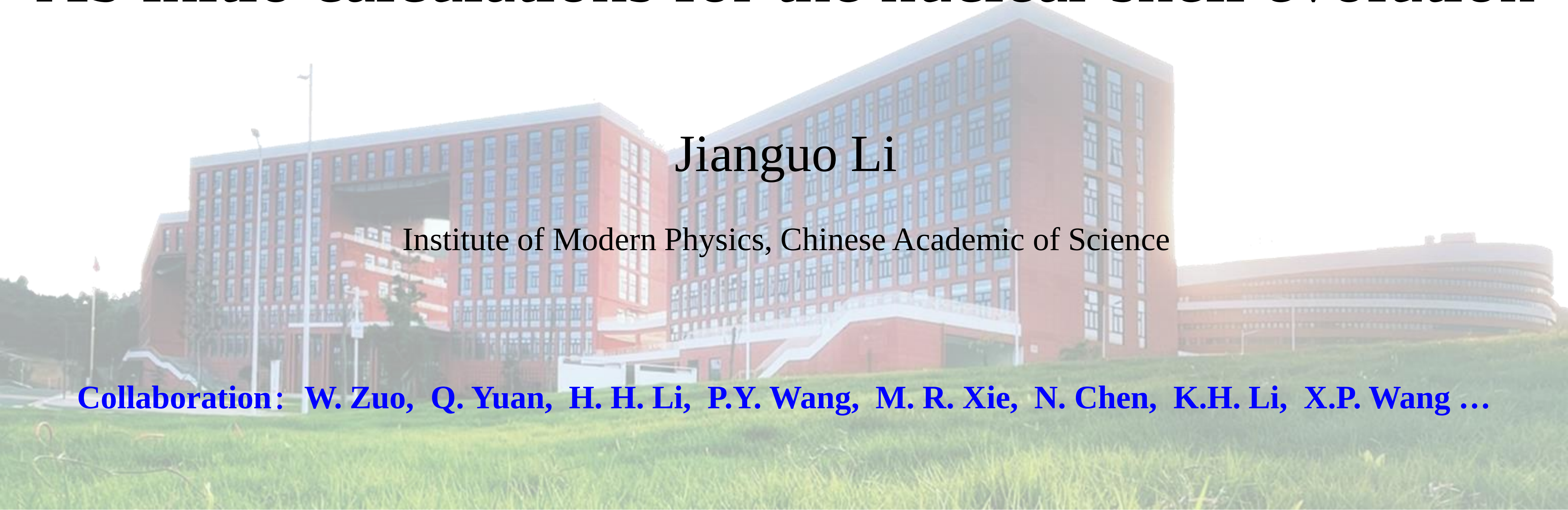
The 2024 ANPhA meeting and ANPhA symposium

2024.11.13-17,Huizhou

Ab initio calculations for the nuclear shell evolution



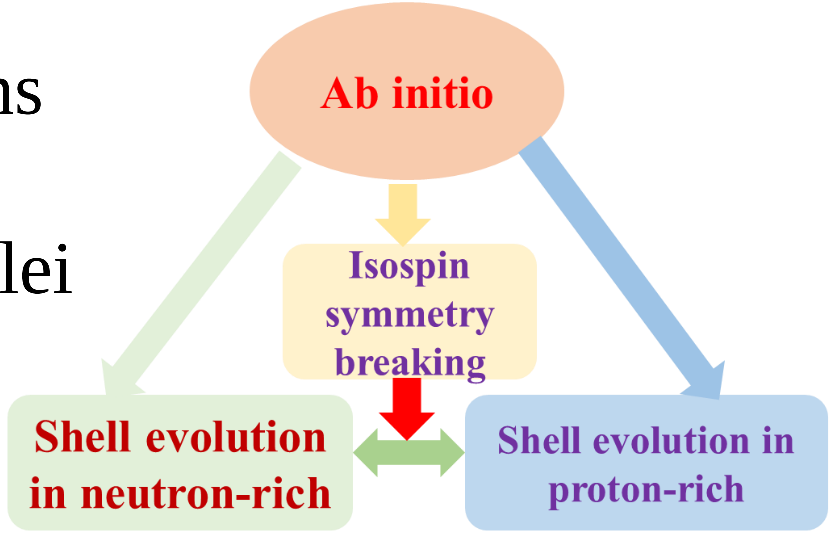
Jianguo Li

Institute of Modern Physics, Chinese Academic of Science

Collaboration： W. Zuo, Q. Yuan, H. H. Li, P.Y. Wang, M. R. Xie, N. Chen, K.H. Li, X.P. Wang …

Content

1. Introduction of ab initio calculations
2. Shell evolution in neutron-rich nuclei
3. Isospin symmetry breaking
4. Isospin symmetry breaking for the shell evolution in proton-rich nuclei
5. Summary



1. Introduction of ab initio calculations

Jianguo Li jianguo_li@impcas.ac.cn

What is *ab initio* calculations?

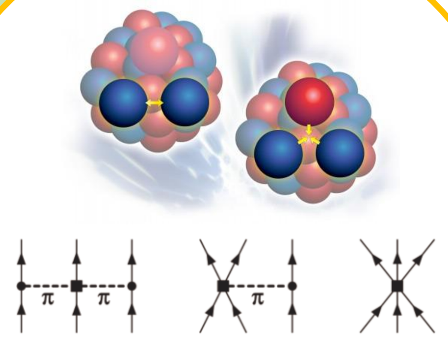
Nuclear Force

Freedom: Pion and Nucleon

Requirement: Reproduce nucleon-nucleon scattering phase shifts

Properties: Short-range repulsion and long-range attraction, strong repulsi

Typical Forces： CD-Bonn、AV18、 χEFT



3NF

Renormalization

Objective: To decouple high and low momentum, soften the nuclear force, and accelerate the convergence speed of many-body calculations.

Representatives: G-Matrix, V_(low-k), SRG

Many-Body Methods

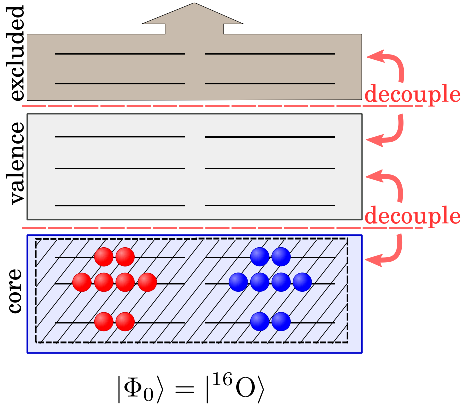
Objective: To solve the Hamiltonian of strongly interacting many-body nuclear systems

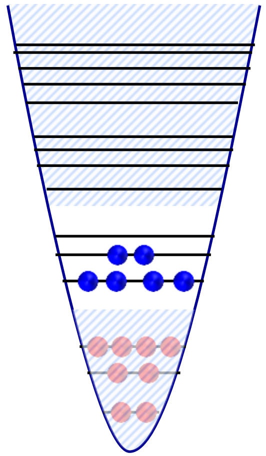
Representatives: NCSM (A≤16), MBPT (A ~ 100), CC (A ~ 100, 208Pb),IMSRG (A ~ 100, 208Pb), ACSE (We are developing this method)...

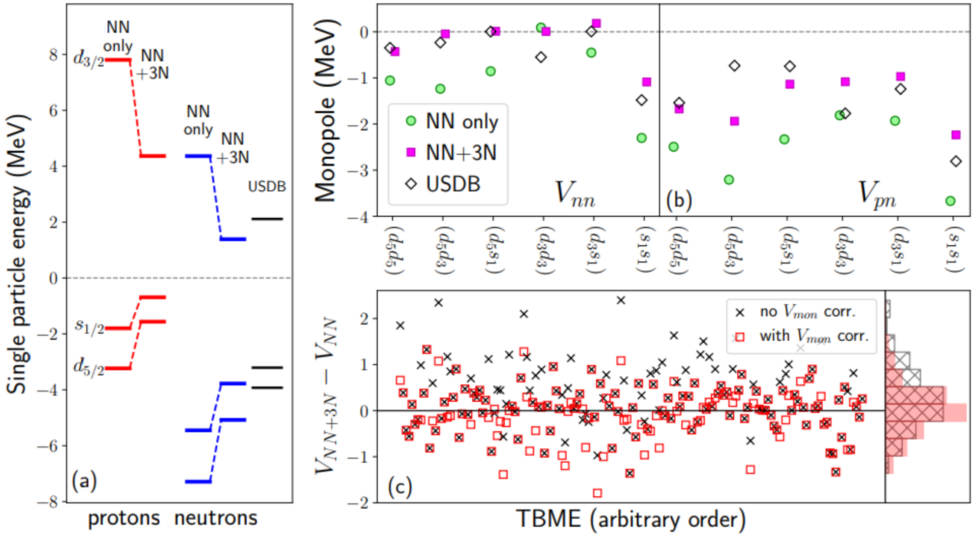
Many-body Method—nuclear shell model—medium-Heavy nuclei

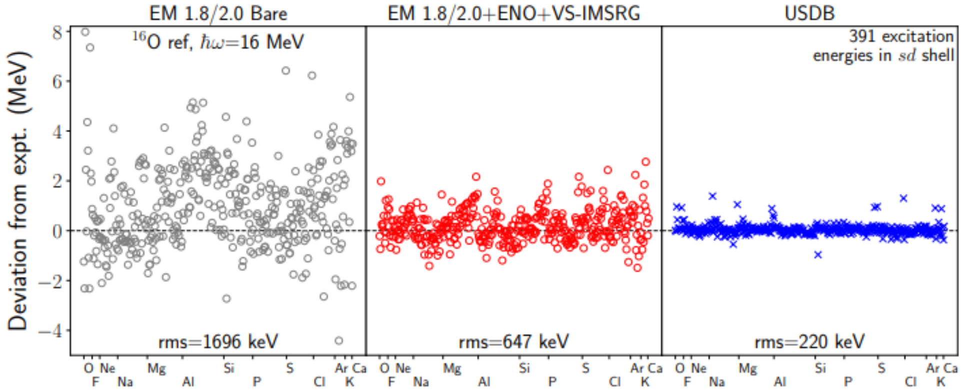
VS-IMSRG realistic interaction vs USDB phenonological shell model interaction

VS-IMSRG



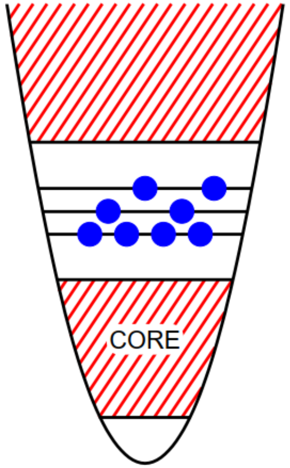






S. Ragnar Stroberg, Scott K. Bogner, Heiko Hergert, Jason D. Holt
Annual Review of Nuclear and Particle Science, 69 307-362 (2019)

USDB SM



VS-IMSRG and MBPT many-body method

Many-body problem： $H|\Psi\rangle = E|\Psi\rangle$

1. A-body Hamiltonian 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. Normal-ordered many-bodu Hamiltonian(Normal Order)

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

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

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

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

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

Normal-ordered two-body interaction capture the main contribution of three-body forces

