

# 重离子碰撞中的非平衡相变

**Non-equilibrium phase transition in heavy ion collisions**

中山大学，中法核工程与技术学院

苏军

肖尔熙

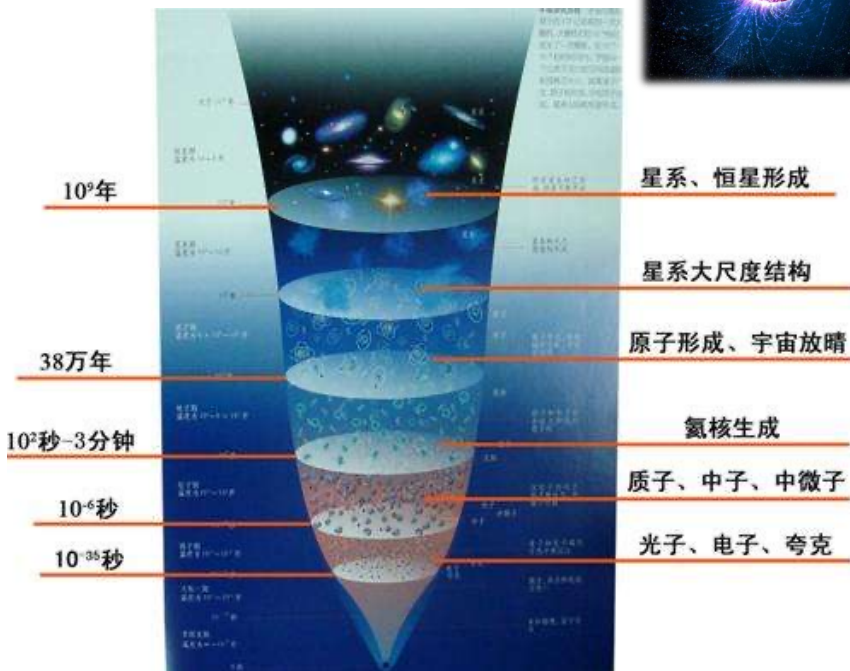
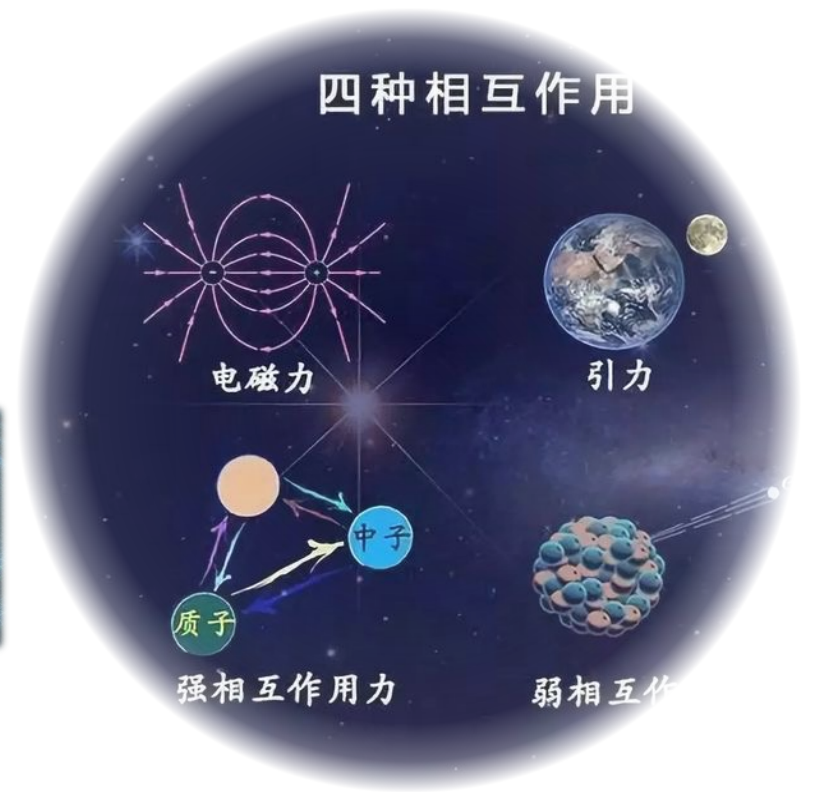
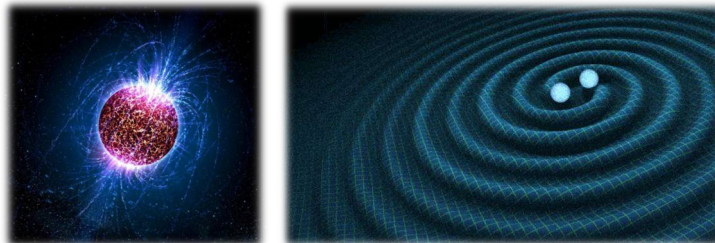
2022年



