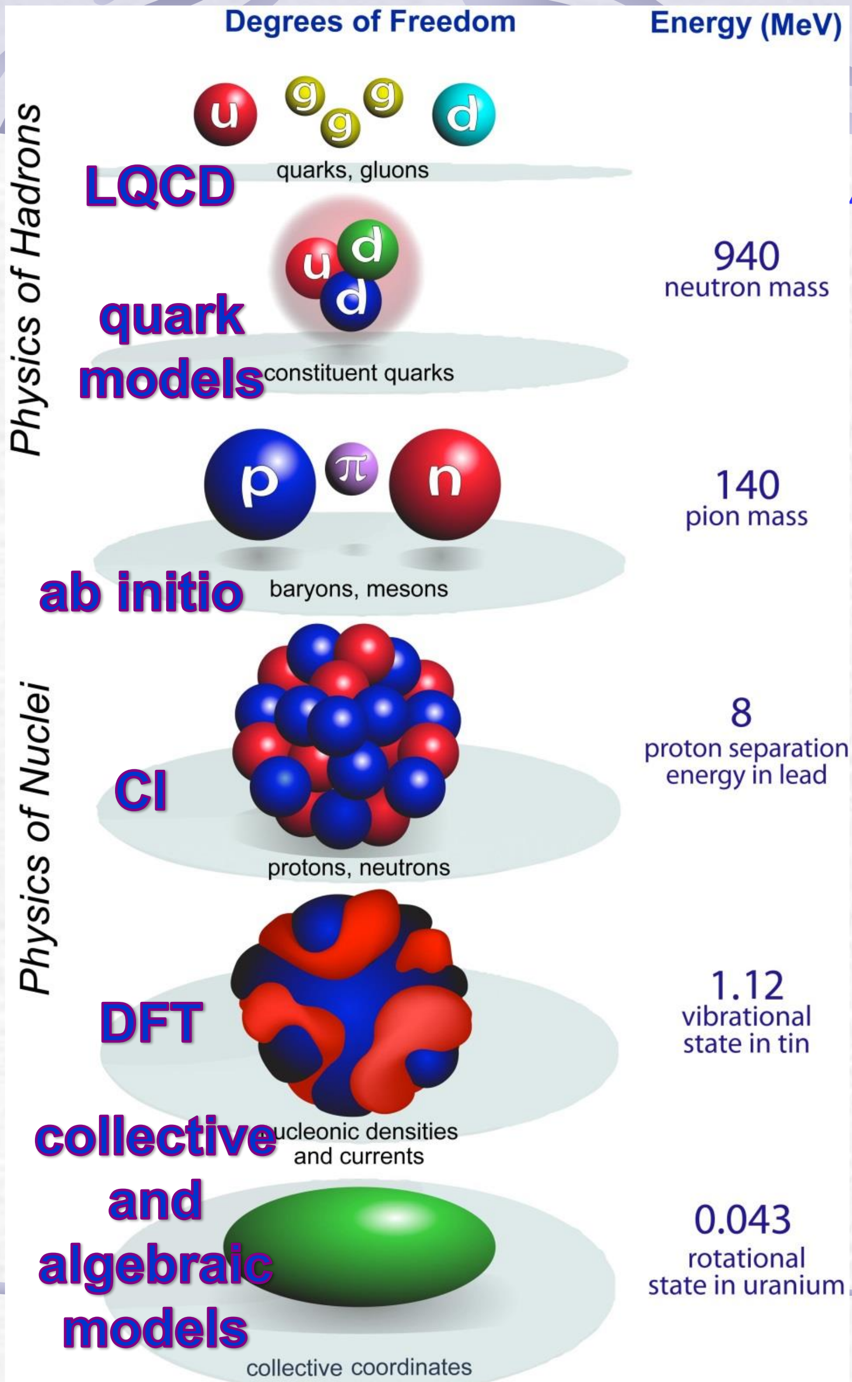
Isospin symmetry for nuclear spectroscopy and the calculations of super-allowed beta-decay

Wojciech Satuła

In colaboration with: Jacek Dobaczewski, Paweł Bączyk, Maciek Konieczka, Koichi Sato, Takashi Nakatsukasa

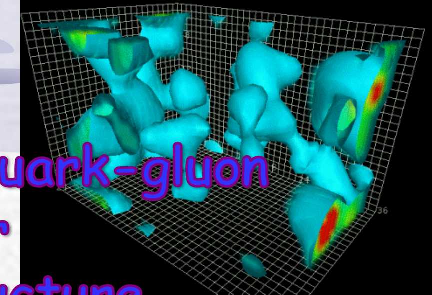
<u>Isospin symmetry</u> studies using SR-DFT and MR-DFT-rooted approaches:

- **new developments:**
  - **DFT-rooted NCCI involving angular-momentum and isospin projections**
  - **pn-mixed SR functionals**
  - **charge-dependent zero-range forces (functionals)**
- **physics highlights**
  - **nuclear structure and beta decays**
  - **strong-force isospin symmetry breaking effects (TDE/MDE)**



Resolution

Effective (field) theories



Hot and dense quark-gluon matter

Hadron structure

Hadron-Nuclear interface

Nuclear structure & reactions

Third Law of Progress in Theoretical Physics by Weinberg:

"You may use any degrees of freedom you like to describe a physical system, but if you use the wrong ones, you'll be sorry!"

Effective or low-energy (low-resolution) theory explores separation of scales. Its formulation requires:

in coordinate space:

→**define R to separate short- and long-distance physics**

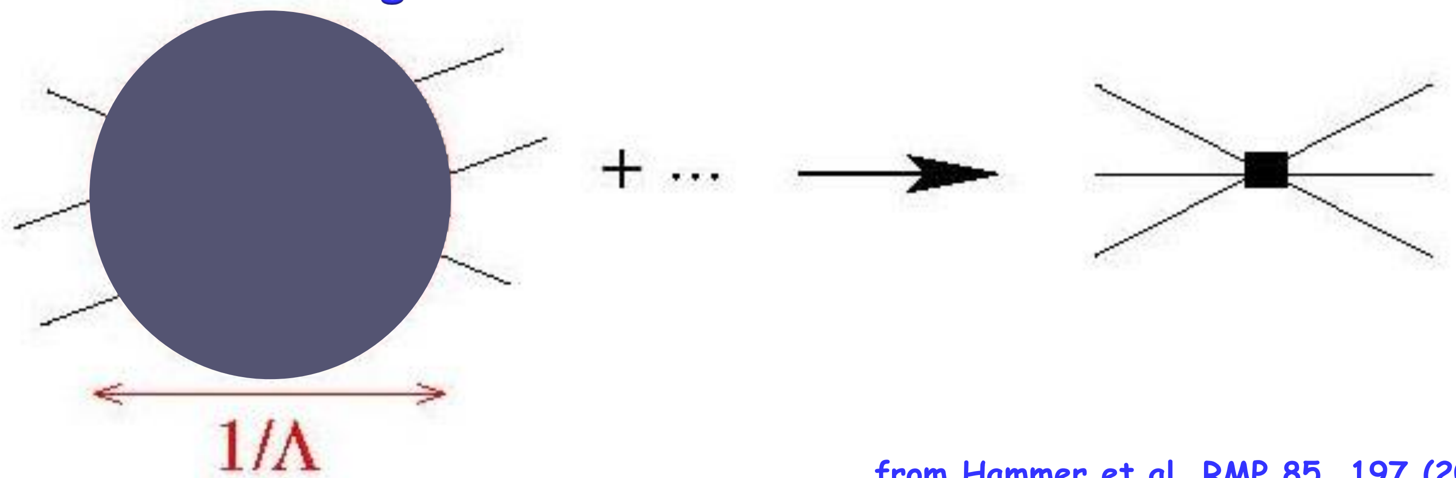
or, in momentum space:

→**define Λ ($1/R$) to separate low and high momenta**

replace (complicated and, in nuclear physics, unknown) short distance (or high momentum) physics by a LCP (local correcting potential)

(there is a lot of freedom how this is done concerning both the scale and form but physics is (should be!) independent on the scheme!!!)

emergence of 3NF due to finite resolution



from Hammer et al. RMP 85, 197 (2013)

Nuclear effective theory for EDF (nuclear DFT)

is based on the same simple and very intuitive assumption that low-energy nuclear theory is independent on high-energy dynamics

ultraviolet cut-off Λ →

$$v_S(q^2) \approx v_S(0) + v_S^{(1)}(0)q^2 + v_S^{(2)}(0)q^4 \ldots ,$$

Fourier

regularization

Coulomb

Long-range part of the NN interaction (must be treated exactly!!!)

hierarchy of scales: $v_{eff}(\boldsymbol{r}) \approx v_{long}(\boldsymbol{r})$

$$+ca^2\delta_a(\boldsymbol{r})$$
$$+d_1a^4\boldsymbol{\nabla}^2\delta_a(\boldsymbol{r}) + d_2a^4\boldsymbol{\nabla}\delta_a(\boldsymbol{r})\boldsymbol{\nabla}$$
$$+\ldots$$
$$+g_1a^{n+2}\boldsymbol{\nabla}^n\delta_a(\boldsymbol{r}) + \ldots ,$$

local correcting potential

$$\frac{2r_oA^{1/3}}{r_o} \sim 2A^{1/3} \sim 10$$

where $\delta_a(\boldsymbol{r})$ denotes an arbitrary Dirac-delta model

$$\delta_a(\boldsymbol{r}) \equiv \frac{e^{-\boldsymbol{r}^2/2a^2}}{(2\pi)^{3/2}a^3} .$$

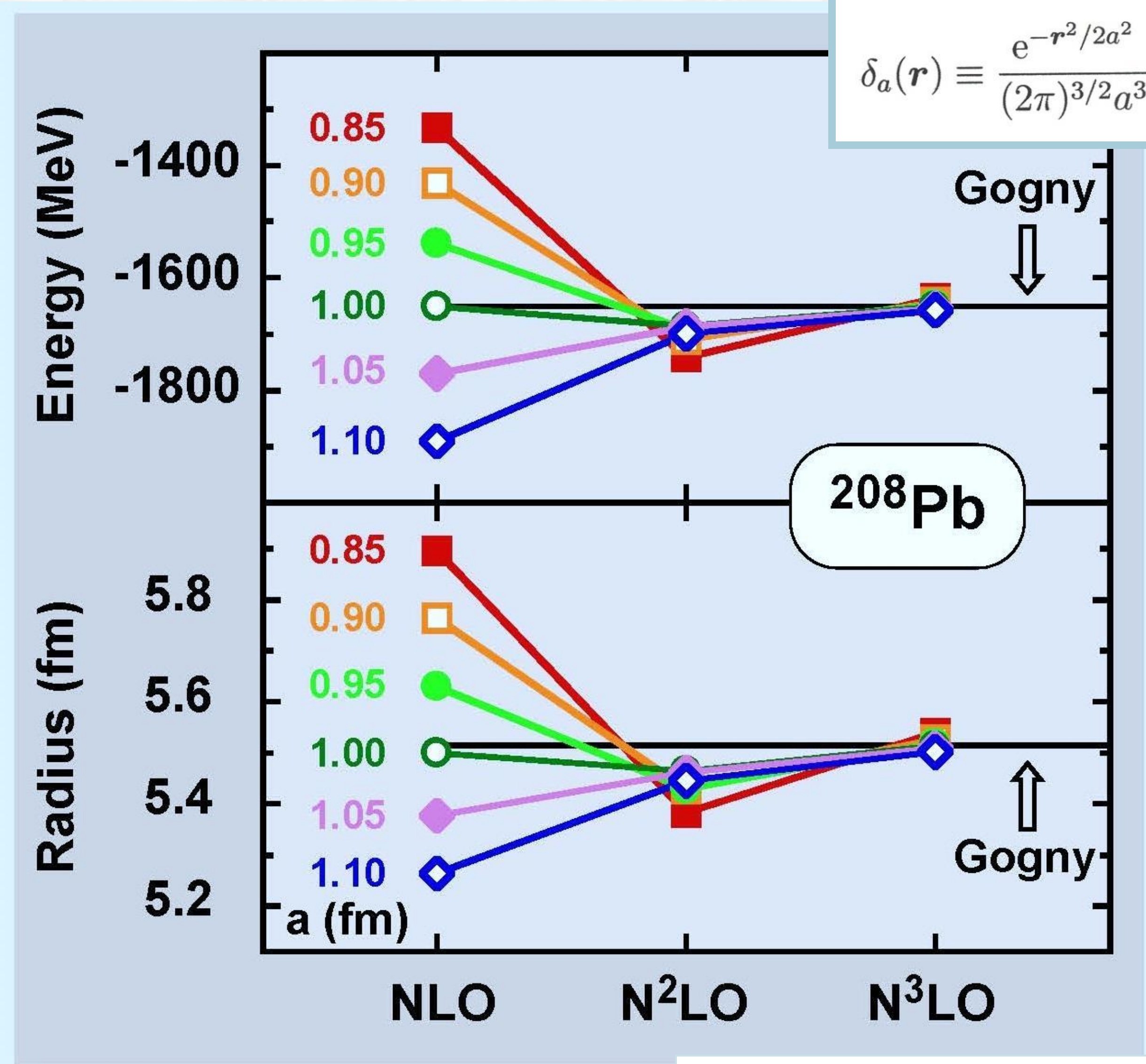
Gaussian regulator

There exist an „infinite” number of equivalent realizations of effective theories

J. Dobaczewski, K. Bennaceur, F. Raimondi, J. Phys. G 39, 125103 (2012)

Proof of principle of the regularization range (scale) independence for the gaussian-regularized density-independent EDFs

$$\delta_a(\boldsymbol{r}) \equiv \frac{e^{-\boldsymbol{r}^2/2a^2}}{(2\pi)^{3/2}a^3}.$$



J. Dobaczewski, K. Bennaceur, F. Raimondi, J. Phys. G 39, 125103 (2012)

Skyrme interaction - specific (local) realization of the nuclear effective interaction: $\lim_{a \to 0} \delta_a$

$$
\begin{aligned}
v(1,2) = & \; t_0(1 + x_0 \hat{P}_\sigma)\delta(\boldsymbol{r}_{12}) \\
& + \frac{1}{2} t_1 (1 + x_1 \hat{P}_\sigma) \left(\hat{\boldsymbol{k}}'^2 \delta(\boldsymbol{r}_{12}) + \delta(\boldsymbol{r}_{12}) \hat{\boldsymbol{k}}^2 \right) \\
& + t_2 (1 + x_2 \hat{P}_\sigma) \hat{\boldsymbol{k}}' \delta(\boldsymbol{r}_{12}) \hat{\boldsymbol{k}} \\
& + \frac{1}{6} t_3 (1 + x_3 \hat{P}_\sigma) \rho_0^\gamma(\boldsymbol{R}) \delta(\boldsymbol{r}_{12}) \\
& + i W_0 (\boldsymbol{\sigma}_1 + \boldsymbol{\sigma}_2) \left(\hat{\boldsymbol{k}}' \times \delta(\boldsymbol{r}_{12}) \hat{\boldsymbol{k}} \right) ,
\end{aligned}
$$

LO

NLO

density dependence

spin-orbit

10(11) parameters

$\boldsymbol{r}_{12} = \boldsymbol{r}_1 - \boldsymbol{r}_2$; $\boldsymbol{R} = (\boldsymbol{r}_1 + \boldsymbol{r}_2)/2$; $\hat{\boldsymbol{k}} = \frac{1}{2i}(\boldsymbol{\nabla}_1 - \boldsymbol{\nabla}_2)$ $\hat{\boldsymbol{k}}' = -\frac{1}{2i}(\boldsymbol{\nabla}_1 - \boldsymbol{\nabla}_2)$ $\hat{P}_\sigma = \frac{1}{2}(1 + \boldsymbol{\sigma}_1 \boldsymbol{\sigma}_2)$

relative momenta

spin exchange

Having defined the generator, the nuclear EDF is built using mean-field (HF or Kohn-Sham) methodology

$$E[\rho(\vec{r}_1, \vec{r}_2)] = \iint d\vec{r}_1 d\vec{r}_2 \, \mathcal{H}(\rho(\vec{r}_1, \vec{r}_2))$$

$$\mathcal{H}(\rho(\vec{r}_1, \vec{r}_2)) = V(\vec{r}_1 - \vec{r}_2) \left[\rho(\vec{r}_1)\rho(\vec{r}_2) - \rho(\vec{r}_1, \vec{r}_2)\rho(\vec{r}_2, \vec{r}_1) \right]$$

direct term exchange term

Skyrme local energy density functional

Skyrme (hadronic) interaction conserves such symmetries like:

→ rotational (spherical) LS symmetry LS LS

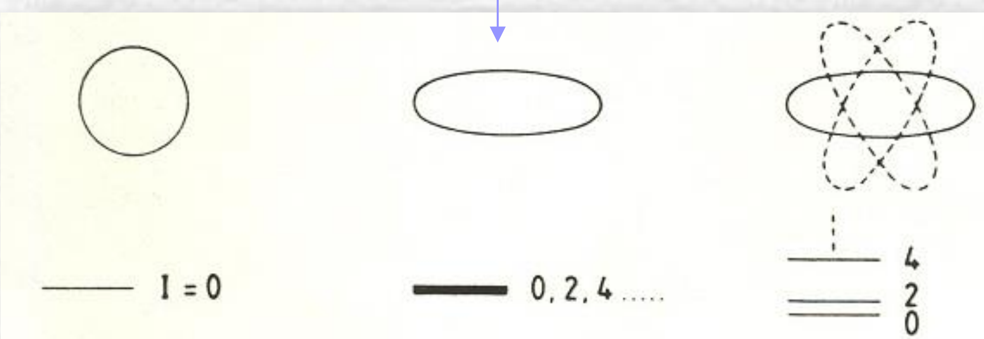
→ isospin symmetry: $V_{nn} = V_{pp} = V_{np}$ (in reality approximate)

→ particle numer, parity…

… but the self-consistent solutions (Slater dets) break them (are deformed) spontaneously

$$\hat{R}(\boldsymbol{Q})|\varphi(\boldsymbol{Q}_0)\rangle = |\varphi(\boldsymbol{Q}')\rangle$$

$$\langle\varphi|\hat{H}|\varphi\rangle = \langle\varphi|\hat{R}^{\dagger}(\boldsymbol{Q})\hat{H}\hat{R}(\boldsymbol{Q})|\varphi\rangle$$



