



2026高能与低能核物理交叉学术研讨会

原子核的短程性质与屏蔽效应

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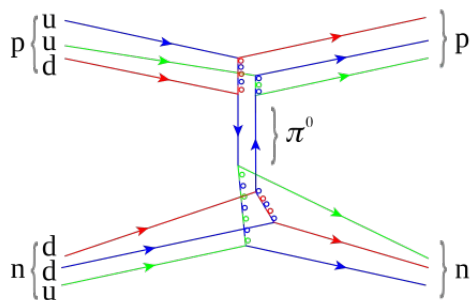
School of Physics, Peking University

华东师范大学, 2026.5.17

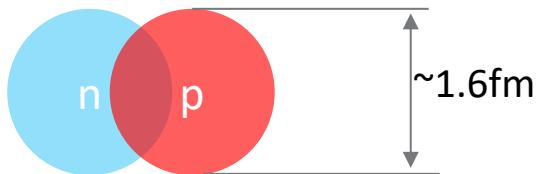
Future problems of nuclear physics

- 相较于其他体系，理解核力本质是一个根本问题

核力的短程部分 <0.6 fm，多体核力的形式，QCD的非微扰性质



Pion exchanges at long and intermediate ranges



Nucleons are not point-like particles
Strongly overlapped at short ranges

- valence quark models fail
- meson exchange fails
- Lattice QCD is still far away



Nuclear forces and QCD
deconfinement
Short range correlations
quark effects in nuclei
**Dense nuclear matter
and neutron stars**
Double-beta decays
High-order transitions
Nuclear reactions
.....

- 近年来量子多体理论方法有了很大进展

IMSRG(PLB-862(2025)139350), quantum Monte Carlo(FCIQMC, arXiv:2508.09252), High-order MBPT(PRC Letter 113, L051302 (2026), Editor's Suggestion), machine learning, quantum computing(Sci.Bull. 71, 1598(2026))...

Nuclear Forces and the Magnetic Moment of the Deuteron

H. S. W. MASSEY & TSI-MING HU

胡济民

Constrain the spatial dependence of tensor force

[Nature](#) 160, 794–795 (1947) | [Cite this article](#)

Nuclear Forces and the Magnetic Moment of the Deuteron

RECENTLY¹ the magnetic moments of the proton, neutron and deuteron have been measured with great precision. It is found that the moment of the deuteron differs from the algebraical sum of the moments of the proton and neutron by an amount much greater than the experimental error. The discovery of the electric quadrupole moment of the deuteron² in 1939 already indicated that the ground-state of the deuteron is not of pure ³S character but contains an admixture of ³D. The observed magnetic moment can be explained if the percentage admixture is 4 per cent. If it can be assumed that relativistic effects are unimportant³, use may be made of this accurate figure to obtain further information about the neutron-proton interaction. Following the method of Rarita and Schwinger⁴ we have taken this to be of the form

$$V(r, \sigma_1, \sigma_2) = - \left\{ (1 - \frac{1}{2}g) + \frac{1}{2}g\vec{\sigma}_1 \cdot \vec{\sigma}_2 + \gamma S \right\} C f(r/a),$$

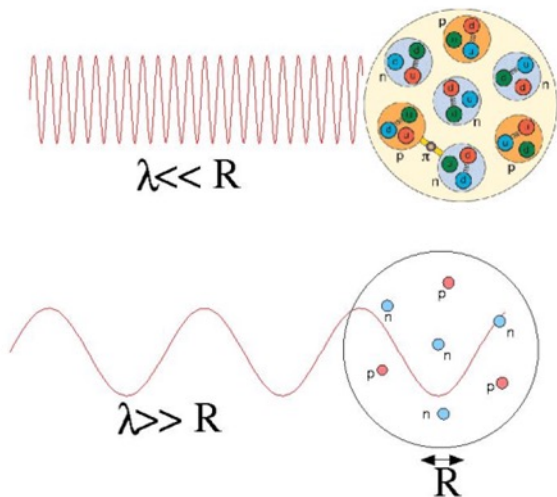
Assumed force law	(a) From magnetic moments	Derived range in 10 ⁻¹³ cm.		
		(b) From scattering of 1-6 MeV. neutrons by protons	(c) From proton-proton scattering	(d) From triton binding energy
Spherical well	2.8	2.45 ± 0.1	2.8	
Gaussian	1.9 ± 0.15	—	1.94	2.22 ⁷
Yukawa	1.4 ± 0.05	1.8 ± 0.05	1.18 _s	1.83 _s ⁷
Exponential	1.6 ± 0.05	1.75 ± 0.05	1.73	1.73 _s ⁸

It will be seen that, while the results of the different methods are reasonably consistent for three of the radial forms assumed, the Yukawa potential appears quite unsatisfactory in this respect.

Indication: one-pion exchange is not enough!

Chiral effective field theory

- 有效场论：能标与分辨率相关



Effective theory of QCD at low energy:
 Chiral EFT: resolution ~ 1 fm
 Pionless EFT: resolution a few fm

	2N Force	3N Force	4N Force
LO $(Q/\Lambda_\chi)^0$		$V_{\text{LO}} = V_{1\pi} + V_{\text{ct}}^{(0)},$	
NLO $(Q/\Lambda_\chi)^2$		$V_{\text{NLO}} = V_{\text{LO}} + V_{2\pi}^{(2)} + V_{\text{ct}}^{(2)},$ $V_{\text{N}^2\text{LO}} = V_{\text{NLO}} + V_{2\pi}^{(3)},$	
NNLO $(Q/\Lambda_\chi)^3$			
N ³ LO $(Q/\Lambda_\chi)^4$			
N ⁴ LO $(Q/\Lambda_\chi)^5$			