# 重离子碰撞

**重离子碰撞**是探索诸多重要科学问题的基本手段

**对称能**的密度依赖是诸多科学问题的关键

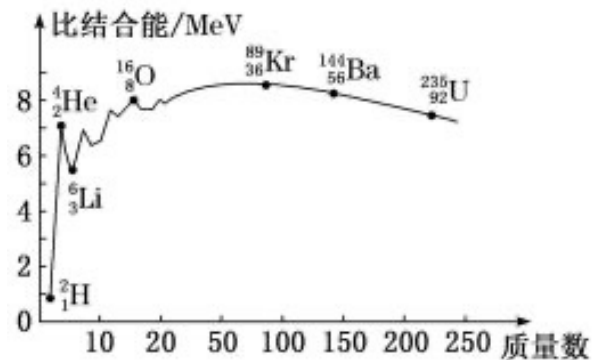


**中子星并合广泛存在？**

**中子星性质？**

**重核如何形成？**

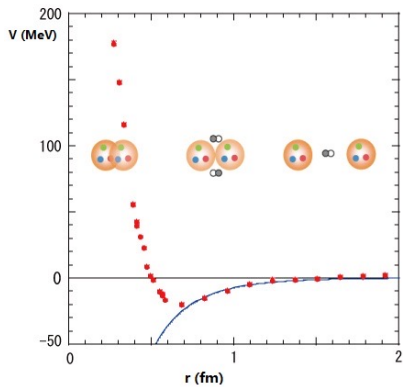
**中子, 质子差异：对称能**



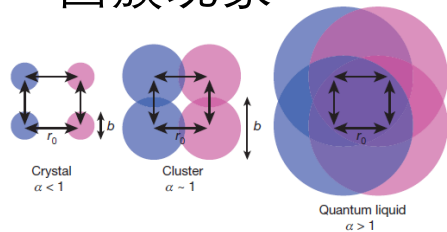


# 无限核物质相图

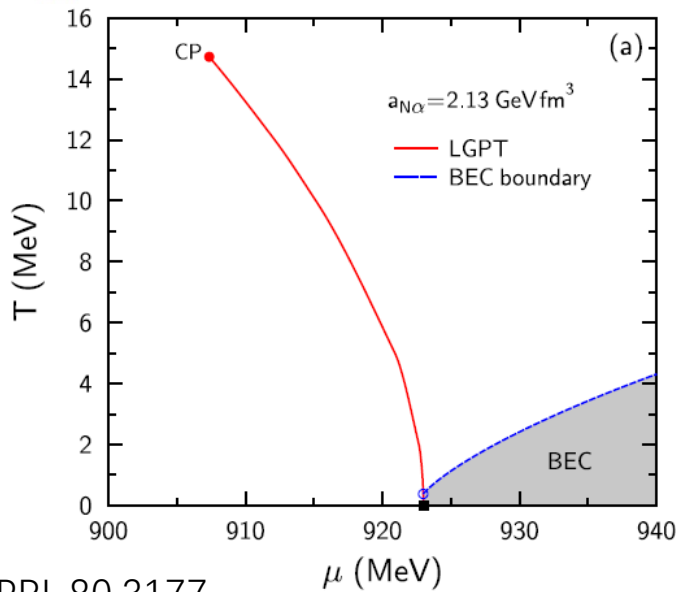
## 长程核力与排斥芯



## 团簇现象

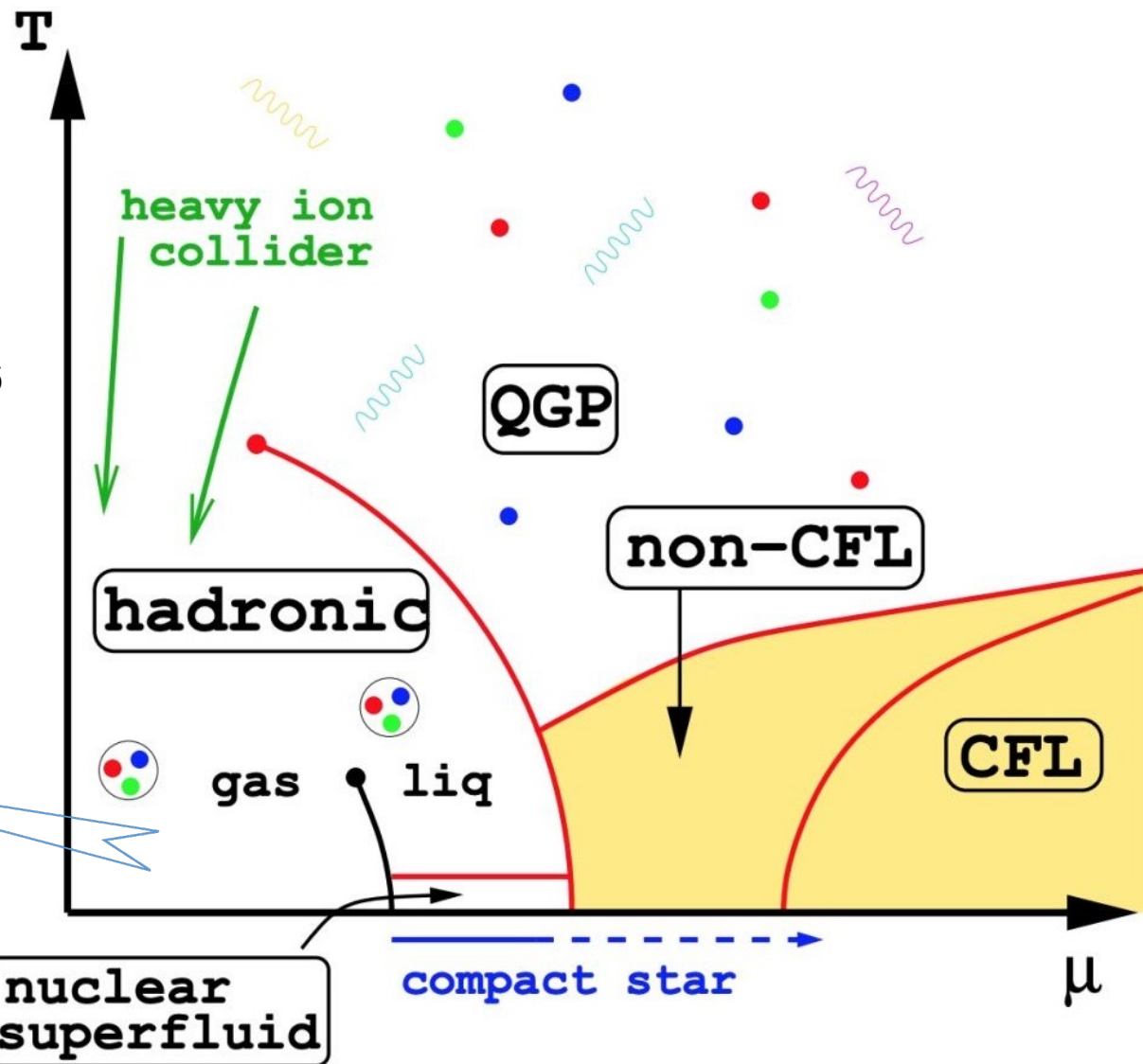


2012-nature11246



1998-PRL.80.3177

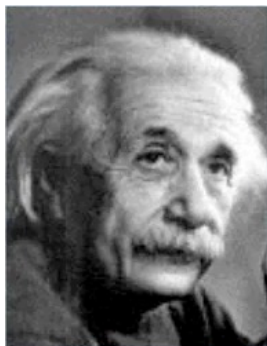
2020-PRC 101, 024913





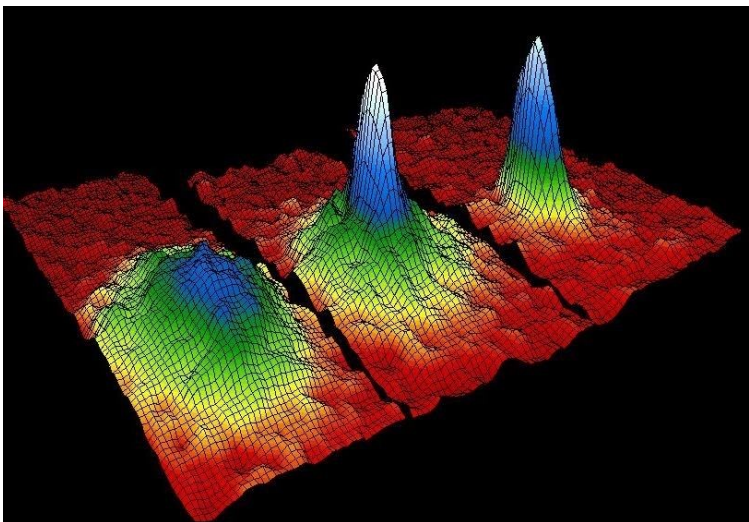
# $\alpha$ 团簇的玻色爱因斯坦凝聚

BEC: Bose-Einstein condensate predicted 1924

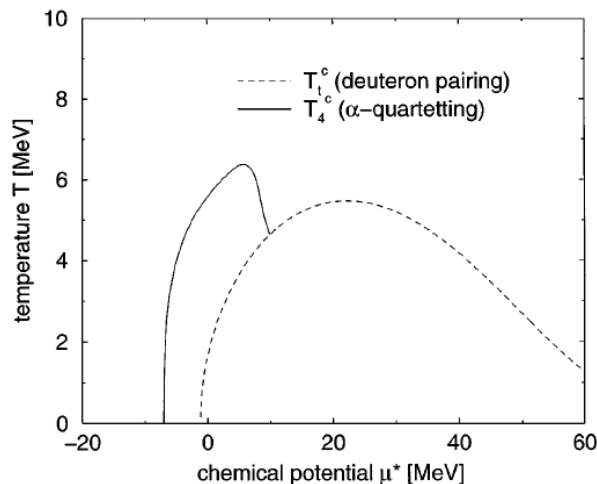


70年

1995年验证/2001年诺贝尔物理学奖  
Eric Cornell, Carl Wieman, Wolfgang Ketterle



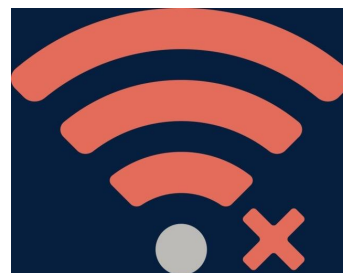
核物质中的 $\alpha$ 团簇及其BEC, 1998预言[PRL.80.3177]



- 2019-PRC.99.024909
- 2019-PRC.100.022201
- 2019-PRC.100.054304
- 2020-PRC.102.035202
- 2020-PRC.102.014305
- 2020-PRC.101.024913

几年后验证?

没有信号

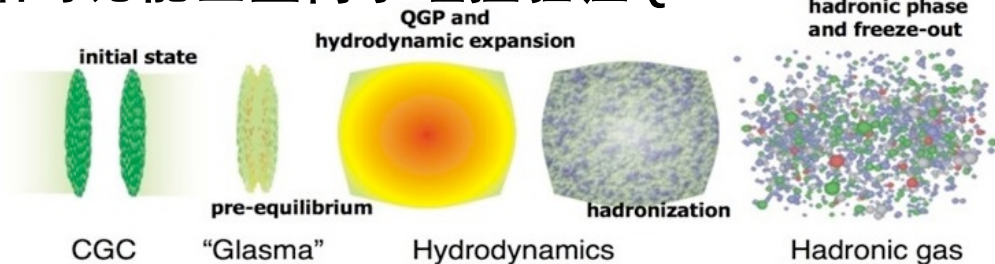


- 2011-PLB 705,65
- 2016-PLB 755, 475
- 2016-PLB 756, 194
- 2019-PRC.100.034320



# 核物质相图的验证——重离子碰撞

## 相对论能区重离子碰撞验证QGP

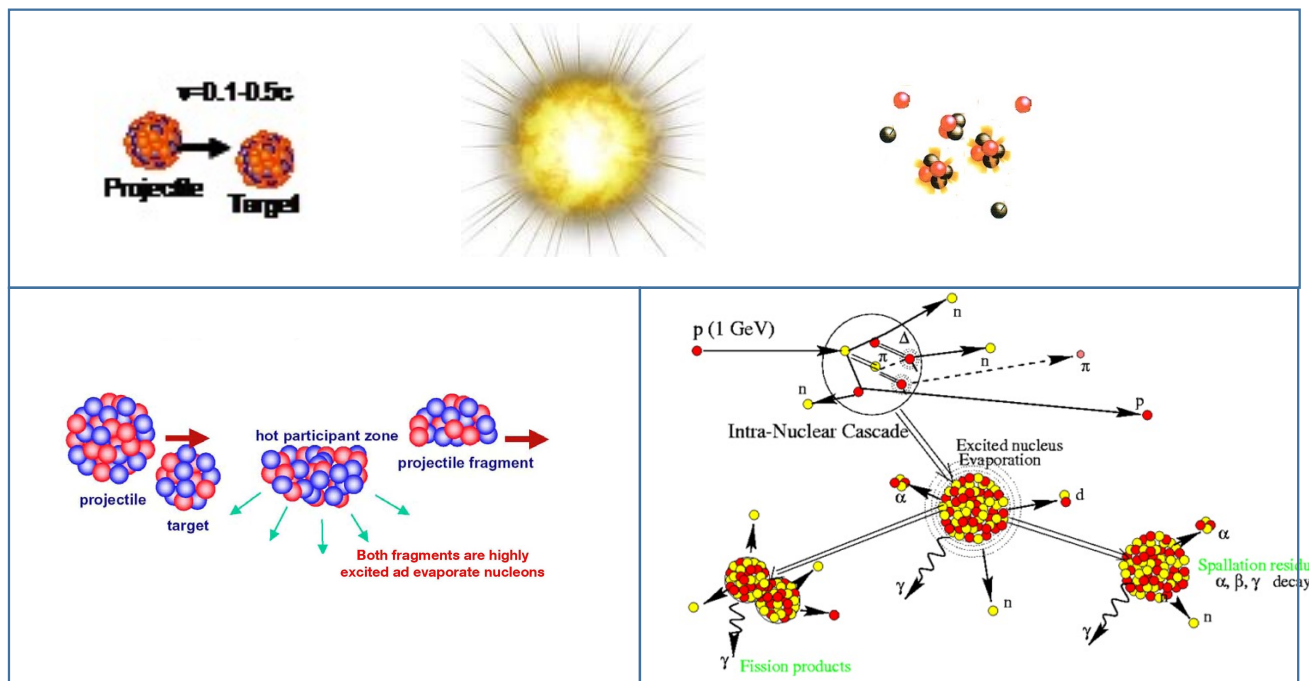
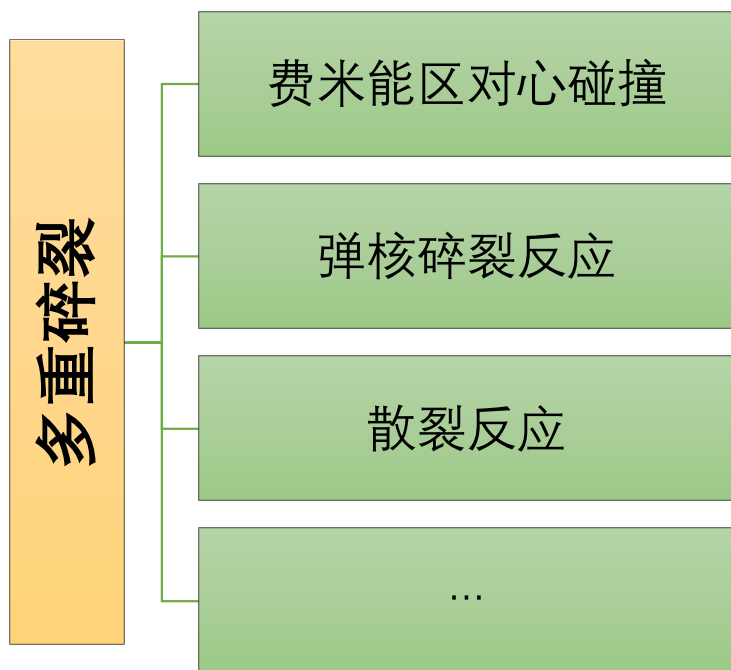


