第九届手征有效场论研讨会

2024.10.18-21, 长沙

第一性原理方法研究原子核中同位旋对称性破缺

李健国

中国科学院近代物理研究所

合作者：许甫荣，左维，袁琪，李红慧，王沛妍、谢萌冉，陈诺，李坤昊，王新鹏…

第一性原理框架

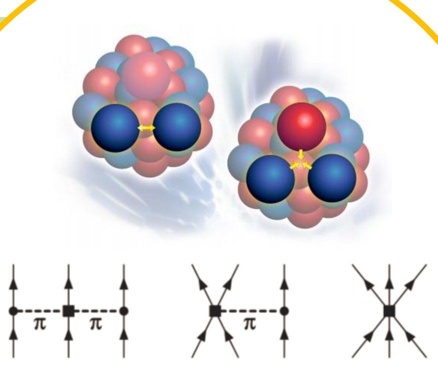
现实核力

自由度：π介子和核子

要求：重现核子-核子散射相移，不引入核结构参数

性质：短程排斥、长程吸引，具有强排斥芯

代表：CD-Bonn、AV18、手征有效场论(χEFT)



三体力

核力重整化

目的：将高低动量退耦合，软化核力，加快多体计算的收敛速度

代表：G-Matrix、$V_{\text{low}-k}$、相似重整化群(SRG),…

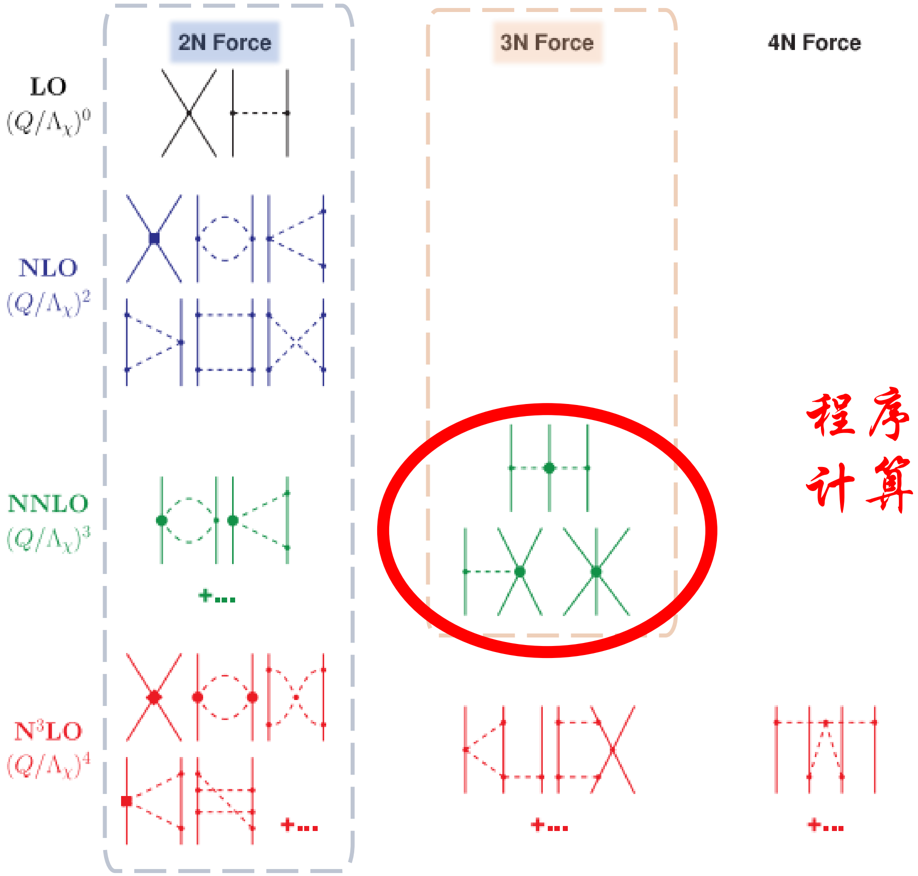
多体方法

目的：求解原子核多体强关联系统的哈密顿量，描述其物理性质

代表：NCSM($A \leq 16$), MBPT($A \sim 100$), CC($A \sim 100$，^{208}Pb),
IMSRG($A \sim 100$，^{208}Pb), ACSE (我们正在发展这个方法)…

现实核力

手征有效场论



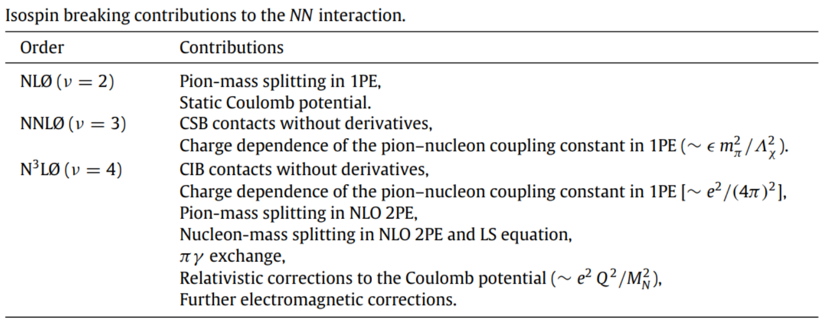
程序复杂

计算量非常大

N^3LO两体力+N^2LO三体力

现实核力 (NN+3N)

□ 同位旋对称性破缺：接触项和π介子交换项



Isospin breaking contributions to the *NN* interaction.

Order	Contributions
NLØ ($\nu = 2$)	Pion-mass splitting in 1PE, Static Coulomb potential.
NNLØ ($\nu = 3$)	CSB contacts without derivatives, Charge dependence of the pion–nucleon coupling constant in 1PE ($\sim \epsilon\, m_\pi^2/\Lambda_\chi^2$).
N^3LØ ($\nu = 4$)	CIB contacts without derivatives, Charge dependence of the pion–nucleon coupling constant in 1PE [$\sim e^2/(4\pi)^2$], Pion-mass splitting in NLO 2PE, Nucleon-mass splitting in NLO 2PE and LS equation, $\pi\gamma$ exchange, Relativistic corrections to the Coulomb potential ($\sim e^2\, Q^2/M_N^2$), Further electromagnetic corrections.

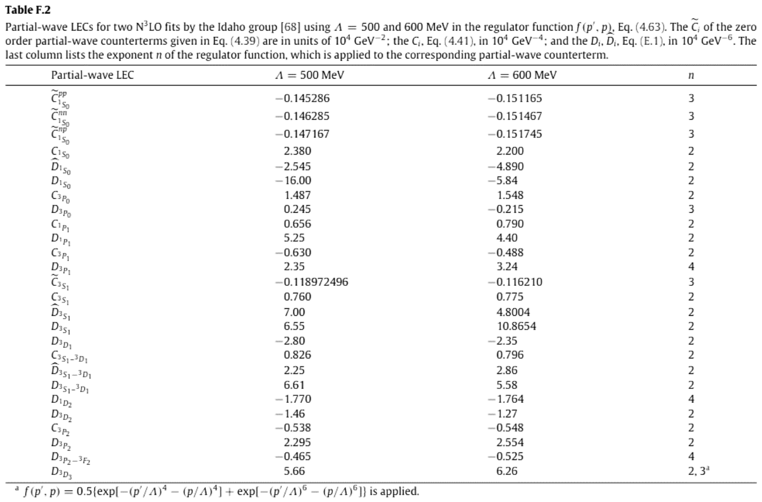


Table F.2

Partial-wave LECs for two N^3LO fits by the Idaho group [68] using $\Lambda = 500$ and 600 MeV in the regulator function $f(p', p)$, Eq. (4.63). The $\widetilde{C}_i$ of the zero order partial-wave counterterms given in Eq. (4.39) are in units of 10^4 GeV^{-2}; the C_i, Eq. (4.41), in 10^4 GeV^{-4}; and the D_i, $\widehat{D}_i$, Eq. (E.1), in 10^4 GeV^{-6}. The last column lists the exponent *n* of the regulator function, which is applied to the corresponding partial-wave counterterm.

Partial-wave LEC	$\Lambda = 500$ MeV	$\Lambda = 600$ MeV	*n*
$\widetilde{C}^{pp}_{^1S_0}$	−0.145286	−0.151165	3
$\widetilde{C}^{nn}_{^1S_0}$	−0.146285	−0.151467	3
$\widetilde{C}^{np}_{^1S_0}$	−0.147167	−0.151745	3
$C_{^1S_0}$	2.380	2.200	2
$\widehat{D}_{^1S_0}$	−2.545	−4.890	2
$D_{^1S_0}$	−16.00	−5.84	2
$C_{^3P_0}$	1.487	1.548	2
$D_{^3P_0}$	0.245	−0.215	3
$C_{^1P_1}$	0.656	0.790	2
$D_{^1P_1}$	5.25	4.40	2
$C_{^3P_1}$	−0.630	−0.488	2
$D_{^3P_1}$	2.35	3.24	4
$\widetilde{C}_{^3S_1}$	−0.118972496	−0.116210	3
$C_{^3S_1}$	0.760	0.775	2
$\widehat{D}_{^3S_1}$	7.00	4.8004	2
$D_{^3S_1}$	6.55	10.8654	2
$D_{^3D_1}$	−2.80	−2.35	2
$C_{^3S_1-^3D_1}$	0.826	0.796	2
$\widehat{D}_{^3S_1-^3D_1}$	2.25	2.86	2
$D_{^3S_1-^3D_1}$	6.61	5.58	2
$D_{^1D_2}$	−1.770	−1.764	4
$D_{^3D_2}$	−1.46	−1.27	2
$C_{^3P_2}$	−0.538	−0.548	2
$D_{^3P_2}$	2.295	2.554	2
$D_{^3P_2-^3F_2}$	−0.465	−0.525	4
$D_{^3D_3}$	5.66	6.26	2, 3[a]

[a] $f(p', p) = 0.5\{\exp[-(p'/\Lambda)^4 - (p/\Lambda)^4] + \exp[-(p'/\Lambda)^6 - (p/\Lambda)^6]\}$ is applied.

价空间-介质相似重整化群(VS-IMSRG)与多体微扰方法

核多体问题： $H|\Psi\rangle = E|\Psi\rangle$

1. **A体哈密顿量H**

$$H = \sum_{i=1}^{A}\left(1-\frac{1}{A}\right)\frac{p_i^2}{2m} + \sum_{i<j}^{A}\left(v_{ij}^{\mathrm{NN}} - \frac{p_i\cdot p_j}{mA}\right) + \sum_{i<j<k}^{A} v_{ijk}^{3\mathrm{N}}$$

2. **对A体哈密顿量做正规乘积 (Normal Order)**

$$E = \left(1-\frac{1}{A}\right)\sum_{i}\langle i\,|T^{(1)}|\,i\rangle n_i + \frac{1}{2}\sum_{ij}\langle ij\,|T^{(2)}+V^{(2)}|\,ij\rangle n_i n_j + \frac{1}{6}\sum_{ijk}\langle ijk\,|V^{(3)}|\,ijk\rangle n_i n_j n_k$$

$$\Gamma_{ijkl} = \langle ij\,|T^{(2)}+V^{(2)}|\,kl\rangle + \sum_{a}\langle ija\,|V^{(3)}|\,kla\rangle n_a$$

$$H_{NO} = \boxed{E} + \sum_{ij}\boxed{f_{ij}} : a_i^{\dagger}a_j : + \frac{1}{4}\sum_{ijkl}\boxed{\Gamma_{ijkl}} : a_i^{\dagger}a_j^{\dagger}a_l a_k : + \frac{1}{36}\sum_{ijklmn}\boxed{W_{ijklmn}} : a_i^{\dagger}a_j^{\dagger}a_k^{\dagger}a_n a_m a_l :$$

$$f_{ij} = \left(1-\frac{1}{A}\right)\langle i|T^{(1)}|j\rangle + \sum_{a}\langle ia\,|T^{(2)}+V^{(2)}|\,ja\rangle n_a + \frac{1}{2}\sum_{ab}\langle iab\,|V^{(3)}|\,jab\rangle n_a n_b$$

$$W_{ijklmn} = \langle ijk\,|V^{(3)}|\,lmn\rangle$$

正规乘积后的两体近似(NO2B)包含三体力效应。

价空间-介质相似重整化群(VS-IMSRG)与多体微统方法

核多体问题： $H|\Psi\rangle = E|\Psi\rangle$

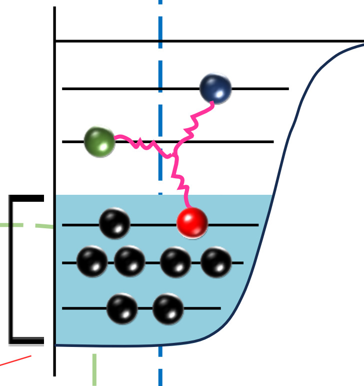
1. A体哈密顿量H

$$H = \sum_{i=1}^{A}\left(1-\frac{1}{A}\right)\frac{p_i^2}{2m} + \sum_{i<j}^{A}\left(v_{ij}^{\mathrm{NN}} - \frac{p_i\cdot p_j}{mA}\right) + \sum_{i<j<k}^{A} v_{ijk}^{3\mathrm{N}}$$