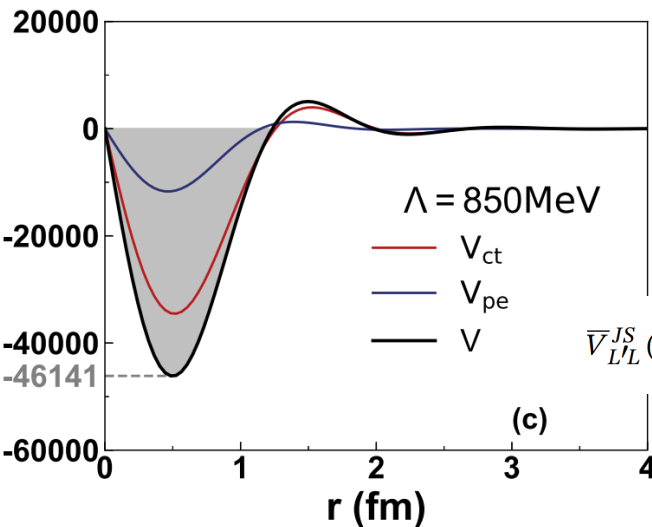
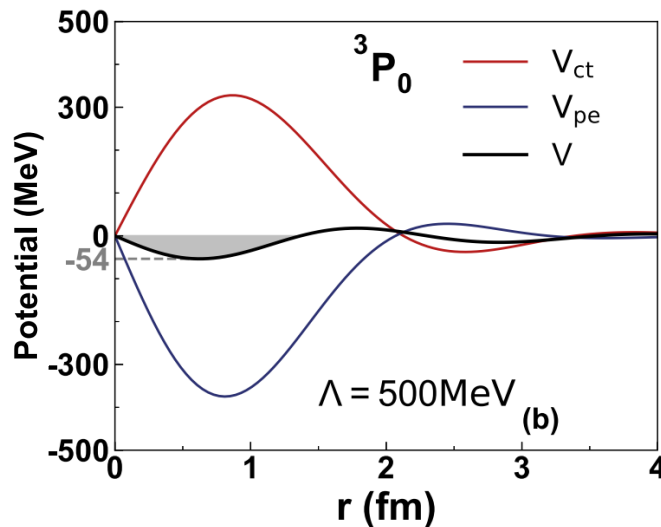
S. Weinberg, Phys. Lett. B251, 288 (1990)

Issues of chiral EFT

- Regulator and Cutoff dependence

$$f(p', p) = \exp[-(p'/\Lambda)^{2n} - (p/\Lambda)^{2n}]$$

High momentum cutoff is not allowed: not renormalizable



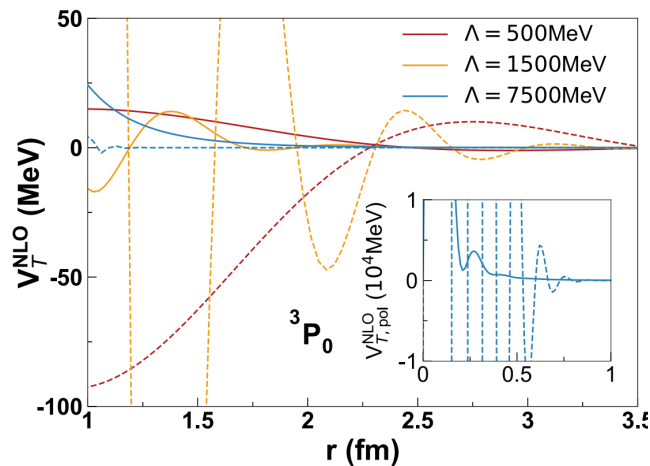
Local projection method:
From momentum to
coordinate-space

$$\bar{V}_{L'L}^{JS}(r) = N_{L'} \int_0^\infty dk dk' \frac{k^2}{k'} j_L(kr) V_{L'L}^{JS}(k', k)$$

Appearance of spurious bound states at N3LO

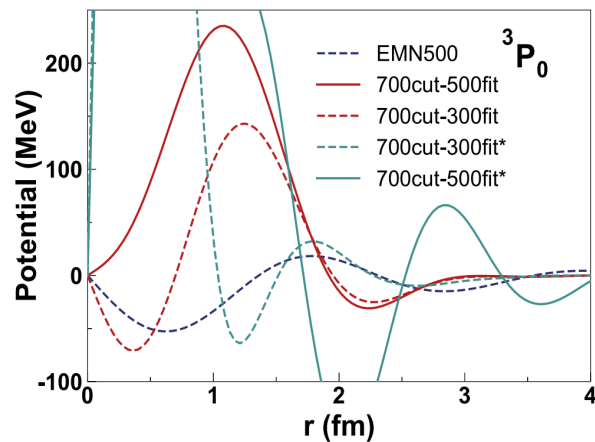
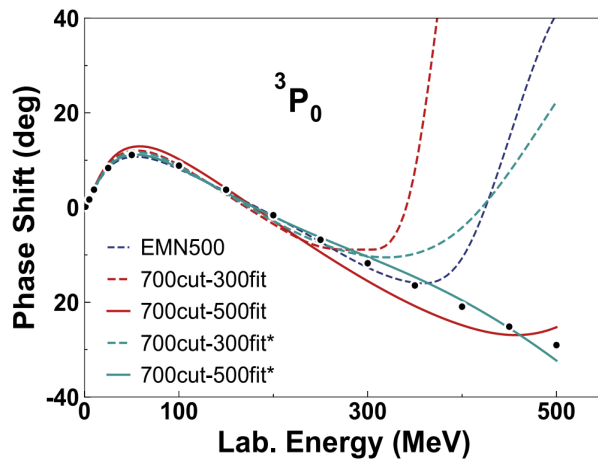
Issues of chiral EFT

Behaviors of oscillations



$$V_T^{\text{NLO}} = V_{T,\text{SF}}^{\text{NLO}} + V_{T,\text{pol}}^{\text{NLO}}$$

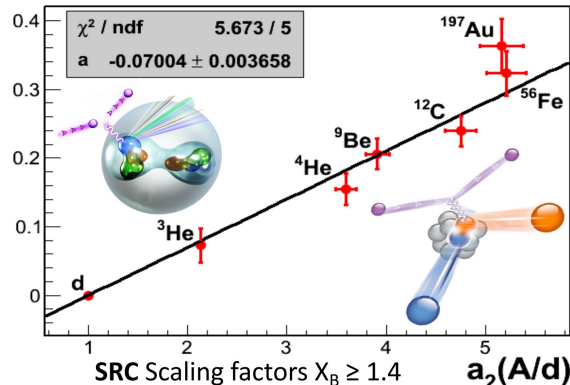
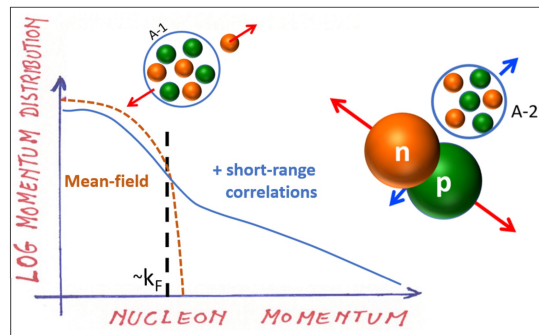
Phase shift and local potential