静态的  
无限核物质



反应中的  
有限核体系

## 多重碎裂验证液气相变





# 我的主要工作

✓ **系统性**：多篇论文被高频次引用；

[PRC84(2011)037601]被引32次

[PRC85(2012)017604]被引29次

[PRC87(2013)017602]被引23次

[PRC89(2014)014619]被引20次

(Web of science 2022年2月数据。)

✓ **团队合作**，与实验组交替式推进研究；

✓ **审稿人肯定**；successful/impressive；

✓ **编辑推荐** Editors' Suggestion

[CPC44(2020)084106]

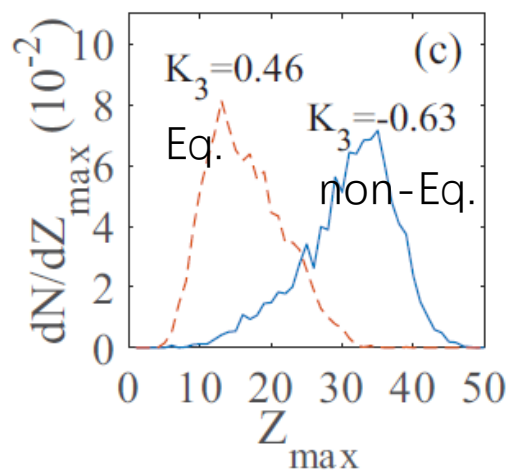
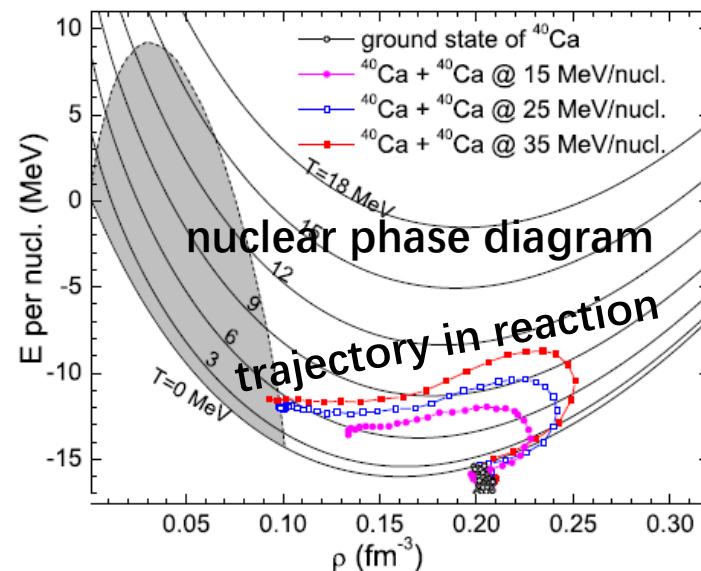
提出了相轨迹分析方法  
[PLB 782(2018)682]

有限尺度  
效应

原子核  
液气相变

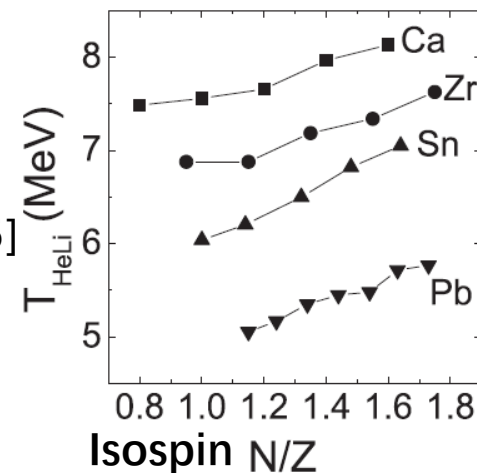
非平衡态  
相变

同位旋  
效应



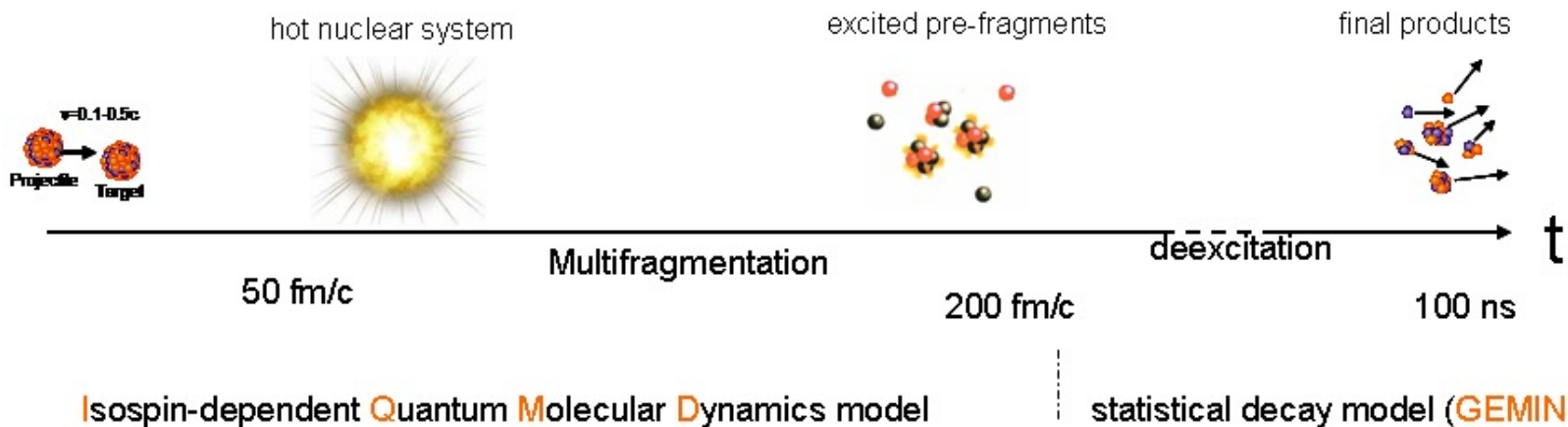
发现了平衡态与非平衡态相变探针的巨大差异  
[PRC105(2022)024608]

证明了相变的同位旋效应  
[CPC44(2020)084106]





# 模型: 量子分子动力学模型

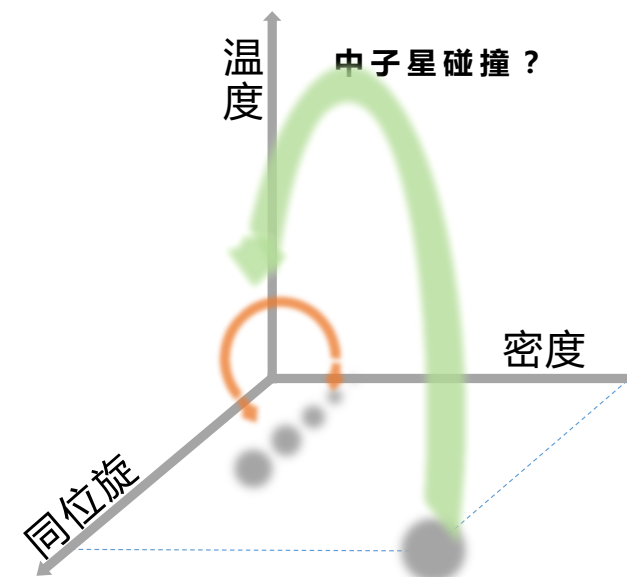


- Evolution in mean field [Code comparison project PRC.93.044609(2016)]

$$\dot{\mathbf{r}}_{i0} = \nabla_{\mathbf{p}_{i0}} H_{eff}$$

$$\dot{\mathbf{p}}_{i0} = -\nabla_{\mathbf{r}_{i0}} H_{eff}$$

- Nucleon-nucleon collision  
 $NN \rightarrow NN$ , Pauli blocking  
 [Code comparison project PRC.97.034625(2018)]  
 $NN \rightarrow N\Delta$ ;  $N\Delta \rightarrow N\Delta$ ;  $\Delta \rightarrow N\pi$ ;  $N\pi \rightarrow \Delta$   
 [Code comparison project PRC.100.044617(2019)]
- Code version: IQMD-BNU (Beijing Normal University)



