A chiral three-body force for realistic nuclear shell model calculations

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- INFN Napoli

In collaboration with

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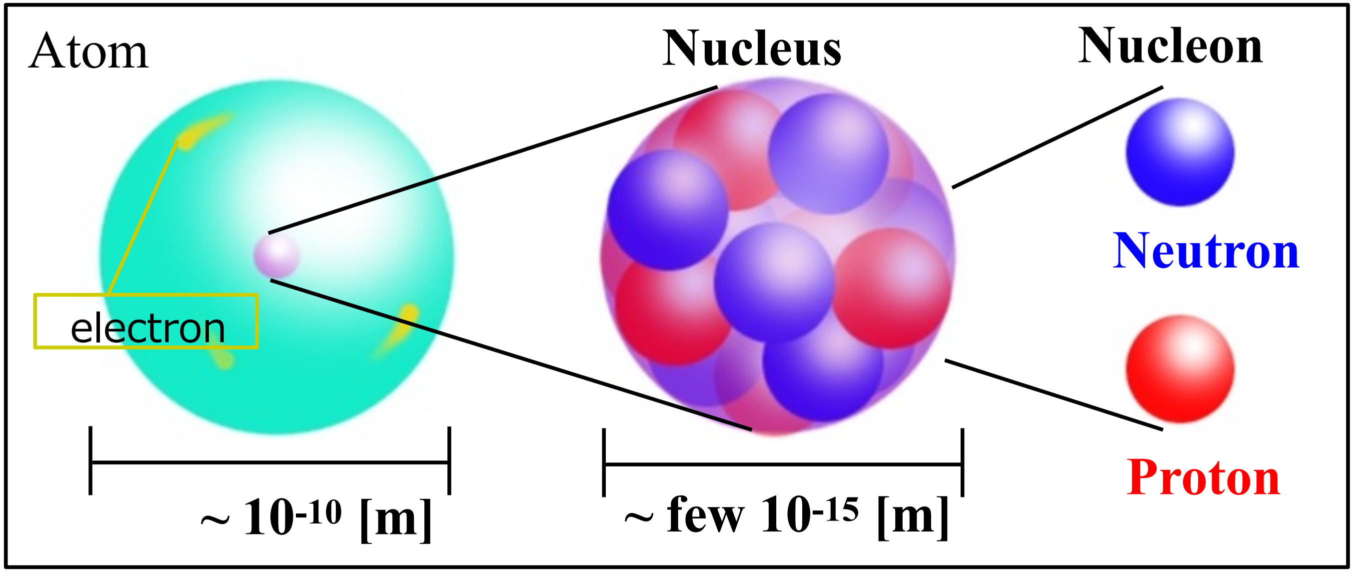
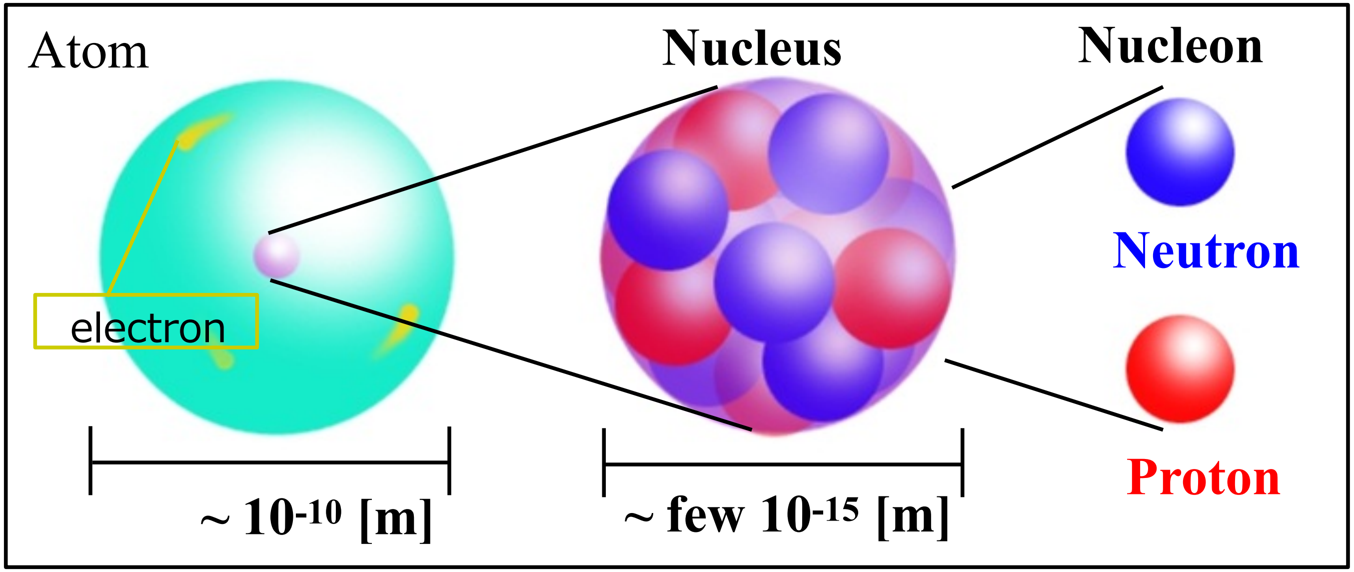
N. Itaco Università degli Studi della Campania Luigi Vanvitelli & INFN Napoli

SM&FT 2019

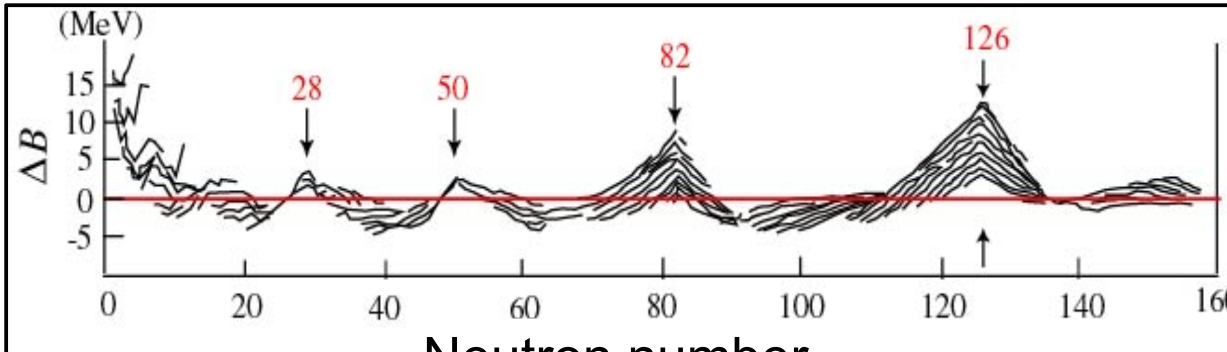


The nucleus is a finite quantum many-body system composed of A interacting nucleons

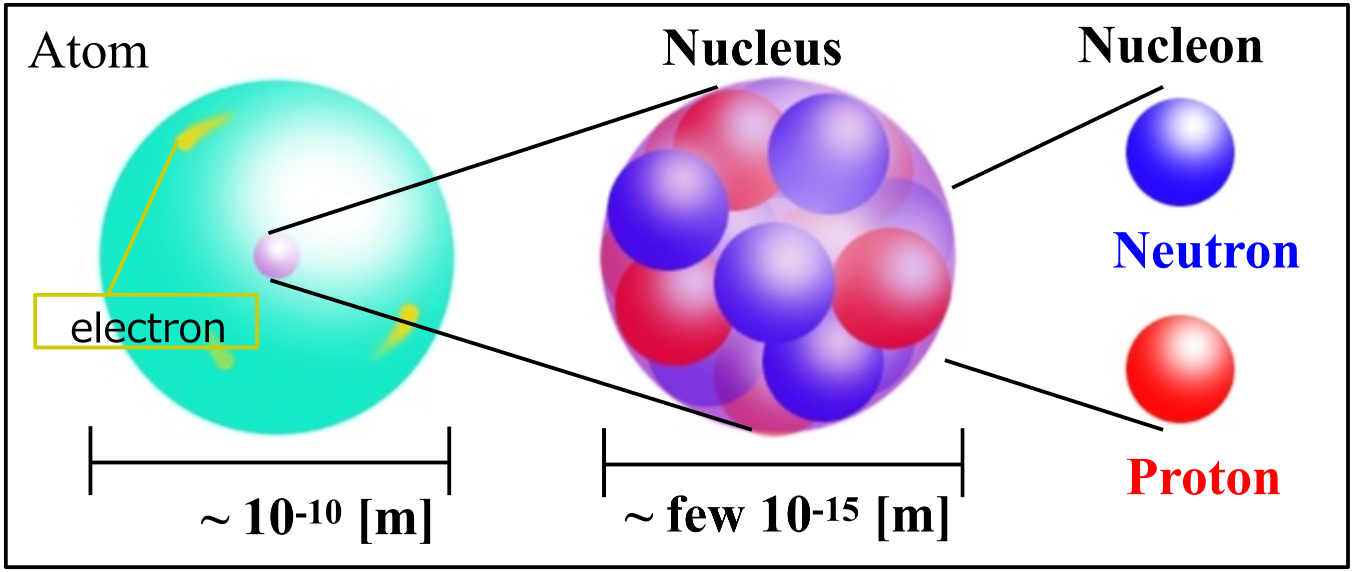


The nucleus is a finite quantum many-body system composed of A interacting nucleons

