同济大学物理科学与工程学院学术交流

第一性原理研究滴线原子核性质

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中国科学院近代物理研究所

① Gamow 壳模型计算滴线外原子核共振结构

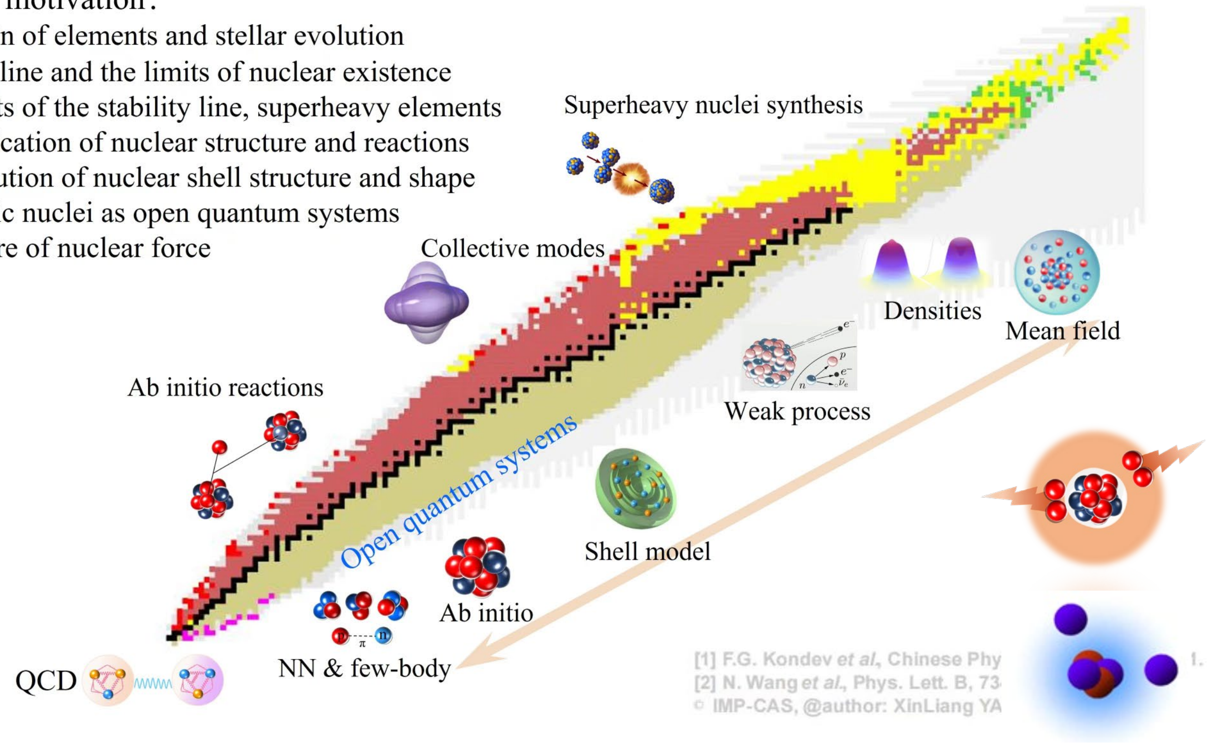
② 核多体方法计算谱因子——核结构与核反应的桥梁

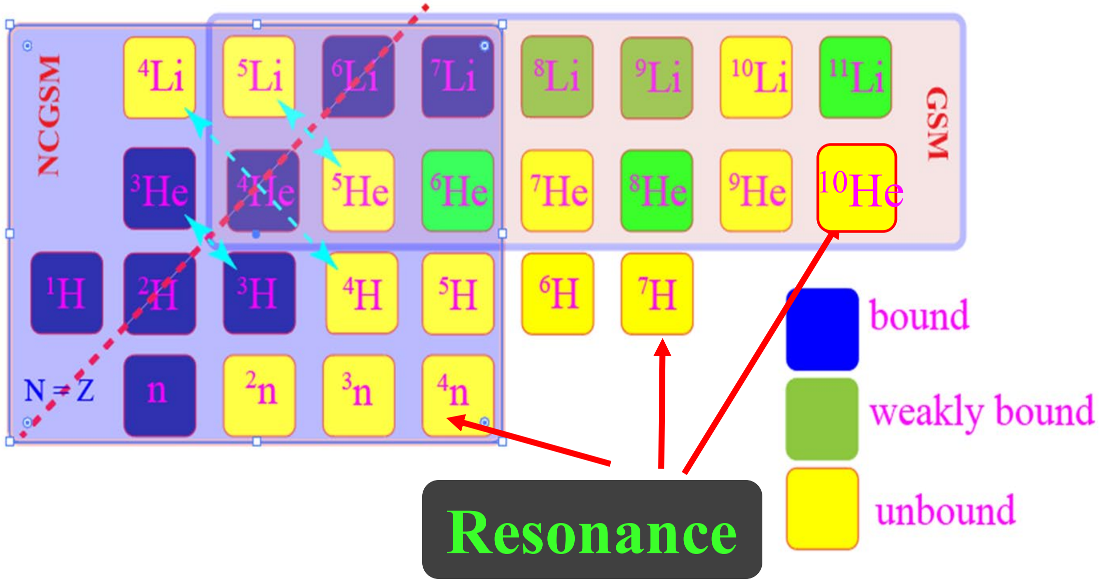
合作者：许甫荣 教授, Nicolas Michel, 左维 研究员, 李红蕙, 谢萌冉…

Gamow 壳模型计算滴线外原子核共振结构

滴线原子核

Physics motivation：
- Origin of elements and stellar evolution
- Drip line and the limits of nuclear existence
- Limits of the stability line, superheavy elements
- Unification of nuclear structure and reactions
- Evolution of nuclear shell structure and shape
- Exotic nuclei as open quantum systems
- Nature of nuclear force





HIAF上重要的科学目标

滴线原子核奇特

- ✓ 晕结构 ^{6,8}He, ^{11}Li, ^{11}Be, ^{8}B, ^{17}Ne, ^{29}F
- ✓ 粒子发射 *p,n,2p,2n,4n,2n+2n,…*
- ✓ Thomas Erhman-shift
- ✓ …

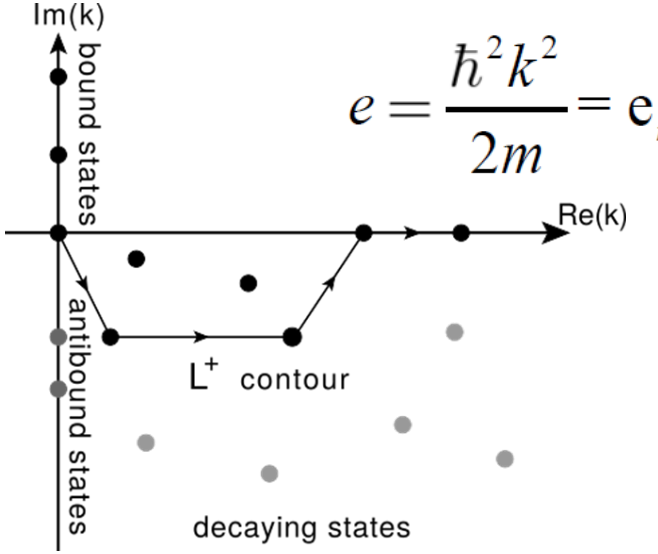
给当前的理论模型提出了巨大的挑战

共振态-粒子发射

共振态具有粒子发射特性，是一个时间相关性的量子多体问题

Berggren 复动量空间，将时间相关问题转化为时间无关问题，便于求解薛定谔定态方程

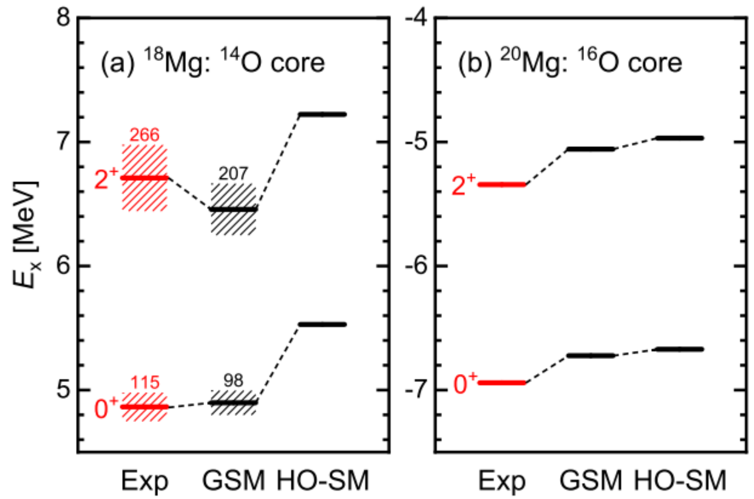
径向波函数 $\psi(\mathbf{r},t)=e^{-iEt/\hbar}\varphi_E(\mathbf{r})=e^{-ie_n t/\hbar}\varphi_E(\mathbf{r})e^{-\gamma_n t/2\hbar}$



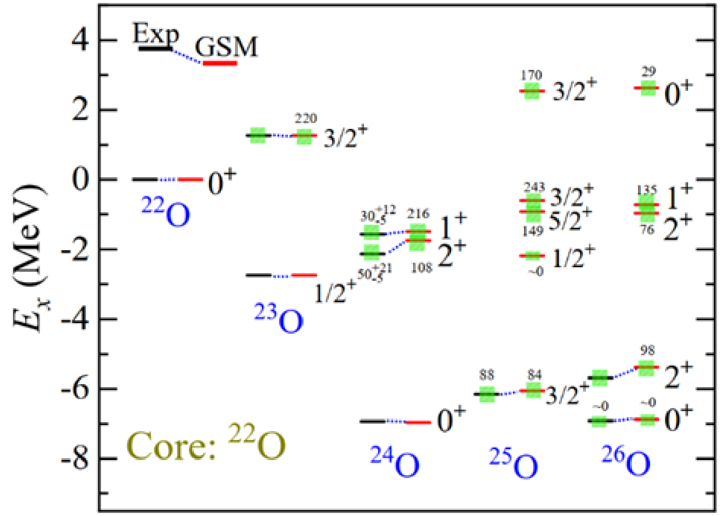
$$e=\frac{\hbar^2 k^2}{2m}=e_n-i\frac{\gamma_n}{2}$$

$$\sum_{n\in(b,d)}|u_n\rangle\langle u_n|+\int_{L^+}|u(k)\rangle\langle u(k)|dk=1$$

T. Berggren, Nucl. Phys. A109 (1968) 265



Y. Jin et al., Phys. Rev. Lett. 127, 262502 (2021).

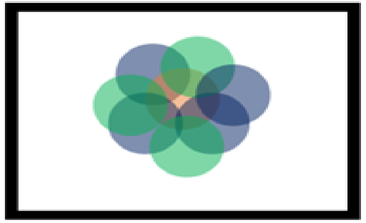


J. G. Li, et al. Phys. Rev. C 103, 034305 (2021)

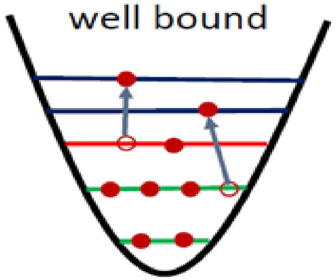
量子多体计算- HO /Berggren 完备基矢

$$H = -\sum_i \frac{\hbar^2}{2m}\nabla_i^2 + \sum_{ij} V_{ij} + \sum_{ijk} V_{ijk}$$

NCSM/SM



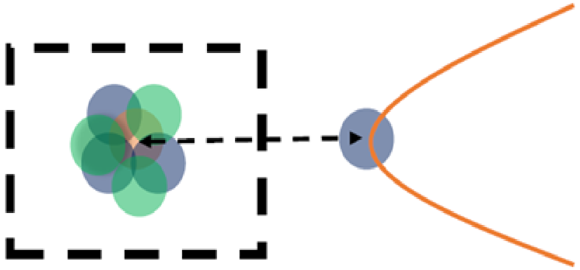
Closed quantum system



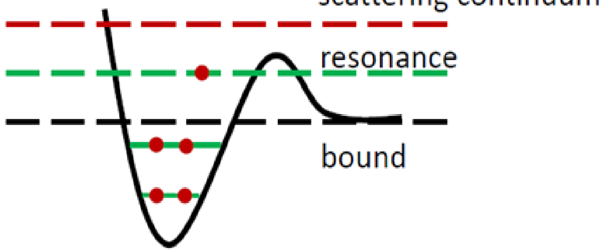
HO basis

Berggren 基矢自洽的包含共振与连续谱耦合

NCGSM/GSM



Open quantum system



Berggren basis

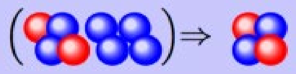
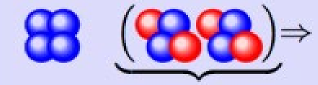
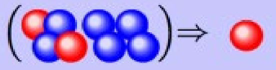
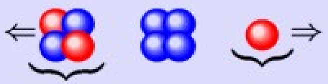
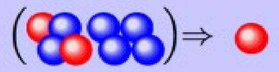
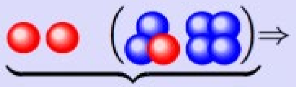
E. Caurier, et al. RMP 77,427 (2005)
T. Otsuka, et al, RMP. 92,015002 (2020)
B. R. Barrett, P. Navratil, and J. P. Vary PPNP 69,131(2013)

N. Michel, M. Płoszajczak, The Gamow Shell Model, Springer ;
N. Michel, et al., JPG 36,013101 (2009)
***J. G. Li**, et al., Physics 3, 977 (2021)*
***J. G. Li**, et al., Phys. Rev. C 100, 054313 (2019)*
***J. G. Li**, et al., Phys. Rev. C 104, 024319 (2021)*

多中子体系实验研究

- More than 50 years of multi-neutron searches, especially the tetraneutron.
  See arXiv:1608.00169[nucl-th] (2016) Eur. Phys. J. A 57,105(2021),
- Earlier experiments gave negative results, no information about the multi-neutron systems.
- In 2002, Marqués *et al* reported the possible existence of a **bound** tetraneutron observed in a breakup reaction of the $^{14}Be \rightarrow ^{10}Be+4n$ channel. Marqués *et al.*, PRC 65, 044006 (2002)
- In 2016, Kisamori *et al* observed of few events of tetraneutron in the doubly charge-exchange reaction $^4He(^8He,^8Be)$. Interpreted the tetraneutron as a candidate **resonance** with **Er = 0.83 ± 0.65(stat) ± 1.25(syst) MeV** and width **Γ ≤ 2.6 MeV**. Kisamori *et al.*, PRL 116, 044006 (2016)

最新实验工作

reaction	initial state	final state	σ	results
$^4He(^8He,\alpha\alpha)\,^4\mathbf{n}$ Shimoura, NP1512-SHARAQ10			nb	$N_{evt} \sim 10$ s; ^4n : E, Γ
$^8He(p,p\alpha)\,^4\mathbf{n}$ Paschalis, NP1406-SAMURAI19			μb	$N_{evt} \sim 1000$ s; ^4n : E, Γ
$^8He(p,2p)\,\{^3\mathbf{H}+^4\mathbf{n}\}$ FMM/Yang, NP1512-SAMURAI34			mb	$N_{evt} \sim$ **10,000** s; ^4n & ^7H : E, Γ, **Ω**

Nature 2022

杨再宏老师工作

多中子体系理论研究-1

Year	Author	Journal	Conclusion
2003	Bertulani et al	J. Phys. G 29, 2431	gave no bound 4n combined dineutron-dineutron molecule and a toy NN potential
2003	Steven C. Pieper	PRL. 90, 252501	employed the GFMC calculated the tetraneutron, showed the modern nuclear force can not tolerate a bound tetraneutron and suggested the a tetraneutron resonance near 2MeV
2005	Lazauskas and Carbonell	PRC 72, 034003	used Complex scaling based on Reid 93 NN potential: no low-lying 4n resonances : no low-lying tetraneutron resonance.
2016 experiment			
2016	E.Hiyama *et al*	PRC **93**, 044004	employed Complex scaling using AV8'+(toy)NNN, low 4*n* resonance possible only by strongly strongly modify the nuclear force
2016	A.M.Shirokov *et al*	PRL **117**,182502	performed the NCSM with JISP16 interaction conformed a resonant state in tetraneutron around 0.8 MeV, width 1.4 MeV
2017	S. Gandofi *et al*	PRL **118**, 232501(2017)	presented the QMC calculations of multi-neutron systems, suggested the trineutron and tetraneutron were both resonance