2. 对A体哈密顿量做正规乘积 (Normal Order)

$$E = \left(1-\frac{1}{A}\right)\sum_i \langle i|T^{(1)}|i\rangle n_i + \frac{1}{2}\sum_{ij}\langle ij|T^{(2)}+V^{(2)}|ij\rangle n_i n_j + \frac{1}{6}\sum_{ijk}\langle ijk|V^{(3)}|ijk\rangle n_i n_j n_k$$

$$\Gamma_{ijkl} = \langle ij|T^{(2)}+V^{(2)}|kl\rangle + \boxed{\sum_a \langle ija|V^{(3)}|kla\rangle n_a}$$

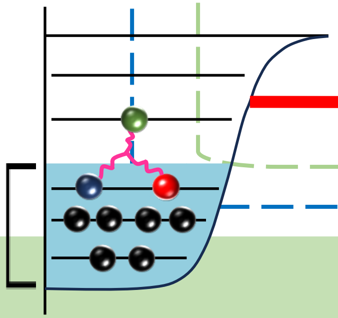


^{16}O core

$$H_{NO} = E + \sum_{ij} f_{ij} : a_i^\dagger a_j : + \frac{1}{4}\sum_{ijkl}\Gamma_{ijkl} : a_i^\dagger a_j^\dagger a_l a_k : + \frac{1}{36}\sum_{ijklmn}\cancel{W_{ijklmn} : a_i^\dagger a_j^\dagger a_k^\dagger a_n a_m a_l :}$$

$$f_{ij} = \left(1-\frac{1}{A}\right)\langle i|T^{(1)}|j\rangle + \sum_a \langle ia|T^{(2)}+V^{(2)}|ja\rangle n_a \boxed{+\frac{1}{2}\sum_{ab}\langle iab|V^{(3)}|jab\rangle n_a n_b}$$

$$W_{ijklmn} = \langle ijk|V^{(3)}|lmn\rangle$$



^{16}O
core

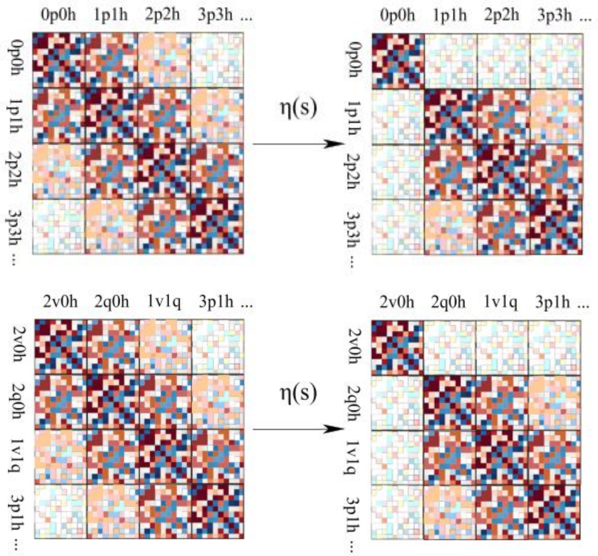
正规乘积后的两体近似(NO2B)包含三体力效应。

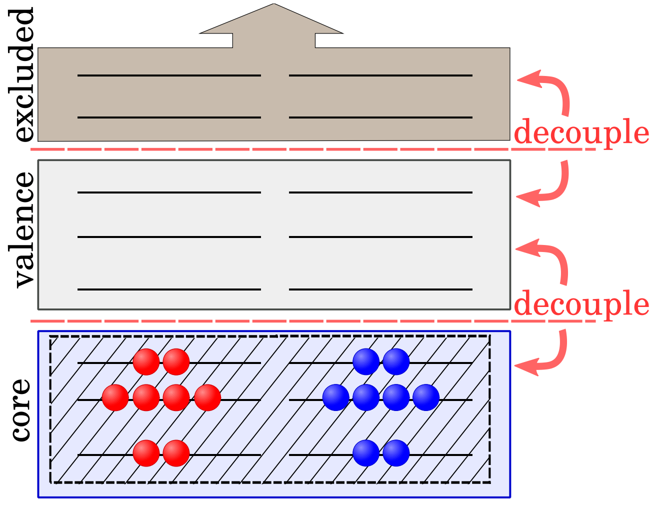
价空间-介质相似重整化群 (VS-IMSRG)与多体微扰方法

3. 通过连续的幺正变换U将正规乘积的哈密顿量脱耦成价空间的有效哈密顿量

$$H_{eff}(s) = U(s)H_{NO}U^{\dagger}(s), (UU^{\dagger} = 1)$$

- **流方程：** $\frac{d}{ds}H_{eff}(s) = [\eta(s), H(s)]$
- **生成子：** $\eta(s) = \frac{dU(s)}{ds}U^{\dagger}(s) = -\eta^{\dagger}(s)$
- **幺正变换：** $U(s) = e^{\Omega(s)} = e^{\int \eta(s)ds}$





$|\Phi_0\rangle = |^{16}\mathrm{O}\rangle$

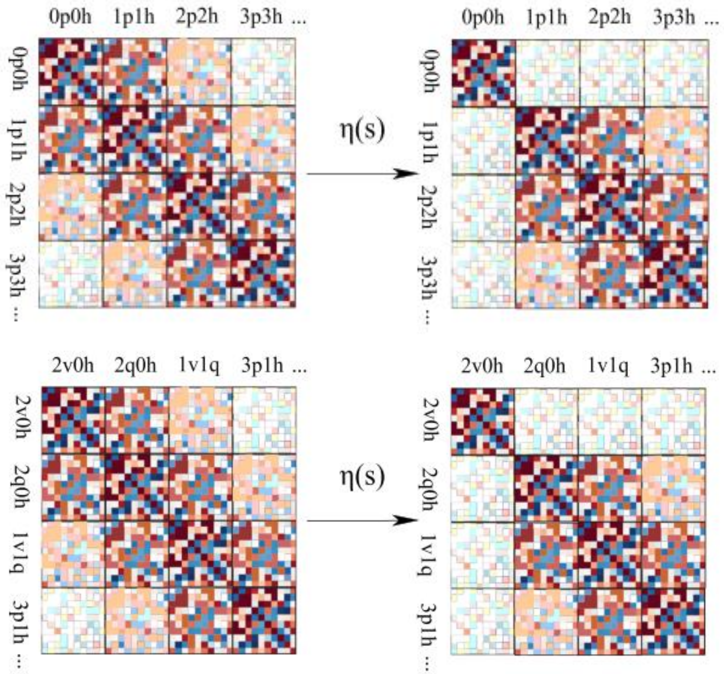
价空间-介质相似重整化群 (VS-IMSRG)

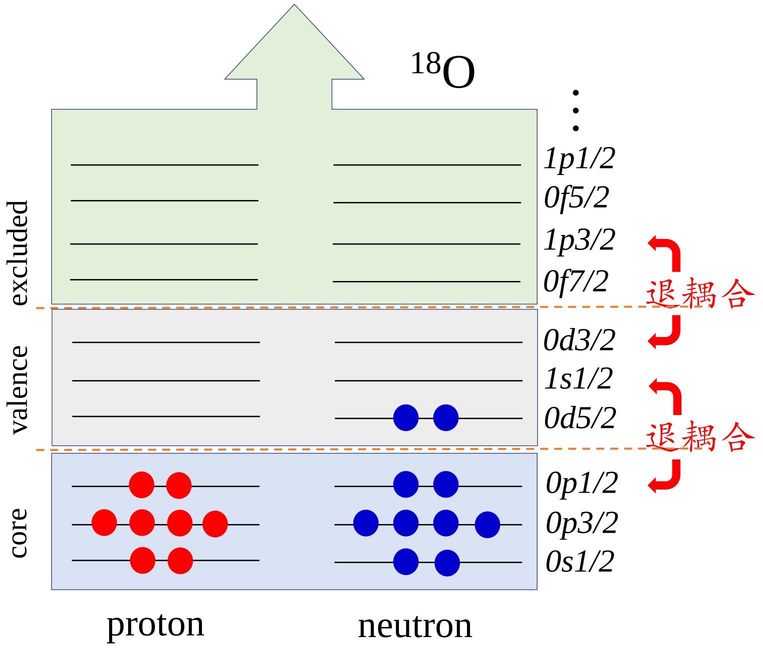
第一性原理 价空间的介质相似重整化群 (*Ab initio* VS-IMSRG)

Ab initio Valence-Space In-Medium Similarity Renormalization Group

➢ 核心思想

$$H(s)=U(s)H(0)U^{+}(s)$$
$$=H^{d}(s)+H^{od}(s)\to H^{d}(\infty)$$





➢ 优势:

- 基于现实核力 (NN+3N)
  - 包括CSB 以及 CIB 效应
  - 同位旋对称性破缺: 接触项和交换项
- 在计算过程中，没有引入额外的参数
- 精确处理核多体系统

壳模型能算的，VS-IMSRG都可以从现实核力出发进行计算

同位旋对称性破缺的起因

- **粒子物理**
  - ✓ u-d 夸克质量区别
  - ✓ 夸克之间的电磁效应

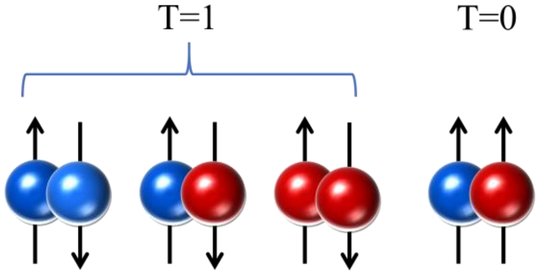
1. p-n 质量区别:

$$m_p = 1.00782503\,u, m_n = 1.00866491u$$

2. p-n 电荷区别:

$$e_p = e, e_n = (-4.3 \pm 7.1) \times 10^{-20} e$$

- **核物理**
  - ✓ 库仑相互作用
  - ✓ 核子-核子相互作用的区别



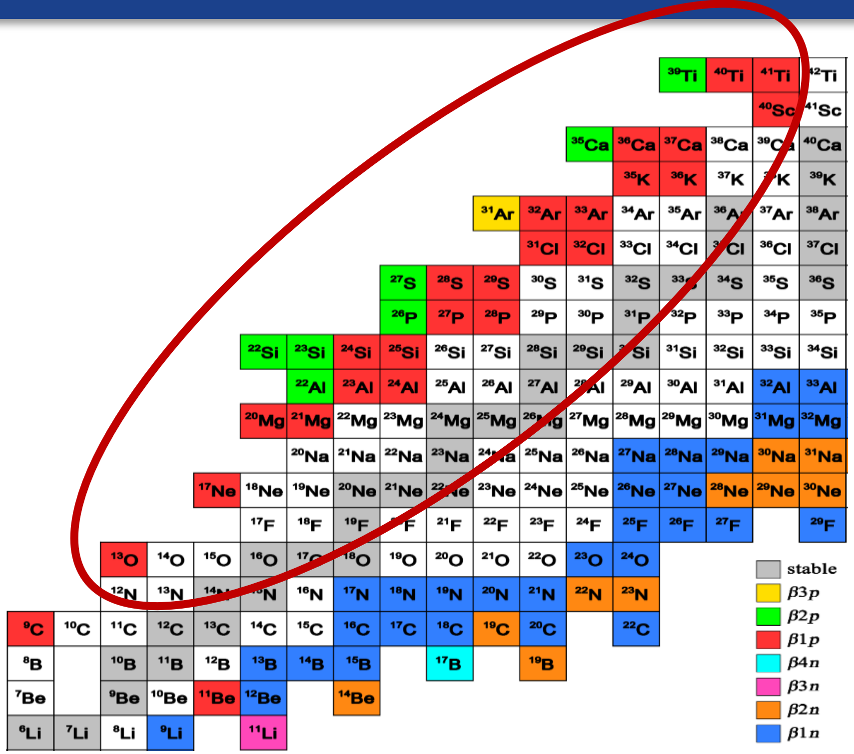
- 电荷对称性破缺（Charge symmetry breaking--CSB）$V_{nn} - V_{pp}$（同位旋矢量）
- 电荷无关性破缺（Charge independent breaking--CIB）$2V_{np} - (V_{nn} + V_{pp})$（同位旋张量）

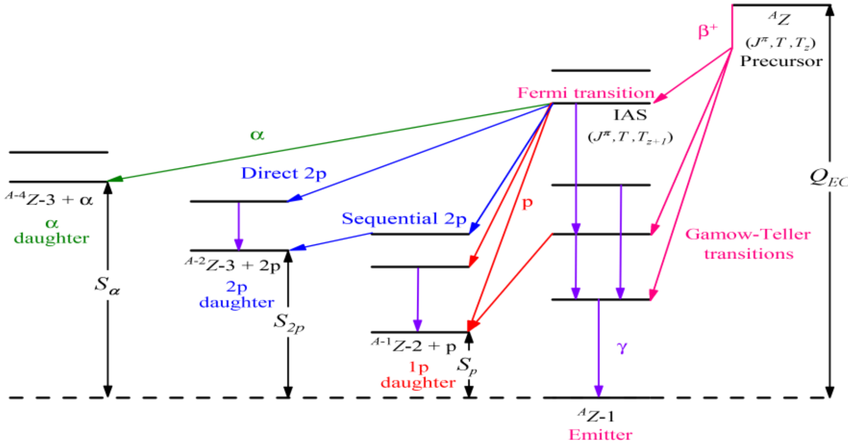
同位旋不守恒力 (Isospin non-conserving force--INC)

