NEW ADVANCES IN SHELL MODEL CALCULATIONS: APPLICATIONS AROUND DOUBLY MAGIC NUCLEI ^{40}Ca AND ^{132}Sn

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ICNT Program: Theory for open-shell near the limits of stability,
May 11-29, 2015

Outline

PART 1 : AROUND ^{40}Ca

1. Ca isotopes shift
2. Isomer shift in ^{38}K
3. Effect of pairing correlations

PART 2 : AROUND ^{132}Sn

1. Choose Valence space/Core
2. develop an effective interaction
3. Calculation of the energies, B(E2) and masses in ^{134,136,138}Sn,
   - Effect of core excitations
   - Closure or no of the sub-shell at N=90
4. Other applications to the open n-p systems : Te, Xe, Ba, Ce and Nd.

PART I : ISOMER SHIFT IN ^{38}K

REMINDER ON *Ca* ISOTOPES SHIFT

ELSEVIER

13 December 2001

Physics Letters B 522 (2001) 240–244

PHYSICS LETTERS B

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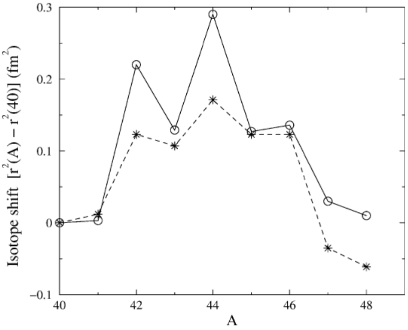
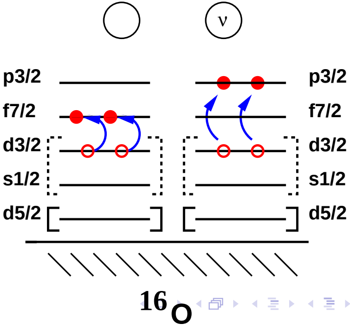
Shell model description of isotope shifts in calcium

E. Caurier [a], K. Langanke [b], G. Martínez-Pinedo [b,c], F. Nowacki [d], P. Vogel [e]





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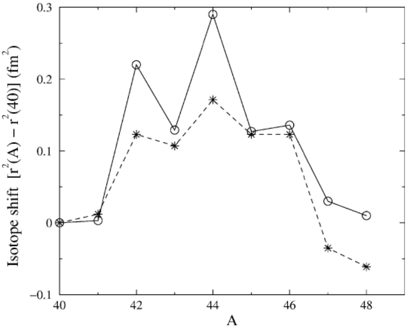
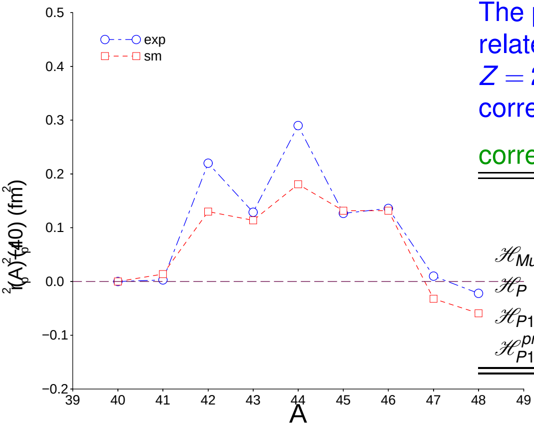


ZBM2 interaction :

- based on realistic TBME
- monopole corrections to ensure ^{40}Ca and ^{48}Ca gaps
- full space calculations
- almost free of center of mass contamination
- provides very good spectroscopy at *sd-pf* interface

$$\delta r_c^2 = \frac{1}{Z} n_{fp}^{\pi}(A) b^2 \quad \begin{cases} n_{fp}^{\pi} & \pi \text{ occupation probability in fp } shell \\ b = 1.974 fm & \text{oscillateur parameter} \end{cases}$$

Isotope shifts in Ca chain



The parabolic dependence on A is related to the partial breaking of the $Z = 20$ shell closure due to the $\pi\nu$ correlations

correlation energies

	^{40}Ca	^{42}Ca	^{44}Ca	^{46}Ca	^{48}Ca
$\mathcal{H}_{Multi}$	-13.1	-17.5	-18.1	-13.6	-6.2
$\mathcal{H}_{P}$	-9.7	-12.5	-11.9	-8.7	-4.0
$\mathcal{H}_{P1}$	-8.9	-11.8	-11.3	-8.4	-3.9
$\mathcal{H}_{P1}^{pn}$	-2.95	-2.2	-1.4	-0.8	-0.2

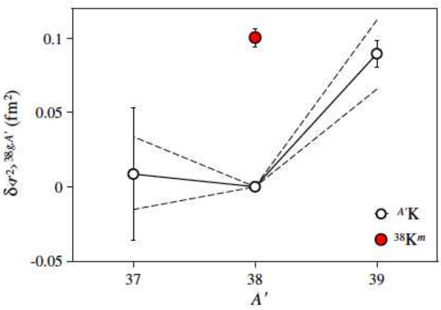
Phys.Lett B 522, 240 (2001)