多中子体系理论研究-2

Year	Author	Journal	Conclusion
2017	K. Fossez *et al.*	PRL **119**, 032501	performed NCGSM gave energy of tetraneutron may be compatible with experimental value, but the width must be too large
2018	A.Deltuva	PRC **97**, 034001 (2018), PLB **782**, 238 (2018)	employed Faddeev method gave the absence of an observable trineutron and tetraneutron resonance based on modern two-body force
2018	A.M.Shirokov *et al.*	AIP Conf. proc 020038	Performed NCSM for tetraneutron with different two-body force, similar results are obtained
2019	A.M.Shirokov *et al.*	Presentation in Nanjing@China 2019	updated their calculations and gave two resonance states in tetraneutron
2019	J. G. Li *et al.*	PRC 100 054313	Performed NCGSM for trineutron and tetraneutron, predicting that E (^{3}n) = 1.29 MeV Γ (^{3}n) = 0.91 MeV E(^{4}n) = 2.64 MeV Γ (^{4}n) = 2.38 MeV
2020 2021	Michael D. Higgins *et al.*	PRL 125,052501 PRC 103 024004	Using adiabatic hyperspherical framework, Predicting that that no resonance and no bound state exists for the tetraneutron system

相互作用：N3LO

ab initio NCGSM

$$H=\frac{1}{A}\sum_{i}^{A}\frac{(p_i-p_j)^2}{2m}+\sum_{i<j}^{A}V_{NN}^{i<j}+\sum_{i}^{A}V_{\rm WS}$$

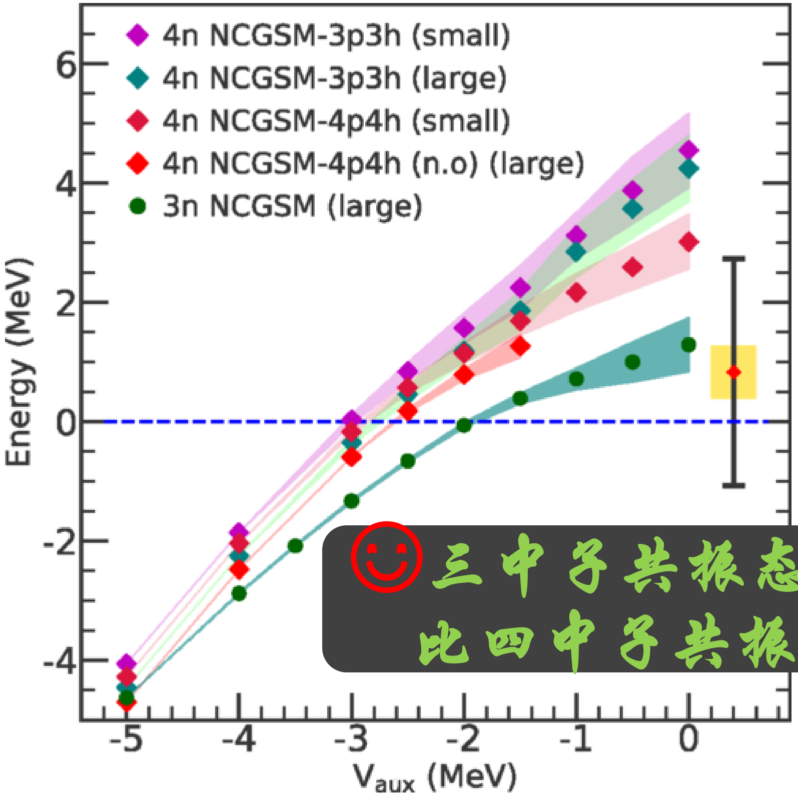
多中子体系

非束缚

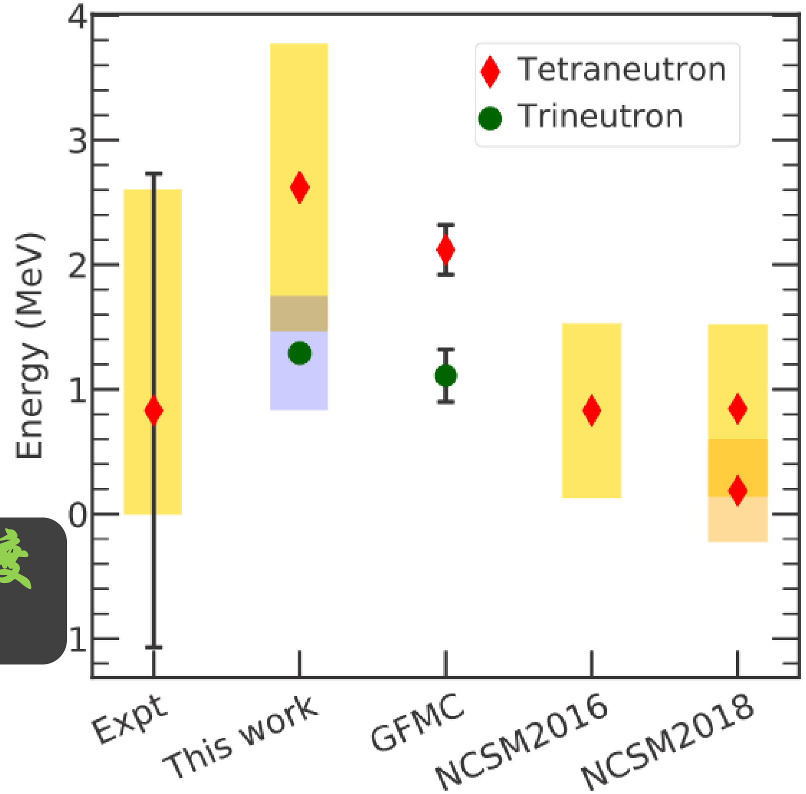
连续态耦合强

$E(^3n) = 1.29$ MeV $\Gamma(^3n) = 0.91$ MeV
$E(^4n) = 2.64$ MeV $\Gamma(^4n) = 2.38$ MeV

三中子的能量比四中子低，
与量子蒙卡的外推结果接近



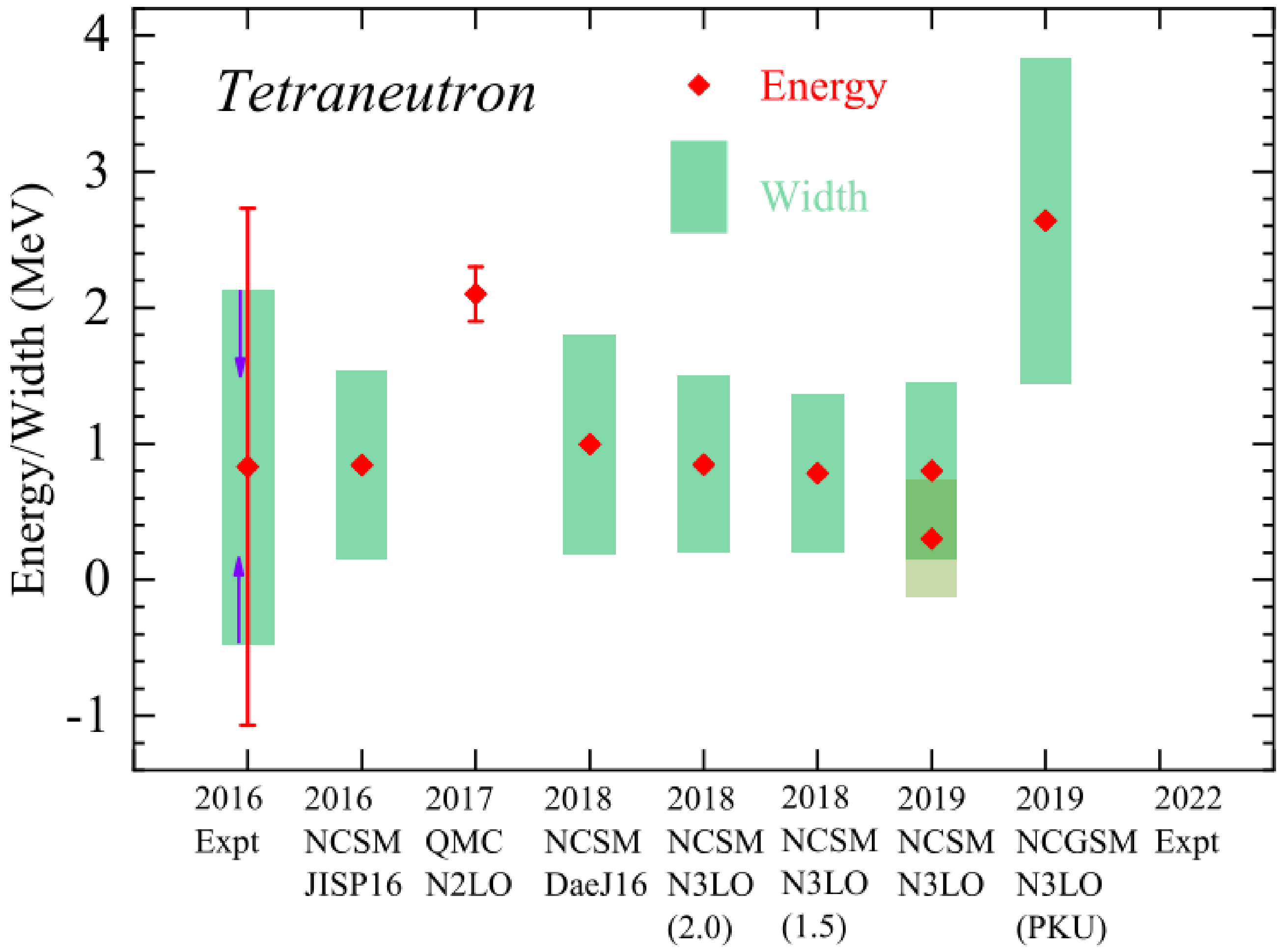
☺三中子共振态的宽度比四中子共振态小。



☺三中子共振态在实验上比四中子共振态更容易探测

J. G. Li, *N. Michel, B. S. Hu, W. Zuo, and F. R. Xu*, Phys. Rev. C 100, 054313 (2019)*

四中子研究-理论+实验



- ✓ 2016 Expt : *Kisamori et al., PRL 116, 044006 (2016)*
- ✓ 2016 NCSM: *A. M. Shirokov,et al, PRL 117,182502 (2016)*
- ✓ 2017 QMC : *S. Gandofi, et al., PRL 118, 232501(2017)*
- ✓ 2018 NCSM : *A. M. Shirokov,et al AIP Conf. proc 020038 (2018)*
- ✓ 2019 NCSM : *A. M. Shirokov Presentation in Nanjing@China 2019*
- ✓ **2019 NCGSM** : ***J. G. Li****, N. Michel, B. S. Hu, W. Zuo, and F. R. Xu*, Phys. Rev. C 100, 054313 (2019)*

实验探测到四中子共振态

Article

Observation of a correlated free four-neutron system

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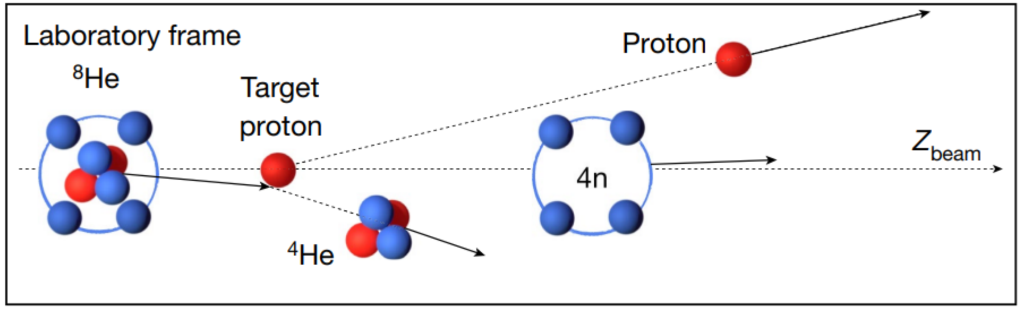
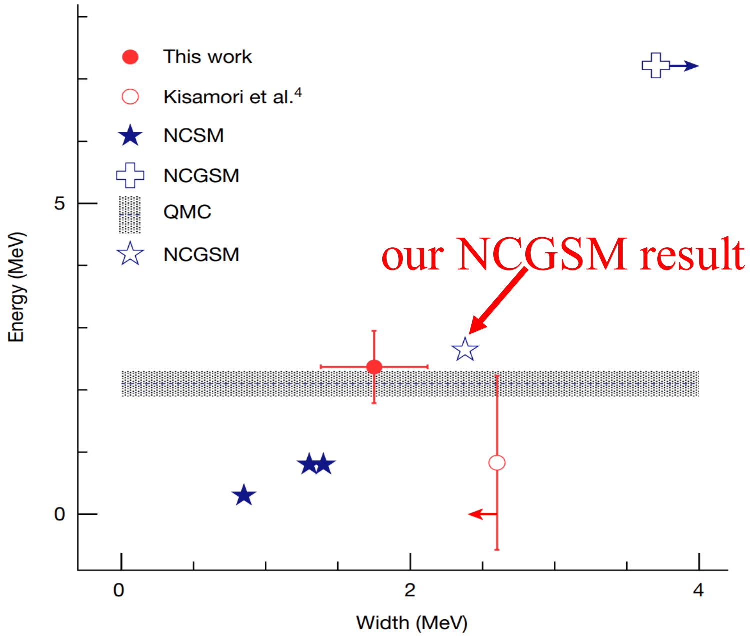
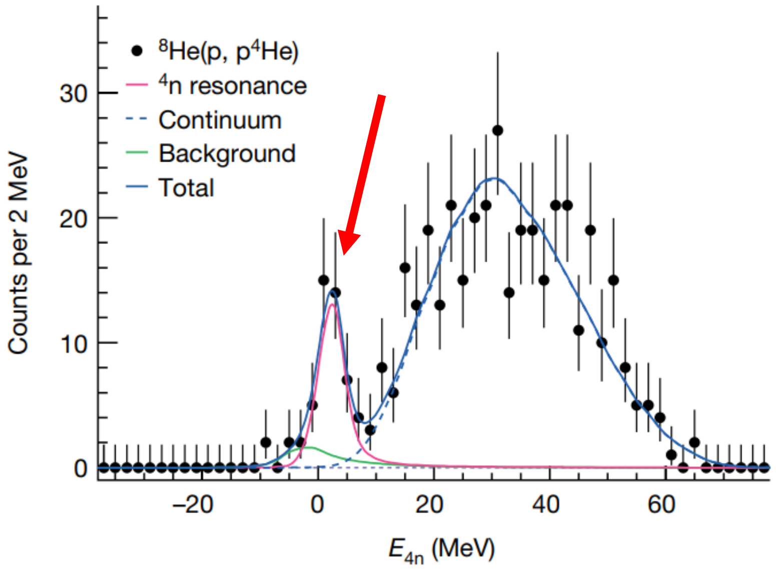
M. Duer[1✉], T. Aumann[1,2,3], R. Gernhäuser[4], V. Panin[2,5], S. Paschalis[1,6], D. M. Rossi[1], N. L. Achouri[7], D. Ahn[5,16], H. Baba[5], C. A. Bertulani[8], M. Böhmer[4], K. Boretzky[2], C. Caesar[1,2,5], N. Chiga[5], A. Corsi[9], D. Cortina-Gil[10], C. A. Douma[11], F. Dufter[4], Z. Elekes[12], J. Feng[13], B. Fernández-Domínguez[10], U. Forsberg[6], N. Fukuda[5], I. Gasparic[1,5,14], Z. Ge[5], J. M. Gheller[9], J. Gibelin[7], A. Gillibert[9], K. I. Hahn[15,16], Z. Halász[12], M. N. Harakeh[11], A. Hirayama[17], M. Holl[1], N. Inabe[5], T. Isobe[5], J. Kahlbow[1], N. Kalantar-Nayestanaki[11], D. Kim[16], S. Kim[1,16], T. Kobayashi[18], Y. Kondo[17], D. Körper[2], P. Koseoglou[1], Y. Kubota[5], I. Kuti[12], P. J. Li[19], C. Lehr[1], S. Lindberg[20], Y. Liu[13], F. M. Marqués[7], S. Masuoka[21], M. Matsumoto[17], J. Mayer[22], K. Miki[1,18], B. Monteagudo[7], T. Nakamura[17], T. Nilsson[20], A. Obertelli[1,9], N. A. Orr[7], H. Otsu[5], S. Y. Park[15,16], M. Parlog[7], P. M. Potlog[23], S. Reichert[4], A. Revel[7,9,24], A. T. Saito[17], M. Sasano[5], H. Scheit[1], F. Schindler[1], S. Shimoura[21], H. Simon[2], L. Stuhl[16,21], H. Suzuki[5], D. Symochko[1], H. Takeda[5], J. Tanaka[1,5], Y. Togano[17], T. Tomai[17], H. T. Törnqvist[1,2], J. Tscheuschner[1], T. Uesaka[5], V. Wagner[1], H. Yamada[17], B. Yang[13], L. Yang[21], Z. H. Yang[5], M. Yasuda[17], K. Yoneda[5], L. Zanetti[1], J. Zenihiro[5,25] & M. V. Zhukov[20]

