基于中子-质子平衡约束核物质状态方程

——第三届“粤港澳”核物理会议

广东 · 深圳

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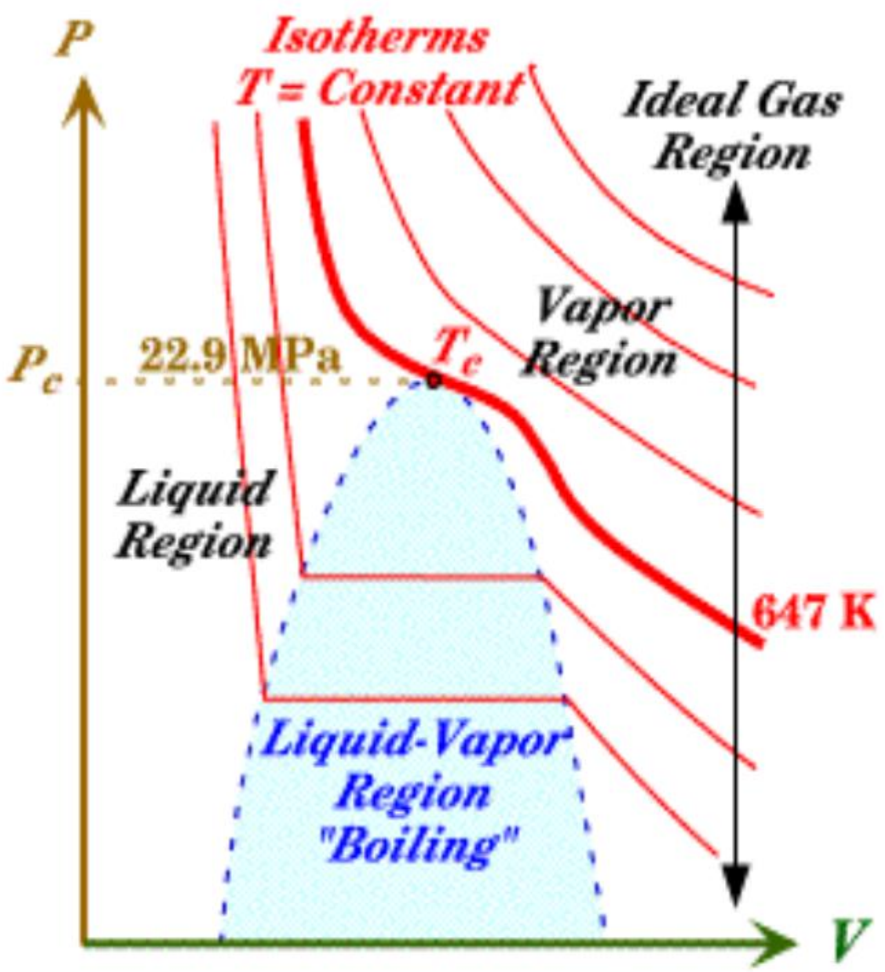
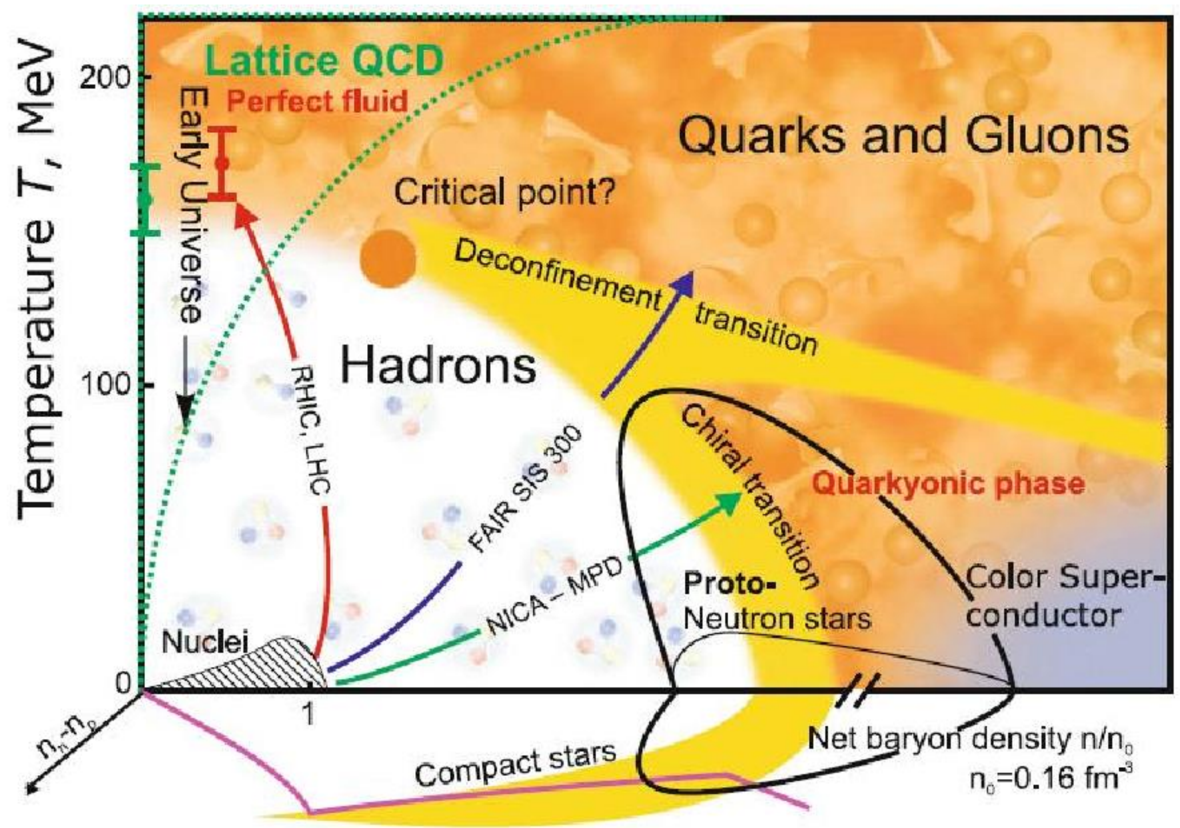
目录

- 研究背景
  - 核物质状态方程
  - 基于同位旋输运约束状态方程
- 理论模型介绍
- 结果与讨论
- 总结

状态方程





Fortov V E. Extreme states of matter : on Earth and in the cosmos.

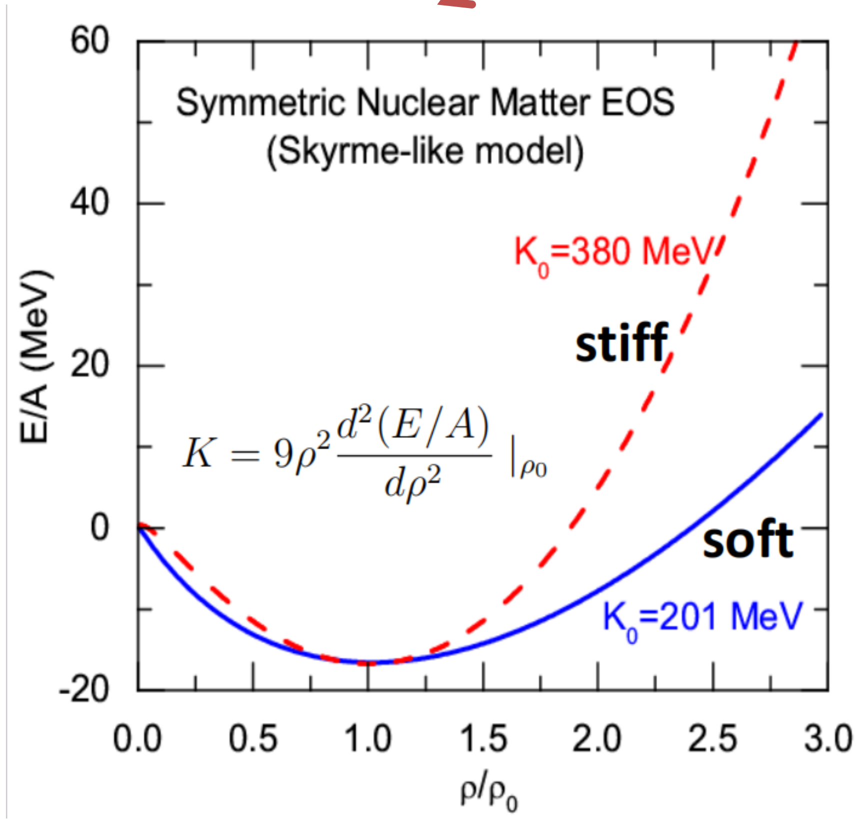
van der Waals EOS: $$[p+a(\frac{n}{\mathrm{v}})^2](\mathrm{v}-nb)=nRT$$

