ROZPAD BETA W UOGÓLNIONYM MODELU FUNKCJONAŁU GĘSTOŚCI

SEMINARIUM FIZYKI JĄDRA ATOMOWEGO, 18.05.2017

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INTRODUCTION

1. A few words about Nuclear Theory, Skyrme interaction and DFT theory

2. How to build realistic nuclear wave function upon a DFT state?

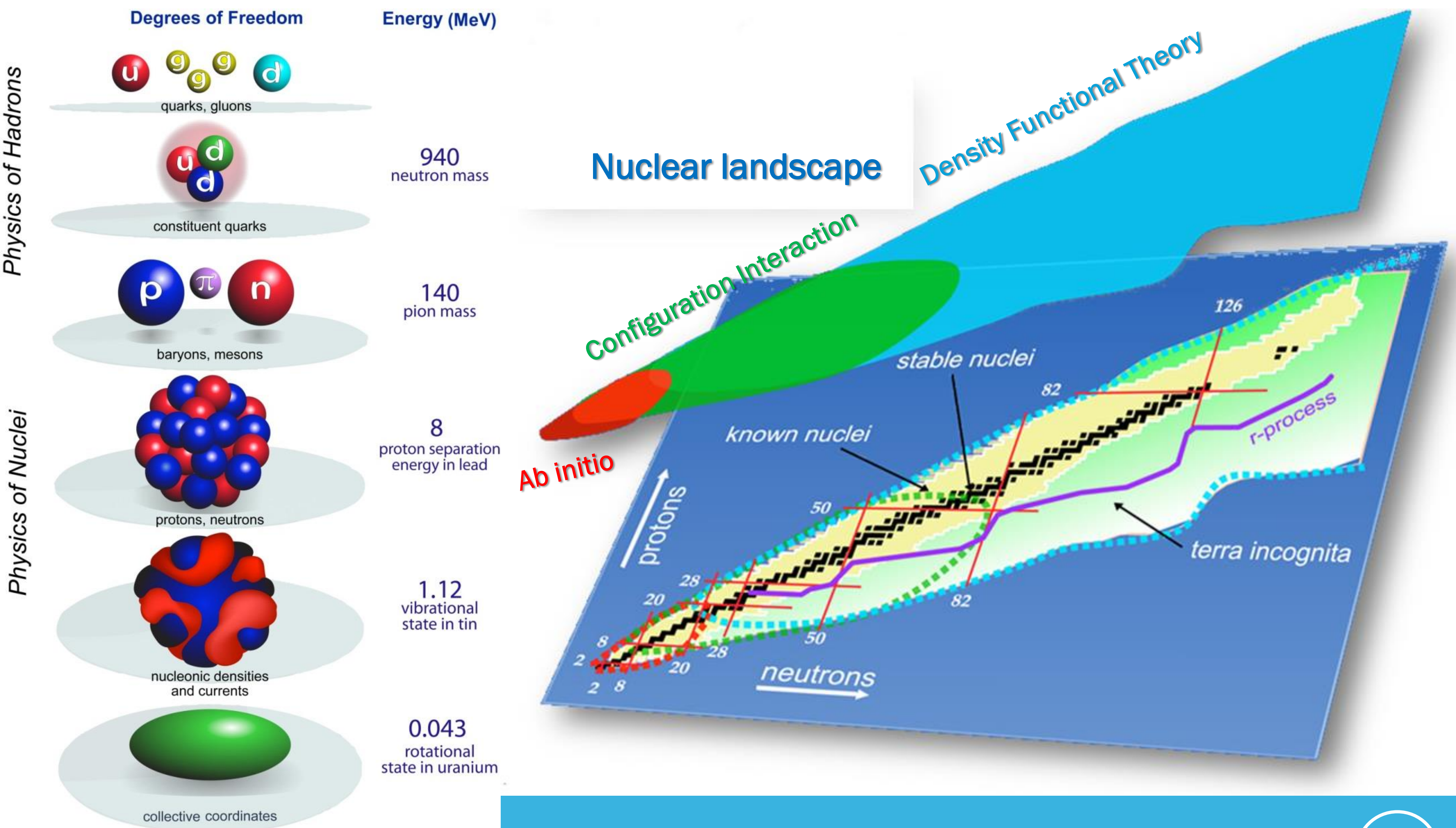
3. Gamow-Teller transitions; mirror nuclei T=1/2; GS to GS transitions, the quenching of g_A

4. Gamow-Teller response function

5. Gamow-Teller sum rule

6. Spin-orbit detector of single particle orbitals

STATUS IN THEORY OF NUCLEAR STRUCTURE



NSM & DFT

NSM

DFT-rooted
No-Core
Configuration-
Interaction

DFT

NSM	DFT
2-body Hamiltonian; correl… after conf. mixing	…ody Hamiltonian; correlations …ncluded in deformed solution
Realistic wave function with laboratory-frame quantum numbers	Spontanous symmetry breaking
Core approximation and restricted valence space; huge matrices to diagonalize etc.	Not directly applicable to spectra and transition rates
Good for nuclear spectroscopy: spectra, transition rates etc.	Good for nuclear spectroscopy: quadrupole moments, masses radii etc.

1-body mean field hamiltonian to generate deformed configurations (DFT)

2-body part of Hamiltonian to mix deformed configurations

A model without neither a core nor the restricted valence space; it includes core-polarization effects

SKYRME NN INTERACTION

Effective interaction!!!

Necessary to separate long from short range (high momenta) physics.
Due to the hard core, one needs to replace short distance by local correcting potentials

Ultraviolet cut-off

$$v_{SK}(q) = v_{SK}(0) + v'_{SK}(0)q^2 + \ldots \longleftarrow$$

Low energy nuclear physics is independent on high momenta transfer

$$v_{SK}(\vec{r}_1 - \vec{r}_2) = t_0(1 + x_0\hat{P}_\sigma)\delta(\vec{r}_1 - \vec{r}_2) + \frac{1}{2}t_1(1 + x_1\hat{P}_\sigma)[\overleftarrow{k}^2\delta(\vec{r}_1 - \vec{r}_2) + \delta(\vec{r}_1 - \vec{r}_2)\overrightarrow{k}^2]$$
$$+ t_2(1 + x_2\hat{P}_\sigma)\overleftarrow{k}\,\delta(\vec{r}_1 - \vec{r}_2)\overrightarrow{k} + \frac{1}{6}t_3(1 + x_3\hat{P}_\sigma)\rho^\alpha\left(\frac{\vec{r}_1 + \vec{r}_2}{2}\right)\delta(\vec{r}_1 - \vec{r}_2)$$
$$+ iW_0(\sigma_1 + \sigma_2)(\overleftarrow{k} \times \delta(\vec{r}_1 - \vec{r}_2)\overrightarrow{k})$$

NN Skyrme interaction

Spin-Orbit term

Description of 3-body terms

FOUNDATION OF DENSITY FUNCTIONAL THEORY

HK theorem: Energy is a functional of density.

$$E_{SHF}[\rho] = T + E_{SK} + E_C$$

long range physics

Exact Coulomb interaction

$$E_{SHF}[\rho] = \frac{\hbar}{2m}\left(1-\frac{1}{A}\right)\int \tau_0(\vec{r})d\vec{r} + \sum_{t=0,1}\int [\mathcal{H}_t^e + \mathcal{H}_t^o]d\vec{r} + \frac{e^2}{2}\int \frac{\rho_p(\vec{r_1})\rho_p(\vec{r_2})}{|\vec{r_1}-\vec{r_2}|}d\vec{r_1}d\vec{r_2} - \frac{e^2}{2}\int \frac{\rho_p(\vec{r_1},\vec{r_2})\rho_p(\vec{r_2},\vec{r_1})}{|\vec{r_1}-\vec{r_2}|}d\vec{r_1}d\vec{r_2}$$

$$\mathcal{H}_t^e = C_t^\rho \rho_t^2 + C_t^{\Delta\rho}\rho_t\Delta\rho_t + C_t^\tau \rho_t\tau_t + C_t^J \vec{\mathcal{J}}_t^2 + C_t^{\nabla J}\rho_t\vec{\nabla}\vec{J}_t$$

$$\mathcal{H}_t^o = C_t^s \vec{s}_t^2 + C_t^{\Delta s}\vec{s}_t\Delta\vec{s}_t + C_t^T \vec{s}_t\vec{T}_t + C_t^j \vec{j}_t^2 + C_t^{\nabla j}\vec{s}_t(\vec{\nabla}\times\vec{j}_t)$$

10 linearly independent parameters

Variation over density

MEAN FIELDS

Kohn-Sham equation

$$(\hat{T} + V_{KS}(\vec{r}))\phi_i(\vec{r}) = E_i\phi_i(\vec{r})$$

HOW TO CONSTRUCT REALISTIC WAVE FUNCTION?

