Correlations versus shell evolution in the Nuclear Shell Model

Frédéric Nowacki[1]

[1]Strasbourg-Madrid Shell-Model collaboration

Shell structure and correlations

- at stability
  - double magicity + superdeformed states: ^{16}O, ^{40}Ca, ^{56}Ni
- far from stability
  - Vanishing of shell closure: ^{11}Li, ^{32}Mg, ^{42}Si, ^{68}Ni, ^{80}Zr ...
  - New gaps: ^{24}O, ^{54}Ca ...

Interplay between
- Monopole field (spherical mean field)
- Multipole correlations (pairing, Q.Q, ...)

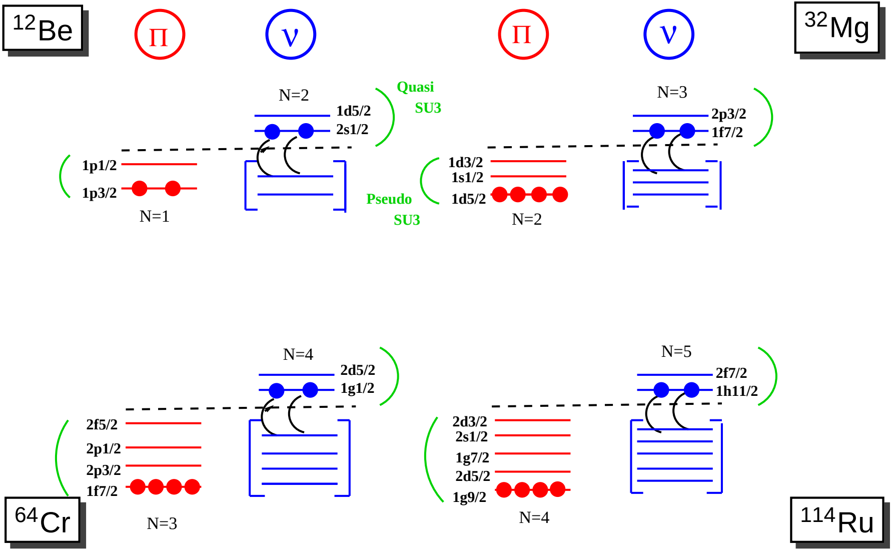
"Pairing plus Quadrupole propose, Monopole disposes"

A. Zuker, Coherent and Random Hamiltonians, CRN Preprint 1994

For the Monopole field itself,

interplay between
- single particle field
- two-body interaction (T=1, T=0)

Development of deformation at N=8,20,40,70



Island of inversion at N=40: an old story

CR and FE AROUND N=40

A NEW REGION OF DEFORMATION.

A. Poves

^{64}Cr

$g(0ph - 2ph) = 5.70$

$g(0ph - 4ph) = 8.30$

$Q = -9.0\ b^2$ CS < 1%

$BE2 = 19.8\ b^4$ $n(d_{5/2}) = 1.1$

$\frac{E(4^+)}{E(2^+)} = 2.7$ $\left[\frac{E(4^+)}{E(2^+)} = (3.2)\,(3.4) \right]$ in the intruder configurations.

A SITUATION THAT REMINDS WHAT IS KNOWN AT N=20 FFS.

MSU

RAPID COMMUNICATIONS

PHYSICAL REVIEW C **81**, 051304(R) (2010)

Collectivity at $N = 40$ in neutron-rich ^{64}Cr

A. Gade,[1,2] R. V. F. Janssens,[3] T. Baugher,[1,2] D. Bazin,[1] B. A. Brown,[1,2] M. P. Carpenter,[3] C. J. Chiara,[3,4] A. N. Deacon,[5] S. J. Freeman,[5] G. F. Grinyer,[1] C. R. Hoffman,[3] B. P. Kay,[3] F. G. Kondev,[6] T. Lauritsen,[3] S. McDaniel,[1,2] K. Meierbachtol,[1,7] A. Ratkiewicz,[1,2] S. R. Stroberg,[1,2] K. A. Walsh,[1,2] D. Weisshaar,[1] R. Winkler,[1] and S. Zhu[3]

[1]*National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824, USA*

[2]*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA*

[3]*Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*

GANIL

RAPID COMMUNICATIONS

PHYSICAL REVIEW C **81**, 061301(R) (2010)

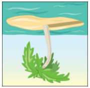
Onset of collectivity in neutron-rich Fe isotopes: Toward a new island of inversion?

J. Ljungvall,[1,2,3] A. Görgen,[1] A. Obertelli,[1] W. Korten,[1] E. Clément,[2] G. de France,[2] A. Bürger,[4] J.-P. Delaroche,[5] A. Dewald,[6] A. Gadea,[7] L. Gaudefroy,[5] M. Girod,[5] M. Hackstein,[6] J. Libert,[8] D. Mengoni,[9] F. Nowacki,[10] T. Pissulla,[6] A. Poves,[11] F. Recchia,[12] M. Rejmund,[2] W. Rother,[6] E. Sahin,[12] C. Schmitt,[2] A. Shrivastava,[2] K. Sieja,[10] J. J. Valiente-Dobón,[12] K. O. Zell,[6] and M. Zielińska[13]

[1]*CEA Saclay, IRFU, Service de Physique Nucléaire, F-91191 Gif-sur-Yvette, France*

[2]*GANIL, CEA/DSM-CNRS/IN2P3, Bd Henri Becquerel, BP 55027, F-14076 Caen, France*

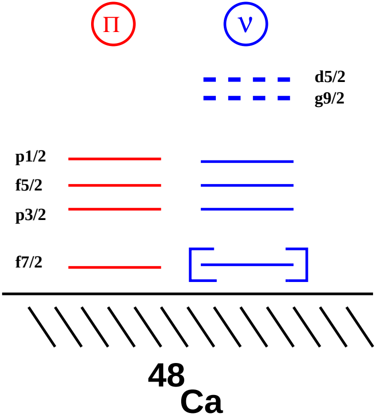
SM framework



Island of inversion around ^{64}Cr

S. Lenzi, F. Nowacki, A. Poves and K. Sieja

Phys. Rev. C 82, 054301, 2010.