ISOMER SHIFT IN ^{38}K

PRL 113, 052502 (2014) PHYSICAL REVIEW LETTERS week ending 1 AUGUST 2014

Proton-Neutron Pairing Correlations in the Self-Conjugate Nucleus ^{38}K Probed via a Direct Measurement of the Isomer Shift

M. L. Bissell,[1,*] J. Papuga,[1] H. Naïdja,[2,3,4] K. Kreim,[5] K. Blaum,[5] M. De Rydt,[1] R. F. Garcia Ruiz,[1] H. Heylen,[1] M. Kowalska,[6] R. Neugart,[5,7] G. Neyens,[1] W. Nörtershäuser,[7,8] F. Nowacki,[2] M. M. Rajabali,[1] R. Sanchez,[3,9] K. Sieja,[2] and D. T. Yordanov[5]



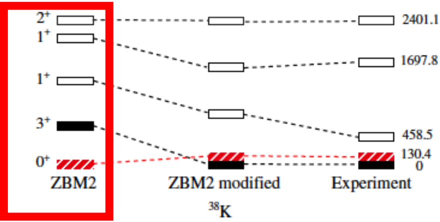
	3^+_{GS}	0^+_m
$\mathcal{H}_{Multi}$	-7.9	-13.2
$\mathcal{H}_P$	-4.2	-9.7
$\mathcal{H}_{P1}$	-4.2	-9.2
$\mathcal{H}_{P1}^{pn}$	-1.4	-6.1

$$\delta r_c^2(0^+) - \delta r_c^2(3^+) = 0.1\,fm^2$$

The strong neutron-proton correlations in 0^+ compared to 3^+

proton occupancy of *fp* shell is reduced in 3^+ compared to 0^+

SM RESULTS : ZBM2



	$n^{\pi}_{fp}(38m)$	$n^{\pi}_{fp}(38g)$	$\delta\langle r_c^2\rangle^{38g,38m}$ (fm^2)
ZBM2	0.86	0.50	0.075
ZBM2 modified	0.82	0.41	0.085
Experiment			0.100(6)

✗ **bad level scheme**

✓ **good variation of r_c**

T=1 matrix elements of the ZBM2 are too strong with respect to the T=0, producing an inversion of the 0^+ and 3^+

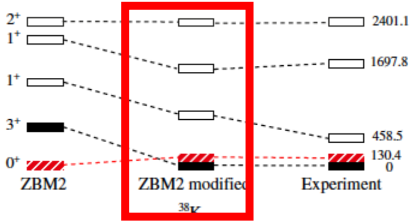
$\Downarrow$

a correction of the ZBM2 is necessary preserving the description of the Ca isotopes shift

SM RESULTS : MODIFIED ZBM2

$$\mathscr{H}_m = \sum \varepsilon_i n_i + \sum a_{ij} n_i \cdot n_j + b_{ij}(T_i \cdot T_j - \frac{3}{4} n\delta_{ij})$$

modified ZBM2 : monopole correction of b_{ij} to $(d_{3/2})^2$ with $\Delta a_{ij} = 0$



	$n^{\pi}_{fp}(38m)$	$n^{\pi}_{fp}(38g)$	$\delta\langle r_c^2\rangle^{38g,38m}$ (fm^2)
ZBM2	0.86	0.50	0.075
ZBM2 modified	0.82	0.41	0.085
Experiment			0.100(6)

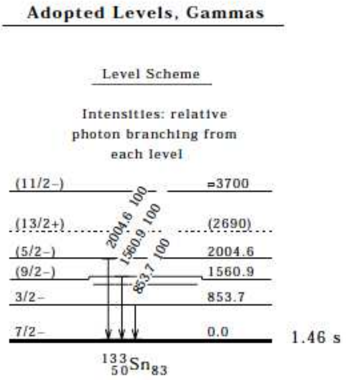
✓ **good level scheme**

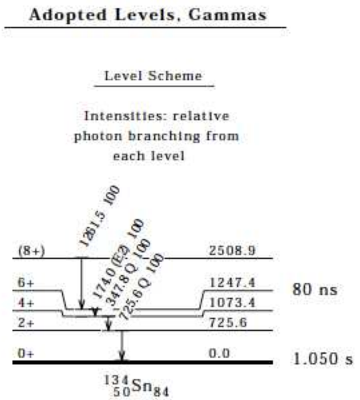
✓ **good variation of r_c**

The modified version of ZBM2 give us a correct order of the states, with conserving a similar composition of the wave functions.

Part II : Spectroscopic properties of the nuclei around ^{132}Sn

Introduction





	^{133}Sn	^{134}Sn	^{135}Sn
BE/A keV	8310.091 (18)	8275.160 (24)	8230.687 (23)

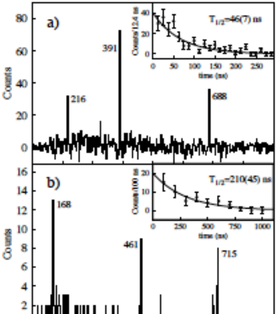
Experimental interest

☞New results of ^{136,138}Sn obtained at RIKEN Nishina center.