- ✓ Nucleus has magic numbers : 2,8,20,28,50,82,126
- ✓ Nucleus makes an averaged "potential"



ΔB = Binding Energy(Exp.) – Empirical formula



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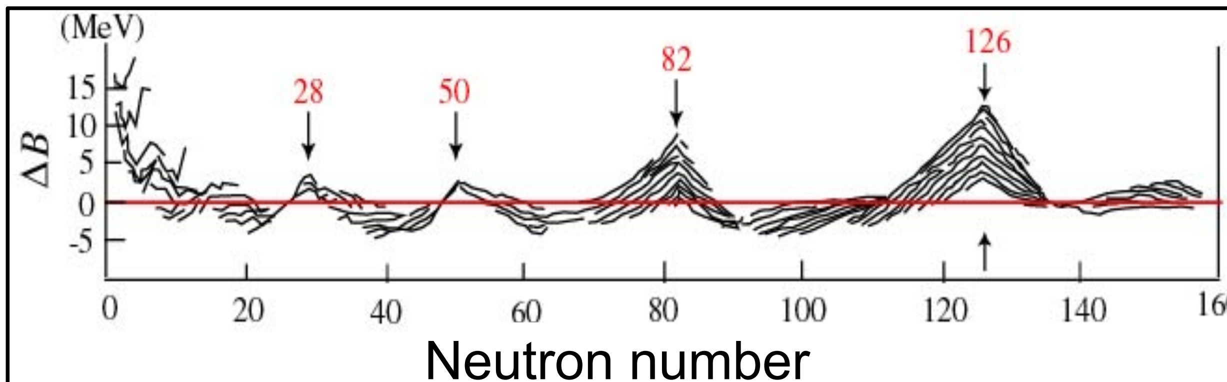


ΔB = Binding Energy(Exp.) – Empirical formula

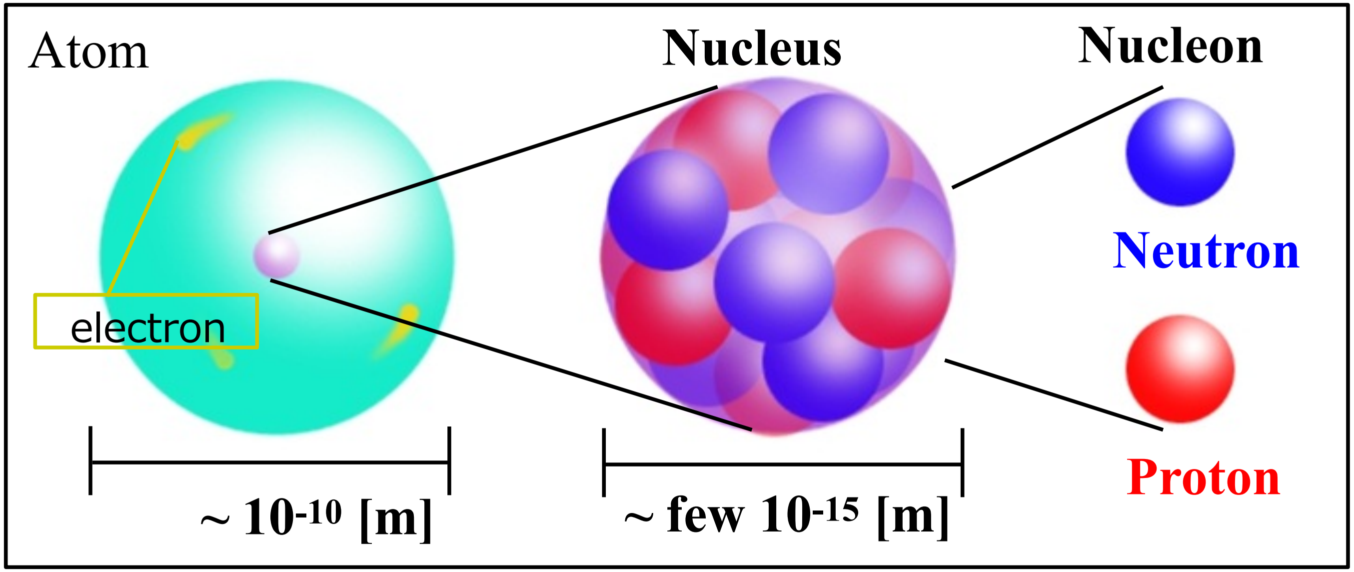
The Hamiltonian has 3A degrees of freedom

$H=T+V$ → $H=H_0+V_{RES}$, $H_0=T+U$

U is the average potential, usually HO+ SO

E. Wigner, M.Goeppert Mayer & J.H.D. Jensen,

Nobel Prize 1963



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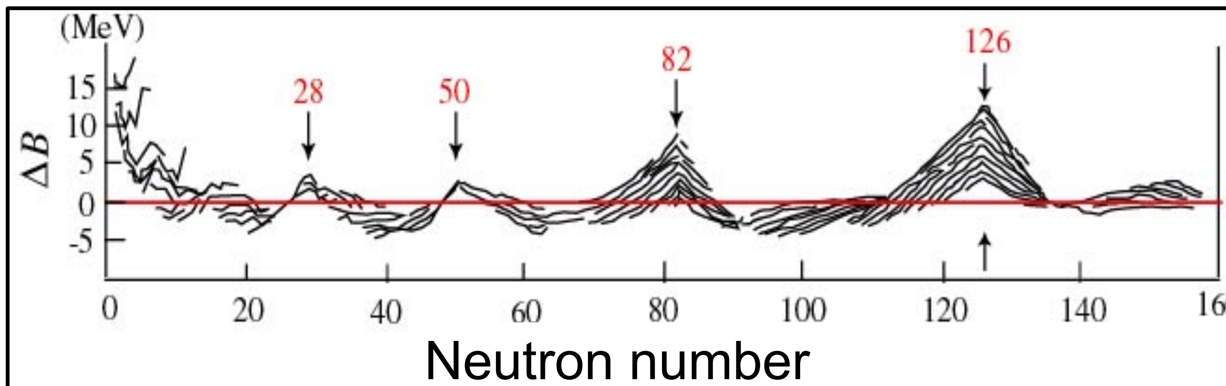