LNPS interaction:

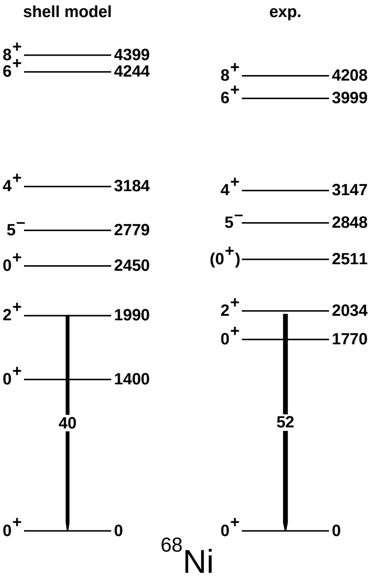
- based on realistic TBME
- new fit of the pf shell (KB3GR, E. Caurier)
- monopole corrections

Calculations:

- up to 14p-14h excitations across Z=28 and N=40 gaps
- up to 10^{10}
- m-scheme code ANTOINE (non public version)

Triple coexistence in ^{68}Ni

- at first approximation, ^{68}Ni has a double closed shell structure for GS
- But low lying structure much more complex
- three (now four) coexisting 0^+ states appear between 0 and $\sim$ 2.5 MeV



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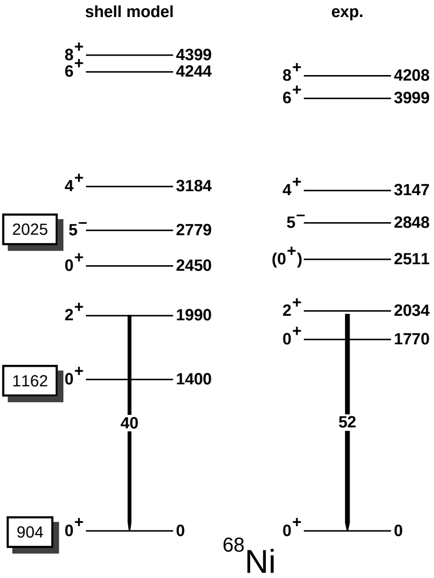
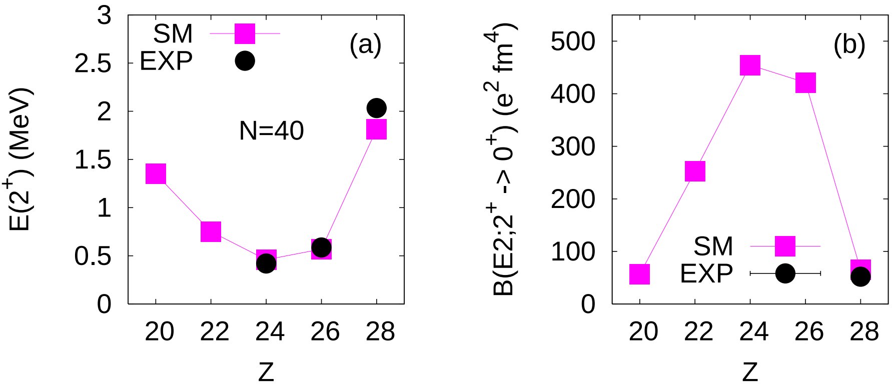
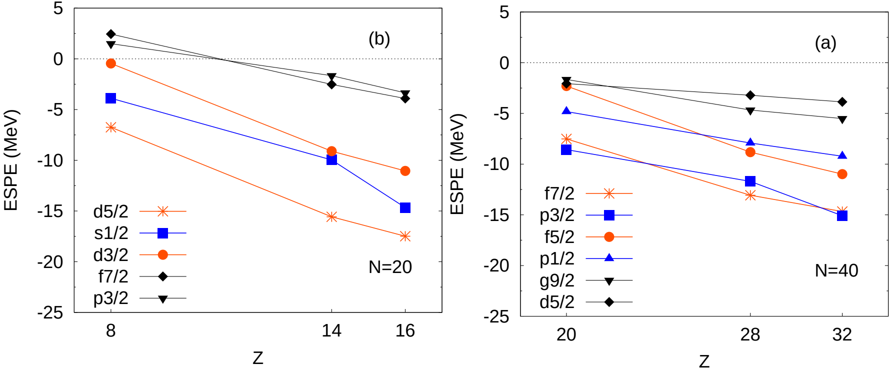


Shape transition at N=40



Nucleus	$\nu g_{9/2}$	$\nu d_{5/2}$	configuration
^{68}Ni	0.98	0.10	0p0h(51%)
^{66}Fe	3.17	0.46	4p4h(26%)
^{64}Cr	3.41	0.76	6p6h(23%)
^{62}Ti	3.17	1.09	4p4h(48%)

Neutron effective single particle energies



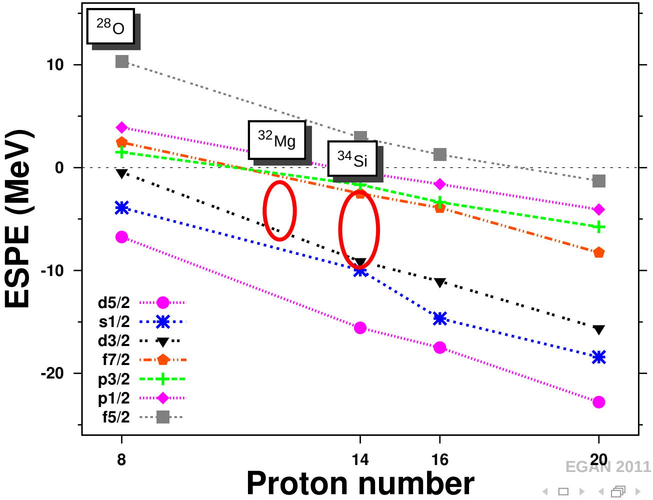
- reduction of the $\nu d_{3/2}$-$f_{7/2}$ gap with removig $d_{5/2}$ protons
- proximity of the quasi-SU3 partner $p_{3/2}$
- reduction of the $\nu f_{5/2}$-$g_{9/2}$ gap with removing $f_{7/2}$ protons
- proximity of the quasi-SU3 partner $d_{5/2}$

Spin-Tensor decomposition

Shell evolution and nuclear forces,
N.A. Smirnova, B. Bally, K. Heyde, F. Nowacki, K. Sieja

Phys. Lett. **B686**, 109 (2010)

$(f_{\frac{7}{2}}$-$d_{\frac{3}{2}})$ shell gap evolution between ^{32}Mg and ^{34}Si



Shell evolution and nuclear forces,
N.A. Smirnova, B. Bally, K. Heyde, F. Nowacki, K. Sieja