Advantage:
SSB is an efficient way to introduce correlations into a single Slater determinant

Disadvantage:
Symmetry must be restored (except for bulk observables) in order to compare theory to data

Isospin symmetry restoration

There are two sources of the isospin symmetry breaking:
- unphysical, caused solely by the HF approximation → Engelbrecht & Lemmer, PRL24, (1970) 607
- physical, caused mostly by Coulomb interaction
  (also, but to much lesser extent, by the strong-force isospin non-invariance)

- Find self-consistent HF solution (including Coulomb) → deformed Slater determinant |HF>:

$$|\mathrm{HF}\rangle = \sum_{T\geq|T_z|} b_{T,T_z}|\alpha;T,T_z\rangle$$

- Apply the isospin projector:

See: Caurier, Poves & Zucker, PL 96B, (1980) 11; 15

$$\hat{P}^T_{T_zT_z} = \frac{2T+1}{2}\int_0^\pi d\beta \sin\beta d^{T*}_{T_zT_z}(\beta)\hat{R}(\beta)$$

in order to create good isospin „basis":

$$|\alpha;T,T_z\rangle = \frac{1}{b_{T,T_z}}\hat{P}^T_{T_zT_z}|\mathrm{HF}\rangle$$

- Diagonalize total Hamiltonian in „good isospin basis" $|\alpha,T,T_z\rangle$ → takes physical isospin mixing

$$\sum_{T'\geq|T_z|}\langle\alpha;T,T_z|\hat{H}|\alpha;T',T_z\rangle a^n_{T',T_z} = E^{\mathrm{AR}}_{n,T_z} a^n_{T,T_z}$$

$$|\alpha;n,T_z\rangle = \sum_{T\geq|T_z|} a^n_{T,T_z}|\alpha;T,T_z\rangle,$$

$$\alpha_C^{\mathrm{AR}} = 1 - |a^{n=1}_{T=T_z}|^2$$

Transition density is proportional to the inverse of overlap and may therefore lead to singularieties

- **Consider the isospin projection:**

SVD eigenvalues
(diagonal matrix)

$$\tilde{O}(\beta) = \begin{pmatrix} \cos\frac{\beta}{2} I_N & -\sin\frac{\beta}{2} O \\ \sin\frac{\beta}{2} O^\dagger & \cos\frac{\beta}{2} I_Z \end{pmatrix} \xrightarrow{\text{SVD}} O = W D V^\dagger$$

$$\tilde{O}(\beta)^{-1} = \begin{pmatrix} \tilde{W}\dfrac{\cos\frac{\beta}{2}}{\cos^2\frac{\beta}{2} I_N + \sin^2\frac{\beta}{2}\tilde{D}^2}\tilde{W}^\dagger & \tilde{W}\dfrac{\sin\frac{\beta}{2}}{\cos^2\frac{\beta}{2} I_N + \sin^2\frac{\beta}{2}\tilde{D}^2}\tilde{D}\tilde{V}^\dagger \\ V\dfrac{-\sin\frac{\beta}{2}}{\cos^2\frac{\beta}{2} I_Z + \sin^2\frac{\beta}{2} D^2} D W^\dagger & V\dfrac{\cos\frac{\beta}{2}}{\cos^2\frac{\beta}{2} I_Z + \sin^2\frac{\beta}{2} D^2} V^\dagger \end{pmatrix} \rightarrow \tilde{O}(\beta)^{-1}_{ij} \sim \frac{1}{\cos\frac{\beta}{2}}$$

singularity (if any) at $\beta=\pi$ is inherited by a transition density ρ

- - **Power [cos(β/2)] counting for the MR EDF:**

$$\mathcal{H}(\beta) \sim \tilde{\rho}^\eta(\beta)\,\mathrm{Det}\tilde{O}(\beta)$$

$$\int d\beta \sin\beta\, d^T_{T_z T_z}(\beta)\, \tilde{\rho}^\eta(\beta)\, \mathrm{Det}\tilde{O}(\beta) \propto \int d\beta \cos^\xi\frac{\beta}{2}$$

↑ ↑ ↑ ↑

1 + |N-Z| - η + |N-Z|+2k

in the worst case i.e. for N=Z and k=1 → η > 3 to get a singularity

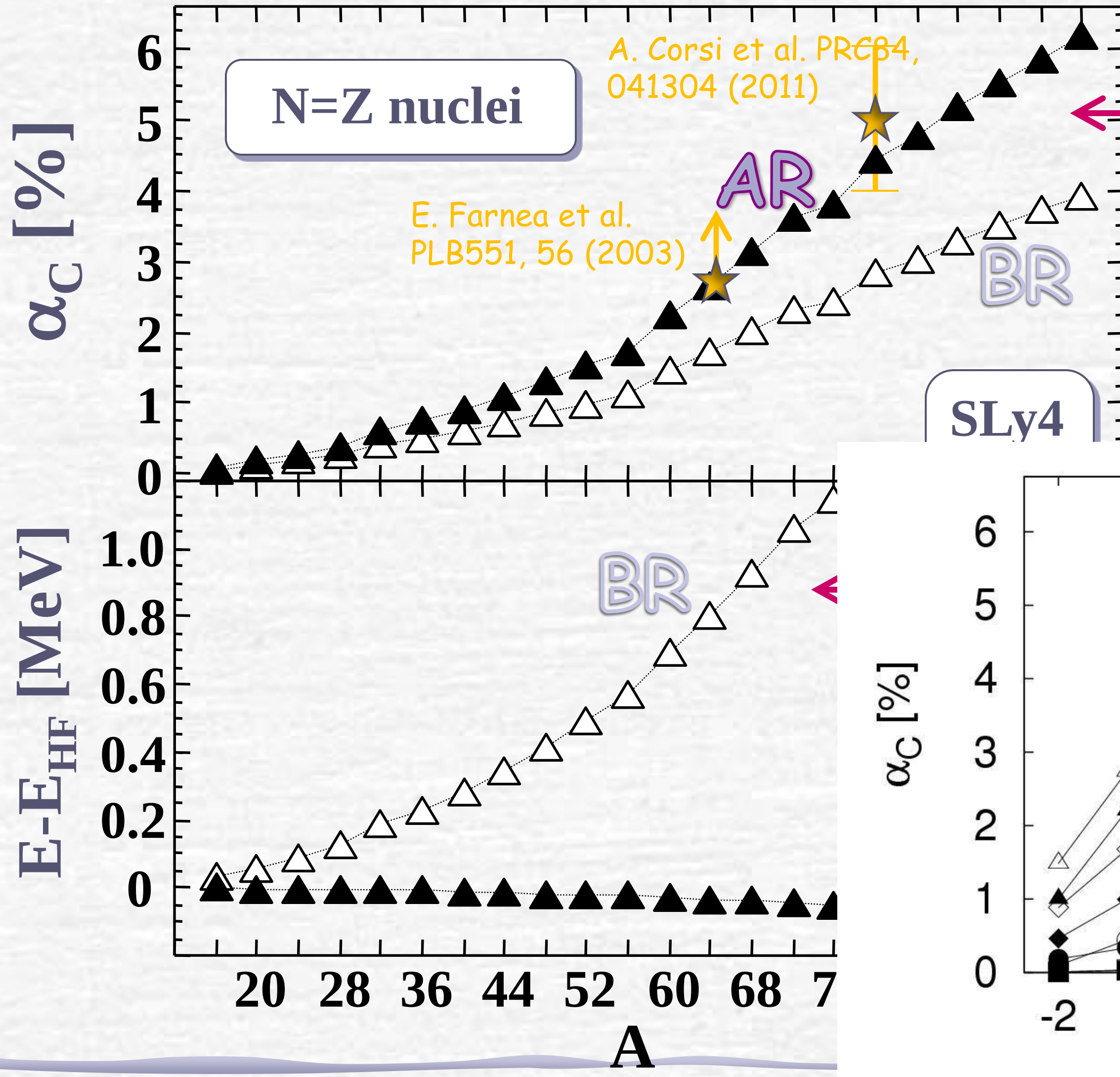
k is a multiplicity of zero singular values

$$|\mathrm{Det}\tilde{O}(\beta)| = |\cos\frac{\beta}{2}|^{N-Z}\prod_{i=1}^{Z}(\cos^2\frac{\beta}{2} + \sin^2\frac{\beta}{2} D_i^2)$$

Isospin-projection is non-singular!!!

W.Satuła, J.Dobaczewski, W.Nazarewicz, M.Rafalski, PRC81 (2010) 054310

Isospin mixing & energy in the ground states of e-e N=Z nuclei:

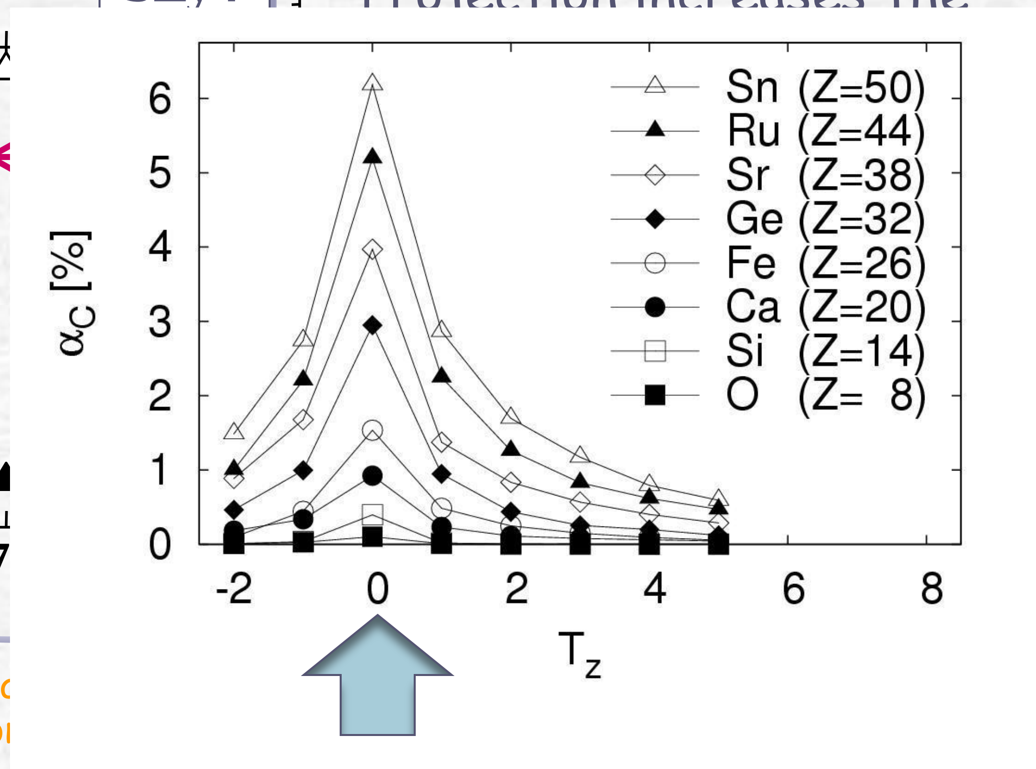


HF tries to reduce the isospin mixing by:

$\Delta\alpha_C$ ~30%

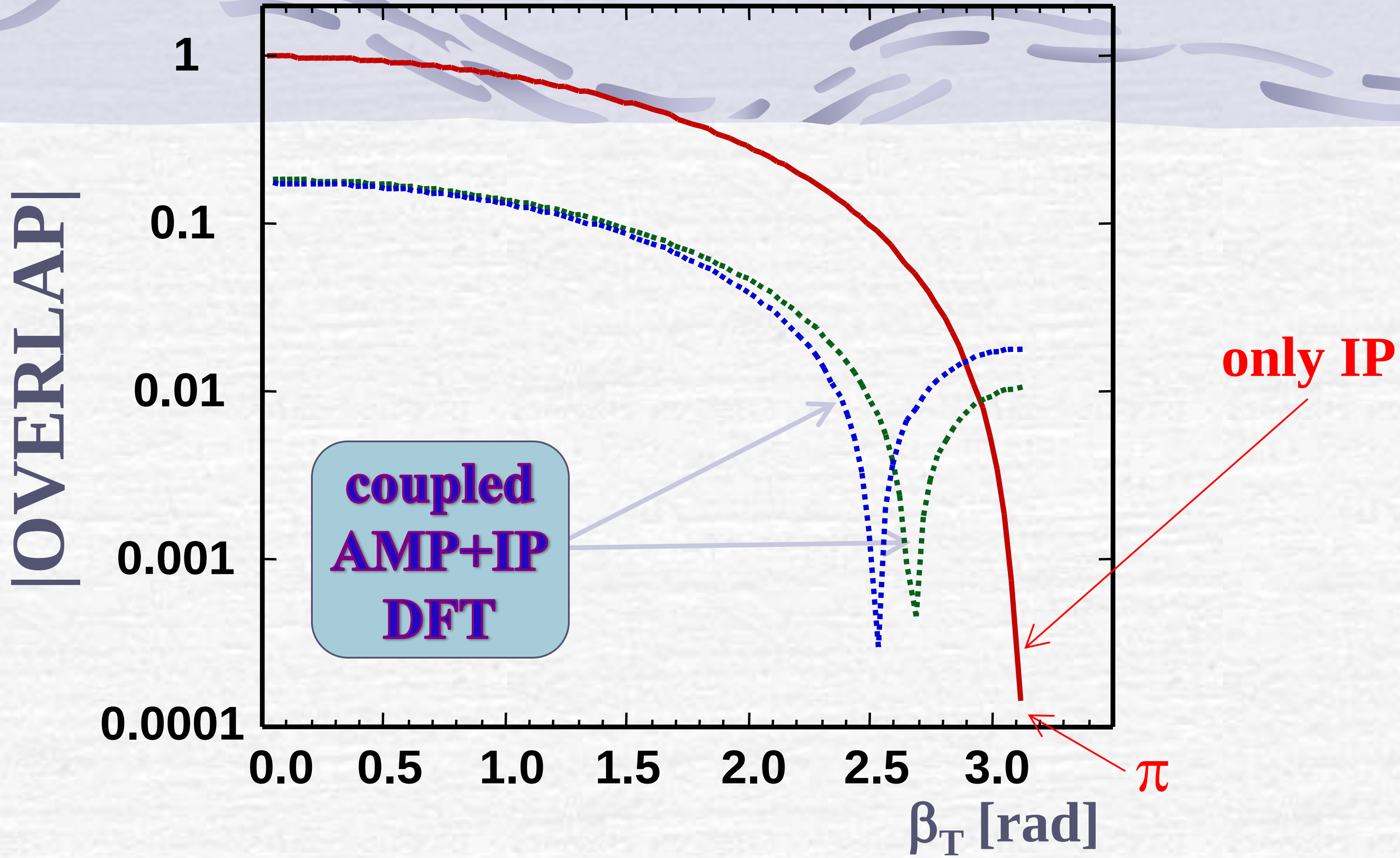
in order to minimize the total energy

Projection increases the



This is not a single Sl

There are no constraints o

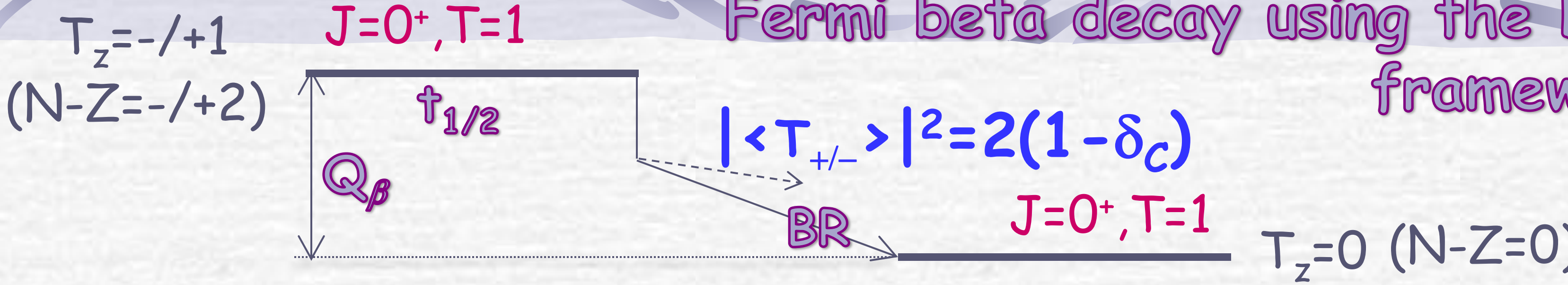


MR DFT is, in general, singular or ill-defined. It can be safely used only with:

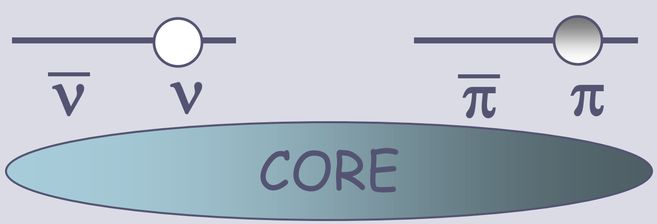
→ EDFs generated by density-independent true interactions like Skyrme SV, Skyrme SLyMR0 or the BDR gaussian functionals…

→ EDFs generated by density-dependent interactions require regularization!!!

How to calculate the superallowed Fermi beta decay using the DFT framework?

