Constraining the in-medium cross section in transport model with Ca+Ni collisions at 140 AMeV

Chi-Kin Tam (Western Michigan University)

10 am, October 29, 2024 (EST)

Dense Nuclear Matter Equation of State from Theory and Experiments
Session : Transport model comparisons

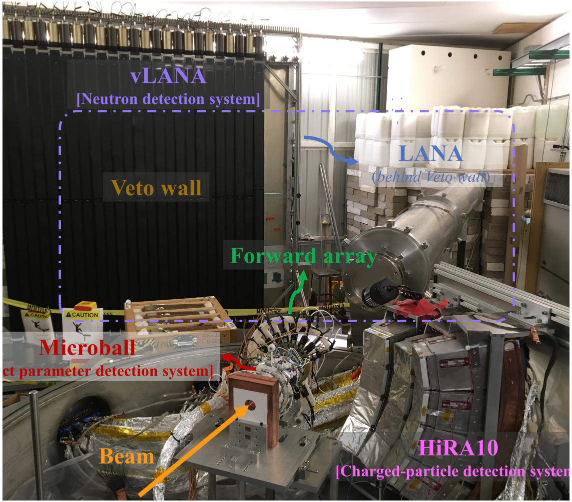
content

1. experiment
   - setup
   - transverse momentum spectra
2. model
   - screened in-medium cross section
   - event selection
   - comparison with data
3. isoscaling result
4. conclusion

experiment

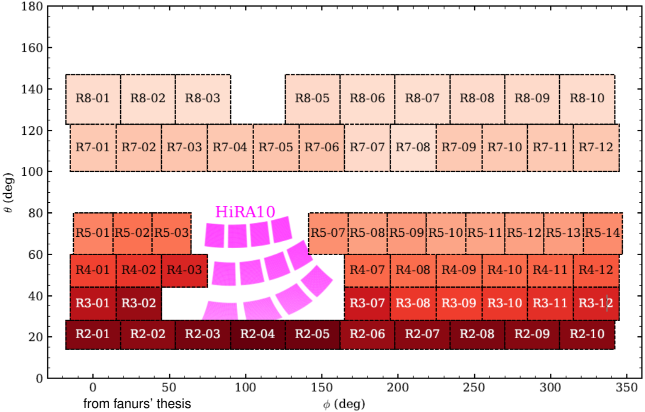
beam	target	E/A [MeV]	δ_{asym}
$^{40}\mathrm{Ca}$	$^{58}\mathrm{Ni}$	56, 140	0.020
$^{40}\mathrm{Ca}$	$^{64}\mathrm{Ni}$	56, 140	0.143

- $\beta \approx 0.22$
- 2019, at NSCL
- $\sim 4\pi$ μball for multiplicity
- Hira10, charged particle spectra
- focus on charged particles

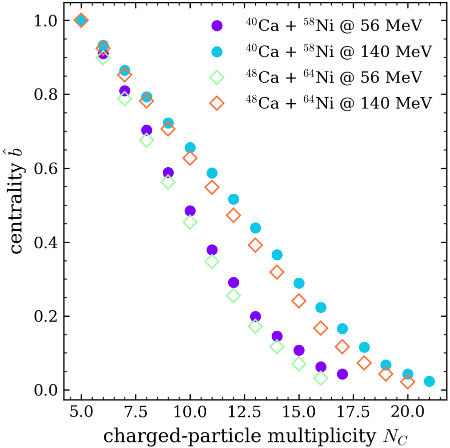


experimental coverage

- μball : $\sim 4\pi$ of CsI(Tl) crystal surrounding the target
- measure charged-particle multiplicity to estimate impact parameter
- 40 % most central events

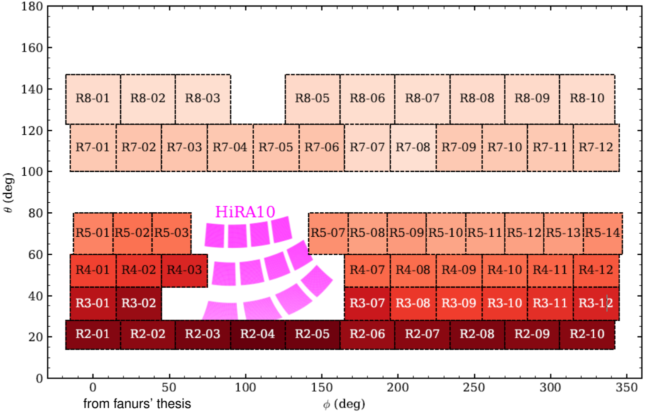


from fanurs' thesis



experimental coverage

- Hira10 : charged particle spectra ($\theta_{\text{lab}} \in (30°, 75°)$)
- PID of $p, d, t, {}^3\text{He}, \alpha$