PRL **113**, 132502 (2014) PHYSICAL REVIEW LETTERS week ending 26 SEPTEMBER 2014

Yrast 6^+ Seniority Isomers of ^{136,138}Sn

G. S. Simpson,[1,2,3] G. Gey,[3,4,5] A. Jungclaus,[6] J. Taprogge,[6,7,5] S. Nishimura,[5] K. Sieja,[8] P. Doornenbal,[5] G. Lorusso,[5] P.-A. Söderström,[5] T. Sumikama,[9] Z. Y. Xu,[10] H. Baba,[5] F. Browne,[11,5] N. Fukuda,[5] N. Inabe,[5] T. Isobe,[5] H. S. Jung,[12,*] D. Kameda,[5] G. D. Kim,[13] Y.-K. Kim,[13,14] I. Kojouharov,[15] T. Kubo,[5] N. Kurz,[15] Y. K. Kwon,[13] Z. Li,[16] H. Sakurai,[5,10] H. Schaffner,[15] Y. Shimizu,[5] H. Suzuki,[5] H. Takeda,[5] Z. Vajta,[17,5] H. Watanabe,[5] J. Wu,[16,5] A. Yagi,[18] K. Yoshinaga,[19] S. Bönig,[20] J.-M. Daugas,[21] F. Drouet,[3] R. Gernhäuser,[22] S. Ilieva,[20] T. Kröll,[20] A. Montaner-Pizá,[23] K. Moschner,[24] D. Mücher,[22] H. Naïdja,[8,15,25] H. Nishibata,[18] F. Nowacki,[8] A. Odahara,[18] R. Orlandi,[26,†] K. Steiger,[22] and A. Wendt[24]



→ ^{136}Sn

→ ^{138}Sn

Theoretical interest

G, ^{132}Sn core, $\pi(gdsh) \otimes \nu(hfpi)$

...CAL REVIEW C 76, 024313 (2007)

Effective interactions and shell model studies of heavy tin isotopes

M. P. Kartamyshev, T. Engeland, M. Hjorth-Jensen, and E. Osnes
Department of Physics and Centre of Mathematics for Applications, University of Oslo, N-0316 Oslo, Norway

PHYSICAL REVIEW C 81, 064328 (2010)

New shell closure for neutron-rich Sn isotopes

SMPN, ^{132}Sn core, $\pi(gdsh) \otimes \nu(hfpi)$

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...ring and Science University, Shibpur, Howrah 711103, India

M. Saha Sarkar†
Nuclear Physics Division, Saha Institute of Nuclear Physics, Kolkata 700064, India

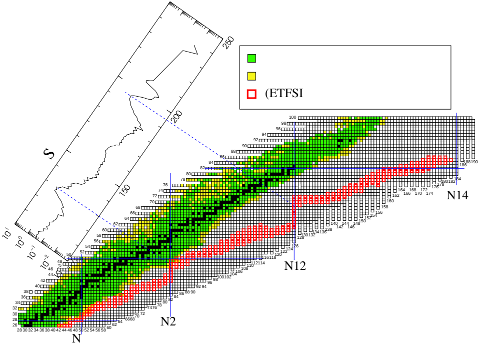
Shell-model study of exotic Sn isotopes with a realistic effective interaction

A Covello[1,2], L Coraggio[2], A Gargano[2] and N Itaco[1,2]
[1]Dipartimento di Scienze Fisiche, Università di Napoli Federico II,
...te S. Angelo, I-80126 Napoli, Italy
...leare,
...te S. Angelo, I-80126 Napoli, Italy

V_{low-k}, ^{132}Sn core, $\pi(gdsh) \otimes \nu(hfpi)$

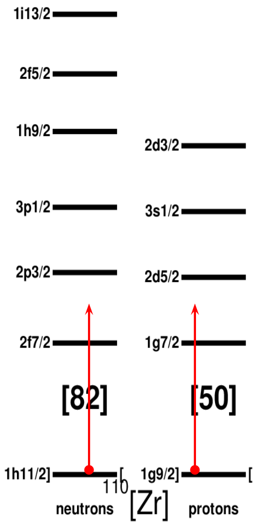
Astrophysical interest

☞ responsible of the synthesis of the heavy elements by r-process, and their nuclear model properties predictions give the inputs for r-process simulations.

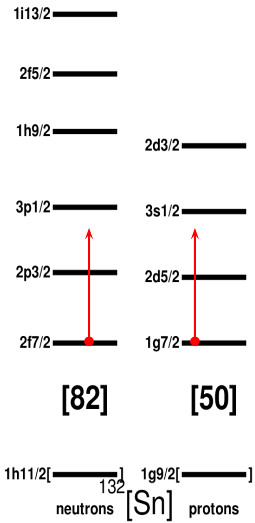


Adapted from K.-L.Kratz

Core and valence space



Core and valence space



- ☞ $1h_{11/2}$ and $1g_{9/2}$ closed $\equiv^{132}Sn$ core
- ☞ $1h_{11/2}$ and $1g_{9/2}$ opened $\equiv^{110}Zr$ core
  - ✓ Opening the ^{132}Sn core constitutes a numerical chalenge in the diagonalisation of the matrix.

