Shell evolution and collectivity in model spaces above ^{78}Ni and ^{132}Sn cores

Kamila Sieja

Institut Pluridisciplinaire Hubert Curien, Strasbourg

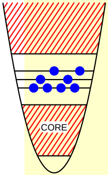
International Collaborations in Nuclear Theory:
Theory for open-shell nuclei near the limits of stability

26.05.2015

Shell model approach

Calculations Ab Initio

- Realistic NN interactions
- Diagonalization in $N\hbar\omega$ h.o.space



- define valence space
- $H_{\rm eff}\Psi_{\rm eff} = E\Psi_{\rm eff}$

⇝ INTERACTIONS

- build and diagonalize Hamiltonian matrix

⇝ CODES

Weak processes:

- β decays
- $\beta\beta$ decays

$[T^{0\nu}_{1/2}(0^+ \to 0^+)]^{-1} = G_{0\nu}|M^{0\nu}|^2\langle m_\nu\rangle^2$

☞ASTROPHYSICS

☞PARTICLE PHYSICS

Collective excitations:

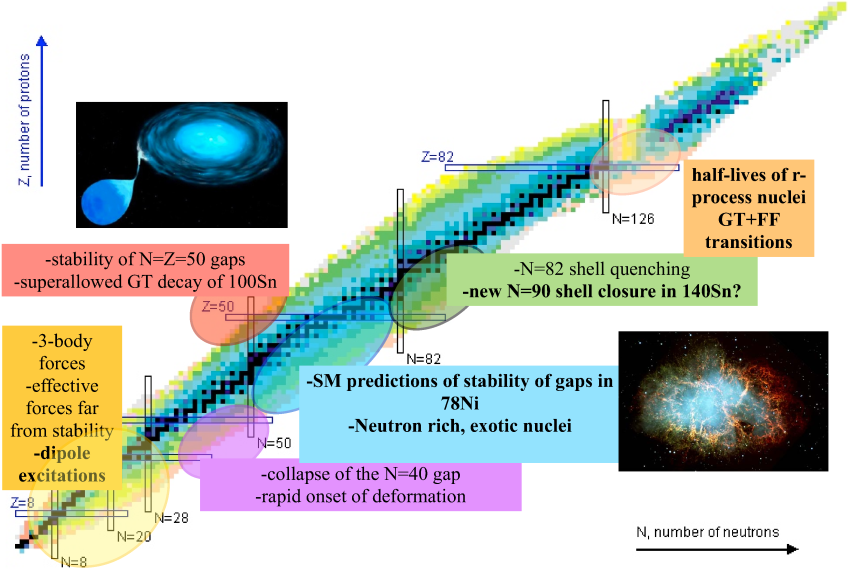
- deformation, superdeformation
- superfluidity
- symmetries

Shell evolution far from stability:

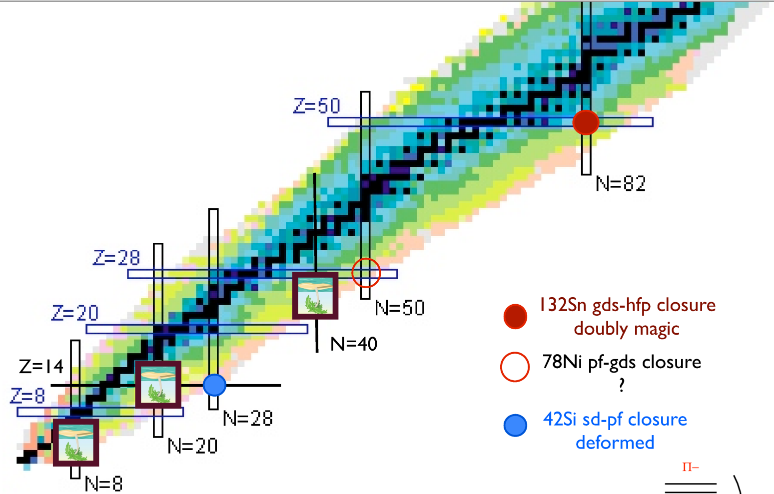
- Shell quenching
- New magic numbers

☞ASTROPHYSICS

SM with empirical interactions: regions of activity



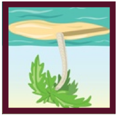
Shell evolution: what have we learned ?