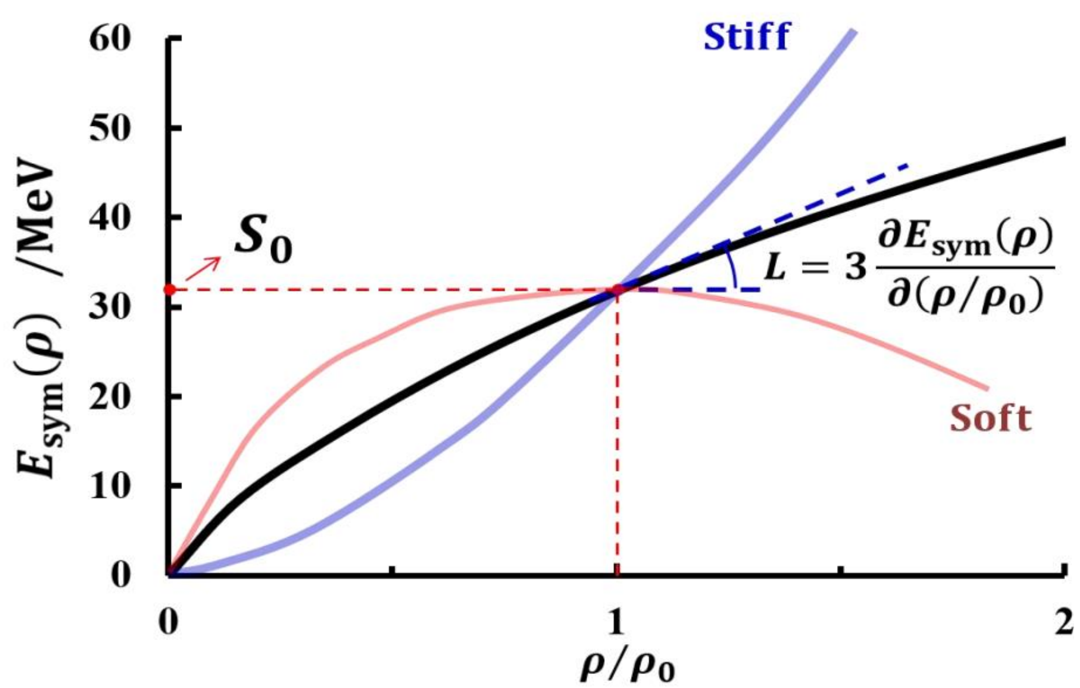
引力项　　斥力项

核物质状态方程 → 核相互作用

核物质状态方程

E/A(ρ,δ) = E/A(ρ,0) + δ²·S(ρ) ; δ = (ρ$_n$- ρ$_p$)/ (ρ$_n$+ ρ$_p$) = (N-Z)/A



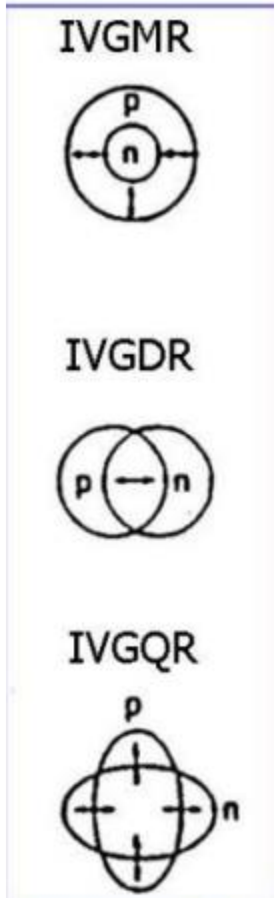


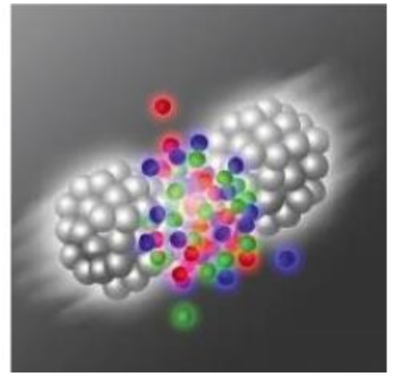
$$E/A(\rho) = \frac{3}{5}\frac{\hbar^2}{2m}(\frac{3\pi^2}{2}\rho)^{2/3} + \frac{\alpha\rho}{2\rho_0} + \frac{\beta\rho^\gamma}{(\gamma+1)\rho_0^\gamma} + g_\tau\frac{\rho^\tau}{\rho_0^\eta}$$

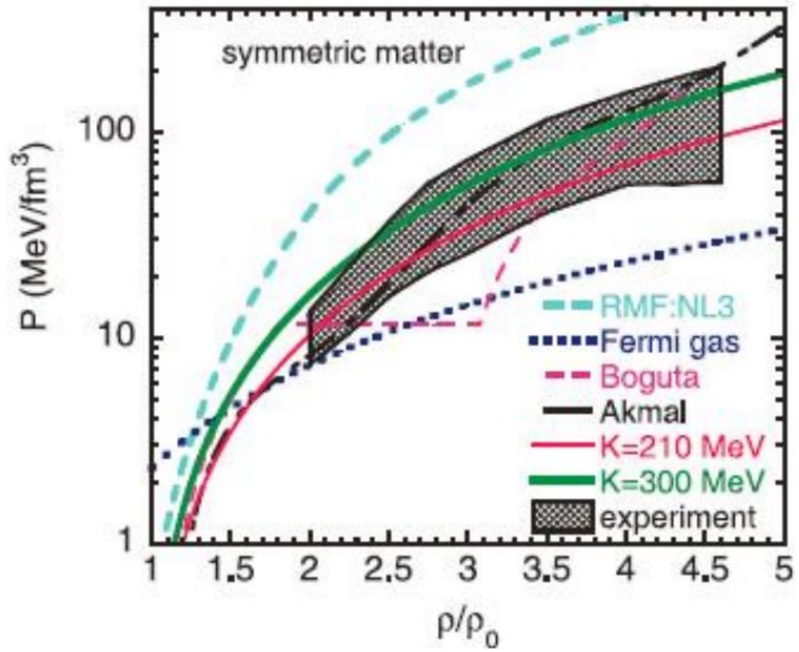
$$E_{sym}(\rho) = \frac{1}{3}\frac{\hbar^2}{2m}(\frac{2}{3}\pi^2\rho)^{2/3} + \frac{C_s}{2}(\frac{\rho}{\rho_0})^{\gamma_i}$$

Physics Reports 464 (2008) 113–281

核结构

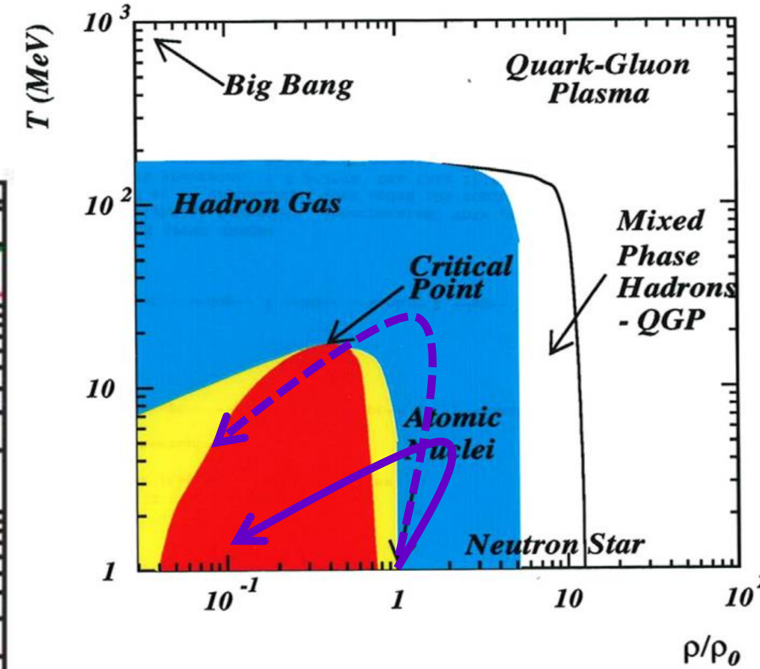






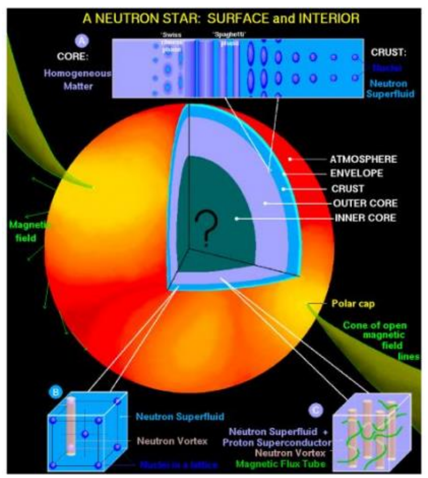
Science, 298,1592 (2002)