$\Downarrow$

Diagonalization in **Antoine** * and **Nathan**† codes using Lanczos procedure, Exemple : ^{140}Sm : D=10 10^{10}

(*)E.Caurier et al, Rev.Mod.Phys 77 (2007)427, and Antoine website

(†)no public version

EFFECTIVE INTERACTION

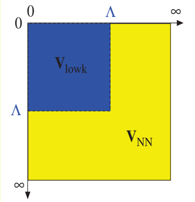
REALISTIC

1. derived from realistic interaction :ArgonneV18, CD-Bonn,N3LO,...
2. renormalised by V_{low-k} or G matrix approach to exclude the repulsive part at short range.
3. adapted to the model space by many body perturbation theory, using $\hat{P}$ and $\hat{Q}$ projection operators into model space and excluded space respectively

$$P = \sum_{i=1}^{d} |\Psi_i><\Psi_i|, \; Q = \sum_{i=d}^{\infty} |\Psi_i><\Psi_i|, \; P+Q=1$$

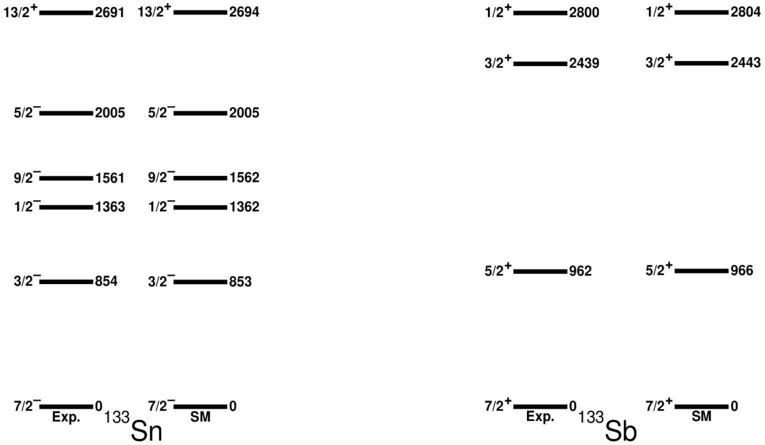
$$V_{eff} = \underbrace{V + V\frac{Q}{E-H_0}V}_{second\ order} + V\frac{Q}{E-H_0}V\frac{Q}{E-H_0}V$$

$$V \rightarrow V_{low-k}$$



M. Hjorth-Jensen et al. Phys.Rep 261 (1995)125

Single particle energies

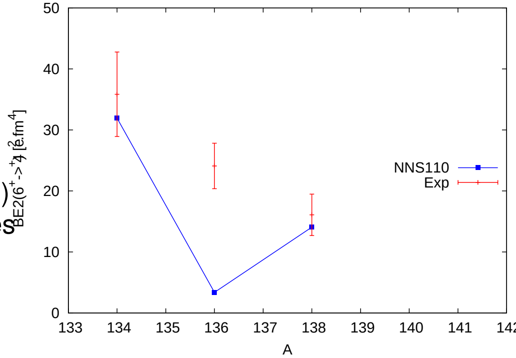


The re-adjustments of the monopole part of V_{low-k} interaction to obtain the experimental level scheme of ^{133}Sn and ^{133}Sb and their masses relative to ^{132}Sn.

NNS110 interaction.

B(E2,$6^+ \rightarrow 4^+$)

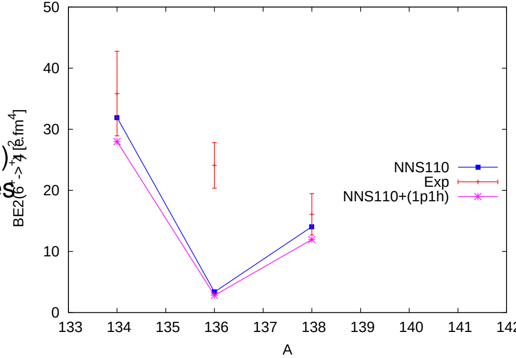
✗ **NNS110** : predicts well the B(E2) in ^{134,138}Sn, but it underestimates it for ^{136}Sn.



$e_{eff}(\nu) = 0.64e$

B(E2,$6^+ \rightarrow 4^+$)

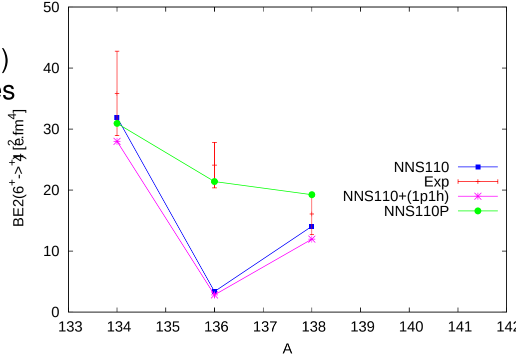
- ✗ **NNS110** : predicts well the B(E2) in ^{134,138}Sn, but it underestimates it for ^{136}Sn.
- ✗ **open core** : still underestimated of ^{136}Sn.



$$e_{eff}(\nu) = 0.5e$$
$$e_{eff}(\pi) = 1.5e$$

B(E2,$6^+ \rightarrow 4^+$)

- ✗ **NNS110** : predicts well the B(E2) in ^{134,138}Sn, but it underestimates it for ^{136}Sn.
- ✗ **open core** : still underestimated of ^{136}Sn.
- ✓ **reducing the pairing (NNS110P)** : gives us a good agreement with the Exp.