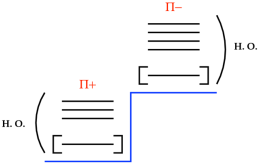
132Sn gds-hfp closure
doubly magic

78Ni pf-gds closure
?

42Si sd-pf closure
deformed



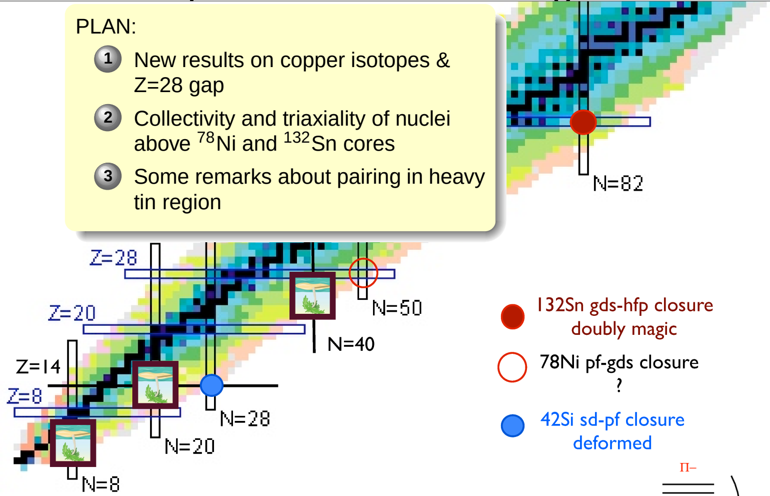
Island of inversion=region of sudden deformation in nuclei with a h.o. neutron shell closure



SM with empirical interactions: regions of activity

PLAN:

1. New results on copper isotopes & Z=28 gap
2. Collectivity and triaxiality of nuclei above ^{78}Ni and ^{132}Sn cores
3. Some remarks about pairing in heavy tin region



132Sn gds-hfp closure doubly magic

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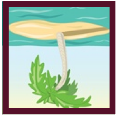

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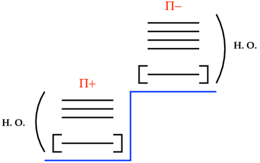
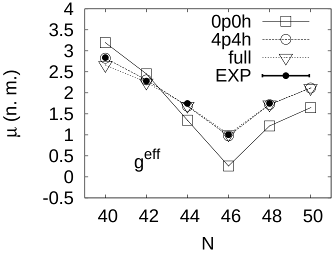
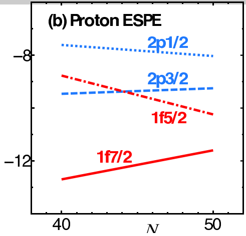
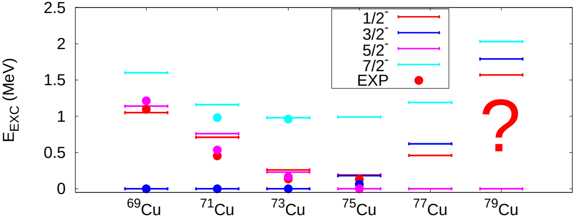




- crucial role of proton-core excitation for the description of magnetic moments

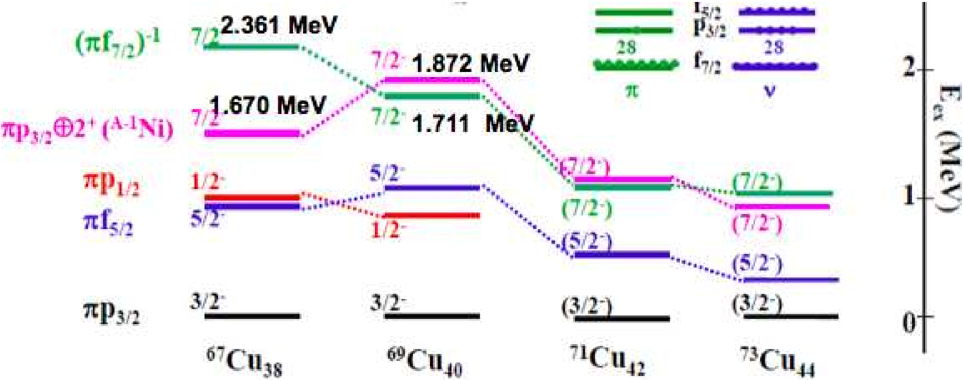


- crossing of $\pi p_{3/2}$-$f_{5/2}$ orbitals with the filling of the $\nu g_{9/2}$
- reduction of the $Z = 28$ gap in ^{78}Ni due to the tensor force