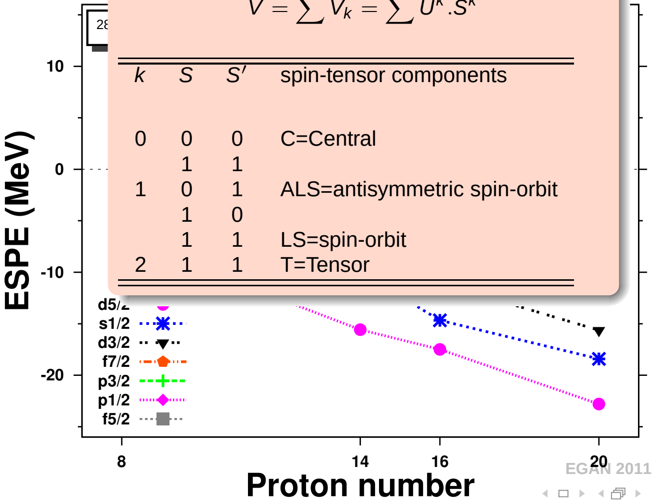
Phys. Lett. **B686**, 109 (2010)

$(f_{\frac{7}{2}}$ … nd ^{34}Si

Spin-Tensor decomposition

$$V = \sum V_k = \sum U^k . S^k$$

k	S	S'	spin-tensor components
0	0	0	C=Central
	1	1	
1	0	1	ALS=antisymmetric spin-orbit
	1	0	
	1	1	LS=spin-orbit
2	1	1	T=Tensor



Spin-Tensor decomposition

Shell evolution and nuclear forces,
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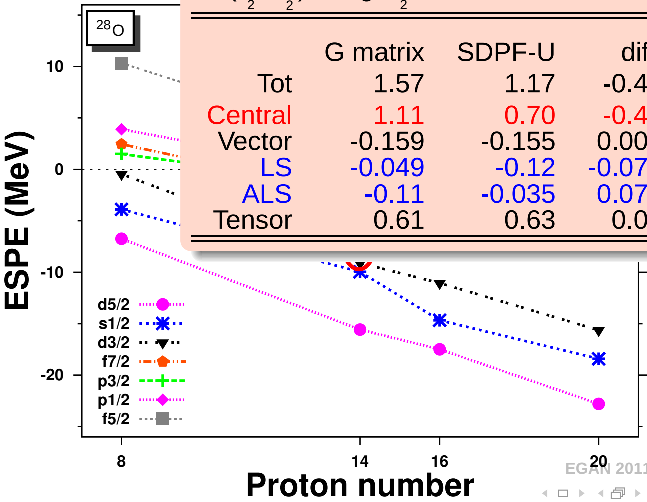
Phys. Lett. **B686**, 109 (2010)

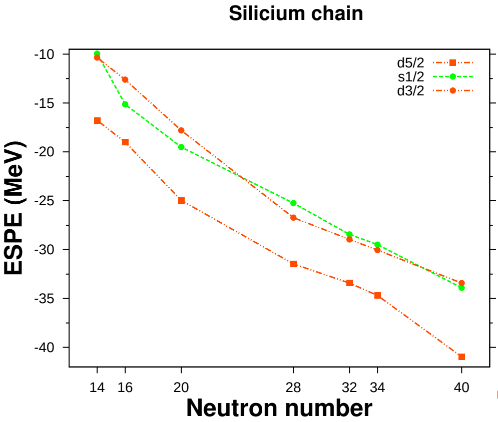
$(f_{\frac{7}{2}}\text{-}d_{\frac{3}{2}})$ shell gap evolution between ^{32}Mg and ^{34}Si

$\Delta\ (f_{\frac{7}{2}}\text{-}d_{\frac{3}{2}})$ filling $d_{\frac{5}{2}}$

	G matrix	SDPF-U	diff.
Tot	1.57	1.17	-0.40
Central	1.11	0.70	-0.41
Vector	-0.159	-0.155	0.004
LS	-0.049	-0.12	-0.071
ALS	-0.11	-0.035	0.075
Tensor	0.61	0.63	0.02



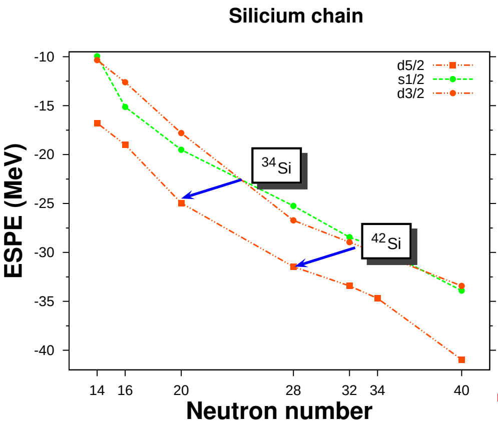
Neutron rich *sd* − *pf* nuclei



- reduction of $d_{\frac{5}{2}} - d_{\frac{3}{2}}$ Z=14 gap with filling $f_{\frac{7}{2}}$ neutron orbital
- reduction of $p_{\frac{3}{2}} - p_{\frac{1}{2}}$ spin-orbitsplitting with filling $s_{\frac{1}{2}}$ proton orbital
- reduction of $f_{\frac{7}{2}} - p_{\frac{3}{2}}$ N=28 gap with filling $d_{\frac{3}{2}}$ neutron orbital

→ "Tensor mecanism"

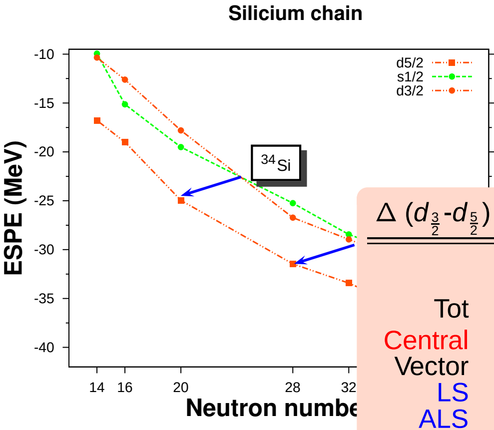
Neutron rich *sd* – *pf* nuclei



- reduction of $d_{\frac{5}{2}} - d_{\frac{3}{2}}$ Z=14 gap with filling $f_{\frac{7}{2}}$ neutron orbital
- reduction of $p_{\frac{3}{2}} - p_{\frac{1}{2}}$ spin-orbitsplitting with filling $s_{\frac{1}{2}}$ proton orbital
- reduction of $f_{\frac{7}{2}} - p_{\frac{3}{2}}$ N=28 gap with filling $d_{\frac{3}{2}}$ neutron orbital

→ "Tensor mecanism"

Neutron rich *sd* – *pf* nuclei



- reduction of $d_{\frac{5}{2}} - d_{\frac{3}{2}}$ Z=14 gap with filling $f_{\frac{7}{2}}$ neutron orbital
- reduction of $p_{3} - p_{1}$ spin-orbitsplitting

$\Delta\ (d_{\frac{3}{2}}\text{-}d_{\frac{5}{2}})$ filling $f_{\frac{7}{2}}$

	G matrix	SDPF-U	diff.
Tot	-3.15	-2.38	+0.77
Central	0.24	-0.11	-0.35
Vector	-0.27	0.55	0.82
LS	-0.11	0.11	0.22
ALS	-0.16	0.44	0.60
Tensor	-2.65	-2.77	0.12

New proton-neutron coupling scheme in ^{92}Pd ?