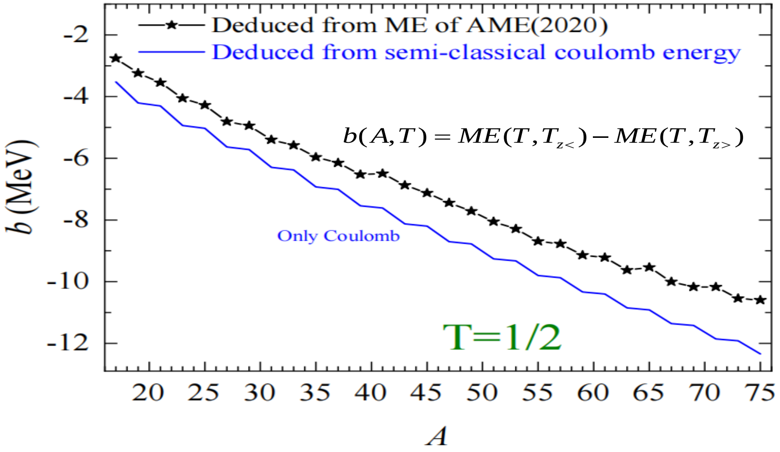
  - ✓ 弱束缚效应

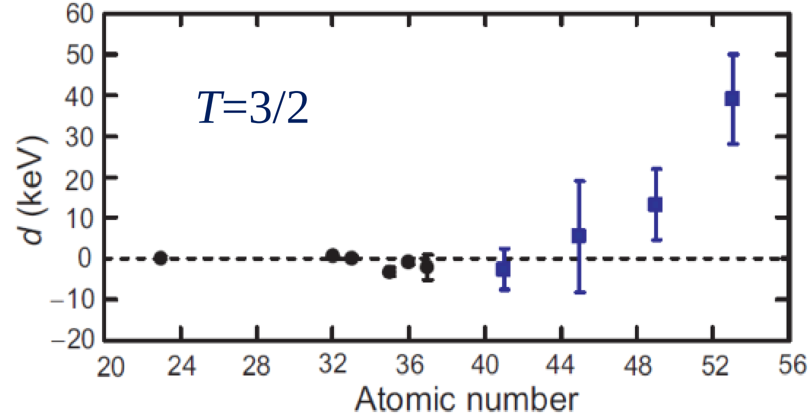
探索同位旋对称性破缺的物理机制：库仑力，核力，弱束缚效应…

同位旋对称性破缺：质子滴线核中的β衰变, IMME









Large deviation for *A*=53, *T*=3/2 quartet.
A non-zero *d* term is found.

Y.-H. Zhang et al, Phys. Rev. Lett. 109 (2012) 102501

质子滴线核中的β衰变-同位旋对称性破缺

镜像能级差异(MED)

$$\mathrm{MED} = E_x(J,T,T_Z=-T) - E_x(J,T,T_Z=T),$$

Thomas-Ehrman Shift

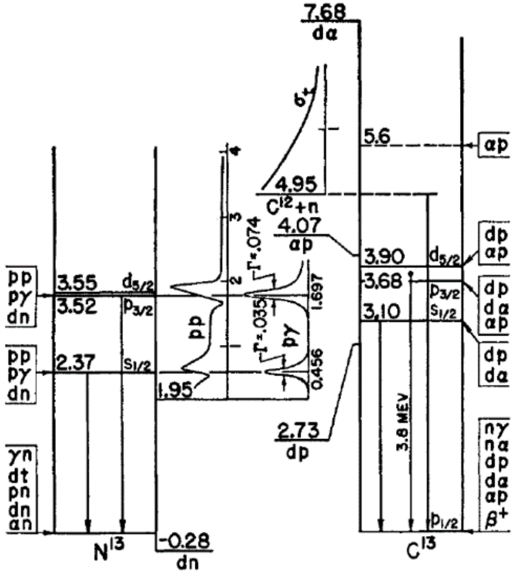
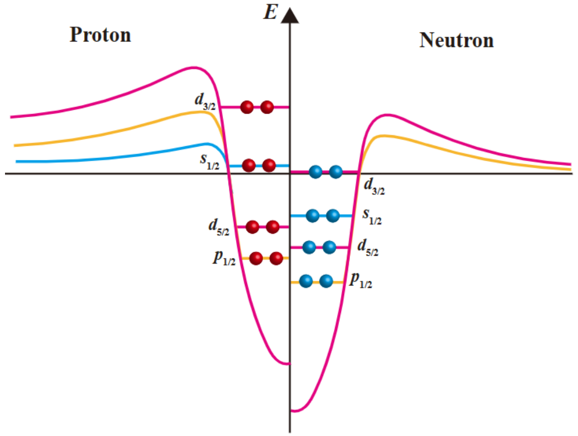


FIG. 1. The energy levels of C^{13} and N^{13} below 6 Mev.

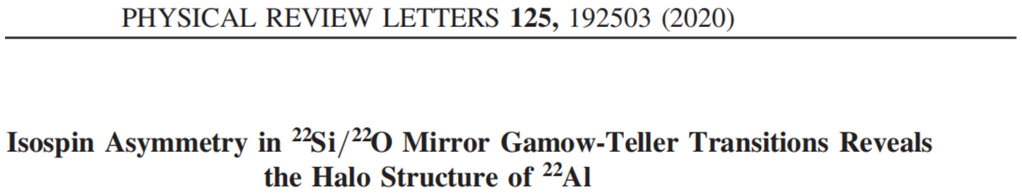
Phys. Rev. 88,1109 (1952)



mirror asymmetry parameter (δ) :

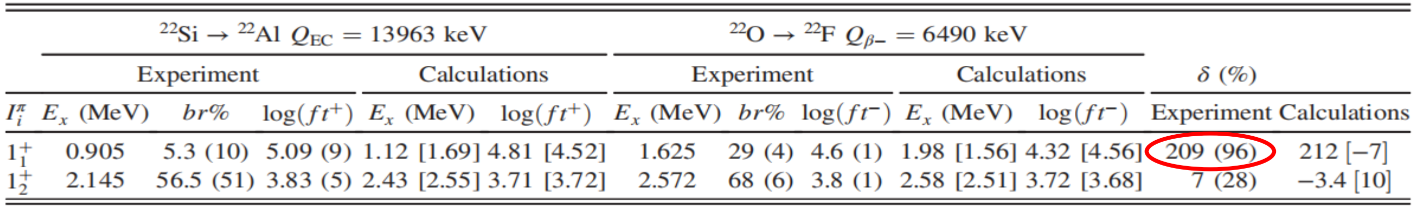
$$\delta = \frac{ft^+}{ft^-} - 1 \quad \longrightarrow$$

$\delta >> 0$
isospin symmetry breaking



PHYSICAL REVIEW LETTERS **125,** 192503 (2020)

Isospin Asymmetry in ^{22}Si/^{22}O Mirror Gamow-Teller Transitions Reveals the Halo Structure of ^{22}Al

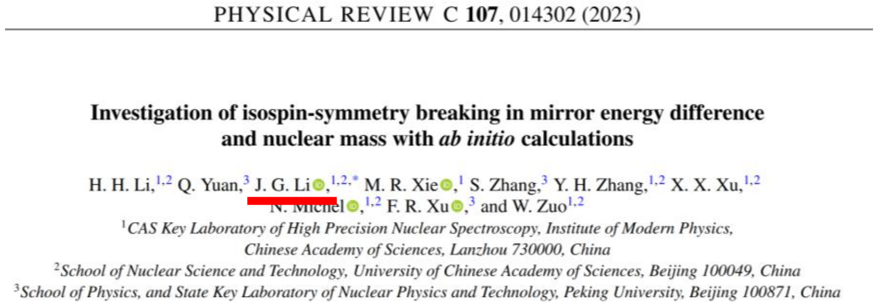


	^{22}Si → ^{22}Al Q_{EC} = 13963 keV					^{22}O → ^{22}F $Q_{\beta-}$ = 6490 keV						
	Experiment			Calculations		Experiment			Calculations		δ (%)	
I_i^π	E_x (MeV)	$br\%$	$\log(ft^+)$	E_x (MeV)	$\log(ft^+)$	E_x (MeV)	$br\%$	$\log(ft^-)$	E_x (MeV)	$\log(ft^-)$	Experiment	Calculations
1_1^+	0.905	5.3 (10)	5.09 (9)	1.12 [1.69]	4.81 [4.52]	1.625	29 (4)	4.6 (1)	1.98 [1.56]	4.32 [4.56]	209 (96)	212 [−7]
1_2^+	2.145	56.5 (51)	3.83 (5)	2.43 [2.55]	3.71 [3.72]	2.572	68 (6)	3.8 (1)	2.58 [2.51]	3.72 [3.68]	7 (28)	−3.4 [10]

Comparing the mirror β decay of ^{22}Si/^{22}O, we found **the largest** value of mirror asymmetry **(δ = 209(96) %)** in low-lying states by far, in the transition to the first 1^+excited state.

镜像能级差异

采用NN(bare)和NN+3N(1.8/2.0)现实核力，利用VS-IMSRG研究镜像核能谱上的破缺



PHYSICAL REVIEW C **107**, 014302 (2023)

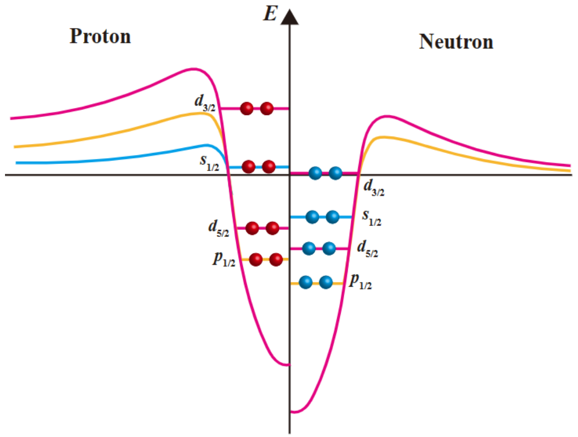
Investigation of isospin-symmetry breaking in mirror energy difference and nuclear mass with *ab initio* calculations

H. H. Li,[1,2] Q. Yuan,[3] J. G. Li,[1,2,*] M. R. Xie,[1] S. Zhang,[3] Y. H. Zhang,[1,2] X. X. Xu,[1,2] N. Michel,[1,2] F. R. Xu,[3] and W. Zuo[1,2]

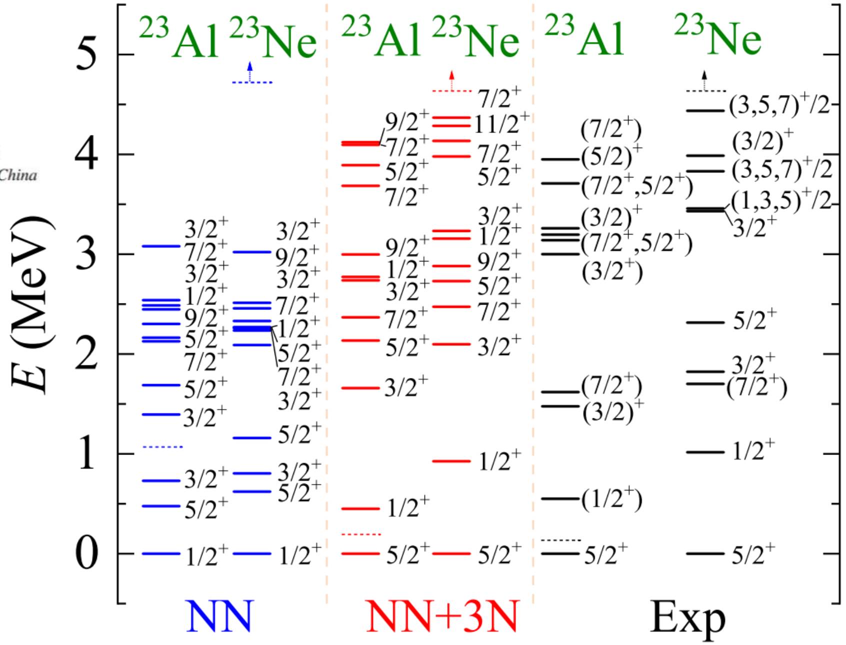
[1] *CAS Key Laboratory of High Precision Nuclear Spectroscopy, Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China*

[2] *School of Nuclear Science and Technology, University of Chinese Academy of Sciences, Beijing 100049, China*

[3] *School of Physics, and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China*