VS-IMSRG and MBPT many-body method

Many-body problem: $H|\Psi\rangle = E|\Psi\rangle$

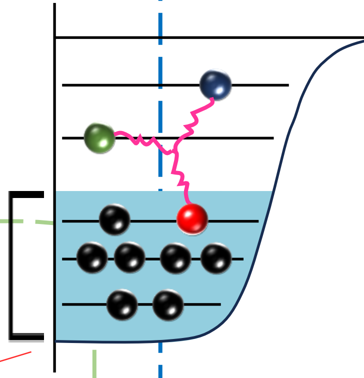
1. A-body Hamiltonian H

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

2. Normal-ordered many-bodu Hamiltonian(Normal Order)

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

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

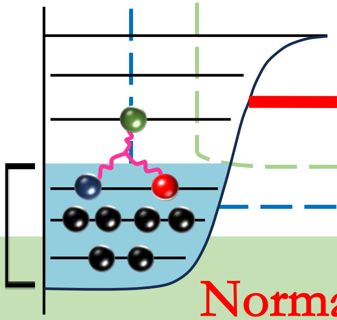


^{16}O core

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

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

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



^{16}O core

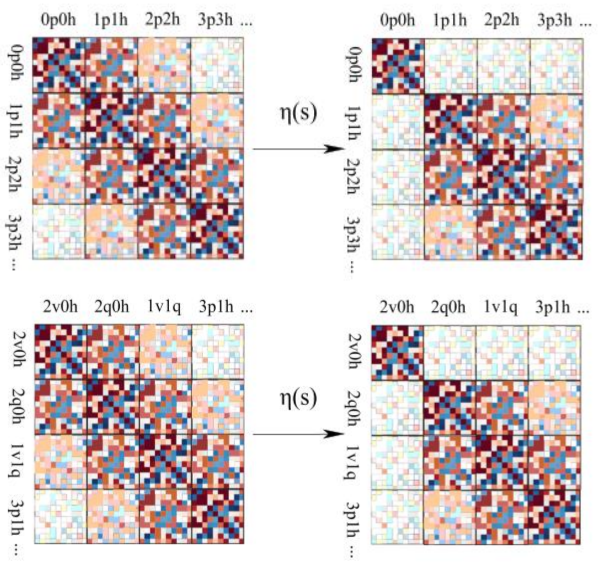
Normal-ordered two-body interaction capture the main contribution of three-body forces

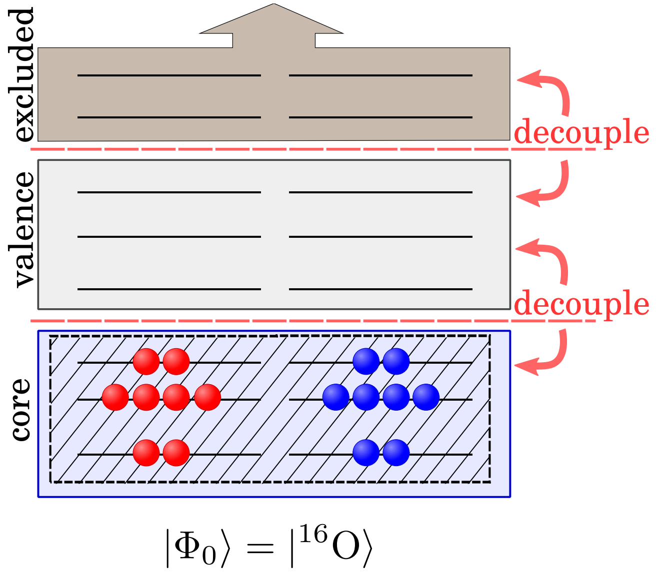
VS-IMSRG and MBPT many-body method

3. **Valence-space Hamiltonian can be constructed by using the unity transformation**

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

- **Flow equation** $\frac{d}{ds}H_{eff}(s) = [\eta(s), H(s)]$
- **Generator：** $\eta(s) = \frac{dU(s)}{ds}U^{\dagger}(s) = -\eta^{\dagger}(s)$
- **Unity transformation：** $U(s) = e^{\Omega(s)} = e^{\int \eta(s)ds}$



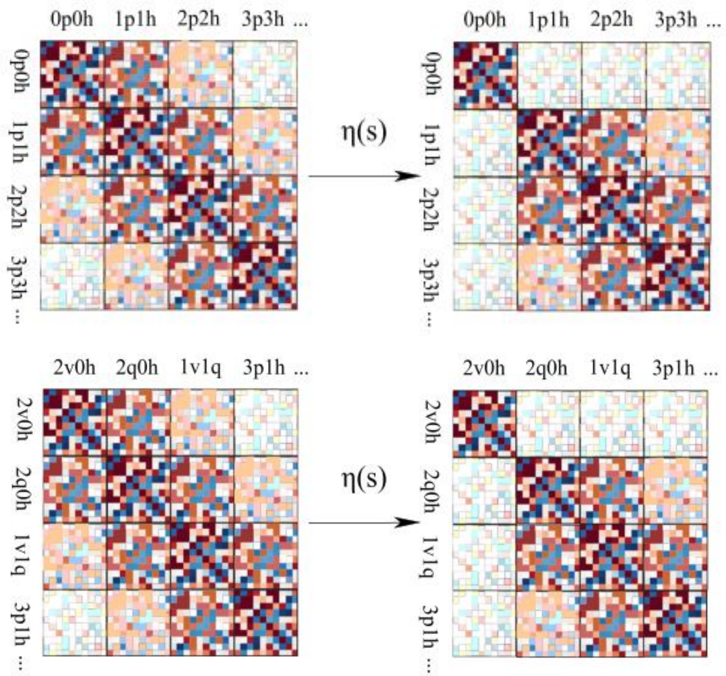


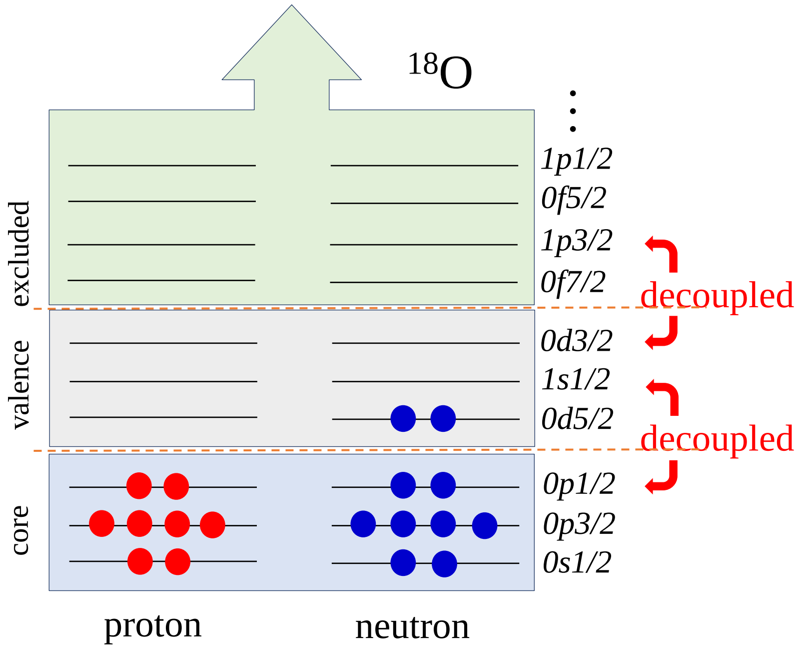
Ab initio VS-IMSRG method

Ab initio Valence-Space In-Medium Similarity Renormalization Group(*Ab initio* VS-IMSRG)

➢ Mainly ides

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





➢ Advantage:

- Realistic nuclear interaction (NN+3N)
  - Including CSB + CIB
  - Isospin symmetry breaking in contact and exchange terms
- No parameter introduced during the calculations
- "Exact" calculations

VS-IMSRG works for nuclei covered by shell model calculations

2. Shell evolution in neutron-rich nuclei

① **J. G. Li***, Phys. Lett. B 840 137892(2023)
② Q. Yuan, **J. G. Li***, H. H. Li, PLB 848 138331 (2024)
③ H. H. Li, **J. G. Li***, M. R. Xie, W. Zuo, PRC (Letter) 109, L061304 (2024).
④ N. Chen, **J. G. Li***, and H. H. Li, Phys. Rev. C 110, 034316(2024)
⑤ M. R. Xie, L. Y. Shen, **J. G. Li***, H. H. Li, Q. Yuan and W. Zuo, CPC 48 074106(2024)
⑥ Q. Yuan, **J. G. Li***, and W. Zuo, Phys. Rev. C(Letter) 109, L041301 (2024)
⑦ X. P. Wang, **J. G. Li***, N. Chen, submitted to PRC

Ab initio

Shell evolution in neutron-rich

Shell evolution is hot topic in nuclear physics

The disappearance of traditional magic number and appearance of new magic number

Disappearance of magic number

Island of Inversion(IOI)

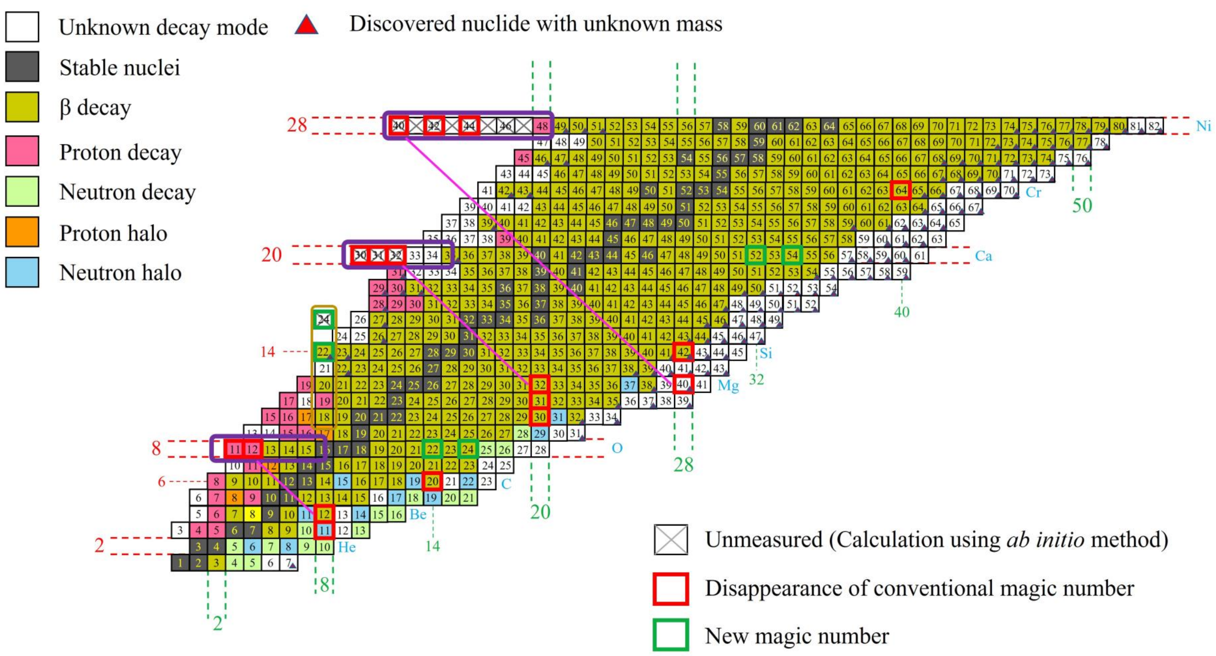
Neutron-rich nuclei in the vicinity of N= 8, 20, 28, and 40 are deformed