K. Sieja et al., Phys. Rev. C81 (2010) 061303R

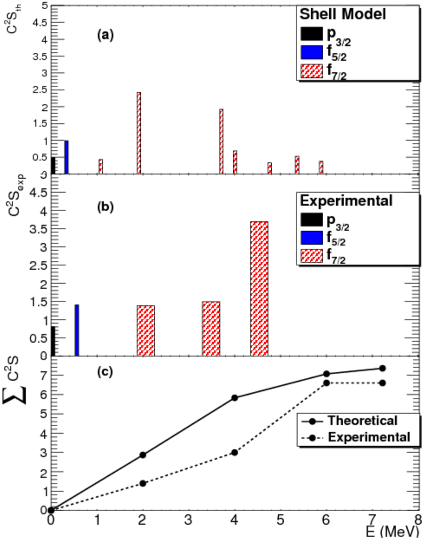
Shell evolution in coppers: $7/2^-$ states



^{71}Cu - SF

- Calculations in πpf-$\nu fpgd$ model space with updated LNPS interaction
  S. M. Lenzi et al., Phys. Rev. C82 (2010) 054301

E (MeV)	J^π	Percentage	Composition
0	$3/2^-$	60%	$0^+_\nu \otimes \pi p_{3/2}$
		14%	$2^+_\nu \otimes \pi p_{3/2}$
0.31	$5/2^-$	36%	$0^+_\nu \otimes \pi f_{5/2}$
		22%	$4^+_\nu \otimes \pi f_{5/2}$
1.09	$7/2^-$	47%	$2^+_\nu \otimes \pi p_{3/2}$
		11%	$4^+_\nu \otimes \pi p_{3/2}$
		10%	$J^+_\nu \otimes \pi f^{-1}_{7/2}$
1.41	$7/2^-$	42%	$2^+_\nu \otimes \pi f_{5/2}$
		12%	$4^+_\nu \otimes \pi f_{5/2}$
		13%	$J^+_\nu \otimes \pi f^{-1}_{7/2}$



P. Morfouace, S. Franchoo, K. Sieja et al., submitted

Shell evolution in copper isotopes: ^{69,71,73}Cu - B(E2)

Nucleus	$J_f^\pi \to J_i^\pi$	E_γ (keV)	B(E2) (e^2fm^4)	EXP
^{69}Cu	$5/2_1^- \to 3/2_1^-$	1156	28.5	50(8)
	$7/2_1^- \to 3/2_1^-$	1804	46	77(12)
	$7/2_2^- \to 3/2_1^-$	2101	0.05	1.5
^{71}Cu	$5/2_1^- \to 3/2_1^-$	276	54	68(8.8)
	$7/2_1^- \to 3/2_1^-$	1115	179	187(2)
	$7/2_2^- \to 3/2_1^-$	1426	14.4	44(20)?
	$3/2_2^- \to 3/2_1^-$	1144	10.4	44(20)?
^{73}Cu	$5/2_1^- \to 3/2_1^-$	62	65	80(9)
	$7/2_1^- \to 3/2_1^-$	875	251	270(3)
	$7/2_2^- \to 5/2_1^-$	1128	0.02	20(11)?
	$5/2_2^- \to 5/2_1^-$	1203	11.4	20(11)?

$\pi p_{3/2} \otimes \nu 2^+$

$\pi f_{5/2} \otimes \nu 2^+$

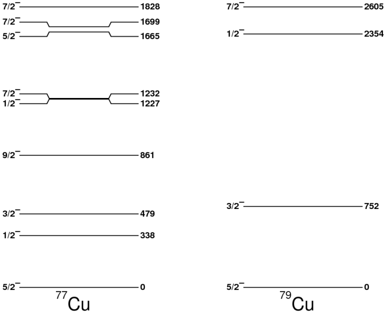
$\pi f_{7/2}^{-1}$

- SM and B(E2)'s consistent with non-observation of low lying strength in ^{71}Cu