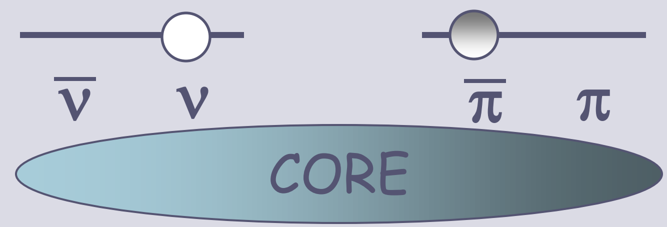


MEAN FIELD



aligned configurations

$\nu\otimes\pi$ or $\bar{\nu}\otimes\bar{\pi}$



anti-aligned configurations

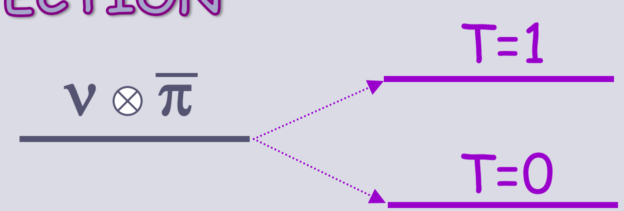
$\nu\otimes\bar{\pi}$ or $\bar{\nu}\otimes\pi$

ISOSPIN PROJECTION

Mean-field can differentiate between

$\nu\otimes\pi$ and $\nu\otimes\bar{\pi}$

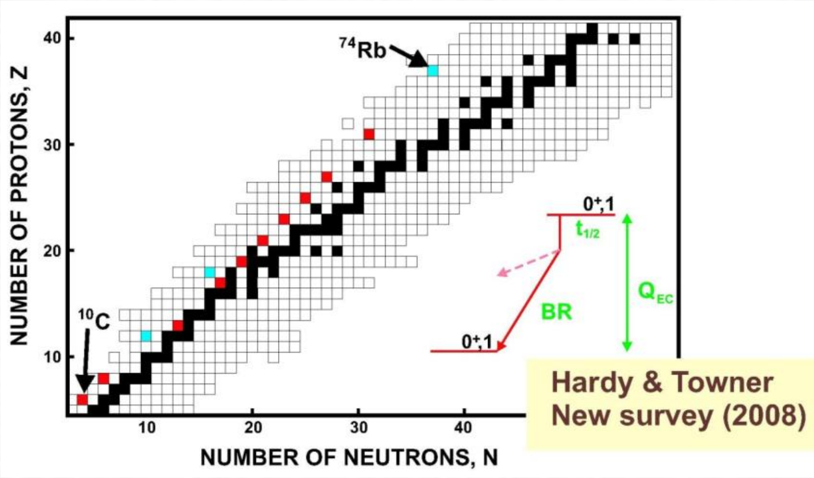
only through time-odd polarizations!



T=1 state
is beyond mean-field!

Testing the fundamental symmetries of nature
Superallowed $0^+ > 0^+$ Fermi beta decays

adopted from J.Hardy's, ENAM'08 presentation



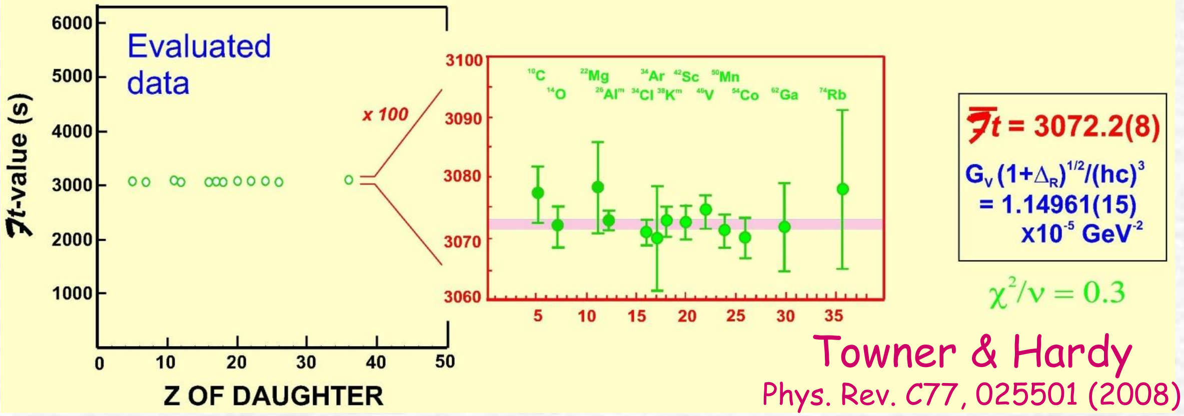
10 cases measured with accuracy ***ft*** ~0.1%
3 cases measured with accuracy ***ft*** ~0.3%

→ test of the CVC hypothesis
(Conserved Vector Current)

INCLUDING RADIATIVE CORRECTIONS

$$\mathcal{F}t = ft\,(1+\delta'_R)[1-(\delta_C-\delta_{NS})] = \frac{K}{2G_V^2\,(1+\Delta_R)}$$

1.5%   0.3% - 1.5%   ~2.4%



Towner & Hardy
Phys. Rev. C77, 025501 (2008)

$|V_{ud}| = 0.97418 \pm 0.00026$

→ test of unitarity of the CKM matrix

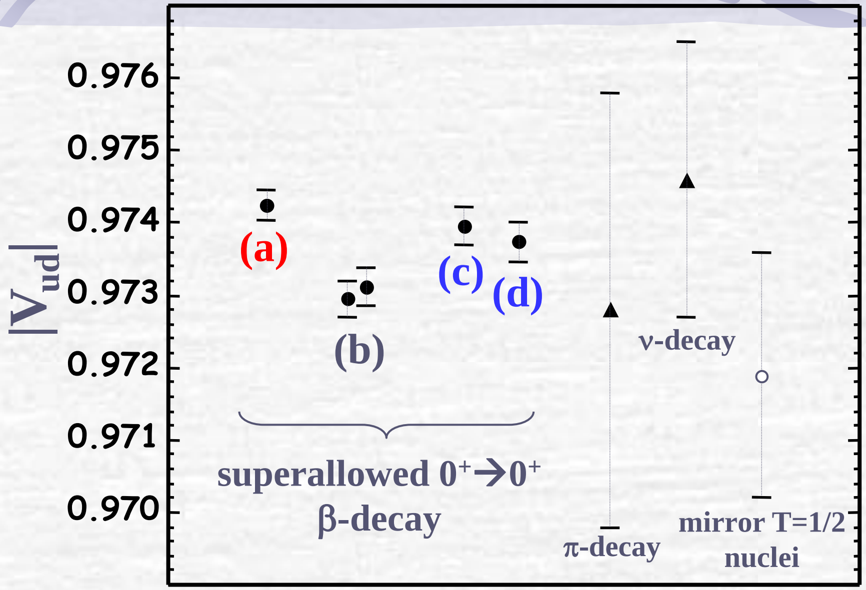
$$|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2=0.9997(6)$$

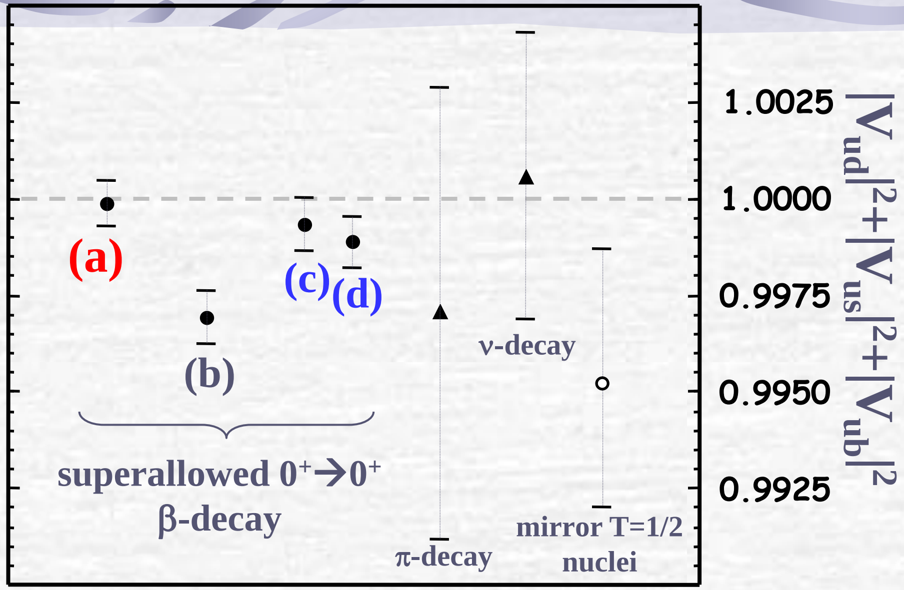
0.9490(4)   0.0507(4)   <0.0001

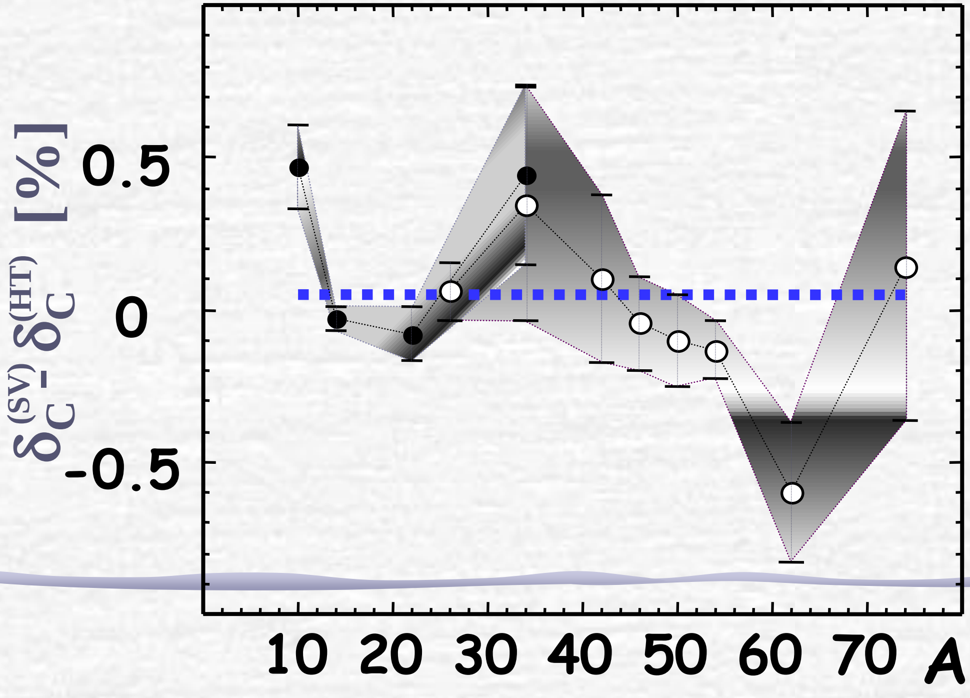
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

weak eigenstates   CKM Cabibbo-Kobayashi-Maskawa   mass eigenstates

$|V_{ud}|$ & the CKM unitarity – world survey







(a) I.S. Towner and J. C. Hardy, Phys. Rev. C **77**, 025501(2008).

(b) H. Liang, N. V. Giai, and J. Meng, Phys. Rev. C **79**,064316 (2009).

(c,d) W. Satuła, J. Dobaczewski, W. Nazarewicz, M. Rafalski Phys. Rev. C **86**, 054314 (2012)

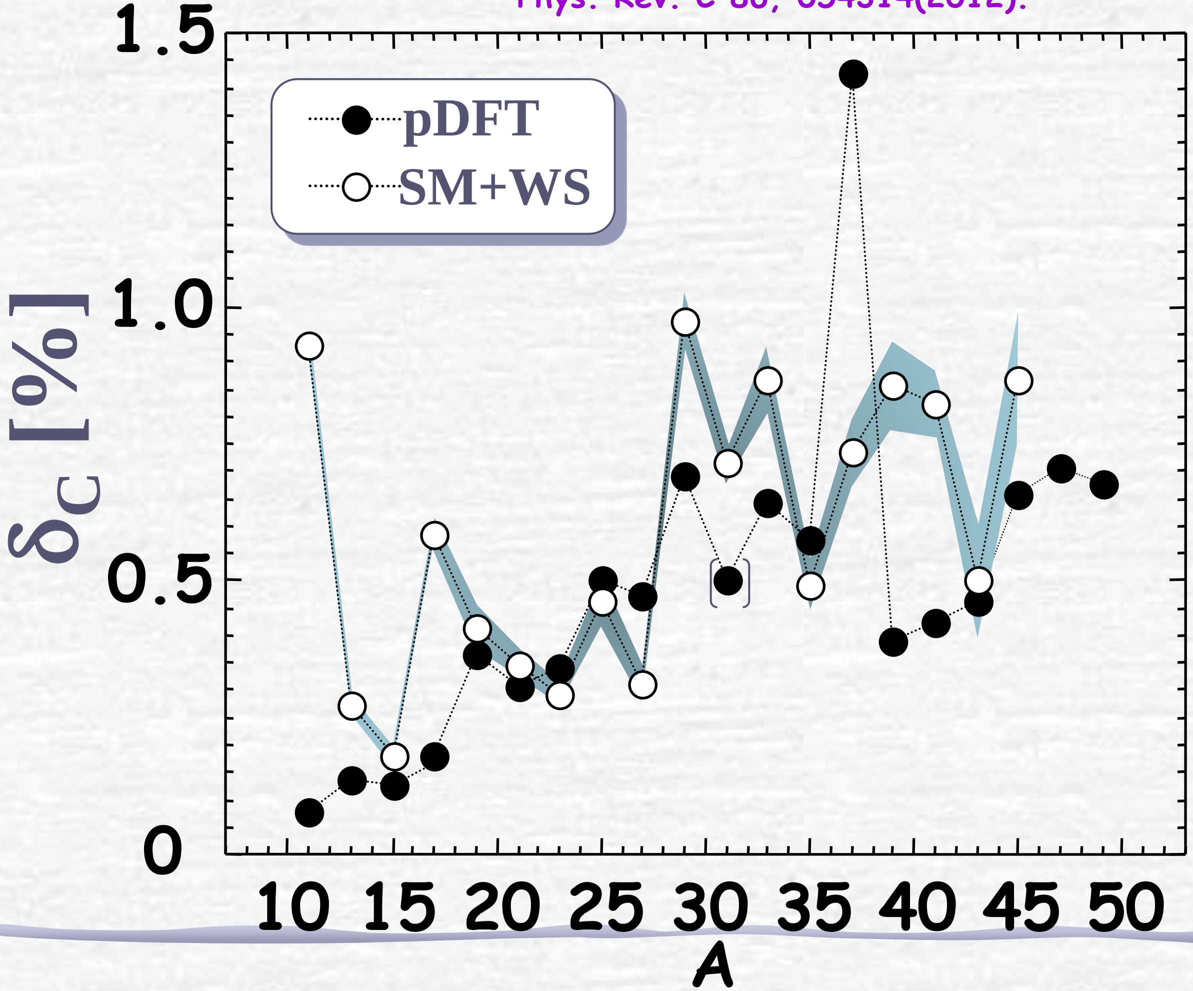
For the NCCI study see: W.Satuła, P.Bączyk, J.Dobaczewski & M.Konieczka, Phys. Rev. C94, 024306 (2016)

O. Naviliat-Cuncic and N. Severijns, Eur. Phys. J. A **42**, 327 (2009); Phys. Rev. Lett. **102**, 142302 (2009).

Testing the fundamental symmetries of nature

Fermi beta decays in T=1/2 mirrors

W. Satuła, J. Dobaczewski, W. Nazarewicz, M. Rafalski
Phys. Rev. C 86, 054314(2012).



See also the NCCI study:

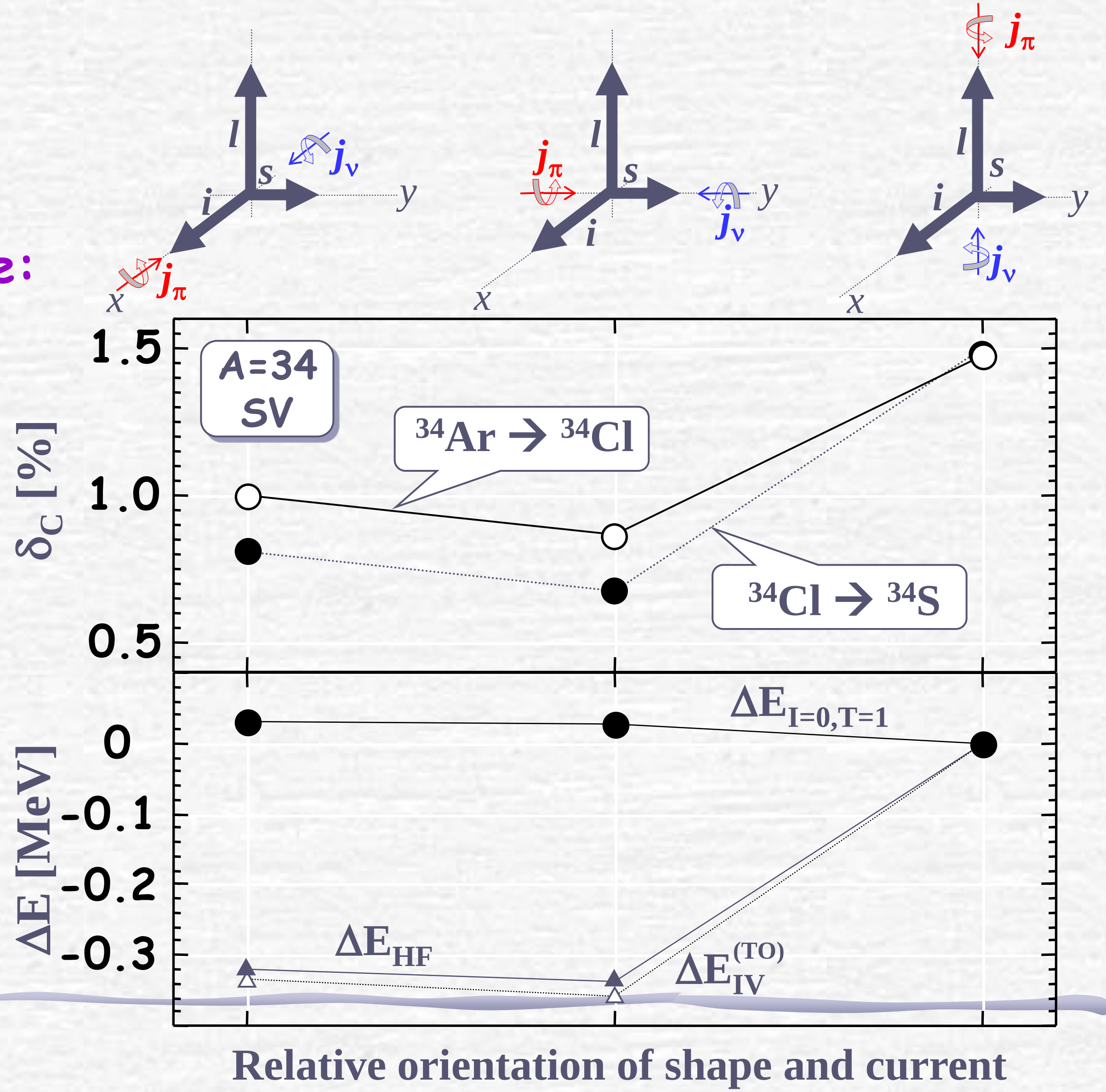
M. Konieczka, P. Bączyk, W. Satuła,
Phys. Rev. C **93**, 042501(R) (2016).