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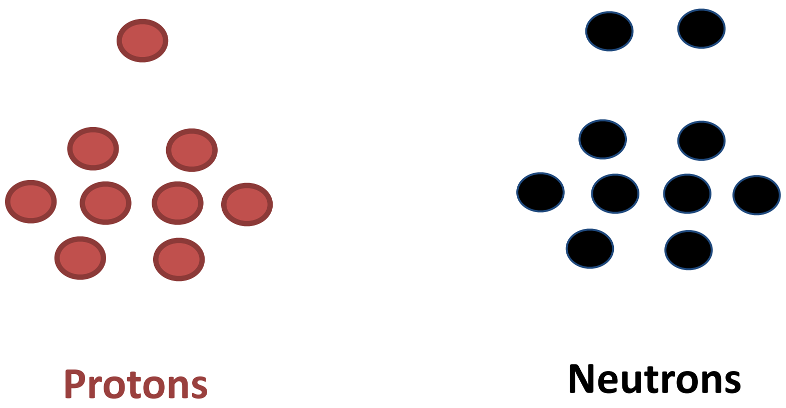
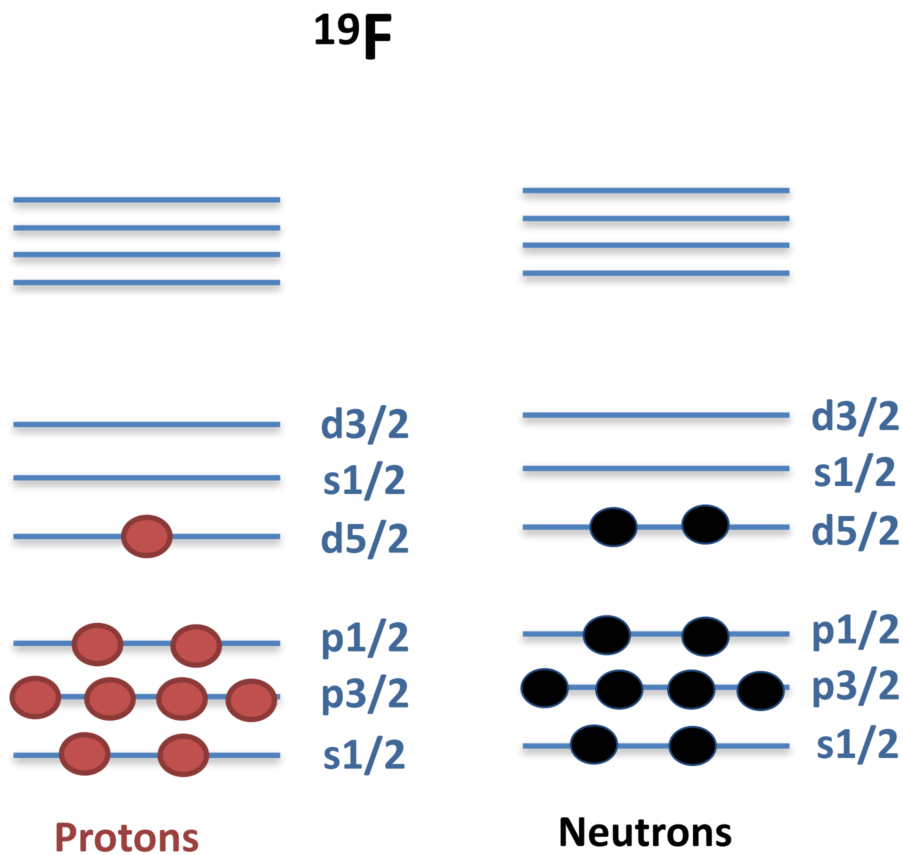
Nuclear shell model: An example ^{19}F

^{19}F

- 9 protons and 10 neutrons
- interacting

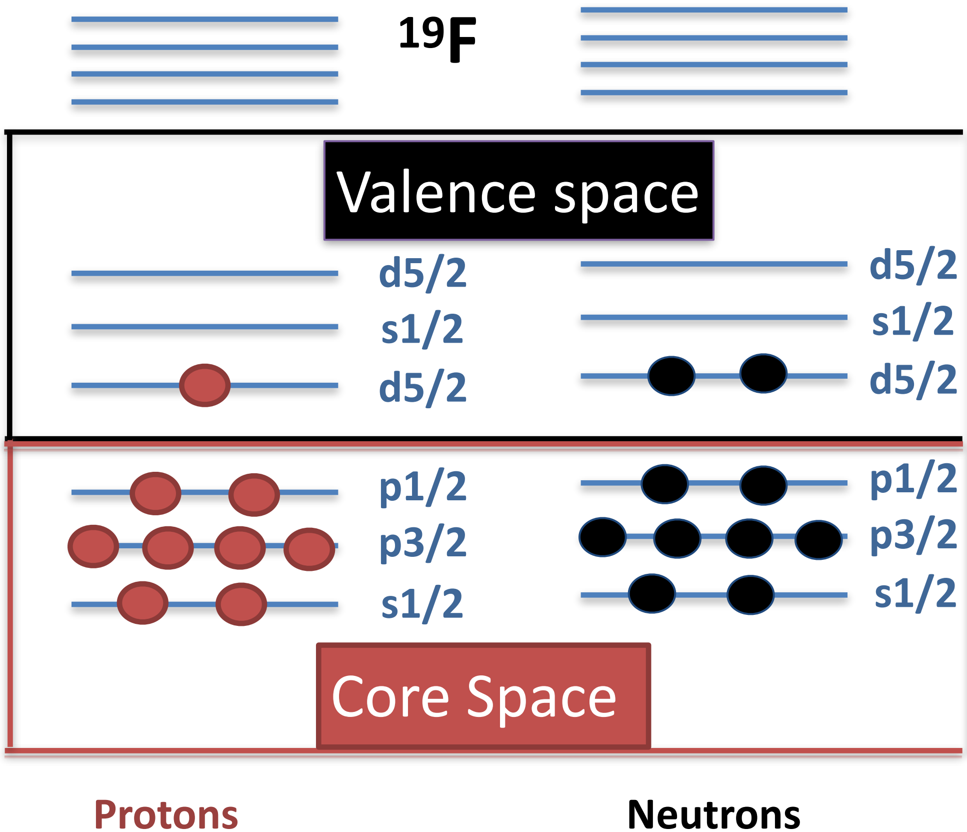


Nuclear shell model: An example ^{19}F



- **9 protons and 10 neutrons interacting**
- **Spherically symmetric mean field (HO)**

Nuclear shell model: An example ^{19}F

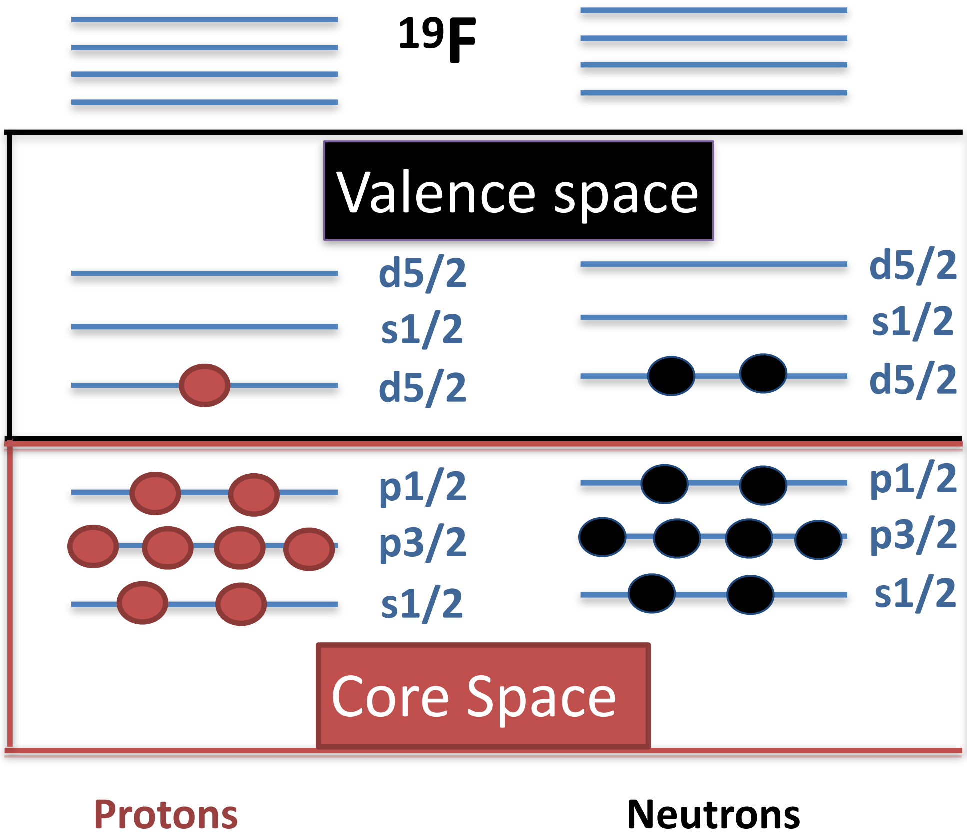


- **9 protons and 10 neutrons interacting**
- **Spherically symmetric mean field (HO)**
- **1 valence proton 2 valence neutron**

The valence nucleons interacts via an effective interaction that takes into account the excluded degrees of freedom

^{16}O

Nuclear shell model: An example ^{19}F



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^{16}O

Infinite Space, **A** nucleons

$$H\psi_\alpha = E_\alpha \psi_\alpha$$

Model Space, v nucleons

$$H_{eff}\phi_\alpha = (T + V_{eff})\,\phi_\alpha = E_\alpha \phi_\alpha$$

$$V_{eff} = V + V\frac{Q}{E - H_0}V_{eff}$$

Shell Model calculations

Workflow

1) Choose a (realistic) *NN* potential (*NNN*)

2) Determine the model space better tailored to study the system under investigation

3) Derive the effective shell-model hamiltonian and operators by way of a many-body theory

4) Calculate the physical observables (energies, e.m. transition probabilities, ...)