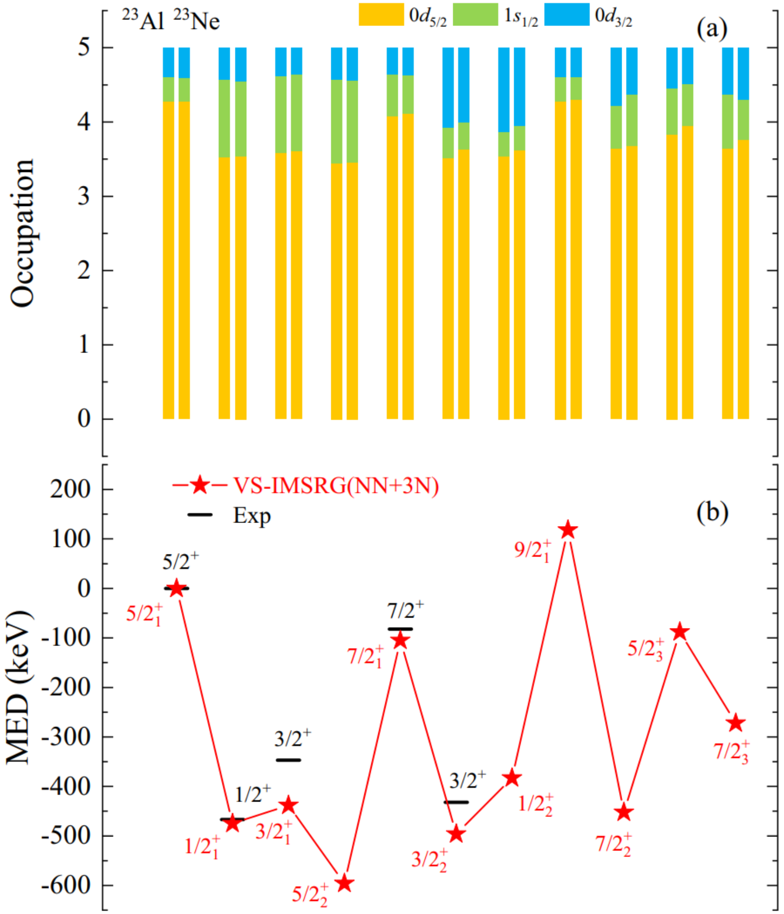


三体力对能谱的研究至关重要。



镜像能级差异→同位旋对称性破缺

$$(\mathrm{MED}) = E_x(\text{丰质子}) - E_x(\text{丰中子})$$

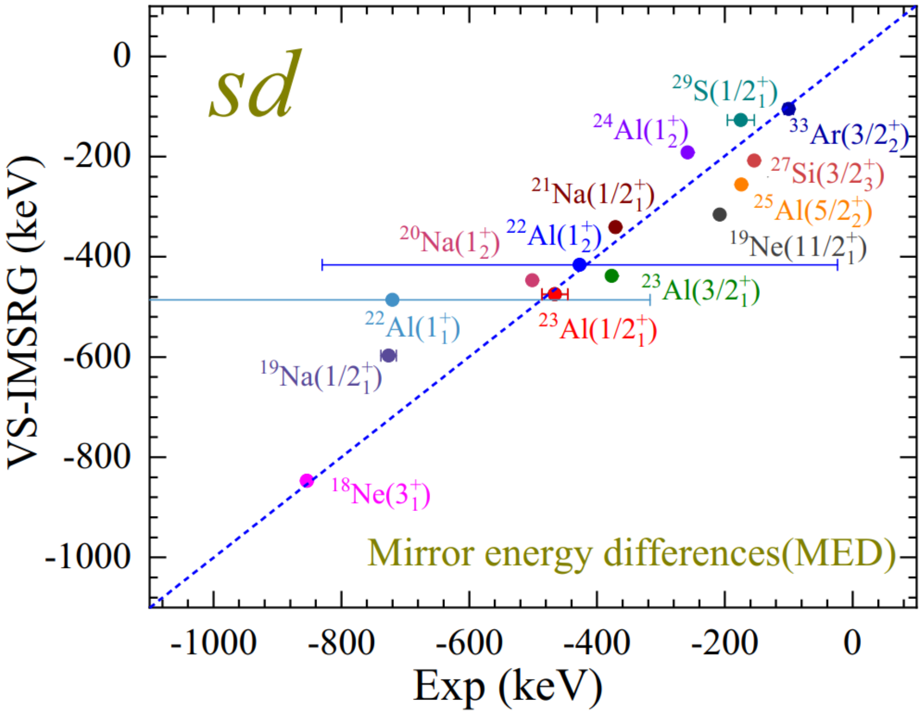


较大的MED主要是由1s1/2轨道占据导致，0d3/2 轨道的占据也做出贡献

镜像能级差异--sd 壳

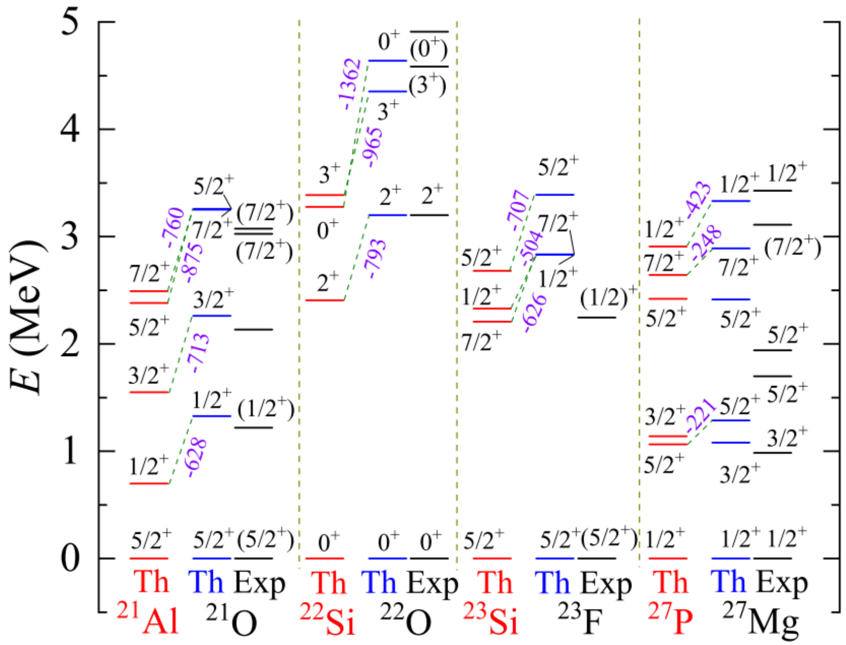
①计算实验上已发现具有较大MED的镜像核相似态。

第一性原理能较好地重现实验结果



第一性原理VS-IMSRG方法可用于预测实验感兴趣的未知原子核。

②预测sd壳质子滴线区原子核的低激发谱。



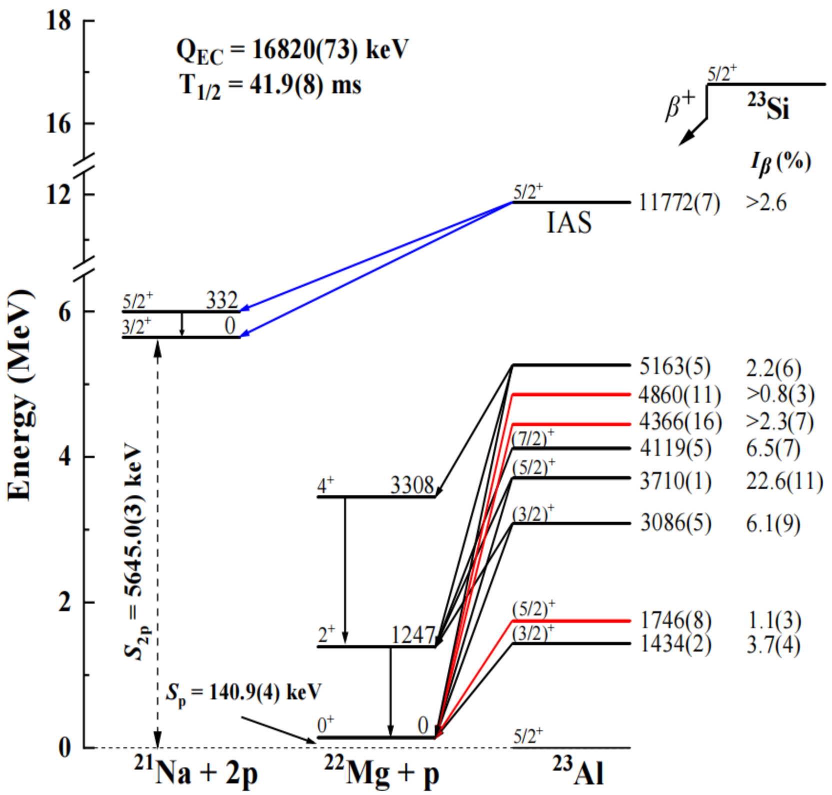
- 其镜像核(对应的丰中子核)的计算结果可与实验比拟。
- 丰质子原子核的预测是可靠。

MED 较大

质子滴线核中的β衰变-同位旋对称性破缺

与近物所徐新星研究员合作

Decay Scheme



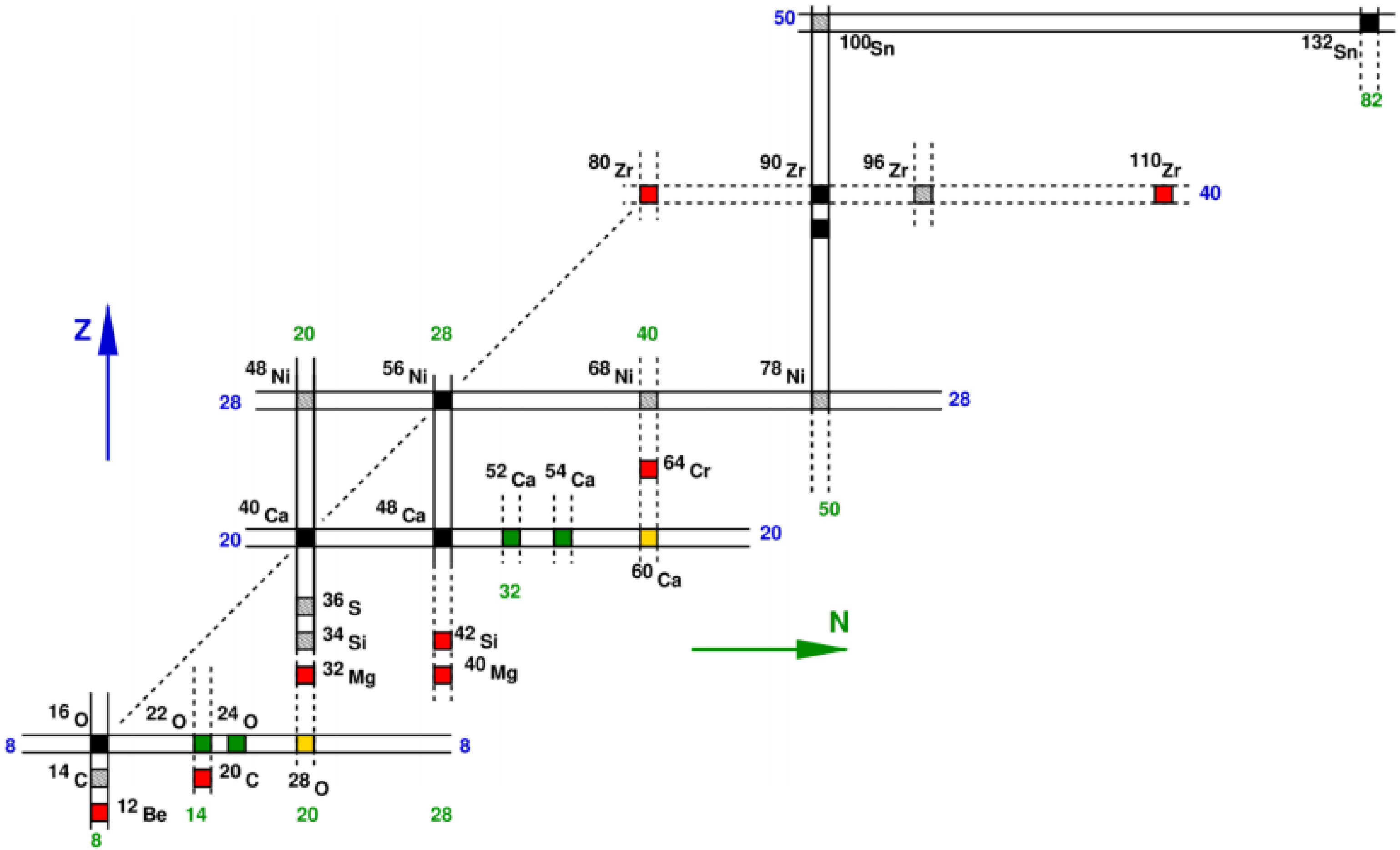
Comparison for Mirror Asymmetry

	^{23}Si $\rightarrow$ ^{23}Al			^{23}F $\rightarrow$ ^{23}Ne						
	Q_{EC} = 16820 keV			$Q_{\beta-}$ = 8440 keV			$\delta(\%)$		MED	
J^π	E_x	$Br(\%)$	log ft^+	E_x	$Br(\%)$	log ft^-	Exp	VS-IMSRG	Exp	VS-IMSRG
$(3/2)^+$	1434	3.7(4)	5.78(5)	1822	10.9(11)	5.65(6)	34(24)	146	−388	−418
$(5/2)^+$	1746	1.1(3)	6.26(12)	2315	5.6(12)	5.78(10)	201(108)	416	−569	−564
$(3/2)^+$	3086	6.1(9)	5.30(7)	3432	12.0(11)	5.05(5)	78(35)	47	−346	−460
$(5/2)^+$	3710	22.6(11)	4.631(25)	3831	22.4(33)	4.62(7)	2(17)	26	−121	−92
$(7/2)^+$	4119	6.5(7)	5.[illegible]0(5)	4[illegible]36	9.4(9)	4.71(6)	145(44)	114	−317	−265
	^{22}Si $\rightarrow$ ^{22}Al			^{22}O $\rightarrow$ ^{22}F						
	Q_{EC} = 13963 keV			$Q_{\beta-}$ = 6490 keV			$\delta(\%)$		MED	
J^π	E_x	$Br(\%)$	log ft^+	E_x	$Br(\%)$	log ft^-	Exp	VS-IMSRG	Exp	VS-IMSRG
1^+	905	5.3(10)	5.09(9)	1625	29(4)	4.6(1)	209(96)	347	−720	−472
1^+	2145	56.5(51)	3.83(5)	2572	68(6)	3.8(1)	7(28)	−24	−427	−396