H.Naïdja et *al*. J.Phys.Conf.series, 580 (2015)012030

seniority mixing

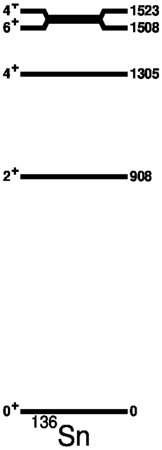
υ=4 84%

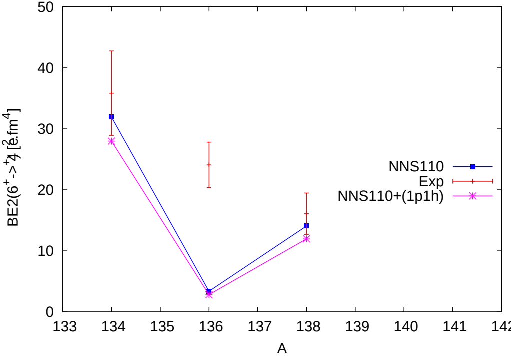
υ=2 96%

υ=2 82%

υ=2 95%

υ=0 98%

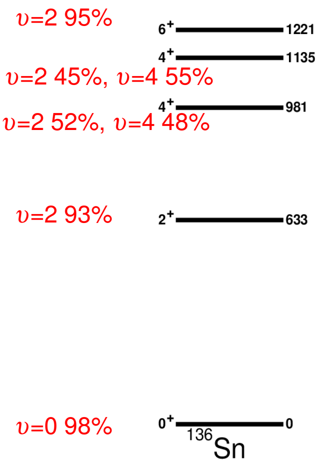


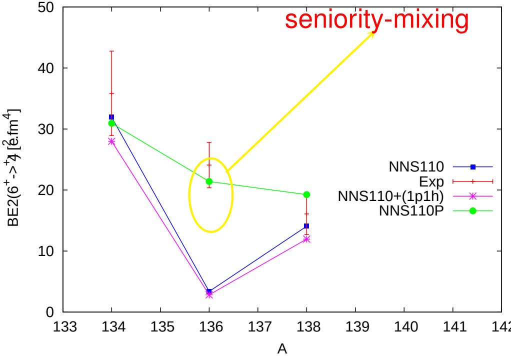


$$B(E2, \upsilon_f = \upsilon_i, J \to J-2) \propto (1 - \frac{2n}{2j+1})^2$$

- 6^+ and 4_1^+ are dominately seniority $\upsilon = 2 \Rightarrow$ vanishing $B(E2)$
- $4_2^+(\upsilon = 4)$ is above the 6^+

seniority mixing





$$B(E2, \upsilon_f = \upsilon_i, J \to \upsilon_i, J-2) \propto (1 - \frac{2n}{2j+1})^2$$

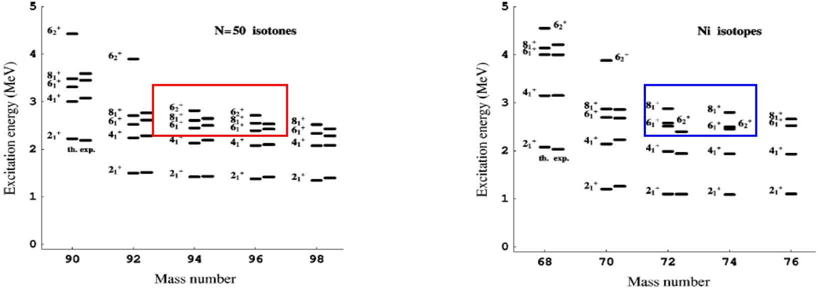
- 4_2^+ is below the 6^+
- mixed seniority $\upsilon = 2$ and $\upsilon = 4$ in 4_1^+ and 4_2^+ states $\Rightarrow$ allowed E2 transitions.

seniority mixing

PHYSICAL REVIEW C 70, 044314 (2004)

New T=1 effective interactions for the $f_{5/2}\, p_{3/2}\, p_{1/2}\, g_{9/2}$ model space: Implications for valence-mirror symmetry and seniority isomers

A. F. Lisetskiy,[1] B. A. Brown,[1] M. Horoi,[2] and H. Grawe[3]

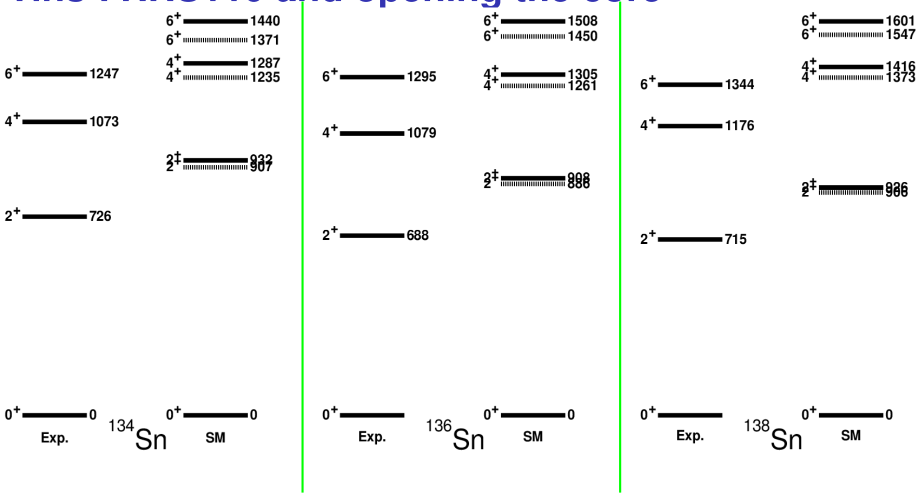


$6_2^+(\upsilon=4)$ is above the 8^+

$6_2^+(\upsilon=2$ and $4)$ is below the 8^+

Pushing down of the $6_2^+(\upsilon=4)$ state opens up a new channel for the fast E2 decay of the 8^+ state.