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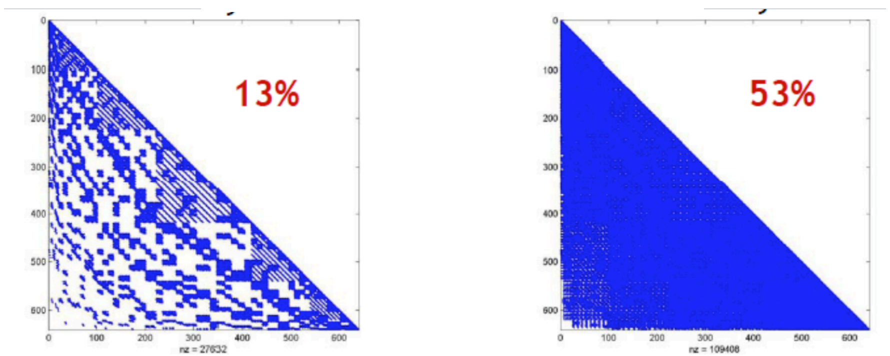
Computational challenges

Major Shell 50-82 10^9 basis state
Major Shell 50-82 + $g_{9/2}$ +$h_{11/2}$ 10^{25} basis state

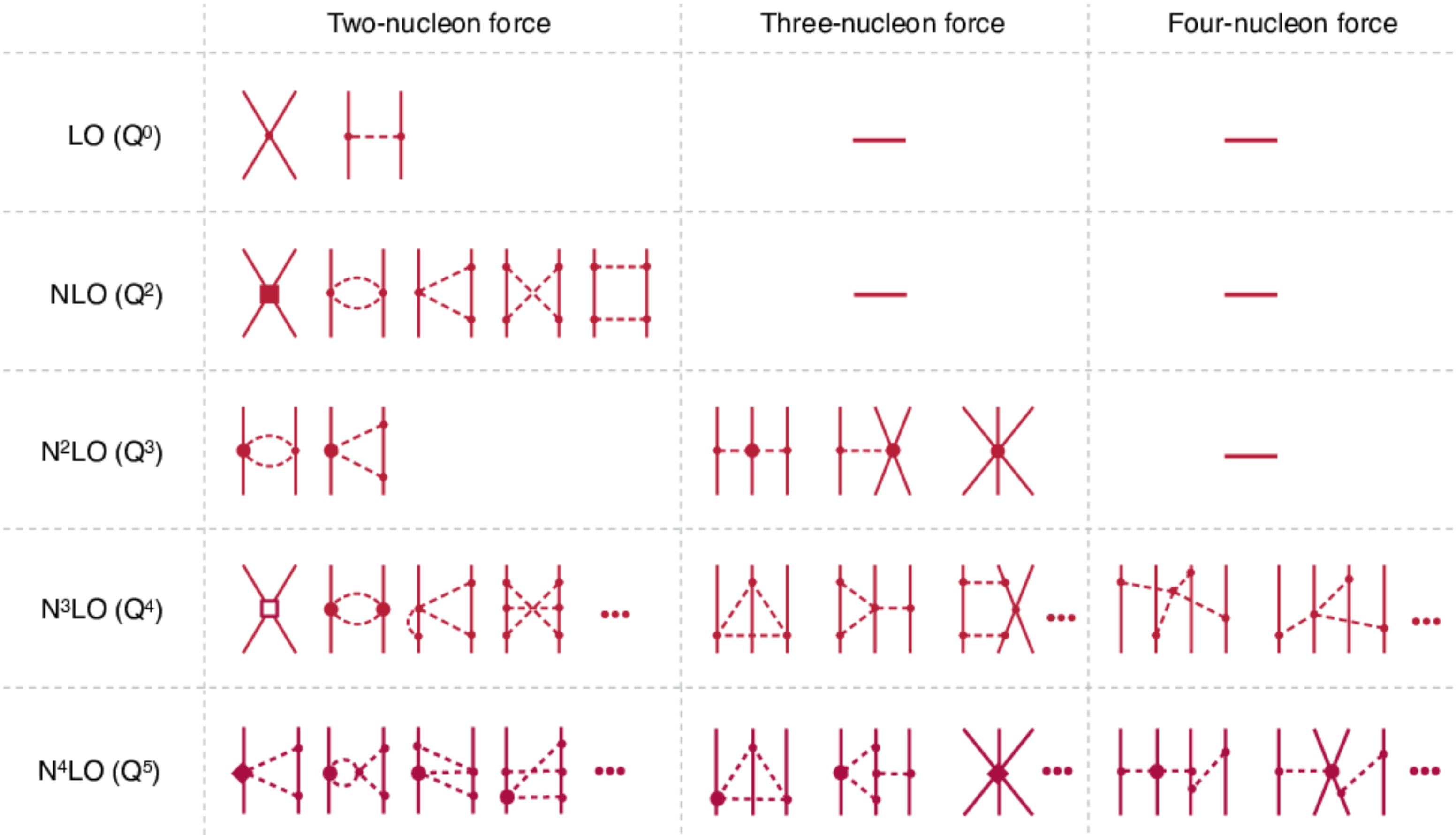
Inclusion of 3N forces, same number

of basis states but less sparse H_{eff}

^{20}Ne sd-shell 640 stati di base



Chiral expansion



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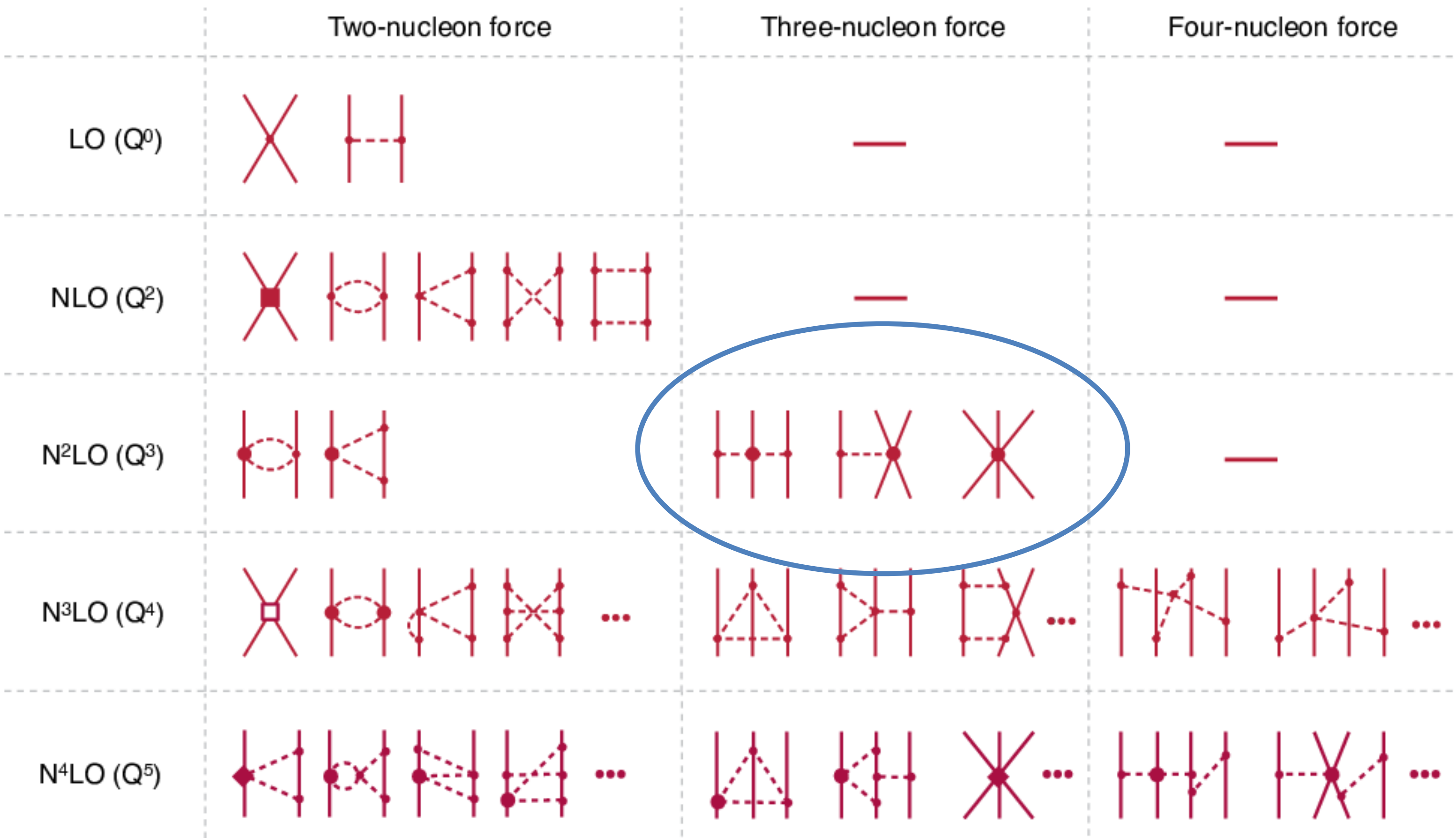
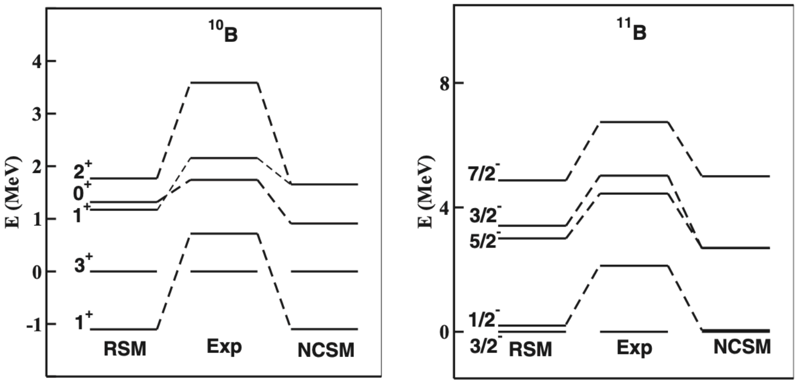