Hao Jian. et al., to be submitted

第一性原理很好的重现^{22}Al的对称性破缺，^{23}Al的结果也与新数据符合很好

^{22}Si 双幻核结构---新幻数



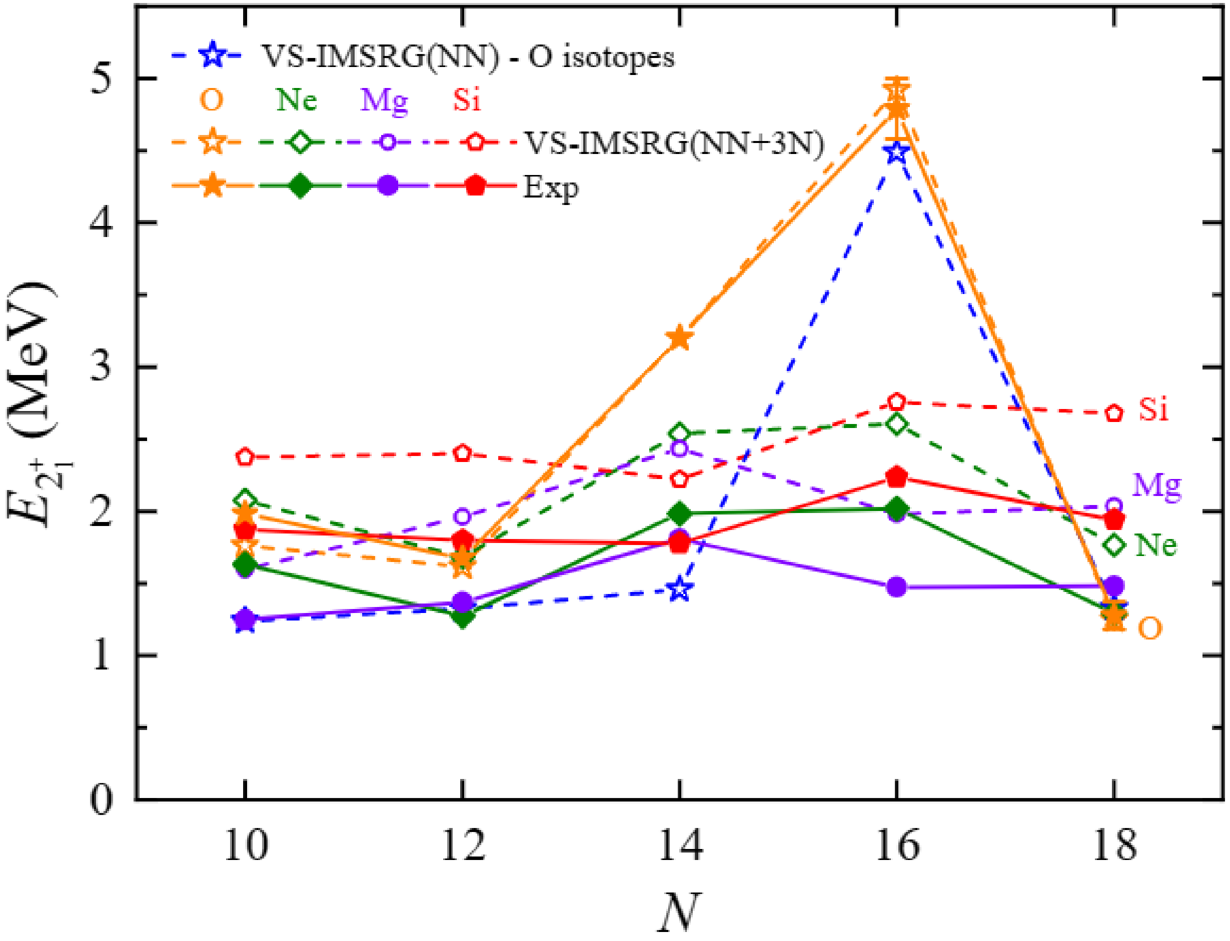
Frédéric Nowacki, Alexandre Obertelli, Alfredo Poves, PPNP 120,103866(2021)

- ✓ 丰中子原子核中新的双幻核：^{22,24}O, ^{52,54}Ca
- ✓ 这些幻数结构在丰质子原子核中还存在吗？
- ✓ 质子滴线原子核中有较强的同位旋对称性破缺现象 (Thomas-Ehrman shift).

Whether ^{22}Si exhibits double-magic characters is an intriguing topic.

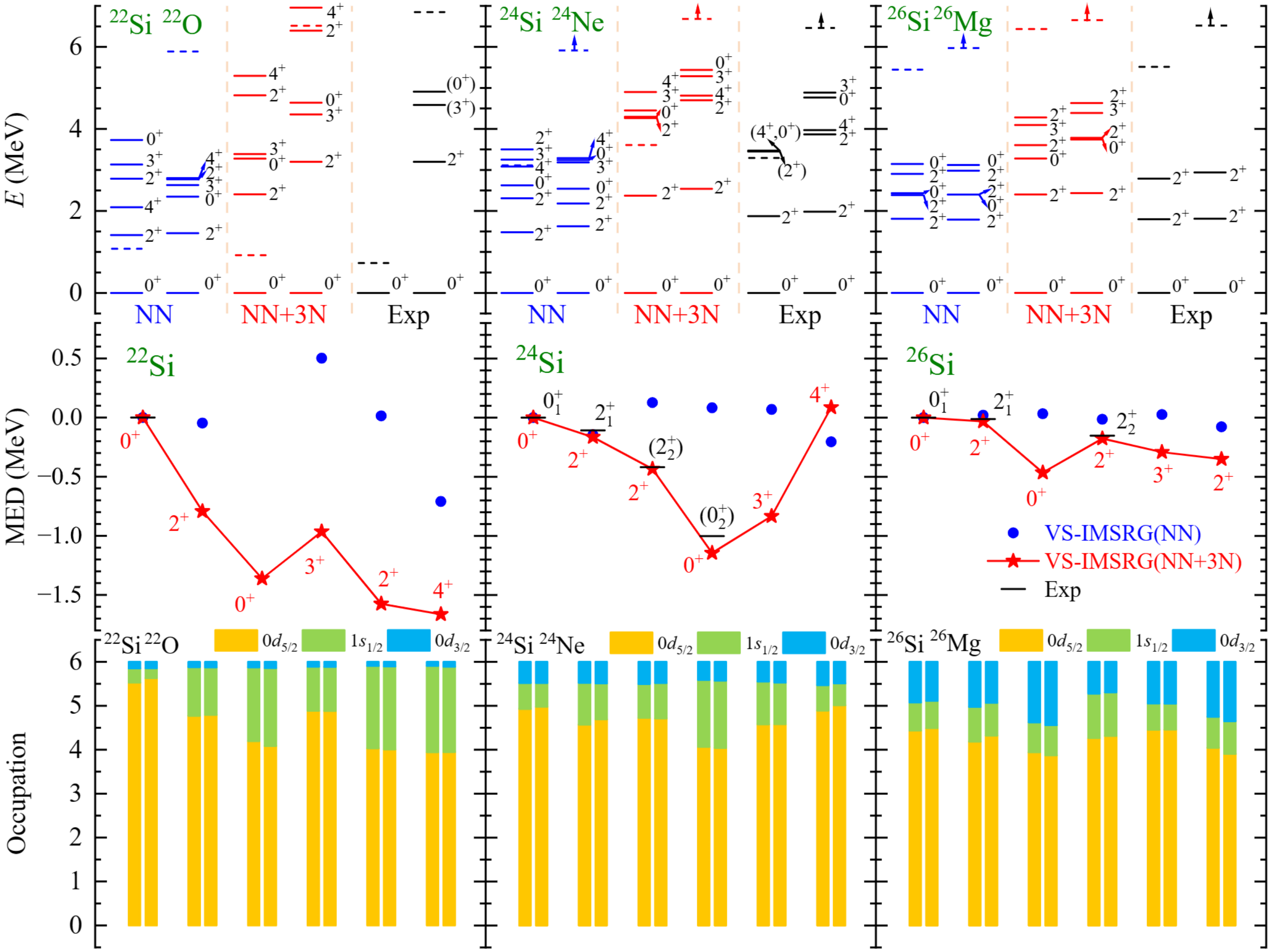
^{22}Si 双幻核结构---新幻数

$N = 14$ 附近原子核壳演化



- ✓ ^{22,24}O, ^{24,26}Ne 与 ^{26}Mg的$E(2_1^+)$比周围的其他同位素的$E(2_1^+)$都高；
- ✓ N=14 的子壳在O, Ne 和 Mg 链中存在，但是在Si链中消失了；
- ✓ 随着^{24}O上添加价质子， N=14 的子壳强度变得更弱

^{22}Si 双幻核结构---新幻数



- ✓ NN + 3N计算的 ^{24}Si/^{24}Ne 和 ^{26}Si/^{26}Mg的能谱与MED与实验符合，尤其计算的MED
- ✓ MED值较大，表明此态具有较明显的同位旋对称性破缺，同时此态的1s1/2轨道的占据较大，如^{24}Si的0_2^+态
- ✓ 计算给出的^{22}Si 与^{22}O的$E(2_1^+)$ 的位置分别为2.4 与 3.2 MeV， Thomas-Ehrman shift 效应
- ✓ 计算显示^{22}Si/^{22}O的0^+与2^+的组态非常接近
- ✓ 尽管^{22}Si的$E(2_1^+)$ 较低，但是与^{22}O相近，^{22}Si依然表现幻数性质。

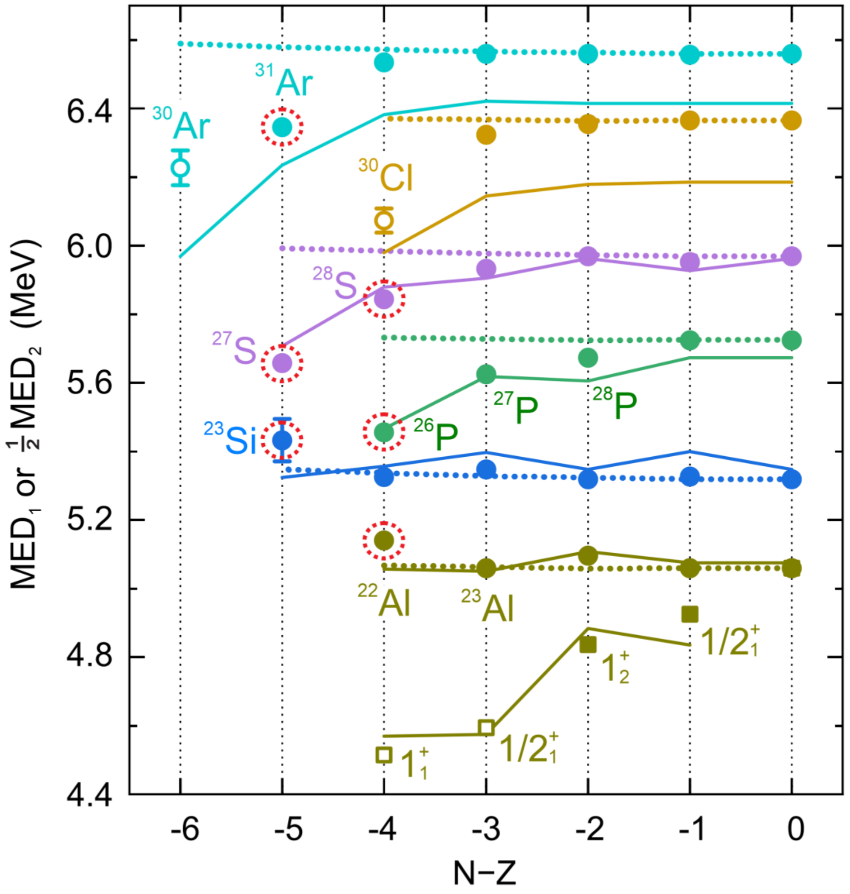
美国FRIB与日本RIKEN RIB 均在计划测量22Si激发态

J.G. Li,* H. H. Li, S. Zhang, Y. M. Xing,* W. Zuo,* *Phys. Lett. B 846(1):138197(2023)*