- Problems in P-wave, but not present in S-wave and D-wave
- High-cutoff is useful for studies of short-range properties and dense nuclear matter

Short Range Correlations: Quark effects in nuclei

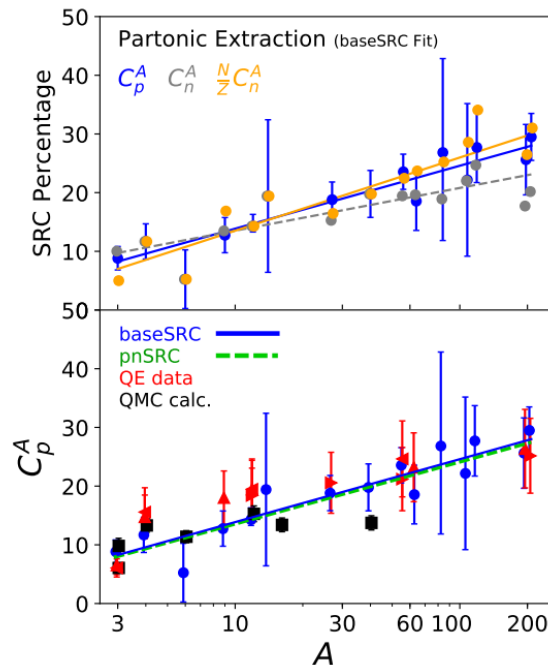
- 核子-核子短程关联：低能与高能核物理的跨能标交叉点
Relevant to nuclear force at short ranges, modification of quark-gluon distribution (PRL 133, 152502-2024), dense nuclear matter, ...



SRC scaling factor a_2 is proportional to EMC effect

PRL 106, 052301(2011)

$$a_2 \sim L \frac{NZ}{A}, L \text{ is Levinger constant}$$

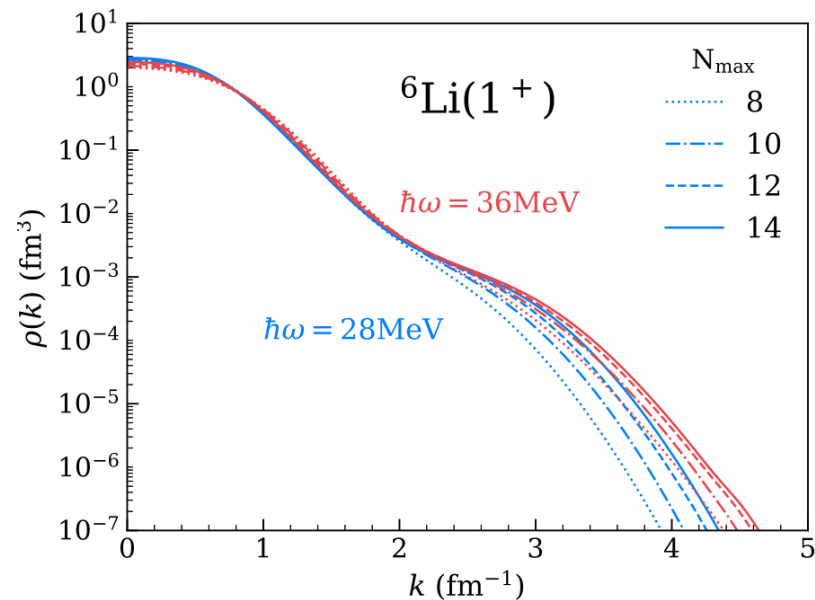
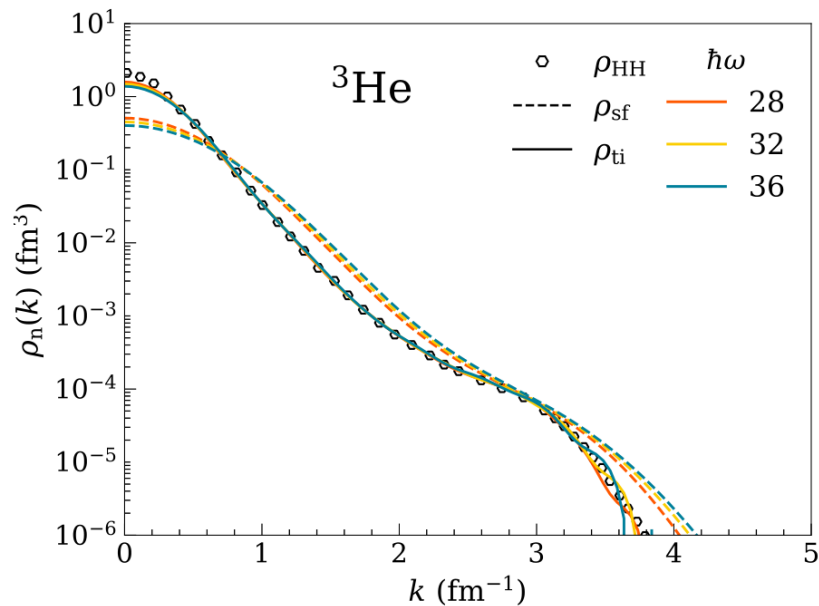


SRC motivated nuclear-PDFs

SRC Scaling factor

- **First NCSM calculations of SRC scaling factor**
- NCSM+N⁴LO chiral force (no softening)
- Decouple CoM motion in momentum space (New)

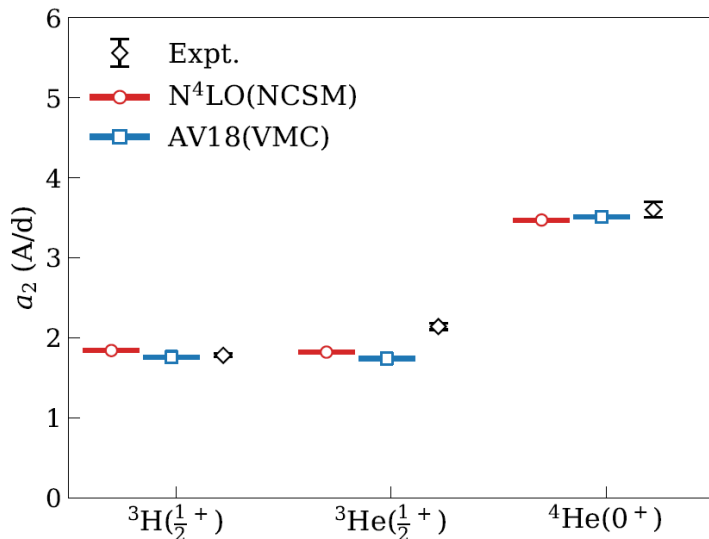
$$\rho_{\text{ti}}(\vec{k}) = \mathcal{F} \left[\frac{\mathcal{F}^{-1} [\rho_{\text{sf}}^{\omega}(\vec{q})] (\vec{r})}{(2\pi)^3 A^3 \mathcal{F}^{-1} [\rho_{\text{cm}}^{\omega}(A\vec{K})] (\vec{r})} \right] (\vec{k}).$$