Restoration of spontanously broken symmetries

$$|\varphi_i; IMK; TT_z\rangle = \frac{1}{\sqrt{\mathcal{N}}} \hat{P}^T_{T_z T_z} \hat{P}^I_{MK} |\varphi_i\rangle$$

Isospin and K-quantum number mixing

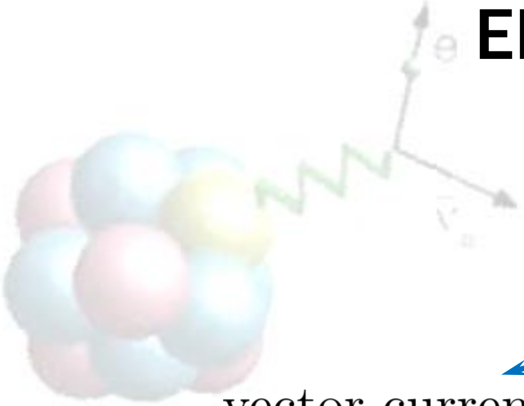
$$|\varphi_i; I_n M; T_z\rangle = \sum_{n,K,T\geq|T_z|} a^{\varphi_i}_{nIT} |\varphi_i; I^\pi MK; TT_z\rangle$$

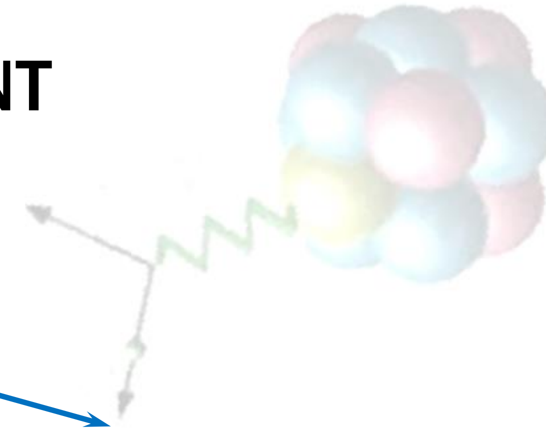
NCCI method:

$$|\Phi, IM; T_z\rangle = \sum_i c_i |\varphi_i; IM; T_z\rangle$$

W. Satułą, et al,
No-Core Configuration-Interaction model for the isospin- and angular-momentum projected states
Phys. Rev.C **94** 024306 (2016)

ELECTROWEAK CURRENT





$$j^\mu = \frac{1}{2}\bar{\Psi}\gamma^\mu(1 \mp \gamma^5)\Psi$$

vector current (Fermi decay)	axial-vector current (Gamow-Teller decay)
$\hat{O}_F = \tau$	$\hat{O}_{GT} = \sigma\tau$

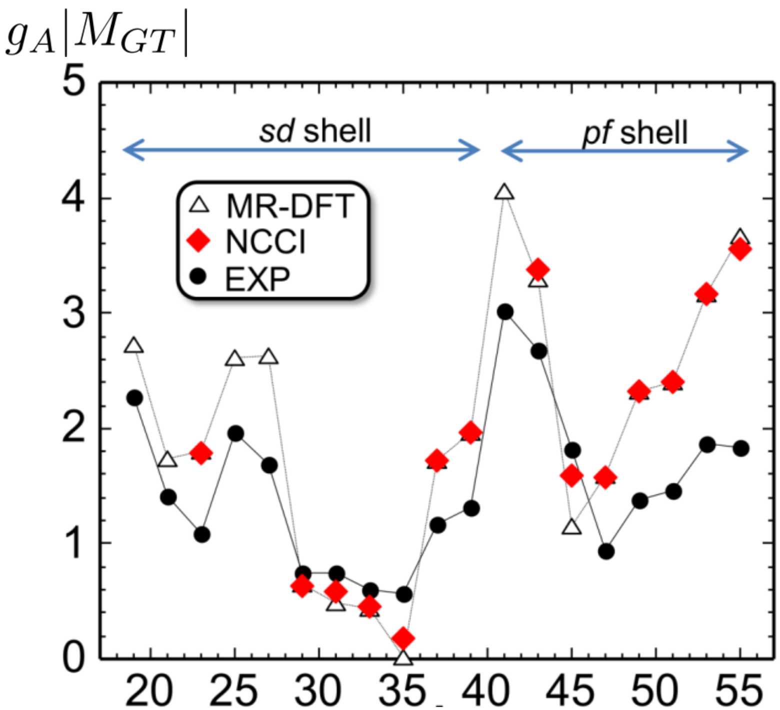
$$|H_{if}|^2 = \frac{g_V^2}{2J_i+1}|M_F|^2 + \frac{g_A^2}{2J_i+1}|M_{GT}|^2$$

CVC hypothesis	PCAC hypothesis
superallowed Fermi beta decay	the quenching effect of g_A

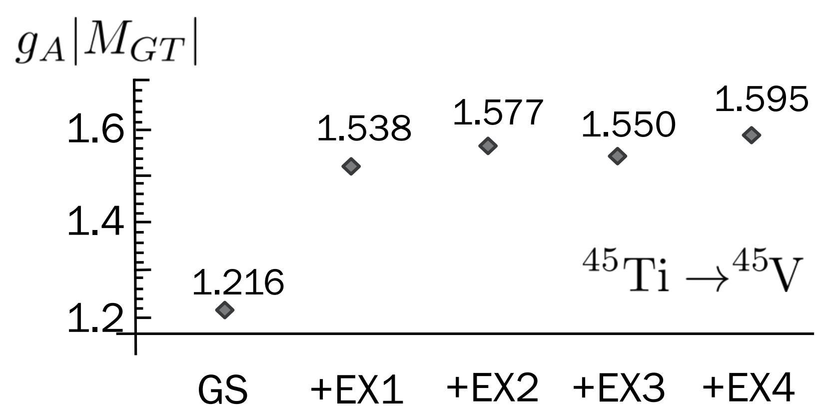
W. Satuła, et al,
Beta-decay study within multi-reference DFT
Phys. Rev. Lett. **106** 132502 (2011)

M. Konieczka, et al,
Beta-decay study within multi-reference DFT
Phys. Rev.C **93** 042501(R) (2016)

GAMOW TELLER BETA DECAY – MIRROR NUCLEI GS TO GS TRANSITIONS IN NCCI



NCCI calculations usually with 3 -5 configurations included



Convergence at MR-DFT !!!

Except for A=45 transition configuration mixing does not change the MR-DFT result !!!

M. Konieczka, et al,
Beta-decay study within multi-reference DFT
Phys. Rev.C **93** 042501(R) (2016)

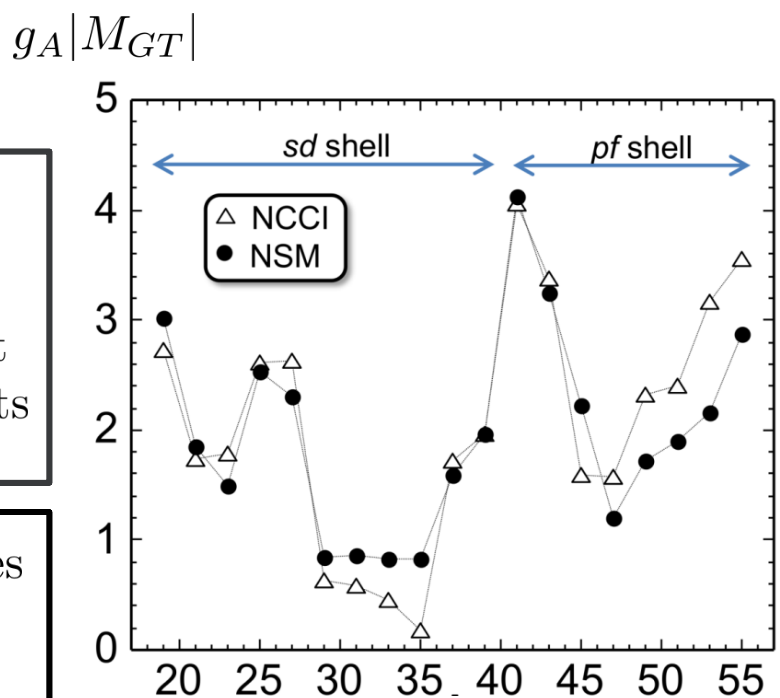
QUENCHING OF AXIAL-VECTOR COUPLING CONSTANT

NCCI vs NSM

NCCI is free from a core approximation and takes into account core polarization effects