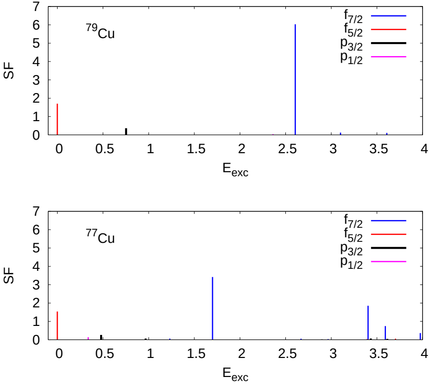
E. Sahin, M. Doncel, K. Sieja et al., Phys. Rev. 91 (2015) 034302

Towards ^{78}Ni: ^{77,79}Cu

Present SM: spectra

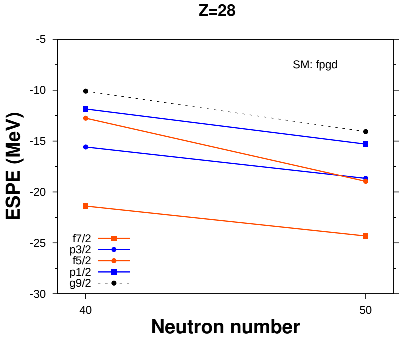


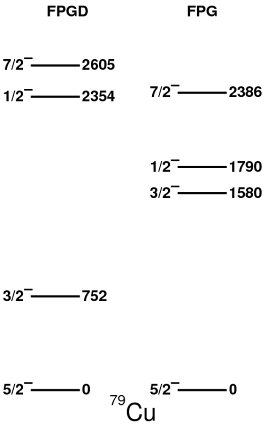
Present SM: SF distributions



- Data from knock-out reactions from RIKEN soon available

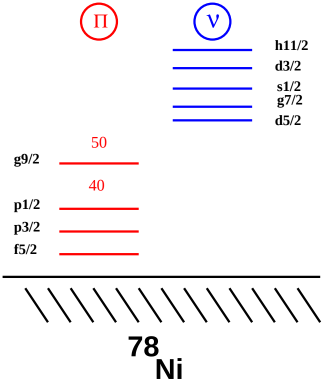
Evolution of proton ESPE in copper isotopes





- Tensor effects seem to be exaggerated (or should be better compensated) in previous interaction in the *fpg* model space.
- 350keV impact on the predicted 2^+ energy of ^{78}Ni (but anyhow missing neutron core excitations).

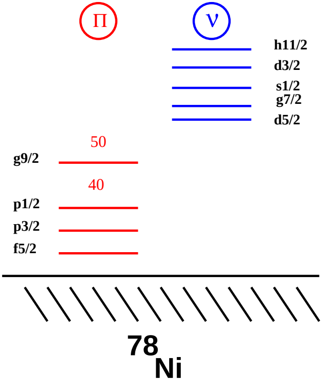
→ see the talk of F. Nowacki for the latest news ☺

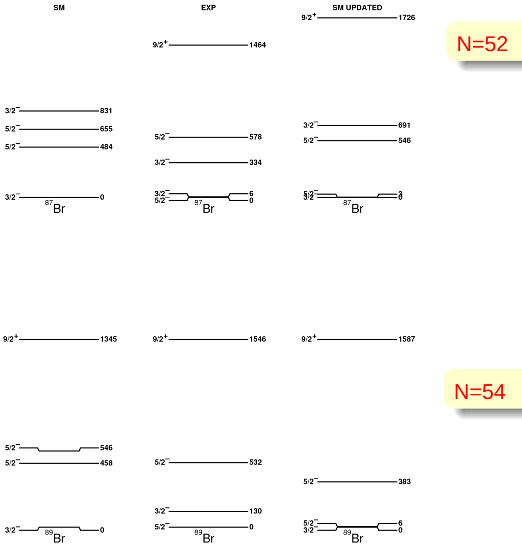


☞Knowing s.p. structure of ^{79}Ni will be useful to validate the model assumptions

Interaction: $\pi\pi$ fit of Lisetskiy & Brown, $\nu\nu$ GCN5082, $\pi\nu$ monopole corrected G-matrix. Proven sucessful and predictive in a large number of applications:

- Structure, mixed symmetry states in Zr isotopes, shell evolution between ^{91}Zr and ^{101}Sn
  K. Sieja et al., Phys. Rev. C79 (2009) 064310
- Isomers and medium-spin structures of ^{95}Y, $^{91-95}$Rb, $^{92-96}$Sr
  PRC85 (2012) 014329, PRC79 (2009) 024319, PRC82 (2010) 024302, PRC79 (2009) 044304
- Collectivity and j-1 anomaly of ^{87}Se
  PRC88 (2013) 034302
- β-decays of Ga nuclei and structure of $N = 52, 54$ isotones
  PRC88 (2013) 047301, PRC88 (2013) 044330, PRC88 (2013) 044314
- Magnetic moments of ^{86}Kr, ^{88}Sr,
  PRC 80 (2014) 064305
- Collectivity of $N = 52, 54$ nuclei
  PRC88 (2013) 034327