同位旋对称性破缺-原子核晕结构-质量测量

与近物所张玉虎与王猛研究员团队合作

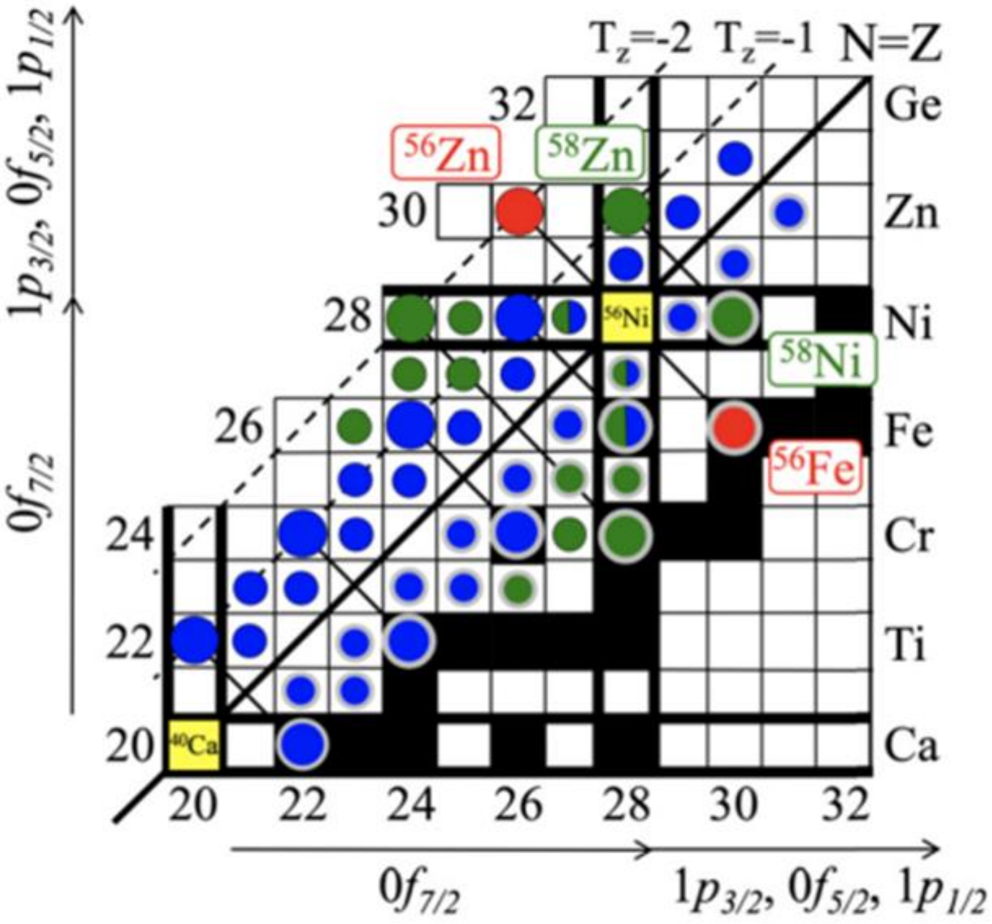
兰州重离子加速器储存环精确质量测量



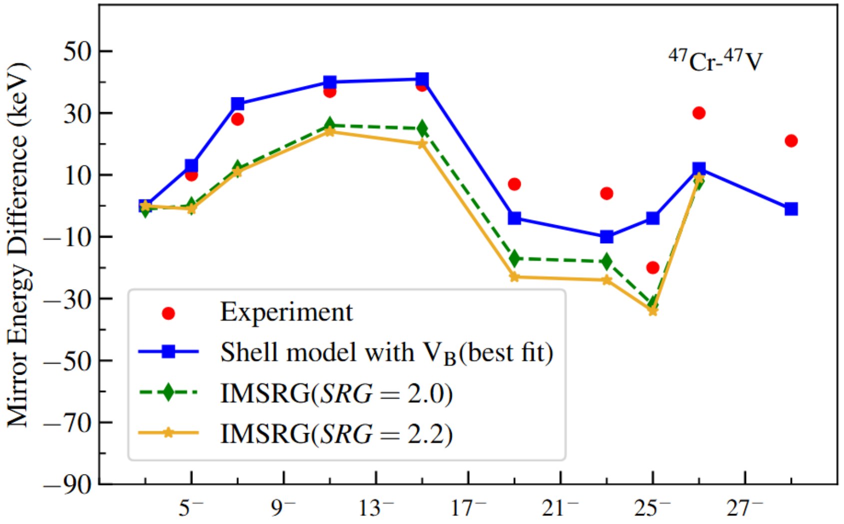
- ✓ 镜像原子核分离能在滴线附近偏离正常曲线
- ✓ Al 同位素激发态存在明显同位旋对称性破缺
- ✓ 滴线原子核^{26}P, ^{27}P, ^{27}S, ^{31}Ar 基态中存在明显同位旋对称性破缺
- ✓ 同位旋对称性破缺的机制与晕核形成机制类似
- ✓ 滴线原子核^{26}P, ^{27}P, ^{27}S, ^{31}Ar具有晕结构

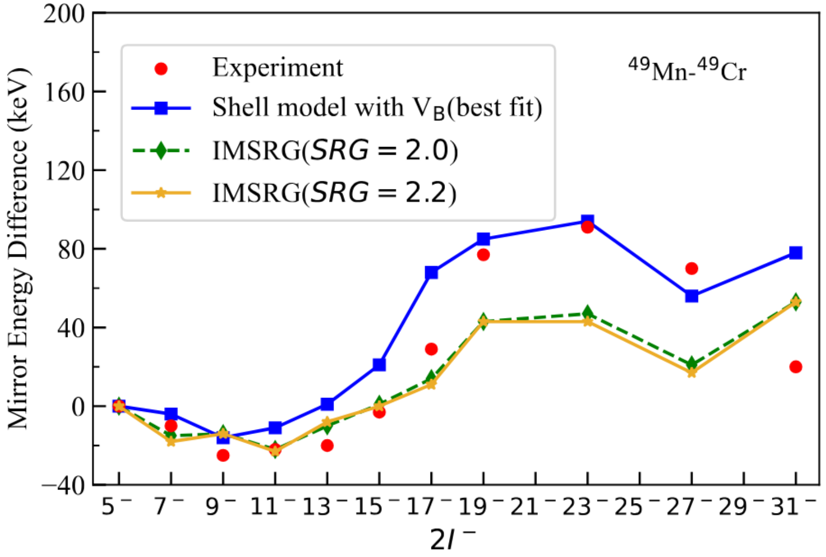
Y. Yu, Y. M. Xing, Y. H. Zhang, M. Wang, X. H. Zhou, **J. G. Li**, H. H. Li, et al., submitted to PRL

pf-壳层原子核中同位旋对称性破缺



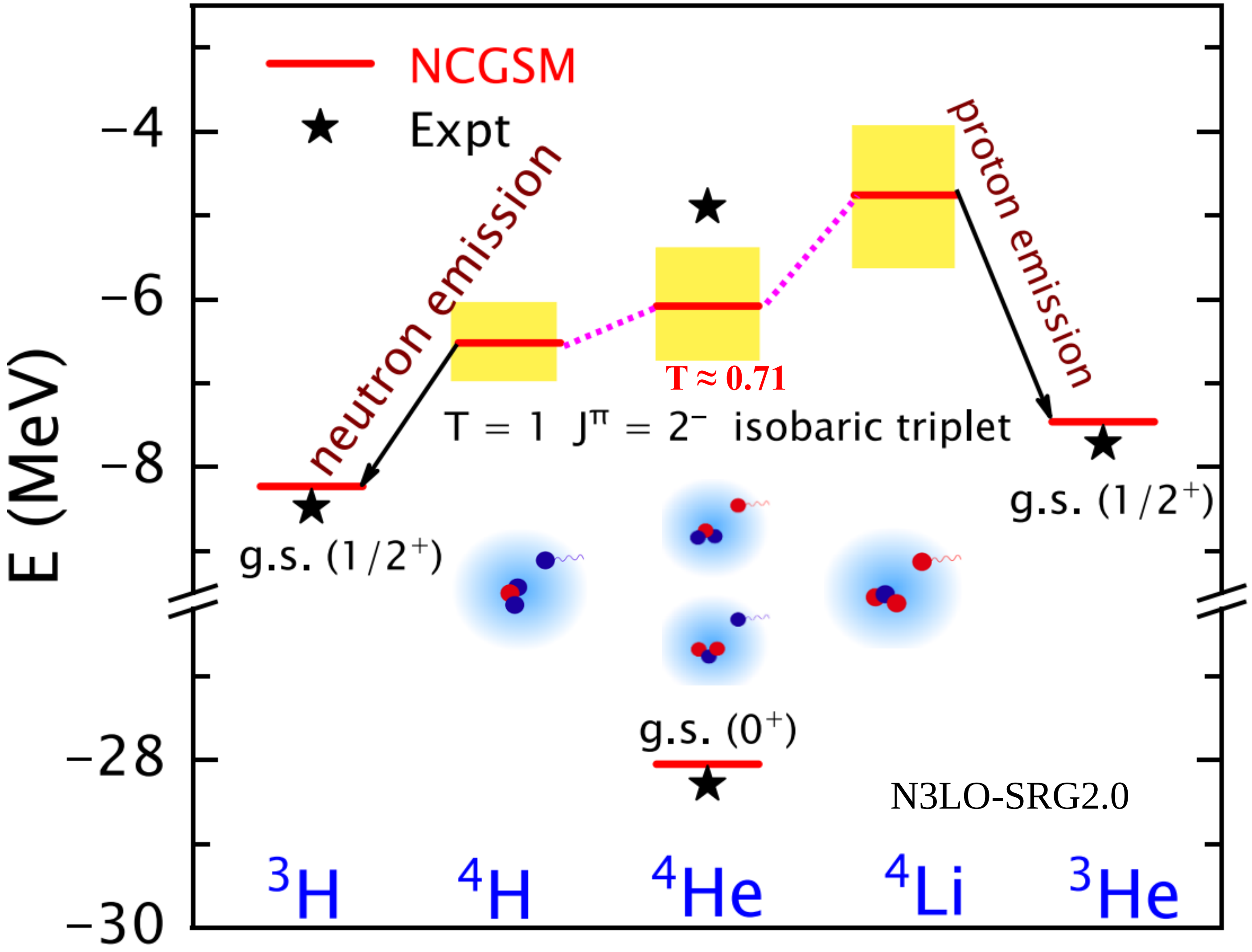
A. Fernández, et al., PLB 823 136784(2021)





J. G. Li, et al., in preparation

A = 4 (^{4}H, ^{4}He and ^{4}Li) T = 1 state



- ✓ Comparing the calculated spectra of the A = 4 systems , the ground states ^{4}Li (T= 1), ^{4}H (T=1) (2- and 1-) with the ground state of ^{4}He (T = 0) and 2$^-$ (T= 1) excited states.
- ✓ The isospin breaking is mainly caused by the Coulomb force.
- ✓ The energies and widths are both different due to the isospin breaking.
- ✓ The splitting of the T =2 isobaric triplet states.

J.G. Li, N. Michel, W. Zuo and F.R. Xu, Phys. Rev. C 104, 024319 (2021)*

总结

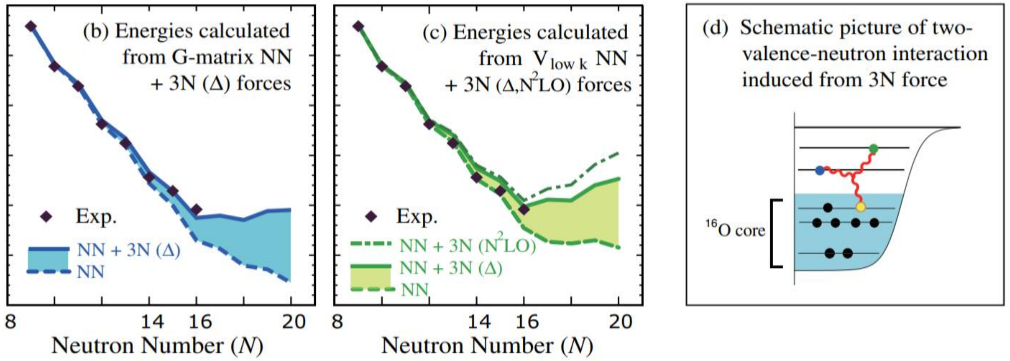
基于第一性原理研究原子核同位旋对称性破缺

1. 镜像能级差异： 弱束缚的$s_{1/2}$轨道的占据是导致较大MED (Thomas-Ehrman位移) 的主要原因
2. 预言^{22}Si是双幻核：较低2+激发能
3. 同位旋对称性破缺与晕结构：滴线原子核同位旋对称性破缺-质量精确测量-
4. 第一性原理计算精确描述fp-壳原子核同位旋对称性破缺
5. 无核芯Gamow壳模型描述轻核中的对称性破缺

请各位老师批评指正！

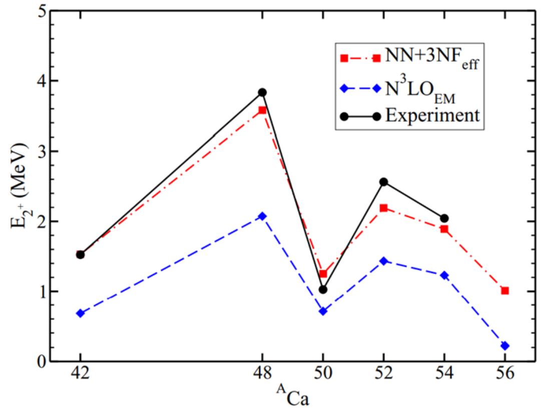
三体力效应-质量-第一性原理计算

滴线位置



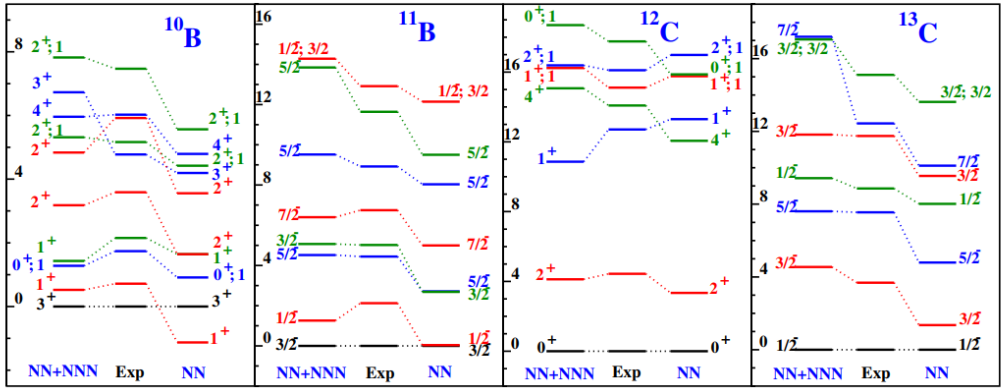
T. Otsuka, *et al.*, Phys. Rev. Lett. 105, 032501 (2010)

