different isospin asymmetries
- Moreover: N_n/N_p ratio is an excellent probe of Δr_{np} and L for a single colliding system and the double ratio of N_n/N_p in isobaric collisions, which can cancel out the detecting efficiency of protons, is also an excellent probe

Thank you!