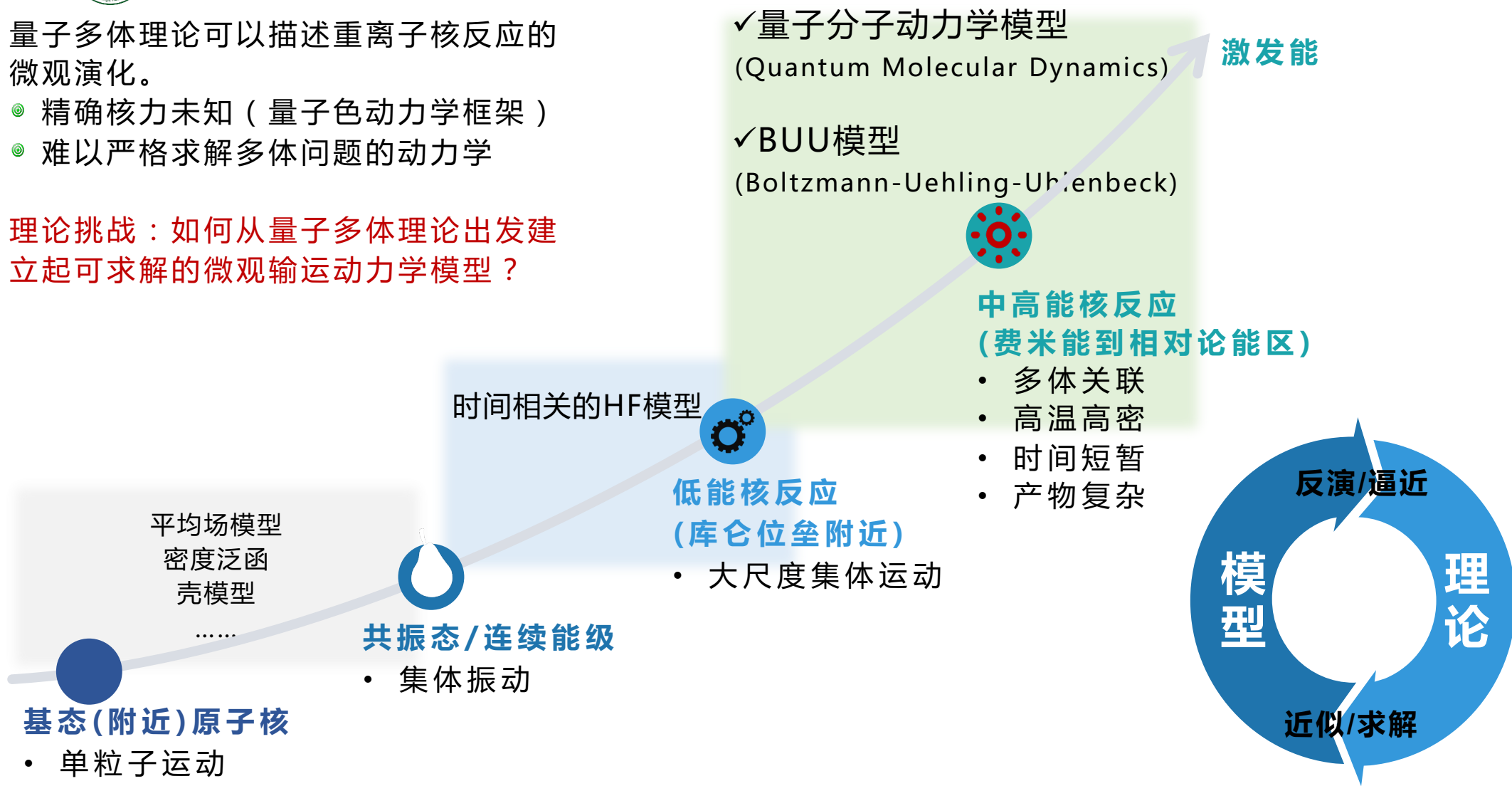


# 原子核尺度的量子多体模型

量子多体理论可以描述重离子核反应的微观演化。

- ◎ 精确核力未知 (量子色动力学框架)
- ◎ 难以严格求解多体问题的动力学

理论挑战：如何从量子多体理论出发建立起可求解的微观输运动力学模型？







## 模型IQMD-BNU是重离子输运模型国际主流之一

研究动机：量子多体理论→可求解的微观输运动力学模型？

### 运输模型的优化

- 更新代码，动力学与统计衰变的耦合；
- 碎裂反应中的奇偶效应研究，论文 [PRC83(2011)014608]被引用38次。

### 领域内认可：运输模型的进一步改进

- 特邀报告，“重离子碰撞的输运理论及裂变现象学术研讨会（2021年桂林）”
- 多篇综述论文引用

Prog. Part. Nucl. Phys. 105 (2019) 139

Prog. Part. Nucl. Phys. 106 (2019) 312

Frontiers of Physics 15 (2020) 54301

始于2009

始于2014

始于2016

始于2020

### 国际合作：加入输运模型评估项目组

- 26套模型参加；
- 获得5次基准计算推荐(仅3套)
- 多篇高被引论文；  
[PRC93(2016)044609]被引94次  
[PRC97(2018)034625]被引68次  
[PRC100(2019)044617]被引33次

### 模型权威：撰写综述论文

- 2篇已经发表  
[PPNP121(2021)103911]；  
[PPNP125 (2022) 103962]



Contents lists available at ScienceDirect

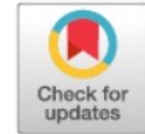
# Progress in Particle and Nuclear Physics

journal homepage: [www.elsevier.com/locate/ppnp](http://www.elsevier.com/locate/ppnp)



## Review

# Transport model comparison studies of intermediate-energy heavy-ion collisions



德国慕尼黑大学Hermann Wolter等人2021年撰写的综述文章“Transport models for intermediate energy heavy-ion studies”中，总结了25种中能区重离子碰撞运输模型；其中，本人发展的IQMD-BNU模型是获得运输模型评估项目全部五次基准计算所肯定的模型之一

QMD Type	Code Correspondents	Energy Range [AGeV]	Relativity	Comparisons
AMD	A. Ono	0.01-0.3	non-rel	1
AMD+JAM	N. Ikeno, A. Ono	0.01-0.3	non-rel+rel	5
BQMD/IQMD	A. Le Fevre, J. Aichelin, C. Hartnack, R. Kumar	0.05-2	rel	1,5
CoMD	M. Papa	0.01-0.3	non-rel	1,3
ImQMD	Y.X. Zhang, N. Wang, Z.X. Li	0.02-0.4	rel	1,2,3
IQMD-BNU	J. Su, F.S. Zhang	0.05-2	rel	1,2,3,4,5
LQMD (QMD-IMP)	Z.Q. Feng, H.G. Cheng	0.01-10	rel	1,2,3,4
IQMD-SINAP	G.Q. Zhang	0.05-2	rel	1
JAM	A. Ono, N. Ikeno, Y. Nara, A. Ohnishi	1-158	rel	3,4
JQMD 2.0	T. Ogawa, K. Niita, S. Hashimoto, T. Sato	0.01-3	rel	3,4
TuQMD/dcQMD	D. Cozma	0.1-2	rel	1,2,3,4,5
UrQMD	Y.J. Wang, Q.F. Li, Y.X. Zhang	0.05-200	rel	1,2,3,5



# 主要结果

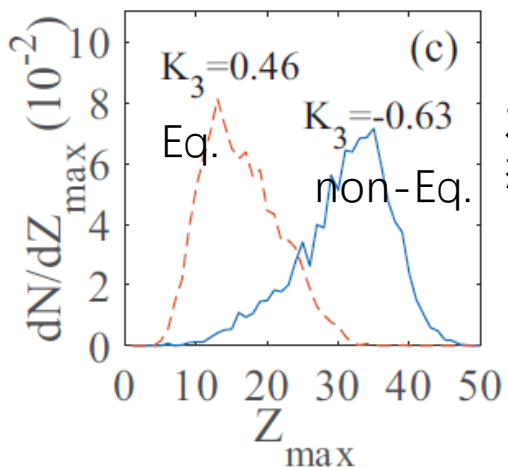
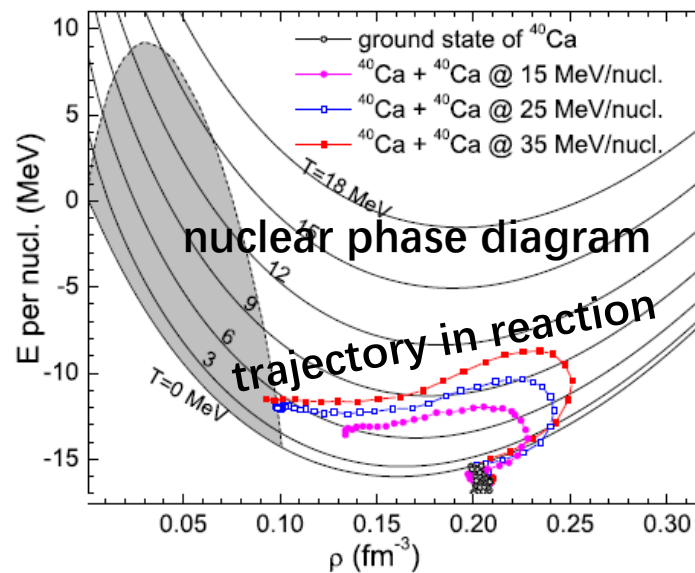
提出了相轨迹分析方法  
[PLB 782(2018)682]

有限尺度  
效应

原子核  
液气相变

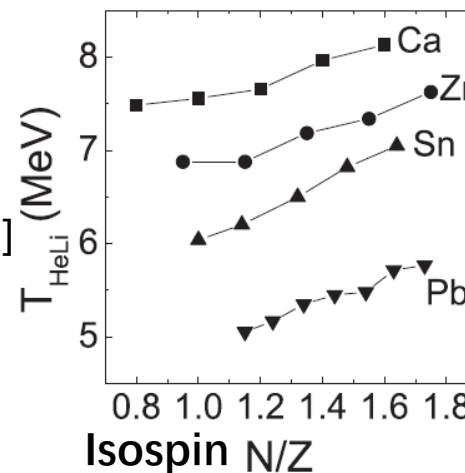
非平衡态  
相变

同位旋  
效应



发现了平衡态与非平衡态相变探针的巨大差异  
[PRC105(2022)024608]

证明了相变的同位旋效应  
[CPC44(2020)084106]