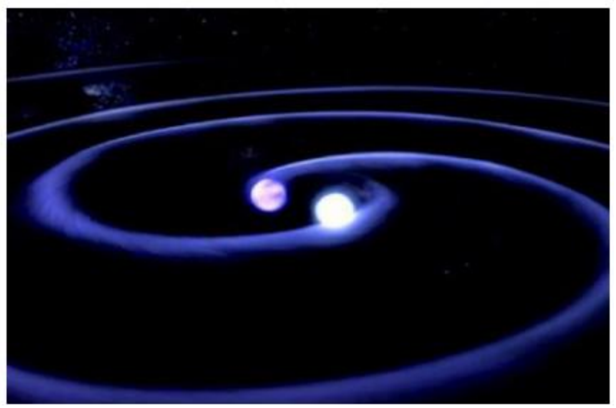
核反应



PPNP, 2019, 105: 82-138

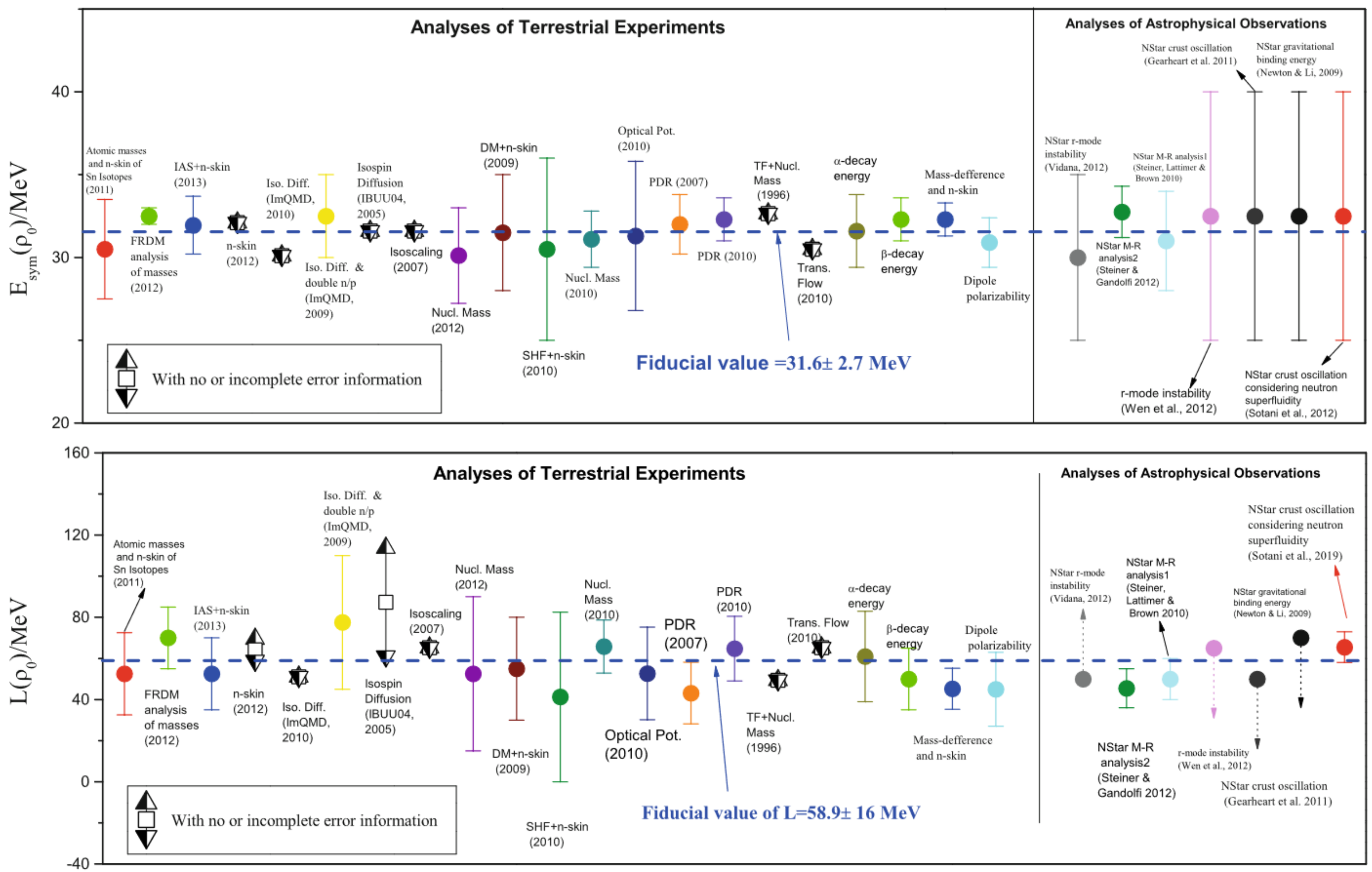
核天体





核状态方程与核物理中的关键科学问题紧密联系

对称能密度依赖——核结构、反应、天体

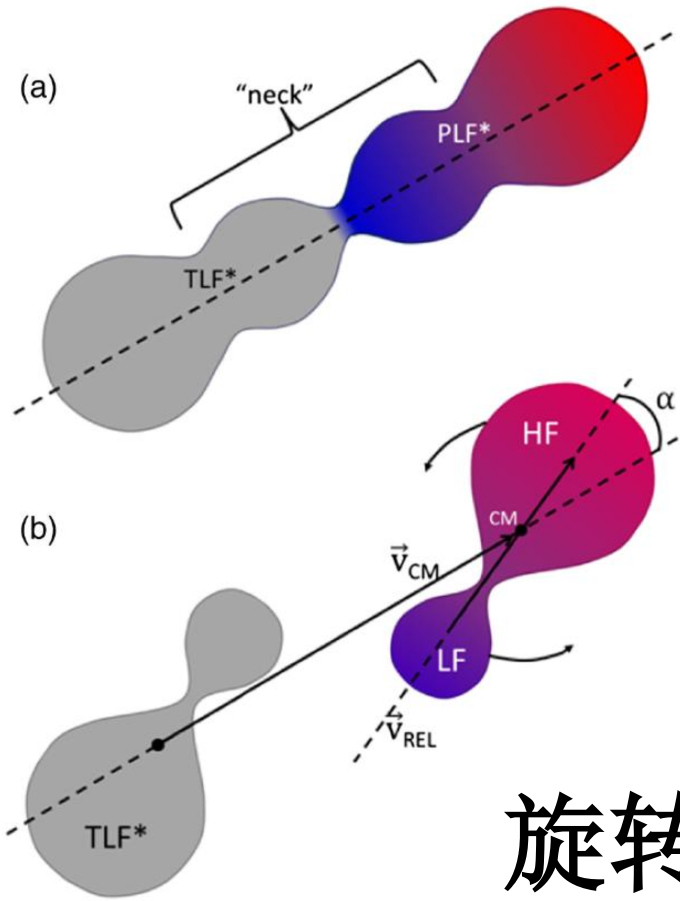


Eur. Phys. J. A (2019) 55: 117

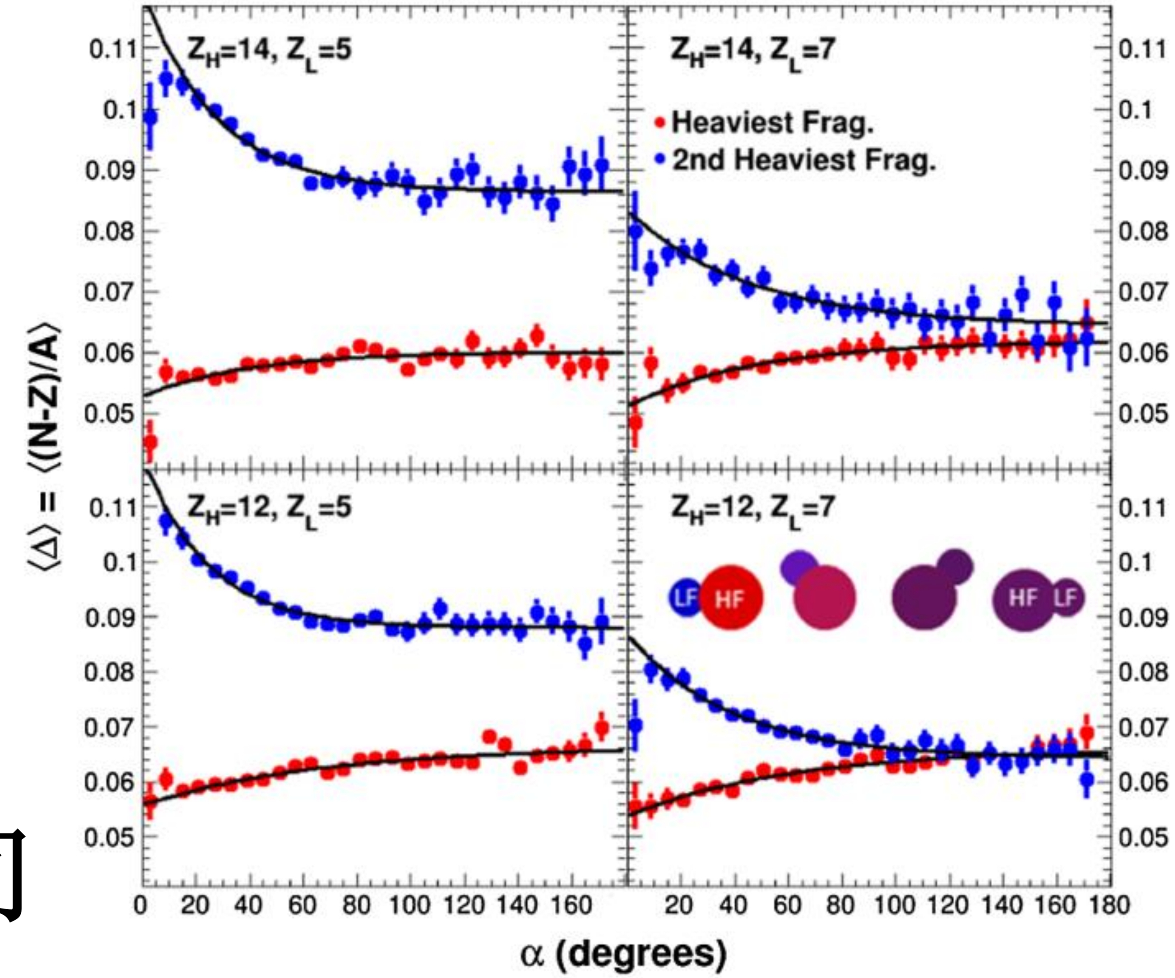
对称能约束的不确定度很大

二元破裂反应中的中子-质子平衡

^{70}Zn + ^{70}Zn @ 35A MeV by the K500 cyclotron at the Texas A&M University



旋转角 → 时间



$$\alpha = \arccos \frac{\vec{v}_{cm} \cdot \vec{v}_{rel}}{|\vec{v}_{cm}|\,|\vec{v}_{rel}|}$$