Tins : NNS110 and opening the core



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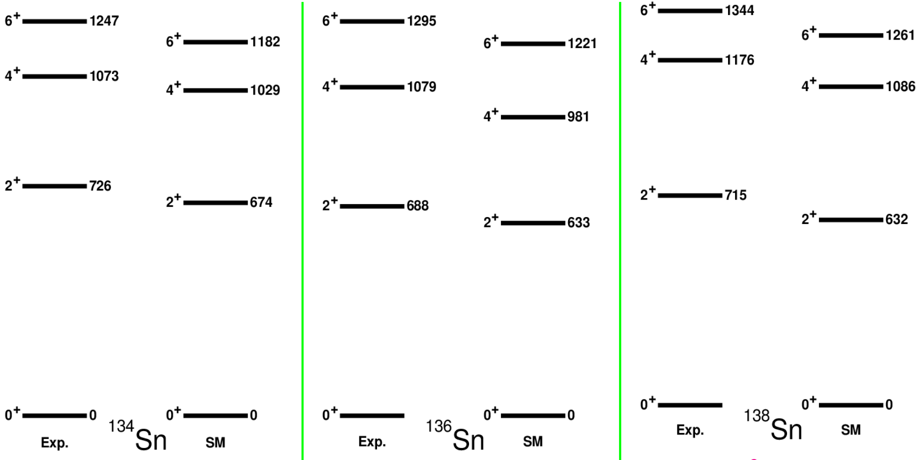
Small effect of the core excitations (1p1h) to the level scheme of tin isotopes.

The robust nature of ^{132}Sn core

Tins : NNS110P interaction



$\nu(f_{7/2})^2 \approx$80%-96% $\nu(f_{7/2})^4 \approx$60%-80% $\nu(f_{7/2})^6 \approx$50%-70%

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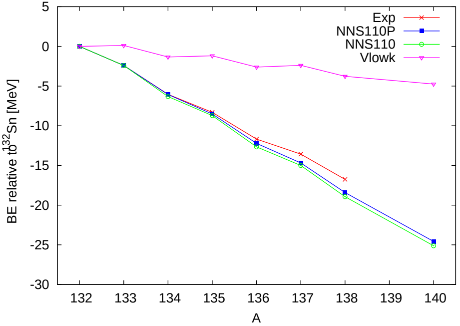
Reducing the pairing strength (NNS110P interaction), improves clearly the agreement with the data.

Masses

- Binding energies relative to ^{132}Sn



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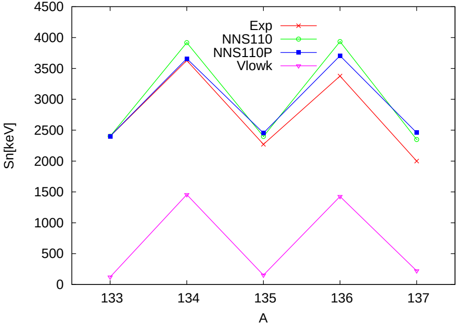
- one neutron separation energy



✓ Our masses are consistent with the data

✓ The 2 body monopole corrections are believed to come from 3 body interaction not included in V_{low-k}

sub-shell closure at N=90 ?

PHYSICAL REVIEW C 81, 064328 (2010)

New shell closure for neutron-rich Sn isotopes

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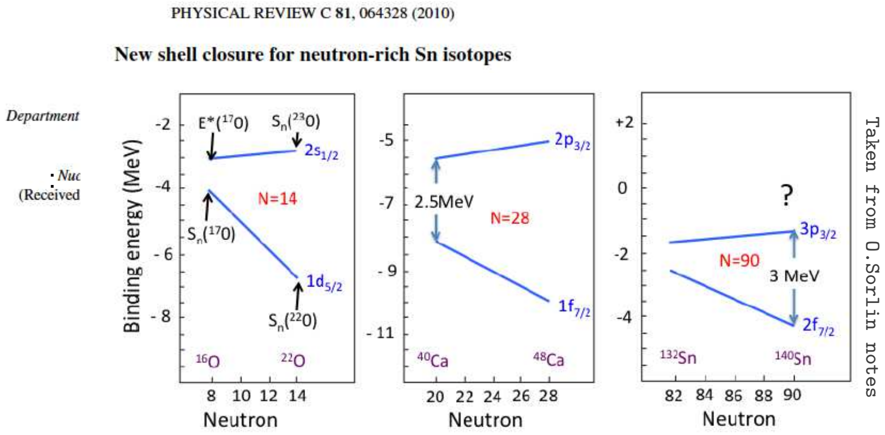
(Received 11 October 2009; revised manuscript received 11 June 2010; published 29 June 2010)

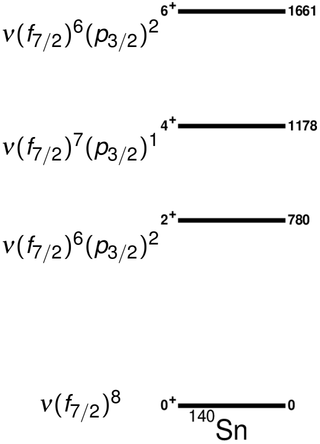
sub-shell closure at N=90 ?