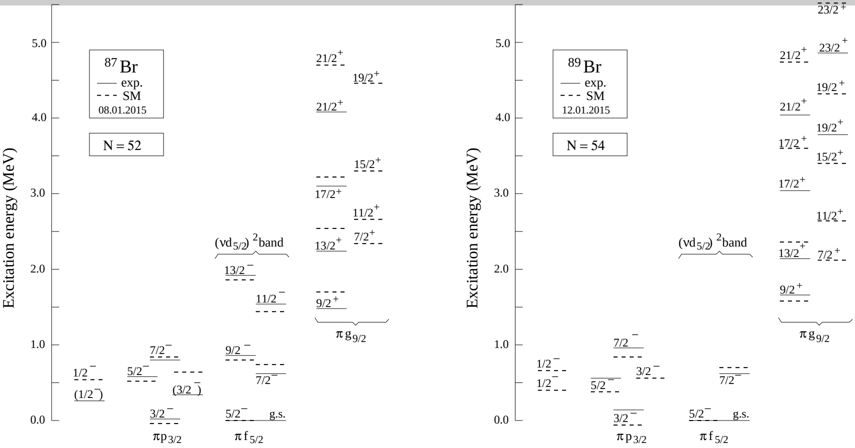


- New estimate of proton $f_{5/2}$-$p_{3/2}$ splitting in the core
- New fit of proton-proton interaction for N=50 isotones, using some new data e.g. ^{83}As from EXILL

P. Baczyk et al., to be published

Nuclei above ^{78}Ni: new developments

Structure of odd and odd-odd nuclei



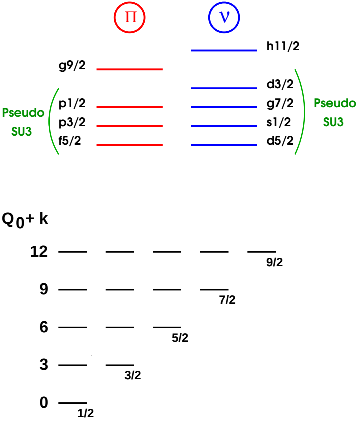
- Satisfactory (*rms* $= 200$keV) description of proton-neutron multiplets in odd-odd nuclei: ^{86,88}Br, ^{90}Rb.

  M. Czerwinski et al., to appear in Phys. Rev. C

  M. Czerwinski et al., to be submitted.

Collectivity and triaxiality above ^{78}Ni

Simple perspective: predictions of the pseudo-SU(3) scheme



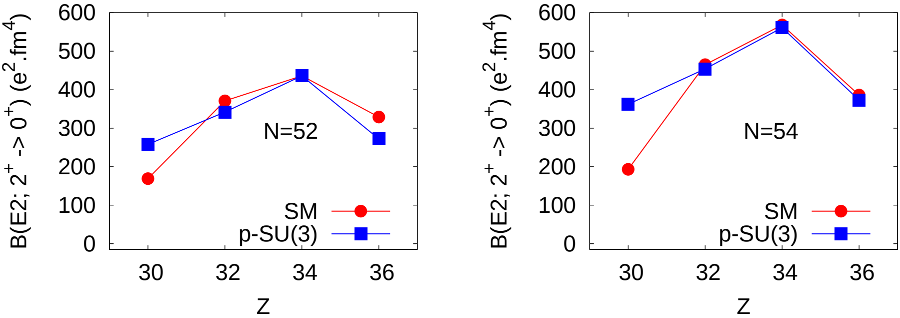
Predictions of pseudo-SU(3) model for N=52,54:

Nucleus	Q_0	$B(E2;2^+ \rightarrow 0^+)$
^{82}Zn	114	258
^{84}Ge	131	342
^{86}Se	148	436
^{88}Kr	117	272
^{84}Zn	135	362
^{86}Ge	151	454
^{88}Se	168	561
^{90}Kr	137	373