Different model spaces

Different treatment of correlations



Quenching – possible solutions:

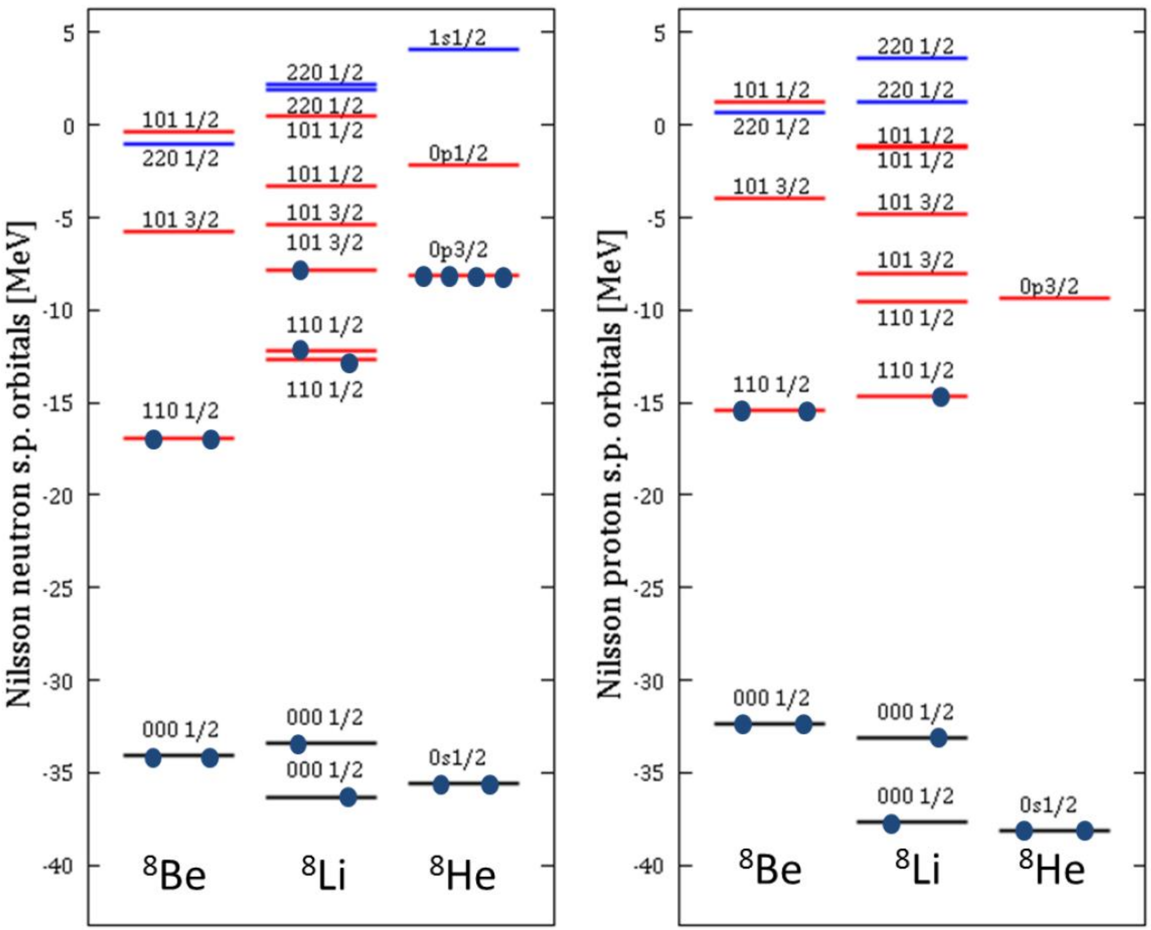
- ~~non-nucleonic degree of freedom~~
- ~~The effect of core approximation~~
- two-body currents

$g_A^{\rm eff} = q g_A$ Quenching of g_A $g_A \approx 1.2701$

q	MR-DFT	NCCI	NSM
sd-shell	0.77	0.78	0.77
pf-shell	0.75	0.69	0.74

M. Konieczka, et al,
Beta-decay study within multi-reference DFT
Phys. Rev.C **93** 042501(R) (2016)

CONFIGURATION SPACE OF NCCI FOR A=8



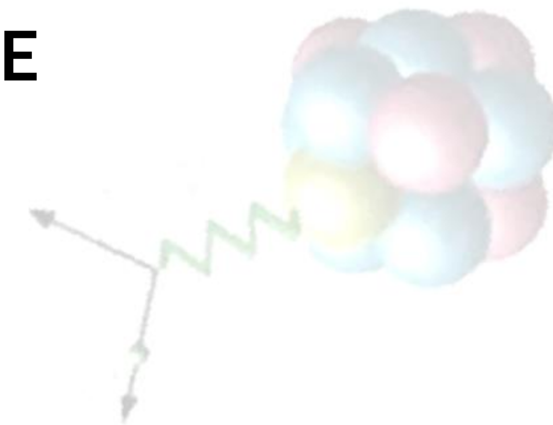
<u>**Isospin restoration**</u>

↓

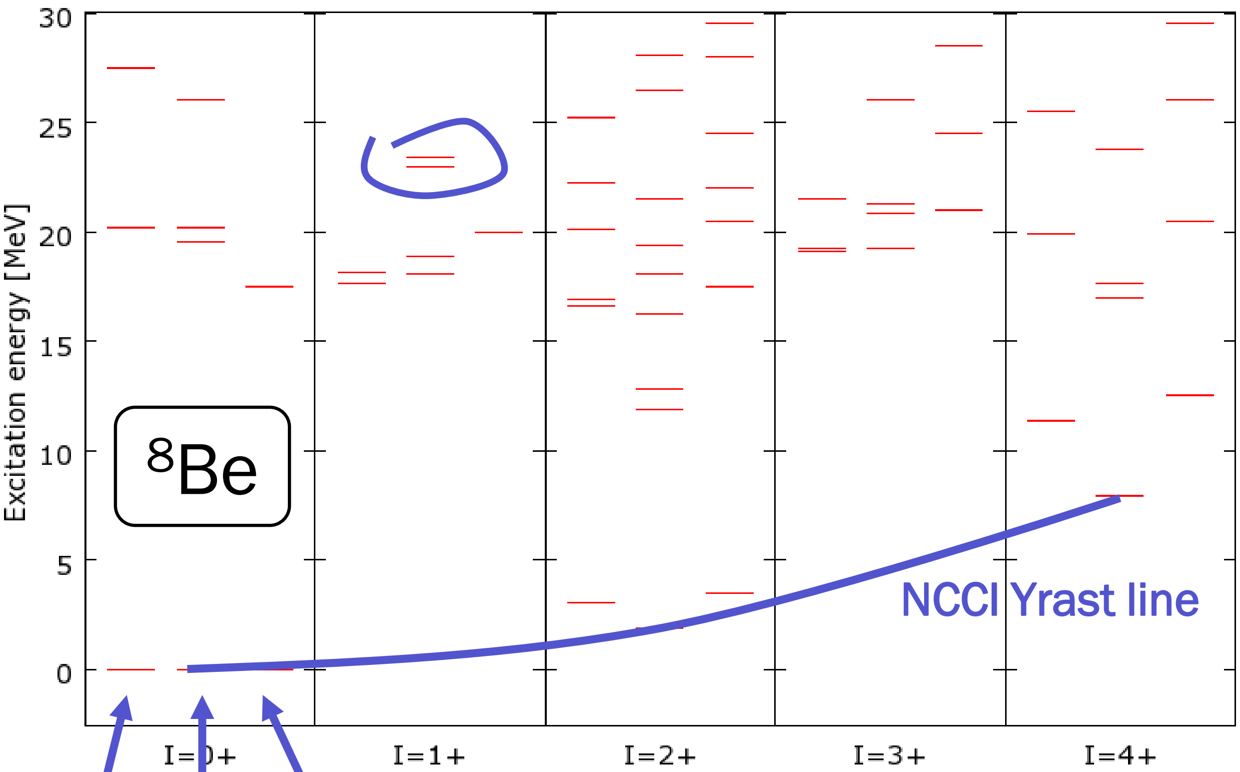
one nucleonic-type excitation only in N=Z nuclei

8Be – 5 1p1h config.
8Li – 12 1p1h config.
8He – 5 1p1h config.