B. Cederwall et al., Nature (London) 469, 68 (2011)

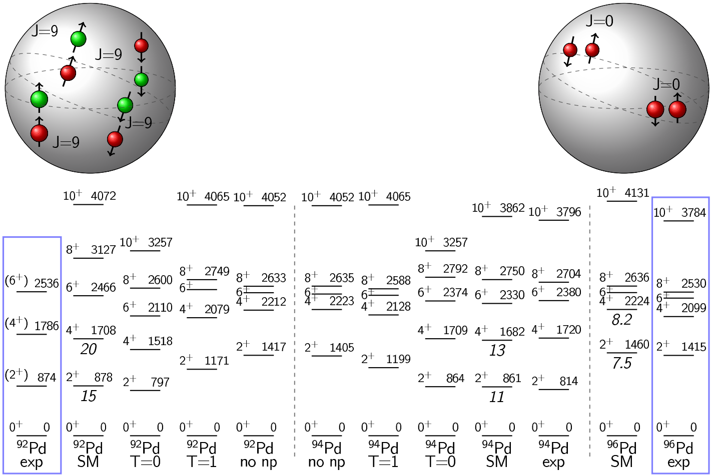
LETTER

doi:10.1038/nature09644

Evidence for a spin-aligned neutron–proton paired phase from the level structure of ^{92}Pd

B. Cederwall[1], F. Ghazi Moradi[1], T. Bäck[1], A. Johnson[1], J. Blomqvist[1], E. Clément[2], G. de France[2], R. Wadsworth[3], K. Andgren[1], K. Lagergren[1,4], A. Dijon[2], G. Jaworski[5,6], R. Liotta[1], C. Qi[1], B. M. Nyakó[7], J. Nyberg[8], M. Palacz[5], H. Al-Azri[3], A. Algora[9], G. de Angelis[10], A. Ataç[11], S. Bhattacharyya[2]†, T. Brock[3], J. R. Brown[3], P. Davies[3], A. Di Nitto[12], Zs. Dombrádi[7], A. Gadea[9], J. Gál[7], B. Hadinia[1], F. Johnston-Theasby[3], P. Joshi[3], K. Juhász[13], R. Julin[14], A. Jungclaus[15], G. Kalinka[7], S. O. Kara[11], A. Khaplanov[1], J. Kownacki[5], G. La Rana[12], S. M. Lenzi[16], J. Molnár[7], R. Moro[12], D. R. Napoli[10], B. S. Nara Singh[3], A. Persson[1], F. Recchia[16], M. Sandzelius[1]†, J.-N. Scheurer[17], G. Sletten[18], D. Sohler[7], P.-A. Söderström[8], M. J. Taylor[3], J. Timár[7], J. J. Valiente-Dobón[10], E. Vardaci[12] & S. Williams[19]

New proton-neutron coupling scheme in ^{92}Pd ?



Claim for transition from Cooper pairs to aligned p-n pairs

New proton-neutron coupling scheme in ^{92}Pd ?

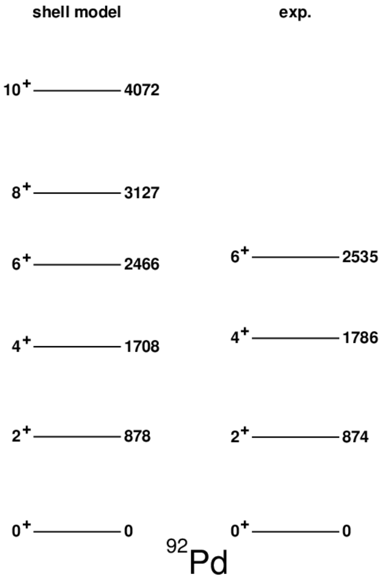
- In A=90-100 region, spin-orbit is at play : strong Z=50 shell closure and the $g_{\frac{9}{2}}$ orbital deeply bound with respect to the remaining *gds* orbitals

- level schemes of $A \sim 90$ nuclei to be described within $g_{\frac{9}{2}}$ orbital

- regular level spacing and constant BE2's

- wave function analysis lead to

  condensate of $(pn)^{J=9+}$ pairs

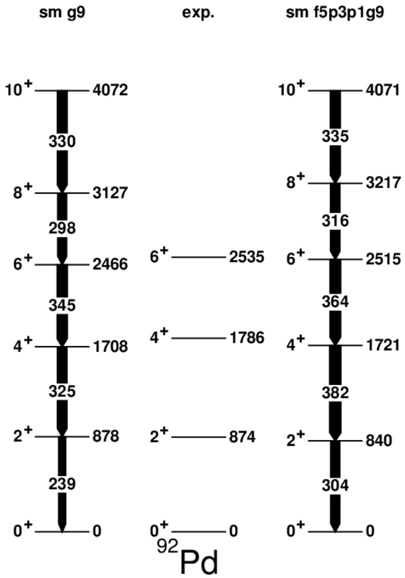


How to assess (pn) condensate regime

- 1) build $(j_p j_n)^N_{J=2j}$ objects
- 2) diagonalise $(J = 2j; T = 0)$ single matrix element for given system
- take the overlap with effective wave function
- take the expectation value of pair counting operator
- first two methods give $\sim$ results , and provide relative estimate
- counting pairs provides absolute estimate

New proton-neutron coupling scheme in ^{92}Pd

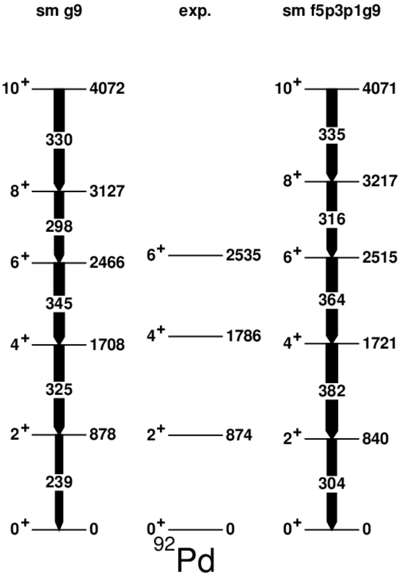
- calculations with effective $g_{\frac{9}{2}}$ (Chong et al.) and JUN45 (Otsuka et al.) interactions
- striking similarity of computed spectra
- regular level spacing and constant BE2's
- BUT quantitative differences between wave functions and underlying physics
- 29% of $(g_{\frac{9}{2}})^{12}$ configuration left in the full space calculation
- - vanishing Q's in $r3g$
  - large and constant in $g_{\frac{9}{2}}$



JT=90 pairs content

Table: correlated JT=90 pairs content in the yrast band of in ^{92}Pd.