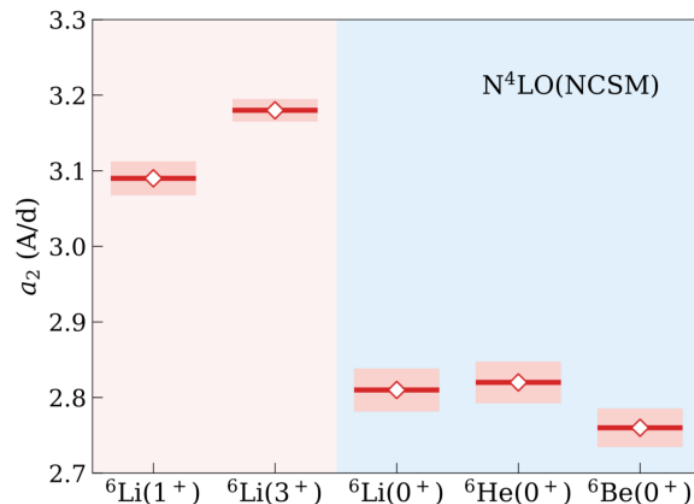
SRC Scaling factor

- First NCSM calculations of SRC scaling factor

$$a_2(A/d) \simeq \lim_{k \rightarrow \infty} \frac{\rho_{\text{ti},A}(k)}{A \left| \tilde{\psi}_d(k) \right|^2}$$



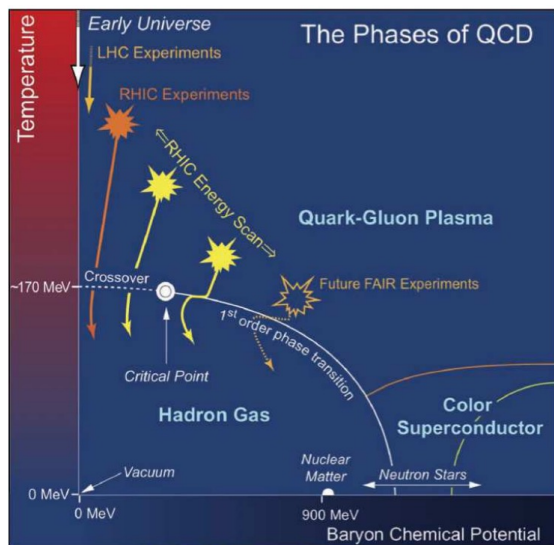
HY Shang, J Chen, R Hu, X Zhen, C Jiang, JC Pei, PLB 871,139976(2025)



SRC标度因子 a_2 与核态有关：多体效应

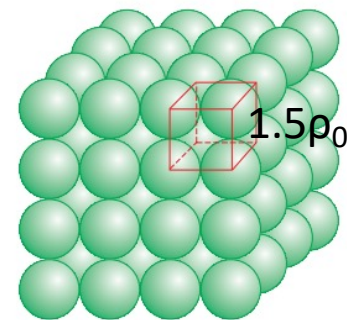
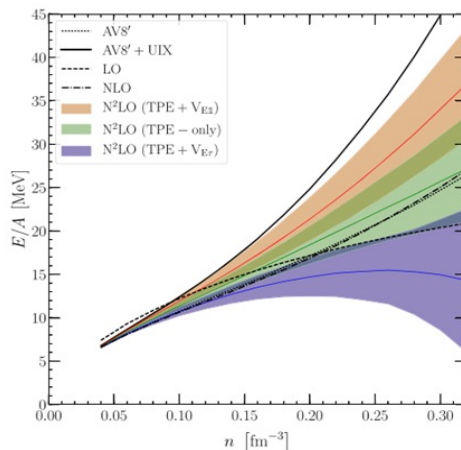
- a_2 is close in isobaric analog states, mainly ${}^1\text{S}_0$ (T=1), while ${}^3\text{S}_1$ (T=0) is suppressed
- Related to the deuterium-like abundance

Dense nuclear matter



- Fundamental interest for strong interactions and phase transition
- Equation of State (EoS) is vital for neutron stars

χ EFT uncertainties



Strongly overlapped at $2.0\rho_0$

Brainwashed by Feynman?

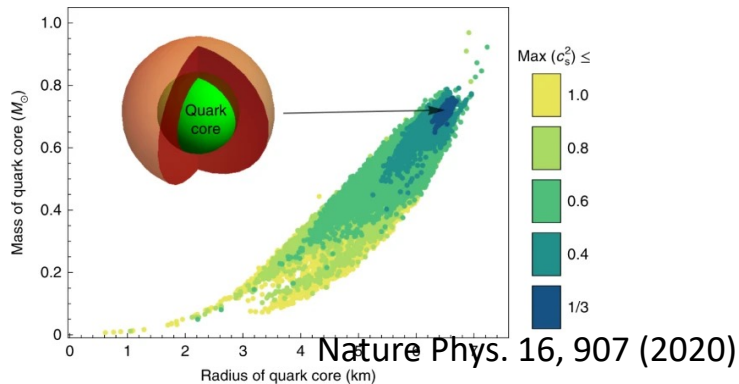
Philip W. Anderson

Physics Today 53, 11(2000)