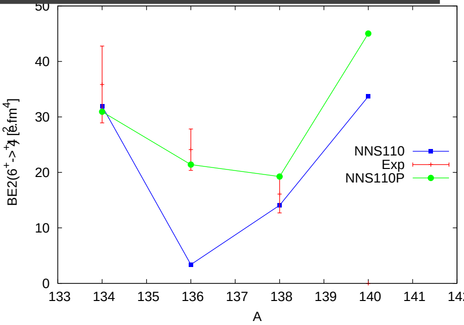
- Analogy between ^{22}O, ^{48}Ca, and ^{140}Sn in the closure of the (sub-)shell at N=14,28, and 90 ?

A.P.Zuker, PRL 90, 042502 (2003)
T.Otsuka et al. PRL 105,032501 (2010)

Sub-shell closure at N=90 ?



our predictions to ^{140}Sn structure using **NNS110P**



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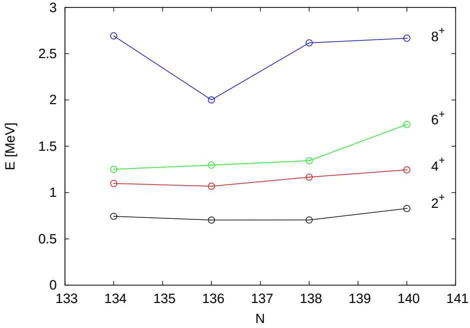
- the excited states are characterized by mixed configurations.

Sub-shell closure at N=90 ?



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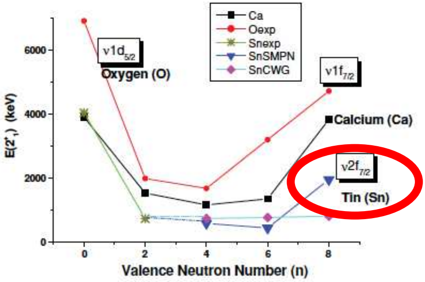
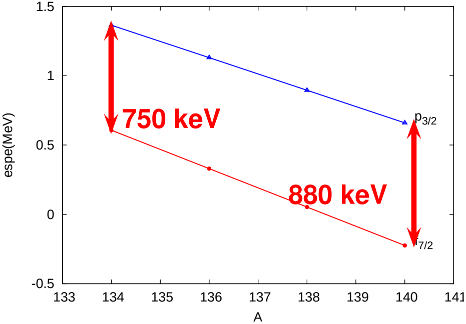


S.Sarkar and M.S.Sarkar Phys.Rev.C 81, 064328(2010)

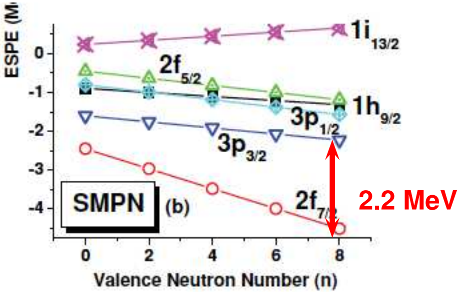
- the spacing $0^+ - 2^+$ remains nearly constant at around 700 keV, except for a small increase at ^{140}Sn owing to the filling of the $(f_{7/2})$.
- a sudden increase for N=90, indicating a closed-shell structure for ^{140}Sn.

2^+ energy in ^{140}Sn in not higher than in the neighboring nuclei.

Evolution of neutron ESPE



H.Naïdja et *al*. J.Phys.Conf.series, 580 (2015)012030



S.Sarkar and M.S.Sarkar Phys.Rev.C 81, 064328(2010)

- The gap between $\nu f_{7/2}$ and $\nu p_{3/2}$ remains constant

$\Downarrow$

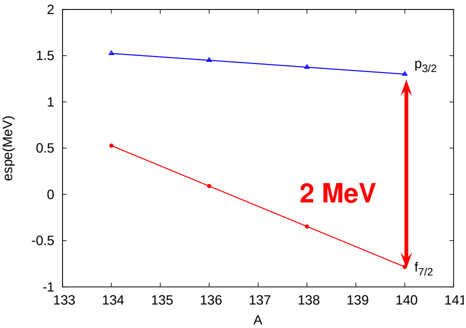
No sub-shell closure at N=90

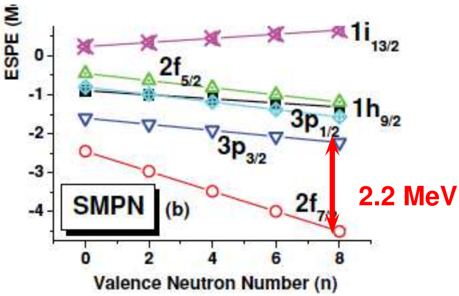
- The gap $\nu f_{7/2}$ and $\nu p_{3/2}$ increases to 2.246 MeV