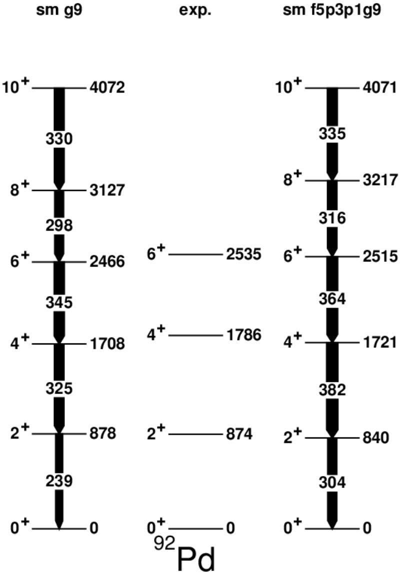
J^π	$\langle cond \vert \Psi_{^{92}Pd} \rangle$ $g_{9/2}$	$\langle cond \vert \Psi_{^{92}Pd} \rangle$ r3g
0^+	0.83	0.45
2^+	0.87	0.48
4^+	0.91	0.58
6^+	0.87	0.62
6^+	0.73	0.57
8^+	0.86	0.69
10^+	0.35	0.34
⋮	⋮	⋮
24^+	1.00	0.99



JT=90 pairs content

Table: Number of correlated JT=90 pairs in the yrast band of ^{92}Pd.

J^{π}	$\mathcal{N}_{pair}$ $g_{9/2}$	$\mathcal{N}_{pair}$ r3g
0^+	2.26	1.34
2^+	2.32	1.48
4^+	2.35	1.65
6^+	2.38	1.69
8^+	2.38	1.69
10^+	2.38	1.69
⋮	⋮	⋮
24^+	3.87	3.87



JT=90 pairs content

Table: Number of correlated JT=90 pairs in th[illegible] ^{92}Pd.

J^π	$\mathcal{N}_p$ [illegible]	
	g_9	
0^+	2.[illegible]	
2^+	2.[illegible]	
4^+	2.[illegible]	
6^+	2.[illegible]	
8^+	2.[illegible]	
10^+	2.[illegible]	
⋮	⋮	
24^+	3.87	3.87

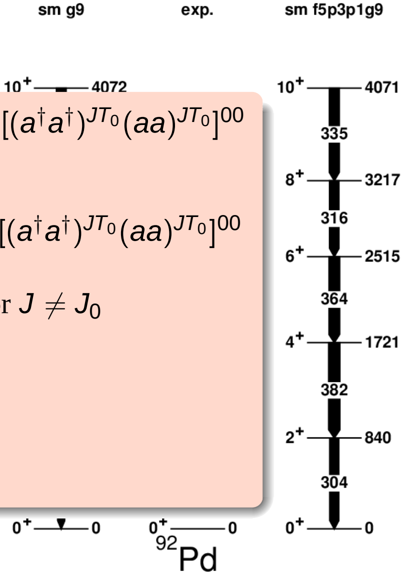
Overestimation with $[(a^\dagger a^\dagger)^{JT_0}(aa)^{JT_0}]^{00}$ operator

$$N_p^{J_0T_0} = \beta_{J_0}\sum_J \alpha_{J,J_0}[(a^\dagger a^\dagger)^{JT_0}(aa)^{JT_0}]^{00}$$

$$\alpha_{J,J_0} = -\frac{2J_0+1}{\sum_J(2J+1)} \text{ for } J \neq J_0$$

$$\alpha_{J_0,J_0} = \frac{\sum_{J\neq J_0}(2J+1)}{\sum_J(2J+1)}$$

$$\beta_{J_0} = \frac{\sum_J(2J+1)}{\sum_{J\neq J_0}(2J+1)}$$



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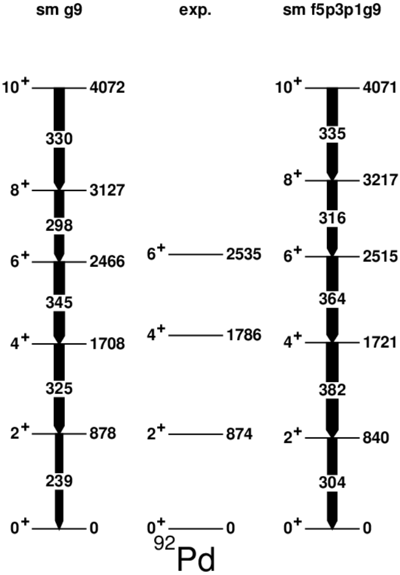
⋮	⋮	⋮
24^+	3.87	3.87



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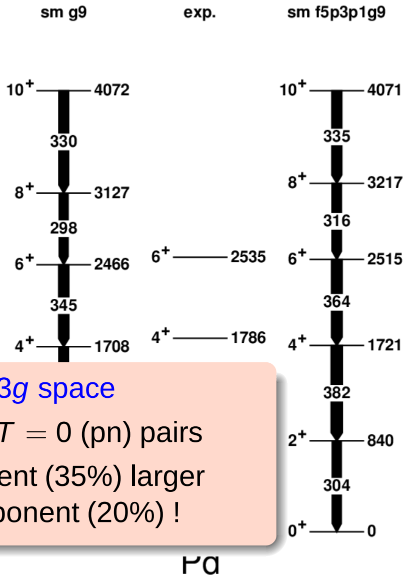
4^+	2.35	1.65
6^+		
8^+		
10^+		
⋮		
24^+		



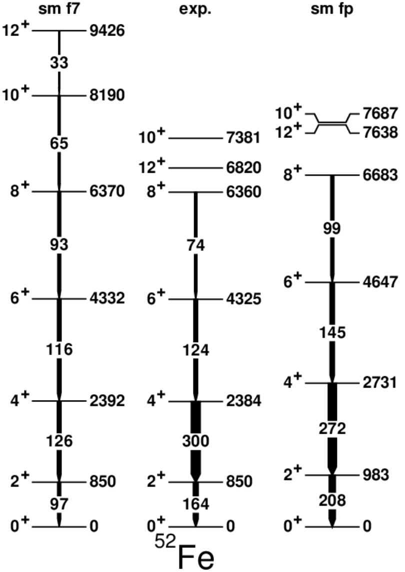
With JUN45 interation in *r3g* space

- weak content of $J = 9 T = 0$ (pn) pairs
- seniority zero component (35%) larger than condensate component (20%) !