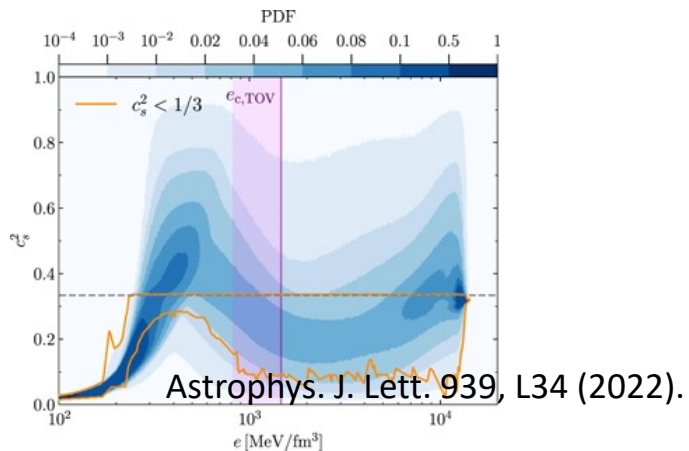
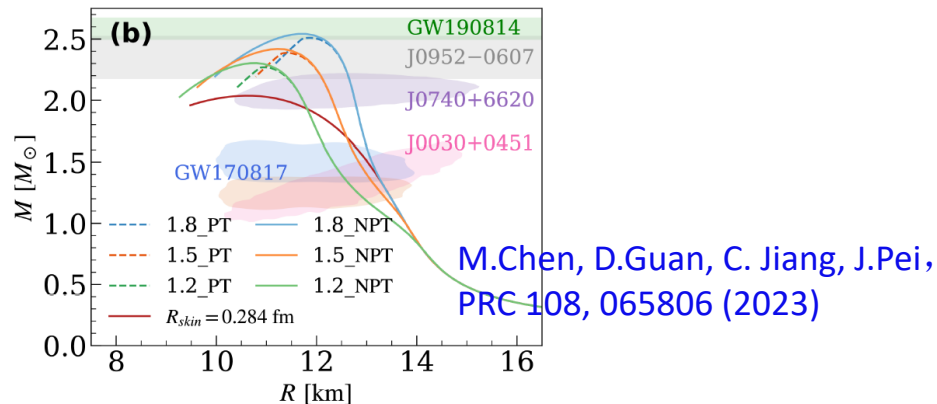
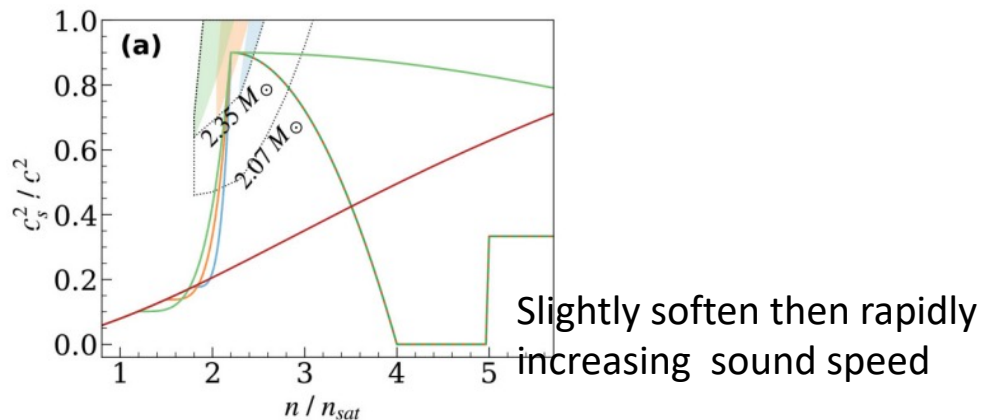
- Pion-exchange picture may not be applicable at short ranges

Dense nuclear matter

● 声速对 neutron star 状态方程的约束



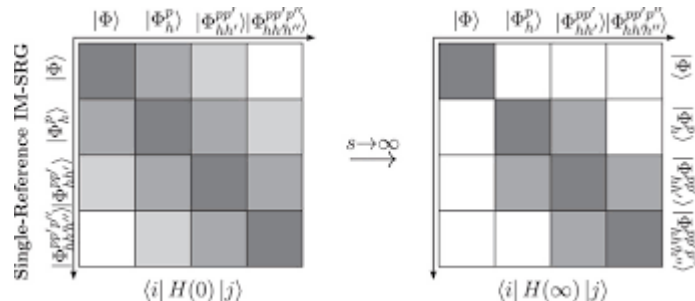
EoS related to thick neutron skin of 208Pb



Dense nuclear matter

- 介质相似重整化群理论-IMSRG

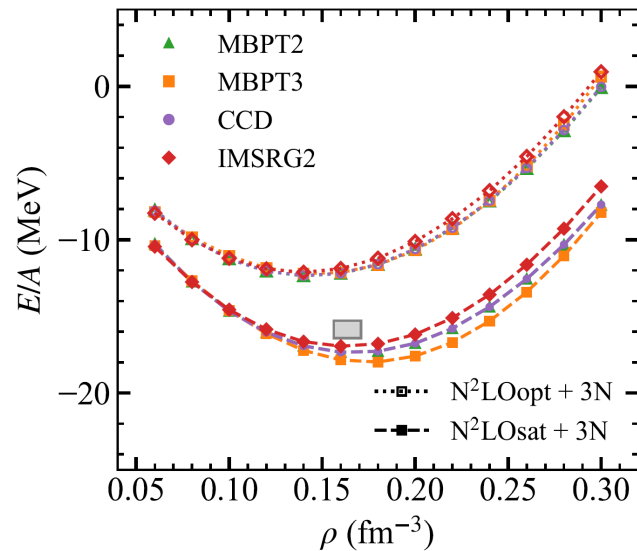
第一性原理非微扰计算核物质状态方程（需要自主的EOS）



$$H(s) = U(s)H(0)U^\dagger(s).$$

X Zhen, R Hu, H Shang, J Chen, JC Pei, FR Xu, PLB 862, 139350(2025)

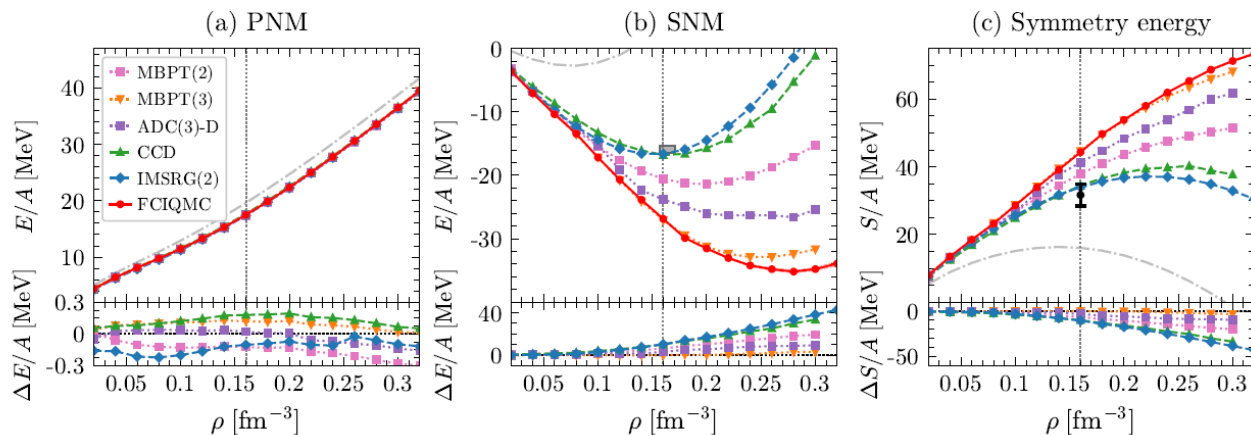
Inference of phase transition, hyperon puzzle, ...