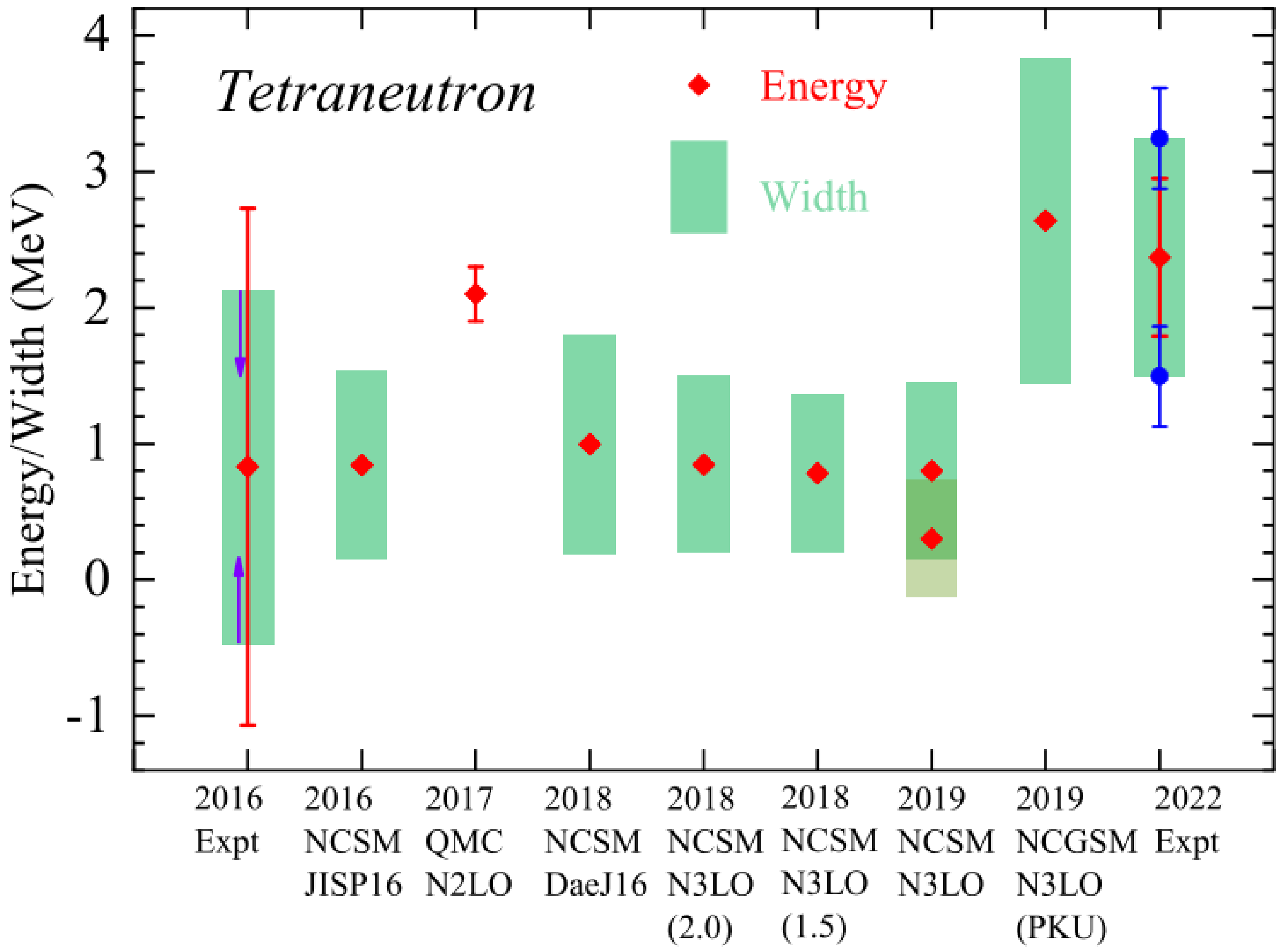






20. Li, J. G., Michel, N., Hu, B. S., Zuo, W. & Xu, F. R. Ab-initio no-core Gamow shell-model calculations of multineutron systems. Phys. Rev. C **100**, 054313 (2019).

四中子研究-理论+最新实验



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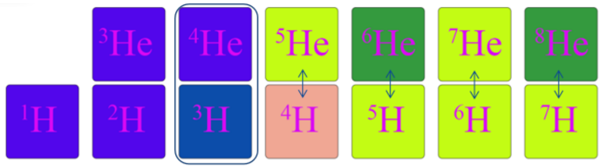
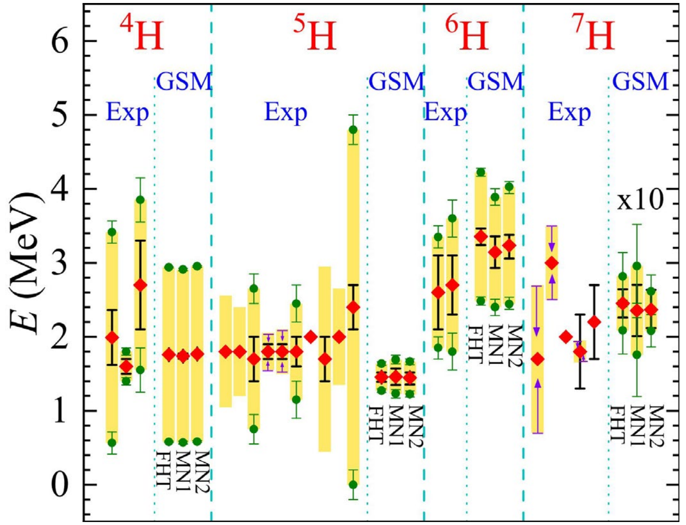
- ✓ 2019 NCSM : *A. M. Shirokov Presentation in Nanjing@China 2019*
- ✓ **2019 NCGSM** : ***J. G. Li****, N. Michel, B. S. Hu, W. Zuo, and F. R. Xu*, Phys. Rev. C 100, 054313 (2019)*
- ✓ 2022 Expt : *M. Duer et al. Nature 606, pages678–682 (2022)*

Gamow壳模型研究滴线外原子核共振结构

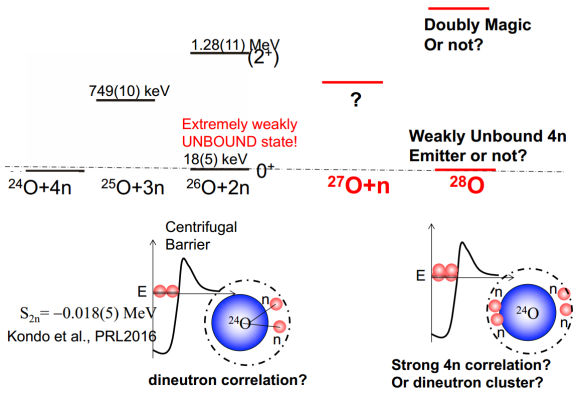


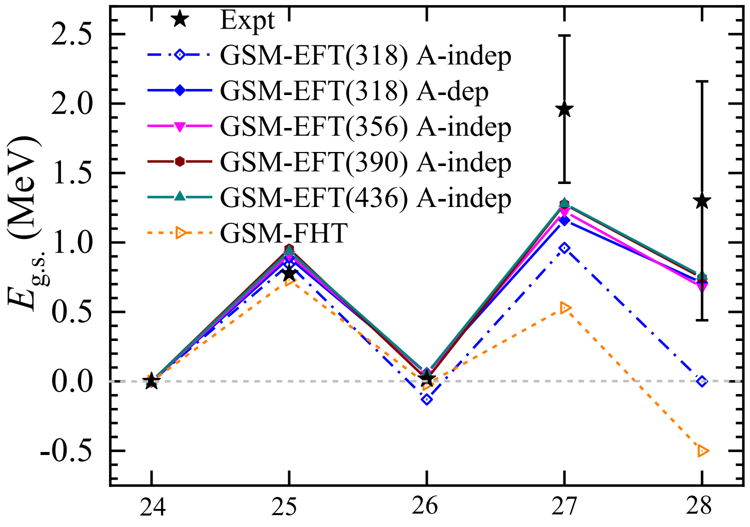
^{7}H 基态：窄共振态



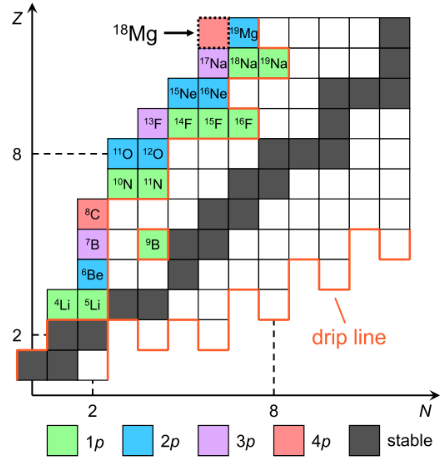
H. H. Li, **J. G. Li**, N. Michel, and W. Zuo, Phys. Rev. C 104, L061306 (2021)

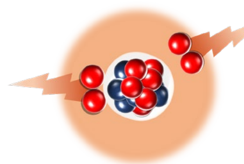
Dineutron Cluster?

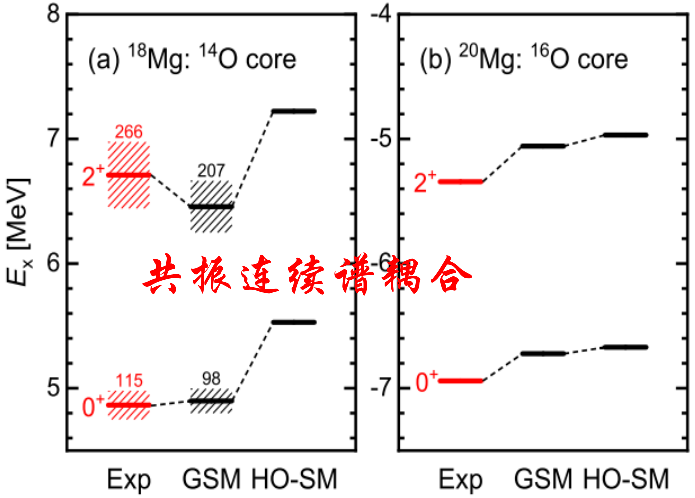




J.G. Li, N. Michel, W. Zuo and F.R. Xu. Phys. Rev. C 103, 034305 (2021)







共振连续谱耦合

N. Michel, **J. G. Li**, F. R. Xu, and W. Zuo, Phys. Rev. C 103, 044319 (2021)

小结

1. 第一性原理无芯Gamow壳模型计算多中子共振态的能量与宽度（三中子+四中子）

   ✓ 计算的四中子共振态的能量与宽度被RIKEN实验证实(*Nature 606, 678 (2022)*)
   ✓ 三中子在是实验上比四中子更容易被探测

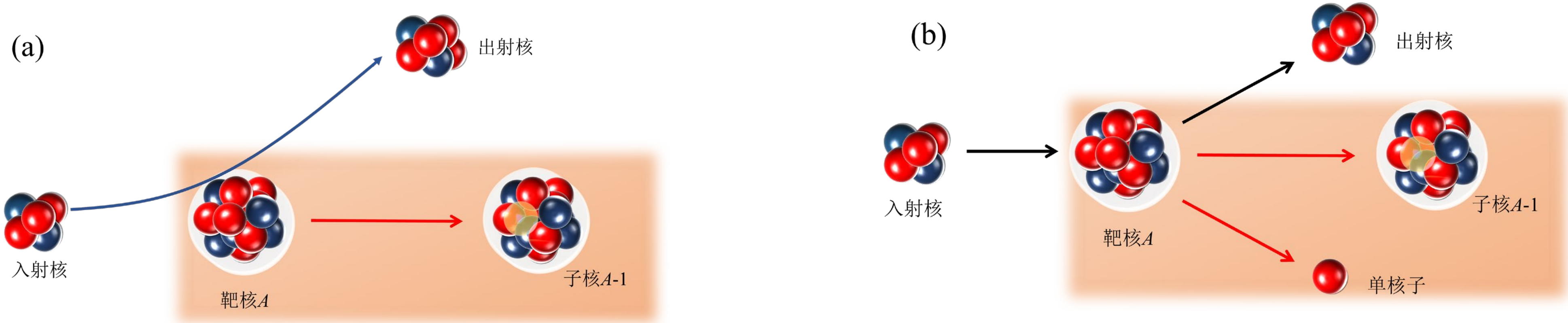
2. Gamow壳模型计算滴线外共振原子核:

共振原子核	Gamow shell model	实验
^{7}H~ ^{3}H + 4n	H. H. Li, **J. G. Li**, N. Michel, and W. Zuo, Phys. Rev. C 104, L061306 (2021)	实验工作-未发表 RIKEN
^{18}Mg~ ^{14}O+4p	N. Michel, **J. G. Li**, F. R. Xu, and W. Zuo, Phys. Rev. C 103, 044319 (2021)	北京大学华辉老师课题组 PRL 127, 262502 (2021)
^{28}O~ ^{24}O+4n	**J. G. Li**, N. Michel, W. Zuo, and F.R. Xu. Phys, Rev. C 103, 034305 (2021)	实验工作-已投稿 RIKEN

核多体方法计算谱因子

核结构与核反应的桥梁

当前敲出/转移反应截面的理论框架



单核子敲出反应截面σ与谱因子直接相关 C^2S

$$\sigma = \sum_{nlj} \left(\frac{A}{A-1}\right)^N C^2S(\alpha, nlj)\,\sigma_{sp}(nlj, S_\alpha^*)$$