# 核物质相变与重离子碰撞相轨迹

## 体系密度涨落

$$\omega \propto \exp \left[ -\frac{1}{2T} \left( \frac{\partial P}{\partial \rho} \right)_T \left( \frac{\Delta \rho}{\rho} \right)^2 \right]$$

$$\overline{\left( \frac{\Delta \rho}{\rho} \right)^2} \left( \frac{\partial P}{\partial \rho} \right)_T = T$$

## 核物质状态方程

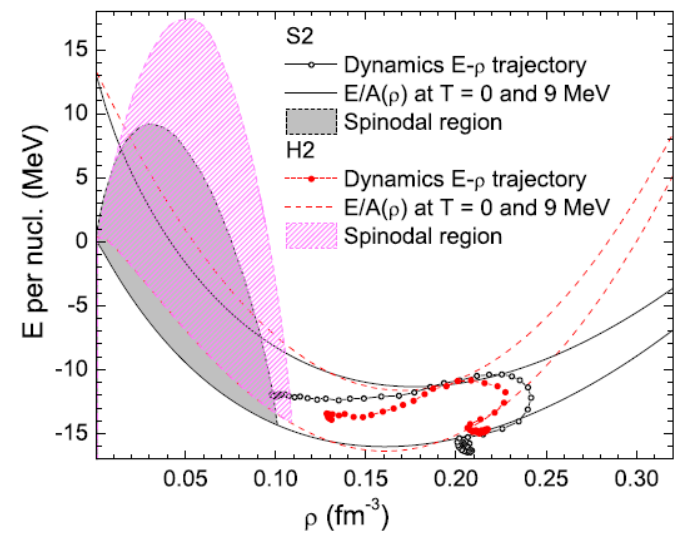
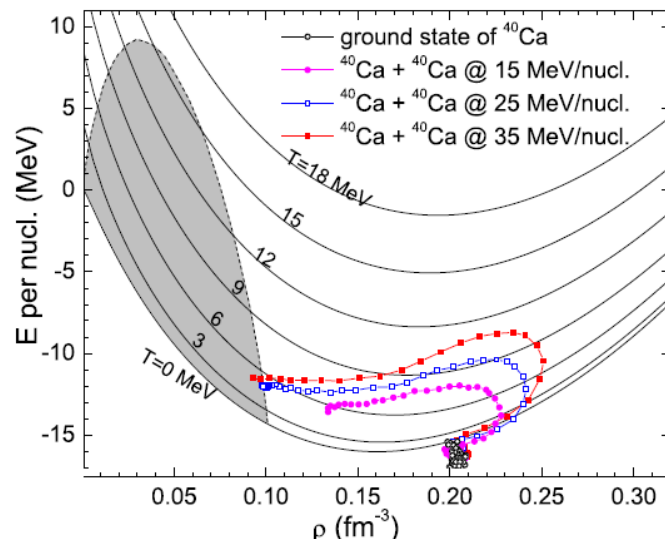
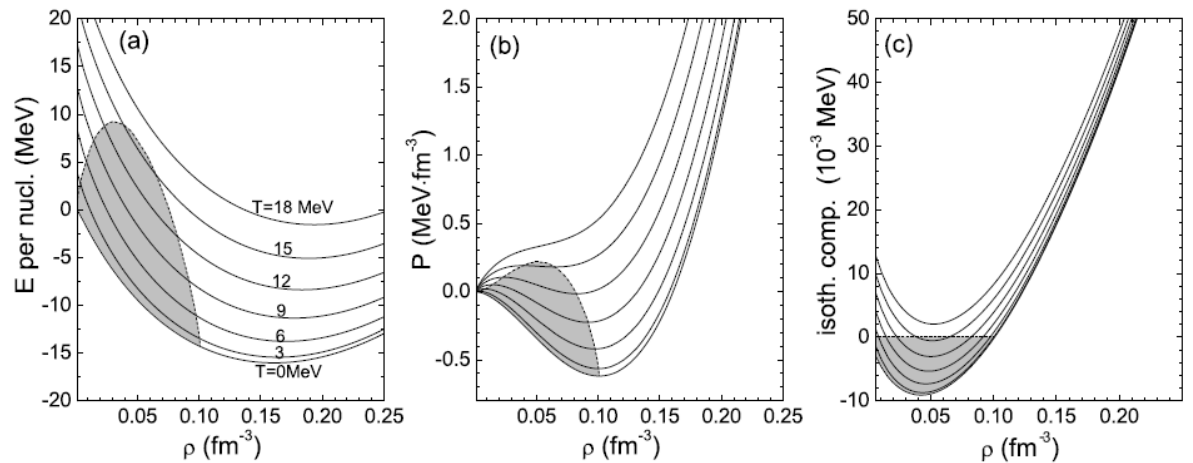
$$V(\rho, \delta) = \frac{\alpha \rho^2}{2 \rho_0} + \frac{\beta \rho^{\gamma+1}}{\gamma+1 \rho_0^\gamma} + \frac{C_{sp}}{2} \left( \frac{\rho}{\rho_0} \right)^{\gamma_1} \rho \delta^2$$

$$E(\rho, \delta, T) = \frac{\int d^3 p \frac{p^2}{2m} f(p)}{\int d^3 p f(p)} + \frac{V(\rho, \delta)}{\rho}$$

$$S = -\frac{2}{h^3} \int d^3 p \sum_{\tau} [n_{\tau} \ln n_{\tau} + (1 - n_{\tau}) \ln(1 - n_{\tau})]$$

$$n_{\tau} = \frac{1}{1 + \exp\left(\frac{p^2}{2m} + u_{\tau} - \mu_{\tau}\right)}$$

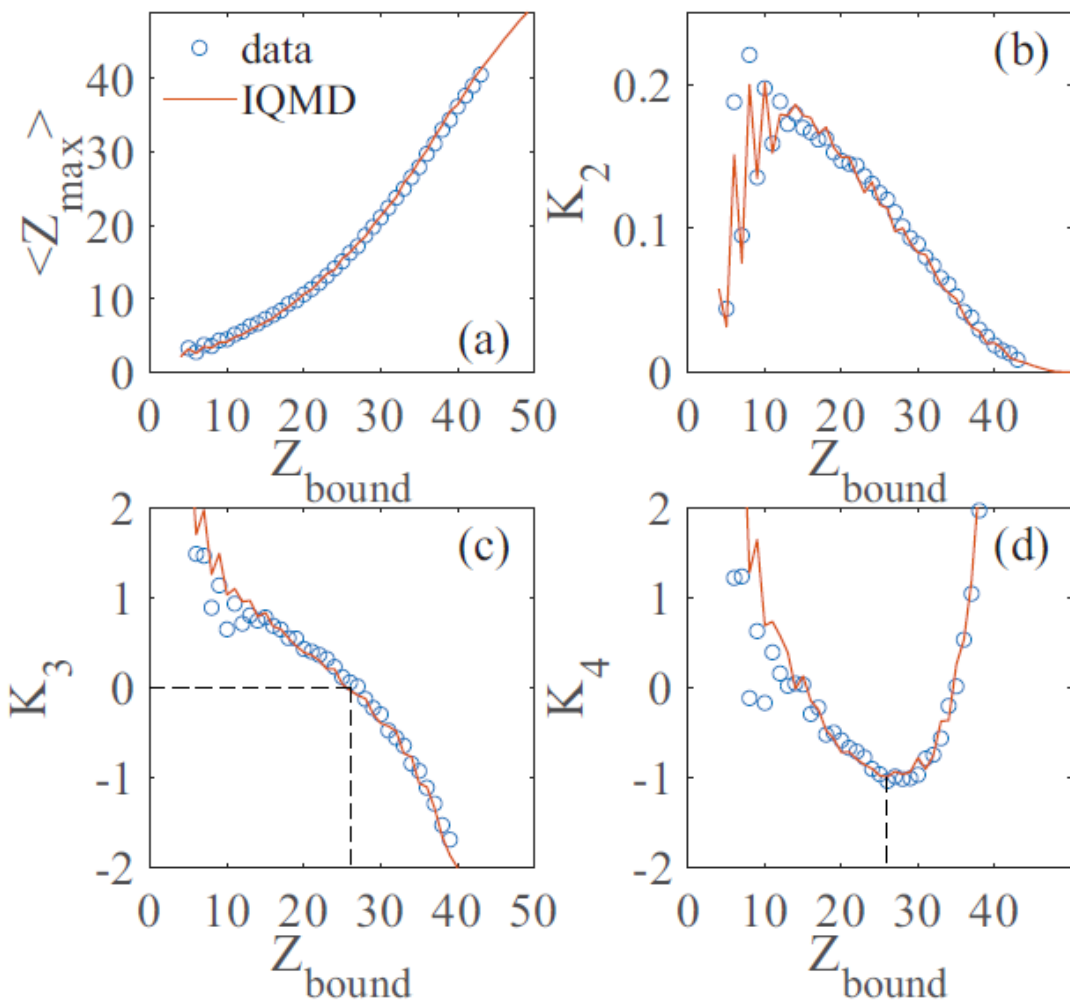
$$P(\rho, \delta, T) = TS - E\rho + \sum_{\tau} \mu_{\tau} \frac{\rho}{2} \left(1 + \frac{|\tau|}{\tau}\right) \delta$$





# 核温度与临界点属性

论文投稿阶段获得审稿人积极评价



PHYSICAL REVIEW C **85**, 017604 (2012)

## Nuclear temperatures from kinetic characteristics

Jun Su,<sup>1,2</sup> Long Zhu,<sup>1,2</sup> Wen-Jie Xie,<sup>1,2,4</sup> and Feng-Shou Zhang<sup>1,2,3,\*</sup>

<sup>1</sup>Technology and Material Modification of Ministry of Education, College of Nuclear

Beijing Normal University, Beijing 100875, China

<sup>2</sup>Beijing Radiation Center, Beijing 100875, China

<sup>3</sup>Nuclear Physics, National Laboratory of Heavy Ion Accelerator of Lanzhou,

<sup>4</sup>Department of Physics, Yuncheng University, Yuncheng 044000, China

(Received 10 January 2012; published 30 January 2012)