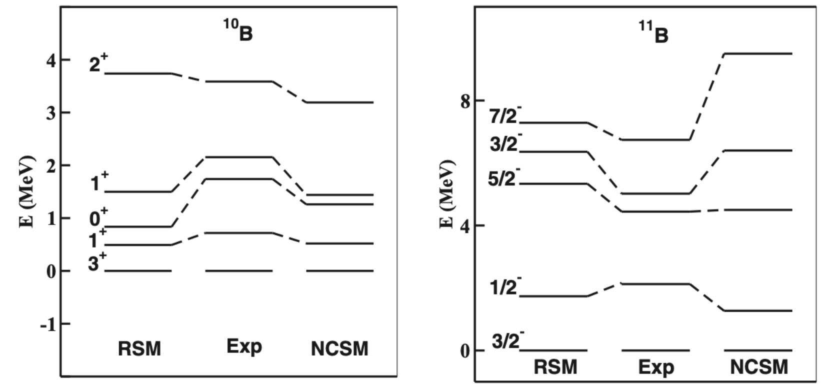
3N interaction: Results

p shell nuclei

T. Fukui Phys. Rev. C **98**, 044305 (2018)



2N



2N+3N

3N interaction: Results

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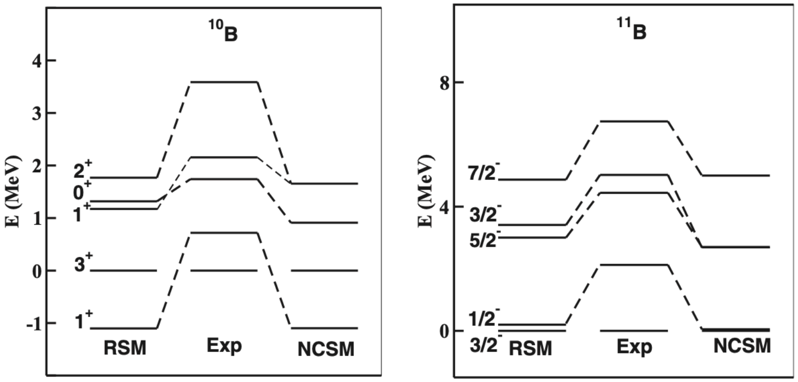
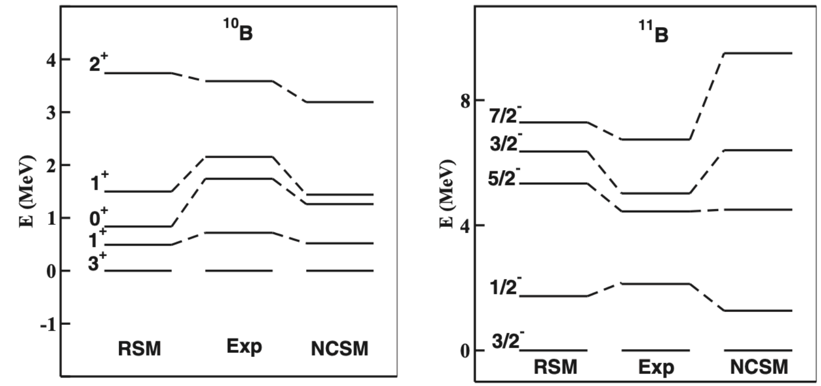
T. Fukui Phys. Rev. C **98**, 044305 (2018)