→ knockout /transfer cross section of nucleon in a single particle state

Total cross section

Spectroscopic factor

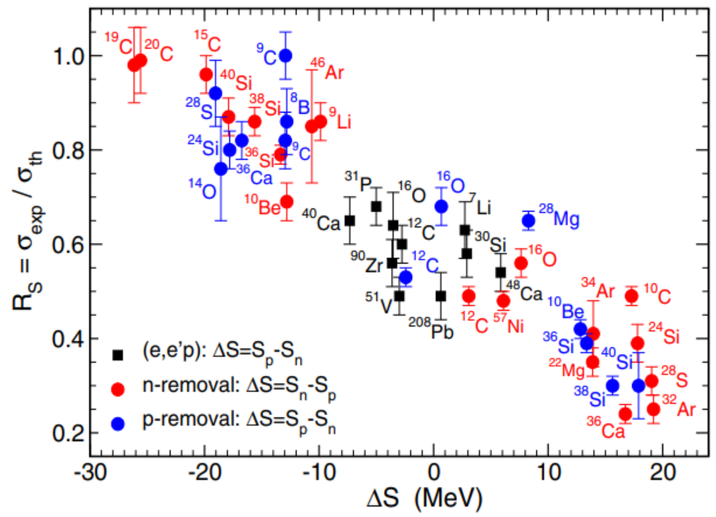
谱因子研究的国内实验方向老师：

核结构与核反应：楼建玲、陈洁、王惠仁、王世陶、孙志宇、叶沿林、杨再宏、孙叶磊、刘红娜等

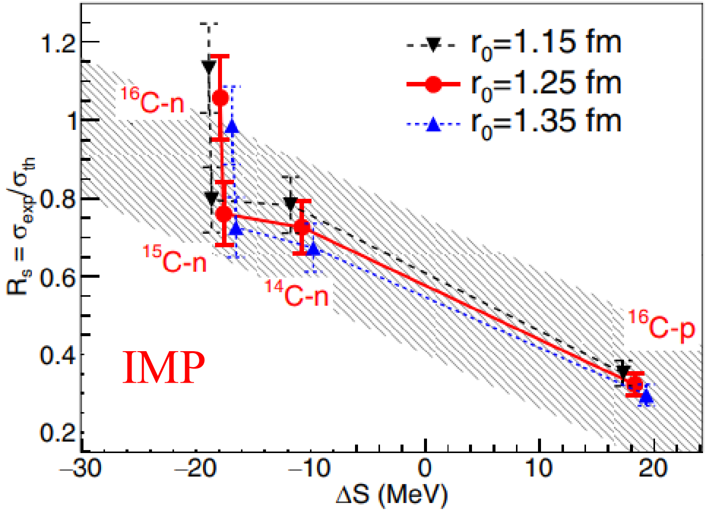
核天体：何建军、郭冰等

核反应计算：金磊，庞丹阳等需要谱因子作为输入量

敲出与转移反应中存在的Puzzling



J. A. Tostevin, and A. Gade PRC 90,057602(2014)



Y. Z. Sun, S. T. Wang et al., PRC 104 014310(2021)

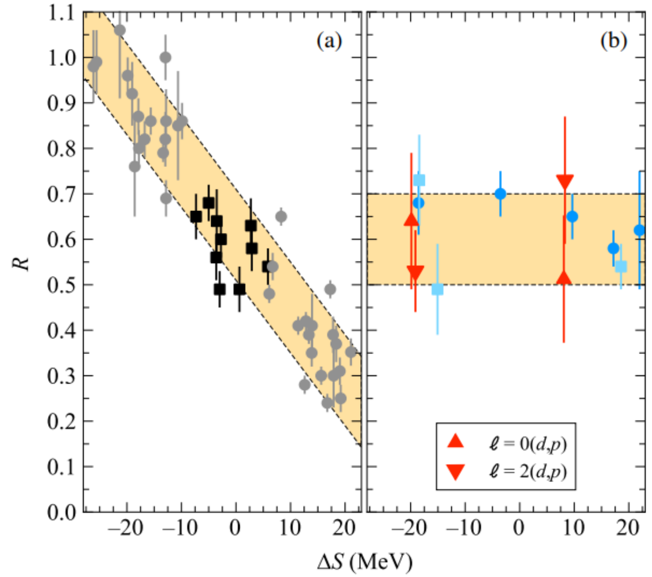
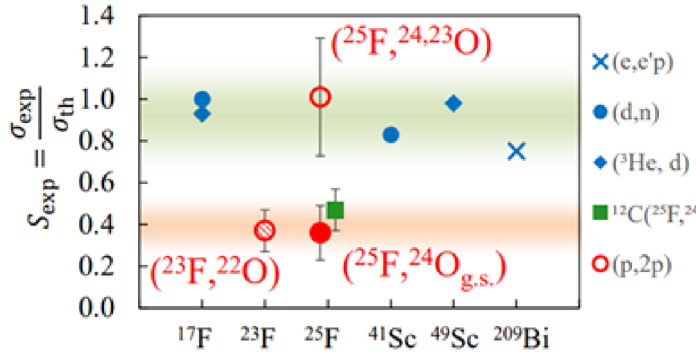


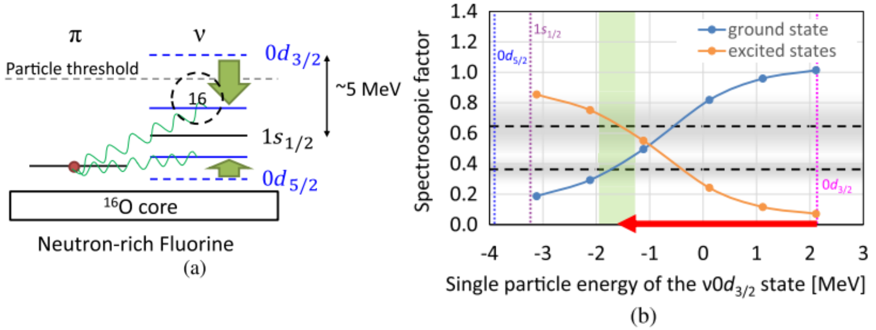
TABLE I. Values of ΔS, DWBA (SF), and shell-model (SF_{SM}) spectroscopic factors, and R for the $1s_{1/2}$ and $0d_{5/2}$ strength in ^{15}C and ^{15}N.

^AX	nlj	ΔS (MeV)	SF	SF_{SM}	R
^{15}C	$1s_{1/2}$	−19.86	0.51(12)	0.80	0.64(15)
	$0d_{5/2}$	−19.12	0.41(7)	0.78	0.53(9)
^{15}N	$1s_{1/2}$	+8.08	0.41(11)	0.80	0.51(14)
	$0d_{5/2}$	+8.29	0.61(12)	0.84	0.73(14)

B. P. Kay, T. L. Tang et al., Phys. Rev. Lett. 129, 152501 (2022)



Channel	J^{π}_{th}	S_{exp}	S_{th}(USDB)	S_{th}(SFO)	S_{th}(SPDF-MU)
(^{25}F, ^{24}O)	$5/2^+$	0.36(13)	1.01	0.90	0.95
(^{25}F, ^{23}O)	$5/2^+$	0.65(25)	0.01	0.07	0.05
(^{25}F, ^{22}O)	$1/2^-$	3.43(1.4)		2.19	
(^{23}F, ^{22}O)	$5/2^+$	0.37(10)	1.08	0.92	1.00
(^{23}F, ^{21}O)	$1/2^-, 3/2^-$	4.9(1.5)		5.21	
(^{23}F, ^{20}O)					

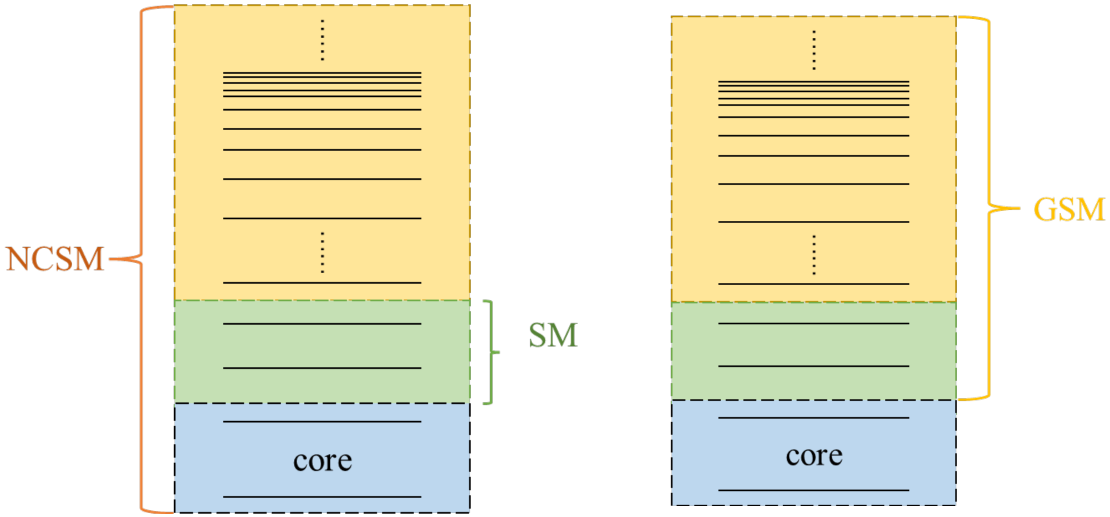


T. L. Tang et al., Phys. Rev. Lett. 124, 212502 (2020)

敲出与转移反应中存在的Puzzling

NCSM/SM **GSM**

HO basis Berggren basis



$$\hat{H}_{\text{NCSM}} = \sum_{i=1}^{A} \frac{\mathbf{p}_i^2}{2m} - \frac{\mathbf{P}^2}{2mA} + \sum_{i<j}^{A} \hat{V}_{ij}^{NN}$$

- ✓ SM/NCSM usually use the HO basis.
- ✓ SM usually choose double magic nuclei as their core.
- ✓ NCSM introduces N_{max} as a model space truncation parameter.

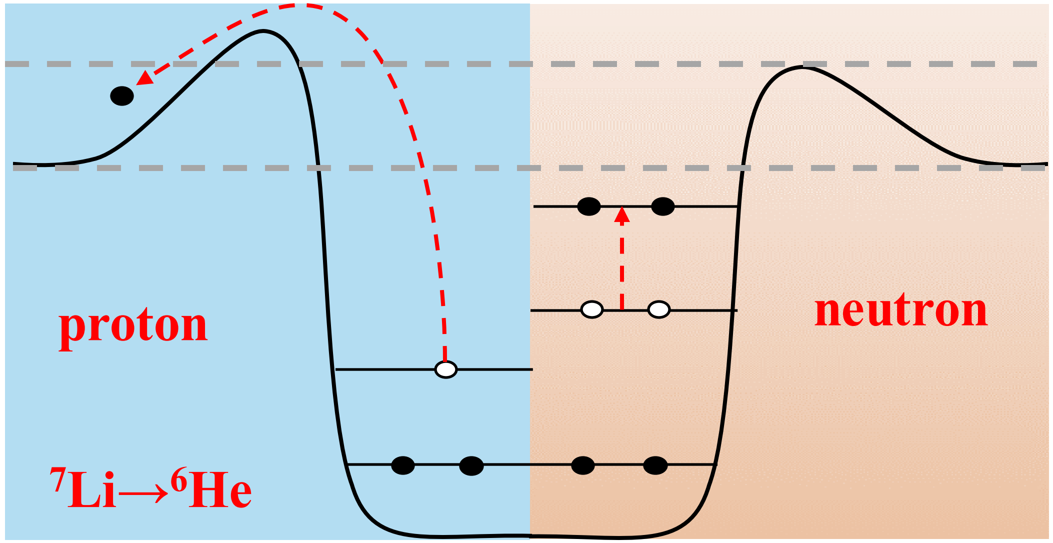
$$\hat{H}_{\text{GSM}} = \sum_{i=1}^{A_{val}} \left(\frac{\mathbf{p}_i^2}{2\mu_i} + \hat{U}_i^{(c)} \right) + \sum_{i<j}^{A_{val}} \left(\hat{V}_{ij}^{(res)} + \frac{\mathbf{p}_i \cdot \mathbf{p}_j}{M_c} \right)$$

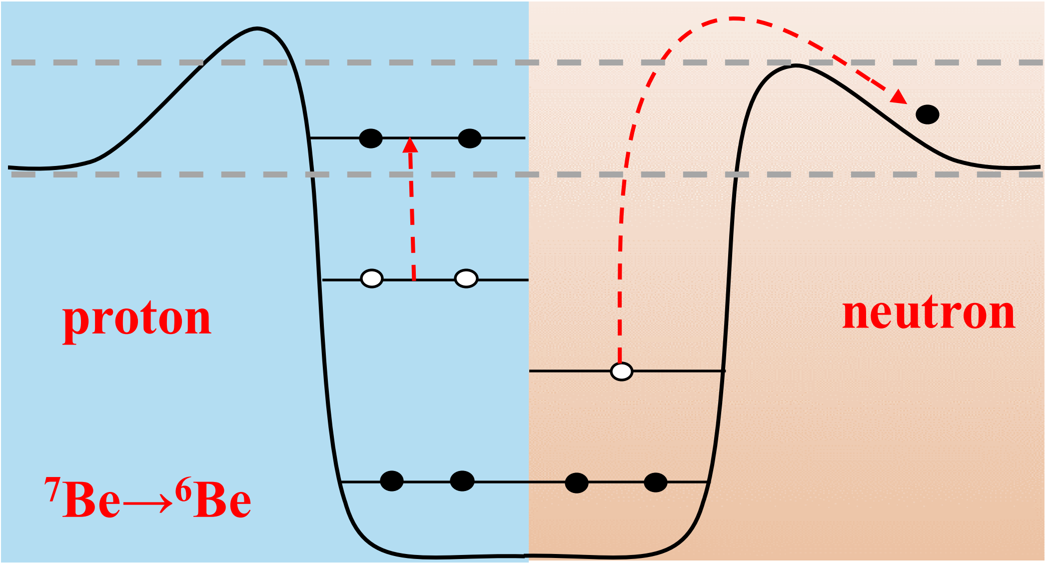
- ✓ GSM uses the Berggren basis, which contains bound, resonance, and scattering states.

$$O(r) = \frac{1}{\sqrt{2J_A+1}} \sum_n \langle \Psi_A^{J_A} || a_{n\ell j}^{+} || \Psi_{A-1}^{J_{A-1}} \rangle \, u_n^{(\ell j)}(r), \quad C^2S = \int_0^{+\infty} O(r)^2 \, dr,$$

量子多体方法计算原子核 谱因子 C^2S (GFMC, VMC, SM, NCSM, GSM, CC, SCGF et al.).

① 滴线核深束缚核子谱因子-弱束缚与不束缚原子核





✓ ^{7}Be 和 ^{7}Li 是深束缚原子核

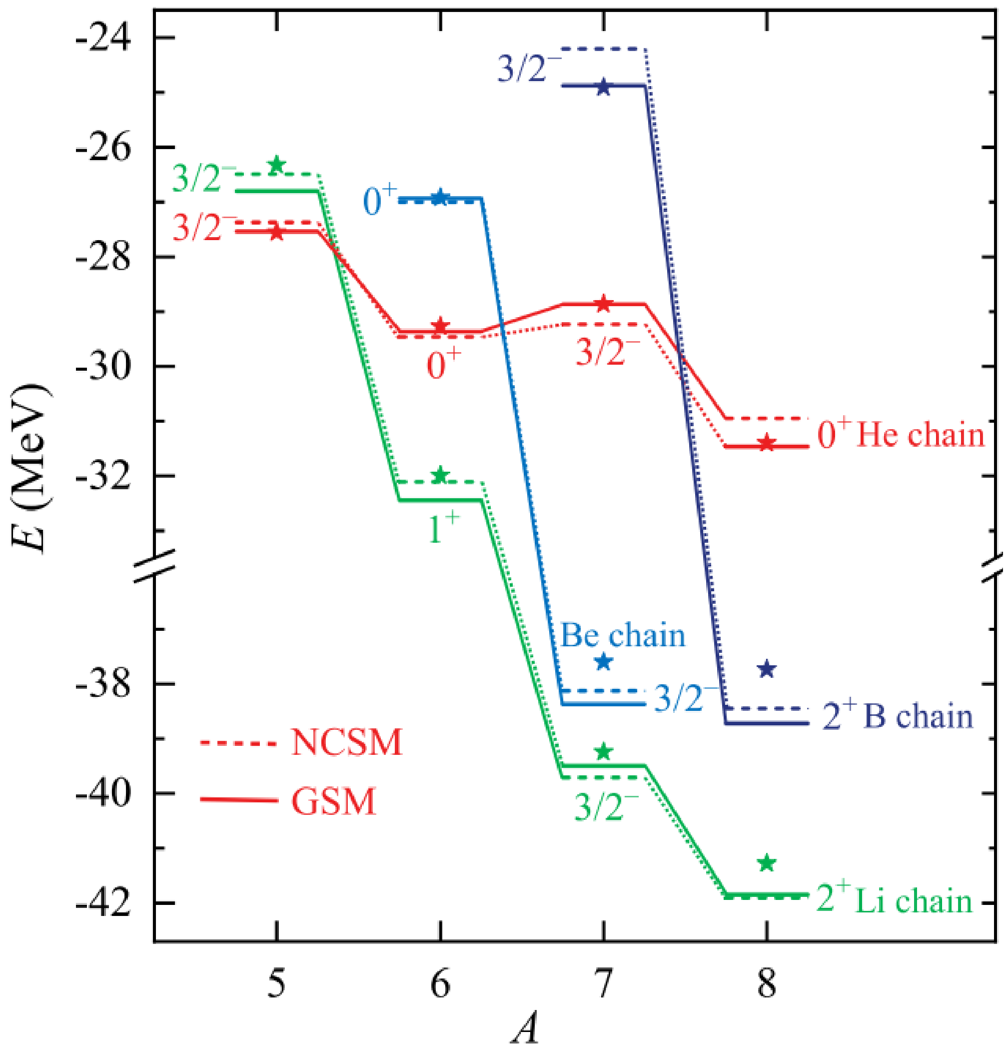
✓ ^{6}He 是弱束缚原子核

✓ ^{6}Be是不束缚原子核

^{7}Li 中价质子与^{7}Be 中价中子的谱因子是否等于1?