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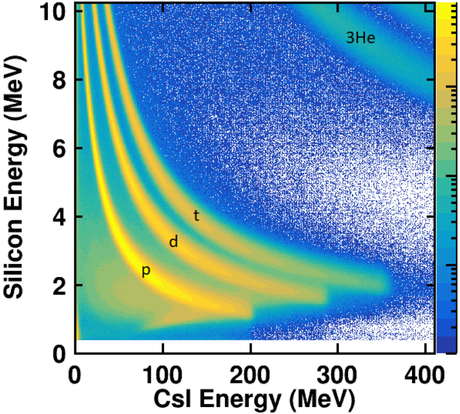
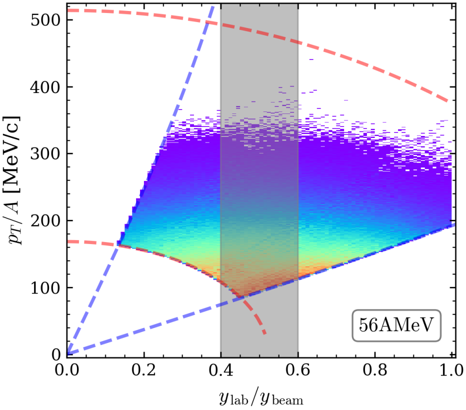


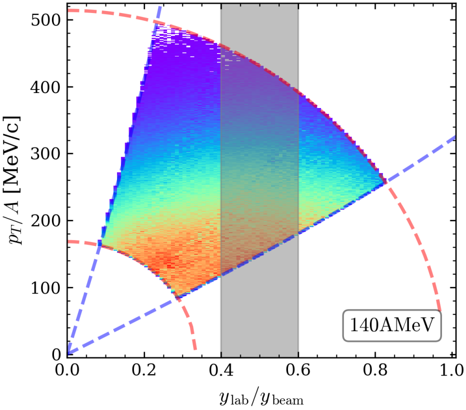
10.1016/j.nima.2021.165798

transverse momentum spectra

- deuteron in $^{40}\mathrm{Ca} + ^{58}\mathrm{Ni}$ at 140 AMeV
- geometric and reaction efficiency corrected
- mid-rapidity $\hat{y} \in (0.4, 0.6)$

- $\theta_{\mathrm{lab}} \in (30°, 75°)$
- $E_{\mathrm{lab}} \in (15.0, 131.5)$ MeV/A



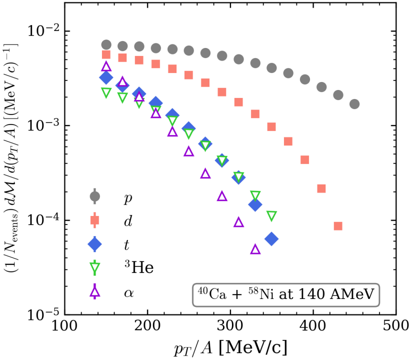


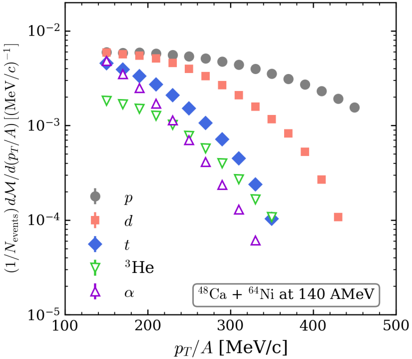
transverse momentum spectra

- $\theta_{\mathrm{lab}} \in (30^\circ, 75^\circ)$
- $\hat{y} \in (0.4, 0.6)$

Reaction	p	d	t	^{3}He	α
^{40}Ca + ^{58}Ni at 140 AMeV	1.58	0.71	0.24	0.20	0.22
^{48}Ca + ^{64}Ni at 140 AMeV	1.37	0.80	0.37	0.18	0.26