Case of ^{52}Fe (mate of ^{96}Cd)

Table: correlated JT=70 pairs content in the yrast band of in ^{52}Fe.

J^{π}	$\langle cond \| \Psi_{^{52}Fe} \rangle$ $f_{7/2}$	$\langle cond \| \Psi_{^{52}Fe} \rangle$ fp
0^+	0.99	0.66
2^+	0.99	0.66
4^+	0.99	0.66
6^+	0.98	0.54
8^+	0.99	0.75
10^+	0.99	0.81
12^+	1.00	0.81

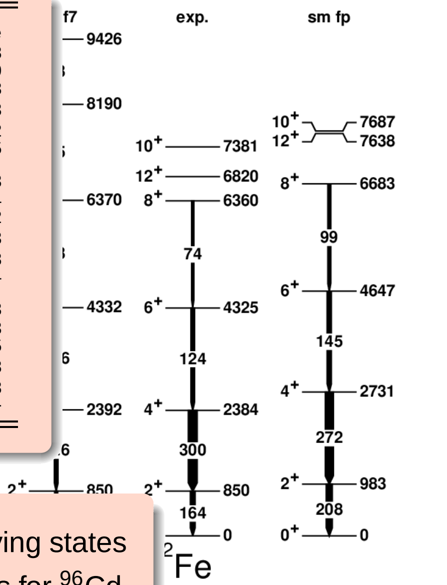


Case of ^{52}Fe (mate of ^{96}Cd)

Table: correlated content in the yras[…] ^{52}Fe.

J^{π}	$\langle cond \vert \Psi_{52} […]$ $f_{7/2}$	
0^+	0.99	
2^+	0.99	
4^+	0.99	
6^+	0.98	
8^+	0.99	
10^+	0.99	0.81
12^+		

	^{52}Fe
$E^*(2^+_1)$ th.	0.98
Q_s	-29
BE2↓ th.	208
Q_i(e.fm^2) from Q_s	103
Q_i(e.fm^2) from B(E2)	102
β	0.25
$E^*(4^+_1)$	2.73
Q_s	-34
BE2↓ th.	272
Q_i(e.fm^2) from Q_s	93
Q_i(e.fm^2) from B(E2)	98
β	0.24
$E^*(6^+_1)$	2.73
Q_s	+3
BE2↓ th.	145
Q_i(e.fm^2) from Q_s	8
Q_i(e.fm^2) from B(E2)	68
β	-



- Rotor regime for low-lying states
- Same conclusion holds for ^{96}Cd

Deformation in light Xenon isotopes

PRL **99,** 022501 (2007) PHYSICAL REVIEW LETTERS week ending 13 JULY 2007

Identification of Excited States in the $T_z = 1$ Nucleus ^{110}Xe: Evidence for Enhanced Collectivity near the $N = Z = 50$ Double Shell Closure

M. Sandzelius,[1] B. Hadinia,[1] B. Cederwall,[1,*] K. Andgren,[1] E. Ganioğlu,[2] I. G. Darby,[3] M. R. Dimmock,[3] S. Eeckhaudt,[4] T. Grahn,[4,†] P. T. Greenlees,[4] E. Ideguchi,[5] P. M. Jones,[4] D. T. Joss,[3] R. Julin,[4] S. Juutinen,[4] A. Khaplanov,[1] M. Leino,[4] L. Nelson,[3] M. Niikura,[5] M. Nyman,[4] R. D. Page,[3] J. Pakarinen,[4,†] E. S. Paul,[3] M. Petri,[3] P. Rahkila,[4] J. Sarén,[4] C. Scholey,[4] J. Sorri,[4] J. Uusitalo,[4] R. Wadsworth,[6] and R. Wyss[1]

[1]*Department of Physics, The Royal Institute of Technology, S-10691 Stockholm, Sweden*
[2]*Science Faculty, Physics Department, Istanbul University, 34459 Istanbul, Turkey*
[3]*Oliver Lodge Laboratory, University of Liverpool, Liverpool L69 7ZE, United Kingdom*
[4]*Department of Physics, University of Jyväskylä, FIN-40014 Jyväskylä, Finland*
[5]*Center for Nuclear Study, University of Tokyo, Wako, Saitama 351-0198, Japan*
[6]*Department of Physics, University of York, Heslington, York Y010 5DD, United Kingdom*
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Gamma-ray transitions have been identified for the first time in the extremely neutron-deficient ($N = Z + 2$) nucleus ^{110}Xe, and the energies of the three lowest excited states in the ground-state band have been deduced. The results establish a breaking of the normal trend of increasing first excited 2^+ and 4^+ level energies as a function of the decreasing neutron number as the $N = 50$ major shell gap is approached for the neutron-deficient Xe isotopes. This unusual feature is suggested to be an effect of enhanced collectivity, possibly arising from isoscalar *n-p* interactions becoming increasingly important close to the $N = Z$ line.

Deformation in light Xenon isotopes

PRL **99,** 022501 (2007)

Identification of Excited

M. Sandzelius,[1] B. Hadinia,[1] B.
T. Grahn,[4,†] P. T. Greenlees,[4] E
L. Nelson,[3] M. Niikura,[5] M. Nyı

[1]*Department*
[2]*Science*
[3]*Oliver Lodg*
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[6]*Department*

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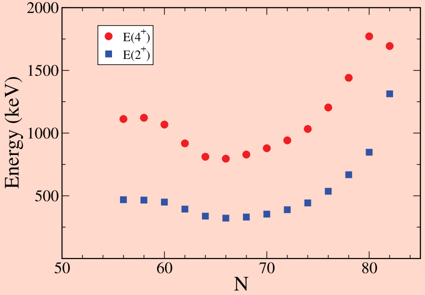
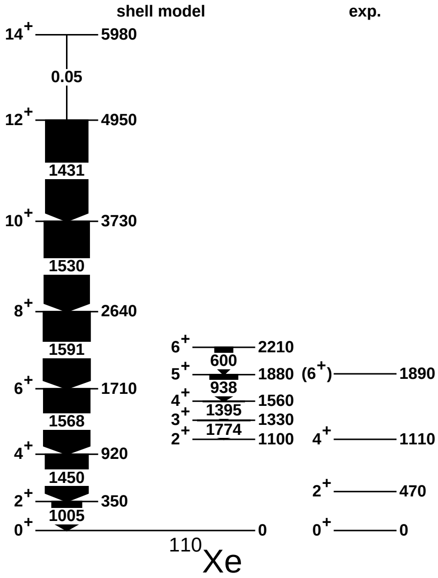


FIG. 3 (color online). Energies of 2_1^+ (squares) and 4_1^+ (circles) states plotted versus neutron number N for even-even Xe isotopes in the mass region $110 \leq A \leq 136$. Data are from the present work and Refs. [23,30].