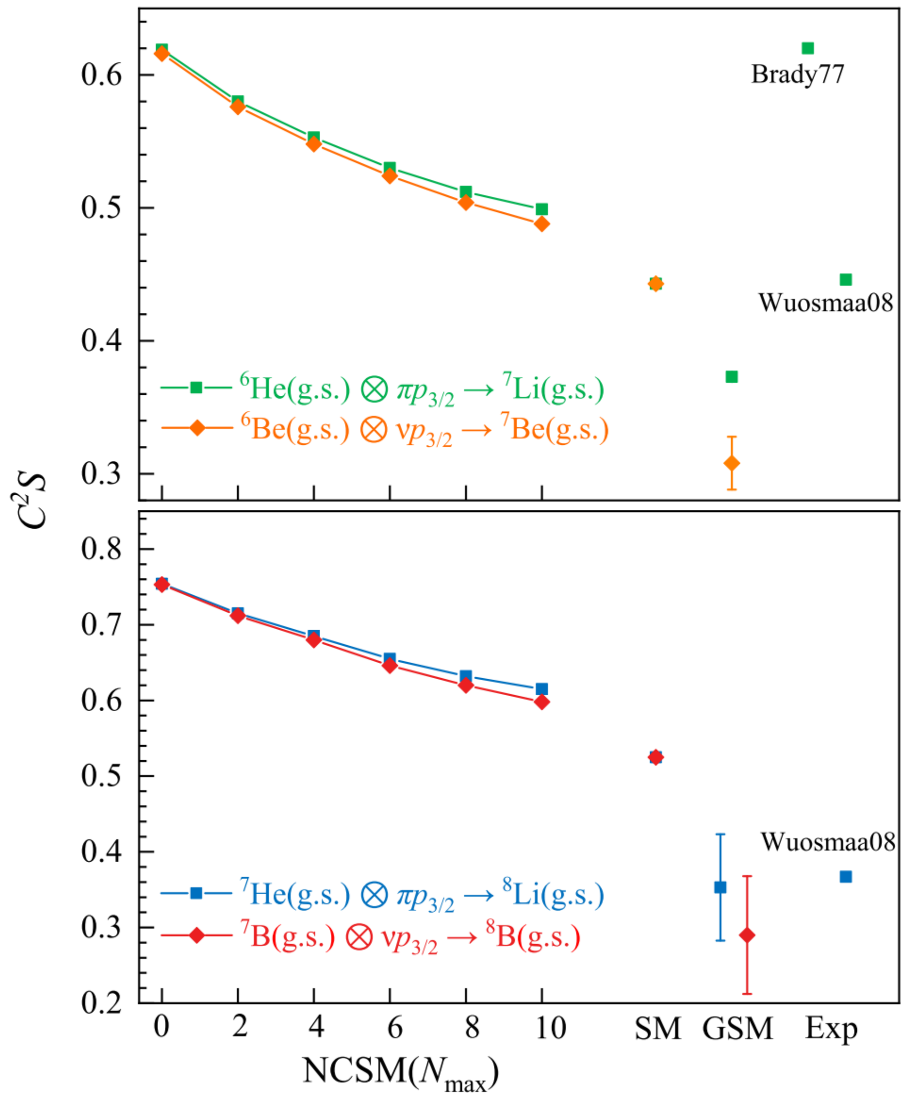
单粒子壳模型图像

① 滴线核深束缚核子谱因子



- ✓ NCSM 使用 DJ16的核子核子相互作用.
- ✓ GSM 计算中使用唯象的FHT 相互作用，并选取 ^{4}He 为核芯.
- ✓ GSM 与NCSM都p-壳原子核基态能量提供很好的描述

① 滴线核深束缚核子谱因子

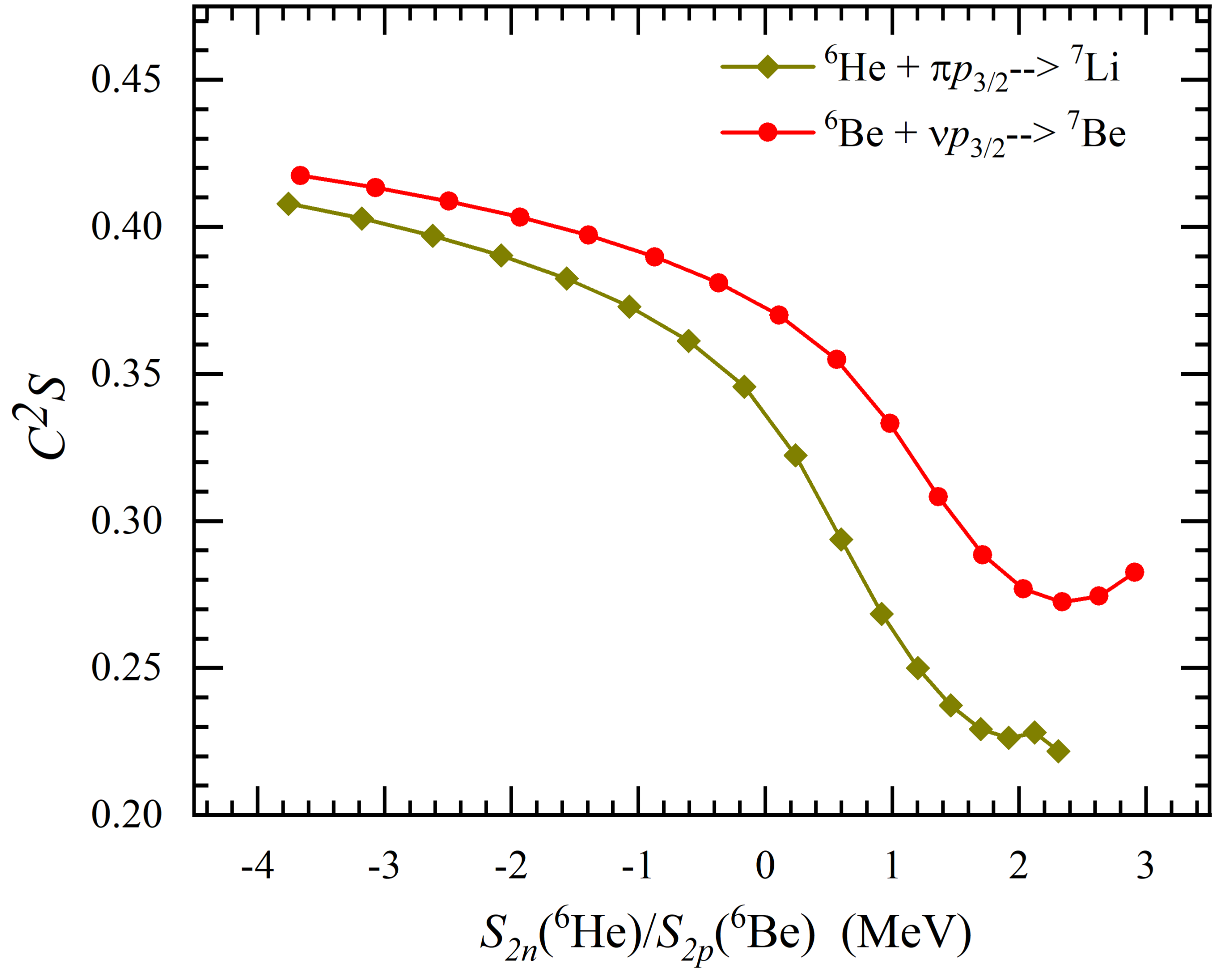


- ✓ C^2S NCSM计算的谱因子随着Nmax增大不收敛;
- ✓ NCSM计算的谱因子同位旋对称性较小;
- ✓ GSM计算的 C^2S 与实验结果符合较好，并且其数值小于 NCSM 与 SM 的计算结果.
- ✓ GSM计算的谱因子 C^2S 表示滴线原子核的谱因子中存在明显的同位旋对称性破缺现象→ 然而，相关的实验还比较缺乏.

实验物理学家基于国内大科学装置能否开展相关实验研究

M. R. Xie, **J. G. Li**, N. Michel, H. H. Li, S. T. Wang, H. J. Ong, and W. Zuo, PLB 839 137800 (2023)

Spectroscopic factors of ^{7}Li & ^{7}Be

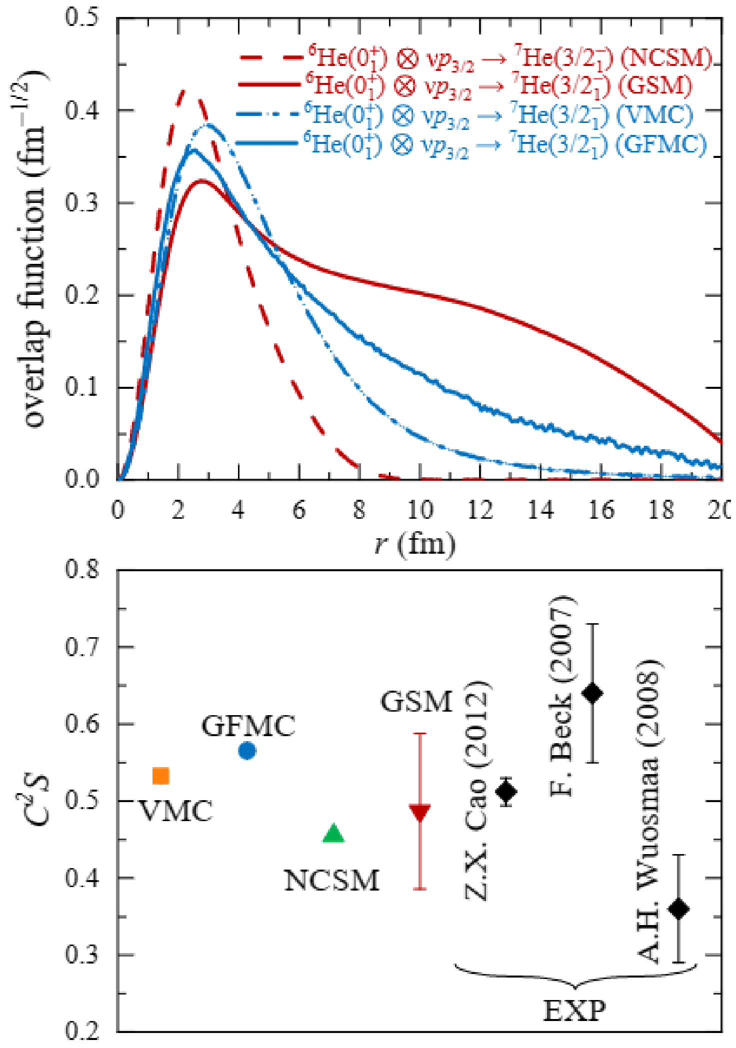


- Further study of the effect of Continuum coupling

1. Change the depth of WS potential to obtain different S_{2n}.
2. C^2S changes significantly near threshold due to continuum coupling
3. There is an inflection point in SF.
4. Further theoretical analysis is needed.

M. R. Xie, **J. G. Li***, N. Michel, W. Zuo, Preliminary results

③ 共振态谱因子计算



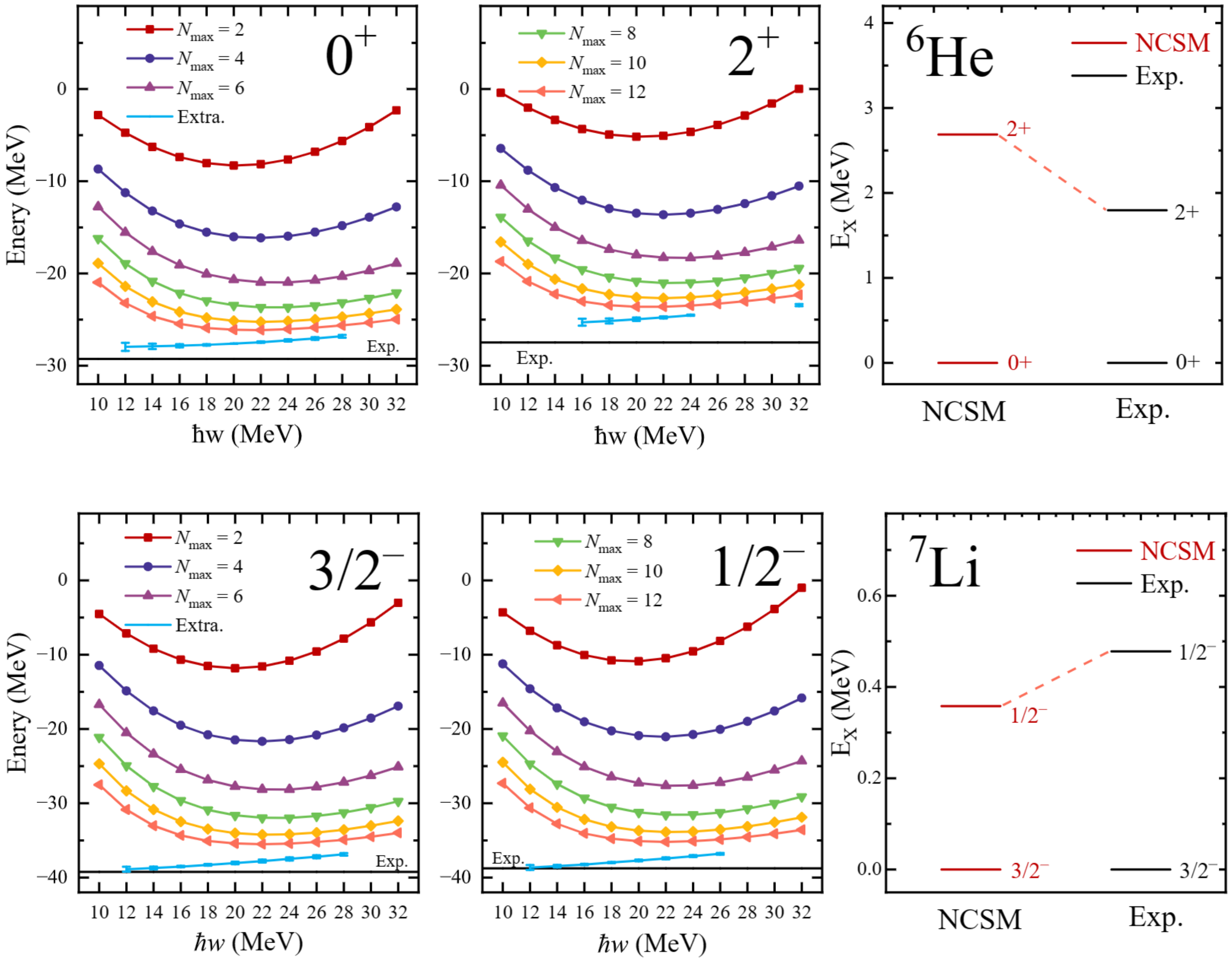
- ✓ 7He(3/2$^-$) is resonance state, the asymptotic region of the overlap function could only be well described in GSM calculation.
- ✓ The GFMC done in coordinate including continuum effects, but difficult for resonance states.
- ✓ The calculated C^2S with GSM are close to experimental data.