- maximal prolate deformation in ^{88}Se
- possible triaxiality in ^{86}Ge

A. P. Zuker et al., Nilsson-SU3 selfconsistency: Quadrupole dominance in heavy N=Z nuclei, http://arxiv.org/abs/1404.0224

Predictions of the pseudo-SU(3) model vs SM diagonalization



☞ pseudo-SU(3) is a good approximation for the proton mid-shell

- maximal prolate deformation in ^{88}Se
- possible triaxiality in ^{86}Ge

Intrinsic shape parameters of shell model states

(Yrast)	State	Q_0	β	γ (deg.)
^{86}Ge	0^+_{gs}	165	0.238	12
	2^+_1	161	0.232	8
	4^+_1	152	0.218	12
	6^+_1	118	0.172	10
^{88}Se	0^+_{gs}	174	0.250	9
	2^+_1	169	0.243	12
	4^+_1	159	0.229	15
	6^+_1	118	0.173	14

(Excited)	State	Q_0	β	γ (deg.)
^{86}Ge	2^+_2	152	0.219	28
	3^+_1	148	0.213	32
	4^+_2	116	0.169	41
	5^+_1	105	0.154	33
^{88}Se	2^+_2	152	0.219	35
	3^+_1	143	0.207	36
	4^+_2	114	0.166	40
	5^+_1	100	0.146	36

$$Q_{int}(s) = \sqrt{\frac{16\pi}{5} p_s^{(2)}}$$

$$\cos 3\gamma(s) = -\sqrt{7/2}\, p_s^{(3)} \left(p_s^{(2)}\right)^{-3/2}$$

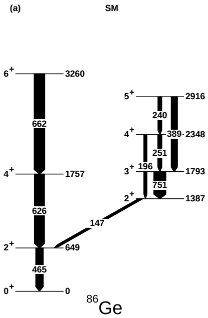
$$\begin{aligned} p_s^{(2)} &= (2I_s+1)^{-1} \sum_r M_{sr}^2 \\ &= \frac{5(I_s+1)(2I_s+3)}{16\pi I_s(2I_s-1)} Q_{spec}^2(s) \\ &+ \sum_{r \neq s} B(E2; s \to r), \end{aligned}$$

M_{sr} = reduced $E2$ matrix elements

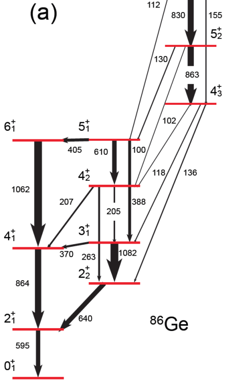
$$p_s^{(3)} = -\sqrt{5}(2I_s+1)^{-1}(-1)^{2I_s}$$
$$\sum_{rt} \begin{Bmatrix} 2 & 2 & 2 \\ I_s & I_r & I_t \end{Bmatrix} M_{sr} M_{rt} M_{ts},$$

K. Kumar, Phys. Rev. Lett. 28 (1972) 249

Triaxiality above ^{78}Ni?



Shell Model using ^{78}Ni core



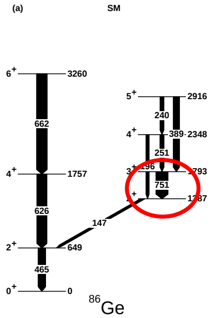
GCM-Gogny

Agreement of excitation energies for the 1st excited band **within keV**!

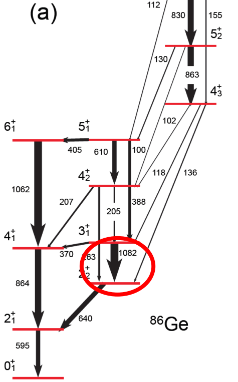
-matrices dimension 10^6
-feasible on a laptop
-typical time of calculations:
5min to 4h on one processor

-symmetry conserved (particle number and angular momentum)
-cluster of 140 CPUs
-typical time of calculations: 1 month

K. Sieja, T.R. Rodriguez, K. Kolos and D. Verney, Phys. Rev. C88 (2013) 034327



Shell Model using ^{78}Ni core



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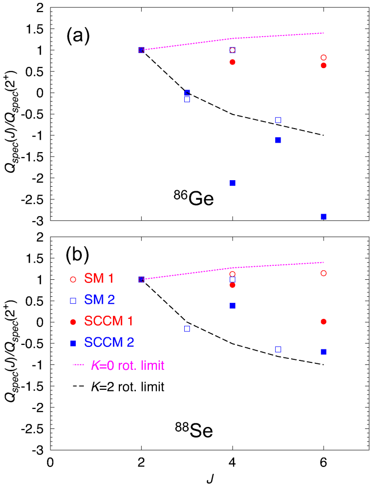
Deformation at N=54 from different models