SM+WS results from:
N. Severijns, M. Tandecki,
T. Phalet, and I. S. Towner,
Phys. Rev. C **78**, 055501 (2008).

THEORETICAL UNCERTAINITIES

- Basis-size dependence: ~5%

- Configuration dependence:



- Functional dependence:

SV: Ft=3073.6(12)

V_{ud}=0.97397(27)

$|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2=$
=0.99935(67)

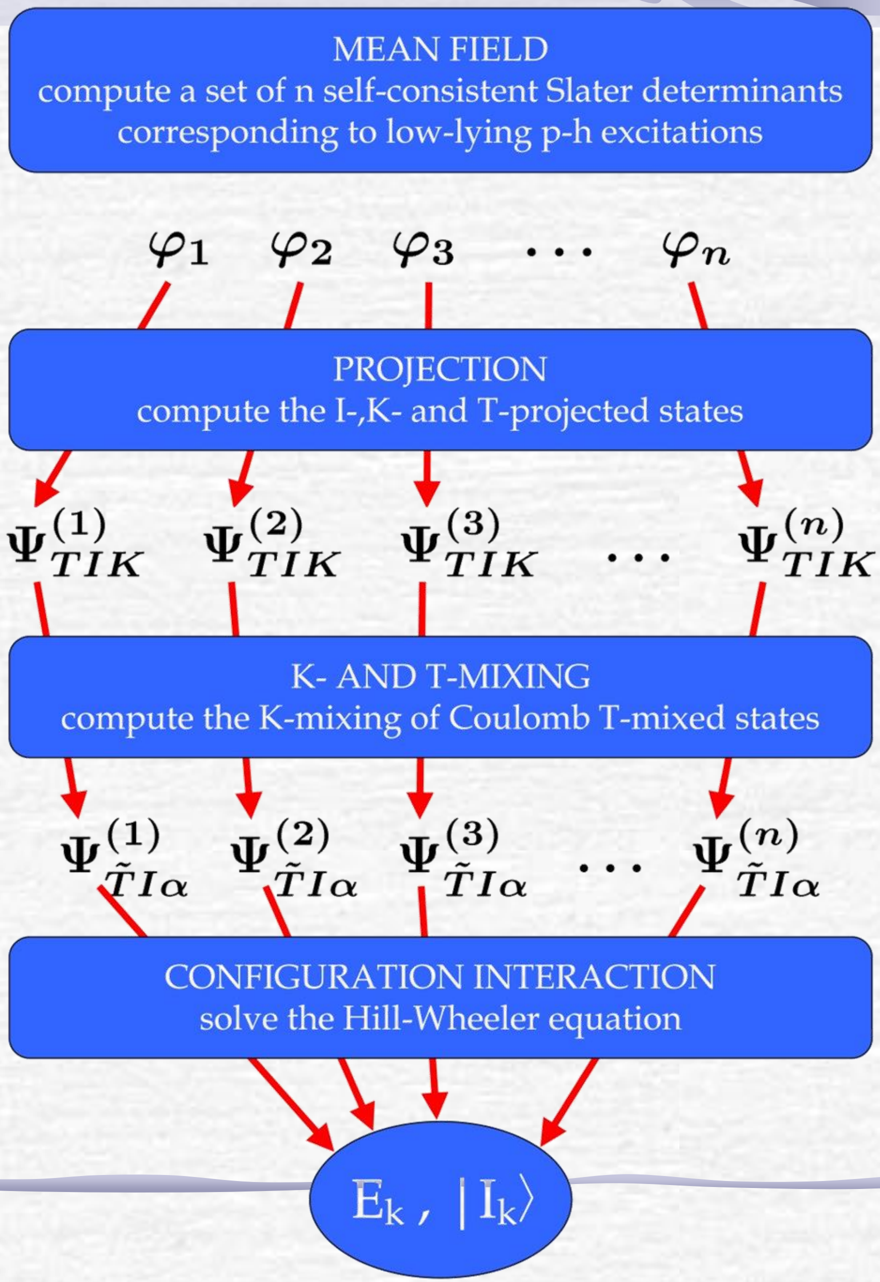
SHZ2: Ft=3075.0(12)

V_{ud}=0.97374(27)

$|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2=$
=0.99890(67)

a_{sym}=42.2MeV!!!

Our DFT-rooted NCCI scheme:



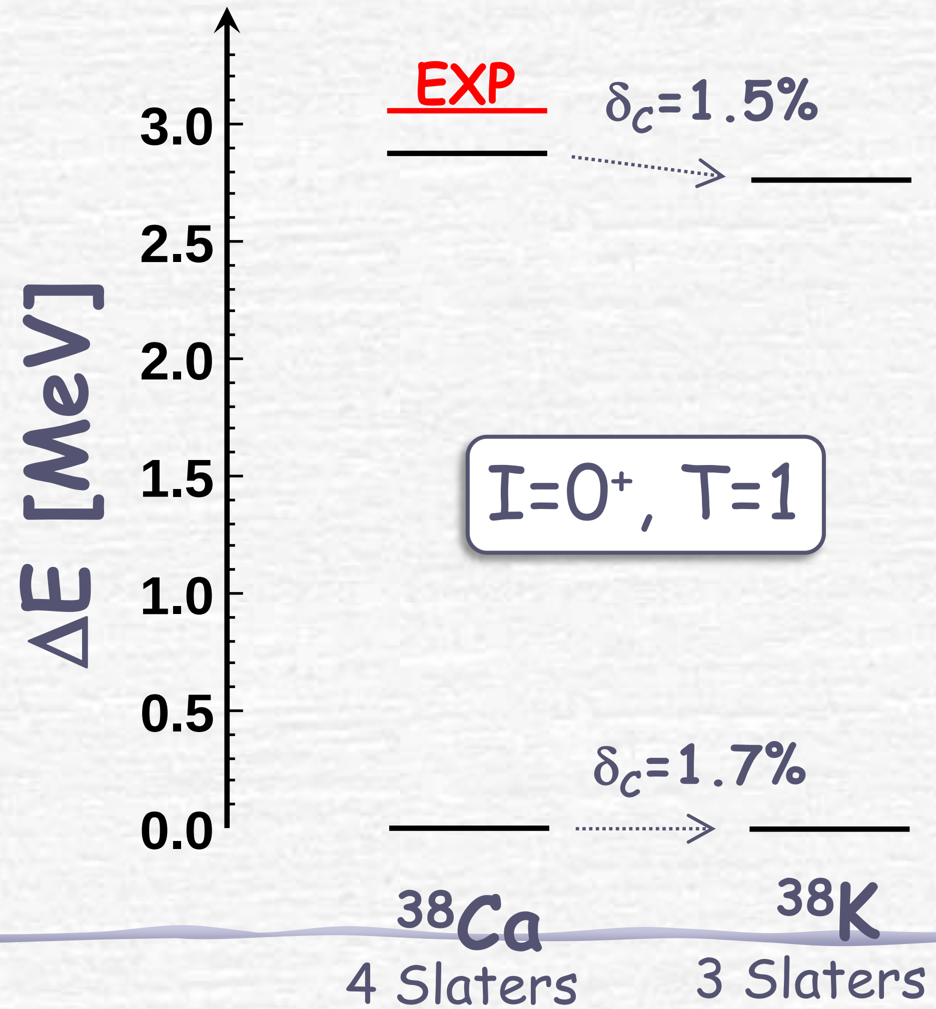
Skyrme SV
(density independent)
is used at this stage

Skyrme SV
(density independent)
is used at this stage

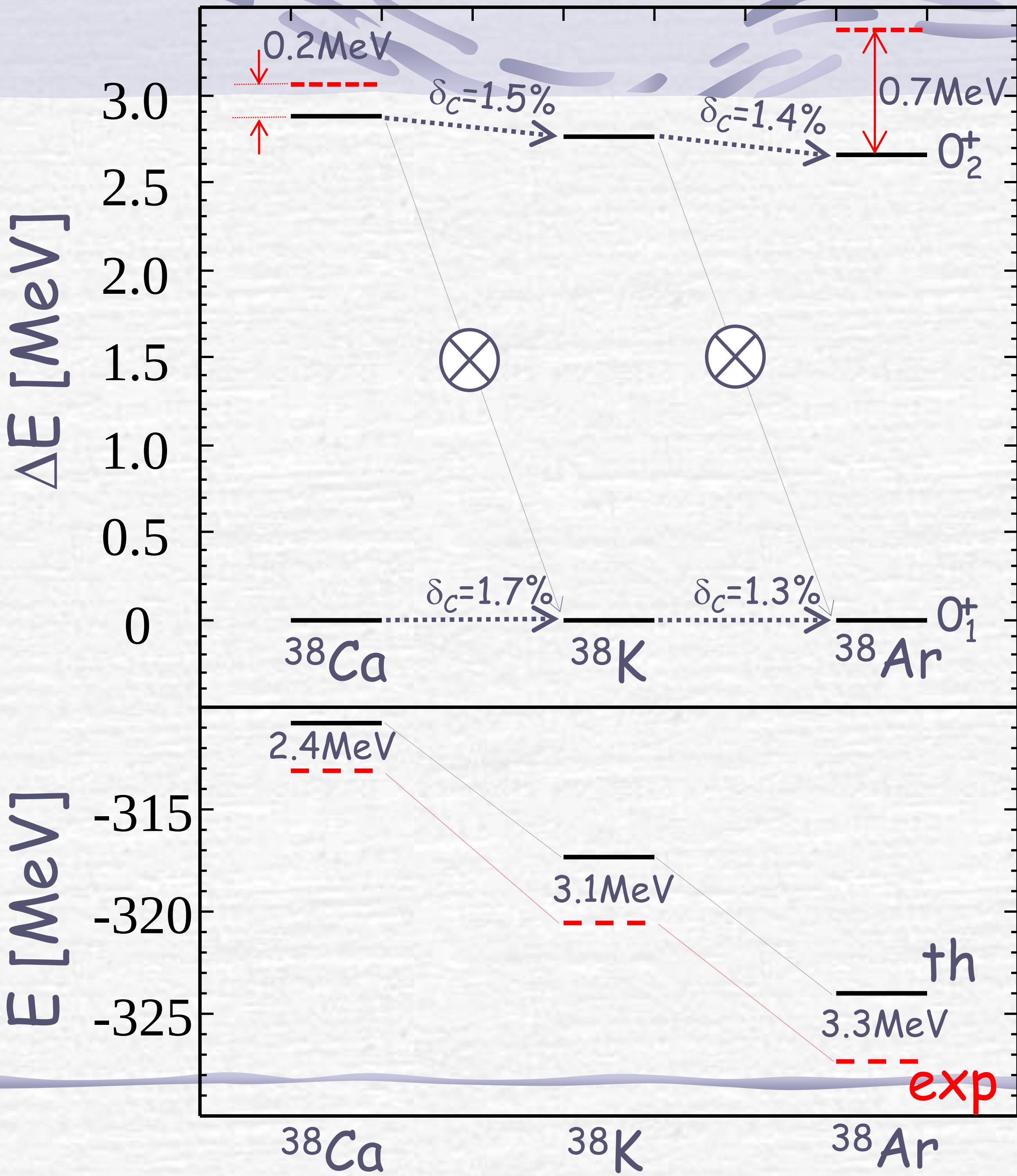
W.Satuła, P.Bączyk, J.Dobaczewski & M.Konieczka, Phys. Rev. C94, 024306 (2016)

A case of A=38 ($^{38}Ca \rightarrow ^{38}K$)

Static approach gives: δ_C=8.9%

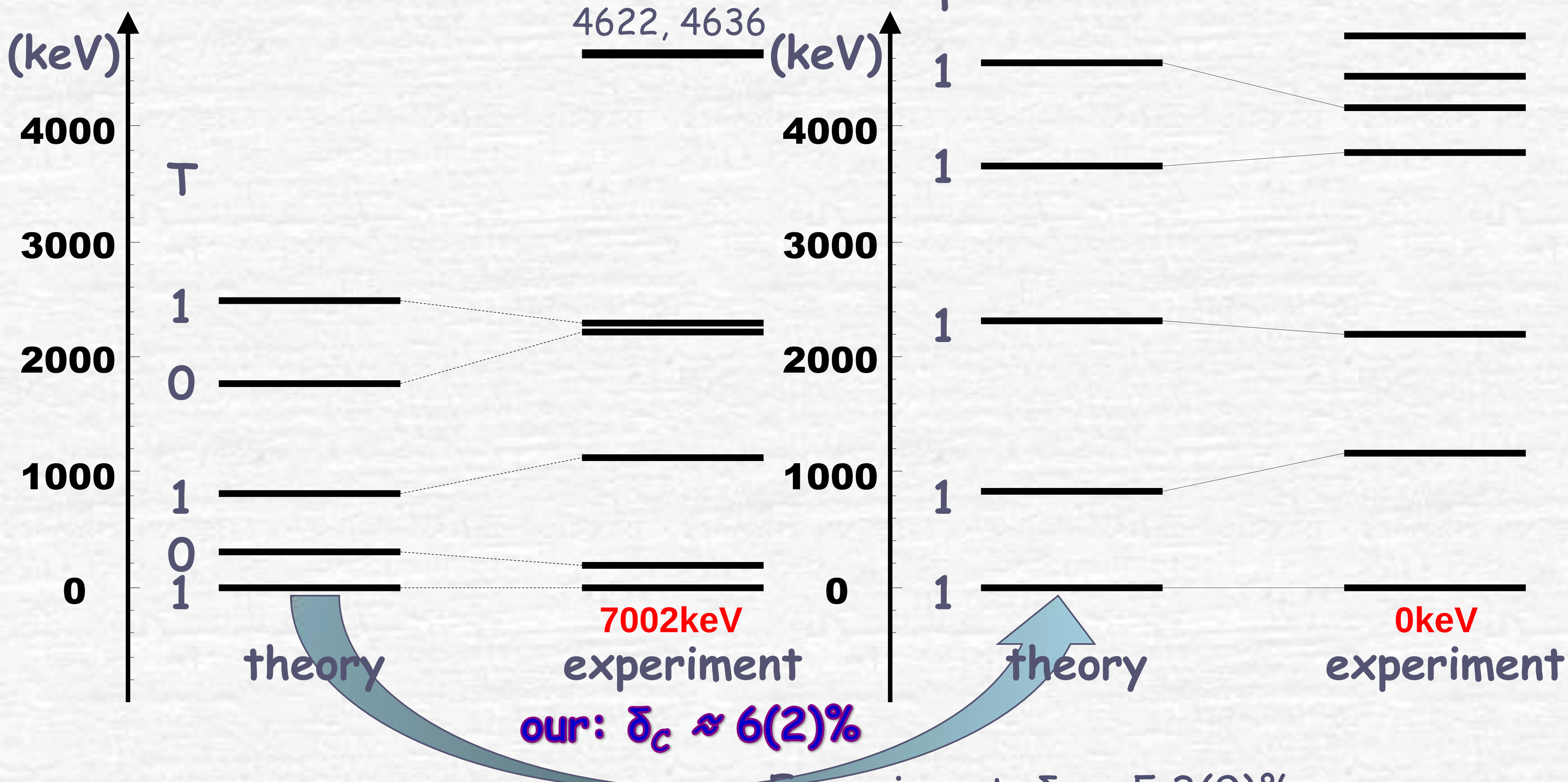


W.Satuła, J.Dobaczewski & M.Konieczka, arXiv:1408.4982;
JPS Conf. Proc. 6, 020015 (2015)



W.Satuła, P.Bączyk, J.Dobaczewski & M.Konieczka, Phys. Rev. C94, 024306 (2016)

^{32}S I=1^{+} ^{32}Cl I=1^{+}



Experiment: $\delta_C \approx 5.3(9)\%$

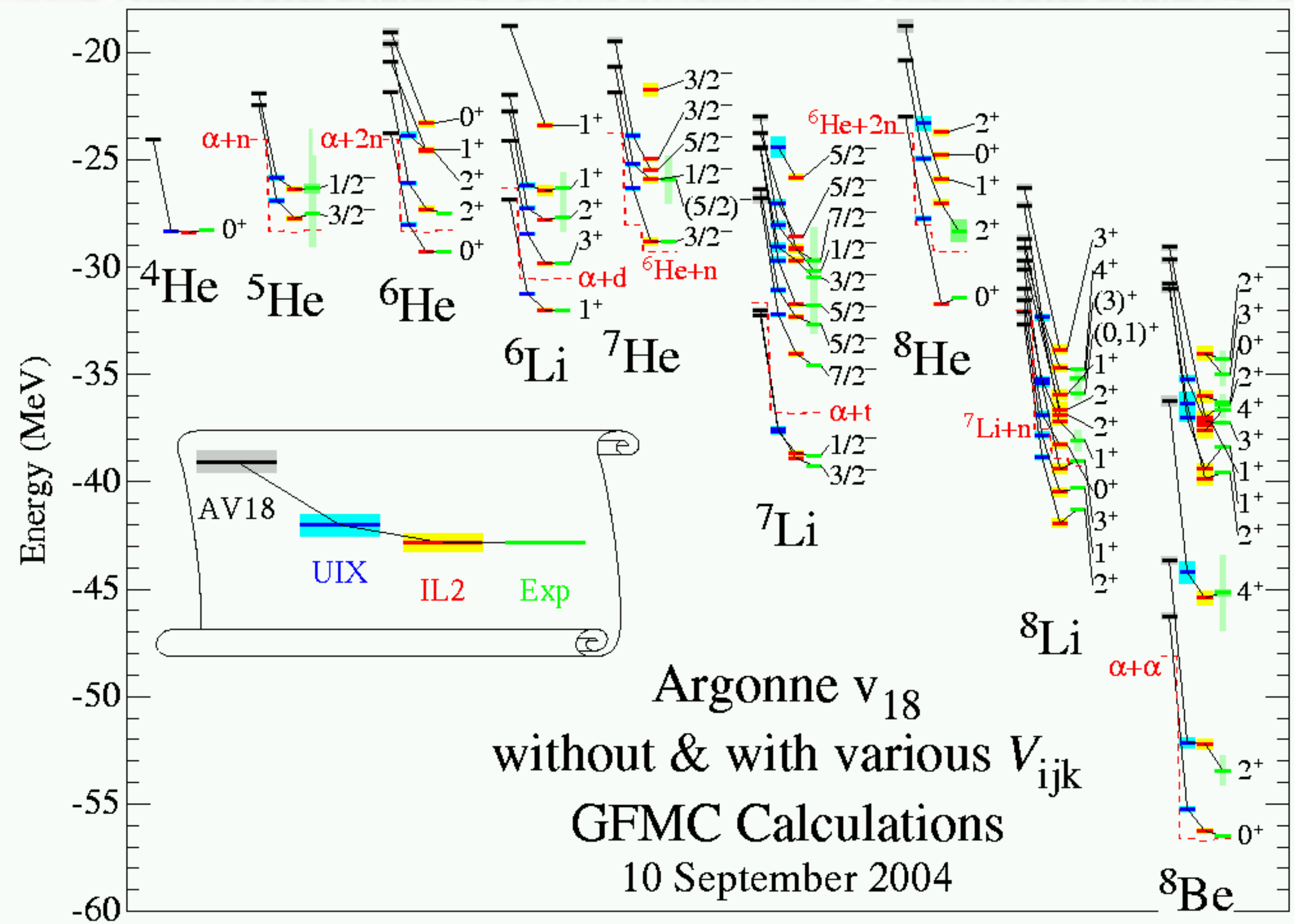
SM+WS calculations: $\delta_C \approx 4.6(5)\%$.