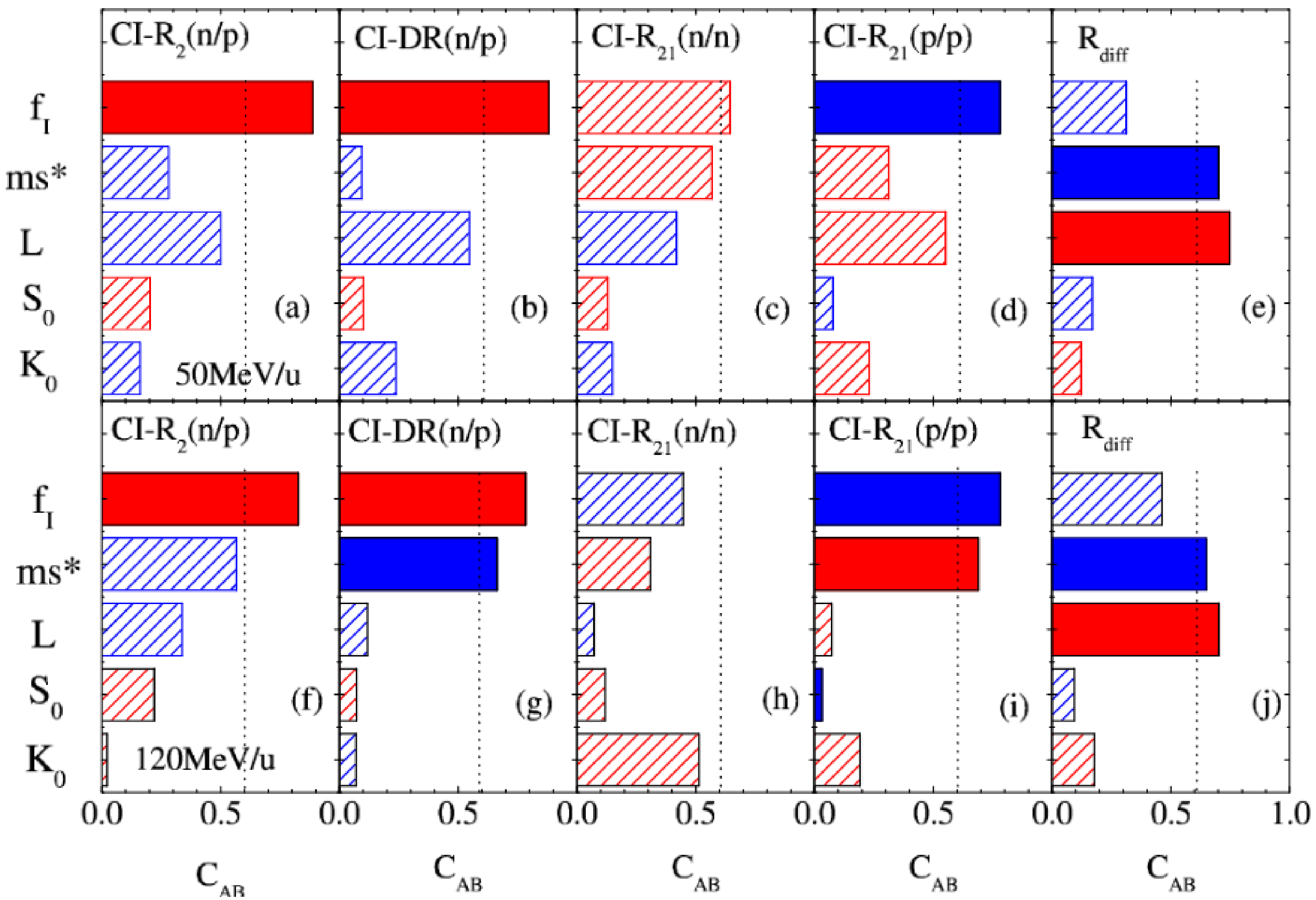
$$\vec{v}_{cm} = (m_H\vec{v}_H + m_L\vec{v}_L)/(m_H + m_L)$$

$$\vec{v}_{rel} = (\vec{v}_H - \vec{v}_L)$$

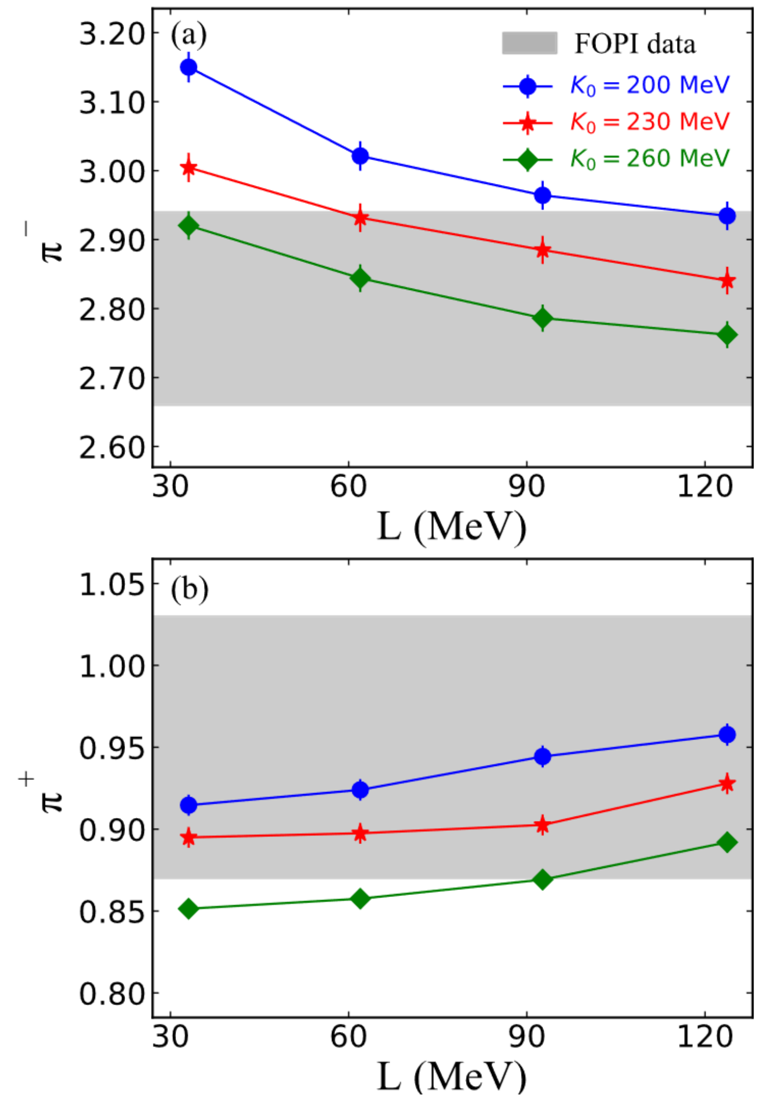
Phys. Rev. Lett. 118, 062501 (2017);
Phys. Rev. C 95, 044604 (2017)

拟合： $(N-Z)/A = a + b\exp(-c\alpha)$

EOS参数关联性



PLB 749 (2015) 262–266



PRC 109, 054619 (2024)

对称能密度依赖的约束需要考虑EOS参数关联性

目录

Isospin-dependent Quantum Molecular Dynamics model

N体薛定谔方程

$$i\hbar\frac{\partial}{\partial t}|\psi^{(k)}_{1\ldots N}(t)\rangle = H_{1\ldots N}|\psi^{(k)}_{1\ldots N}(t)\rangle$$

高斯波包 $$\phi_i(\mathbf{r},\mathbf{r}_i,\mathbf{p}_i,t)=\frac{1}{(2\pi L)^{3/4}}exp[-\frac{(\mathbf{r}-\mathbf{r}_i(t))^2}{4L}]exp[\frac{i\mathbf{p}_i(t)\cdot\mathbf{r}}{\hbar}]$$

直积 $$\Phi(\mathbf{r},\mathbf{r}_1,\cdots,\mathbf{r}_N,\mathbf{p}_1,\cdots,\mathbf{p}_N,t)=\prod_i\phi_i(\mathbf{r},\mathbf{r}_i,\mathbf{p}_i,t)$$