N =8 : ^{12}Be

N=20: ^{30}Ne,^{32}Mg

N=28: ^{42}Si,^{40}Mg

N=40: ^{64}Cr



appearance of new magic number

New magic number N=14,16,32 and 34

N=14: ^{22}O

N=16: ^{24}O

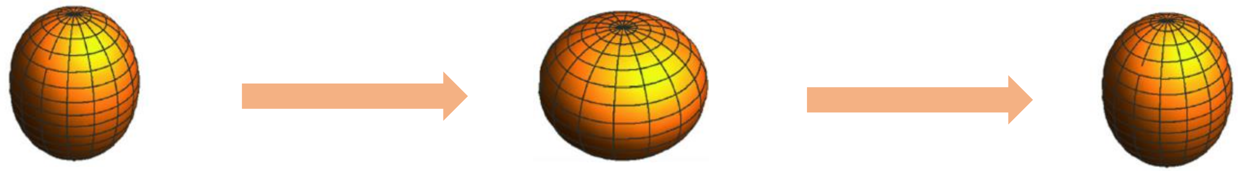
N=32: ^{52}Ca

N=34: ^{54}Ca

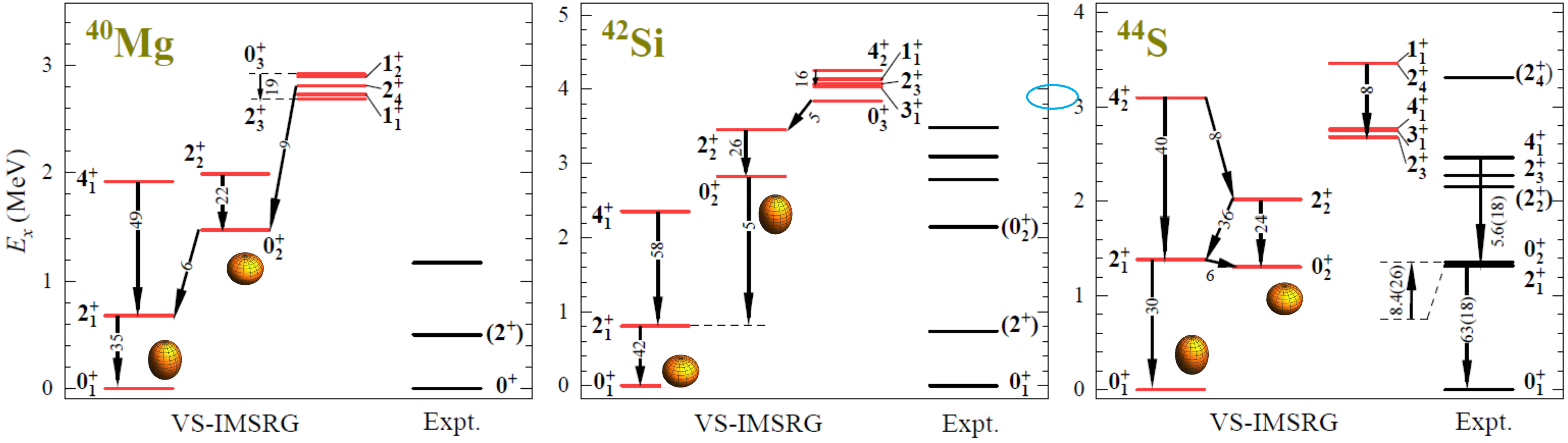
Deep understanding of the shell evolution is important for the study of properties of heavy nuclei

1.Shape transition in ^{40}Mg, ^{42}Si and ^{44}S near N = 28

Ground state



prolate | oblate | prolate



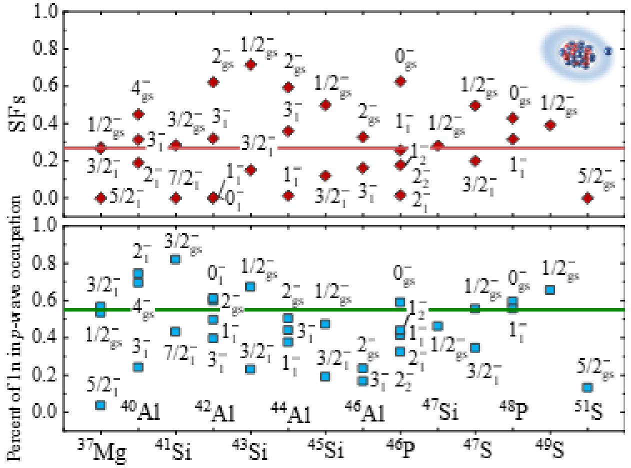
Nuclei	Q (efm^2)		$n_\nu[0f_{7/2}]$		$n_\pi[0d_{5/2}]$	
	2_1^+	2_2^+	0_1^+	0_2^+	0_1^+	0_2^+
^{40}Mg	-12.0	9.6	4.91	4.52	3.06	2.96
^{42}Si	13.2	-10.2	4.86	5.30	4.36	4.38
^{44}S	-6.0	4.7	6.04	5.74	5.26	5.35

- Rotational band of ^{40}Mg, ^{42}Si, ^{44}S constructed via BE2
- shape coexistence and shape transition in 40Mg, 42Si,and 44S
- ^{44}S: 4_1^+ high-K isomer

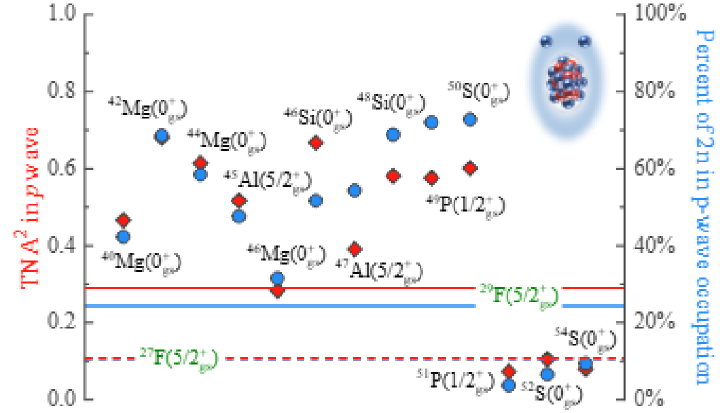
Q. Yuan, **J. G. Li***, H. H. Li, PLB 848 138331 (2024)

2. Ab initio predictions of halo nuclei in medium-mass region

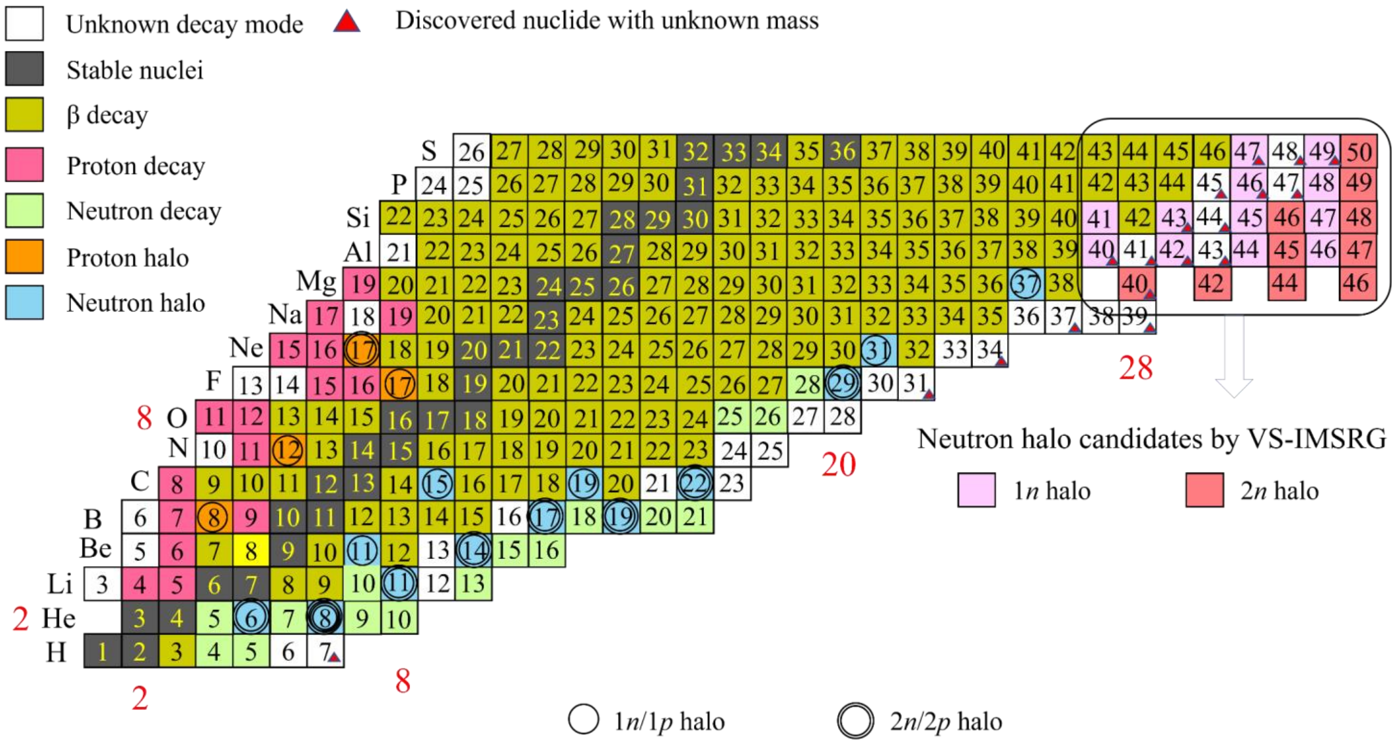
SFs+ occupations



TNA + occupations

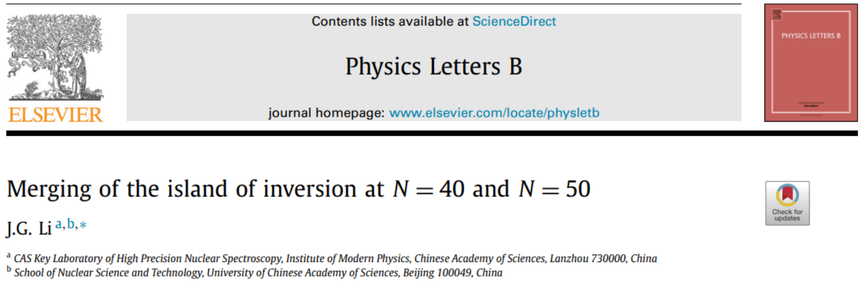


Based on the ab initio calculations, we use the spectroscopic factor (SF) and two-nucleon amplitude (TNA) to predict the one- and two-neutron halo, respectively