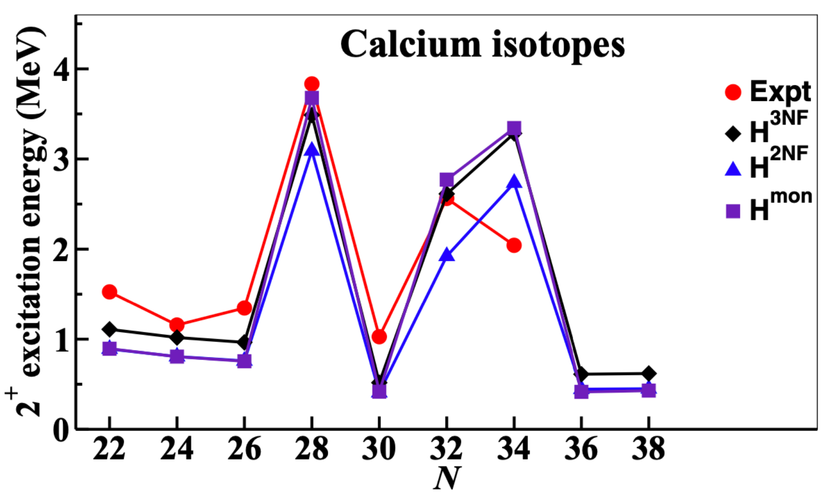


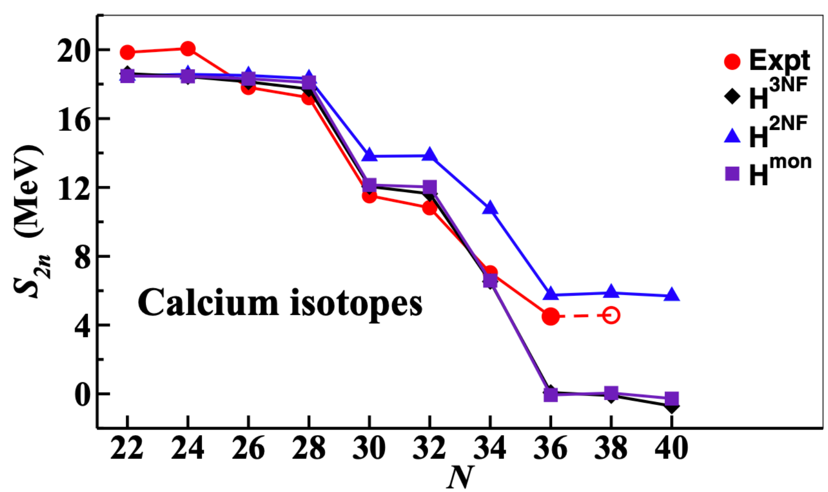
2N

2N+3N

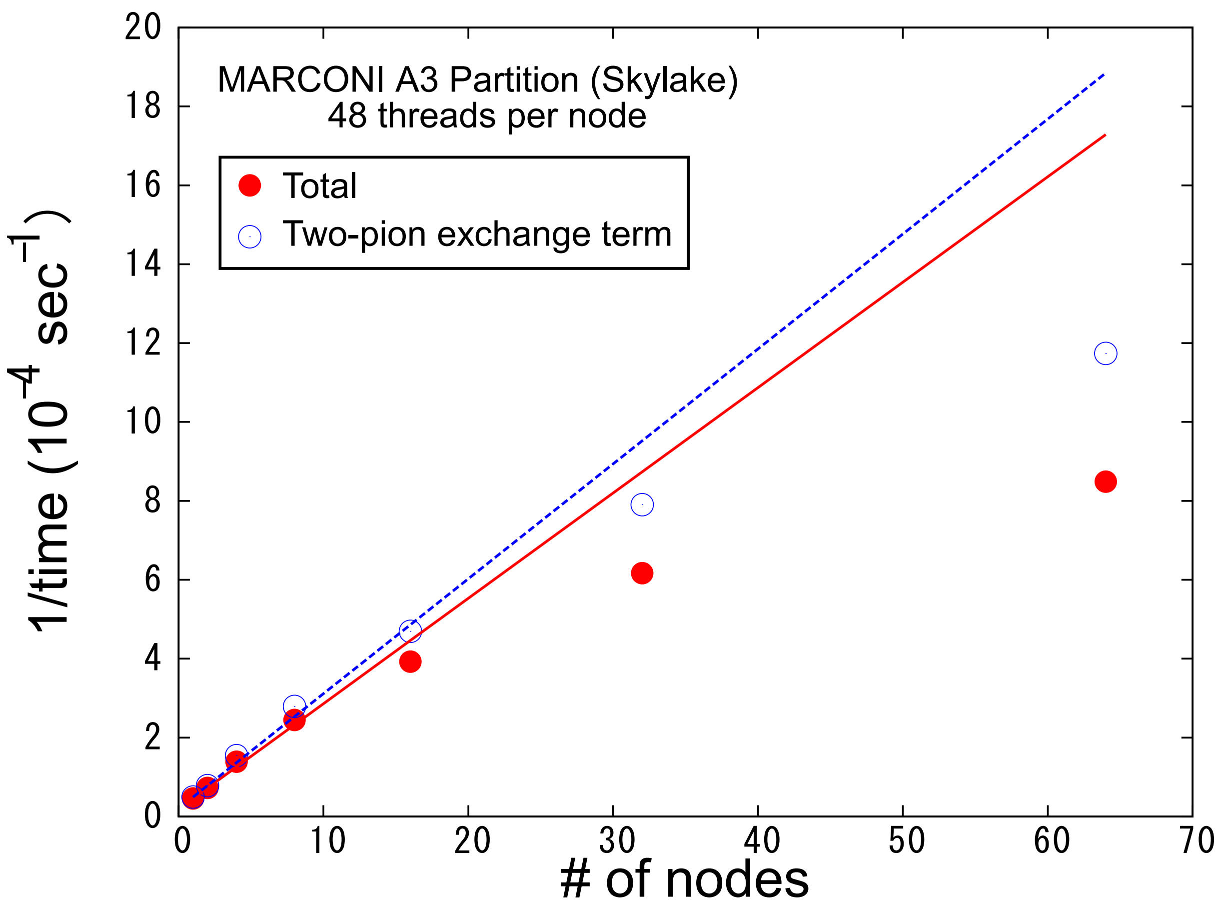
fp shell nuclei

Y. Z. Ma Phys. Rev. C **100**, 034324 (2019)





3N interaction code @MARCONI



Improvements are needed!!!!

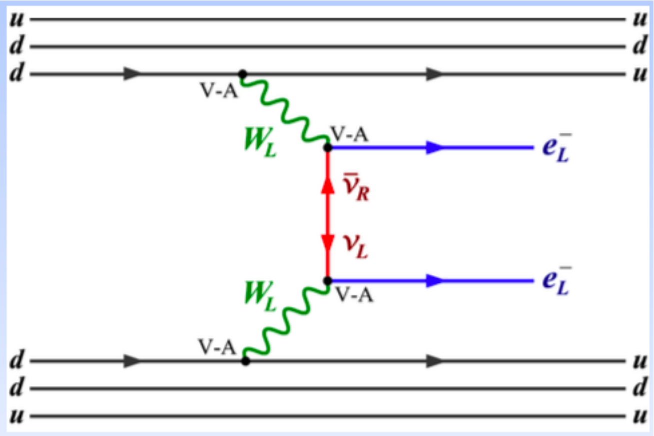
ISCRA Class C Projects Ch3B

Assigned budget :35.000 on MARCON2

The neutrinoless double β-decay

The inverse of the $0\nu\beta\beta$-decay half-life is proportional to the squared nuclear matrix element (NME). This evidences the relevance to calculate the NME

$$[T_{1/2}^{0\nu}]^{-1} = G^{0\nu} |M^{0\nu}|^2 \langle m_\nu \rangle^2$$



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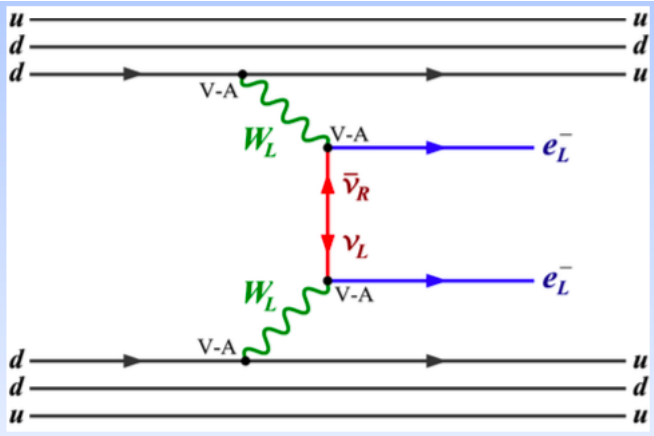

- $G^{0\nu}$ is the so-called phase-space factor, obtained by integrating over she single electron energies and angles, and summing over the final-state spins
- $\langle m_\nu \rangle = | \sum_k m_k U_{ek}^2 |$ effective mass of the Majorana neutrino, U_{ek} being the lepton mixing matrix

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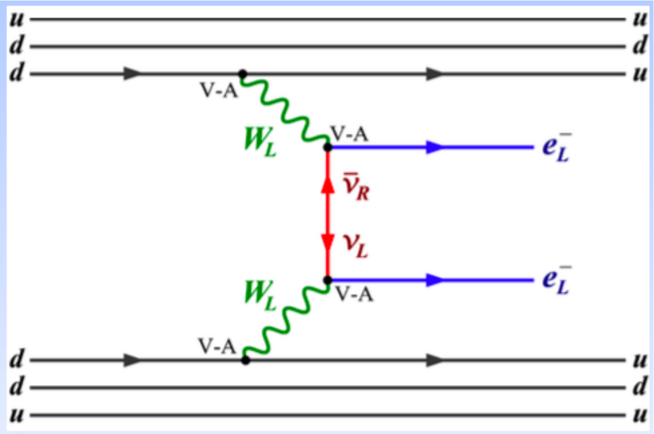

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$$M^{0\nu} = M_{GT}^{0\nu} - \left(\frac{g_V}{g_A}\right)^2 M_F^{0\nu} - M_T^{0\nu}$$

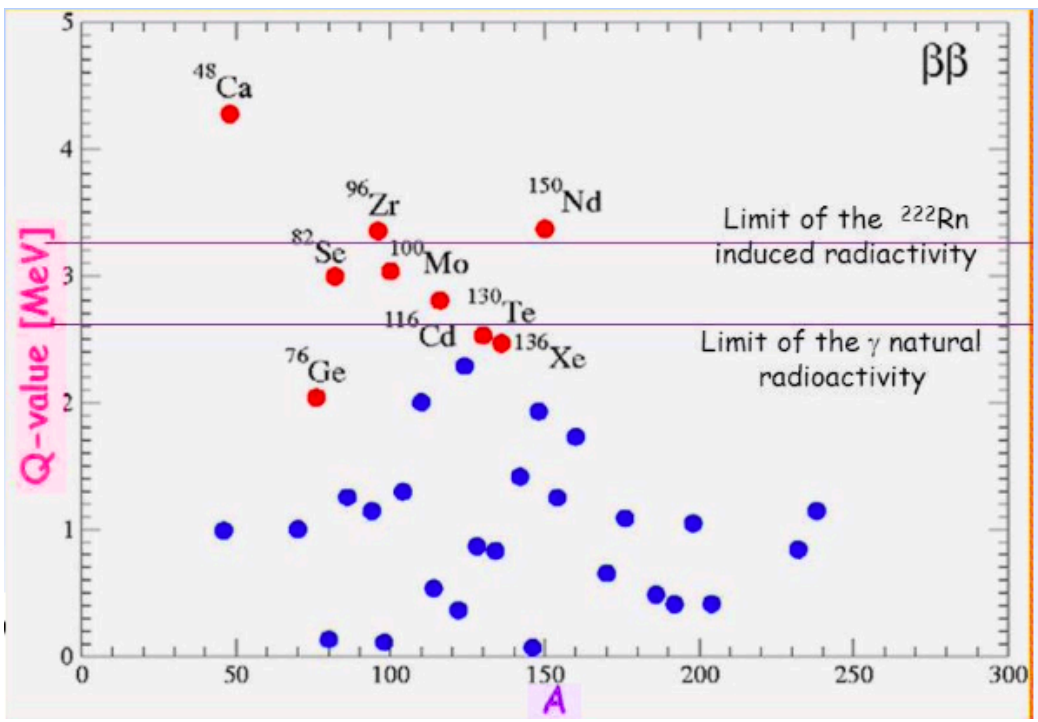
$$M_\alpha^{0\nu} = \sum_k \langle p_1 p_2 | O_\alpha(k) | n_1 n_2 \rangle \langle f | a_{p_1}^\dagger a_{n_1} | k \rangle \langle k | a_{p_2}^\dagger a_{n_2} | i \rangle$$