魏格纳变换 $$f(\mathbf{r},\mathbf{p},t)=\sum_i\frac{1}{(\pi\hbar)^3}e^{-\frac{[\mathbf{r}-\mathbf{r}_i(t)]^2}{2L}}e^{-\frac{[\mathbf{p}-\mathbf{p}_i(t)]^2\cdot 2L}{\hbar^2}}$$

广义变分原理 $$S=\int_{t_1}^{t_2}\mathbf{L}[\Phi,\Phi^*]dt \qquad \mathbf{L}=\langle\Phi|i\hbar\frac{d}{dt}-H|\Phi\rangle$$

IQMD 模型

$$\dot{\mathbf{r}}_i=\frac{\partial\langle H\rangle}{\partial\mathbf{p}_i}$$
$$\dot{\mathbf{p}}_i=\frac{\partial\langle H\rangle}{\partial\mathbf{r}_i}$$

IQMD模型

基本相互作用：

$$\langle H \rangle = \langle T \rangle + \langle U^{nucl} \rangle + \langle U^{Coul} \rangle$$

$$\langle T \rangle = \int f(\mathbf{r},\mathbf{p},t)\frac{\mathbf{p}^2}{2m}d^3rd^3p = \sum_i \frac{\mathbf{p}_i^2}{2m_i} + C$$

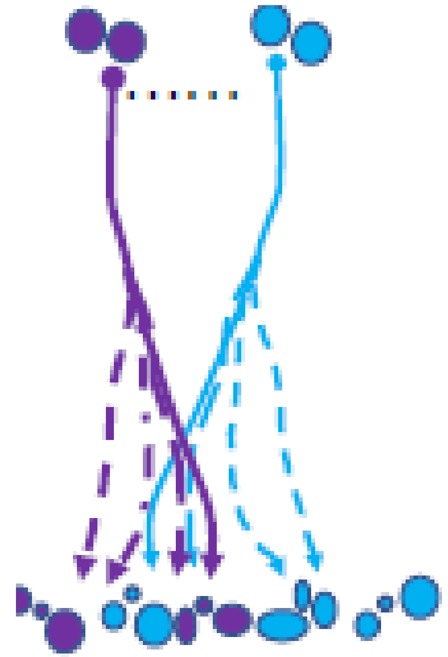
$$\langle U^{Coul} \rangle = \frac{e^2}{4}\sum_i \sum_{j,j\neq i} \frac{(1-t_{zi})(1-t_{zj})[1-erfc(|\mathbf{r}_i-\mathbf{r}_j|/\sqrt{4L})]}{|\mathbf{r}_i-\mathbf{r}_j|}$$

$$\langle U^{nucl} \rangle = \frac{\alpha}{2}\sum_i \sum_{j,j\neq i}\frac{\rho_{ij}}{\rho_0} + \frac{\beta}{1+\gamma}\sum_i(\sum_{j,j\neq i}\frac{\rho_{ij}}{\rho_0})^{\gamma} + g_{\tau}\sum_i(\sum_{j,j\neq i}\frac{\rho_{ij}}{\rho_0})^{\eta}$$
$$+ \frac{C_{sym}}{2}\sum_i \sum_{j,j\neq i} t_{zi}t_{zj}\frac{\rho_{ij}}{\rho_0}$$
$$+ \frac{g_{sur}}{2}\sum_i \sum_{j,j\neq i}\frac{\rho_{ij}}{\rho_0}[\frac{3}{2L} - (\frac{\mathbf{r}_i-\mathbf{r}_j}{2L})^2]$$

相互作用
势能密度

$$\rho_{ij} = \frac{1}{(4\pi L)^{3/2}}exp[-\frac{(\mathbf{r}_i-\mathbf{r}_j)^2}{4L}]$$

核子-核子碰撞



$$d \leq \sqrt{\sigma_{NN}/\pi}$$

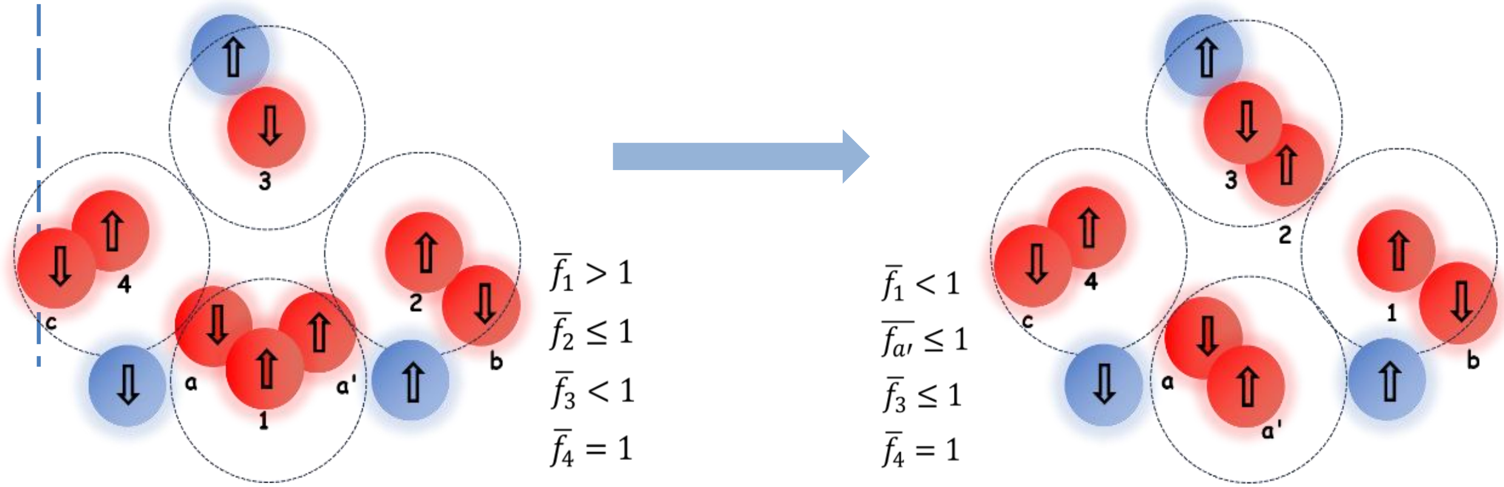
$$\left(\frac{d\sigma}{d\Omega}\right)_{el(inel)} = \sigma^{free}_{el(inel)} f^{med}_{el(inel)} f^{angl}_{el(inel)}$$

$$N+N \to N+N$$
$$N+N \to N+\Delta, N+\Delta \to N+N$$

相空间约束方法(费米子属性改善)

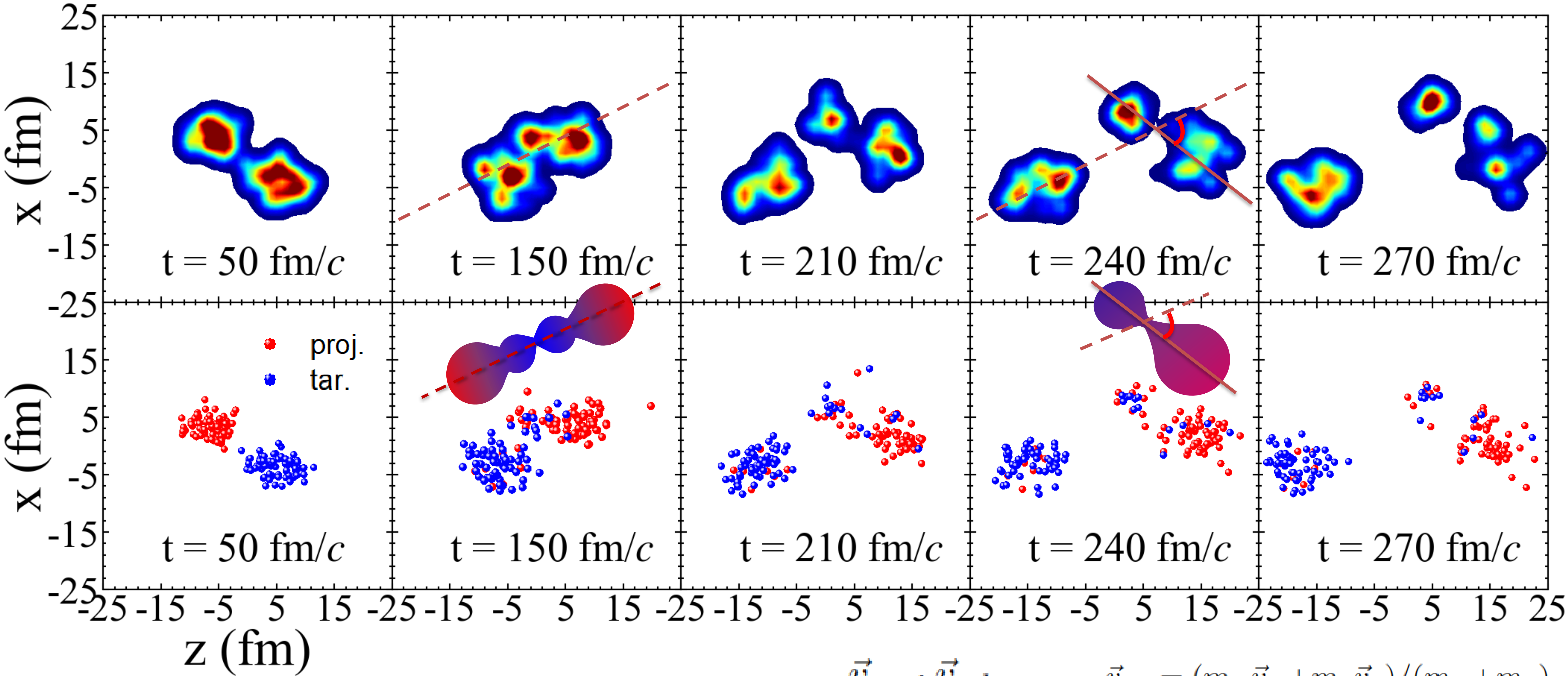
Physical Review C 64(2): 024612

$$\bar{f}_i = 0.621 + \sum_{j\neq 1}^{N}\frac{\delta_{\tau_j,\tau_i}}{2}\int_{h^3}\frac{1}{\pi^3\hbar^3}e^{-\frac{(r_j-r_i)^2}{2L}-\frac{(p_j-p_i)^2}{\hbar^2/2L}}d^3rd^3p.$$