Z. X. Cao, Y. L. Ye, J. Xiao, et al, PLB 707,46 (2012)

- ✓ Due to the localization of NCSM calculation, the calculated C^2S of NCSM is smallest.

M. R. Xie, **J. G. Li***, N. Michel, et al., Submitted to PRC

NCSM calculations with NNLOopt interaction

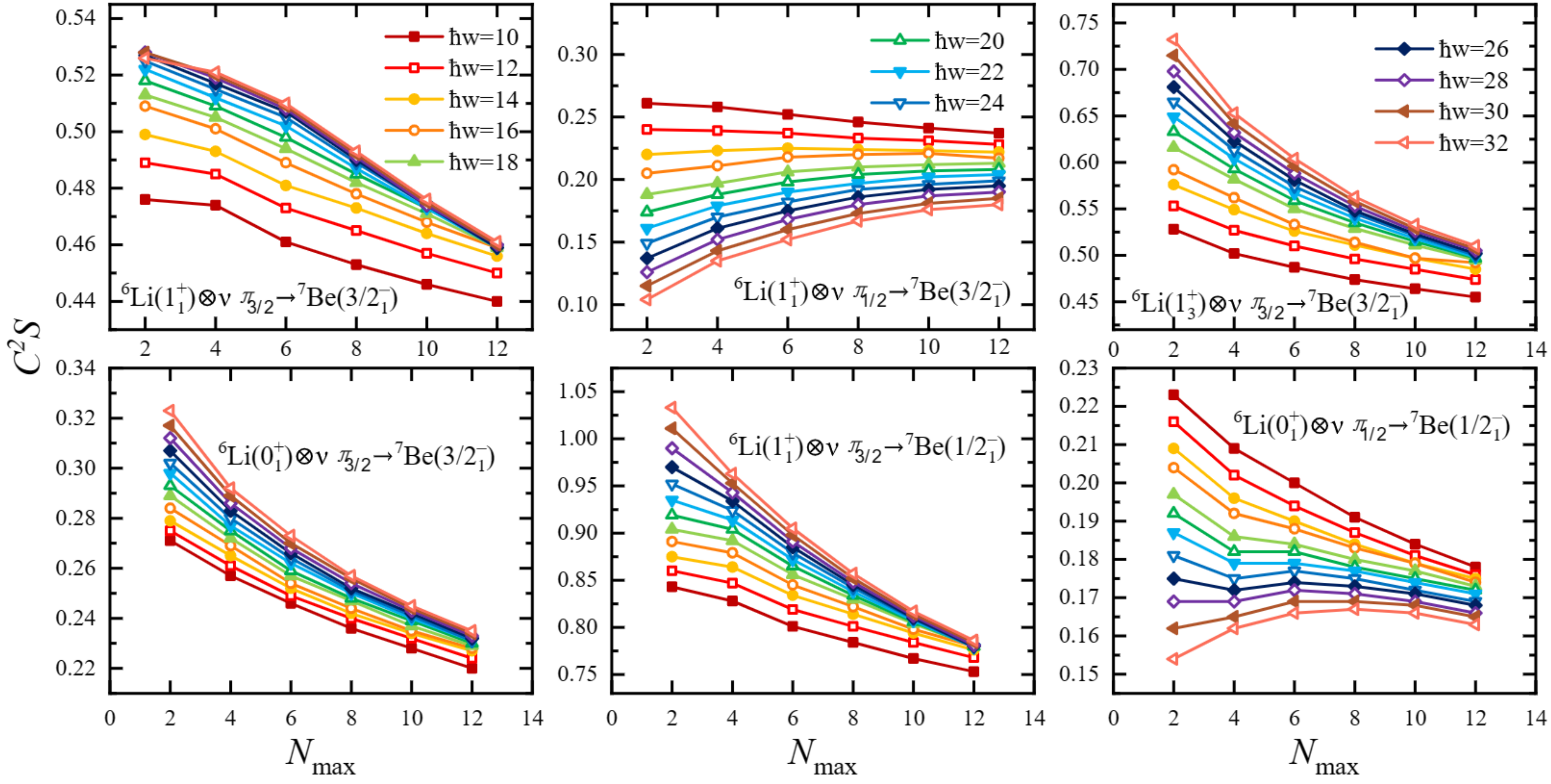


1. The results for energy levels converge quickly.
2. Use the exponential extrapolation formula to obtain spectra convergence results.

$$E(N_{max}) = A_0 + A_1 \exp(-A_2 * N_{max})$$

M. R. Xie, **J. G. Li***, W. Zuo, preliminary results

④ 第一性原理无芯壳模型计算谱因子



the exponential extrapolation formula does not apply to SF

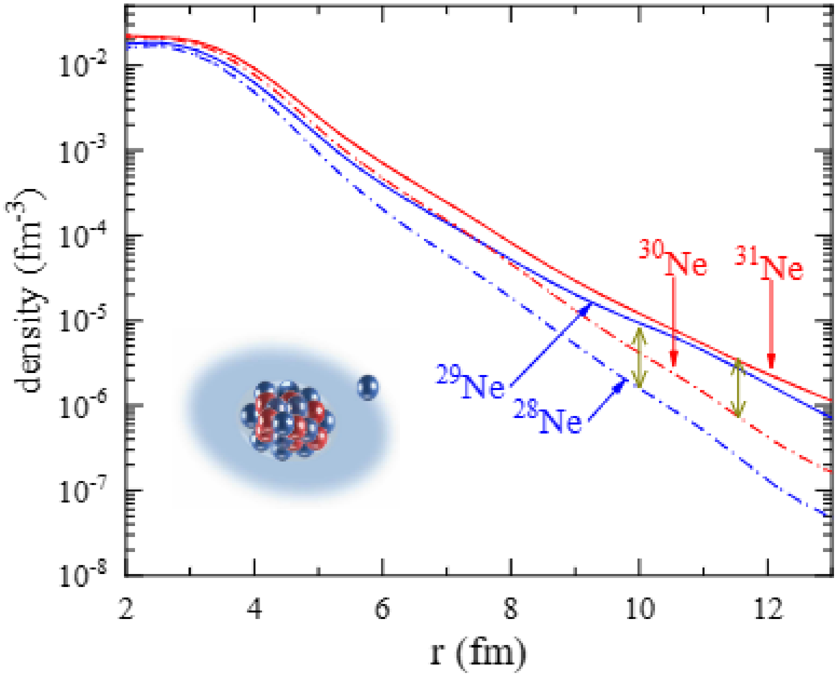
M. R. Xie, **J. G. Li***, W. Zuo, preliminary results

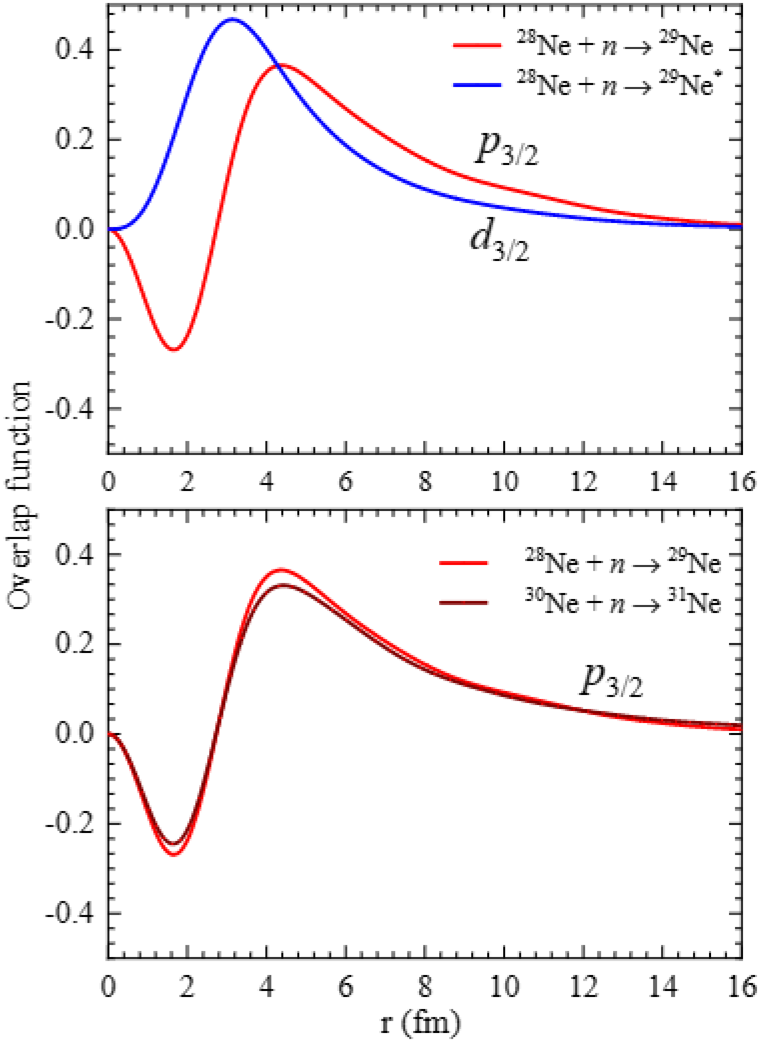
⑤ 谱因子/overlap function 研究单核子晕结构性质

Gamow 壳模型研究 ^{29}Ne 单中子晕结构

✓ ^{31}Ne： 单中子晕

L. Gaudefroy, et al. PRL. 109, 202503(2012)
T. Nakamura et al. PRL. 112, 142501(2014)





*p*3/2 C^2S

^{29}Ne： 0.540
^{31}Ne： 0.392

J. G. Li, et al., PLB 832, 137225 (2022)

总结

□Gamow壳模型计算原子核共振结构

- ✓ 计算的四中子共振态的能量与宽度被RIKEN实验证实(Nature 606, 678 (2022))
- ✓ Gamow壳模型预言滴线外原子核共振结构（^{7}H,^{28}O,^{18}Mg）

□原子核多体方法计算谱因子

- ✓ 连续态效应对深束缚核子谱因子与共振态的谱因子很关键
- ✓ 第一性原理无芯壳模型对于谱因子计算收敛性差
- ✓ 谱因子/overlap function 研究单核子晕结构

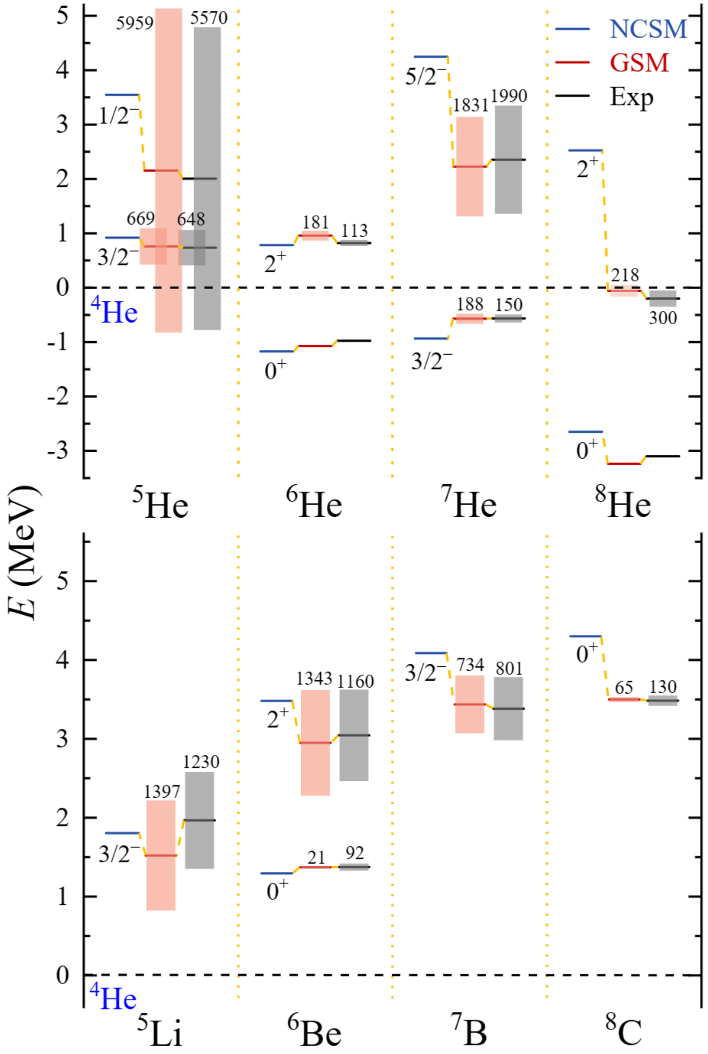
请各位老师批评指正！

李健国 jianguo_li@impcas.ac.cn

Backslide

 李健国 jianguo_li@impcas.ac.cn

③ 共振态谱因子计算



Resonance states lie above decay thresholds, so that they can decay via the emission of particle.

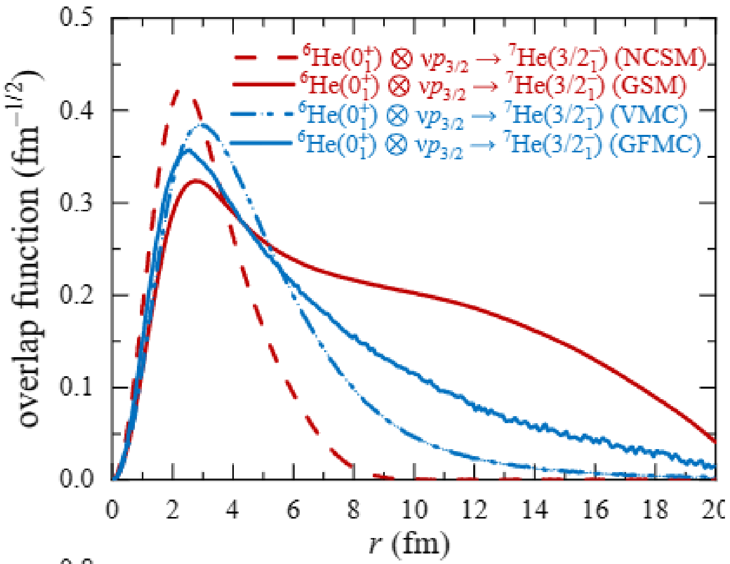
$$E = E_0 - i\Gamma/2$$

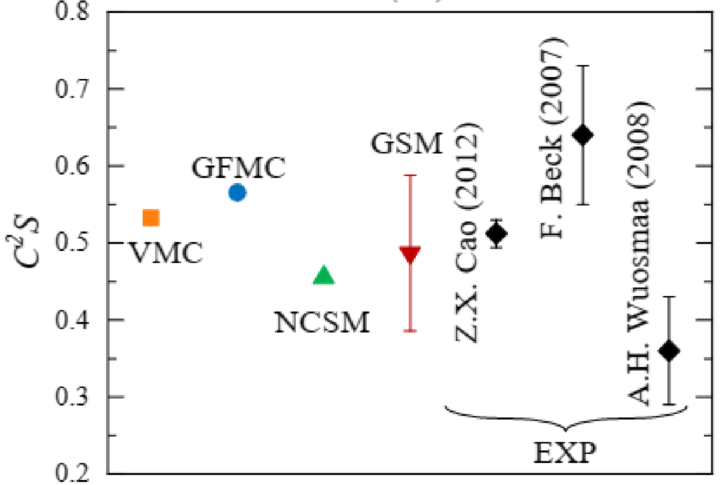
- ✓ The resonance can only be expanded with Berggren basis, but can not with HO basis.
- ✓ The resonance states can be well described with GSM, particularly the calculated width is close to experimental data.
- ✓ NCSM lacks continuum coupling

- ✓ Broad resonance state: ^{5}He($1/2^-$), ^{7}He($5/2^-$), ^{5}Li($3/2^-$), ^{6}Be(2^+), ^{7}B($3/2^-$), et al.
- ✓ Weakly-bound and loose-unbound states : ^{6,8}He(0+), ^{7}He($3/2^-$), ^{6}Be(0^+), ^{8}C(0^+), et al.