- Build code from scratch: IMSRG, MBPT, Coupled Cluster
- Non-perturbative calculations of strongly correlated systems
- Considerable differences using hard nuclear forces for symmetric nuclear matter

Dense nuclear matter

- **全组态空间量子蒙卡 (FCIQMC)** : *Ab initio* Exact Calculation of Strongly-Correlated Nucleonic Matter
- Full many-body correlations, no Fermion sign problem
- for rigorously benchmark many-body methods and assess the degree to which the nucleonic matter is strongly correlated



Symmetric nuclear matter is strikingly strongly-correlated than expected
Raising questions on previous *ab initio* calculations of nuclear matter with truncations

多体微扰理论高阶计算PTQMC

- 三阶以上MBPT计算由于组态空间指数增长而几乎无法实现
- 采用量子蒙特卡罗组态空间随机游走, 避免显示计算高阶图或算符, 实现16阶计算
- 经过Padé求和得到精确的多体关联
- 基于香农熵的有效组态数表示波函数复杂度, 微扰收敛性与适用边界

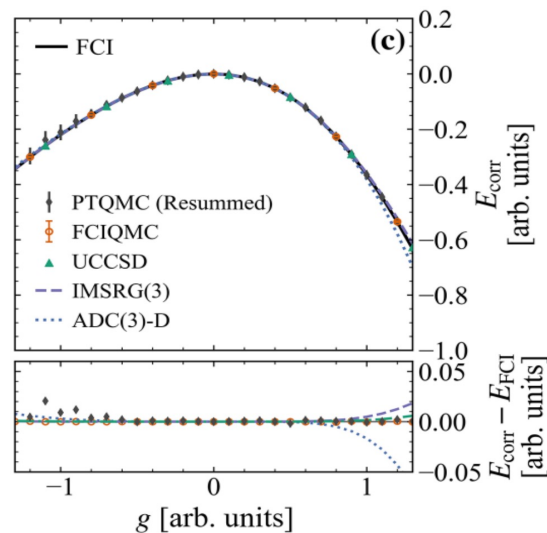
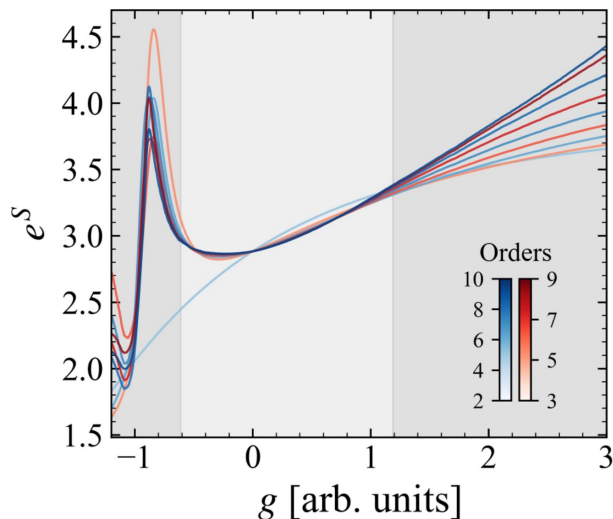
PHYSICAL REVIEW C **113**, L051302 (2026)

Letter

Editors' Suggestion

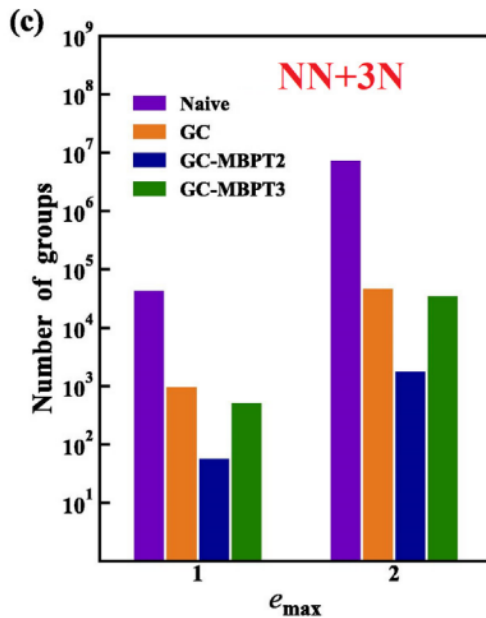
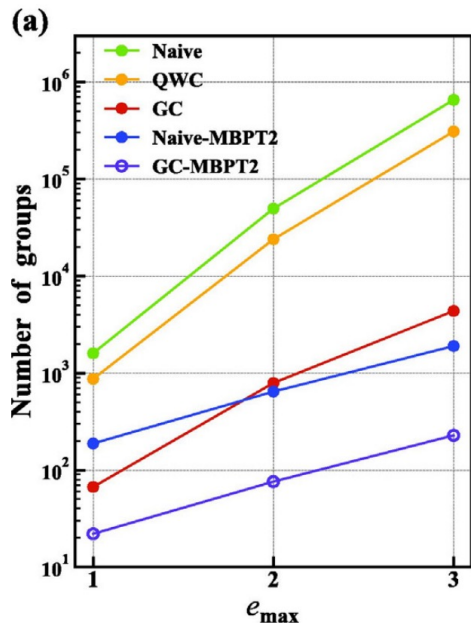
Stochastic many-body perturbation theory for high-order calculations