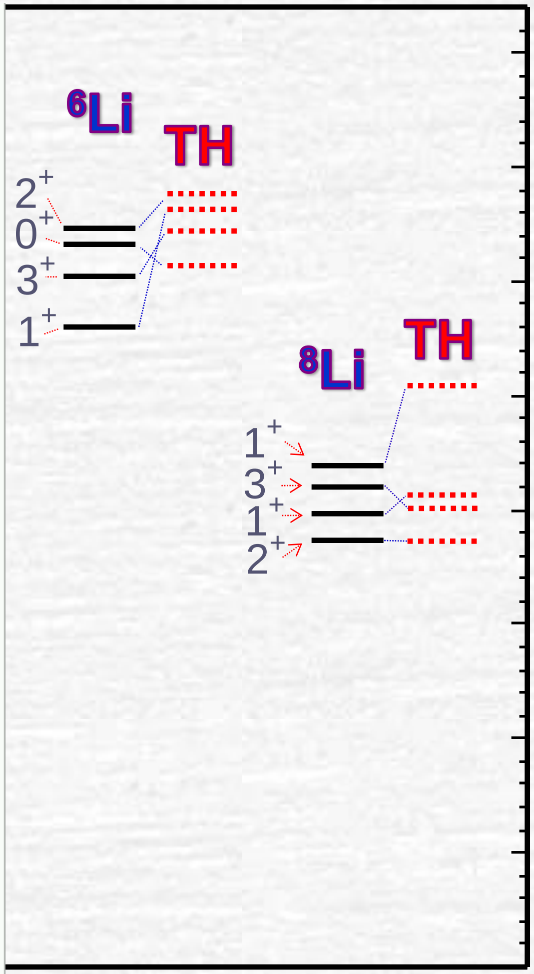
D. Melconian et al., Phys. Rev. Lett. **107**, 182301 (2011).

W.Satula, J.Dobaczewski, M.Konieczka, W.Nazarewicz, Acta Phys. Polonica B45, 167 (2014)

mixing of states projected from just three-four p-h configurations

For details see: W.Satuła, P.Bączyk, J.Dobaczewski & M.Konieczka, Phys. Rev. C94, 024306 (2016)

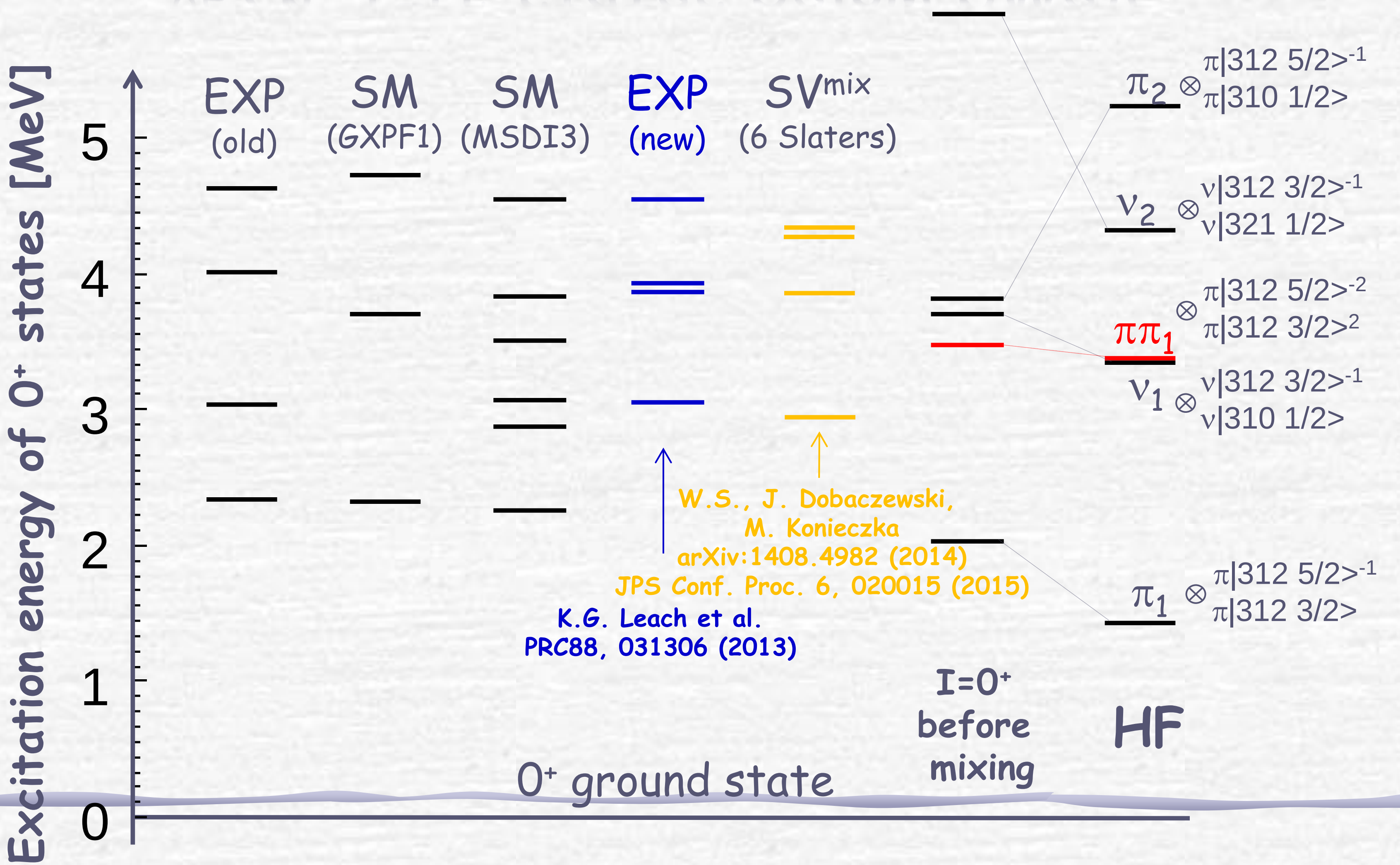




No-core configuration-interaction formalism based on the isospin and angular momentum projected DFT

W.Satuła, J.Dobaczewski & M.Konieczka, arXiv:1408.4982; JPS Conf. Proc. 6, 020015 (2015)

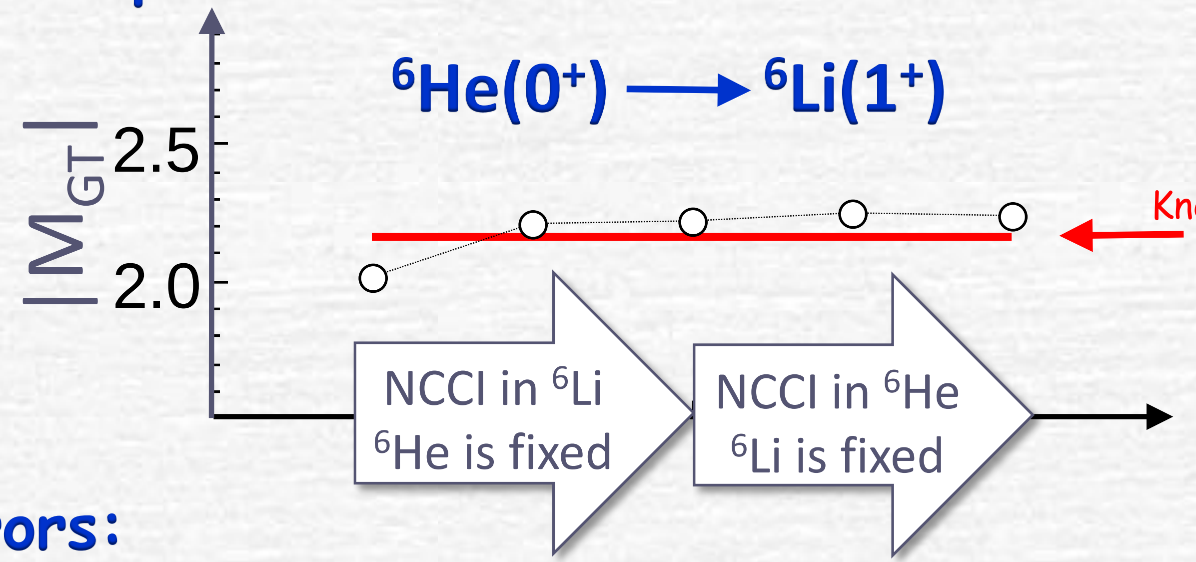
^{62}Zn, I=0$^+$ states below 5MeV



Gamow-Teller and Fermi matrix elements in T=1/2 sd- and ft- mirrors. The NCCI study

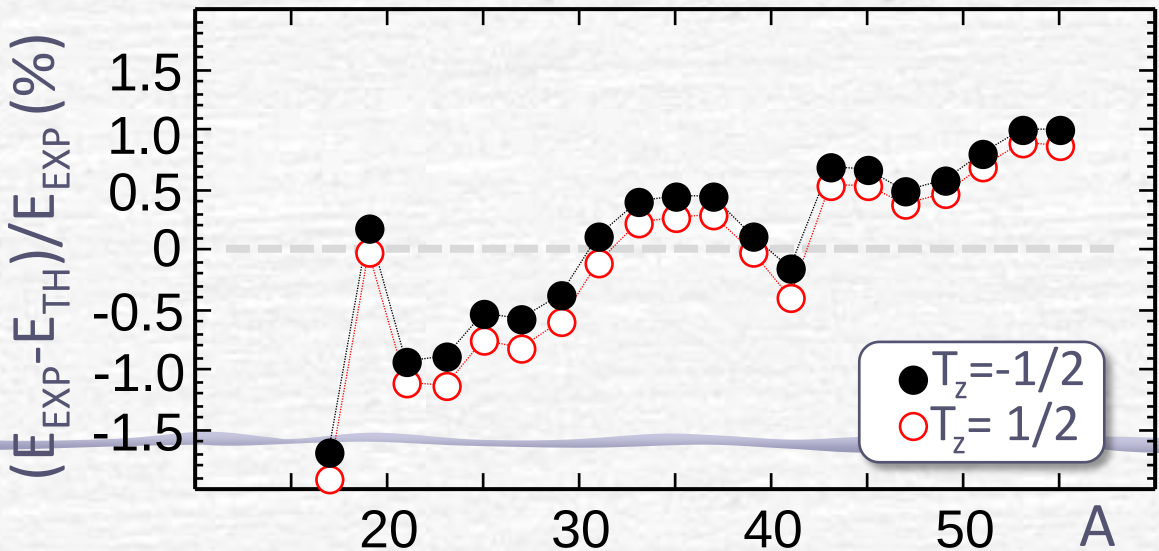
M.Konieczka, P.Bączyk, W.Satuła, Phys. Rev. C93, 042501(R) (2016); arXiv:1509.04480

Proof-of-principle calculation:



T=1/2 mirrors:

- masses:



$|g_A M_{GT}|$

Shell-model:

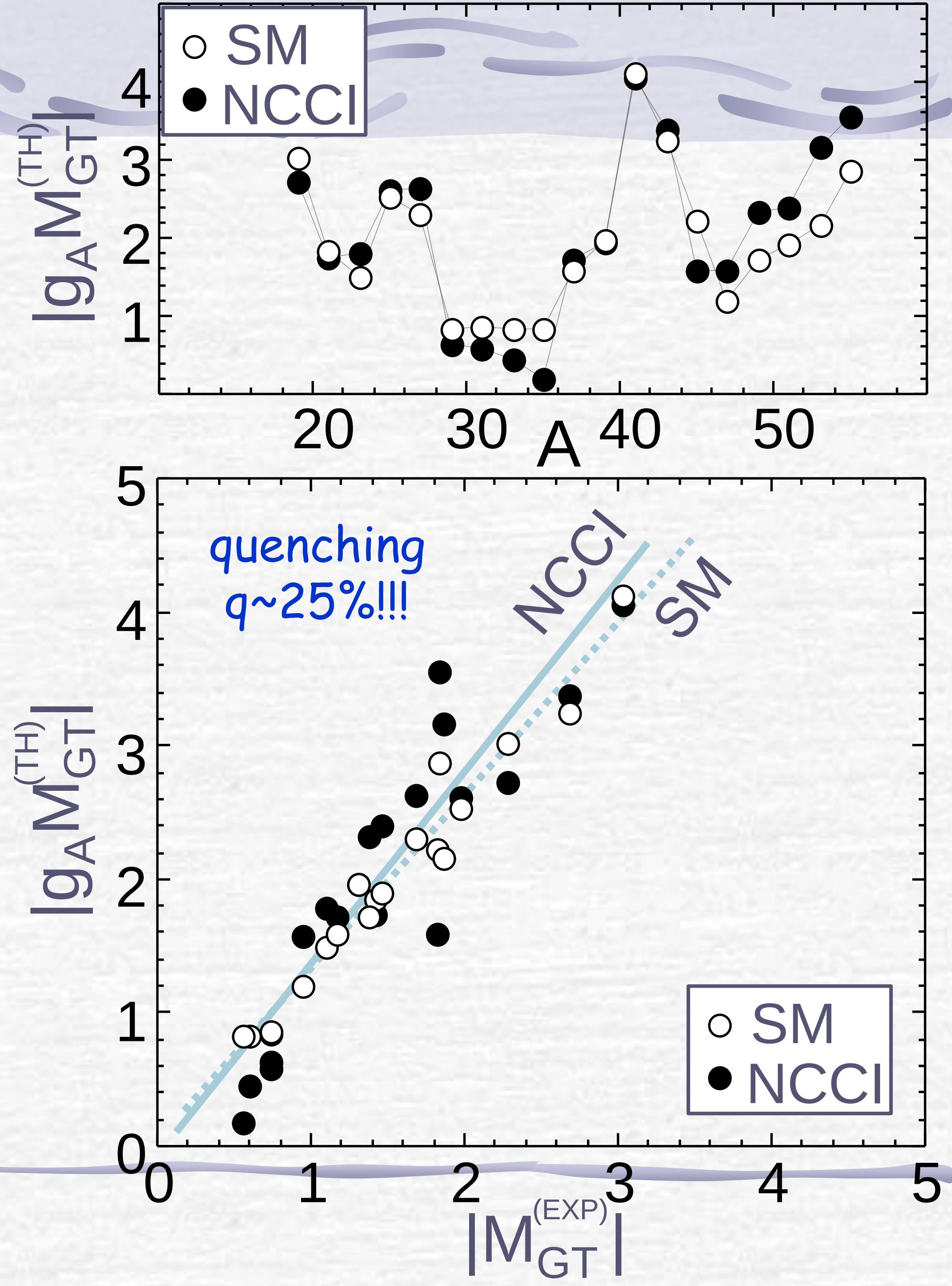
B. A. Brown and B. H. Wildenthal,
Atomic Data and Nuclear
Data Tables **33**, 347 (1985).

G. Martinez-Pinedo *et al.*,
Phys. Rev. ***C* 53**, R2602 (1996).

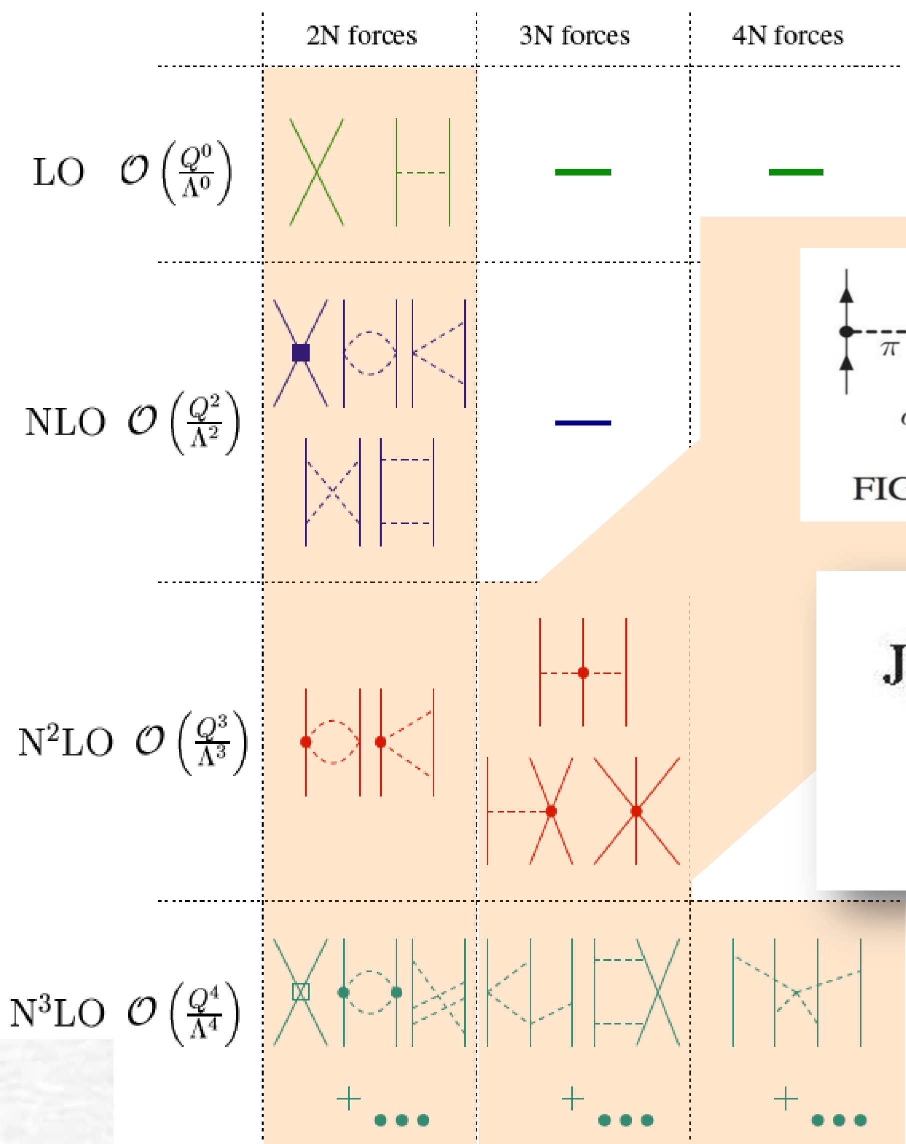
T. Sekine *et al.*,
Nucl. Phys. ***A* 467**, (1987).