SPECTROSCOPY OF 8BE



Unassigned doublet in the exp of about 23MeV



Characteristics of 8Be GS

- $$R_{4/2} = \frac{E_{I=4_1^+}}{E_{I=2_1^+}}$$

EXP	TH
3.75	3.77

- deformation parameters

$$\beta_2 = 0.69$$

$$r_x = 1.09\mathrm{fm}, r_y = 1.09\mathrm{fm}, r_z = 1.96\mathrm{fm}$$

Root-mean-square radii

EXP

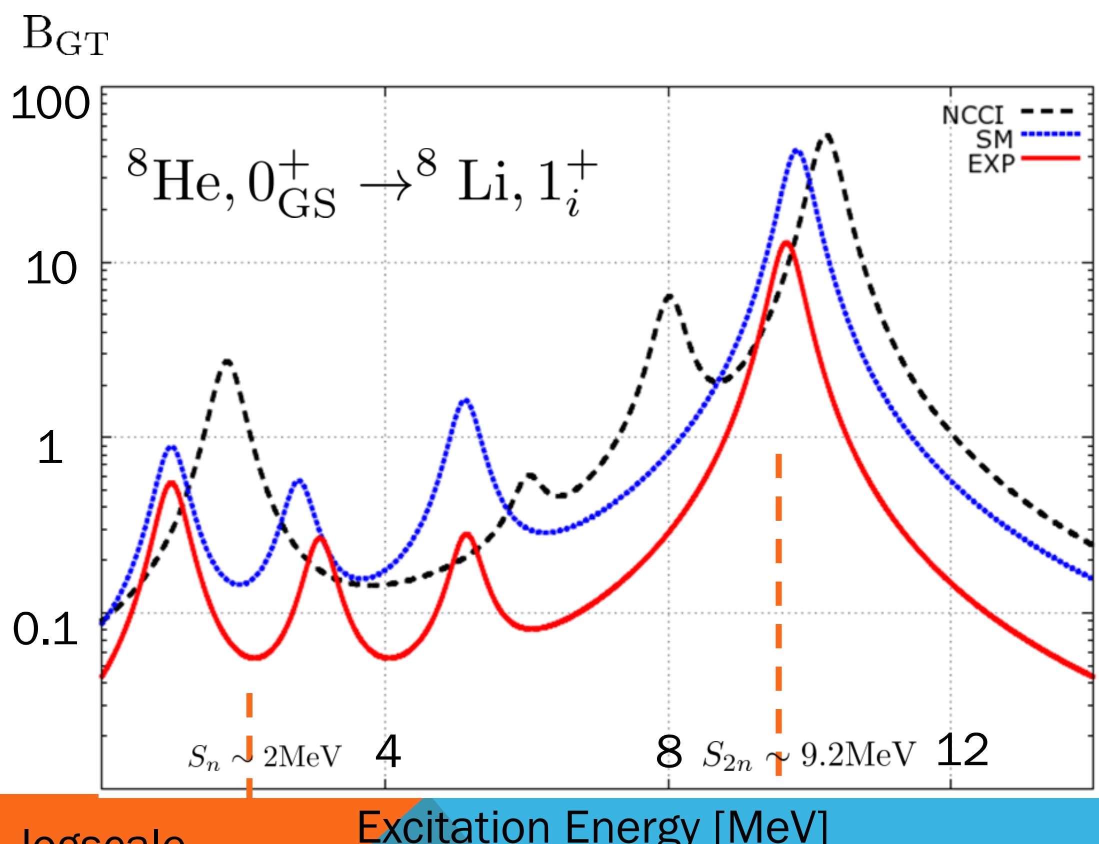
NCCI

M. Konieczka, et al, in preparation

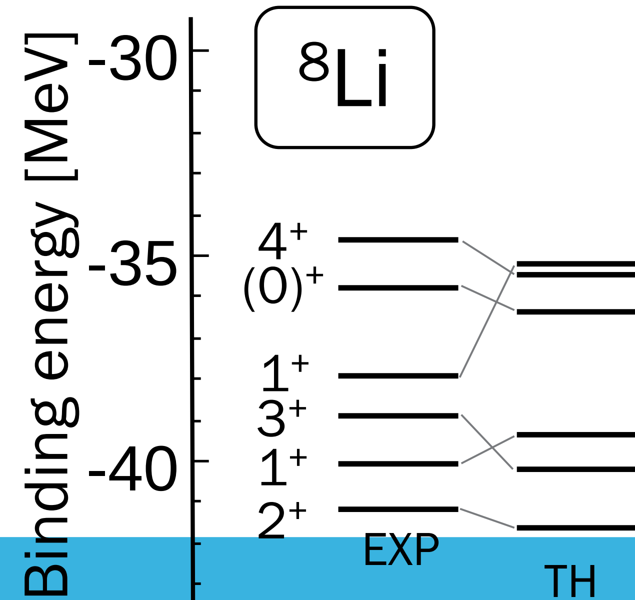
AB-INITIO

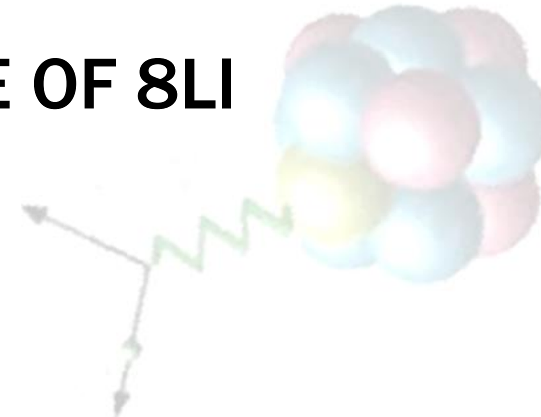
P. Maris, et al, Phys. Rev.C **91** 014310 (2015)

GAMOW-TELLER RESPONSE OF 8LI



logscale



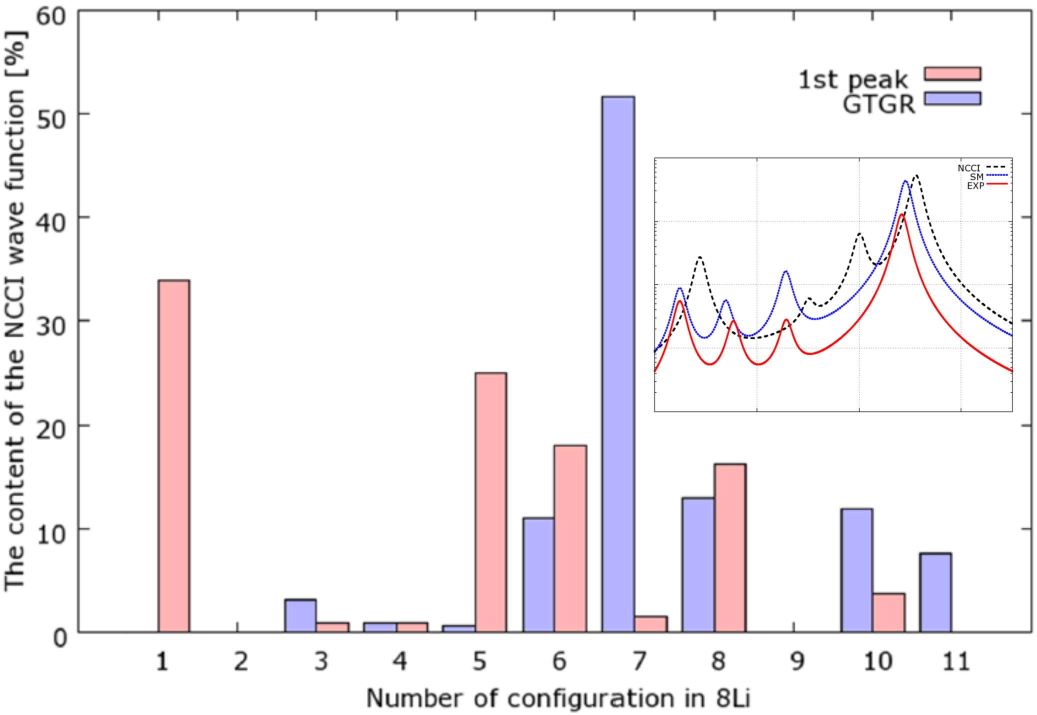


Shell-Model: F.C. Barker, E.K. Warburton, Nuc. Phys. A **487**, 269 (1988).