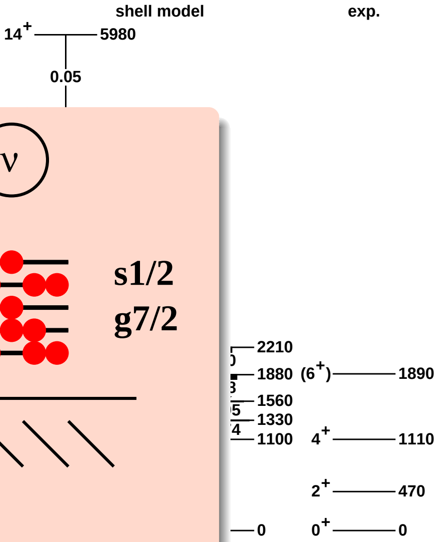
claim for enhanced collectivity due to isoscalar n-p interactions

Deformation in light Xenon isotopes

- In A=100 region, spin-orbit is at play : strong Z=50 shell closure and the $g_{\frac{9}{2}}$ orbital deeply bound with respect to the remaining *gds* orbitals
- the natural valence space beyond ^{100}Sn is made of $g_{\frac{7}{2}}$, $d_{\frac{5}{2}}$, $d_{\frac{3}{2}}$, $s_{\frac{1}{2}}$, and $h_{\frac{11}{2}}$ orbitals
- but at N=Z, $h_{\frac{11}{2}}$ is higher and the other orbitals close to each other
- → one recovers a pseudo-fp space where SU3 symmetry scheme available



Deformation in light Xenon isotopes



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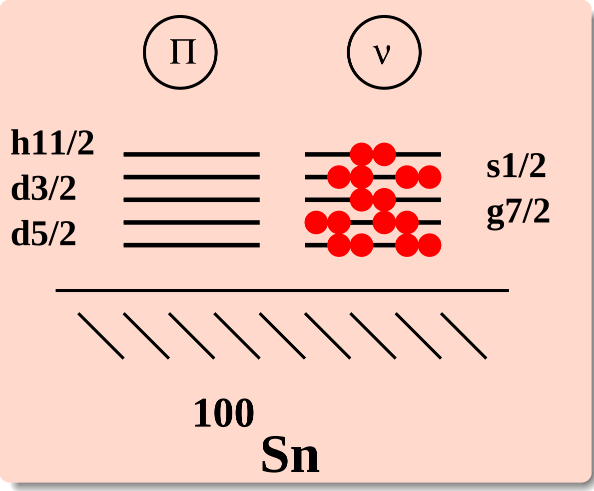

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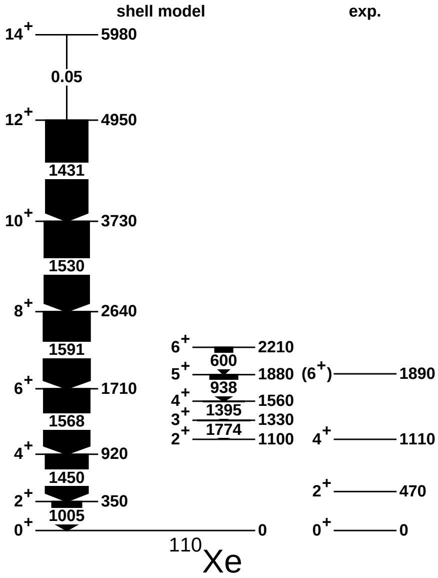


A case of extreme triaxiality: ^{110}Xe

E. Caurier, F. Nowacki, A. Poves, K. Sieja, Phys. Rev. **C82**, 064304 (2010)

J	E*	E_γ	BE2	Q_{sp}	Q_0 (BE2)	Q_0 (Q_{sp})	β
2^+	0.35	0.35	1005	-62	225	217	0.16
4^+	0.92	0.57	1450	-78	226	215	0.16
6^+	1.71	0.79	1568	-83	224	208	0.16
8^+	2.64	0.94	1591	-87	220	207	0.16
10^+	3.73	1.09	1530	-86	213	198	0.15
12^+	4.95	1.22	1431	-85	204	191	0.15
14^+	5.98	0.99	0.05	-126	1	279	
16^+	6.63	0.69	111	-125	56	273	
18^+	7.51	0.88	1184	-130	183	282	
20^+	8.51	1.00	1043	-134	172	288	
2^+_2	1.10			+61			
3^+	1.33	0.23	1774	-1.3			
4^+_2	1.56	0.23	1395	-38	219	261	0.18
5^+	1.88	0.32	938	-54	217	234	0.17
6^+_2	2.21	0.33	600	-74	209	259	0.17

one could extract the γ from:

$$\frac{BE2(2^+_\gamma \to 2^+_1)}{BE2(2^+_\gamma \to 0^+_1)} \qquad \gamma = 20^o$$

Notice $Q(2^+_\gamma)$ = - $Q(2^+_{Yrast})$ and $Q(3^+) \sim 0$ as results from $3K^2 - J(J+1)$ for K=2 and J=3

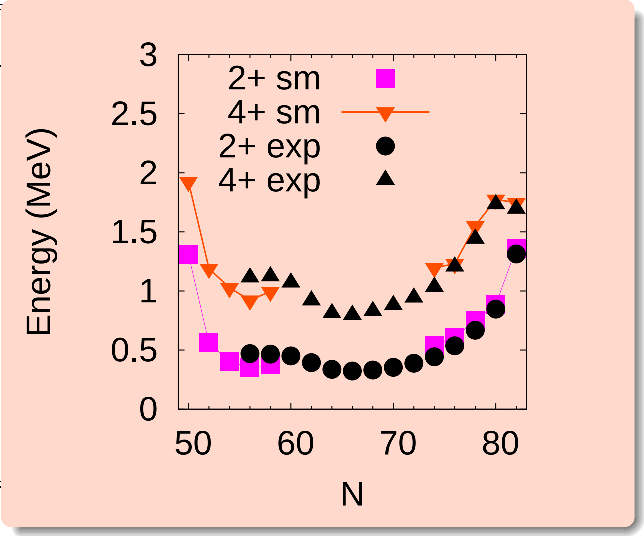
Comments about $h_{\frac{11}{2}}$ influence

- reduced M. I. : $E(2^+)$ = 0.19
- slight increase of coll. : $BE2(2^+)$ =1110
- no backbending
- reduced triaxiality $\gamma = 12^o$
- better J(J+1)
- magnetic moments consistent with rot. model up to J=20