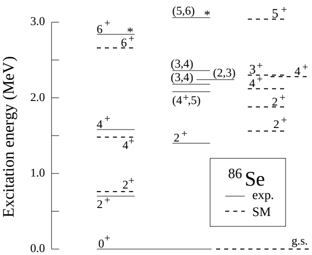


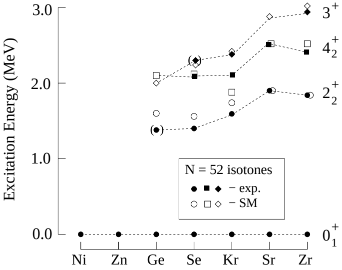
- ^{88}Se more spherical than ^{86}Ge in SCCM
- the opposite in SM
- where is located the 2^+ of ^{88}Se? 886 keV or 651 keV ?

- both SCCM and SM agree ^{86}Ge is the most triaxial
- both SCCM and SM predict γ-band does not continue to 4_2^+

Some experimental results at N=52

T. Materna et al., to be published





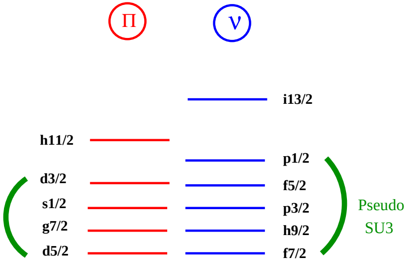
- Second excited state in ^{84}Ge is 2_2^+, in agreement with predictions of 5DCH-D1S Gogny model, which gives a γ-soft ground state. SM supports the Gogny predictions with 2_2^+ being a head of a quasi-γ band.

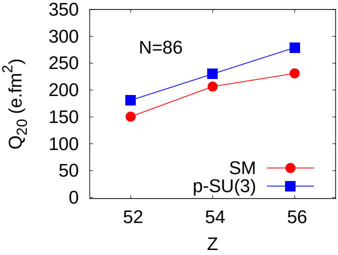
  K. Kolos et al., Phys. Rev. C88 (2013) 047301; A. Korgul et al., Phys. Rev. C88 (2013) 044330
- ^{86}Se appears little deformed ($\beta \sim 0.1$) but γ-soft from analysis of n-body quadrupole moments.
- Recent B(E2) from lifetimes (Cologne) in ^{86}Se in good agreement with the SM ones!

Collectivity above ^{132}Sn core

pseudo-SU(3) predictions

In analogy to what we have seen above the ^{78}Ni, collectivity should also thrive for the open-shell nuclei above the ^{132}Sn core (N=54→N=86). In the pseudo-SU(3) scheme (pseudo *pf* for protons and pseudo *gds* for neutrons) one obtains:



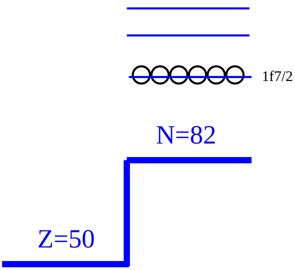


- Diagonalization in proton *gds* -neutron *hfp* model space, interaction under development.
- Some K-mixing should be possible in realistic calculations leading to triaxially deformed shapes.

- SM results in good agreement with experiment in ^{138}Te and ^{140}Xe (EXILL data) where an emerging γ-band was possibly observed.

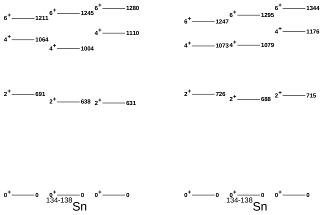
Above ^{132}Sn

- Taking ^{132}Sn as a core (or ^{110}Zr, see talk of H. Naidja) proton $r4h$ and neutron $r5i$ model space
- S.p. energies as usually used by other authors:
  $\varepsilon_{p_{3/2}}$=0.854 MeV
  $\varepsilon_{p_{1/2}}$=1.363 MeV
  $\varepsilon_{f_{5/2}}$=2.005 MeV
  $\varepsilon_{h_{9/2}}$=1.561 MeV
  $\varepsilon_{i_{13/2}}$=2.694 MeV
- TBME derived from CD-Bonn (N3LO) potentials using V_{lowk} and MBPT ($10\hbar\omega$ in $\hat{Q}$-box)