论文从投稿到发表仅20天

动力学计算结果符合ALADIN实验相变信号

$$K_2 = \langle (Z_{max} - \langle Z_{max} \rangle)^2 \rangle / \langle Z_{max} \rangle^2$$

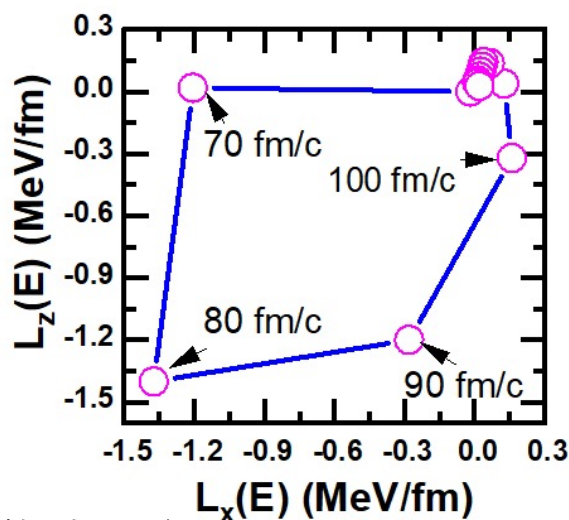
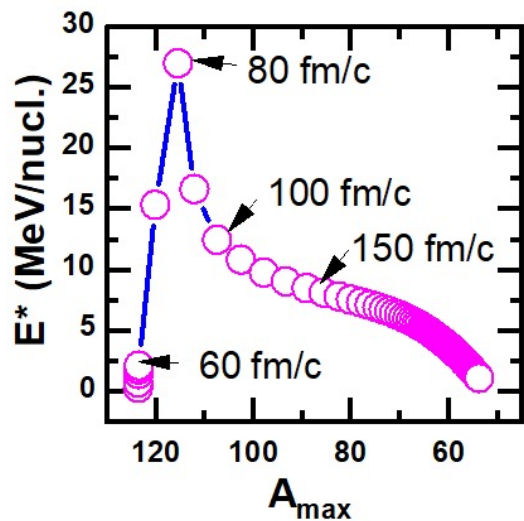
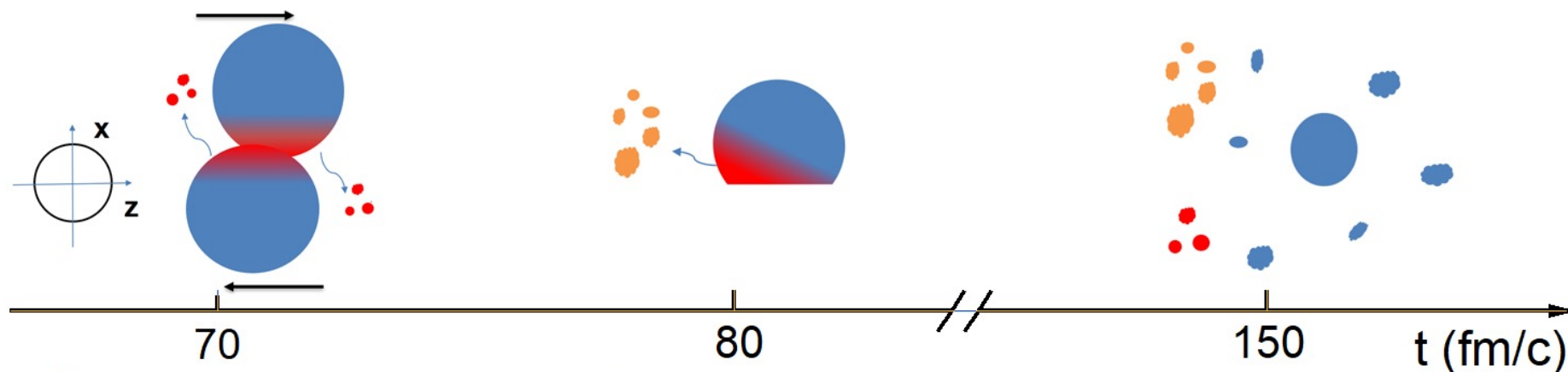
$$K_3 = \langle (Z_{max} - \langle Z_{max} \rangle)^3 \rangle / \langle (Z_{max} - \langle Z_{max} \rangle)^2 \rangle^{3/2}$$

$$K_4 = \langle (Z_{max} - \langle Z_{max} \rangle)^4 \rangle / \langle (Z_{max} - \langle Z_{max} \rangle)^2 \rangle^2 - 3,$$

[PRC105(2012)024608]审稿意见摘录: The agreement with experimental data is **impressive**. Additionally, the authors argue that non-equilibrium effects may play an important role in properly describing experimental data. I find that the content and relevance of reported results is **good enough** to deserve publication in Physical Review C. 本文计算值与实验数据的一致性令人钦佩。此外, 作者认为非平衡效应可能在正确描述实验数据方面发挥重要作用。该论文的内容和意义已经足够好, 值得在Physical Review C上发表。

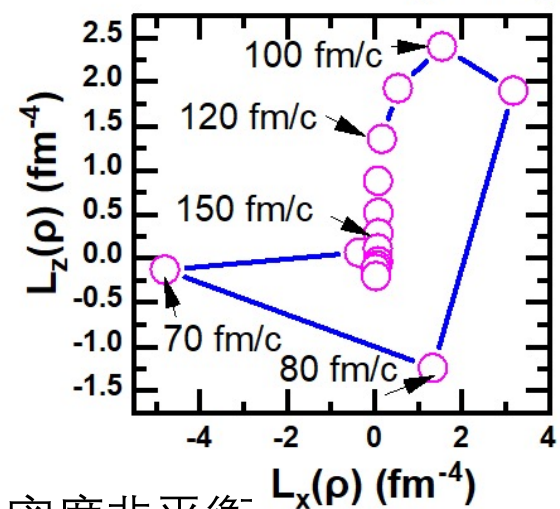


# 重离子碰撞过程中的非平衡



动能非平衡

$$L_x(E) = \frac{\sum_i^N x_i E_i - N \bar{x} \bar{E}}{\sum_i^N x_i^2 - N \bar{x}^2}$$

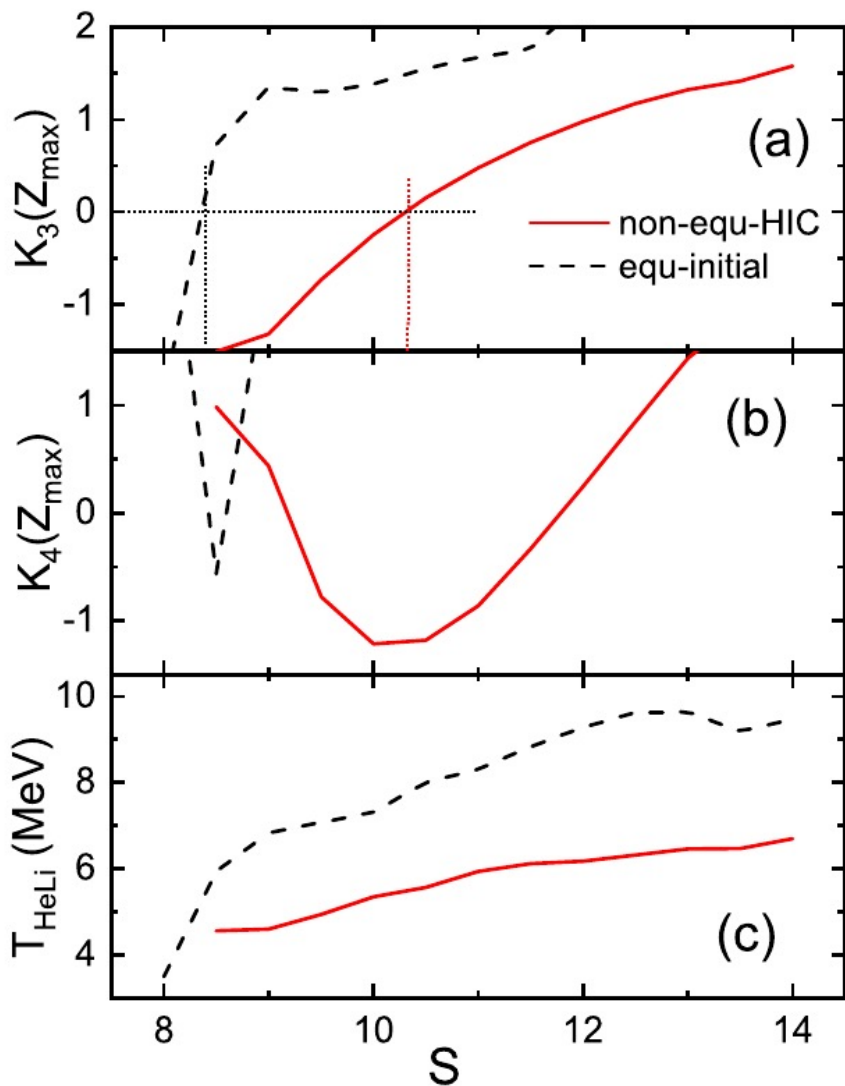


密度非平衡

$$L_x(\rho) = \frac{\sum_i^N x_i \rho(r_i) - N \bar{x} \cdot \bar{\rho}}{\sum_i^N x_i^2 - N \bar{x}^2}$$