A case of extreme triaxiality: ^{110}Xe

E. Caurier, F. Nowacki, A. Poves, K. Sieja, Phys. Rev. **C82**, 064304 (2010)

J
2^+
4^+
6^+
8^+
10^+
12^+
14^+
16^+
18^+
20^+
2^+_2
3^+
4^+_2
5^+
6^+_2



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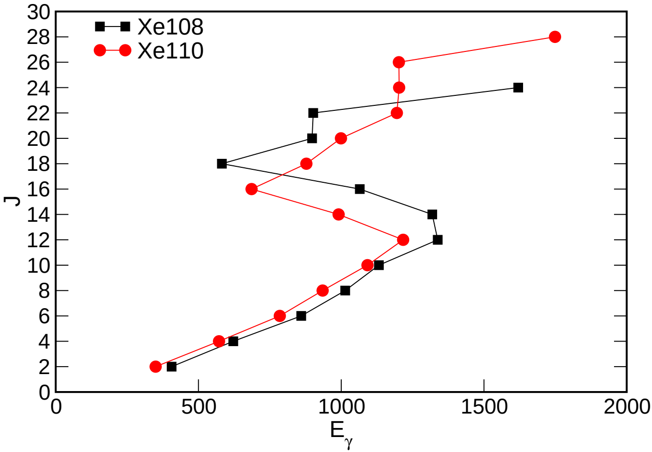
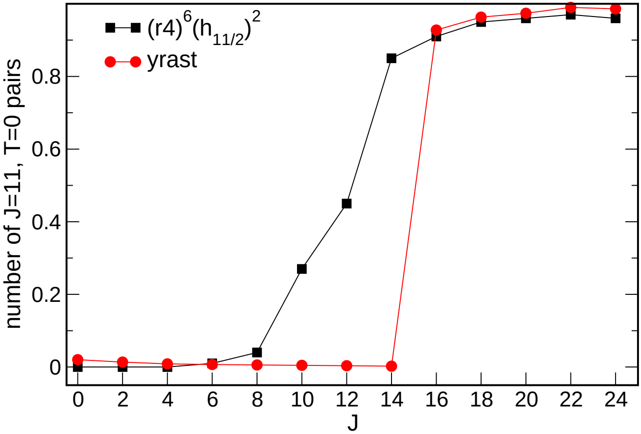
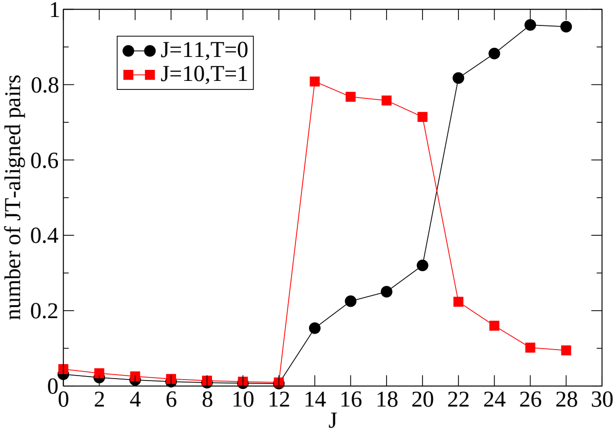
Backbend plots



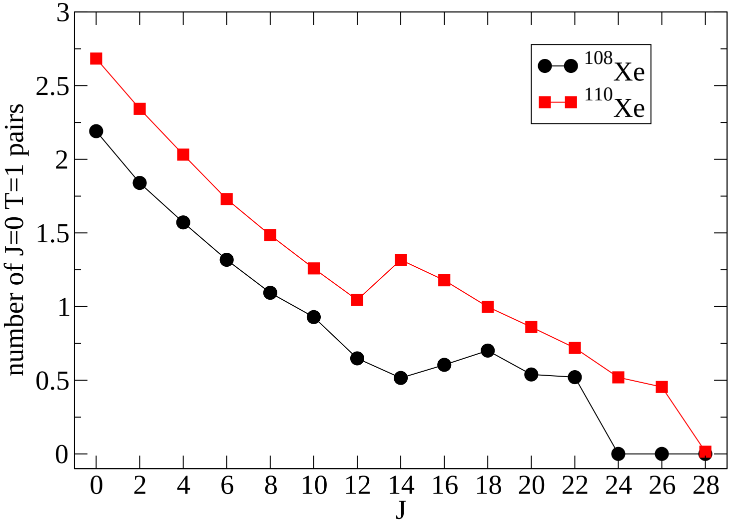
Alignment properties in ^{108}Xe



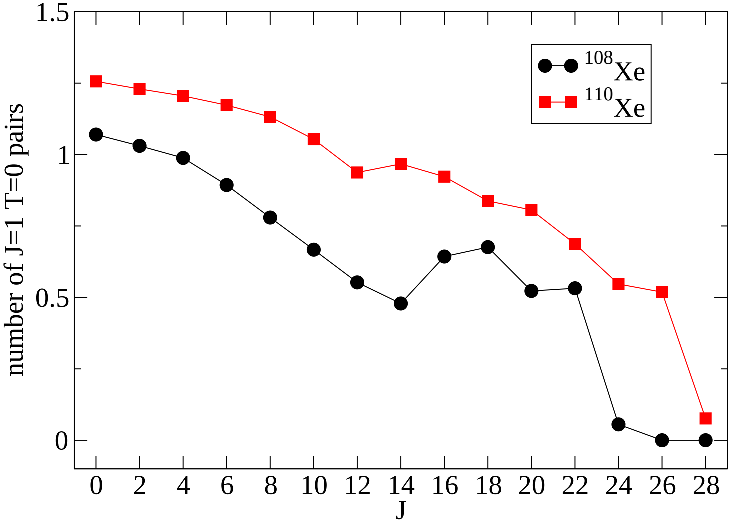
Alignment properties in in ^{110}Xe



Isovector pairing properties



Isoscalar pairing properties



Summary

- Monopole drift develops in all regions but the Interplay between correlations (pairing + quadrupole) and spherical mean-field (monopole field) determines the physics. It can vary from :
  - island of deformation at N=20 and N=40
  - deformation at Z=14, N=28 for ^{42}Si and shell weakening at Z=28, N=50 for ^{78}Ni
- Spin-Tensor analysis of the effective interaction in sd-pf show mainly central and tensor components effects
- Quadrupole energies can be huge and understood in terms of symmetries
- As well as in lighter systems, in mid-mass nuclei (like Xenon isotopes) isoscalar correlations in $N \sim Z$ nuclei appear to be weak for low-lying states
- In $A \sim 90$ region for ^{92}Pd and ^{96}Cd do not show condensate regime in LSSM

Thanks to:

- E. Caurier, K. Sieja, A. Zuker
- A. Poves
- H. Grawe, S. Lenzi, O. Sorlin