The neutrinoless double β-decay

It is necessary to locate the nuclei that are the best candidates to detect the $0\nu\beta\beta$-decay

The main factors to be taken into account are:

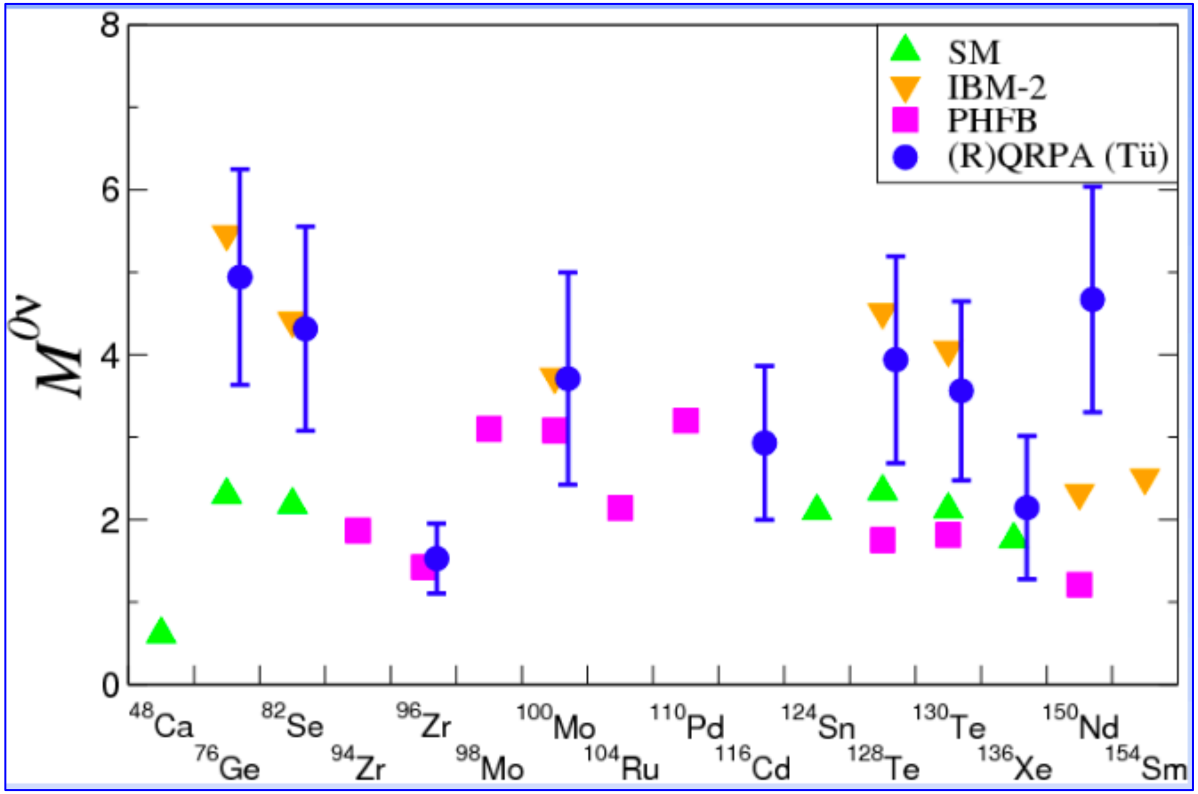
- the Q-value of the reaction;
- the phase-space factor $G^{0\nu}$;
- The isotopic abundance.



- First group: ^{76}Ge ^{130}Te and ^{136}Xe
- Second group: ^{82}Se, ^{100}Mo and ^{116}Cd
- Third group: ^{48}Ca, ^{96}Zr and ^{150}Nd

The neutrinoless double β-decay

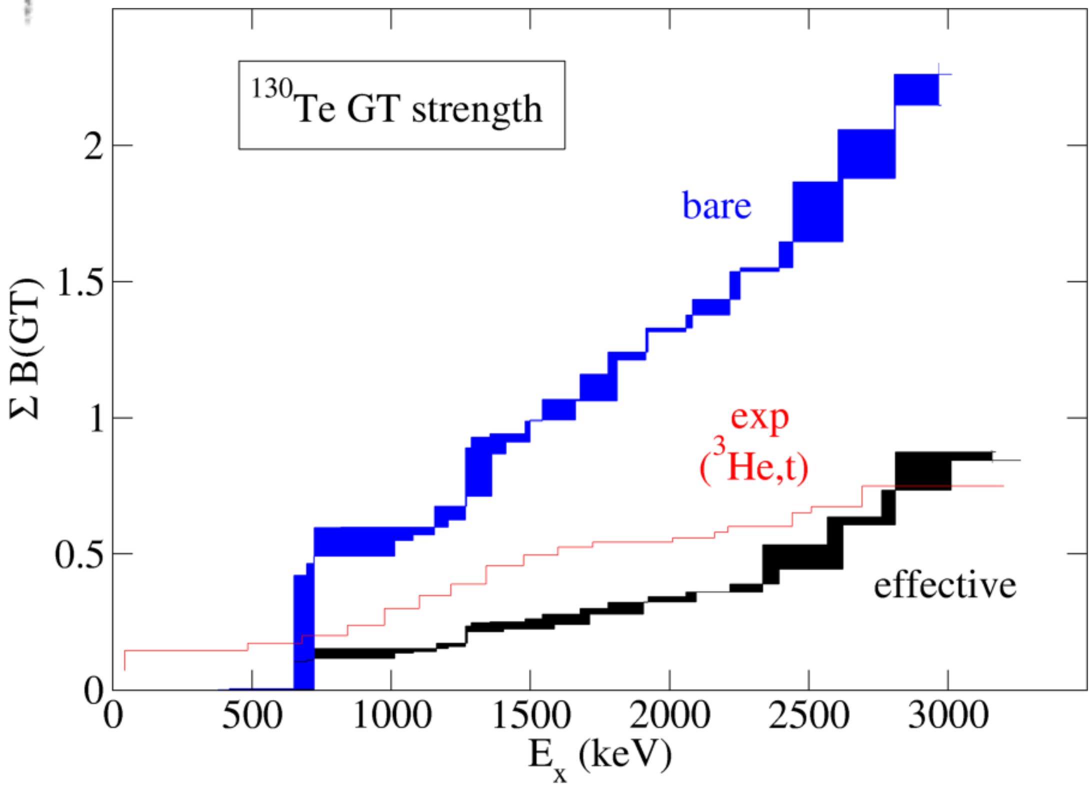
To describe the nuclear properties detected in the experiments, one needs to resort to nuclear structure models.