## 非平衡特征对最大碎片统计性质的影响



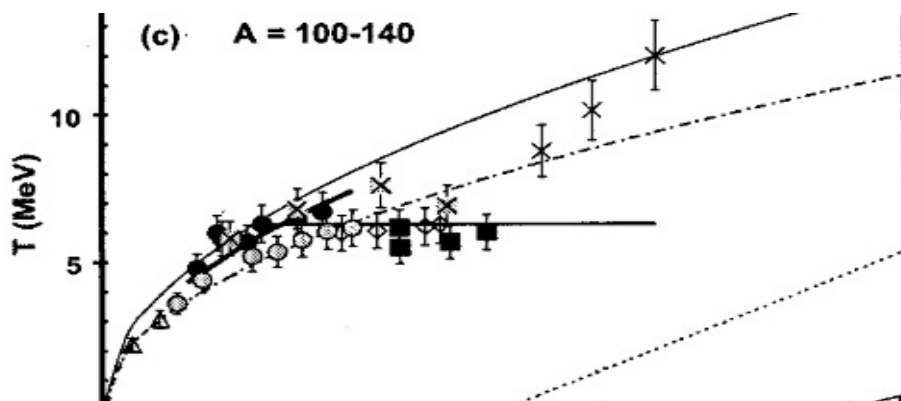
以信息熵作为控制量，依然可以观察到最大碎片电荷高阶涨落的规律变化，这表明信息熵是衡量系统沉积能量的有用观测量。

相变信号明显依赖于演化模式，非平衡系统需要更多的沉积能量才能实现核子蒸发与多重碎裂的过渡。

双同位素温度计计算值在合理范围内 *J. B. NATOWITZ et al. PRC(2002) 65 034618*

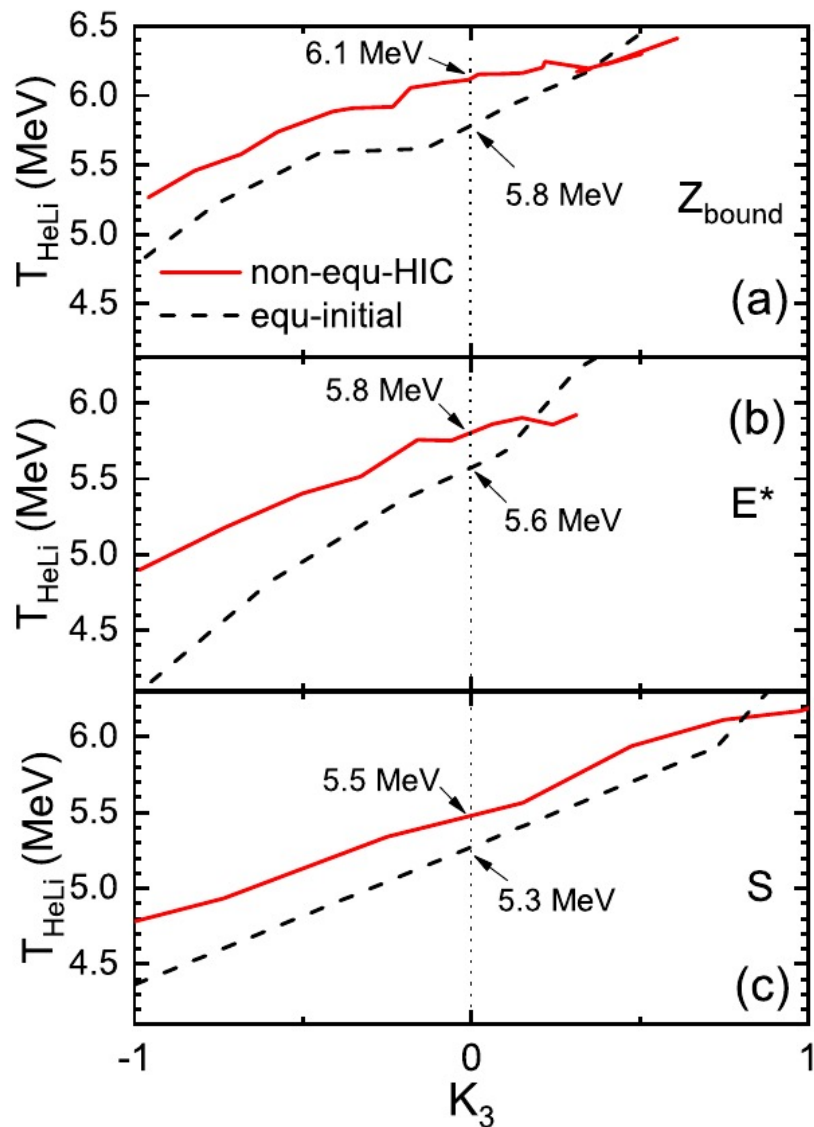
$$T_{\text{HeLi}} = (13.3 \text{ MeV}) / \ln 2.2 \frac{Y_{6\text{Li}}/Y_{7\text{Li}}}{Y_{3\text{He}}/Y_{4\text{He}}}$$

$$S = - \int p(x) \ln(p(x)) dx \quad S = S_r + S_k \geq 3(1 + \ln \pi) \cong 6.434$$





## 临界参数的非平衡效应



非平衡效应明显影响了核液气相变的性质，然而临界参数 (transition temperature) 弱依赖于系统的非平衡 ( $\Delta T = 0.2$  MeV)。

无论以约束电荷，激发能，和信息熵来挑选碎裂事件，非平衡系统指示的过渡温度略大于平衡系统的，这可以为基于平衡态假设模型描述激发核的碎裂带来合理的非平衡修正。

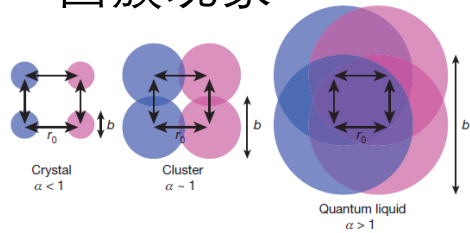
另外，在不同系综中，临界点的确定也没得到统一。



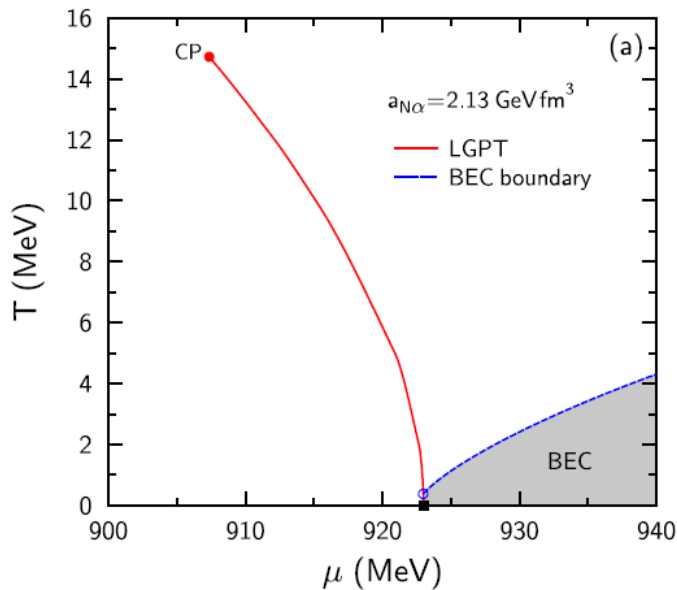


# $\alpha$ 团簇的玻色爱因斯坦凝聚

## 团簇现象



2012-nature11246



1998-PRL.80.3177

2020-PRC 101, 024913

有限体系对应现象

## 谐振子模型

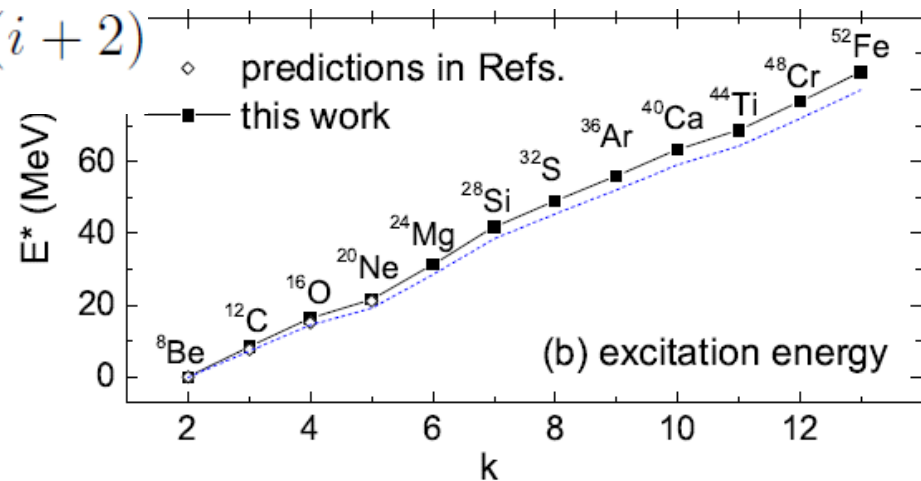
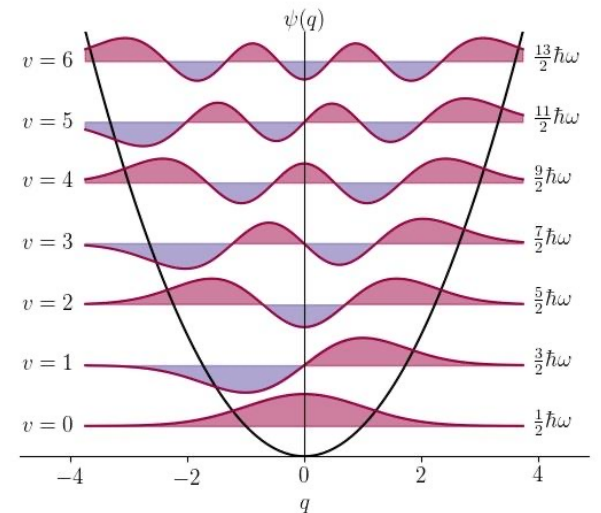
$$\left[ -\frac{\hbar^2}{2M} \nabla^2 + U \right] \psi = E\psi$$