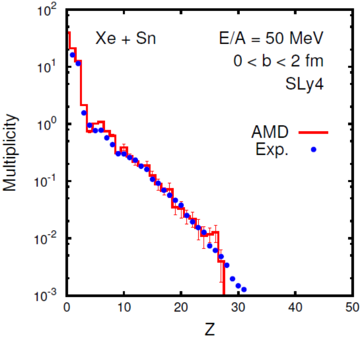
Table: integrated yield of light particles



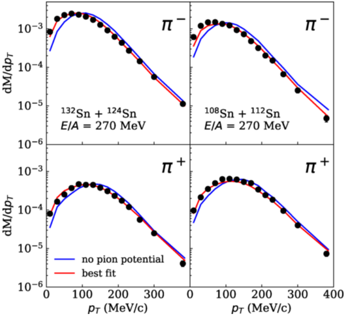


Antisymmetrized Molecular Dynamics (AMD)

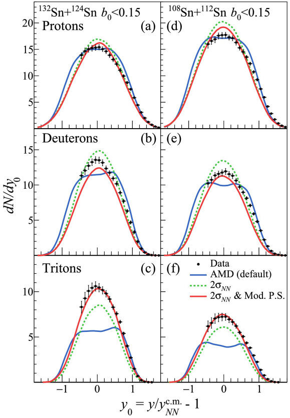
- dynamics of many-nucleon system by the time evolution of a Slater determinant of Gaussian wave packets.
- explicitly incorporated cluster correlation, $N_1 + N_2 + B_1 + B_2 \rightarrow C_1 + C_2$
- successfully described observables in different reactions



Akira Ono 2013
J. Phys.: Conf. Ser. 420 012103



J. Estee et al. (SπRIT Collaboration)
Phys. Rev. Lett. 126, 162701



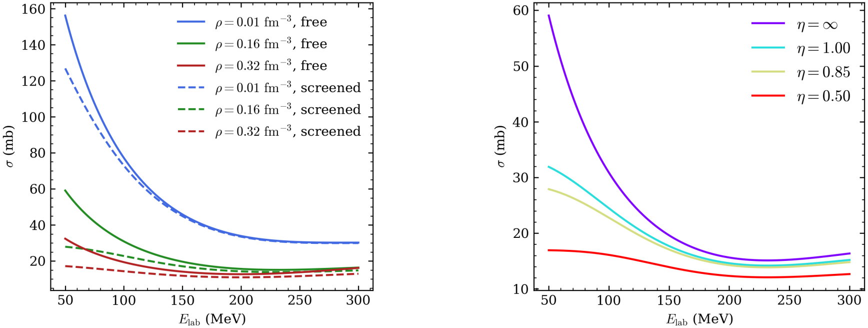
M. Kaneko et al. (SπRIT Collaboration)
Phys. Lett. B Vol. 822

screened in-medium cross section

$$\sigma_{\mathrm{NN}} = \sigma_0 \tanh(\sigma_{\mathrm{free}}/\sigma_0), \text{ with } \sigma_0 = \eta(\rho')^{-2/3}$$

Phys. Rev. C 48, 1702
Phys. Rev. C 49, 566
Acta Phys. Pol. B 33, 45

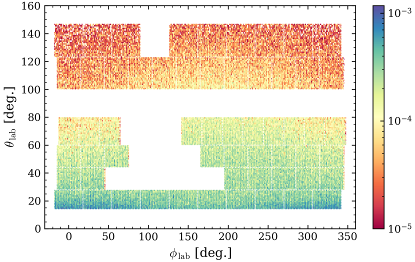
- for a particle going through medium with density ρ, the cross section for two-body coliision should be less than the order of $\rho^{-2/3}$, i.e. $\sigma_{\mathrm{NN}}^{\mathrm{med.}} \leq \eta(\rho)^{-2/3}$
- larger density means stronger suppression
- $\sigma_{\mathrm{NN}}^{\mathrm{med.}} \to \sigma_{\mathrm{free}}$ as $\eta \to \infty$