NCCI vs shell-model:

- The NCCI takes into account a core and its polarization
- Completely different model spaces
- Different treatment of correlations
- Different interactions



Renormalization of axial-vector coupling constant by 2B-currents



c_i from πN and NN:

$$c_1 = -0.9^{+0.2}_{-0.5}\,,\ c_3 = -4.7^{+1.2}_{-1.0}\,,\ c_4 = 3.5^{+0.5}_{-0.2}$$

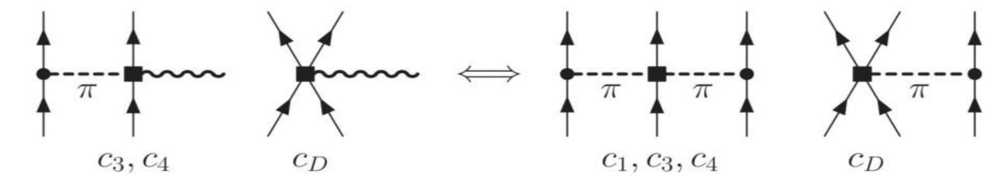


FIG. 1. Chiral 2*b* currents and 3*N* force contributions.

Menendez et al. PRL107, 062501 (2011)

$$\mathbf{J}^{\rm eff}_{i,2b} = -g_A \boldsymbol{\sigma}_i \boldsymbol{\tau}_i^- \frac{\rho}{F_\pi^2}\left[\frac{c_D}{g_A\Lambda_\chi} + \frac{2}{3}c_3\frac{\mathbf{p}^2}{4m_\pi^2+\mathbf{p}^2} + I(\rho,P)\left(\frac{1}{3}(2c_4-c_3)+\frac{1}{6m}\right)\right],$$

β^- decays of ^{14}C and $^{22;24}O$

Ekstrom et al. PRL 113, 262504 (2014)

q^2~0.84-0.92 (from Ikeda sum rule)

q~0.9

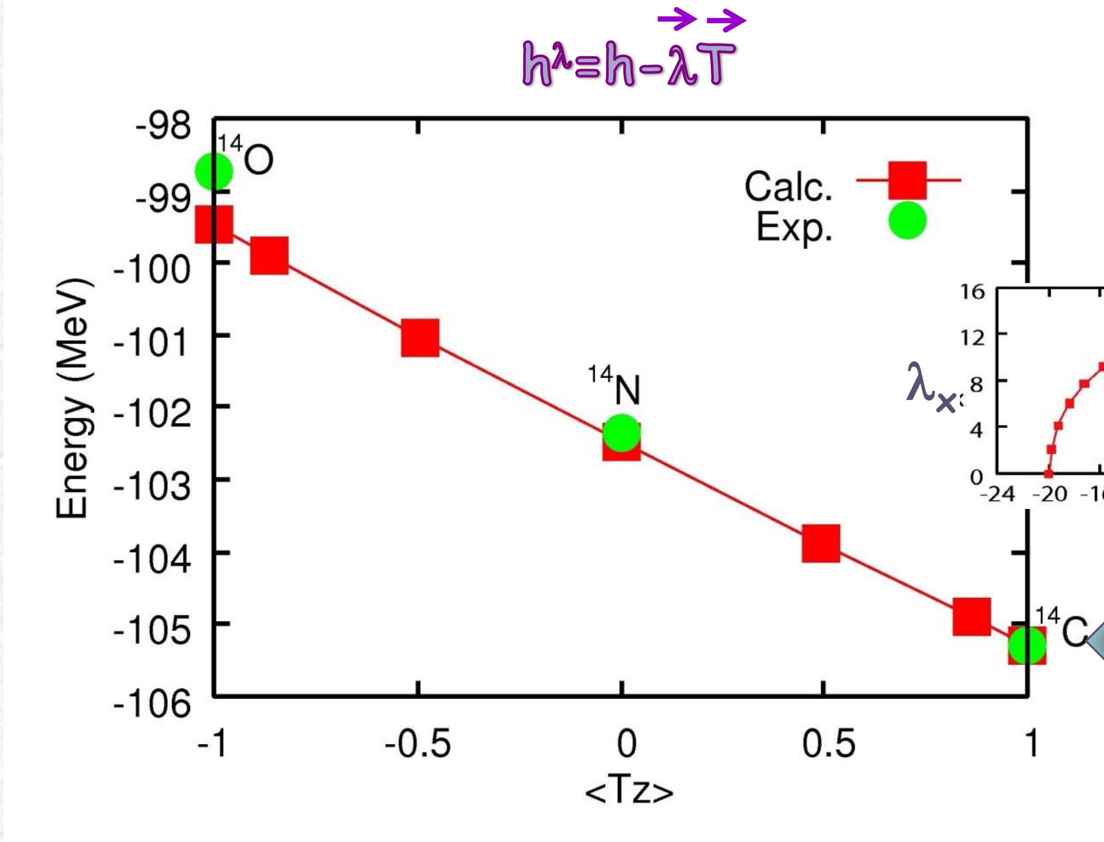
See also:

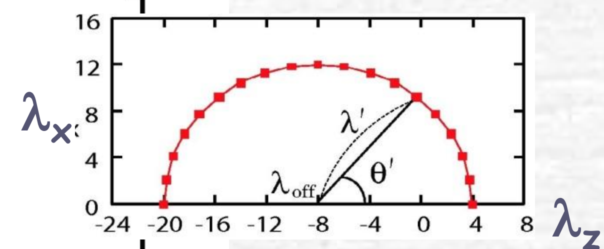
Klos et al. PRC89, 029901 (2013)

Engel et al. PRC89, 064308 (2013)

$T=1, I=0^+$ isobaric analogue states from self-consistent 3D-isocranked HF: $h^{\lambda}=h-\vec{\lambda}\vec{T}$

K. Sato, J. Dobaczewski, T. Nakatsukasa, and W. Satuła, Phys. Rev. C88 (2013), 061301





normalized:
theory (red curve)
shifted
by 3.2MeV

separable solution ← p-n mixed solution ← separable solution

$|n\rangle \pm |p\rangle$

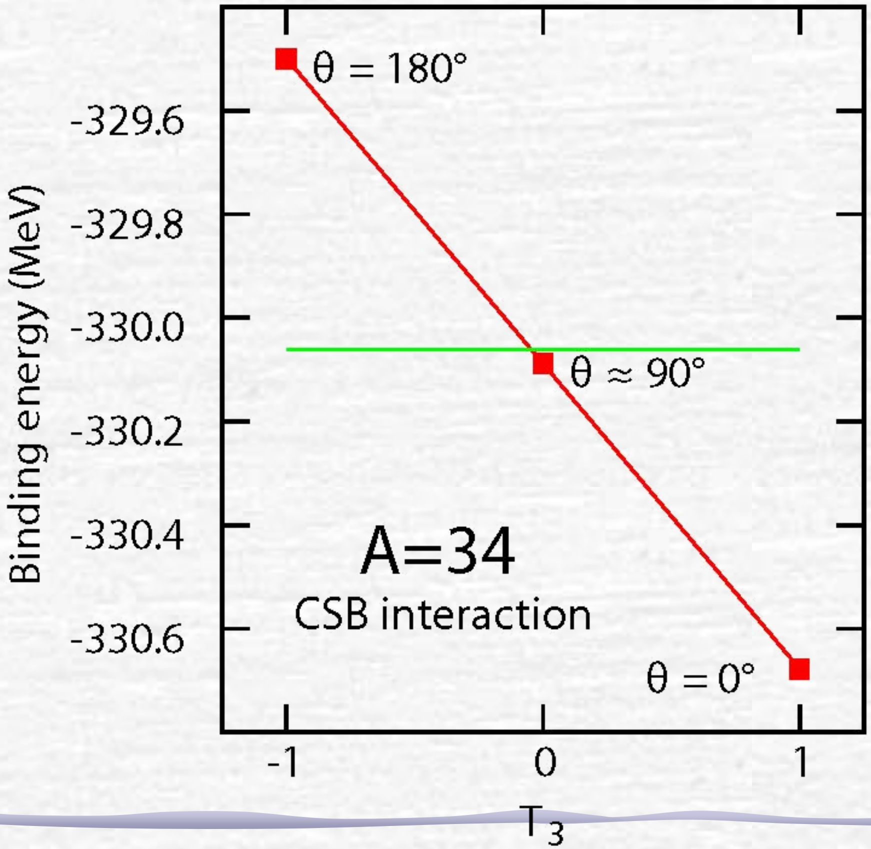
CD local (strong) corrections to the Skyrme force
(class II (CIB) and III (CSB) Henley-Miller forces)

$$\hat{V}^{\rm II}(i,j) = t_0^{\rm II}\,\delta(\boldsymbol{r}_i - \boldsymbol{r}_j)\left(1 - x_0^{\rm II}\,\hat{P}^{\sigma}_{ij}\right)\left[3\hat{\tau}_3(i)\hat{\tau}_3(j) - \hat{\vec{\tau}}(i)\circ\hat{\vec{\tau}}(j)\right],$$

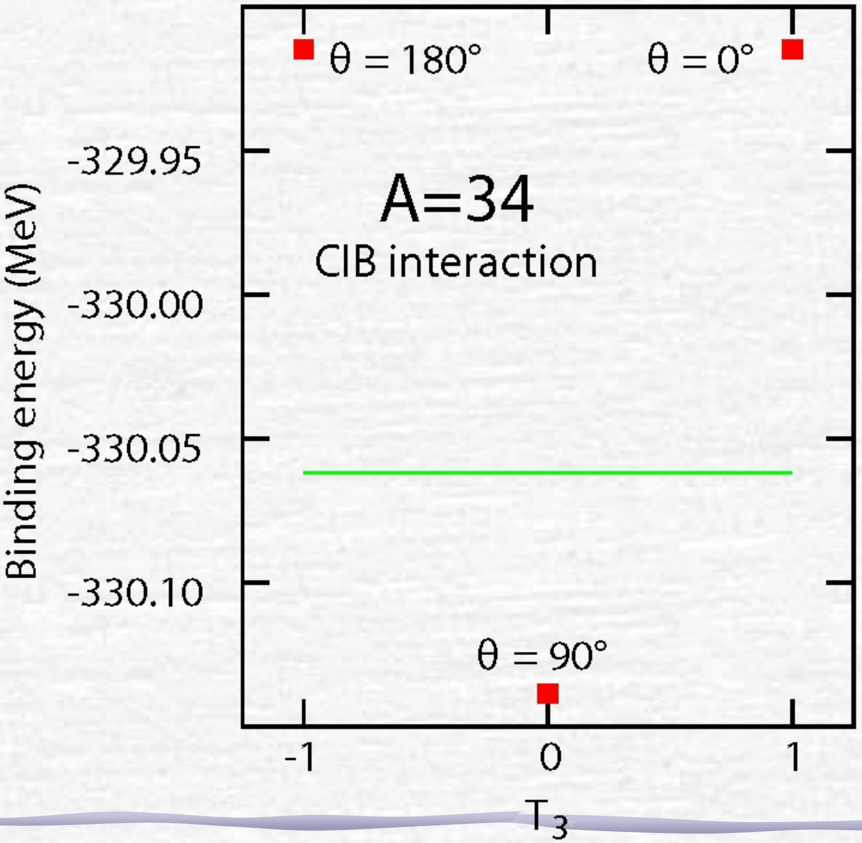
$$\hat{V}^{\rm III}(i,j) = t_0^{\rm III}\,\delta(\boldsymbol{r}_i - \boldsymbol{r}_j)\left(1 - x_0^{\rm III}\,\hat{P}^{\sigma}_{ij}\right)\left[\hat{\tau}_3(i) + \hat{\tau}_3(j)\right],$$

$$\mathcal{H}_{\rm II} = \tfrac{1}{2}t_0^{\rm II}\left(1 - x_0^{\rm II}\right)\left(\rho_n^2 + \rho_p^2 - 2\rho_n\rho_p - 2\rho_{np}\rho_{pn} - \boldsymbol{s}_n^2 - \boldsymbol{s}_p^2 + 2\boldsymbol{s}_n\cdot\boldsymbol{s}_p + 2\boldsymbol{s}_{np}\cdot\boldsymbol{s}_{pn}\right),$$

$$\mathcal{H}_{\rm III} = \tfrac{1}{2}t_0^{\rm III}\left(1 - x_0^{\rm III}\right)\left(\rho_n^2 - \rho_p^2 - \boldsymbol{s}_n^2 + \boldsymbol{s}_p^2\right),$$



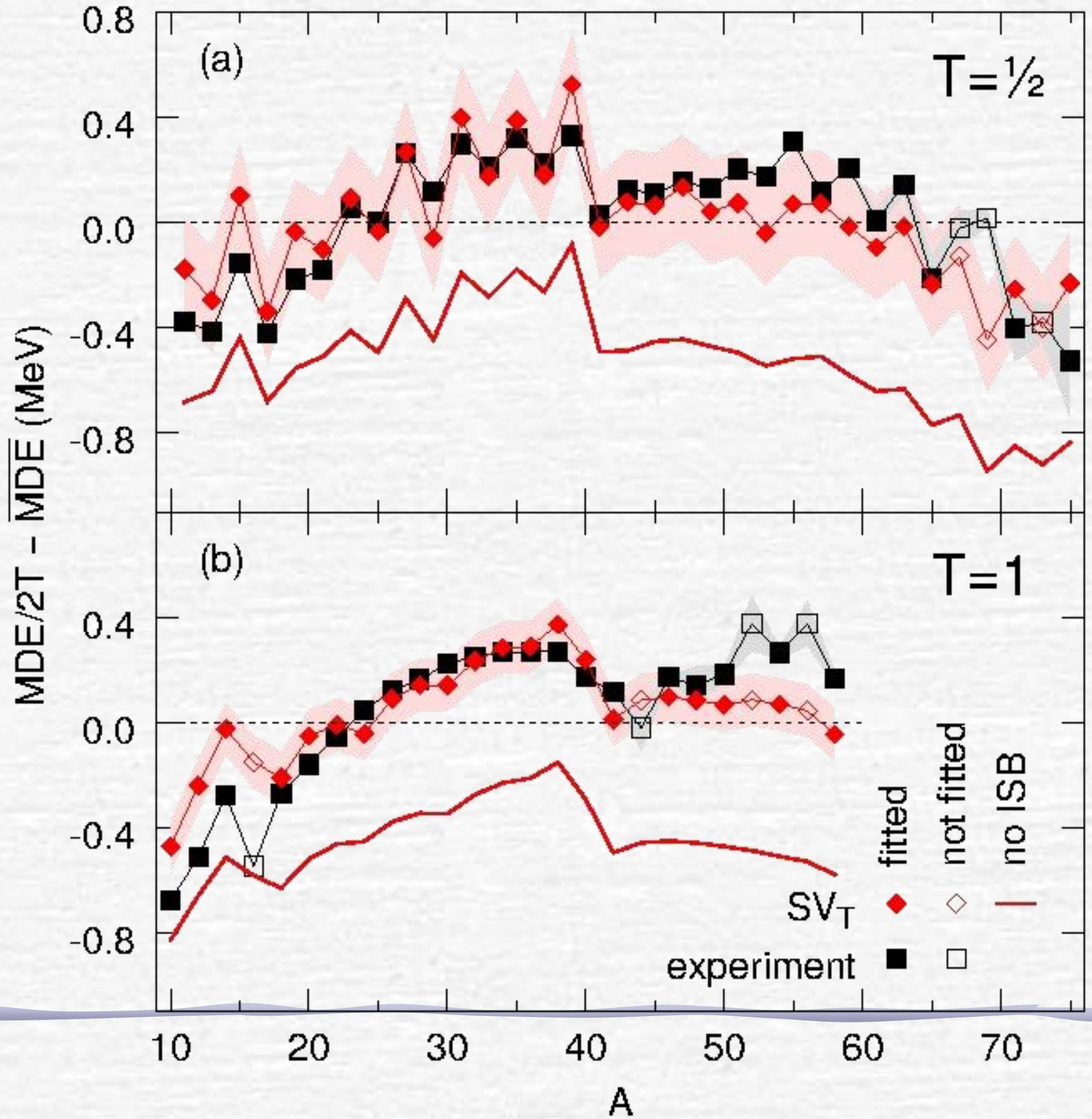
Class III corrects for MDE



Class II corrects for TDE

Mirror displacement energies with class II and III local corrections to the Skyrme force