$$U = \frac{1}{2} M^2 \omega^2 - V$$

$$E_i = \left( i + \frac{3}{2} \right) \hbar \omega - V$$

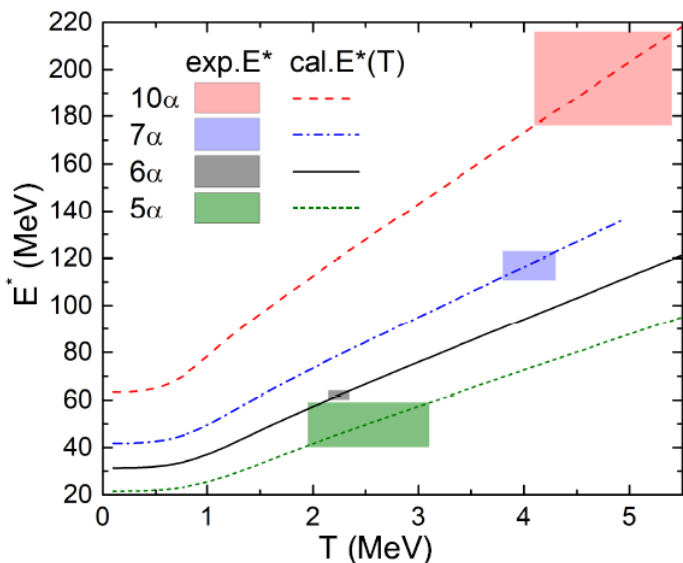
$$i = 2n + l,$$

$$g_i = \frac{1}{2} (i + 1)(i + 2)$$





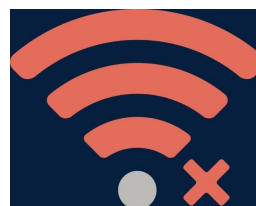
# $\alpha$ 团簇的玻色爱因斯坦凝聚



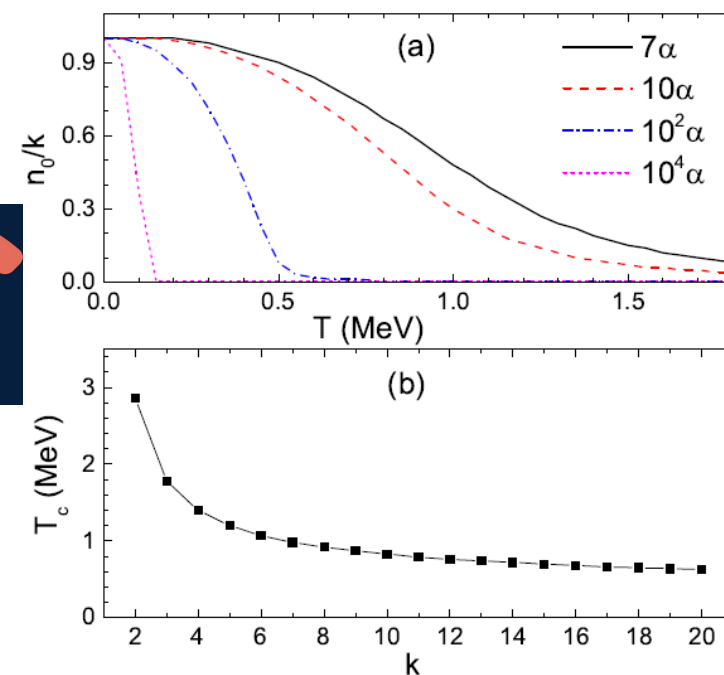
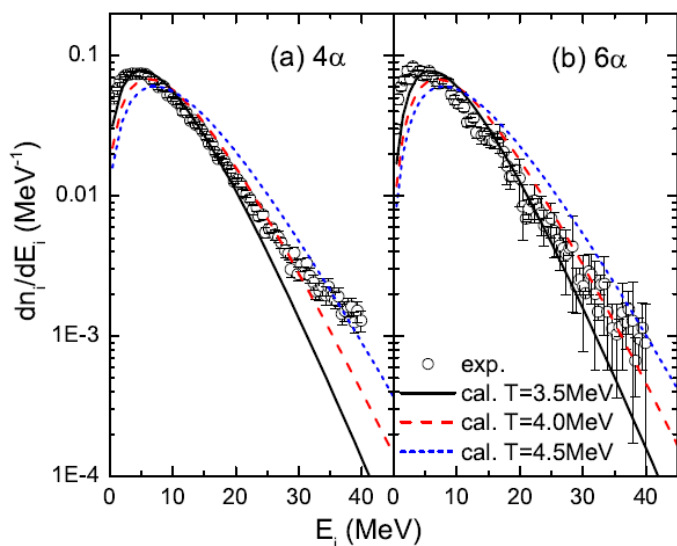
Heavy-ion collision		$k\alpha$ source	T (MeV)	
system	E (MeV/nucleon)		HO model	IQMD
$^{16}\text{O} + ^{12}\text{C}$	10	$5\alpha$	$2.47 \pm 0.47$	
$^{12}\text{C} + ^{12}\text{C}$	7.9	$6\alpha$	$2.25 \pm 0.10$	
$^{28}\text{Si} + ^{12}\text{C}$	35	$7\alpha$	$4.05 \pm 0.25$	5.0
$^{40}\text{Ca} + ^{40}\text{Ca}$	35	$10\alpha$	$4.75 \pm 0.65$	5.5
$^{40}\text{Ca} + ^{12}\text{C}$	25	$4\alpha/6\alpha$	about 4	4.5

$$n_i(E_i) = \frac{g_i}{\exp\left(\frac{E_i - \mu}{T}\right) - 1}$$

温度太高是  
没有信号的原因



- 2011-PLB 705,65
- 2016-PLB 755, 475
- 2016-PLB 756, 194
- 2019-PRC.100.034320



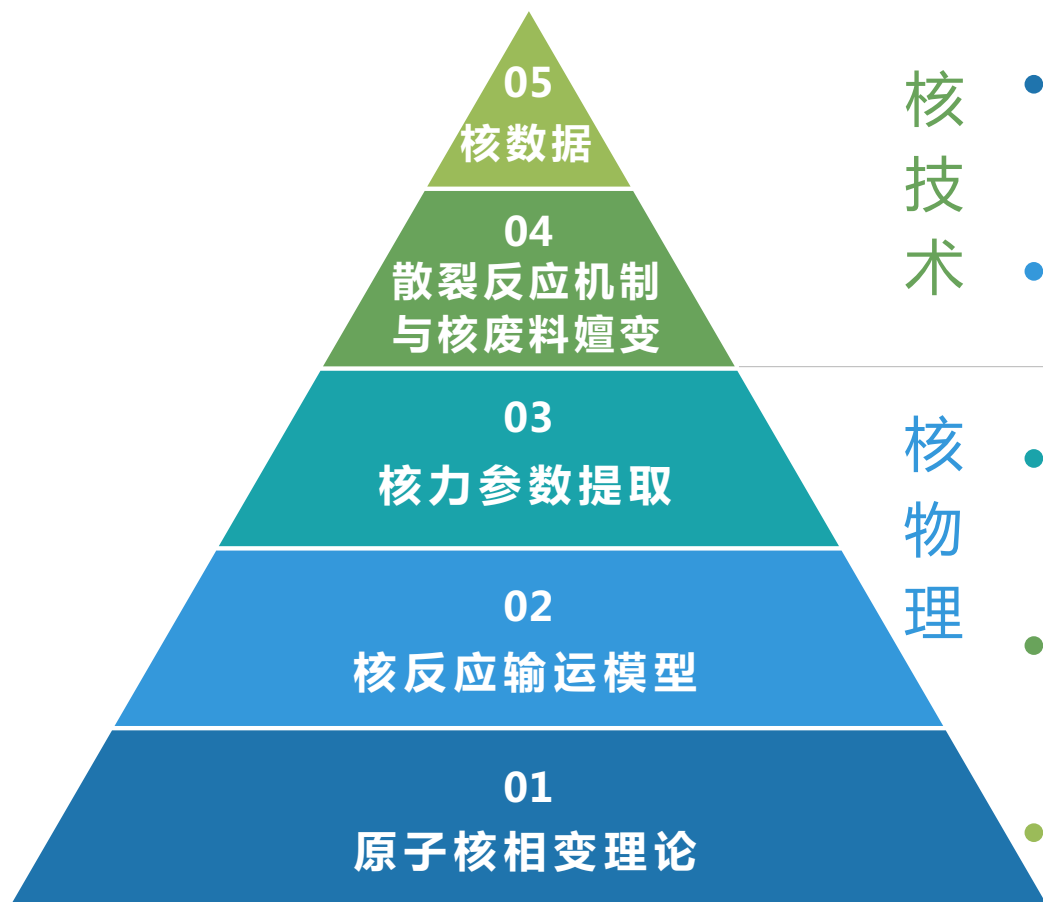


## 总结

- 高能QGP相变与低能液气相变，玻色爱因斯坦凝聚
- 静态无限核物质相变与动力学有限体系的对应现象
- 动力学求解有限体系相变信号
- 非平衡态属性、核物理中的玻色爱因斯坦凝聚



# 结束语

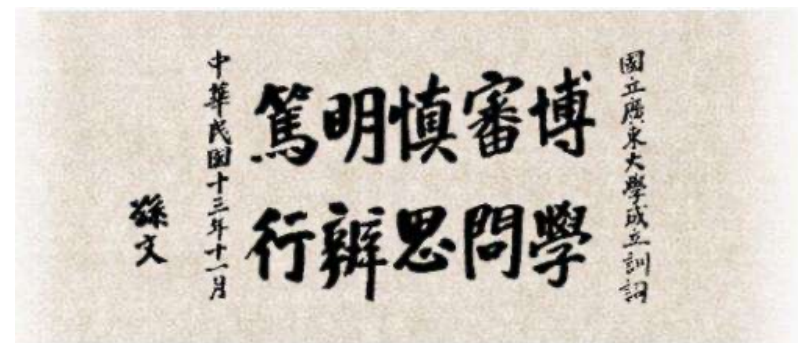


## 核技术

- 数据 校对被采纳算法入指南
- 应用 从机制研究到应用研究

## 核物理

- 机制 实验引用参与实验
- 模型 国际主流领域认可
- 理论 实验报告编辑推荐



# 欢迎批评与指正！