目录

弹核二元破裂反应



^{70}Zn + ^{70}Zn @ 35A MeV

$$\alpha = \arccos \frac{\vec{v}_{cm} \cdot \vec{v}_{rel}}{|\vec{v}_{cm}|\,|\vec{v}_{rel}|}$$

$$\vec{v}_{cm} = (m_H \vec{v}_H + m_L \vec{v}_L)/(m_H + m_L)$$

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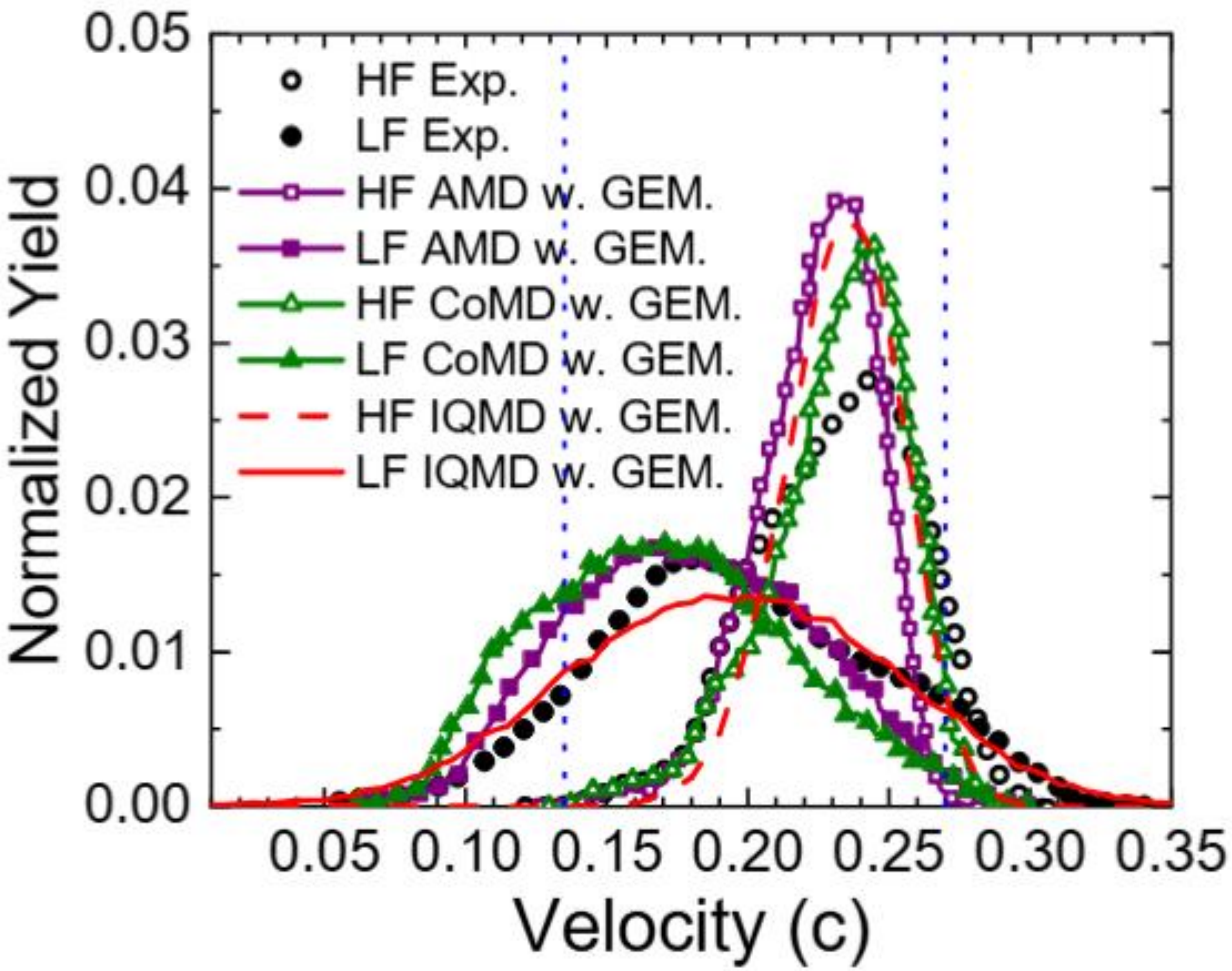
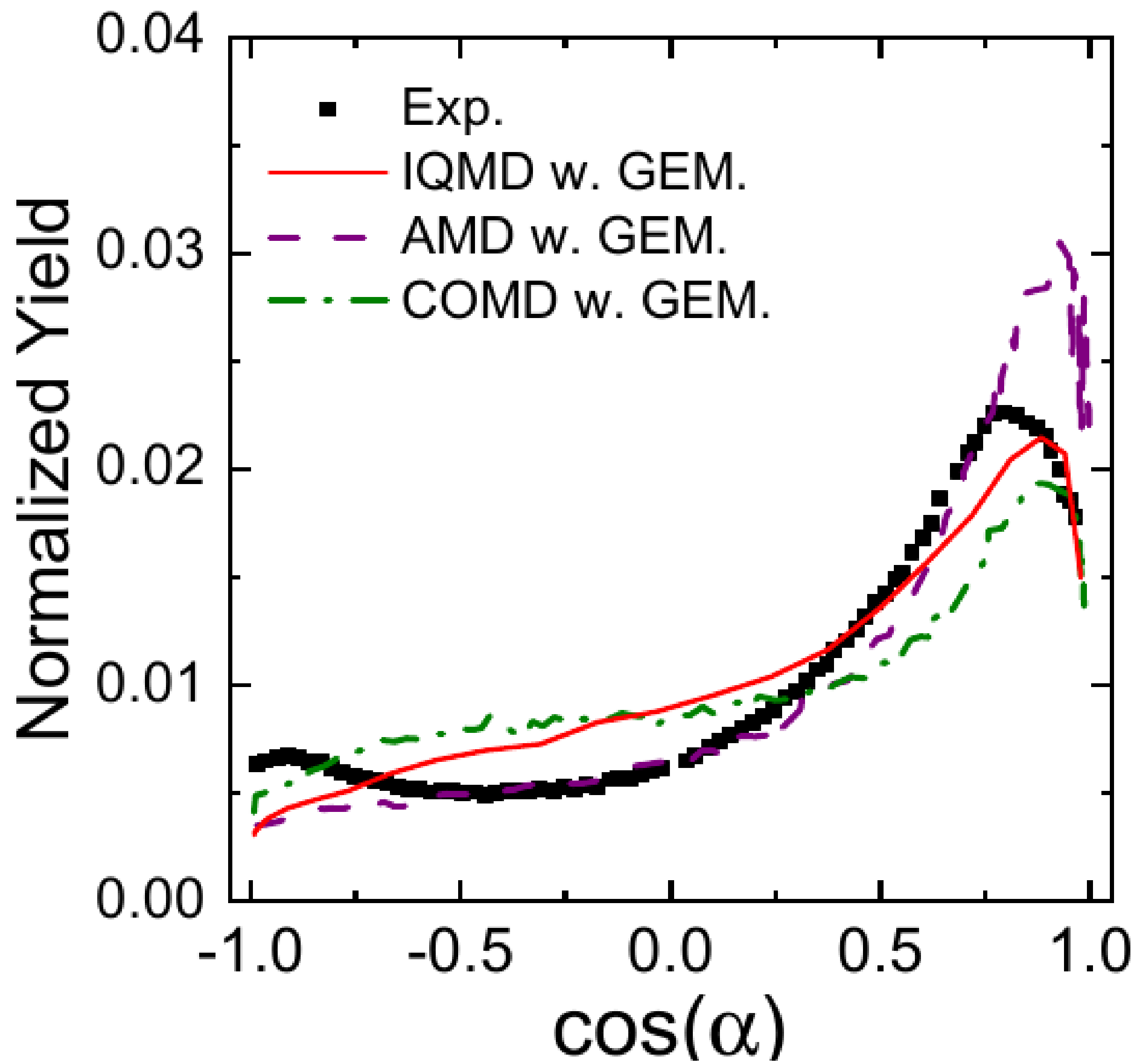
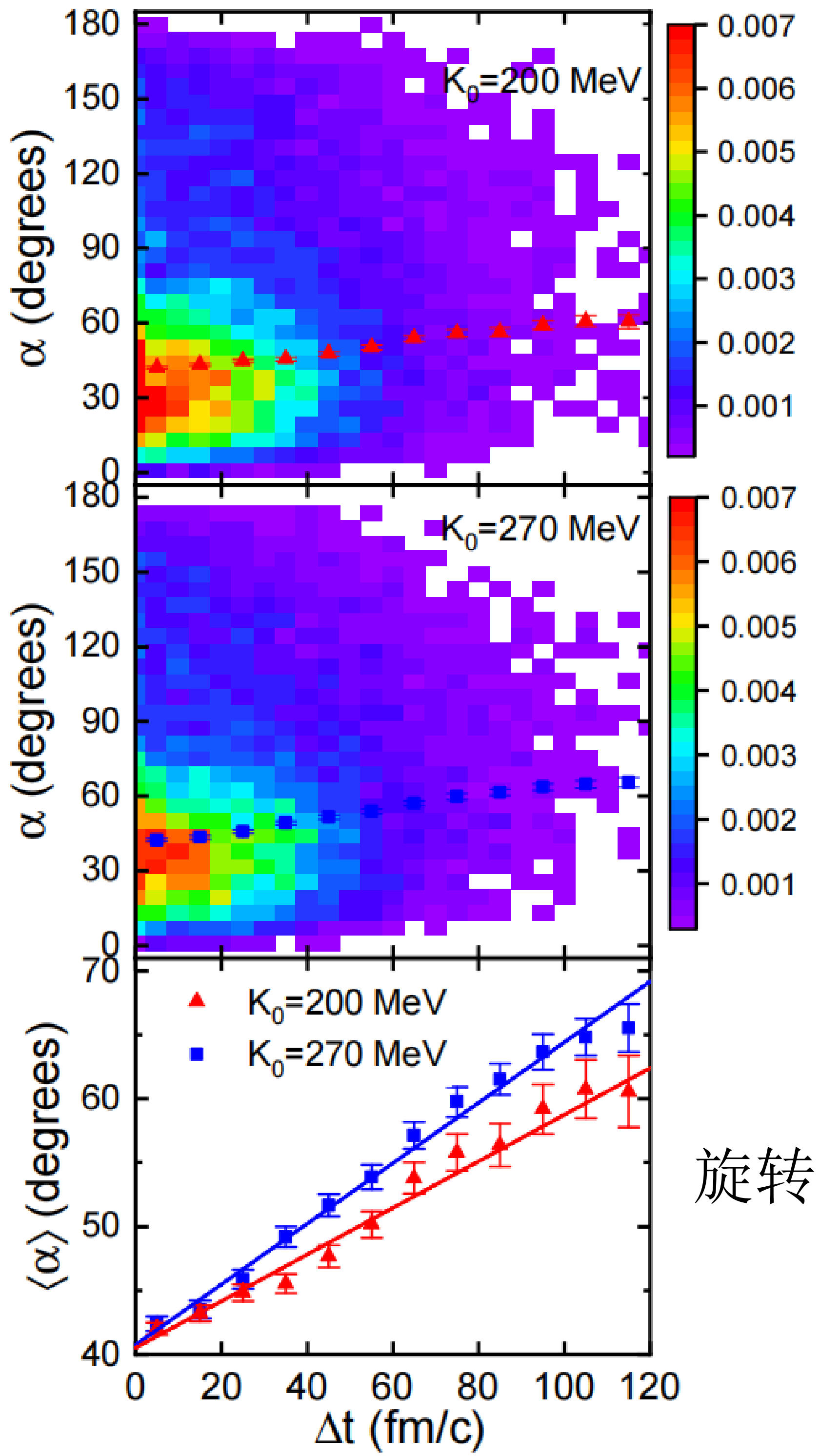
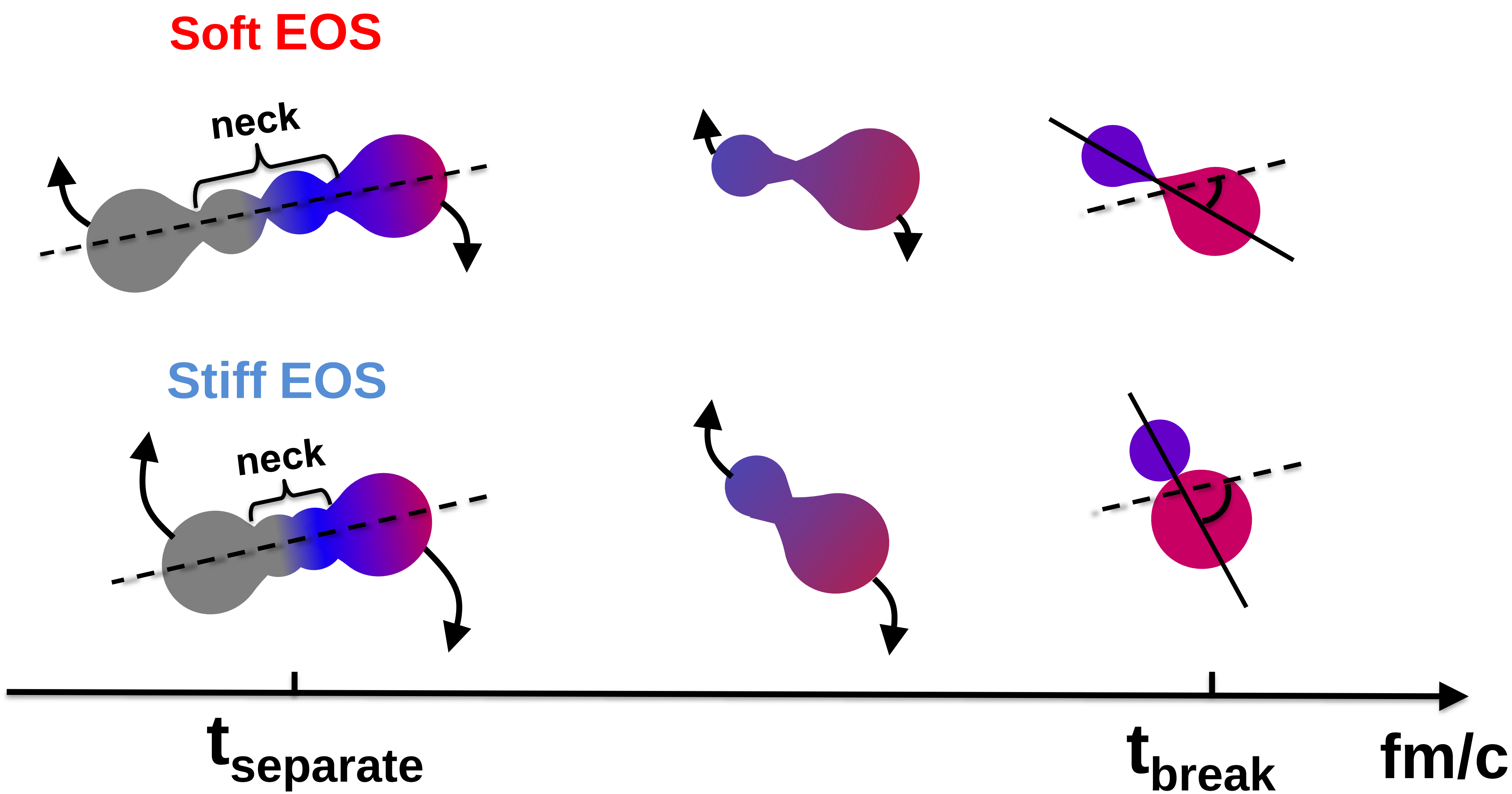