X. Zhen¹, R. Z. Hu¹, J. C. Pei^{1,*} and F. R. Xu^{1,2,†}



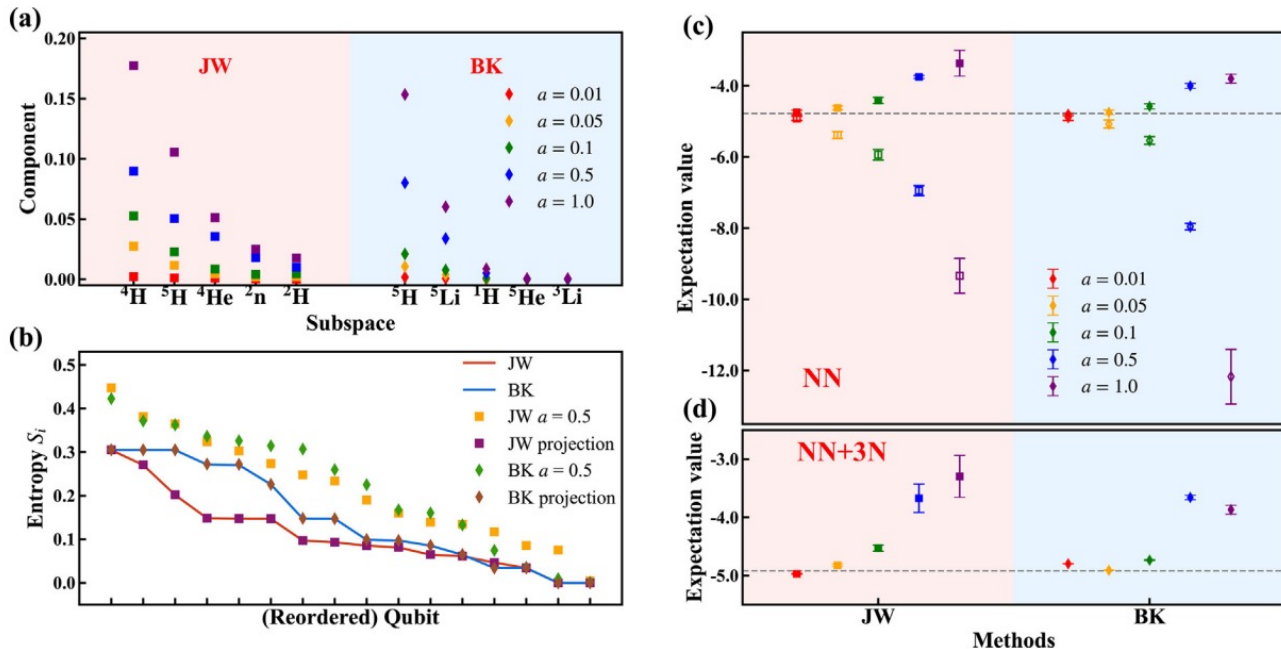
第一性原理核结构量子计算

- 变分量子计算瓶颈：算符测量极其耗时，含噪音的量子比特门
- NN+3N手征核力，NCSM无核芯壳模型模拟计算 ${}^3\text{H}$ ，16个含噪音的量子比特
- 基于算符对易关系采用GC同时分组测量，显著减少测量时间（2~3个量级）



第一性原理核结构量子计算

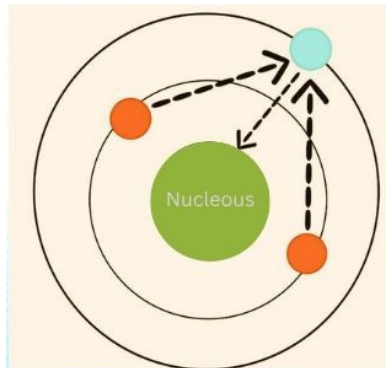
- 噪音导致model space受到 2^N 个所有组态的扩散污染，守恒量遭到破坏
- 采用对称性投影测量，特别是粒子数恢复，极大改善了测量精度



原子核屏蔽效应 Screening effect

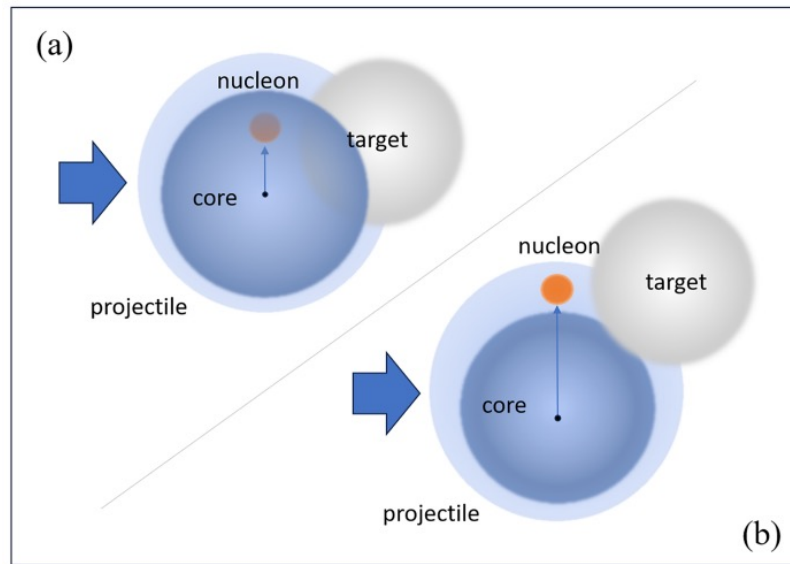
- 电子屏蔽效应:

outer electrons have weaker interaction with the nucleus due to screening

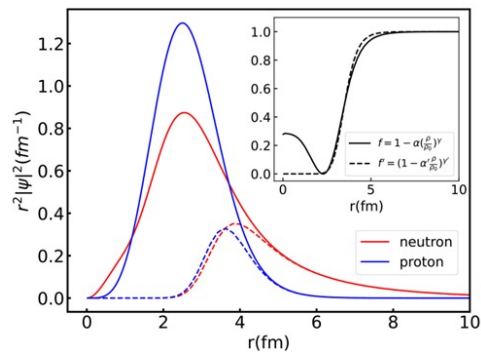


- 核子屏蔽效应:

it is difficult for heavy ion targets to “see” deeply bound nucleons



对敲出反应中谱因子压低之谜的解释

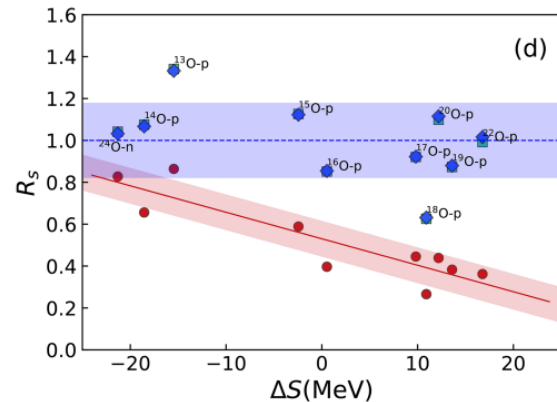
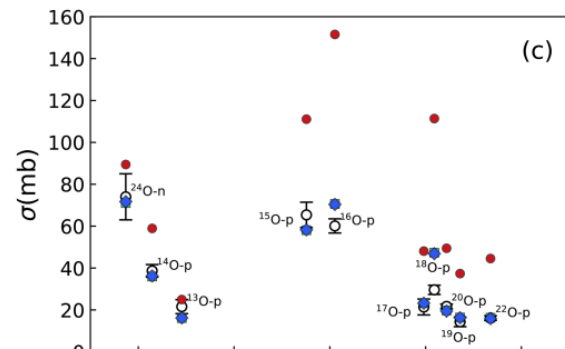
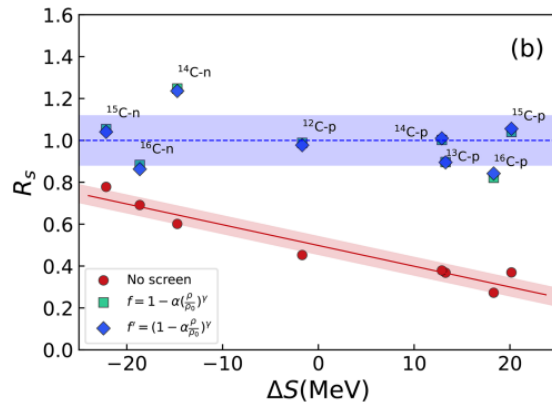
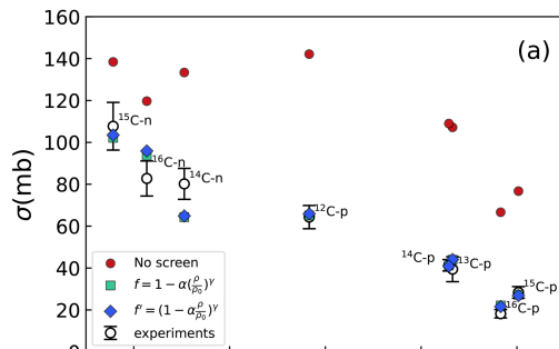


$$\sigma_{\text{sp}}^{\text{str}} = \frac{1}{2j+1} \sum_m \iint d\mathbf{b}_n d\mathbf{r} (1 - |S_n(b_n)|^2) \times |S_c(b_c)|^2 |\psi_{jm}(\mathbf{r})|^2,$$

$$\sigma_{\text{sp}}^{\text{dif}} = \frac{1}{2j+1} \sum_m \iint d\mathbf{b}_n d\mathbf{r} |S_n S_c - \langle S_n S_c \rangle|^2 |\psi_{jm}|^2$$

$$f(r) = 1 - \alpha \left(\frac{\rho(r)}{\rho_0} \right)^\gamma,$$

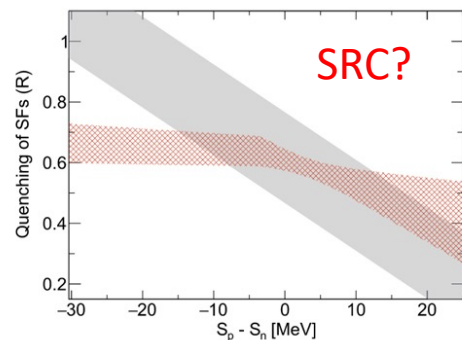
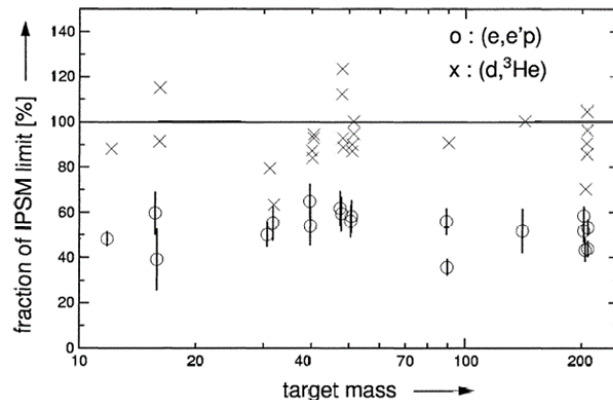
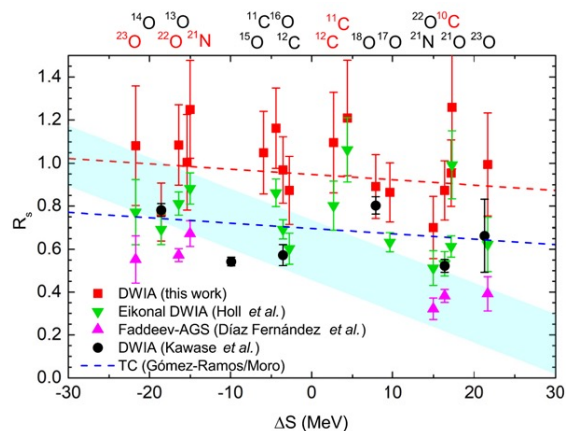
$$|\psi_{jm}(r)|^2 \rightarrow |f(r)\psi_{jm}(r)|^2.$$



Shichang Li, J. Pei, D.Y. Pang, SCPMA 69, 242011(2026)

核芯屏蔽效应的讨论

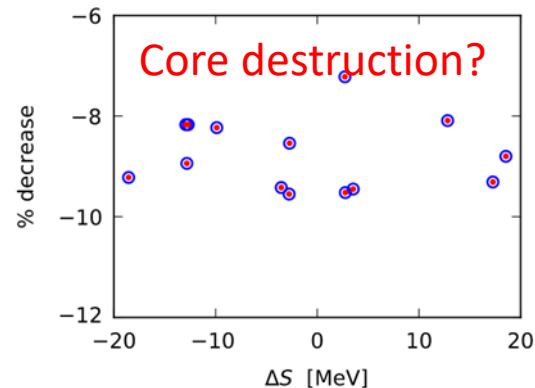
● 关联缺失 or 复杂的反应机制?



Physics Letters B 800 (2020) 135110

● Complex reaction mechanism between two composition systems:

- Core screening is not conflict with core destruction or multi-step scattering;
- Many-body dynamical reaction theory is needed by including non-adiabatic non-equilibrium effects



Physics Letters B 846 (2023) 138250

Summary

- 理解核结构的短程性质有广泛的影响，代表我们对原子核与核物质认识的精度极限
- 第一性原理计算核结构揭示短程关联的多体效应，有助于定量理解核的夸克效应
- 第一性原理多体计算取得了很大进展：IMSRG, FCIQMC, PTQMC, quantum computing, 意味着核力将是主要的问题
- 核芯屏蔽效应对敲出谱因子压低提供了有效解释，反映复杂的多体量子体系反应机制

Thank you for your attention!