M. Konieczka, et al, in preparation

GAMOW-TELLER RESPONSE OF 8LI

i	$\vert{}^8\mathrm{Li};\varphi_i\rangle$	E_{HF}	β_2	γ	K
1	$\vert\nu 101\,3/2+\rangle\otimes\vert\pi 110\,1/2-\rangle$	−39.08	0.38	0°	1_Z
2	$\vert\nu 101\,3/2+\rangle\otimes\vert\pi 110\,1/2+\rangle$	−39.03	0.36	0°	2_Z
3	$\vert\nu 101\,1/2+\rangle\otimes\vert\pi 110\,1/2+\rangle$	−34.04	0.36	0°	1_Z
4	$\vert\nu 101\,1/2-\rangle\otimes\vert\pi 110\,1/2+\rangle$	−33.44	0.35	0°	0_Z
5	$\vert\nu 110\,1/2+\rangle\otimes\vert\pi 110\,1/2-\rangle$	−36.51	0.04	60°	0_Z
6	$\vert\nu 101\,3/2-\rangle\otimes\vert\pi 101\,3/2+\rangle$	−35.68	0.03	0°	0_Y
7	$\vert\nu 101\,1/2-\rangle\otimes\vert\pi 110\,1/2-\rangle$	−31.19	0.03	60°	1_Z
8	$\vert\nu 101\,3/2-\rangle\otimes\vert\pi 101\,3/2+\rangle$	−35.54	0.03	0°	0_X
9	$\vert\nu 101\,3/2+\rangle\otimes\vert\pi 101\,1/2+\rangle$	−32.34	0.12	0°	2_Z
10	$\vert\nu 101\,3/2-\rangle\otimes\vert\nu 110\,1/2-\rangle$ $\otimes\vert\nu 101\,1/2+\rangle\otimes\vert\pi 101\,3/2+\rangle$	−29.25	0.02	60°	0_Y
11	$\vert\nu 101\,3/2-\rangle\otimes\vert\nu 110\,1/2+\rangle$ $\otimes\vert\nu 101\,1/2+\rangle\otimes\vert\pi 101\,3/2+\rangle$	−29.06	0.03	60°	1_Y

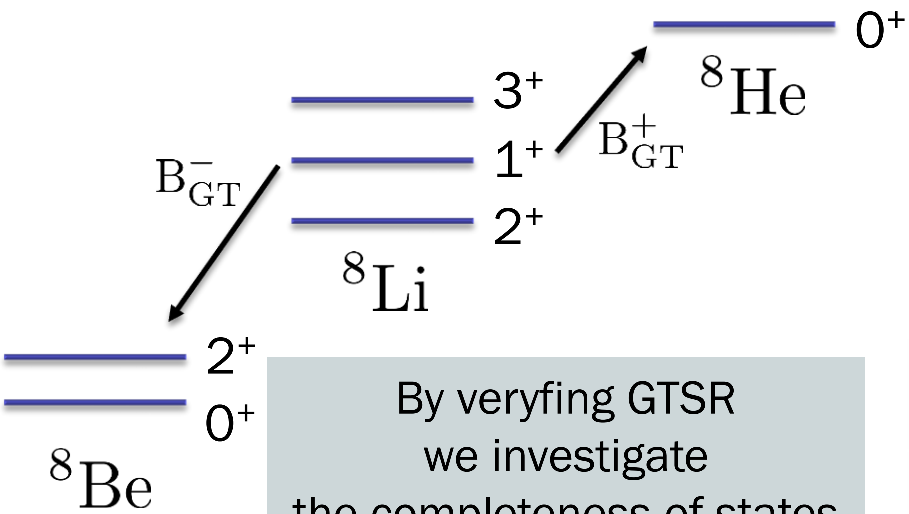


i	$\vert{}^8\mathrm{He};i\rangle$	E_{HF}	β_2	γ	$\langle j\rangle$
1	$\nu p_{3/2}\otimes\pi s_{1/2}$	−37.26	0	0°	0
2	$\vert\nu 101\,3/2-\rangle^{-1}\otimes\vert\nu 101\,1/2+\rangle^{1}$	−32.47	0.14	0°	2_Z
3	$\vert\nu 101\,3/2+\rangle^{-1}\otimes\vert\nu 101\,1/2-\rangle^{1}$	−30.81	0.03	60°	1_Y
4	$\vert\nu 110\,1/2+\rangle^{-1}\otimes\vert\nu 101\,1/2+\rangle^{1}$	−30.04	0.03	60°	0_Y
5	$\vert\nu 110\,1/2+\rangle^{-1}\otimes\vert\nu 101\,1/2-\rangle^{1}$	−29.13	0.02	0°	1_Z

NCCI gives an opportunity to get the physical meaning of a GTR function in terms of mean field configurations !!!

GAMOW-TELLER SUM RULE

$$\sum_f \left[\mathrm{B}^-_{\mathrm{GT}}(I_i^\pi \to I_f^\pi) - \mathrm{B}^+_{GT}(I_i^\pi \to I_f^\pi) \right] = 3(N-Z)$$

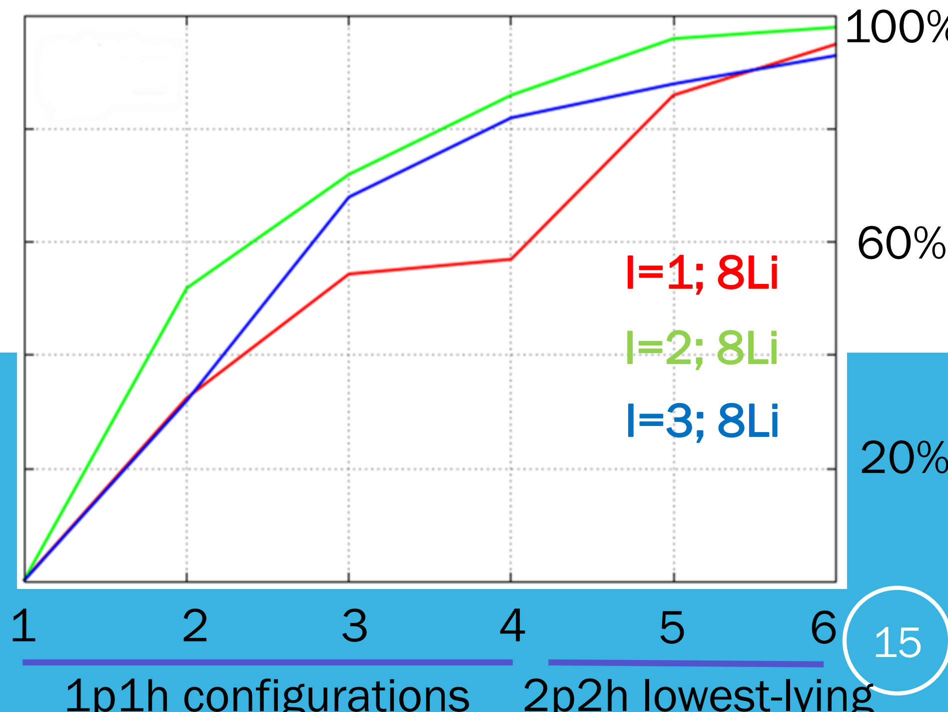


By veryfing GTSR
we investigate
the completeness of states
with given multipole

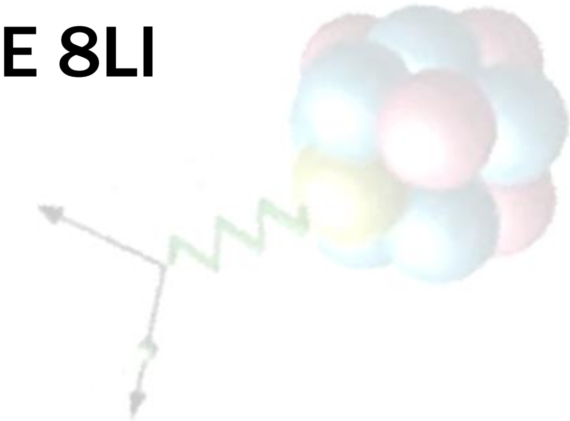
We keep all conf in 8Li and change
only those in 8Be and 8He