壳演化



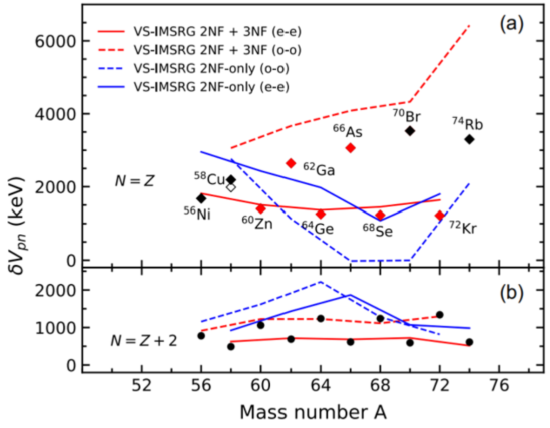
G. Hagen, *et al.*, Phys. Rev. Lett. 109, 032502 (2012)

能谱结构



P. Navrátil, *et al.*, Phys. Rev. Lett. 99, 042501 (2013)

质子中子对关联



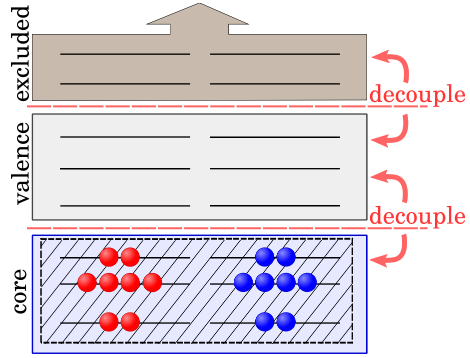
M. Wang,, *et al.*, Phys. Rev. Lett 130, 192501(2023)

三体力效应在原子核性质中扮演着非常重要的角色

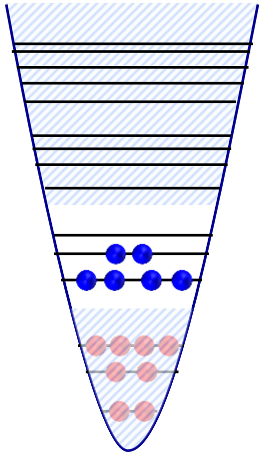
原子核多体方法

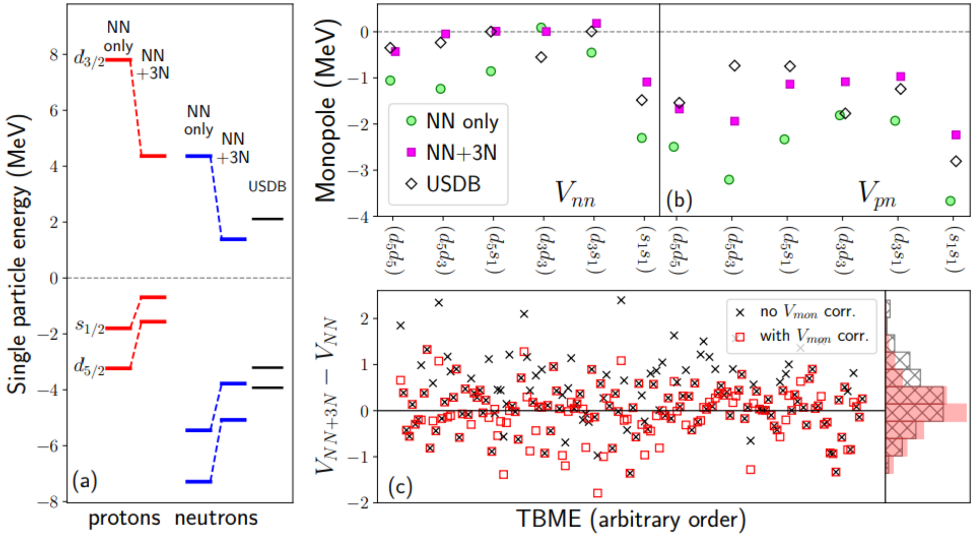
VS-IMSRG 相互作用 vs USDB 壳模型相互作用

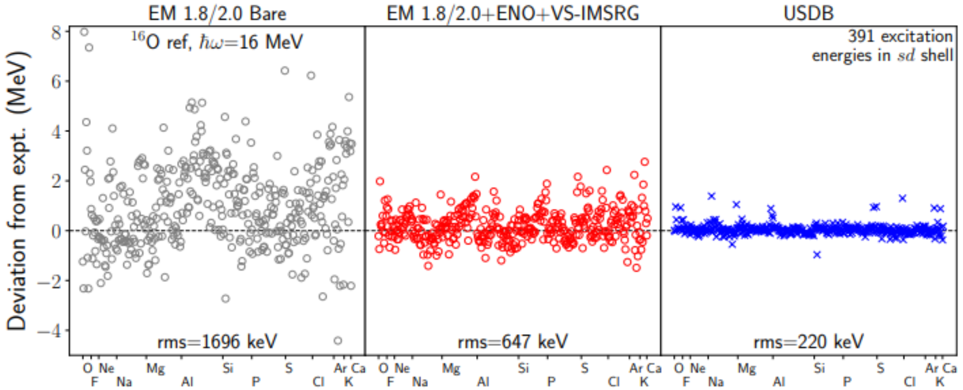
VS-IMSRG



$|\Phi_0\rangle = |^{16}O\rangle$

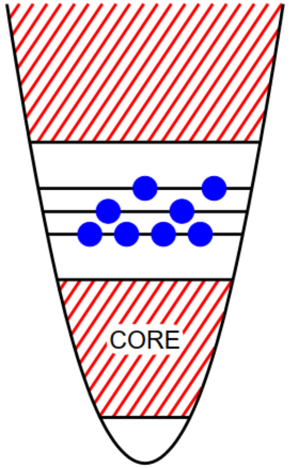




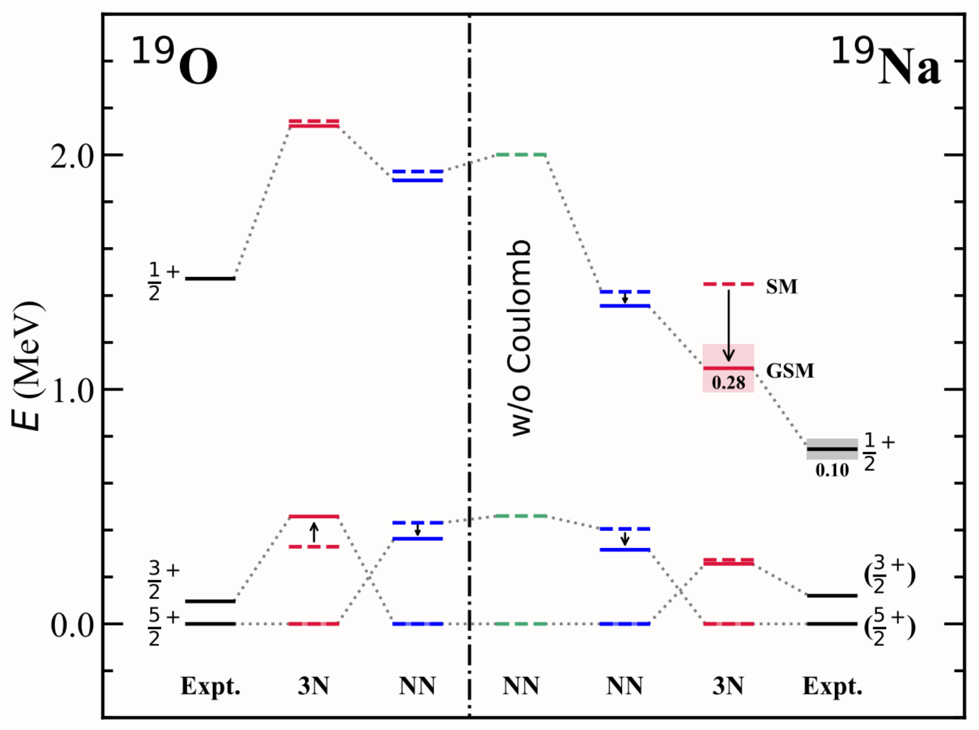


S. Ragnar Stroberg, Scott K. Bogner, Heiko Hergert, Jason D. Holt
Annual Review of Nuclear and Particle Science, 69 307-362 (2019)

USDB SM



1. 同位旋对称性破缺的机制



*S. Zhang, Y. Z. Ma, **J. G. Li**, B. S. Hu, Q. Yuan, Z. H. Cheng, F. R. Xu. Phys. Lett. B (2022)*

CSB 与 CIB 在GSM计算中没有包含

$$H = H_{NN} + H_{CSB+CIB} + H_{Coulomb}$$

w/o coulomb : CSB+CIB part of NN

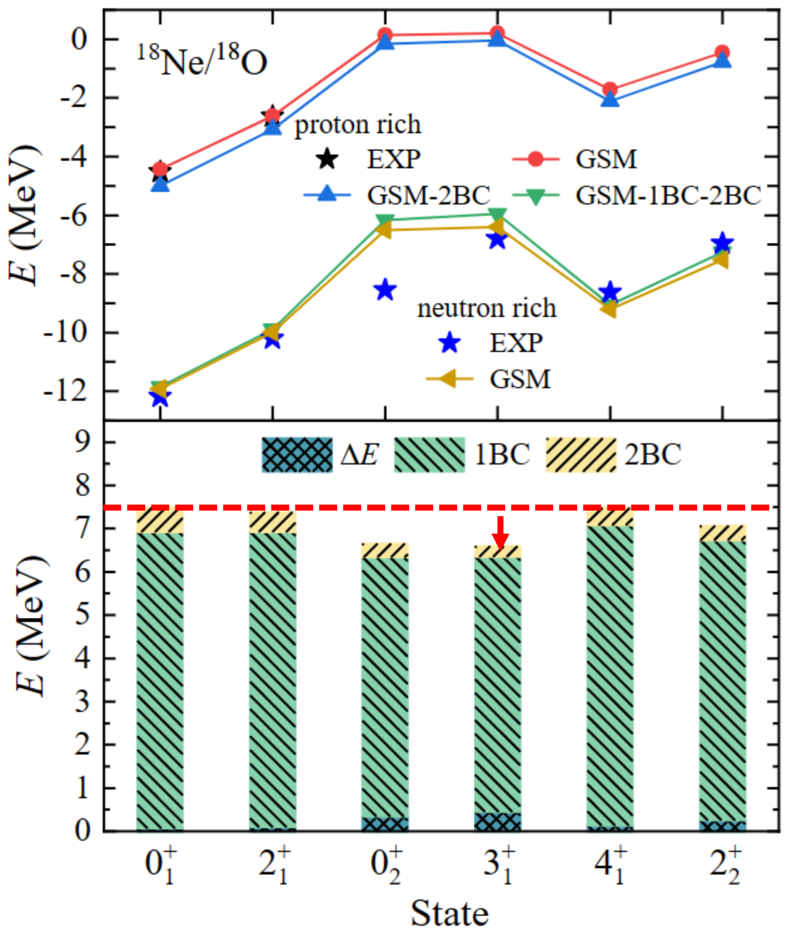
Model - Basis	wavefunction-continuum effects
SM : HO basis	partially included
GSM : Berggren basis	well treated

GSM 的计算量非常大 !!!