H. H. Li, **J. G. Li*,** M. R. Xie, W. Zuo, PRC (Letter) 109, L061304 (2024).

3. Prediction of N=50 Island of inversion


Contents lists available at ScienceDirect

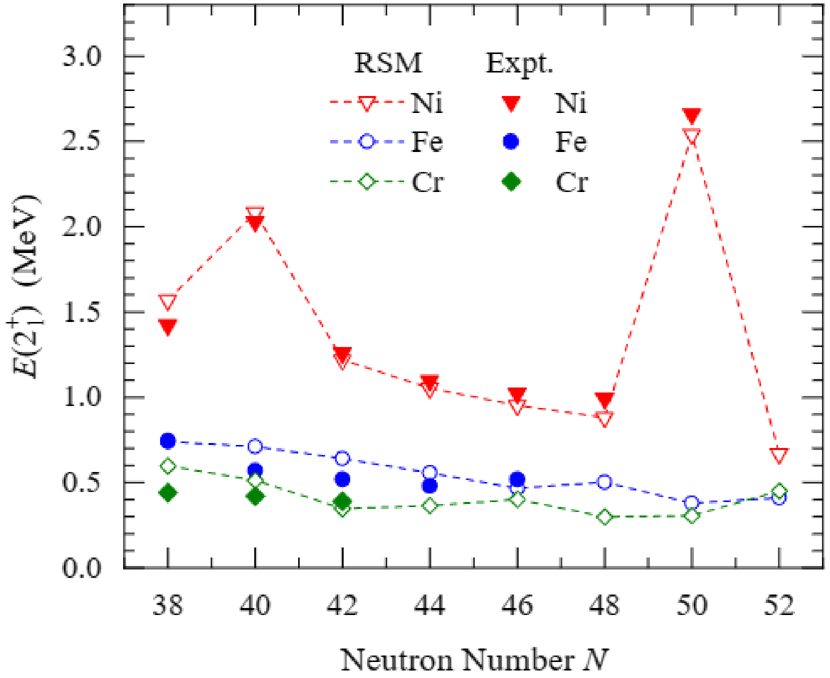
Physics Letters B

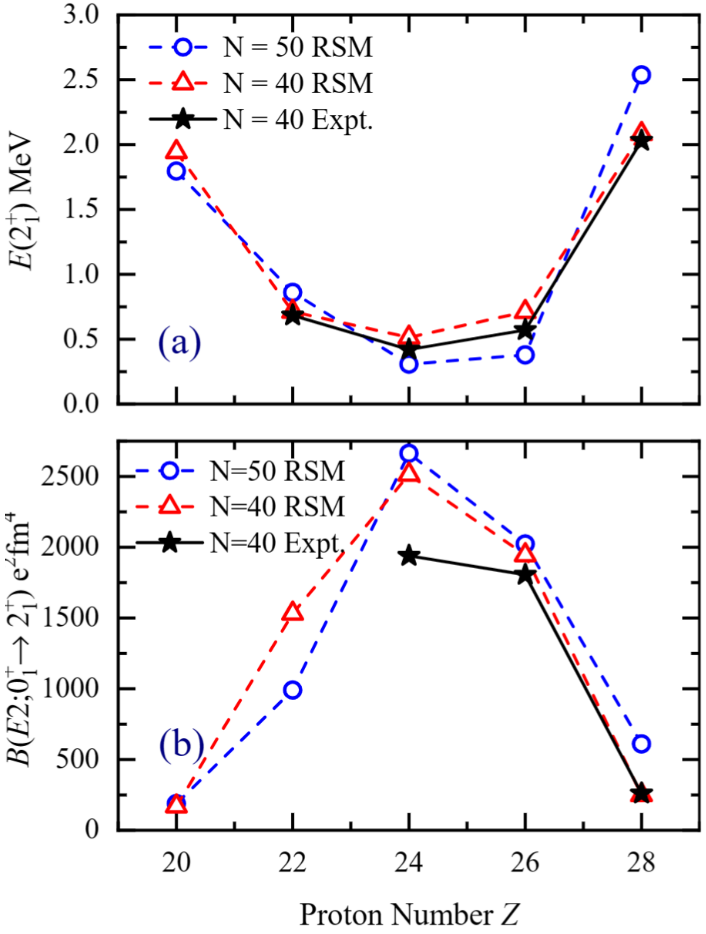
journal homepage: www.elsevier.com/locate/physletb

Merging of the island of inversion at $N = 40$ and $N = 50$

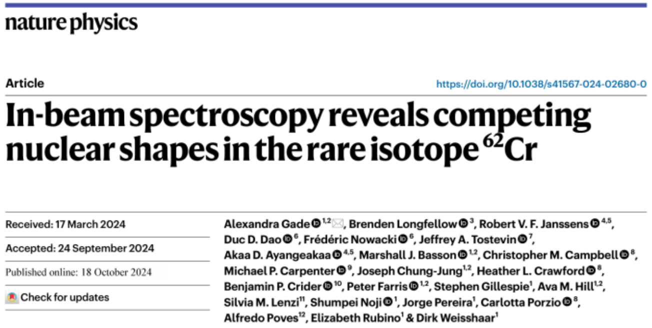
J.G. Li [a,b,*]

[a] CAS Key Laboratory of High Precision Nuclear Spectroscopy, Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China
[b] School of Nuclear Science and Technology, University of Chinese Academy of Sciences, Beijing 100049, China





Cited by


nature physics

Article

https://doi.org/10.1038/s41567-024-02680-0

In-beam spectroscopy reveals competing nuclear shapes in the rare isotope ^{62}Cr

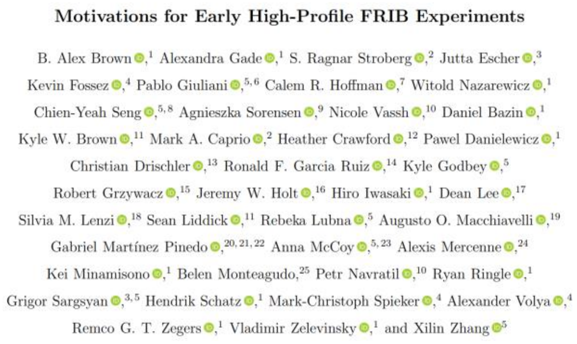
Received: 17 March 2024

Accepted: 24 September 2024

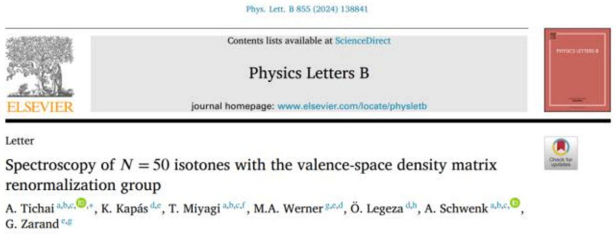
Published online: 18 October 2024

Check for updates

Alexandra Gade, Brenden Longfellow, Robert V. F. Janssens, Duc D. Dao, Frédéric Nowacki, Jeffrey A. Tostevin, Akaa D. Ayangeakaa, Marshall J. Basson, Christopher M. Campbell, Michael P. Carpenter, Joseph Chung-Jung, Heather L. Crawford, Benjamin P. Crider, Peter Farris, Stephen Gillespie, Ava M. Hill, Silvia M. Lenzi, Shumpei Noji, Jorge Pereira, Carlotta Porzio, Alfredo Poves, Elizabeth Rubino & Dirk Weisshaar


Motivations for Early High-Profile FRIB Experiments

B. Alex Brown, Alexandra Gade, S. Ragnar Stroberg, Jutta Escher, Kevin Fossez, Pablo Giuliani, Calem R. Hoffman, Witold Nazarewicz, Chien-Yeah Seng, Agnieszka Sorensen, Nicole Vassh, Daniel Bazin, Kyle W. Brown, Mark A. Caprio, Heather Crawford, Pawel Danielewicz, Christian Drischler, Ronald F. Garcia Ruiz, Kyle Godbey, Robert Grzywacz, Jeremy W. Holt, Hiro Iwasaki, Dean Lee, Silvia M. Lenzi, Sean Liddick, Rebeka Lubna, Augusto O. Macchiavelli, Gabriel Martínez Pinedo, Anna McCoy, Alexis Mercenne, Kei Minamisono, Belen Monteagudo, Petr Navratil, Ryan Ringle, Grigor Sargsyan, Hendrik Schatz, Mark-Christoph Spieker, Alexander Volya, Remco G. T. Zegers, Vladimir Zelevinsky and Xilin Zhang


Phys. Lett. B 855 (2024) 138841

Contents lists available at ScienceDirect

Physics Letters B

journal homepage: www.elsevier.com/locate/physletb

Letter

Spectroscopy of $N = 50$ isotones with the valence-space density matrix renormalization group

A. Tichai, K. Kapás, T. Miyagi, M.A. Werner, Ö. Legeza, A. Schwenk, G. Zarand

- ✓ Reproduce of properties of N=40 nuclei
- ✓ Predict the existence of N=50 IoI

N=40 and N=50 Isotones exhibit similar properties

^{81}Zn@Xiaofei Yang's talk

3. Isospin symmetry breaking in nuclear systems

① H. H. Li, Q. Yuan, **J. G. Li***, M. R. Xie, S. Zhang, Y. H. Zhang, X. X. Xu, N. Michel, F. R. Xu, and W. Zuo, Phys. Rev. C 107, 014302(2023)

② H. H. Li, **J. G. Li**,* M. R. Xie, W. Zuo, Chinese Physics C 47, 12 (2023) 124101

③ M.Z. Sun, Y. Yu, X.P. Wang, M. Wang, **J.G. Li*,** Y.H. Zhang*, et al., Chin. Phys. C(2024)

④ Y. Yu, Y. M. Xing, Y. H. Zhang, M. Wang, X. H. Zhou, **J. G. Li**, H. H. Li, et al., PRL(Accepted)

Ab initio

↓

Isospin symmetry breaking

Nuclear isospin symmetry breaking

- ➢Particle physics level
  - ✓ mass of u-d quark is difference
  - ✓Coulomb forces between quarks

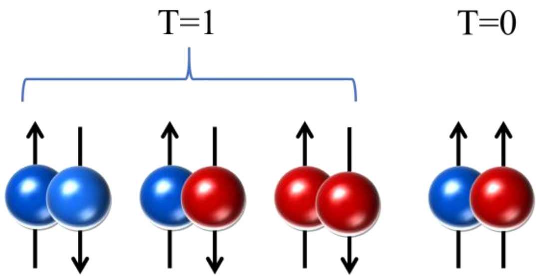
1. p-n mass difference:

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

2. p-n charge difference:

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

- ➢Nuclear physics level
  - ✓Coulomb forces
  - ✓Nucleon-nucleon interaction
    - Charge symmetry breaking—CSB $V_{nn} - V_{pp}$ (isospin vector)
    - Charge independent breaking--CIB) $2V_{np} - \left(V_{nn} + V_{pp}\right)$ (isospin tensor)



Isospin non-conserving force--INC

- ✓Weakly-bound effects

Study the mechanism of isospin symmetry breaking: Coulomb, nuclear forces, and weakly-bound effects…

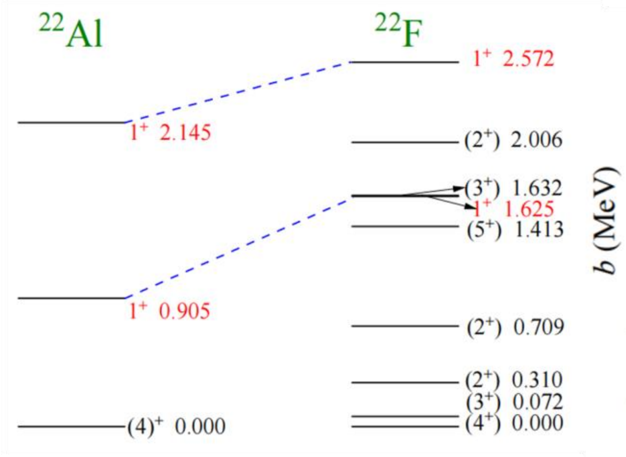
Status of study of isospin symmetry breaking

➢ **Isospin：（approximation）** proton $t_z = -1/2$ neutron $t_z = 1/2$

In 1932, introduced by Heisenberg
The properties of mirror nuclei should be same

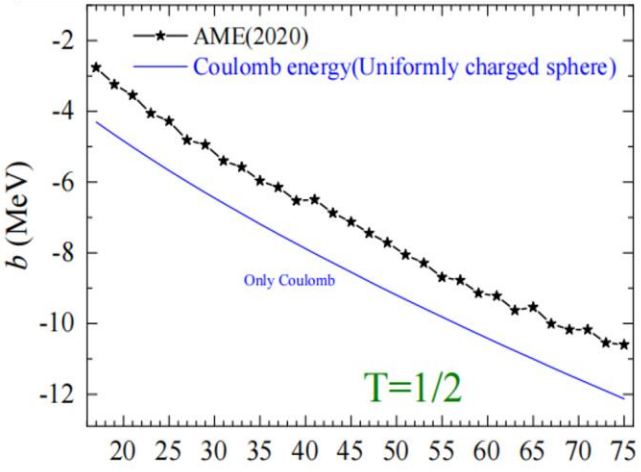
Isospin symmetry breaking：Experimental results

镜像核能谱
(Thomas-Ehrman shift)



J. Lee, X.X. Xu, et al., PRL 125,192503(2020)

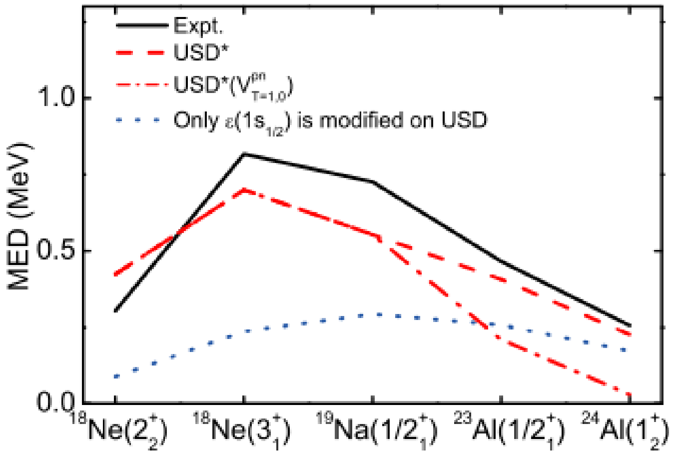
同位旋多重质量方程
(Nolen-Schiffer anomaly)



Y. H. Zhang et al., PRL 109, 102501(2012)

➢ **Theoretical calculations: shell model**

Phenomenological ways：
Adjusting the matrix elements related to 1s1/2 to reproduce the experimental data.