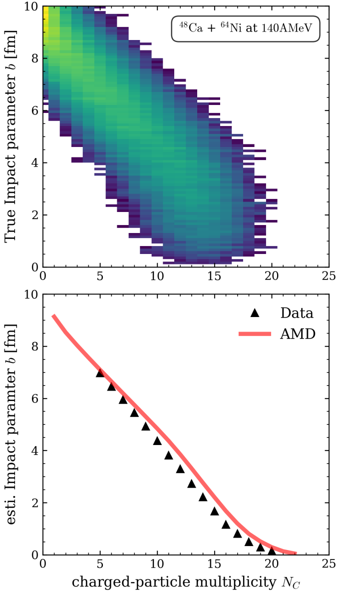


event selection

$$\hat{b} = \frac{b(N_C)}{b_{\max}} \propto \sqrt{\sum_{N=N_C}^{\infty} P(N)}$$

- $b_{\max}$ is the maximum impact parameter considered
- $P(N)$ is the probability of detecting N charged-particles
- assume b decreases monotonically with N_C





✓ event selected by gating on N_C, as in experimental data

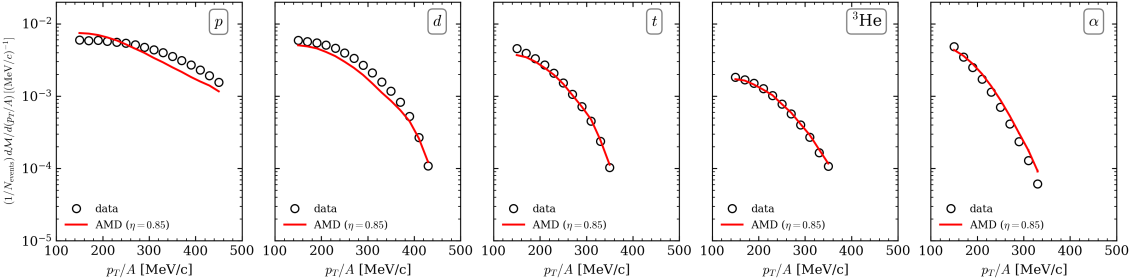
p_T spectra comparison $140\mathrm{AMeV}$

$$\sigma_{\mathrm{NN}} = \sigma_0 \tanh(\sigma_{\mathrm{free}}/\sigma_0),$$

with $\sigma_0 = \eta\rho^{-2/3}$

- Skyrme parameterization SLy4 ($L = 46$ MeV)
- screened in-medium cross-section parameter $\eta = 0.85$
- parameters for reproducing rapidity in Sn + Sn reaction at 270 AMeV
- reconstructed $\hat{b}$ agrees with that of data

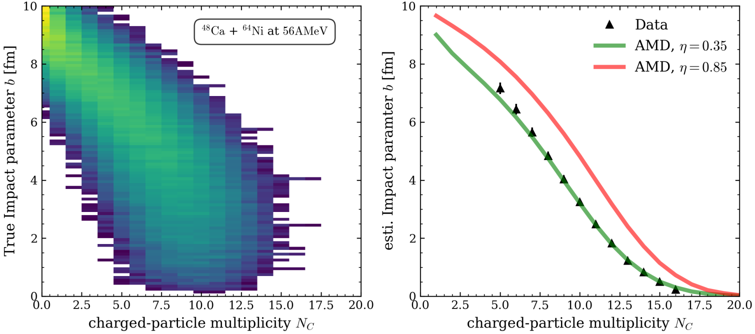
$^{48}\mathrm{Ca} + ^{64}\mathrm{Ni}$ at 140 AMeV



p_T spectra comparison $56\mathrm{AMeV}$

$$\sigma_{\mathrm{NN}} = \sigma_0 \tanh(\sigma_{\mathrm{free}}/\sigma_0),$$
$$\text{with } \sigma_0 = \eta\rho^{-2/3}$$

- Skyrme parameterization SLy4 ($L = 46$ MeV)
- screened in-medium cross-section parameter $\eta = 0.35, 0.85$
- reconstructed $\hat{b}$ agrees with that of data