M. R. Xie, **J. G. Li***, N. Michel, H. H. Li, and W. Zuo, Submitted to PRC

③ 共振态谱因子计算





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Z. X. Cao, Y. L. Ye, J. Xiao, et al, PLB 707,46 (2012)

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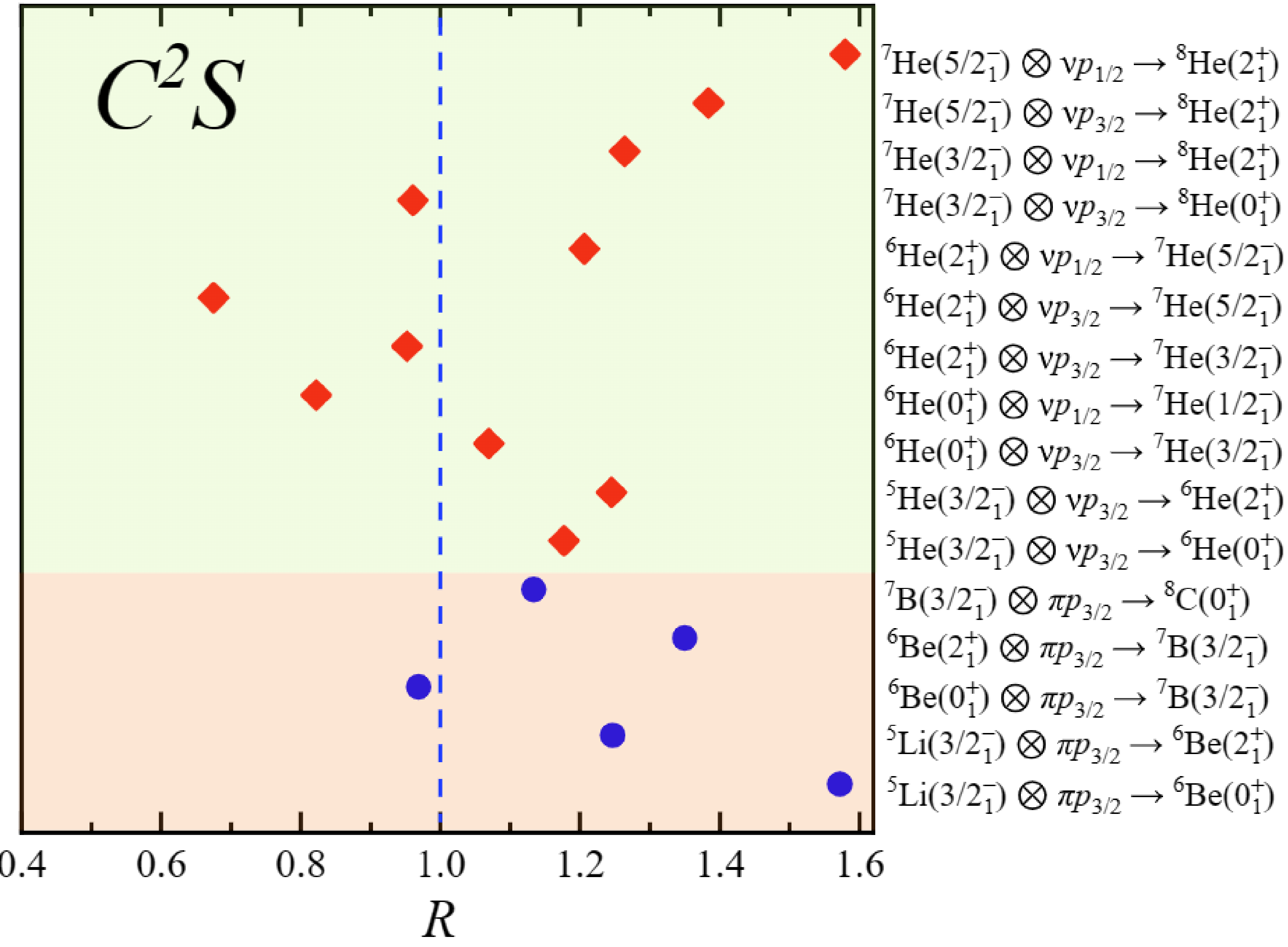
M. R. Xie, **J. G. Li***, N. Michel, et al., Submitted to PRC

③ 共振态谱因子计算



$$R = \frac{C^2S_{GSM}}{C^2S_{NCSM}}$$

- ✓ $|R-1| \sim 0.2-0.6$: strong coupling to continuum→ related to broad resonance states. For example $^7He(5/2\text{-}) + p3/2$ →$^8He(2+)$
- ✓ Broad resonance state: $^5He(1/2^-)$, $^7He(5/2^-)$, $^5Li(3/2^-)$, $^6Be(2^+)$, $^7B(3/2^-)$, et al.
- ✓ $|R-1| \sim 0$: related to narrow resonance states or weakly-bound state.
- ✓ Weakly-bound and loose-unbound states : $^{6,8}He(0+)$, $^7He(3/2^-)$, $^6Be(0^+)$, $^8C(0^+)$, et al.

M. R. Xie, **J. G. Li***, N. Michel, H. H. Li, and W. Zuo, Submitted to PRC

NCGSM for multi-neutron systems

Interaction : N3LO $V_{\text{low-}k}$ 2.1fm^{-1}
Model space : $s_{1/2}$, $p_{3/2}$ in Bergrren basis (45 points)
$p_{1/2}$, $d_{5/2,3/2}$, $f_{5/2,7/2}$, $g_{9/2}$ in HO basis. ($N_{\max}\leq 20$)
Method : Davison + overlap method
N. Michel, W. Nazarewicz, M. Ploszajczak, and T. Vertse, JPG 36, 013101 (2009)

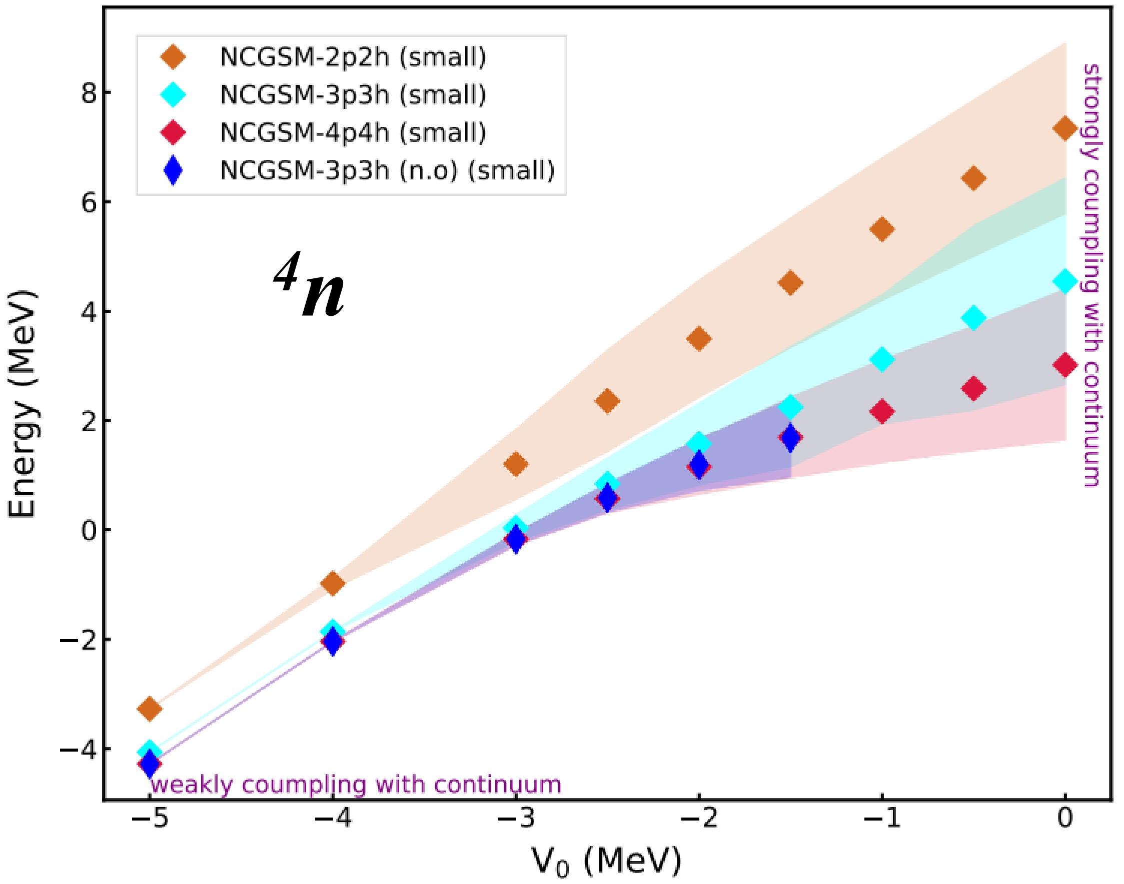
Multineutron systems

Unbound

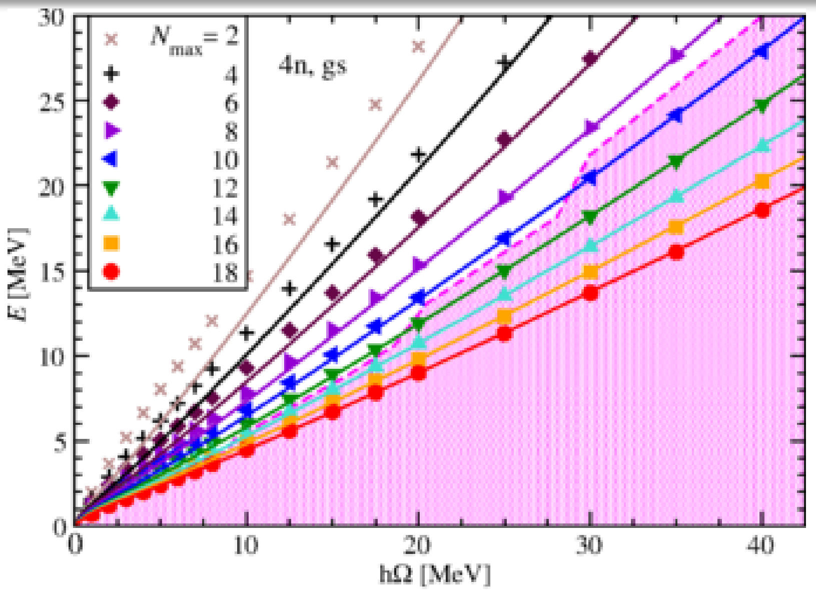
Strongly coupling with continuum

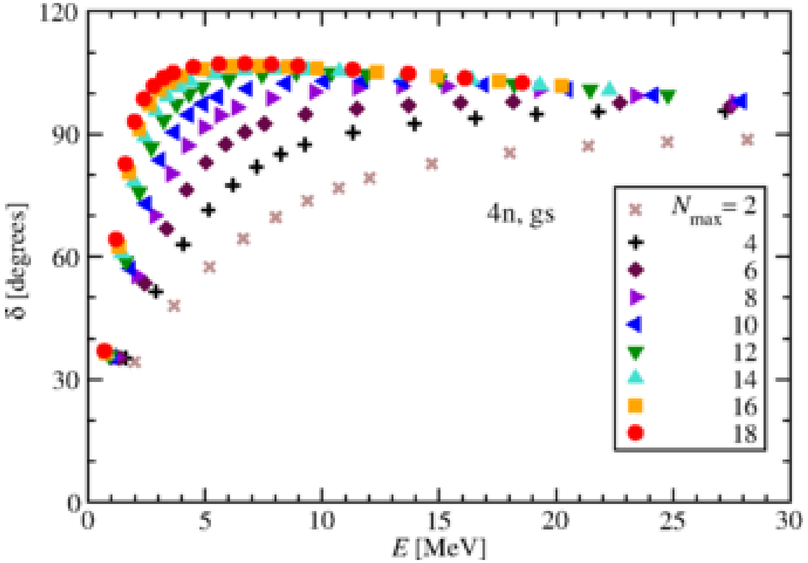
$$H = \frac{1}{A}\sum_{i}^{A}\frac{(p_i - p_j)^2}{2m} + \sum_{i<j}^{A} V_{NN}^{i<j} + \sum_{i}^{A} V_{\mathrm{WS}}$$

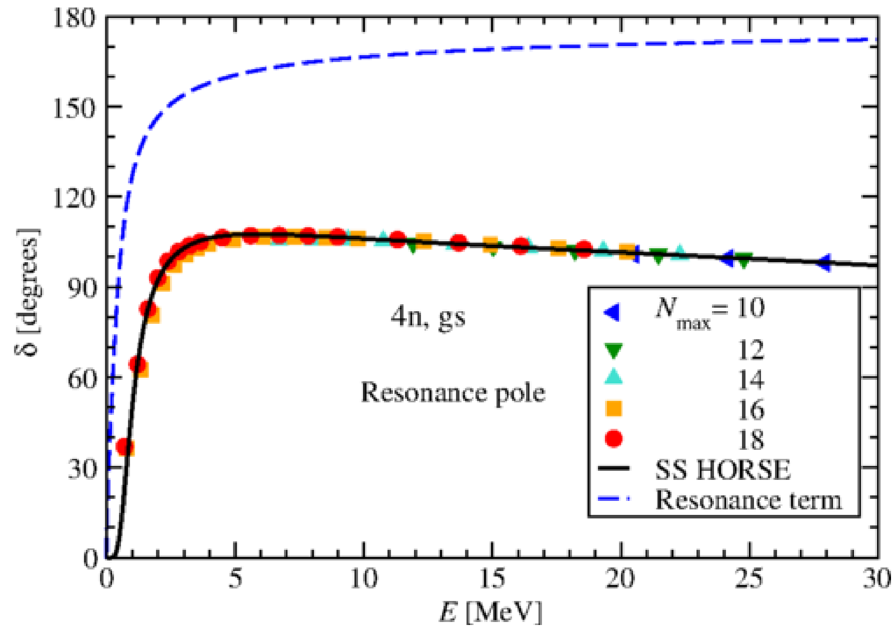
small model space : $s_{1/2}$, $p_{3/2}$ in Bergrren basis (45 points)
$p_{1/2}$, $d_{5/2,3/2}$, $f_{5/2,7/2}$, $g_{9/2}$ in HO basis. ($N_{\max}\leq 4$)