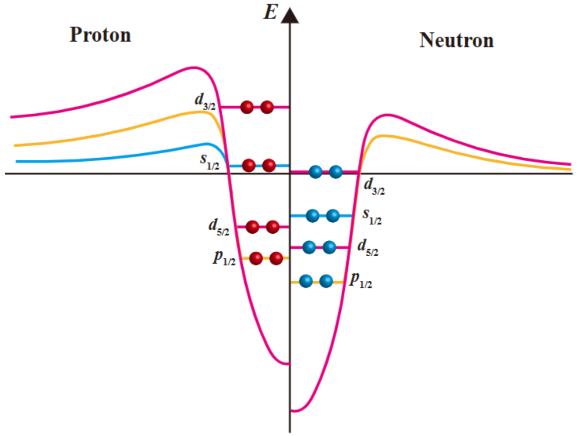


No parameter needs to be adjusted within ab initio calculations, which is suitable for the investigations of isospin symmetry breaking

β-decay in proton-dripline nuclei-isospin symmetry breaking

Mirror Energy difference (MED)

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



Thomas-Ehrman Shift

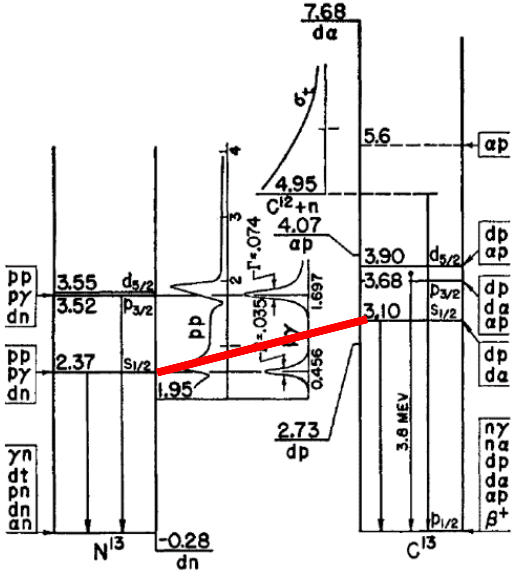


FIG. 1. The energy levels of C^{13} and N^{13} below 6 Mev.

Phys. Rev. 88,1109 (1952)

mirror asymmetry parameter (δ) :

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

$\delta >> 0$
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.

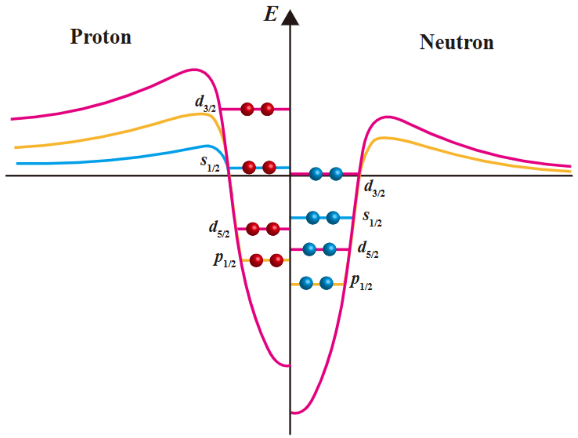
1. Ab initio calculations for the mirror energy difference

Adopting NN(bare) and NN+3N(1.8/2.0)interaction, VS-IMSRG calculations for the mirror states

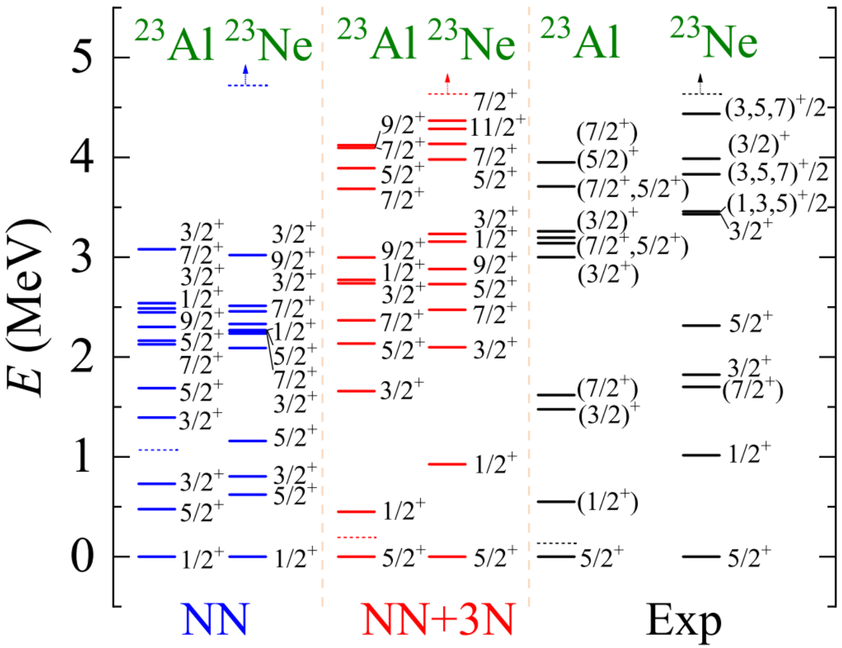
PHYSICAL REVIEW C 107, 014302 (2023)

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*

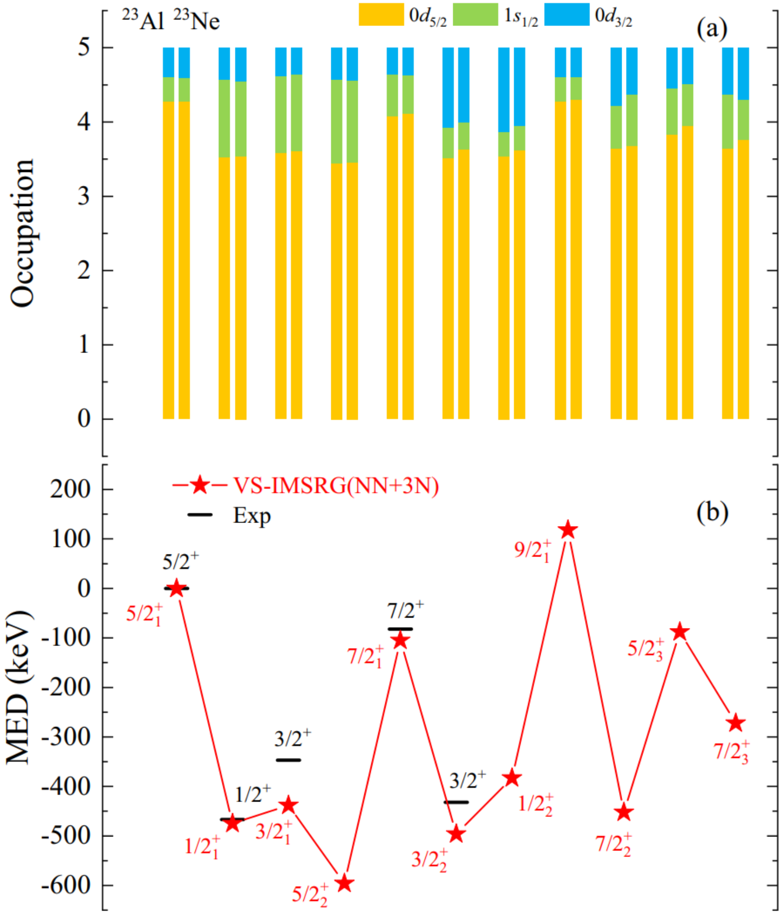


Three-Body forces are important for spectra



MED→isospin symmetry breaking

$(MED) = E_x(n\_rich) - E_x(p\_rich)$

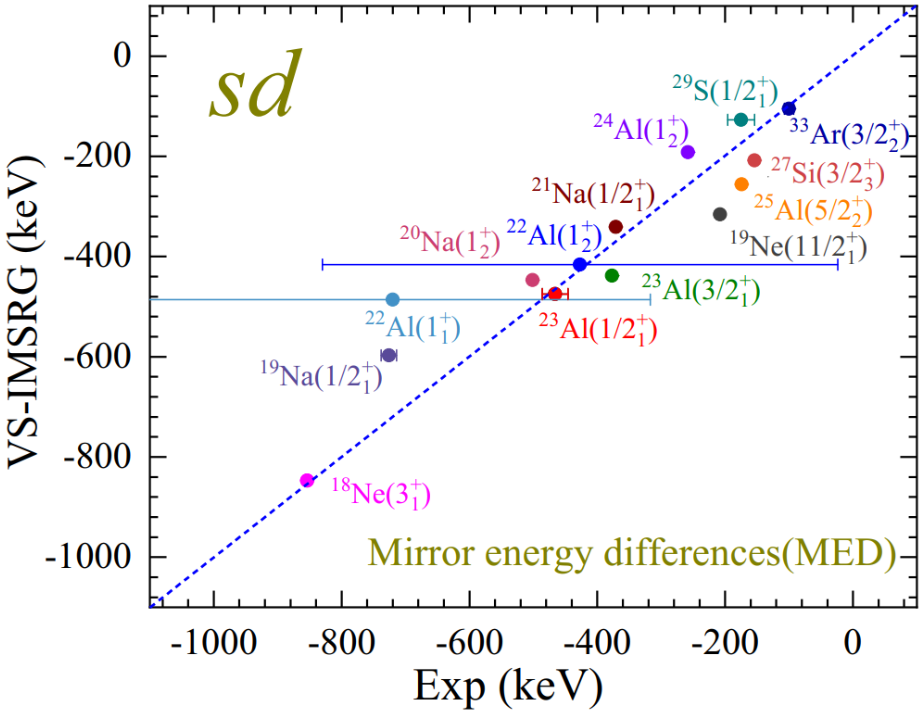


Large MED is mainly caused by the occupying of weakly-bound 1s1/2 orbital

1. Ab initio calculations for the mirror energy difference

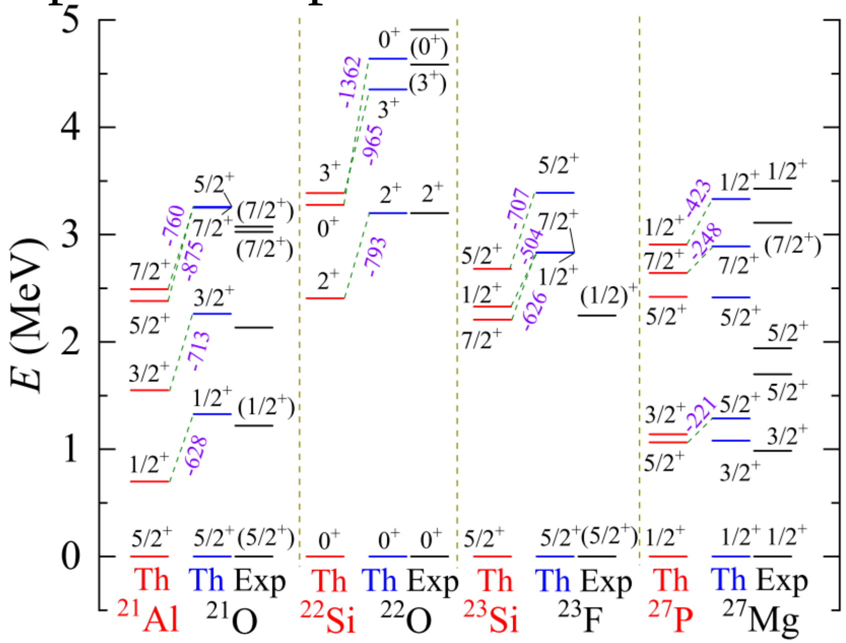
①Calculations of mirror states with large MED。

Ab initio calculations well reproduce data



Ab initio VS-IMSRG can be used to predict the spectra for unknown in experiments.