1 1p1h configuration in 8Be
cannot be converged; lowest-lying 2p2h
are covering the missing correlations

Sum rule saturation against number of conf in 8Be

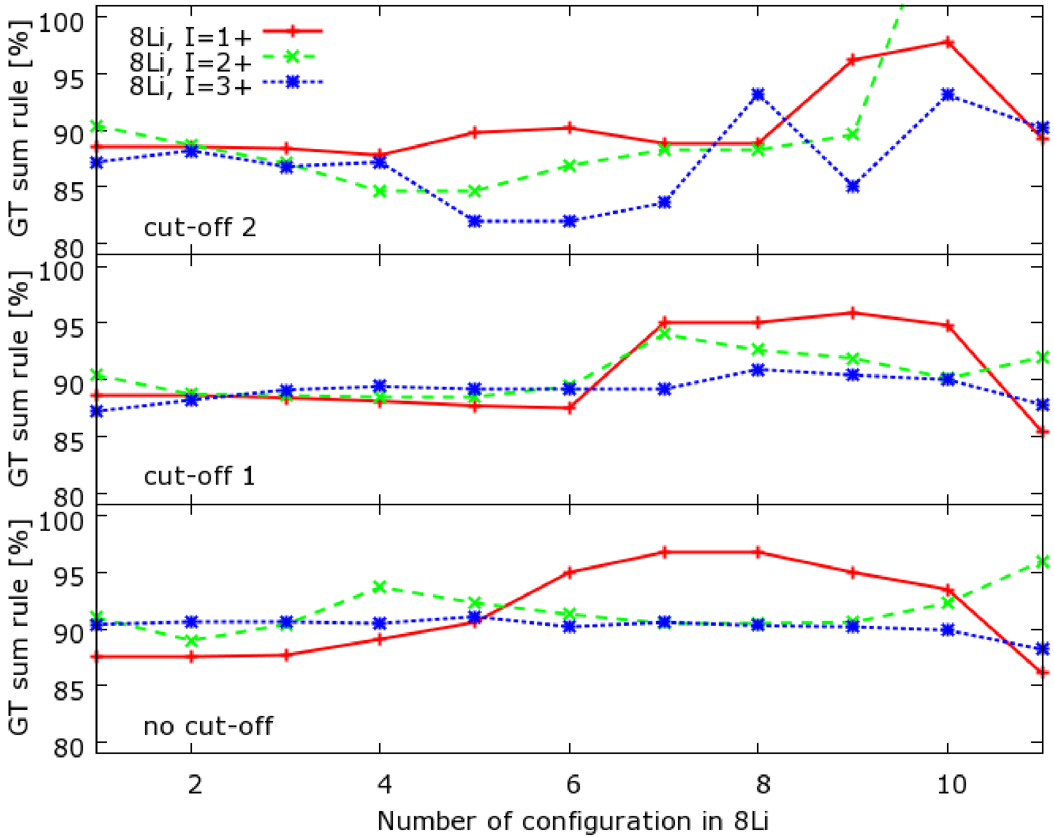


GAMOW-TELLER SUM RULE 8LI



$$\sum_f \left[\mathrm{B}^{-}_{\mathrm{GT}}(I_i^\pi \to I_f^\pi) - \mathrm{B}^{+}_{GT}(I_i^\pi \to I_f^\pi) \right] = 3(N-Z)$$

Gamow-Teller sum rule saturation
against numer of configurations in 8Li

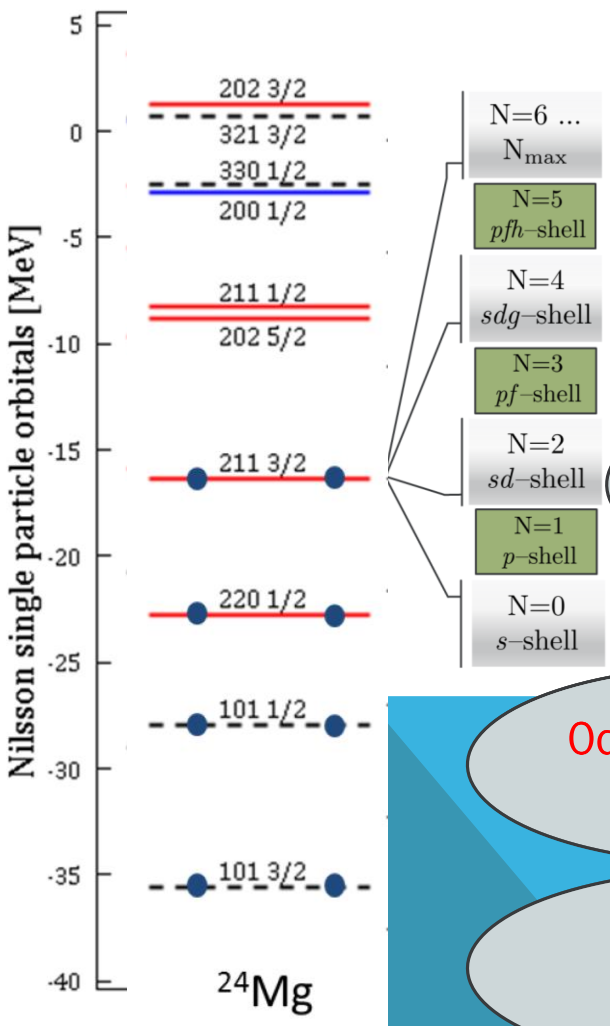


Cut-off on very low (0.001) eigenvalues of norm matrix

No cut-off

M. Konieczka, et al, in preparation

GAMOW-TELLER RESPONSE OF 24MG



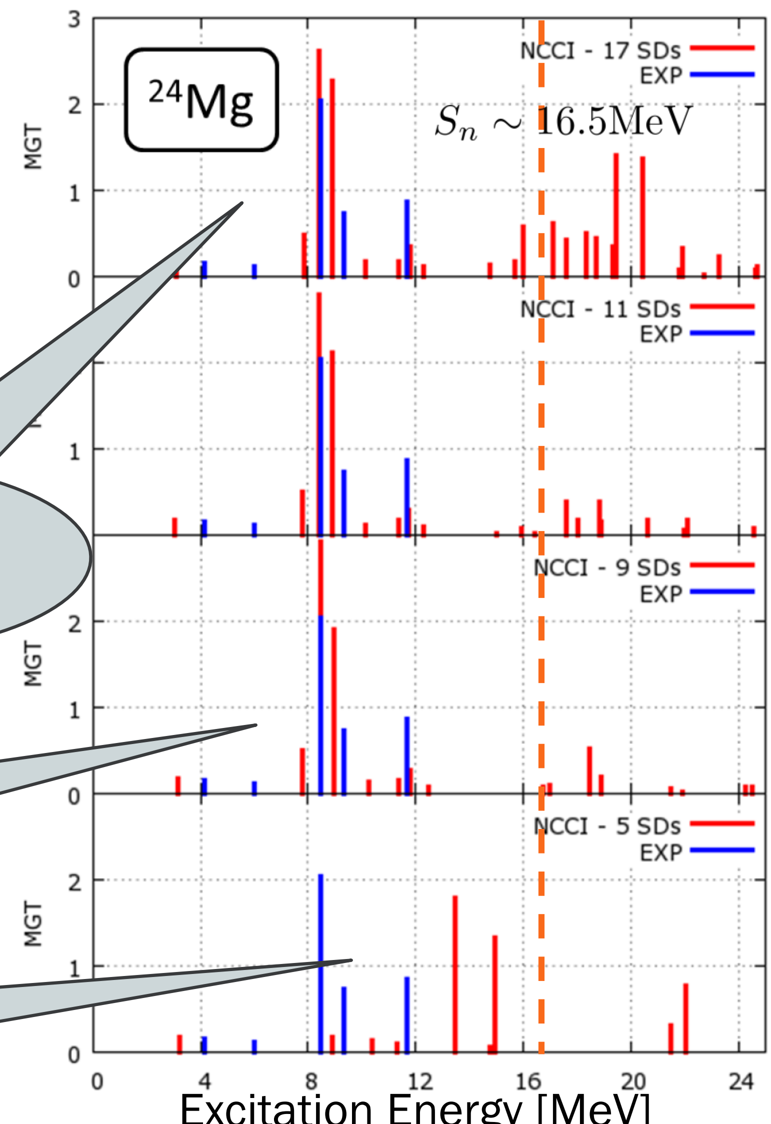
<u>Isospin restoration</u>

↓

neutron excitation only in N=Z nuclei

In overall 17 1p1h configurations

$^{24}\mathrm{Al}, 4^+_{\mathrm{GS}} \rightarrow {}^{24}\mathrm{Mg}, (3^+_i, 4^+_i, 5^+_i)$