$^{48}\mathrm{Ca} + ^{64}\mathrm{Ni}$ at 56 AMeV

p_T spectra comparison $56\mathrm{AMeV}$

$$\sigma_{\mathrm{NN}} = \sigma_0 \tanh(\sigma_{\mathrm{free}}/\sigma_0),$$
with $\sigma_0 = \eta\rho^{-2/3}$

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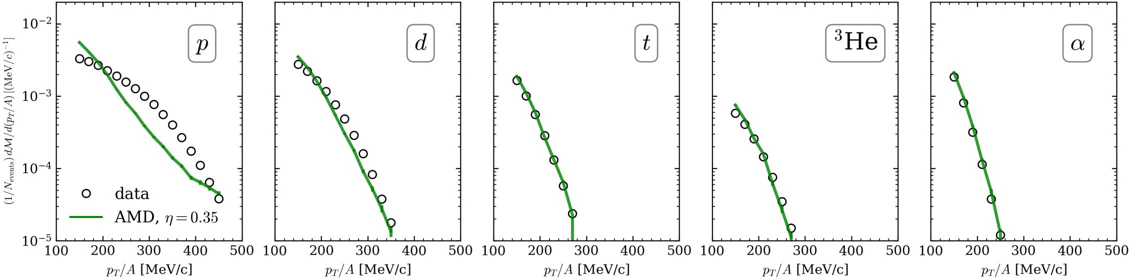
$^{48}\mathrm{Ca} + ^{64}\mathrm{Ni}$ at 56 AMeV



Dependence on in-medium cross-section

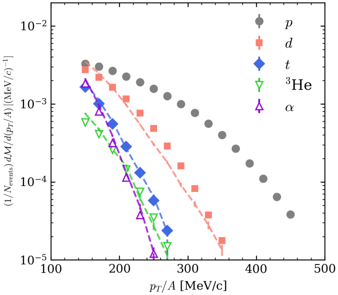
$^{48}\mathrm{Ca} + ^{64}\mathrm{Ni}$ at $56\ \mathrm{AMeV}$
$\sigma^{\mathrm{MED.}}_{NN}(\eta = 0.35)$

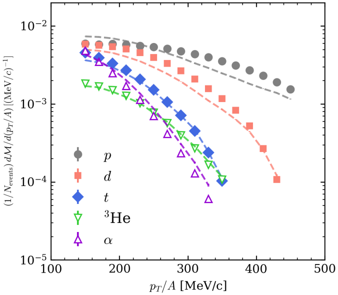
→

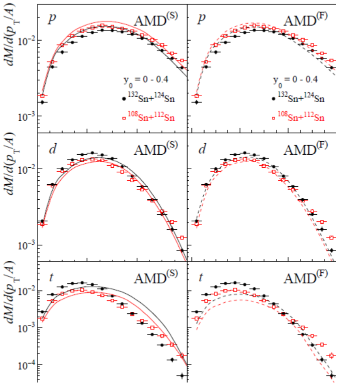
$^{48}\mathrm{Ca} + ^{64}\mathrm{Ni}$ at $140\ \mathrm{AMeV}$
$\sigma^{\mathrm{MED.}}_{NN}(\eta = 0.85)$

→

$^{132}\mathrm{Sn} + ^{124}\mathrm{Sn}$ at $270\ \mathrm{AMeV}$
$(2)\sigma^{\mathrm{MED.}}_{NN}(\eta = 0.5)$







- $\sigma^{\mathrm{MED.}}_{NN}$ is more suppressed at reactions with smaller E_{beam}, densities.

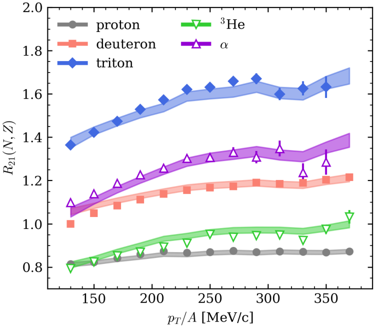
Lee, J.W., Tsang, M.B., Tsang, C.Y. et al. Eur. Phys. J. A 58, 201 (2022).