②Predictions of low-lying states in *sd*-shell proton-dripline nuclei.

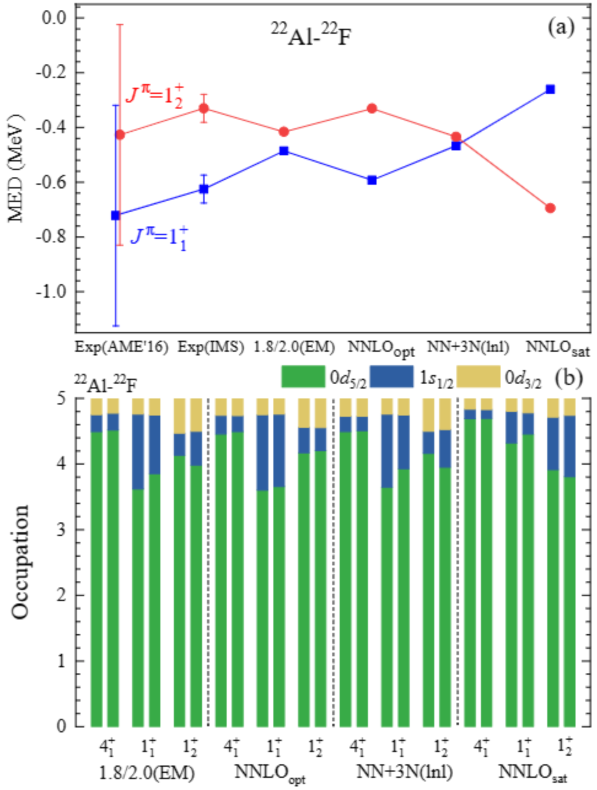


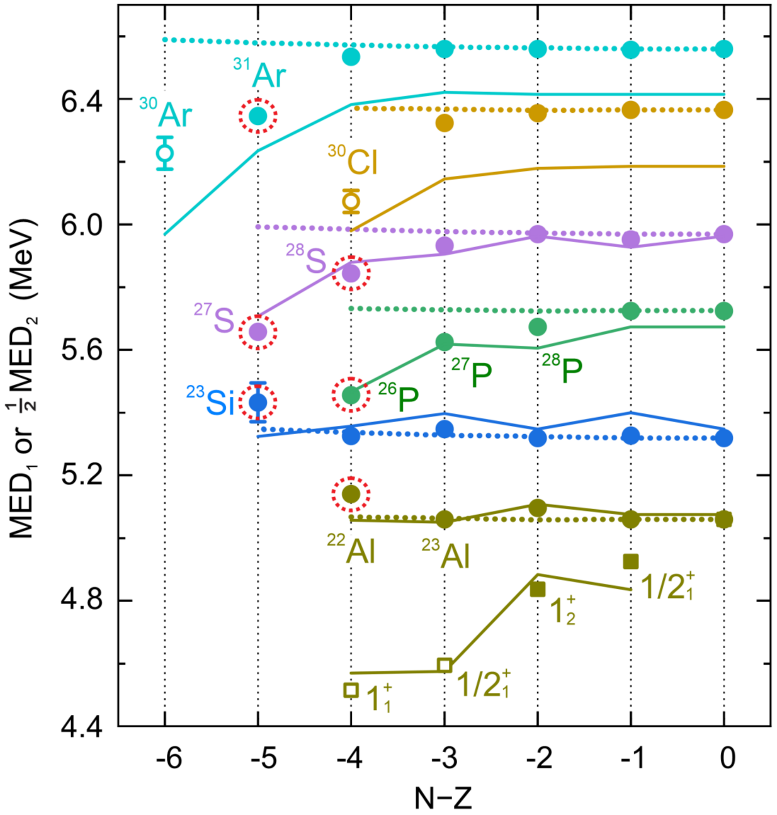
- Low-lying spectra of neutron-rich nuclei can be well produced.
- The reliability of our prediction for proton-rich nuclei.

Jianguo Li jianguo_li@impcas.ac.cn

Collaborations with IMP mass measurement group

see Prof. Yuhu Zhang's talk





- ✓ Significant isospin symmetry breaking in the excited states of Al isotopes
- ✓ The ground state of ^{26}P,^{27}P,^{27}S, ^{31}Ar dripline exhibit significant isospin symmetry breaking
- ✓ The similar mechanism of significant isospin symmetry breaking and halo structure
- ✓ ^{26}P, ^{27}P, ^{27}S, ^{31}Ar are halo nuclei

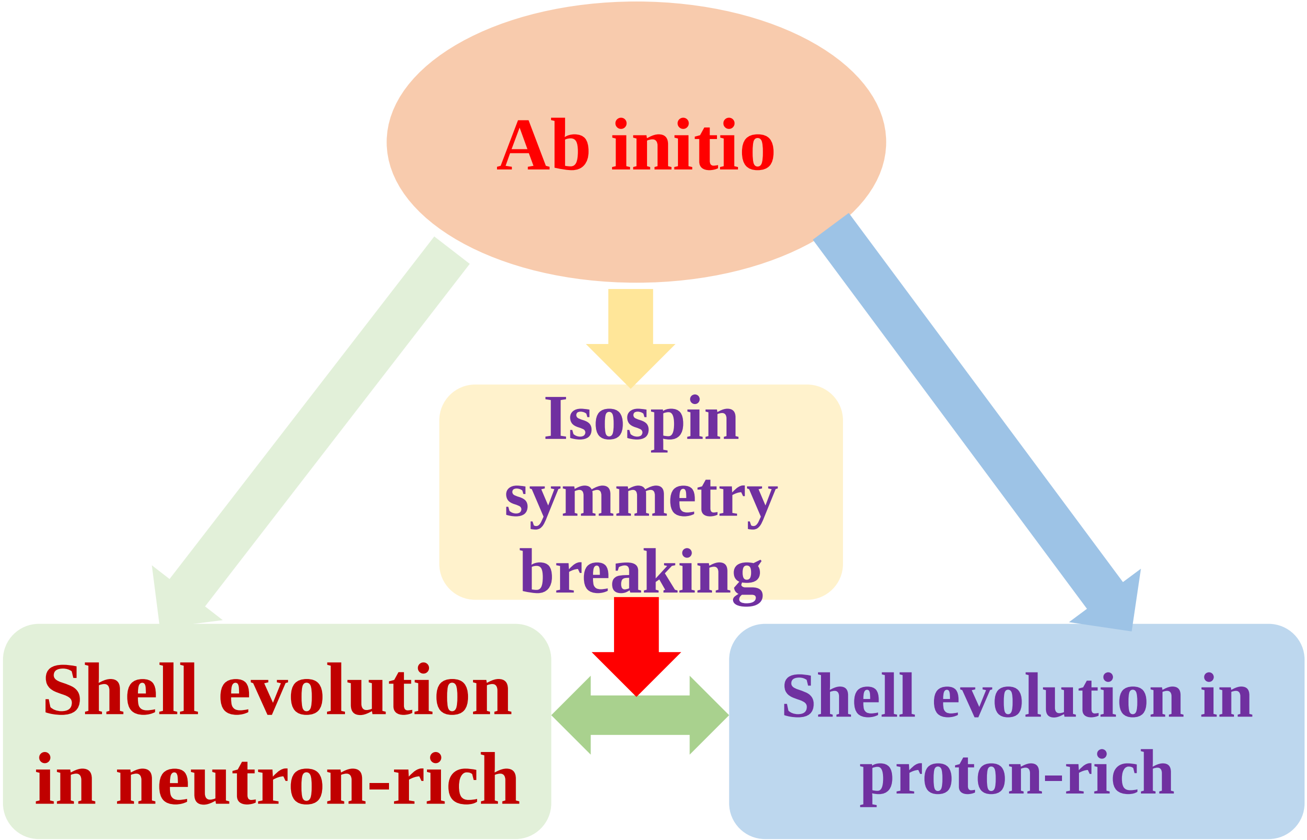
M.Z. Sun, Y. Yu, X.P. Wang, M. Wang, **J.G. Li*,** Y.H. Zhang*, et al., Chin. Phys. C(2024)

Y. Yu, Y. M. Xing, Y. H. Zhang, M. Wang, X. H. Zhou, **J. G. Li**, H. H. Li, et al., PRL(Accepted)

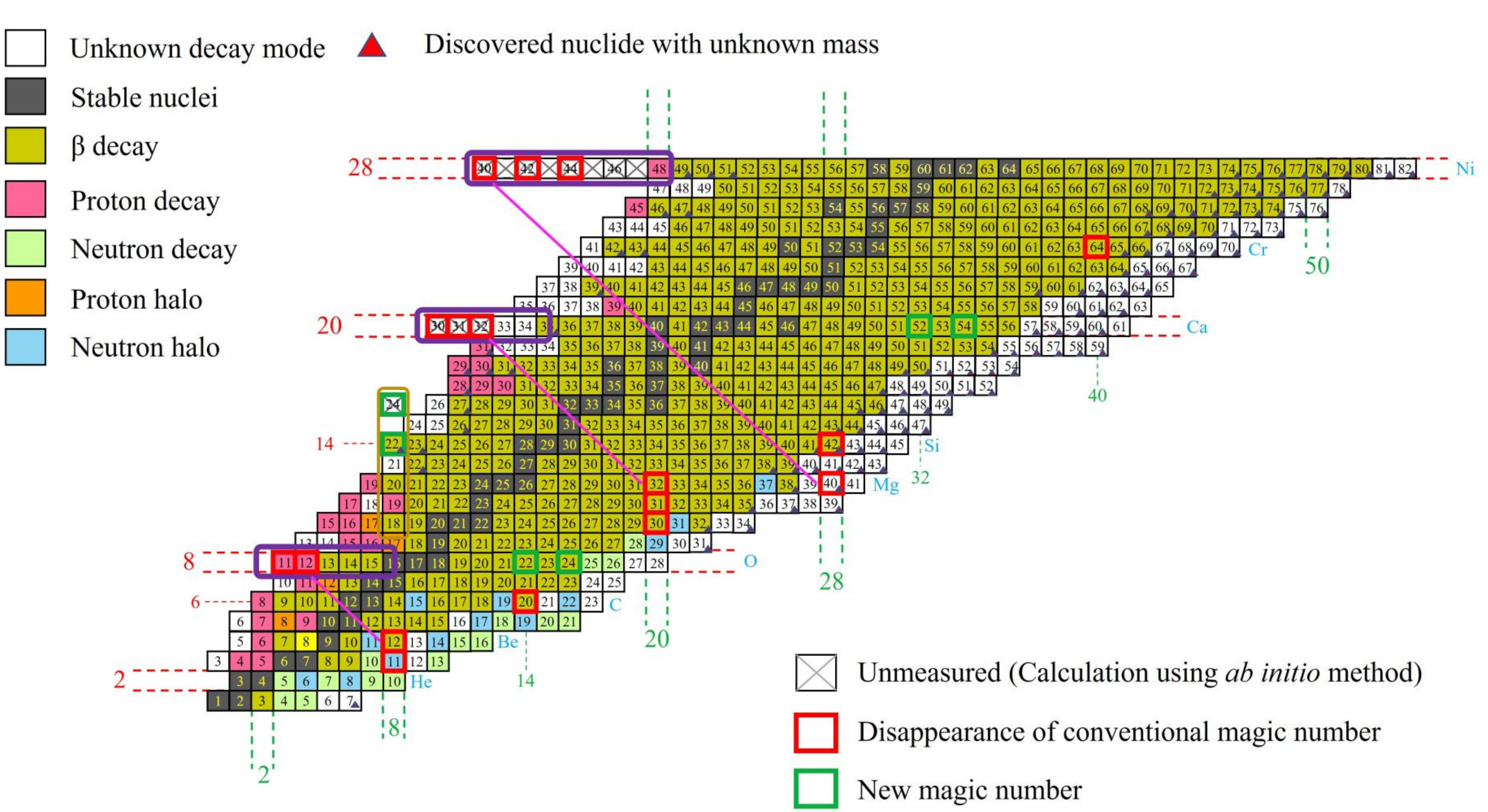
4. Isospin symmetry breaking for the shell evolution in proton-rich nuclei