第一性原理无芯壳模型计算四中子共振态







E(tetraneutron) = 0.8 MeV Γ (tetraneutron) = 1.4 MeV

*A. M. Shirokov,et al, PRL **117**,182502 (2016)*

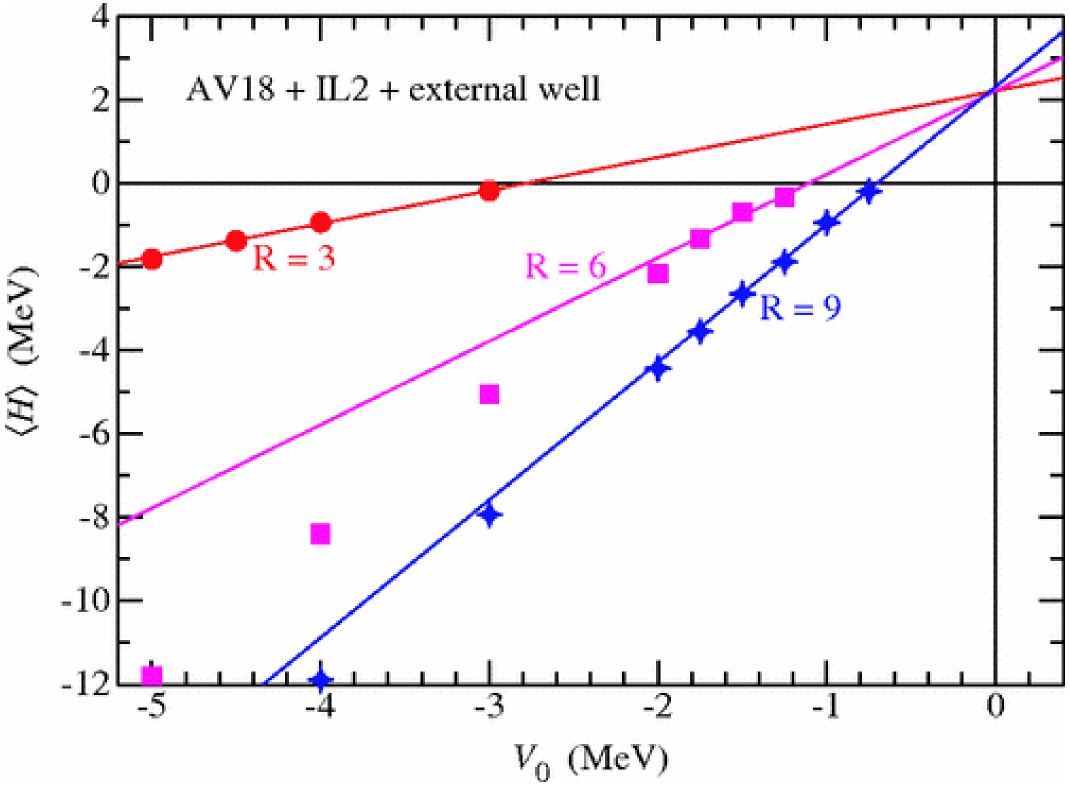
2019南京会议上，预言四中子具有两个共振态

1st: E(4n) ~ 0.3 MeV Γ (4n) ~ 0.8 MeV
2st: E(4n) ~ 0.8 MeV Γ (4n) ~ 1.3 MeV

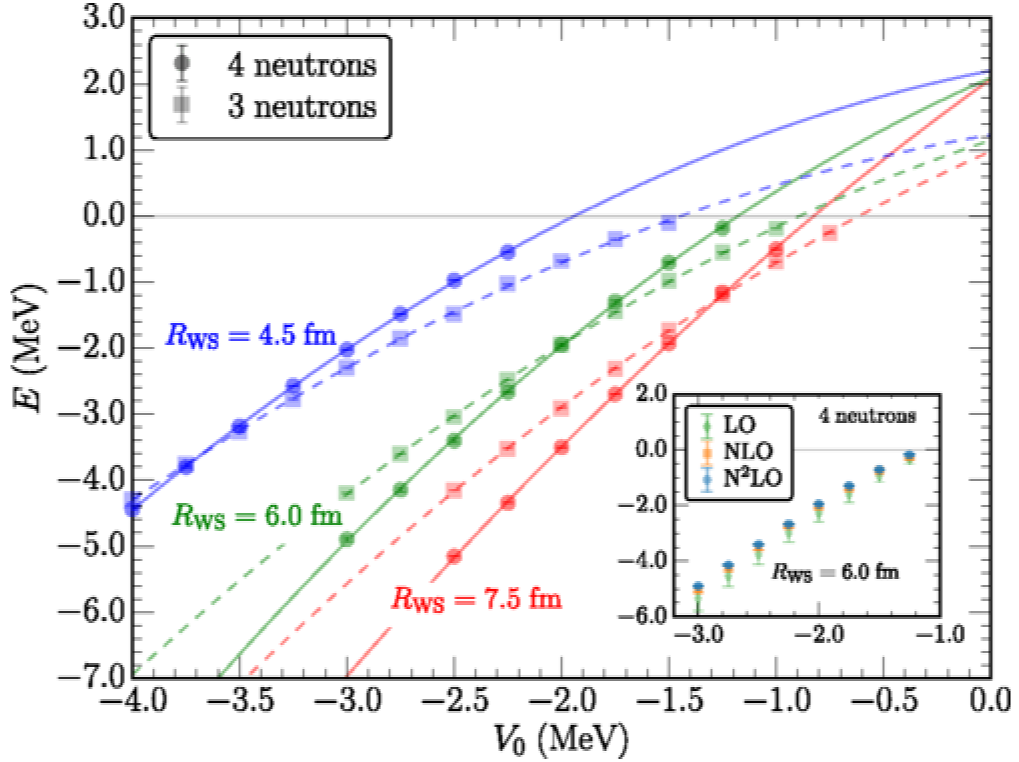
A. M. Shirokov Presentation in Nanjing@China 2019

量子蒙特卡洛方法计算多中子体系

$$H=-\sum_i \frac{\hbar^2}{2m}\nabla_i^2+\sum_i V_{\mathrm{WS}}(r_i)+\sum_{i<j}V_{ij}+\sum_{i<j<k}V_{ijk}$$



*Steven C. Pieper PRL **90**, 252501(2002)*

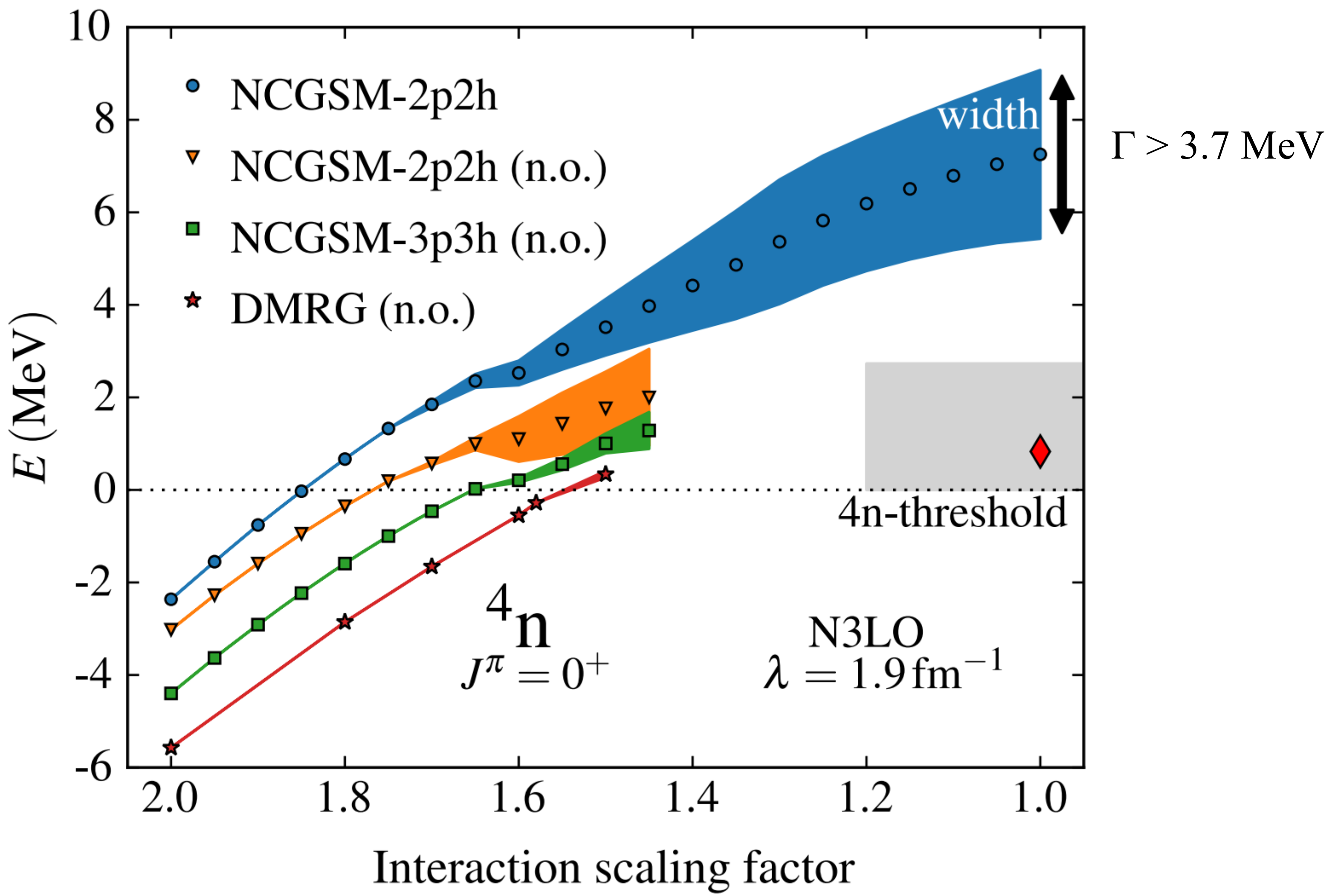


*S. Gandofi, et al., PRL **118**, 232501(2017)*

只能计算能量，无法计算宽度

无芯Gamow壳模型计算四中子

	$\lambda = 1.7\ \text{fm}^{-1}$	$\lambda = 1.9\ \text{fm}^{-1}$	$\lambda = 2.1\ \text{fm}^{-1}$
N3LO	7.27 (3.69)	7.28 (3.67)	7.28 (3.69)
$N2LO_{opt}$	7.32 (3.74)	7.33 (3.78)	7.34 (3.95)
$N2LO_{sat}^{*}$	7.24 (3.48)	7.22 (3.58)	7.27 (3.55)
JISP16		7.00 (3.72)	

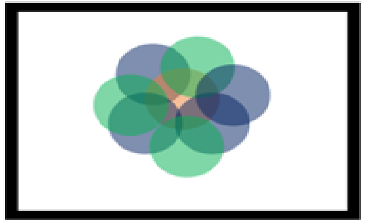


K. Fossez, J. Rotureau, N. Michel, and M. Ploszajczak, PRL ***119****, 032501 (2017)*

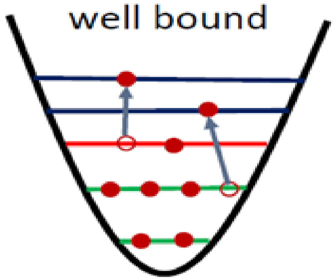
量子多体计算- HO /Berggren 完备基矢

$$H = -\sum_i \frac{\hbar^2}{2m}\nabla_i^2 + \sum_{ij} V_{ij} + \sum_{ijk} V_{ijk}$$

NCSM/SM



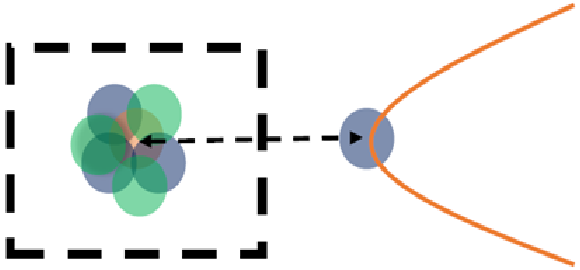
Closed quantum system



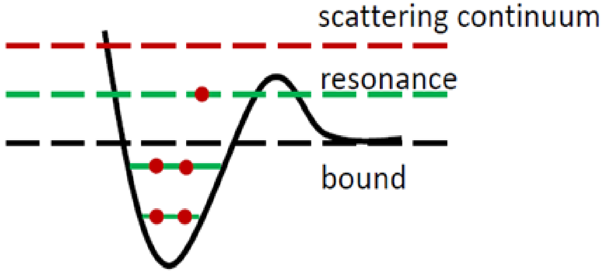
HO basis

Berggren 基矢自洽的包含共振与连续谱耦合

NCGSM/GSM



Open quantum system



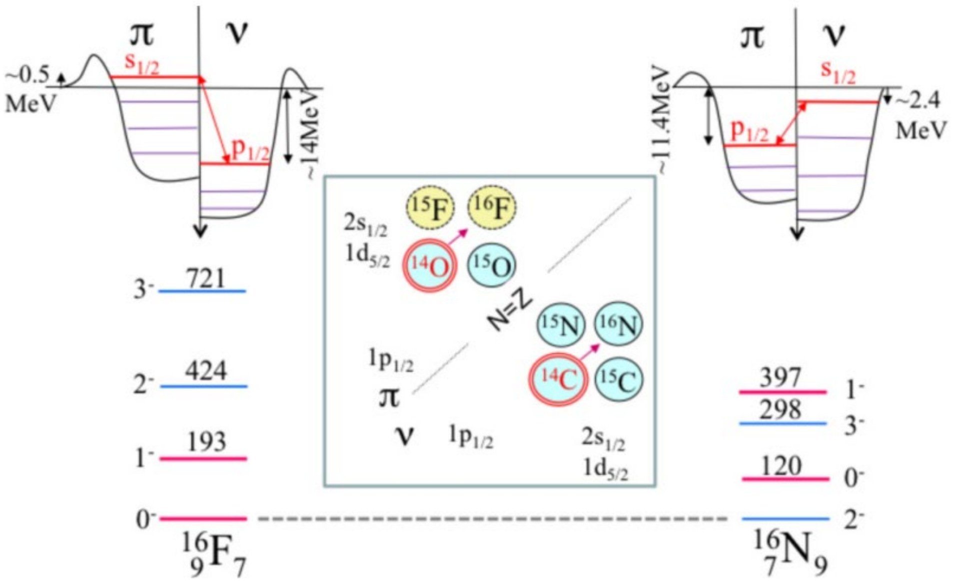
Berggren basis

E. Caurier, et al. RMP 77,427 (2005)
T. Otsuka, et al, RMP. 92,015002 (2020)
B. R. Barrett, P. Navratil, and J. P. Vary PPNP 69,131(2013)

N. Michel, M. Płoszajczak, The Gamow Shell Model, Springer ;
N. Michel, et al., JPG 36,013101 (2009)
***J. G. Li**, et al., Physics 3, 977 (2021)*
***J. G. Li**, et al., Phys. Rev. C 100, 054313 (2019)*
***J. G. Li**, et al., Phys. Rev. C 104, 024319 (2021)*

滴线原子核的共振与连续谱耦合:举例

$^{16}F/^{16}N$ 中的基态反转

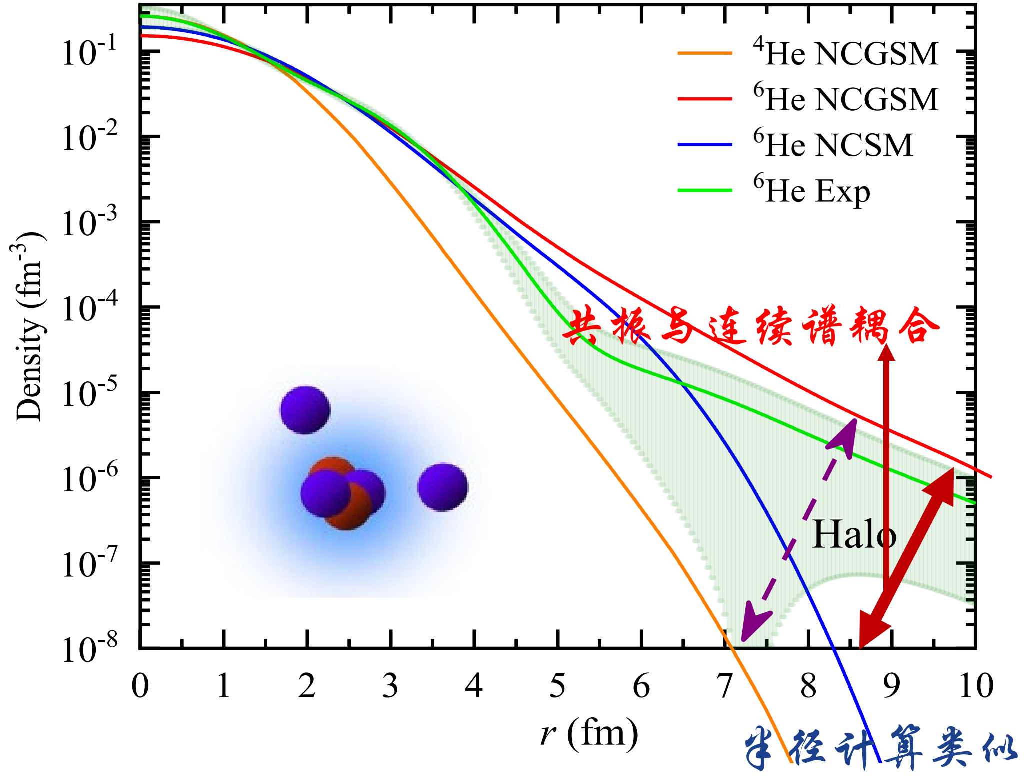


I.Stefan et al., PRC 90, 014307(2014)

*N. Michel, **J. G. Li**, et al PRC 106, L011301(2022)*

S. Zhang, F. R. Xu et al, submitted to PRC

^6He: 双中子晕结构



***J. G. Li**, et al.,* 文章准备中

共振与连续谱耦合非常关键，理论模型计算中应该考虑