spectral ratio R_{21} Data

- spectral ratio of neutron-rich to neutron-deficient reaction

$$R_{21}(N,Z) = \frac{d\mathcal{M}_2(N,Z)}{d\mathcal{M}_1(N,Z)} = \frac{d\mathcal{M}(^{48}\mathrm{Ca} + ^{64}\mathrm{Ni}\,@\,140\,\mathrm{AMeV})}{d\mathcal{M}(^{40}\mathrm{Ca} + ^{58}\mathrm{Ni}\,@\,140\,\mathrm{AMeV})}(N,Z)$$

- grouping of ratios with the same $N - Z$ value



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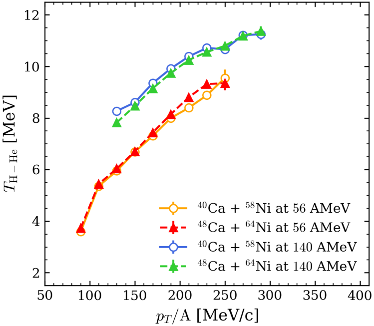
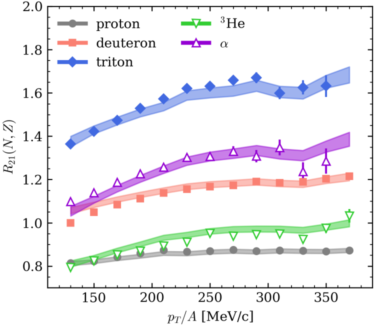
- similar temperature in both reactions is assumed, $T_{\text{H-He}} = 14.3 / \ln\left[1.6 \frac{\mathrm{Y}(d)\cdot\mathrm{Y}(\alpha)}{\mathrm{Y}(t)\cdot\mathrm{Y}(^{3}\mathrm{He})}\right]$

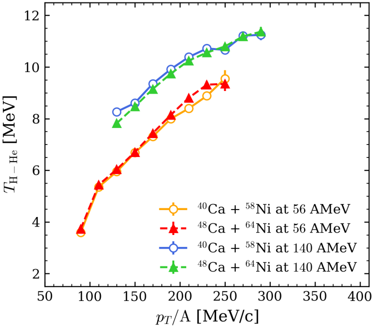


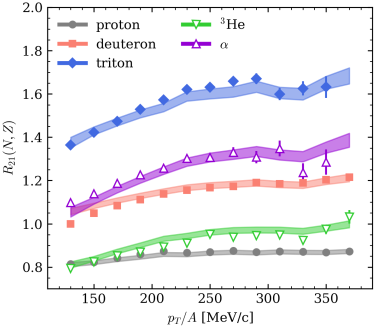


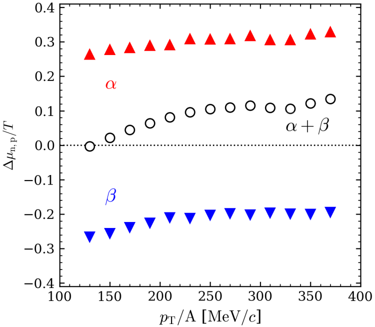
spectral ratio R_{21} and Isoscaling (Data)

$$R_{21}(N,Z) = \frac{d\mathcal{M}(^{48}\mathrm{Ca} + ^{64}\mathrm{Ni} \,@\, 140\,\mathrm{AMeV})}{d\mathcal{M}(^{40}\mathrm{Ca} + ^{58}\mathrm{Ni} \,@\, 140\,\mathrm{AMeV})} \propto \exp(\alpha N + \beta Z)$$

- effective chemical potentials $\alpha = \Delta\mu_n/T$ and $\beta = \Delta\mu_p/T$.
- utilized for constructing pseudo-neutron $Y(p) \cdot Y(t)/Y(^3\mathrm{He})$
- $|\alpha| \approx |\beta|$ in previous works but not necessarily true



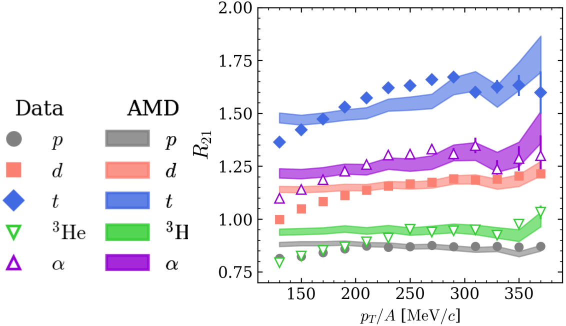




R_{21} and isoscaling (AMD vs Data)

$$R_{21}(N,Z) = \frac{d\mathcal{M}({}^{48}\mathrm{Ca} + {}^{64}\,\mathrm{Ni}\,@\,140\,\mathrm{AMeV})}{d\mathcal{M}({}^{40}\mathrm{Ca} + {}^{58}\,\mathrm{Ni}\,@\,140\,\mathrm{AMeV})} \propto \exp(\alpha N + \beta Z)$$