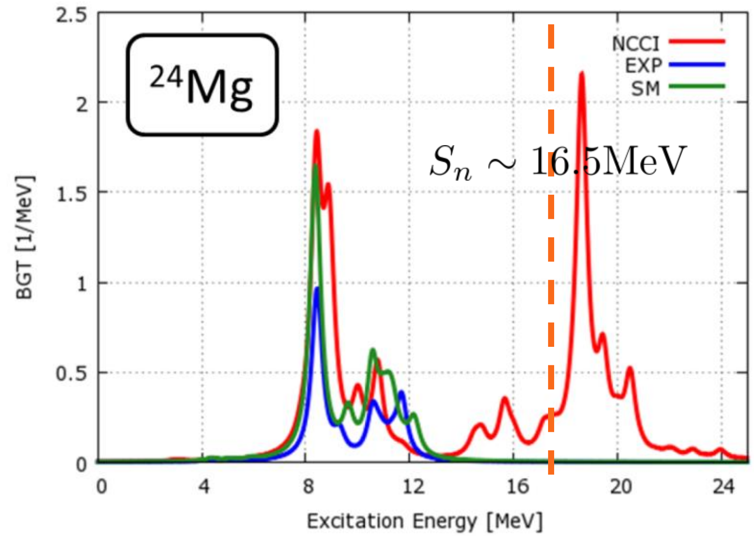
entire sd-shell

0d5/2 + 211 ½ (0d3/2)

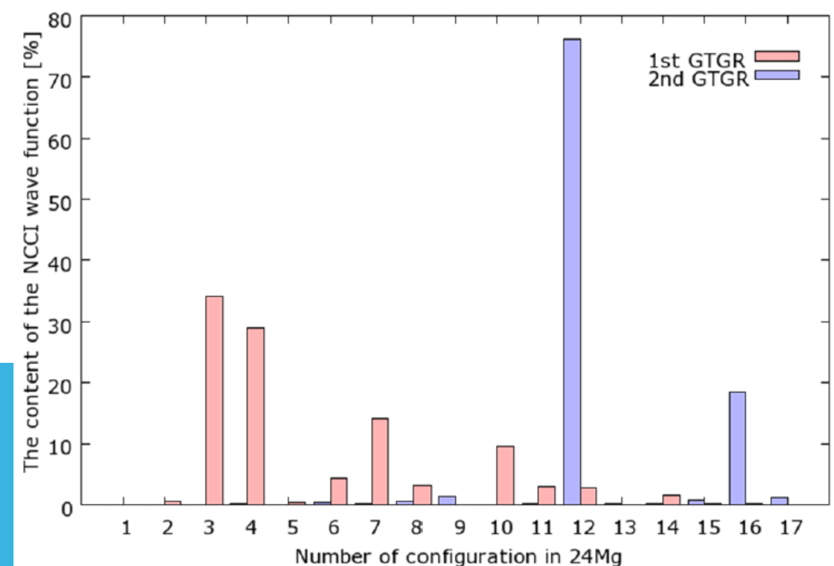
0d5/2 only

GAMOW-TELLER RESPONSE OF 24MG

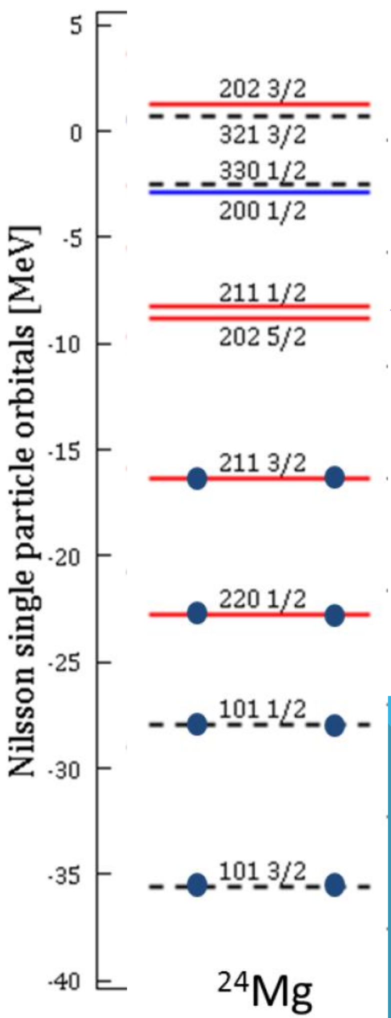
i	$\|{}^{24}\text{Mg}; i\rangle$	E_{HF}	β_2	γ	K
1	g.s.	−194.33	0.42	0°	0
2	$\|\nu 211\,3/2-\rangle^{-1} \otimes \|\nu 202\,5/2-\rangle^{1}$	−187.92	0.34	0°	1_Z
3	$\|\nu 211\,3/2+\rangle^{-1} \otimes \|\nu 202\,5/2-\rangle^{1}$	−187.25	0.34	0°	4_Z
4	$\|\nu 211\,3/2+\rangle^{-1} \otimes \|\nu 211\,1/2-\rangle^{1}$	−187.46	0.43	0°	2_Z
5	$\|\nu 211\,3/2-\rangle^{-1} \otimes \|\nu 211\,1/2-\rangle^{1}$	−184.89	0.40	0°	1_Z
6	$\|\nu 220\,1/2-\rangle^{-1} \otimes \|\nu 202\,5/2-\rangle^{1}$	−183.34	0.24	0°	2_Z
7	$\|\nu 220\,1/2+\rangle^{-1} \otimes \|\nu 202\,5/2-\rangle^{1}$	−183.27	0.23	0°	3_Z
8	$\|\nu 211\,3/2+\rangle^{-1} \otimes \|\nu 200\,1/2+\rangle^{1}$	−181.79	0.36	0°	1_Z
9	$\|\nu 211\,3/2+\rangle^{-1} \otimes \|\nu 200\,1/2-\rangle^{1}$	−181.50	0.34	0°	2_Z
10	$\|\nu 220\,1/2+\rangle^{-1} \otimes \|\nu 211\,1/2-\rangle^{1}$	−181.99	0.35	0°	1_Z
11	$\|\nu 220\,1/2-\rangle^{-1} \otimes \|\nu 211\,1/2-\rangle^{1}$	−180.78	0.33	0°	0_Z
12	$\|\nu 211\,3/2-\rangle^{-1} \otimes \|\nu 202\,3/2+\rangle^{1}$	−178.83	0.34	0°	3_Z
13	$\|\nu 211\,3/2+\rangle^{-1} \otimes \|\nu 202\,3/2+\rangle^{1}$	−177.16	0.33	0°	0_Z
14	$\|\nu 220\,1/2-\rangle^{-1} \otimes \|\nu 200\,1/2-\rangle^{1}$	−177.04	0.27	0°	0_Z
15	$\|\nu 220\,1/2+\rangle^{-1} \otimes \|\nu 200\,1/2-\rangle^{1}$	−176.94	0.25	0°	1_Z
16	$\|\nu 220\,1/2-\rangle^{-1} \otimes \|\nu 202\,3/2+\rangle^{1}$	−174.00	0.25	0°	2_Z
17	$\|\nu 211\,3/2+\rangle^{-1} \otimes \|\nu 202\,3/2+\rangle^{1}$	−173.47	0.24	0°	1_Z