arXiv: 2410.18569

不可压缩性系数对二元破裂反应的影响

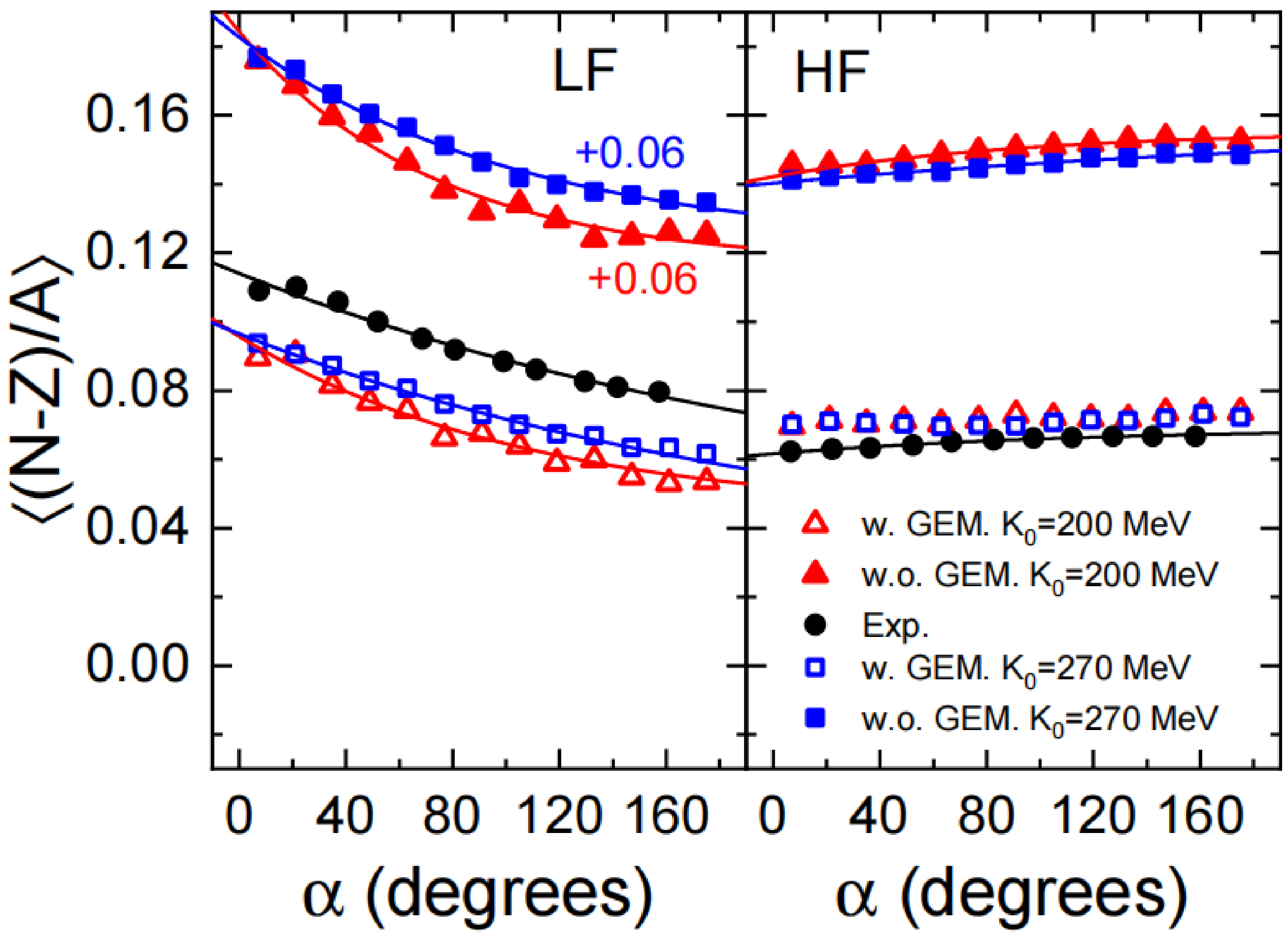


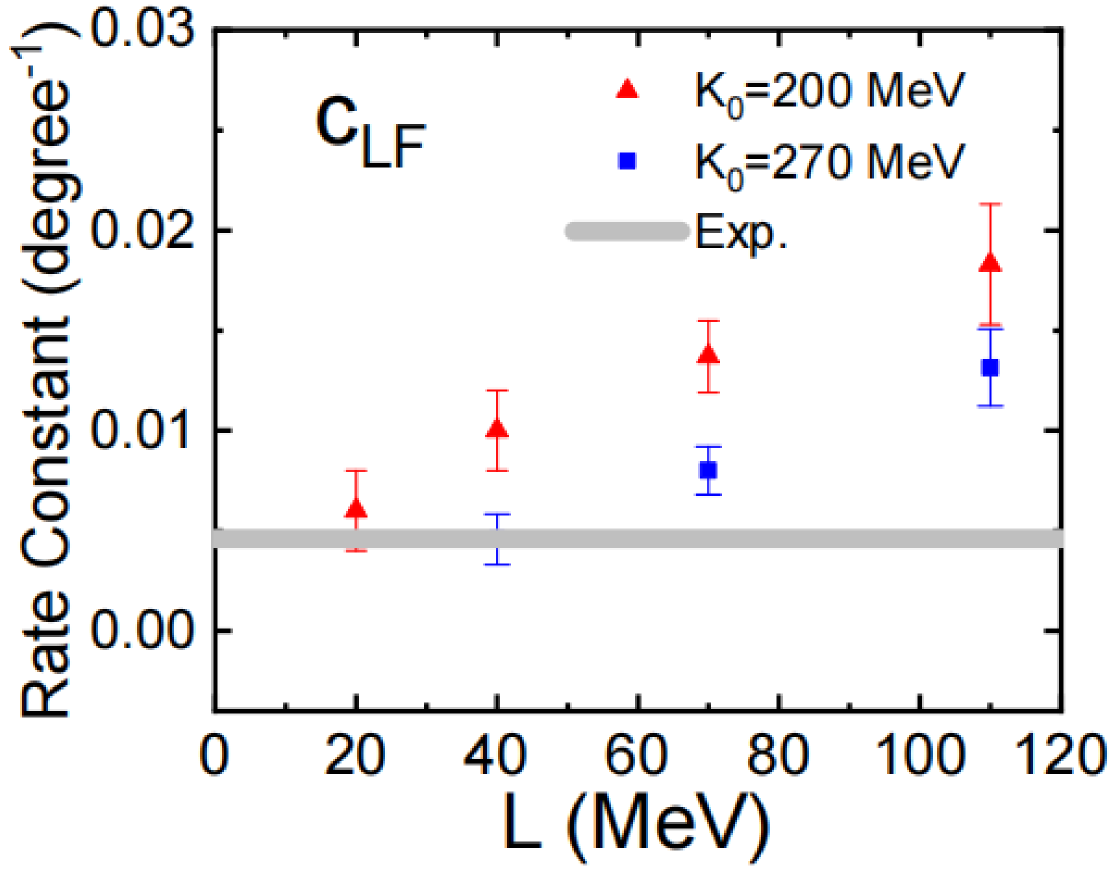


旋转时间Δt = 弹核二元破裂时刻 – 弹靶分离时刻

不可压缩性K_0影响了系统角动量的耗散

基于中子-质子平衡约束对称能的密度依赖





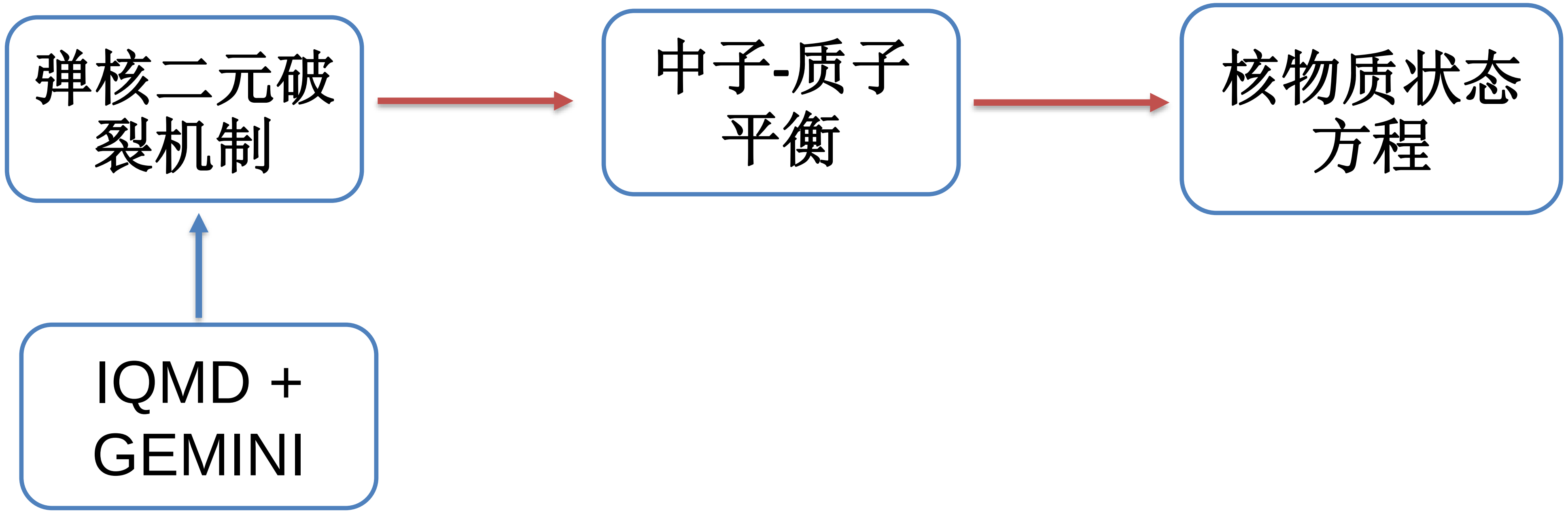
$$
\begin{aligned}
(N-Z)/A &= a + b\exp(-\boxed{c}\alpha) \\
&= a + b\exp\left(-\frac{t}{\tau}\right) \\
&= a + b\exp\left(-\frac{1}{k\tau}\alpha\right)
\end{aligned}
$$

不可压缩性K_0 → 旋转角/时间 → 平衡速率

$$L = 20 \sim 40\ \text{MeV}$$

arXiv: 2410.18569

总结



- □不可压缩性系数K_0通过影响旋转角与时间线性关系进而改变中子-质子平衡性质
- □利用中子-质子平衡约束对称能需考虑K_0与L的关联
- □基于K0与L关联，L = 20 ∽ 40 MeV

请各位专家批评指正！