- spectra ratio $R_{21}(N,Z)$ moderately reproduced



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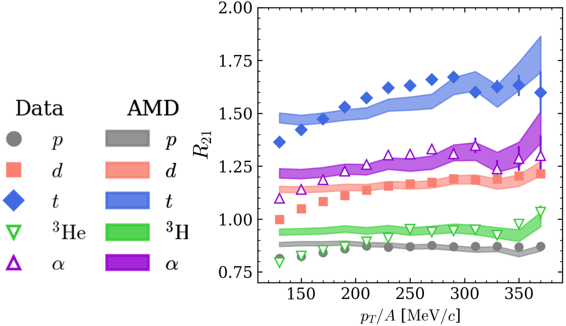
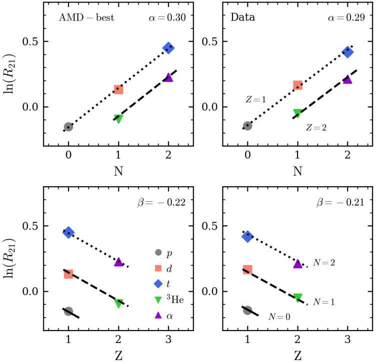
- spectra ratio $R_{21}(N,Z)$ moderately reproduced
- isoscaling observed in data and AMD





Summary and Outlook

- ✓ Choice of AMD parameters guided by the reconstructed impact parameter
- ✓ reproduced p_T spectra in Ca + Ni collisions at 56 and 140 AMeV
- ✓ Dependence of in-medium cross section on E_{beam} and reaction densities
- ✓ Observed isoscaling in data and AMD opens possibility for pseudo neutron

- ○ including neutron the analysis might gives insight in comparison with AMD calculation
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Thank you and Q. and A.

Back up : AMD Model details

- ○ dynamics of many-nucleon system by the time evolution of a Slater determinant of Gaussian wave packets.
- ✓ explicitly incorporated cluster correlation in the final state of two-nucleon collision, $(N_1 + N_2 + B_1 + B_2 \to C_1 + C_2)$
- ✓ collision cross section of a specific final state C_1, C_2 is given by

$$\frac{d\sigma(C_1, C_2)}{d\Omega} = P(C_1, C_2, p_f, \Omega)\frac{p_i}{v_i}\frac{p_f}{v_f}|M|^2\frac{p_f}{p_i}$$

- ✓ matrix element for two-nucleon scattering $|M|^2$, is an important input to AMD calculation since it can be modified in nuclear medium. It can be connected to the in-medium two-nucleon cross sections through

$$|M|^2 = (2/m_N)^2 d\sigma_{NN}/d\Omega$$

Back up : AMD definition of density

$$\sigma_{\rm NN} = \sigma_0 \tanh(\sigma_{\rm free}/\sigma_0),\ \text{with } \sigma_0 = \eta(\rho')^{-2/3}$$

- phase-space density instead of normal density
- $\rho' = \left((\rho'_1)^{\rm init}(\rho'_2)^{\rm init}(\rho'_1)^{\rm final}(\rho'_2)^{\rm final}\right)^{1/4}$ where

$$(\rho'_i)^{\rm init/final} = \left(\frac{2\nu}{\pi}\right)^{3/2} \sum_{k\neq i} \Theta(p_{\rm cut} > |(\mathbf{P}_i)^{\rm init/final} - \vec{\mathbf{P}}_k|) e^{-2\nu(\vec{\mathbf{R}}_i - \vec{\mathbf{R}}_k)^2}$$

- suppress clusters in medium by forming clusters only in low phase-space density region with the condition $\rho' < 0.125 {\rm fm}^{-3}$.

Akira Ono, JPS Conf. Proc. , 010076 (2020)