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

② H. H. Li, **J. G. Li*,** M. R. Xie, W. Zuo, in preparation

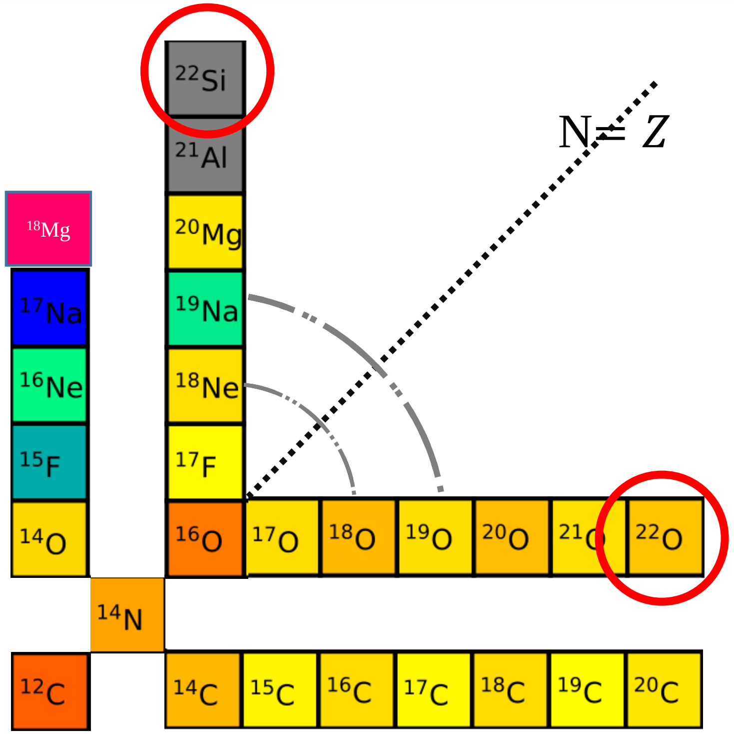


Shell evolution—isospin symmetry breaking—shell evolutions in neutron-rich nuclei



- ✓ The disappearance of traditional magic number and appearance of new magic number
- ✓ What about the shell evolutions in proton-rich nuclei? The effects of isospin symmetry breaking.

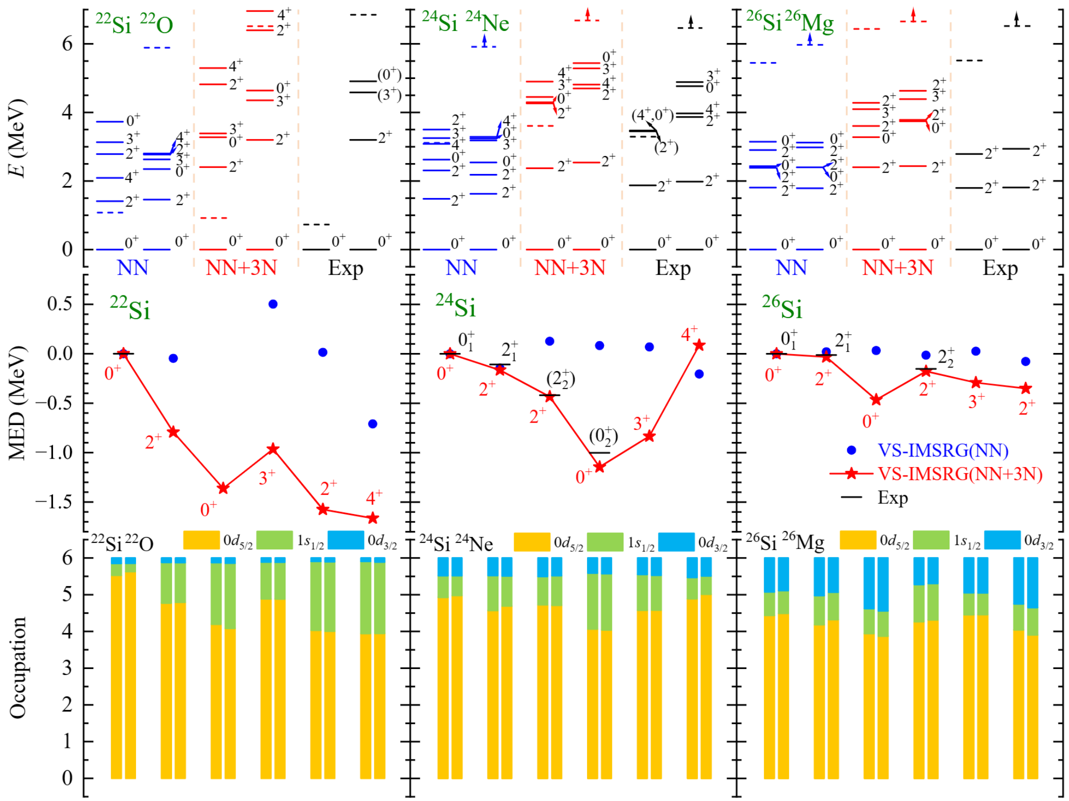
1. ^{22}Si double magic nuclei---new magic number



FRIB and RIKEN plan to done the experiments of ^{22}Si

- ✓ Neutron-rich double magic nuclei: ^{22}O
- ✓ Isospin symmetry breaking for the magicity

Whether ^{22}Si is a double magic nuclei?

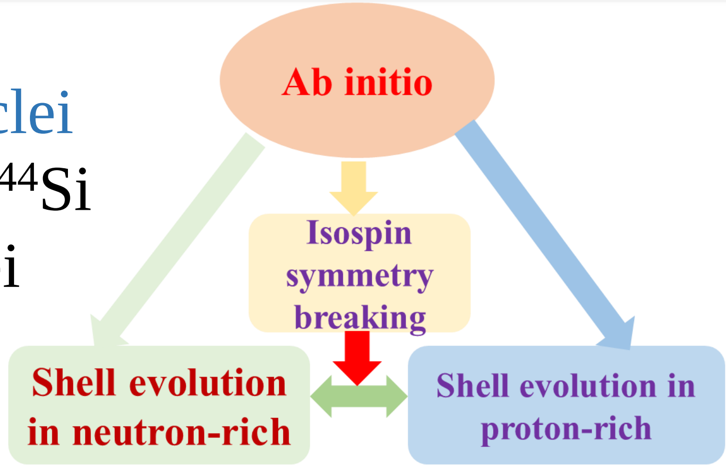


- The excitation energies of 22O is well reproduced with 3.2 MeV; Due to Thomas-Ehrman shift effect, the E(21+) of 22Si is 2.4 3.2 MeV
- Although the E(21+) of 22Si is small, but the ground state properties of 22Si/22O is similar.

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

Summary

1. Ab initio calculations for island of inversion in neutron-rich nuclei
   - shape coexistence and shape transition in ^{40}Mg, ^{42}Si and ^{44}Si
   - Predicted halo in Mg, Al, Si, P and S neutron-rich nuclei
   - The study of N=40 and N=50 Island of Inversion



2. Isospin symmetry breaking in mirror nuclei—mirror energy difference

   large MED (Thomas-Ehrman shift) is mainly caused by the occupation of 1s1/2

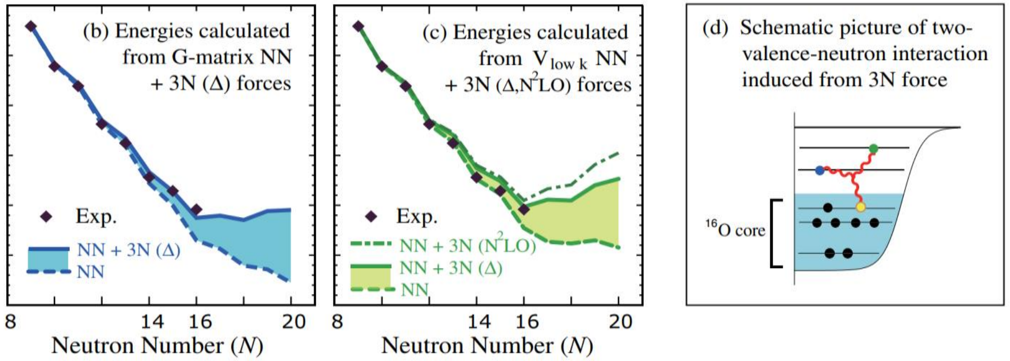
3. Isospin symmetry breaking for shell evolution in proton-rich nuclei
   - Predicted doubly magic nuclei ^{22}Si with small 2+ excitation energy
   - *Proton-rich nuclei near Z*=8、20 and 28 show deformation, which belong to IOI

Thank you for your attention!

Jianguo Li jianguo_li@impcas.ac.cn

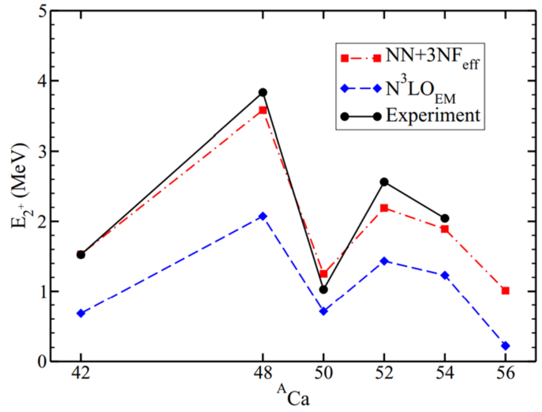
三体力效应-质量-第一性原理计算

滴线位置



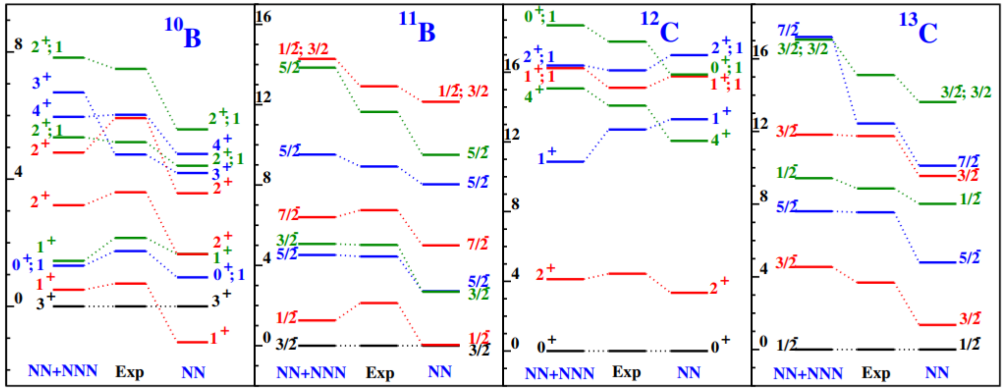
T. Otsuka, *et al.*, Phys. Rev. Lett. 105, 032501 (2010)