P. Bączyk, J. Dobaczewski, M. Konieczka, W. Satuła, T. Nakatsukasa, K. Sato, arXiv:1701.04628



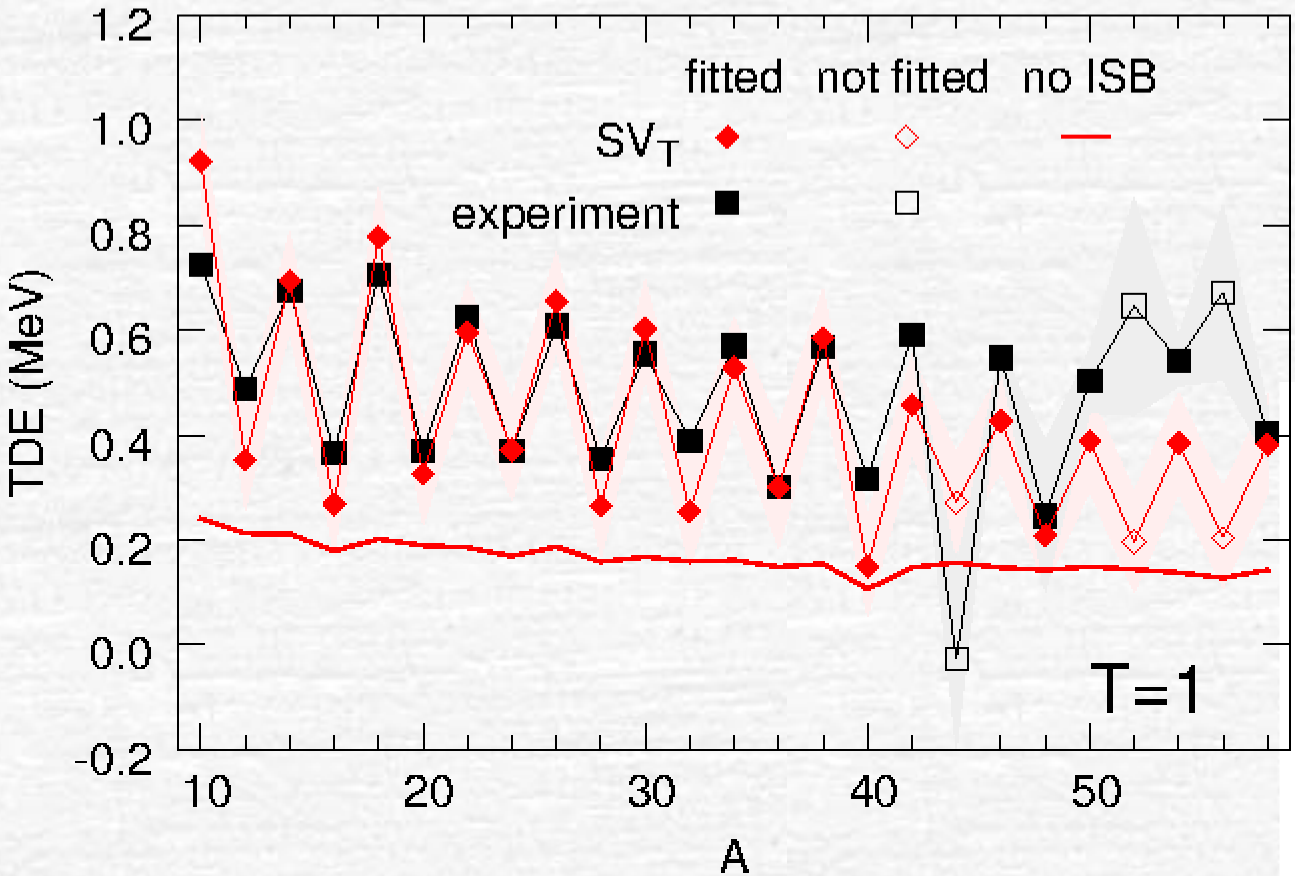
Triplet Displacement Energies (TDE) with class II and III local corrections to the Skyrme force

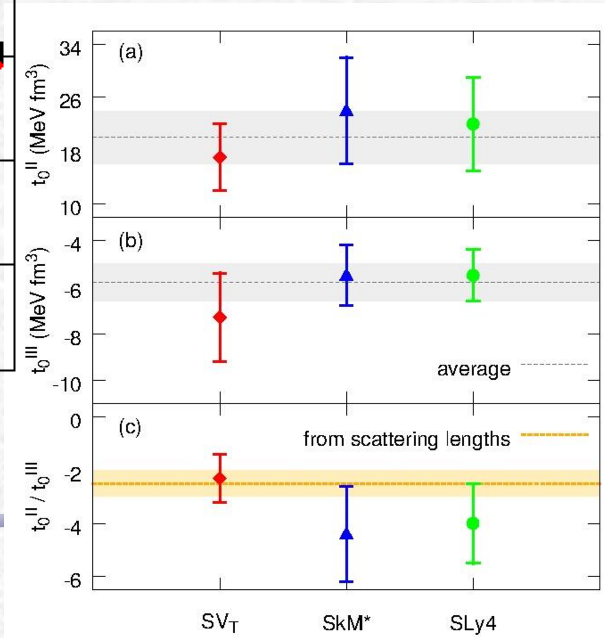
$$\hat{V}^{\mathrm{II}}(i,j) = t_0^{\mathrm{II}}\,\delta(\boldsymbol{r}_i-\boldsymbol{r}_j)\left(1-x_0^{\mathrm{II}}\,\hat{P}^{\sigma}_{ij}\right)\left[3\hat{\tau}_3(i)\hat{\tau}_3(j)-\hat{\vec{\tau}}(i)\circ\hat{\vec{\tau}}(j)\right],$$

$$\hat{V}^{\mathrm{III}}(i,j) = t_0^{\mathrm{III}}\,\delta(\boldsymbol{r}_i-\boldsymbol{r}_j)\left(1-x_0^{\mathrm{III}}\,\hat{P}^{\sigma}_{ij}\right)\left[\hat{\tau}_3(i)+\hat{\tau}_3(j)\right],$$

$$\mathcal{H}_{\mathrm{II}} = \tfrac{1}{2}t_0^{\mathrm{II}}\left(1-x_0^{\mathrm{II}}\right)\left(\rho_n^2+\rho_p^2-2\rho_n\rho_p-2\rho_{np}\rho_{pn} -\boldsymbol{s}_n^2-\boldsymbol{s}_p^2+2\boldsymbol{s}_n\cdot\boldsymbol{s}_p+2\boldsymbol{s}_{np}\cdot\boldsymbol{s}_{pn}\right),$$

$$\mathcal{H}_{\mathrm{III}} = \tfrac{1}{2}t_0^{\mathrm{III}}\left(1-x_0^{\mathrm{III}}\right)\left(\rho_n^2-\rho_p^2-\boldsymbol{s}_n^2+\boldsymbol{s}_p^2\right),$$





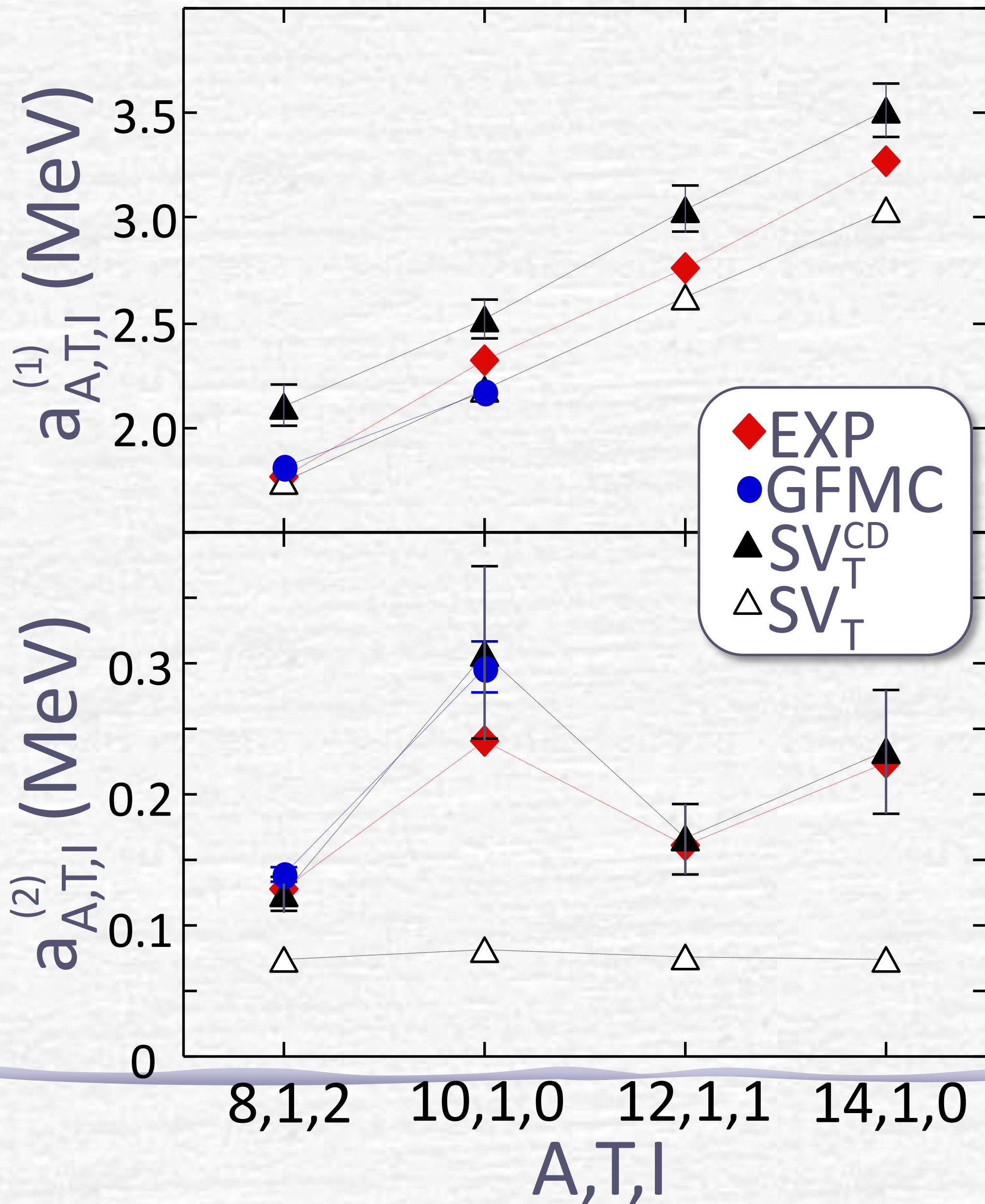
$$\mathrm{TDE} = BE\,(T=1,T_z=-1)+BE\,(T=1,T_z=+1) -2BE\,(T=1,T_z=0)$$

Isobaric Multiplet Mass Equation (IMME)

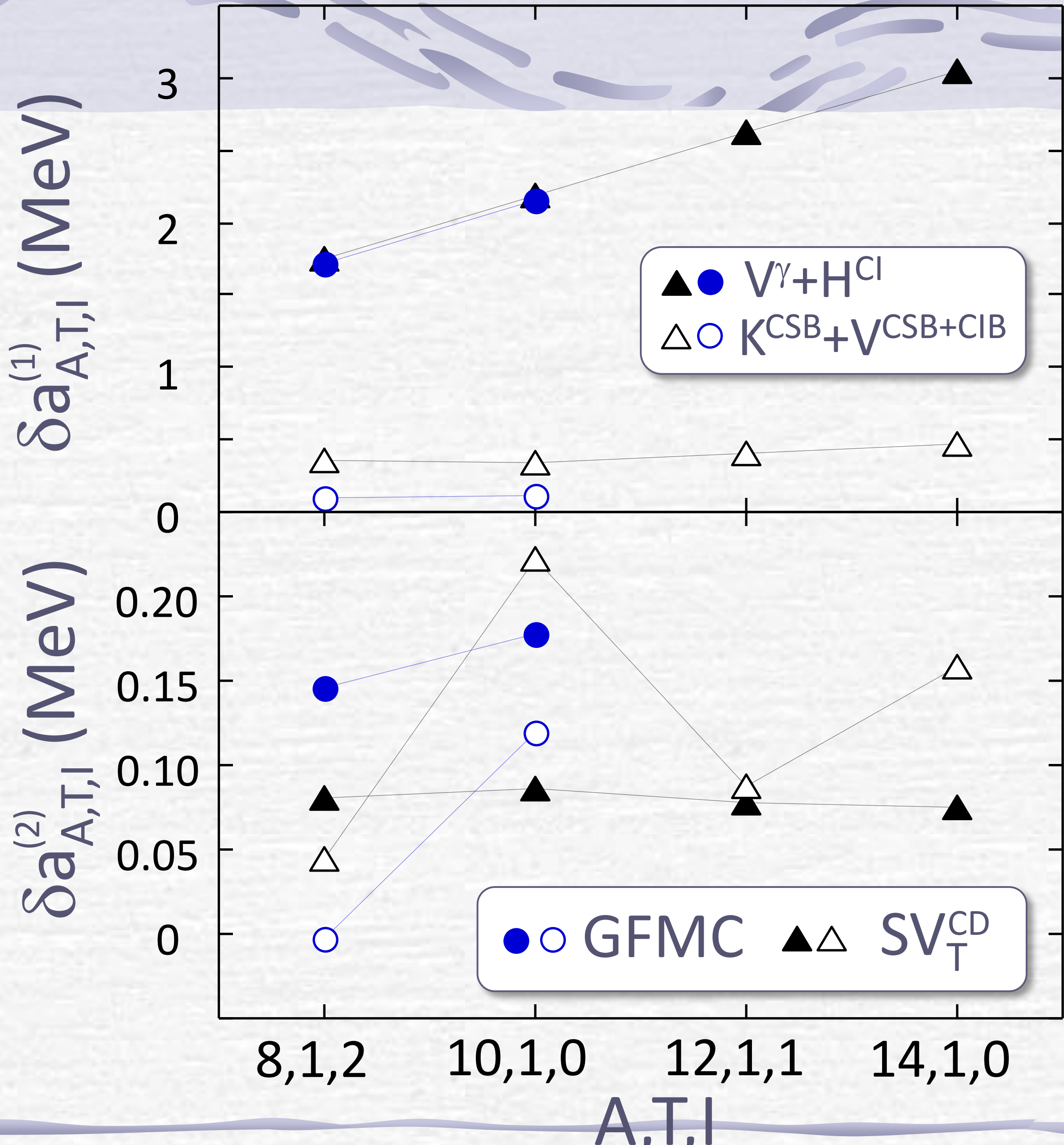
$$E_{A,T,I}(T_z) = \sum_{n \leq 2T} a^{(n)}_{A,T,I} Q_n(T, T_z),$$