The spread of nuclear structure calculations evidences inconsistencies among results obtained with different models

^{130}Te ⟶ ^{130}Xe 2ν nuclear matrix element

$$M_{2\nu}^{GT} = \sum_n \frac{\langle 0_f^+ \| \vec{\sigma}\tau^- \| 1_n^- \rangle \langle 1_n^- \| \vec{\sigma}\tau^- \| 0_i^+ \rangle}{E_n + E_0}$$



Coraggio L. et al. Phys Rev. C **95**, 064324 (2017)

^{130}Te → ^{130}Xe nuclear matrix element

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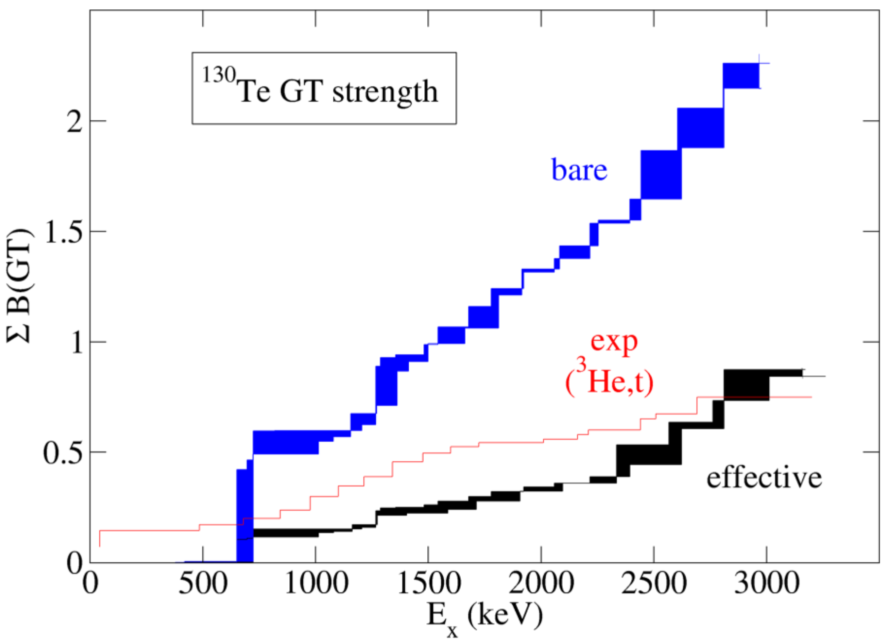
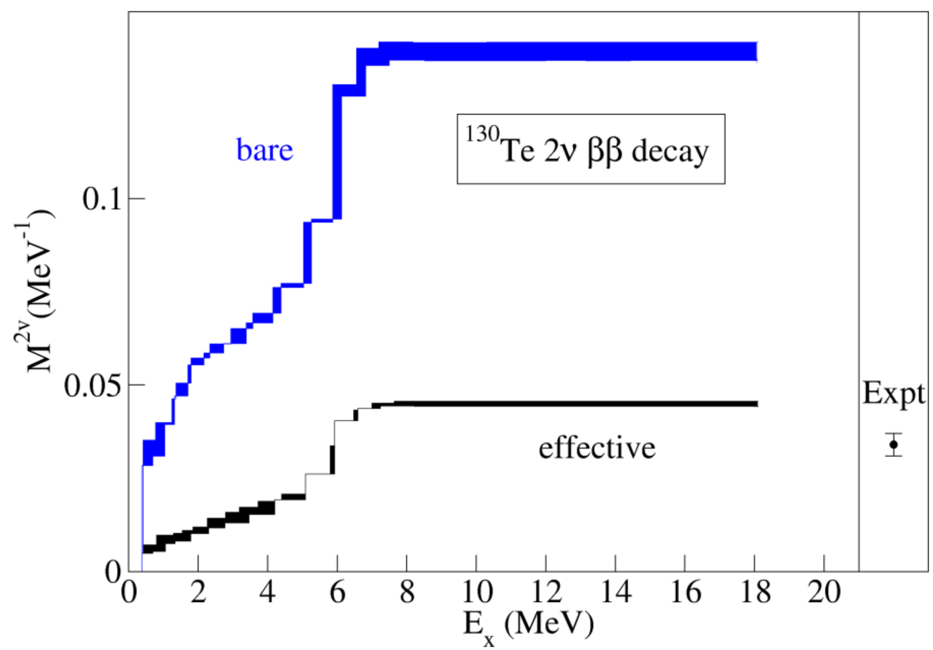
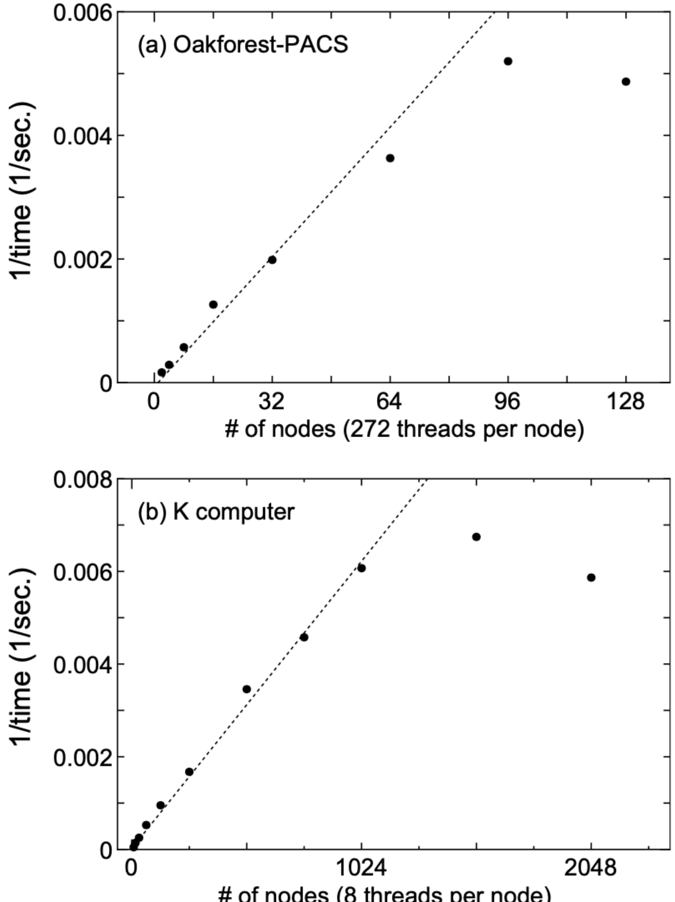


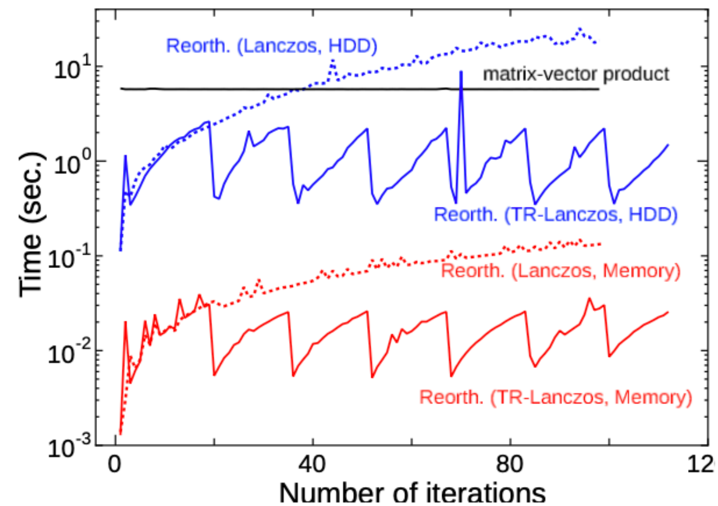


Coraggio L. et al. Phys Rev. C **95**, 064324 (2017)

KSHELL code

Utilizing 8192 cores at FX10 supercomputer at the University of Tokyo, it takes 145 seconds to compute the ground-state energy of 56Ni in pf-shell, corresponding the eigenvalue problem of 1,087,455,228-dimension matrix.





N. Shimizu arXiv:1902.02064 [nucl-th]

ISCRA Class B Project NLDBD

Assigned budget: 125.000 standard hours on MARCONI

Assigned budget: 250.000 standard hours on GALILEO

On going: the ^{100}Mo decay

$$M_{2\nu}^{GT} = \sum_n \frac{\langle 0_f^+ \parallel \vec{\sigma}\tau^- \parallel 1_n^- \rangle \langle 1_n^- \parallel \vec{\sigma}\tau^- \parallel 0_i^+ \rangle}{E_n + E_0}$$

$$|i\rangle = ^{100}Mo \longrightarrow |1_n^+\rangle = ^{100}Tc \longrightarrow |f\rangle = ^{100}Ru$$

^{100}Tc: 1$^+$ states up to 2MeV

Dimension of the Ham=407900809

Memory for one global Lanczos vector: 3.039 GB

Number of Lanczos vector allocated in Memory: 667

Memory required for the calculation: 2TB

With 1 node, 144 threads, time=10h:43m:13s

@MetaCentrum (CZ)

Summary and Conclusions

- The Role of three-body forces is fundamental for describing the spectra of p and fp shell nuclei within RSM.
- RSM calculations provide a satisfactory description of observed GT-strength distributions and $2\nu2\beta$ NME $2\nu\beta\beta$

Perspectives

3N force:

Calculation of 3N matrix elements for heavier systems

$2\nu\beta\beta$

- Role of real three-body forces and two-body currents (present collaboration with Pisa group)
- Evaluation of the contribution of three-body correlations (blocking effect)

$0\nu\beta\beta$

- Beyond closure approximation

Thank you for the attention!