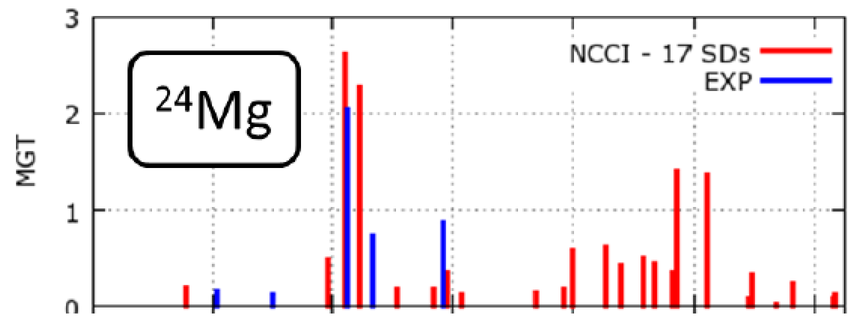
The content of GT resonances



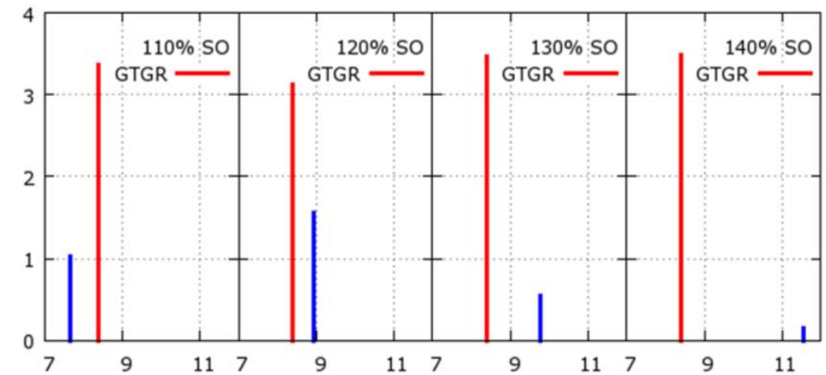
SPIN-ORBIT DETECTOR FOR SP ORBITALS ?



202 5/2 and 211 1/2 mix strongly



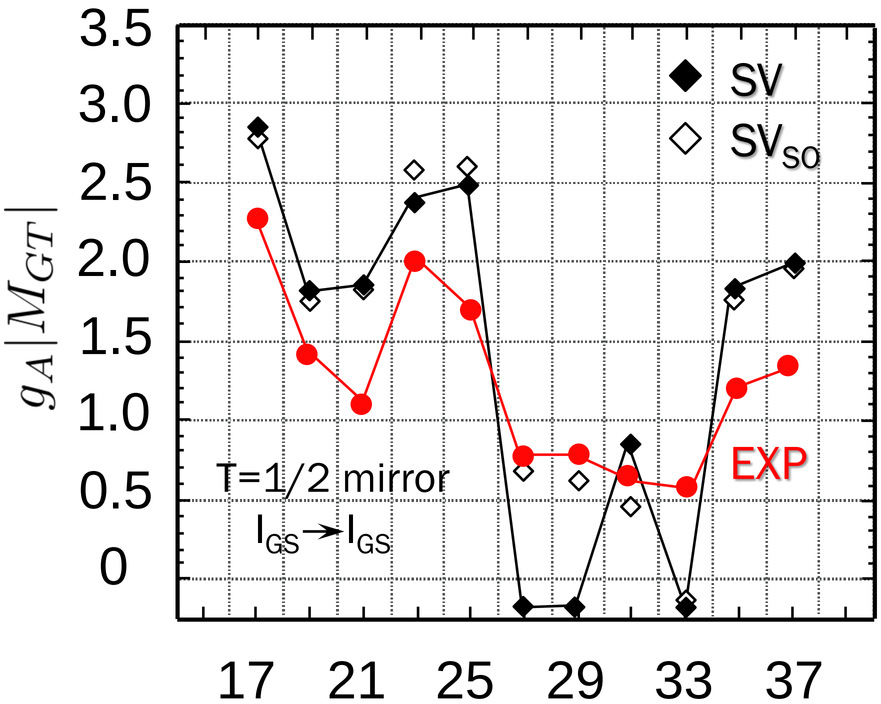
The change of peaks with the change of the strength of the spin-orbit interaction

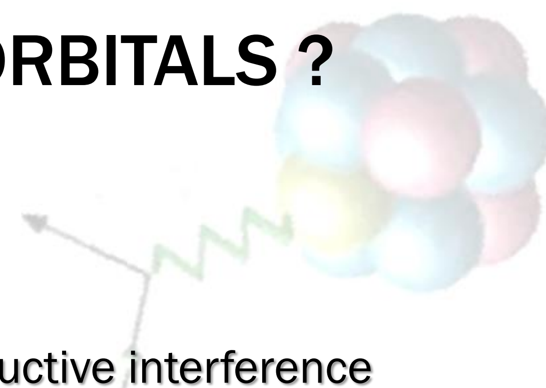


The change of peaks with the change of the strength of the spin-orbit interaction

Preliminary results published:
M. Konieczka, et al,
Nuclear structure calculations in 20Ne with NCCI model
Acta Phys. Pol. B**48** 293 (2017)

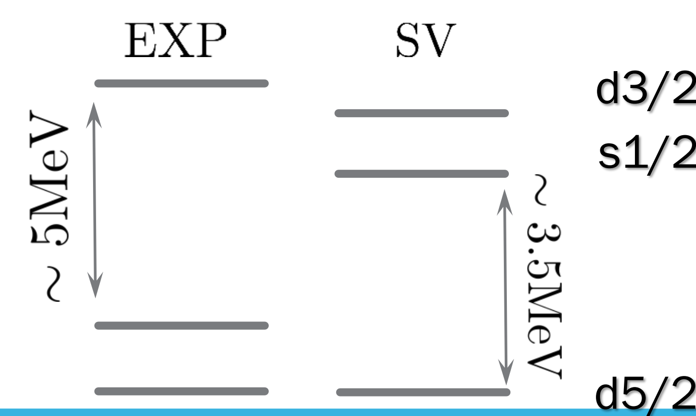
SPIN-ORBIT DETECTOR FOR SP ORBITALS ?



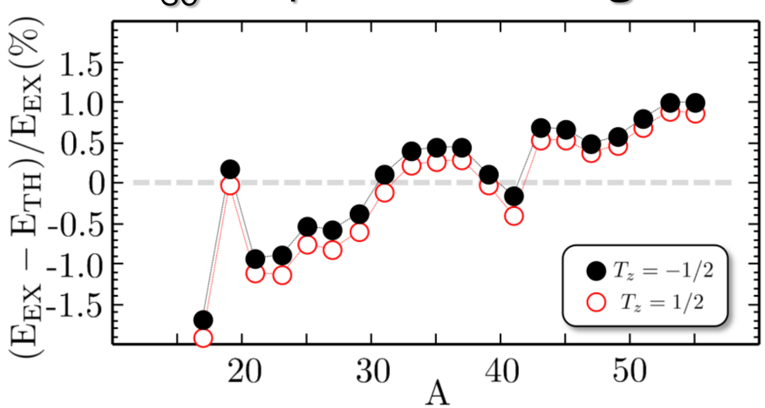


destructive interference
of $1s_{1/2}$ and $0d_{3/2}$ subshell

Single particle energies (sd shell) in ^{17}O



SV_{SO} - Spin- orbit tunning



$$\mathcal{M}^{sp}_{GT}(1s_{1/2}1s_{1/2}) = \sqrt{2} \approx 1.4$$

$$\mathcal{M}^{sp}_{GT}(0d_{3/2}0d_{3/2}) = -\frac{2}{\sqrt{5}} \approx -0.9$$

SUMMARY AND OUTLOOK

MR-DFT and NCCI results show that

1. MR-DFT and NCCI results are fully consistent in Fermi MEs
2. MR-DFT and NCCI results are fully consistent in GT ME calculations of mirror nuclei (T=1/2) except for A=45 transition

MR-DFT seems to be sufficient to describe transitions between ground states

3. The quenching effect does not depend on the core approximation.

4. NCCI is able to capture general feature of Gamow-Teller response in ^{8}Li.
5. Small amount of NCCI states is sufficient to satisfy 90% of GTSR
6. The spin-orbit int. may indicate the physical spacing between orbitals

VERY PRELIMINARY !!!

OTHER FIELDS OF INTENSIVE WORK

pn mixing correlations – PhD project of Paweł Bączyk

Zero-range tensor intetraction

3D projection on isospin from HFB reference states

double beta decay, neutrino-nucleus scattering

Rozpad beta w uogólnionym modelu funkcjonału gęstości

Seminarium Fizyki Jądra Atomowego, 18.05.2017

Our team:

Wojciech Satuła

Jacek Dobaczewski

Markus Korteleinen

Paweł Bączyk

Dziękuję za uwagę!