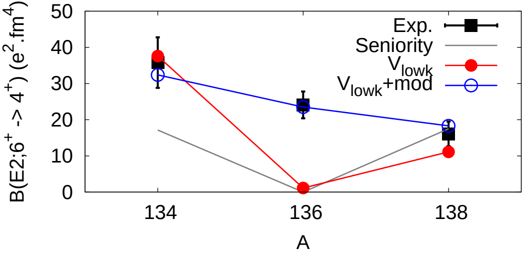
Seniority isomers in the tin chain

THEO EXP



Exp - PhD work of G. Gey (LPSC Grenoble)

G. Simpson et al., PRL 113, 132502 (2014)



- Previous SM calculations wrong by a factor 2 for the $B(E2;6^+ \to 4^+)$ in ^{136}Sn
- reduction of $f_{7/2}$ diagonal and non-diagonal pairing by 150 keV in the $V_{lowk} + mod$ interaction

$$B(E2;\nu J \to \nu J-2) \sim \left(1 - \frac{2n}{(2j+1)}\right)^2$$

Isomeric transitions in tins: seniority mixing

Table: Dominating seniority components of the low lying states in tin isotopes

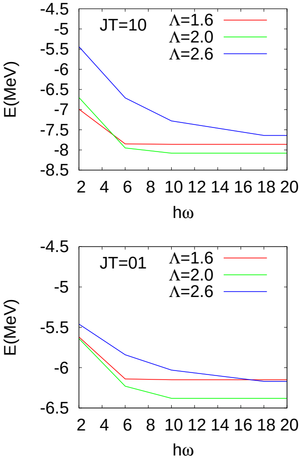
J^π	seniority	^{136}Sn	^{138}Sn
0^+	$\nu = 0$	98%	96%
	$\nu = 2$	2%	4%
2^+	$\nu = 2$	93%	87%
	$\nu = 4$	7%	10%
4^+	$\nu = 2$	46%	84%
	$\nu = 4$	54%	12%
6^+	$\nu = 2$	95%	87%
	$\nu = 4$	5%	9%

- Minor role of core excitations $\rightarrow$ talk of H. Naidja
- The seniority mixing effects were observed important in other cases, e.g. ^{72,74}Ni

Interactions from MBPT & pairing

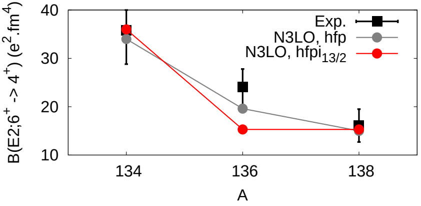
- *B. Maheshwari, A. K. Jain, P.C. Srivastava, Phys. Rev. C91 (2015) 024321*
  reduction of pairing matrix elements by 25keV (instead of our 150keV) in the RCDB interaction from OXBASH package to get the agreement on isomeric transitions
- our interaction includes 2nd order diagramms up to 10$\hbar\omega$ in $\hat{Q}$-box
- which interaction is better suited for tin isotopes?

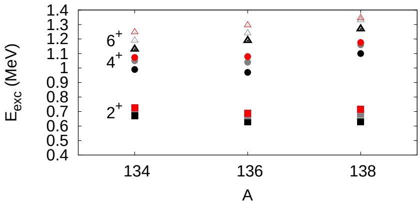
Convergence of pairing eigenvalue in the *sd*-shell with number of $\hbar\omega$ excitations in the $\hat{Q}$-box



Interactions from MBPT & pairing

Role of the intruder orbital





N. Tsunoda et al., Multishell effective interactions, Phys. Rev. C89 (2014) 024313

☞would be interesting to check the heavy tin region!

☞what one would get from non-perturbative resummations?

Summary

- Understanding of the mechanisms driving shell evolution (3N forces, tensor forces) allows for a better modelling all over the nuclear chart.
- Pseudo-SU(3) model predictions are in good agreement with SM diagonalizations & SCCM for $N = 52, 54$ nuclei. Collectivity and triaxiality predicted above ^{78}Ni core. The same should happen above ^{132}Sn core.
- No unique mulitpole interactions for SM from MBPT theory. Could one use on a daily basis TBME interactions from CC or IM-SRG?

Thanks for your attention !