$$Q_0 = 1, \quad Q_1 = T_z,$$

$$Q_2 = \frac{1}{2}\{3T_z^2 - T(T+1)\}$$

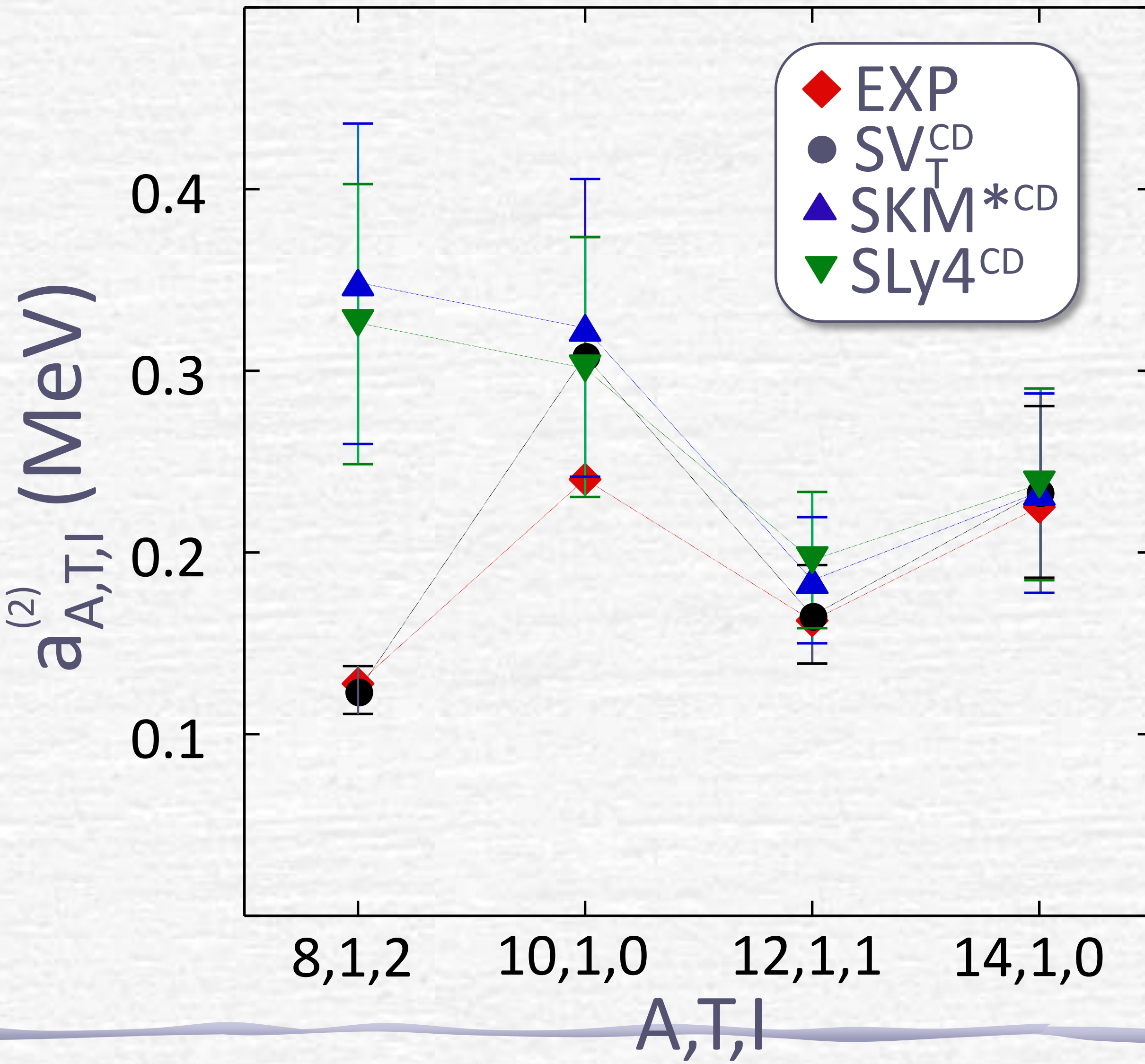


P.Bączyk, J.Dobaczewski, M.Konieczka, W.Satuła, in preparation

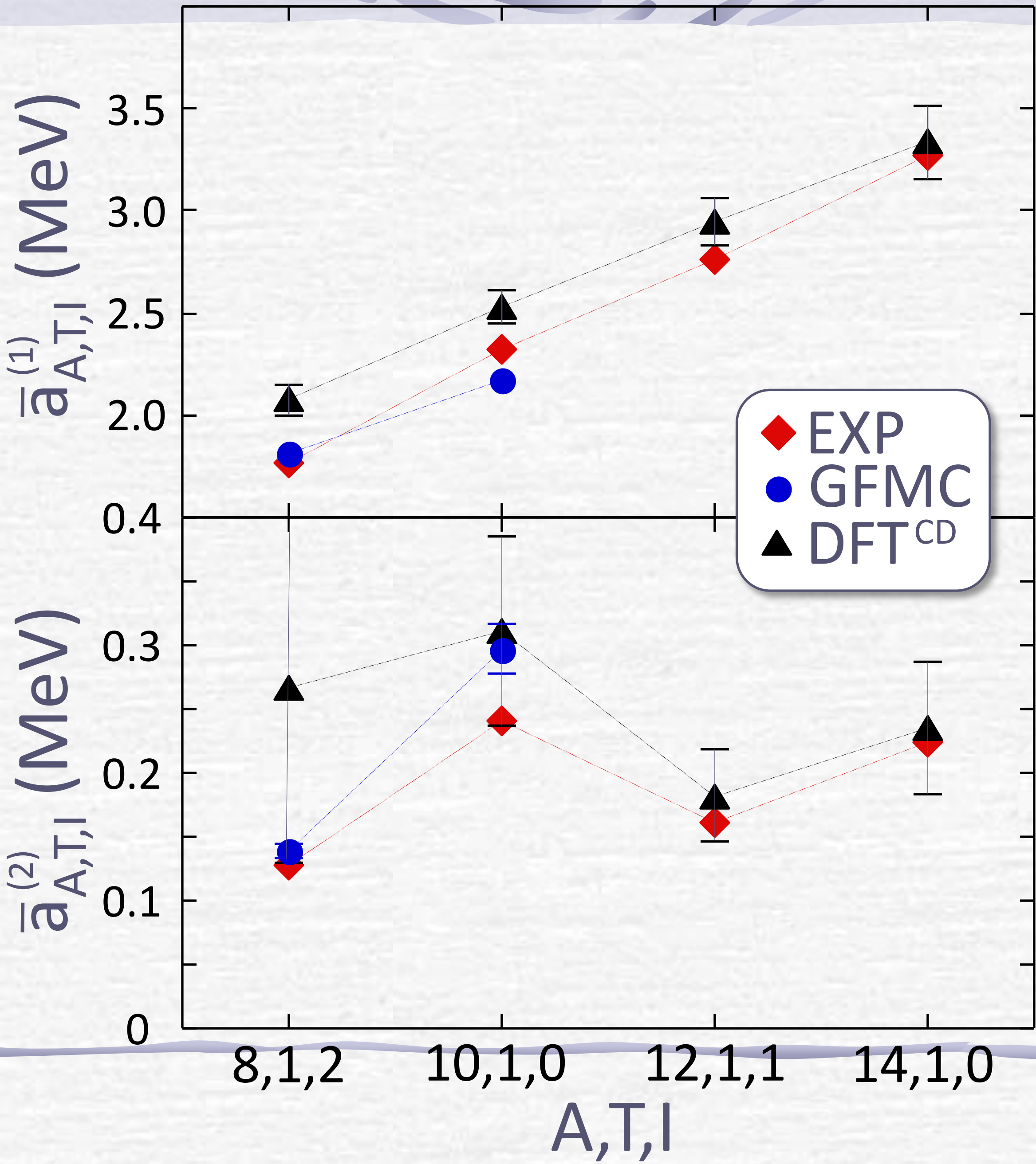


$\delta a^{(1)}_{A,T,I}$ (MeV)
3
2
1
0
$V^{\gamma}+H^{CI}$
$K^{CSB}+V^{CSB+CIB}$
$\delta a^{(2)}_{A,T,I}$ (MeV)
0.20
0.15
0.10
0.05
0
GFMC
SV^{CD}_{T}
8,1,2
10,1,0
12,1,1
14,1,0
A,T,I

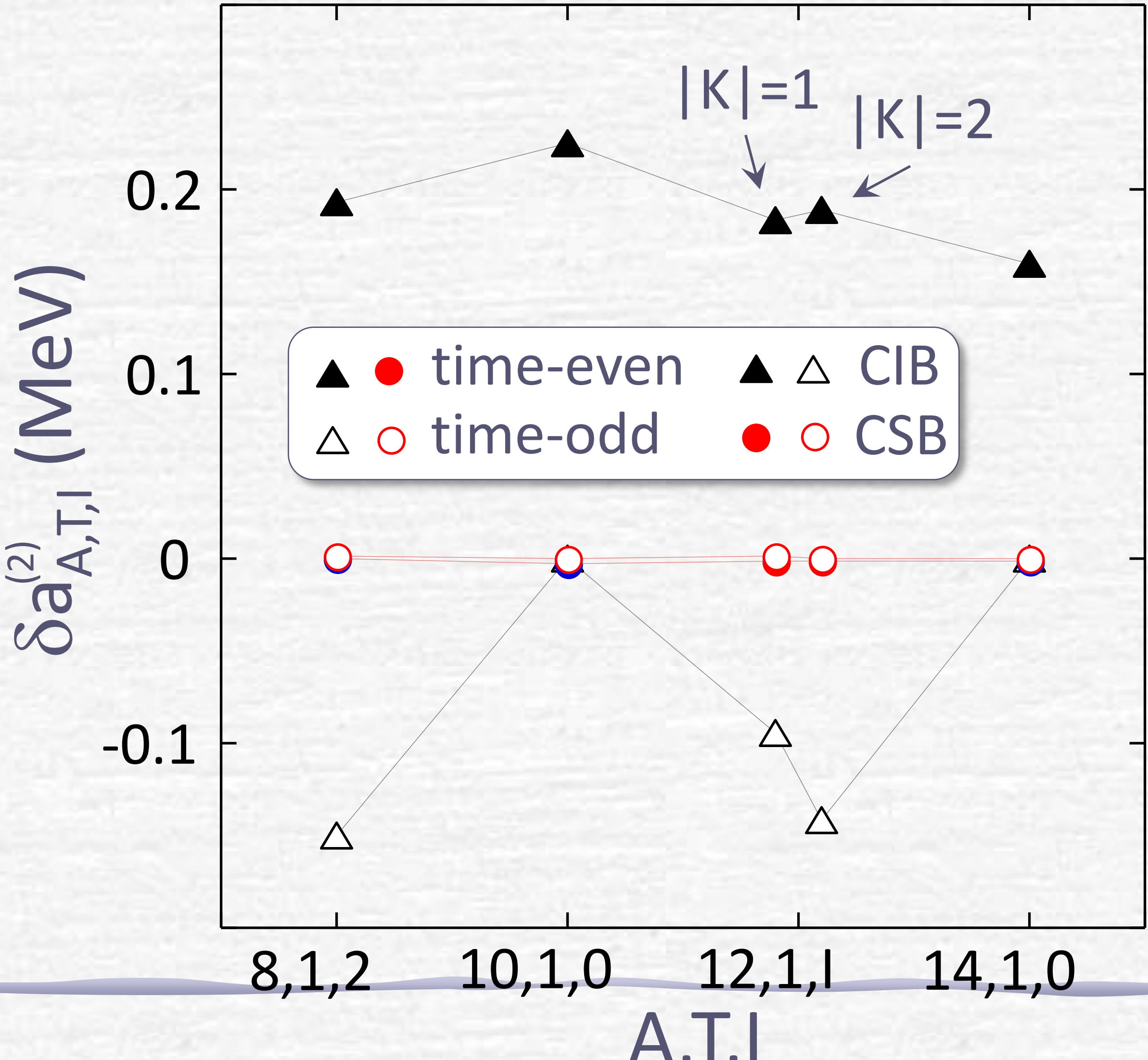
Isobaric Multiplet Mass Equation (IMME)



Mean IMME coefficients averaged over SV_T^{CD}, SkM^{*CD}, $SLy4^{CD}$



Staggering in $a^{(2)}$ is due to TIME-ODD part of CIB (type II) short-range functional



[CSB=0]

MR-DFT-rooted methods are extremely attractive because:

"The purpose of computing is insight, not numbers"

(Richard Hamming, 1962)

"According to Einstein's theory, if we move the computer real fast, we can go back in time and recover the files you accidentally deleted."

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XXXV Mazurian Lakes Conference on Physics

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- Challenges in nuclear theory
- Nuclear structure and reactions
- Nuclear astrophysics and nucleosynthesis
- Nuclear fission and super-heavy elements
- Novel experimental techniques and facilities
- Interdisciplinary studies and societal applications

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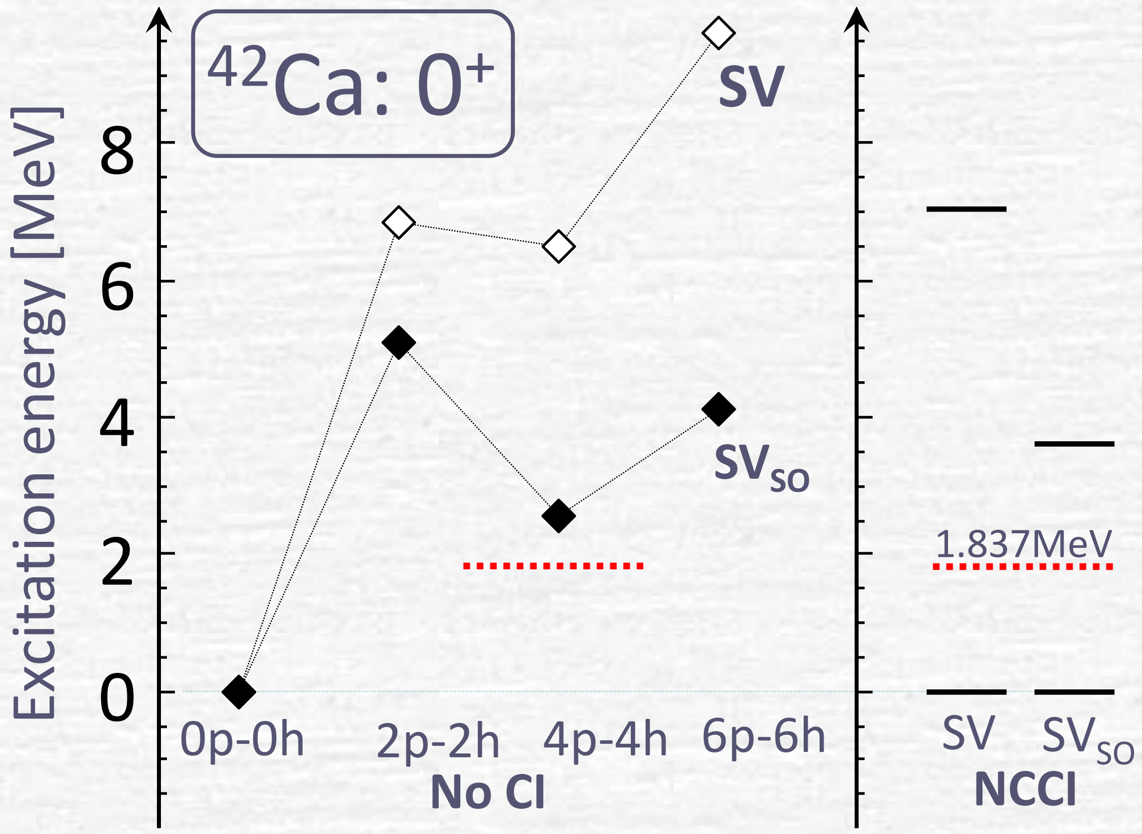
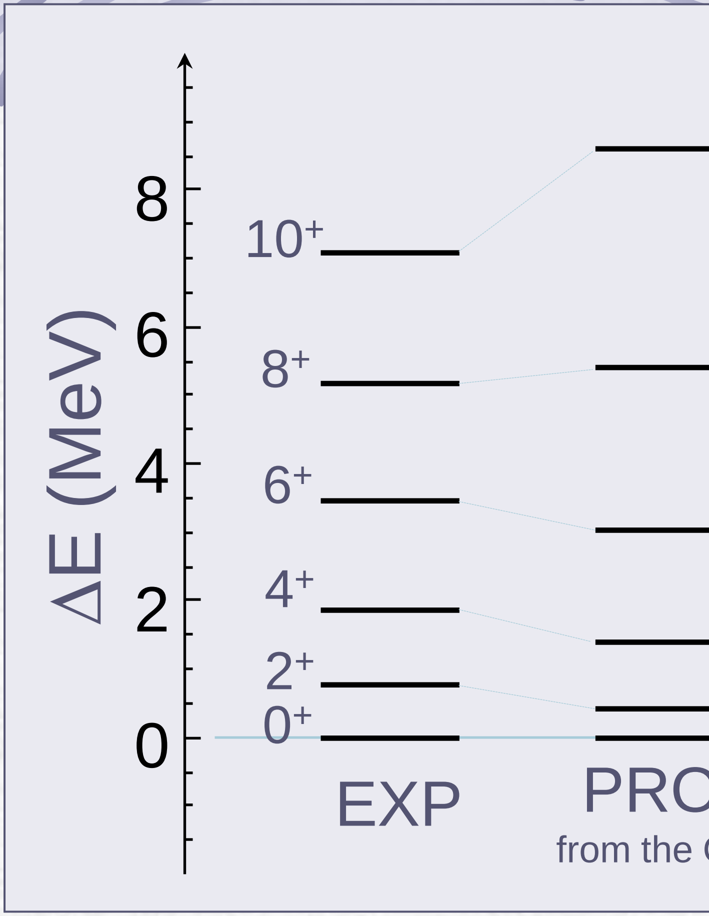
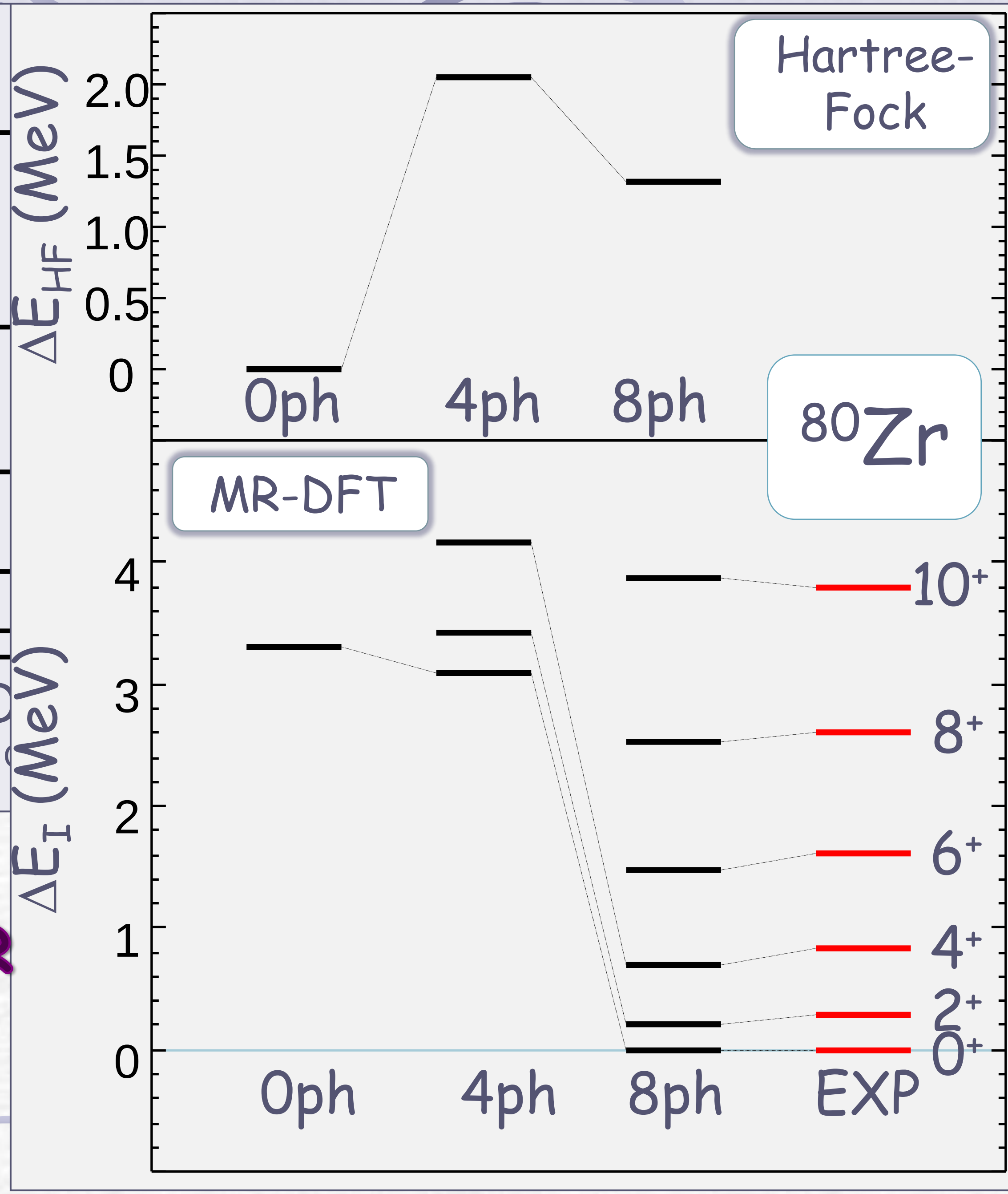
PRO PHYSICA



42Ca: 0+
Excitation energy [MeV]
8
6
4
2
0
SV
SVSO
0p-0h
2p-2h
4p-4h
6p-6h
No CI
1.837MeV
SV
SVSO
NCCI

PREDICTIONS FOR COLLECTIVE BANDS





Challenges for Low-Energy Nuclear Theory

- Perform proof-of-principle lattice QCD calculation for the lightest nuclei
- Develop first-principles framework for light, medium-mass nuclei, and nuclear matter from 0.1 to twice the saturation density
- Derive predictive nuclear energy density functional rooted in first-principles theory
- Carry out predictive and quantified calculations of nuclear matrix elements for fundamental symmetry tests.
- Unify the fields of nuclear structure and reactions.
- Develop predictive microscopic model of fusion and fission that will provide the missing data for astrophysics and nuclear energy research.
- Develop and utilize tools for quantification of theoretical uncertainties.
- Provide the microscopic explanation for observed, and new, (partial-) dynamical symmetries and simple patterns