壳演化



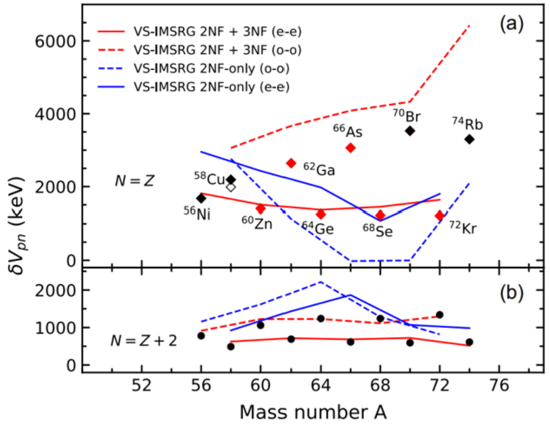
G. Hagen, *et al.*, Phys. Rev. Lett. 109, 032502 (2012)

能谱结构



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

质子中子对关联

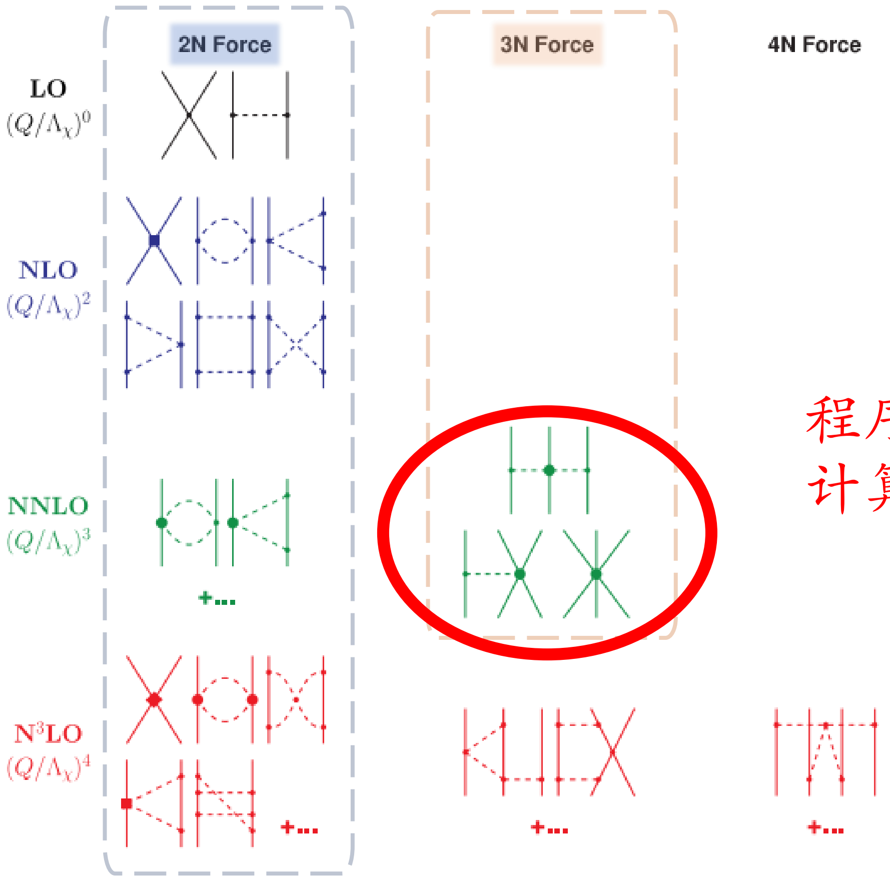


M. Wang,, *et al.*, Phys. Rev. Lett 130, 192501(2023)

三体力效应在原子核性质中扮演着非常重要的角色

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

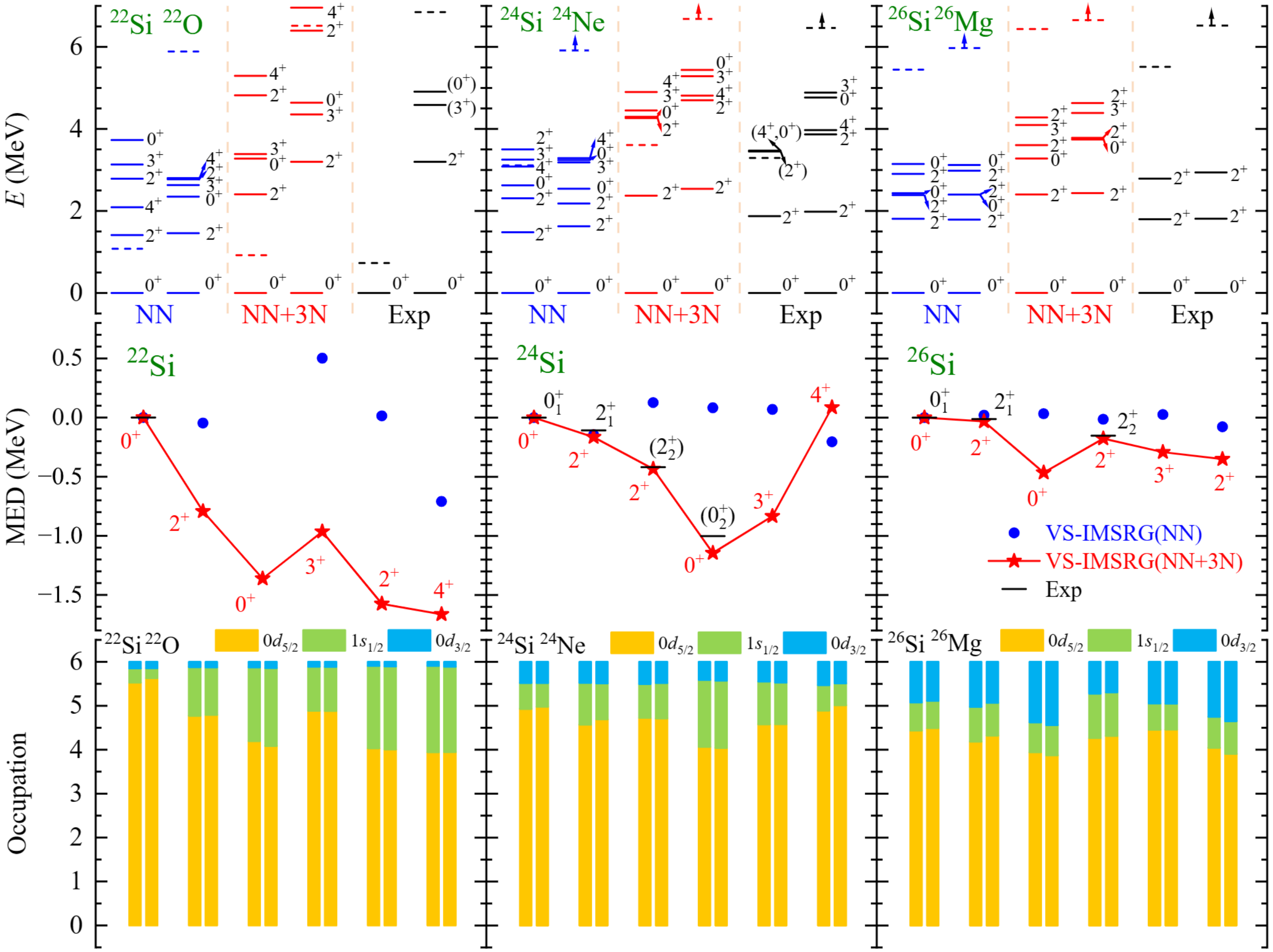
Partial-wave LECs for two N^3LO fits by the Idaho group [68] using $\Lambda = 500$ and 600 MeV in the regulator function $f(p', p)$, Eq. (4.63). The $\widetilde{C}_i$ of the zero order partial-wave counterterms given in Eq. (4.39) are in units of 10^4 GeV^{-2}; the C_i, Eq. (4.41), in 10^4 GeV^{-4}; 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
$C_{^3P_2}$	[illegible]	[illegible]	2
$D_{^3P_2}$	[illegible]	[illegible]	2
$D_{^3P_2-^3F_2}$	[illegible]	[illegible]	4
$D_{^3D_3}$	5.66	6.26	2, 3[a]

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

美国FRIB与日本RIKEN RIB均在计划测量22Si激发态

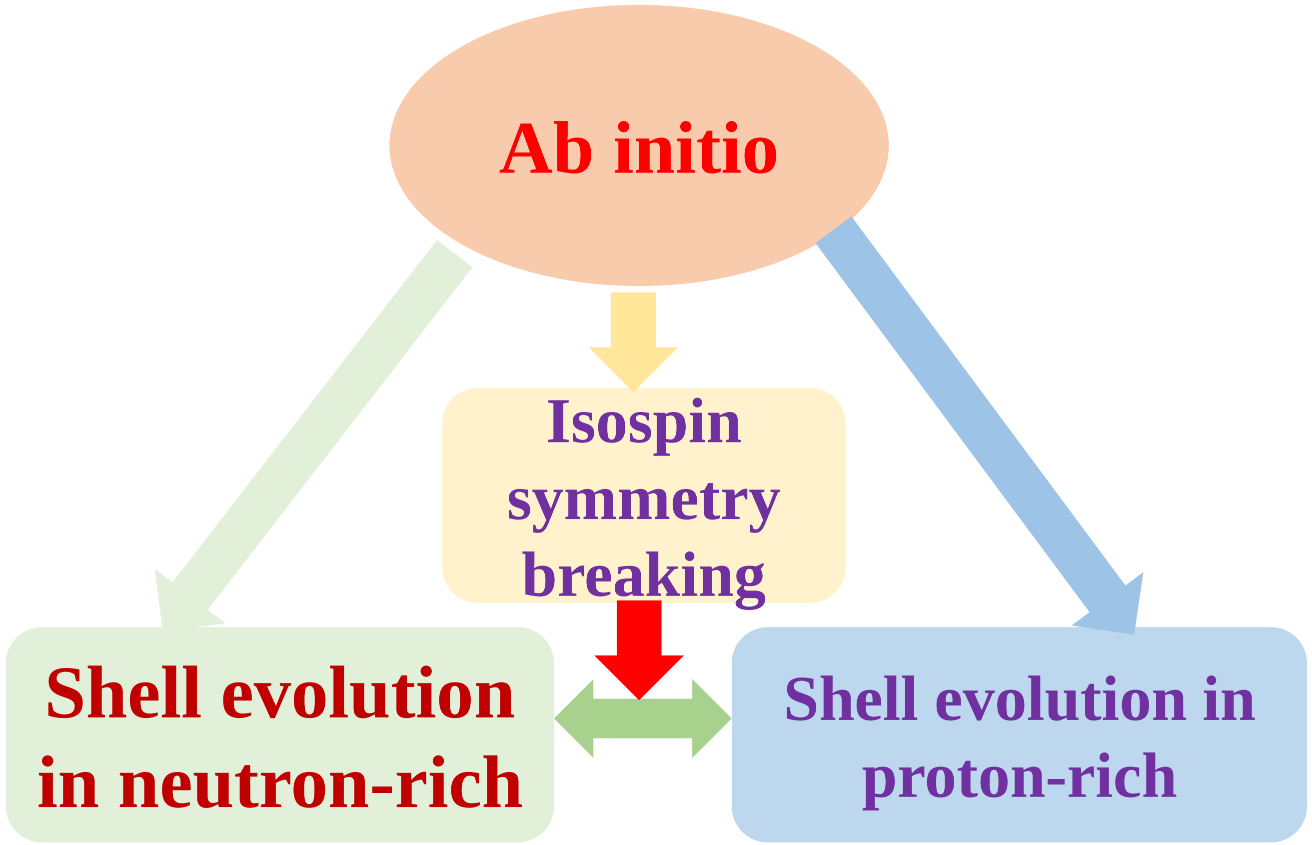
^{22}Si 双幻核结构---新幻数



- ✓ 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)*



Jianguo Li jianguo_li@impcas.ac.cn