库仑力→ 丰质子原子核变得弱束缚或者不束缚→

→ 波函数延展→ Thomas-Ehrman shift (大的镜像核能级差异)

同位旋对称性破缺的机制



CSB and CIB is not included in the present GSM calculation.

$$H = H_{NN} + H_{1BC} + H_{2BC}$$

$$\Delta E = \langle \Psi_{proton} | H_{NN} | \Psi_{proton} \rangle - \langle \Psi_{neutron} | H_{NN} | \Psi_{neutron} \rangle$$

1BC：单体库仑力的贡献

核芯-价质子

2BC: 两体库仑力贡献

价质子-价质子

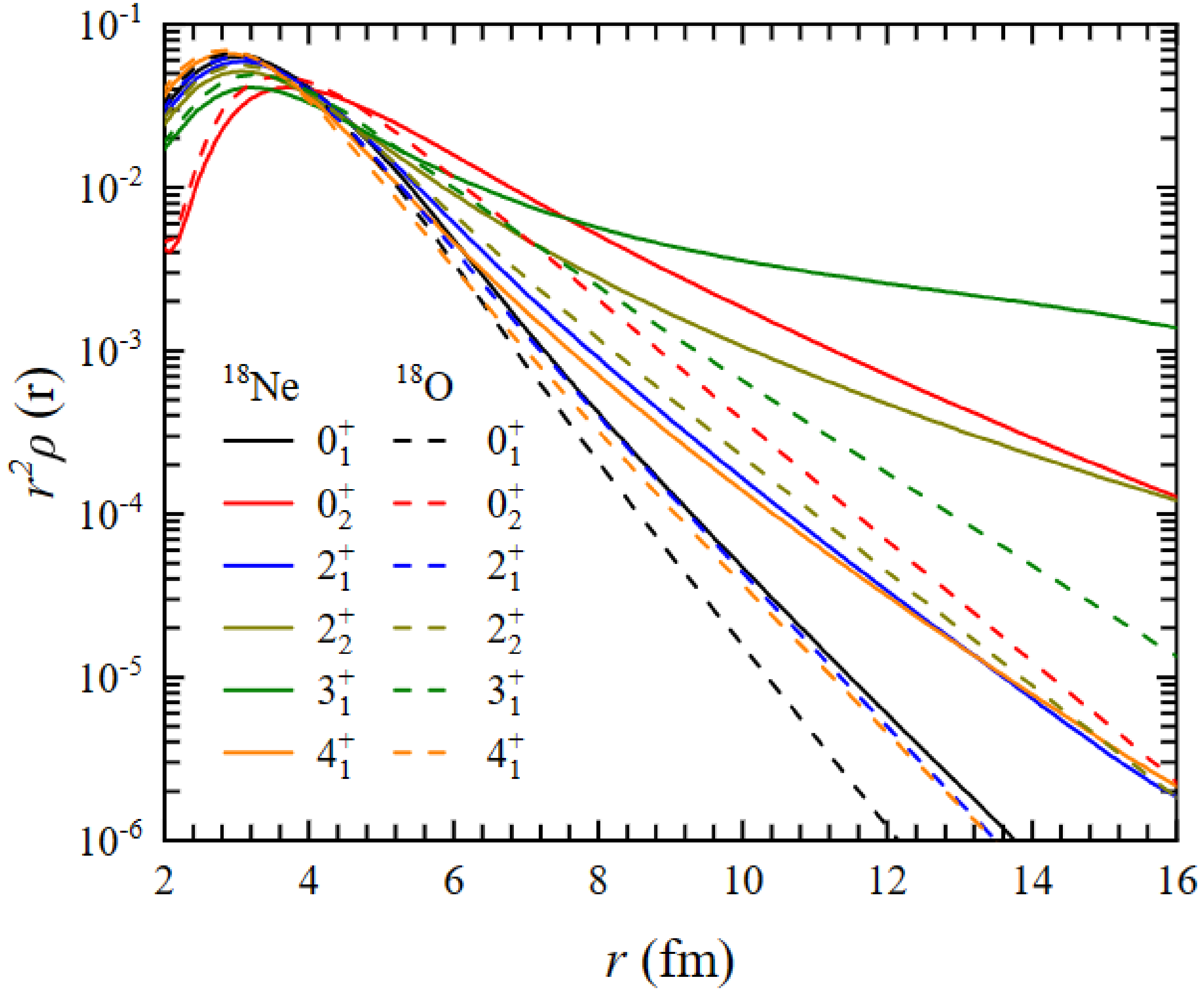
ΔE, 1BC 与 2BC 均对镜像核能级差异(MED) 有贡献

大的镜像核能级差异主要由单体库仑力导致

库仑力→丰质子原子核变得弱束缚或者不束缚→

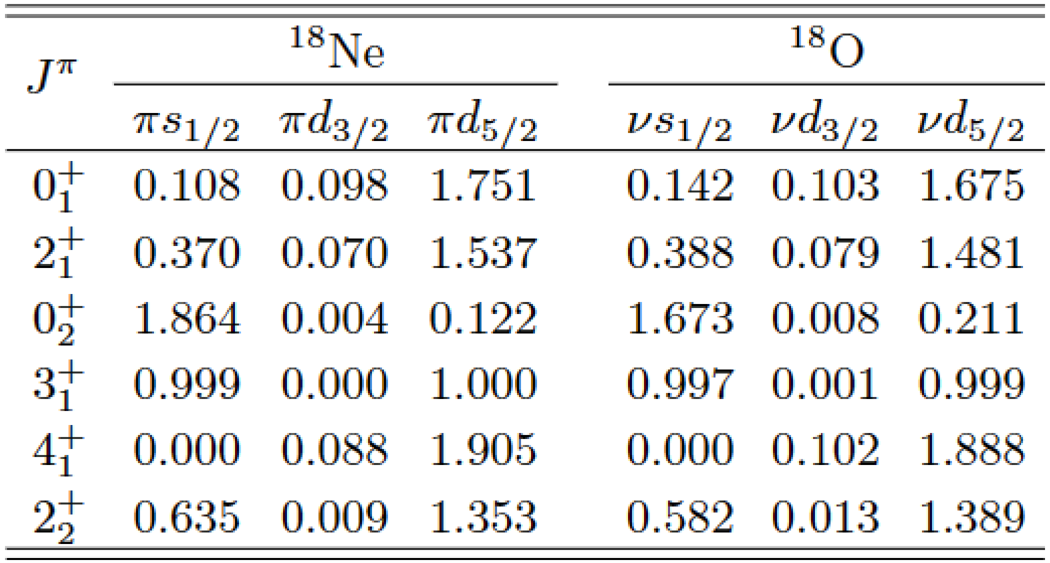
不同的多体波函数→1BC，2BC, ΔE都贡献

同位旋对称性破缺的机制



Density distributions of valence nucleons are almost same for the mirror state, except for the 3_1^+ in ^{18}Ne/^{18}O.

occupations/configuration of the mirror states in ^{18}Ne/^{18}O are close



J^π	^{18}Ne			^{18}O		
	$\pi s_{1/2}$	$\pi d_{3/2}$	$\pi d_{5/2}$	$\nu s_{1/2}$	$\nu d_{3/2}$	$\nu d_{5/2}$
0_1^+	0.108	0.098	1.751	0.142	0.103	1.675
2_1^+	0.370	0.070	1.537	0.388	0.079	1.481
0_2^+	1.864	0.004	0.122	1.673	0.008	0.211
3_1^+	0.999	0.000	1.000	0.997	0.001	0.999
4_1^+	0.000	0.088	1.905	0.000	0.102	1.888
2_2^+	0.635	0.009	1.353	0.582	0.013	1.389

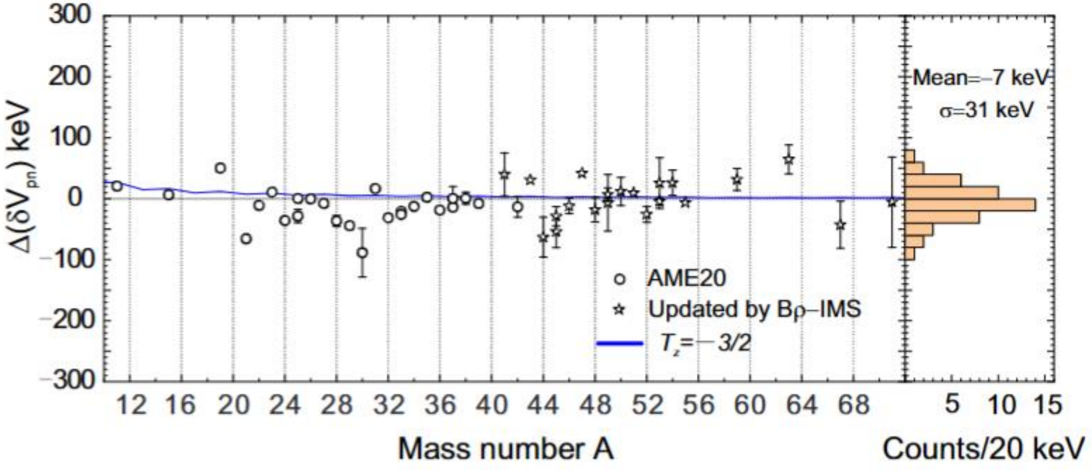
J. G. Li*, et al., in preparation

3、质量中的同位旋对称性破缺

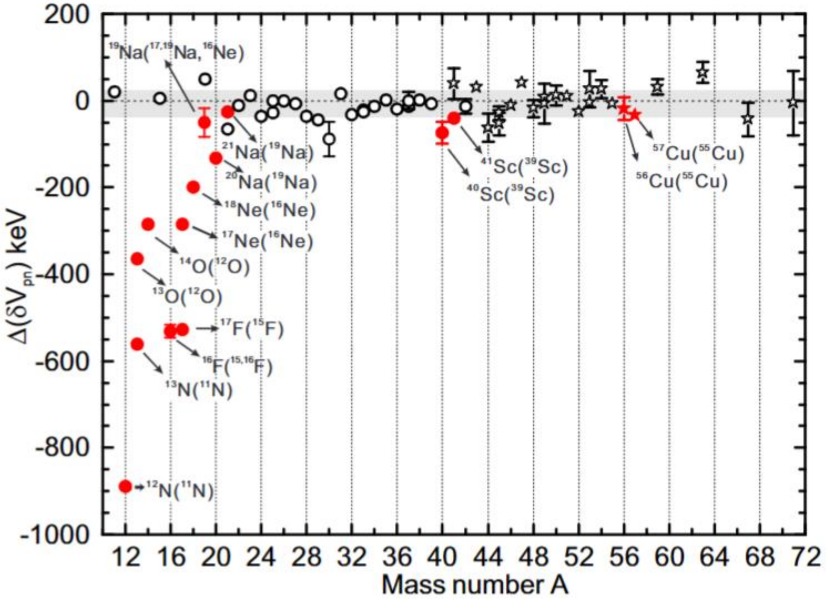
Effective proton-neutron interaction in mirror nuclei

Y. M. Xing,[1] Y. F. Luo,[1,2] K. H. Li,[1,3] Y. H. Zhang,[1,2,*]
J. G. Li,[1,†] M. Wang,[1,2,‡] M. Zhang,[1,2] T. Liao,[1,2] and X. Zhou[1]

[1] *Heavy Ion Science and Technology Key Lab, Institute of Modern Physics,*
Chinese Academy of Sciences, Lanzhou 730000, China
[2] *School of Nuclear Science and Technology, University of Chinese Academy of Sciences, Beijing 100049, China*
[3] *Institute of Particle and Nuclear Physics, Henan Normal University, Xinxiang 453007, China*



Kelson-Garvey relations

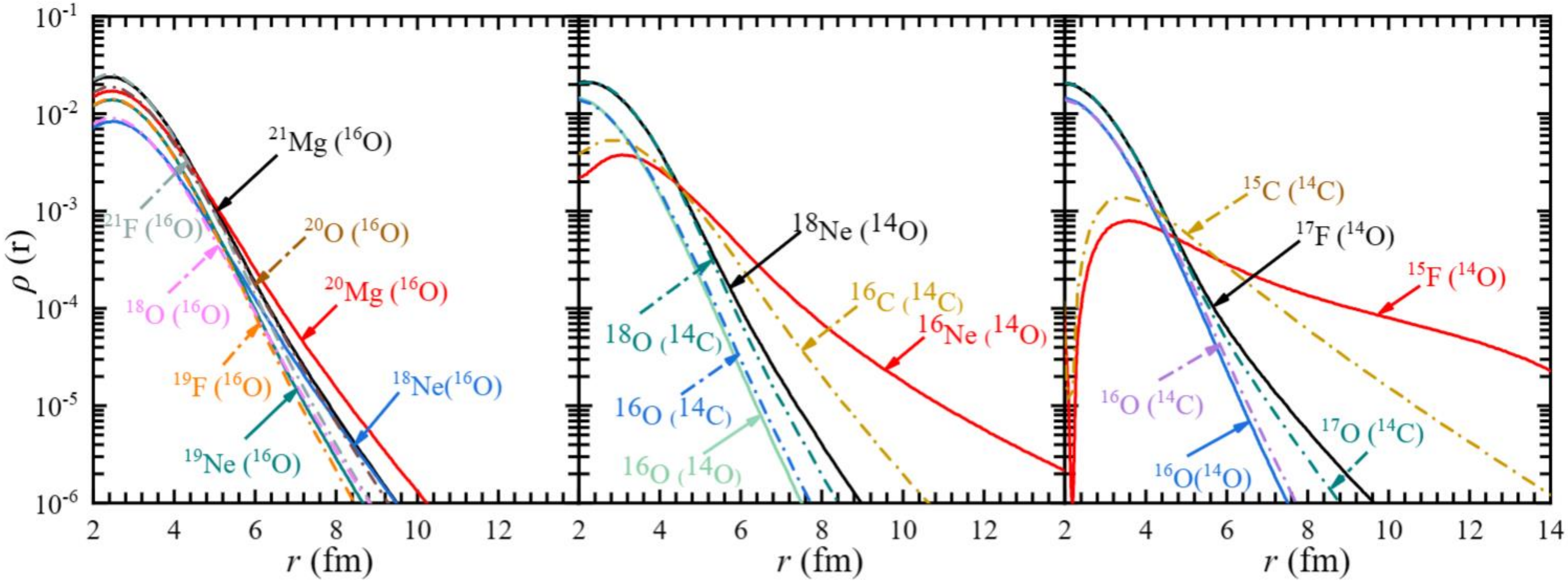


3、质量中的同位旋对称性破缺

^{21}Mg:
Exp: -66 keV
GSM: -77 keV

^{18}Ne:
Exp: -200 keV
GSM: -222 keV

^{17}F:
Exp: -527 keV
GSM: -473 keV



Vpn的破却主要由Thomas-Erhman shift效应导致