$\Downarrow$

^{140}Sn is doubly magic nucleus

Evolution of neutron ESPE





S.Sarkar and M.S.Sarkar Phys.Rev.C 81, 064328(2010)

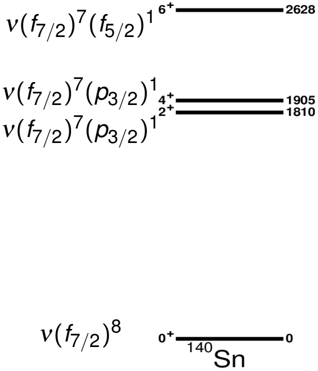
- Increasing the gap by changing the monopole part

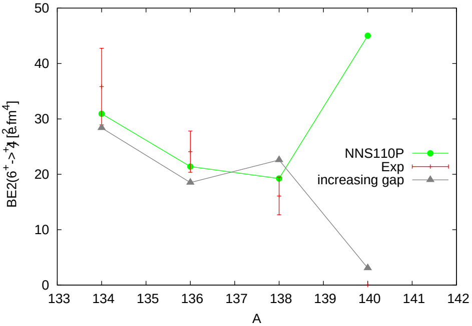
- The gap $\nu f_{7/2}$ and $\nu p_{3/2}$ increases to 2.246 MeV

$\Downarrow$

^{140}Sn is a doubly magic nucleus

Increasing the gap



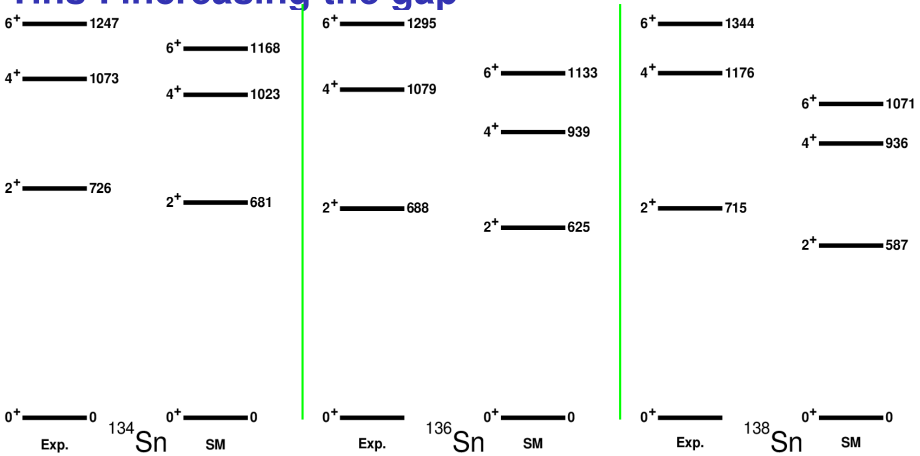


Increasing the gap by changing the monopole part

$\Downarrow$

- Transitions are slightly inconsistent with the experience
- sudden decrease of B(E2) in ^{140}Sn
    1. E(2) favor the transitions from $j \to j+2(p_{3/2} \to f_{7/2})$ compared as $j \to j+1(f_{5/2} \to f_{7/2})$

Tins : increasing the gap



increasing $f_{7/2} - p_{3/2}$ gap, has an apparent effect to ^{138}Sn structure.

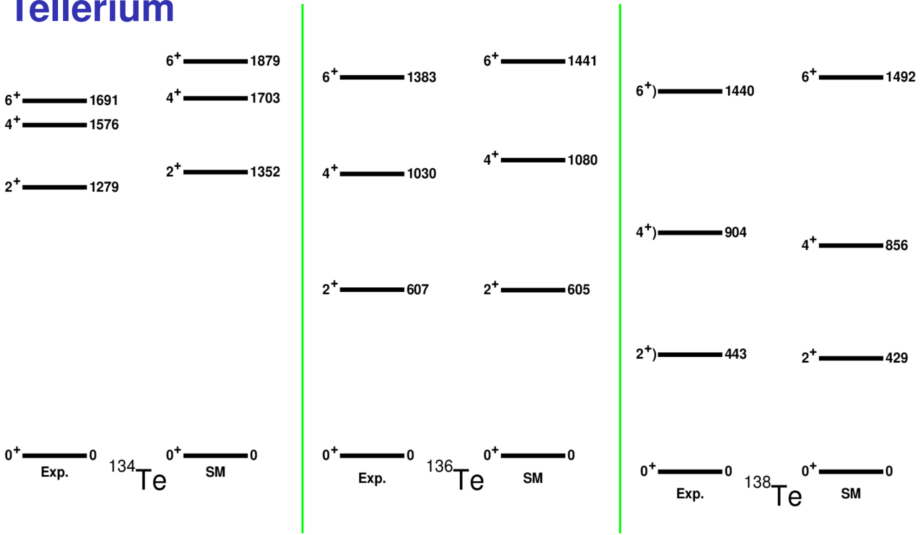
$\Downarrow$

Losing the spectroscopic properties.

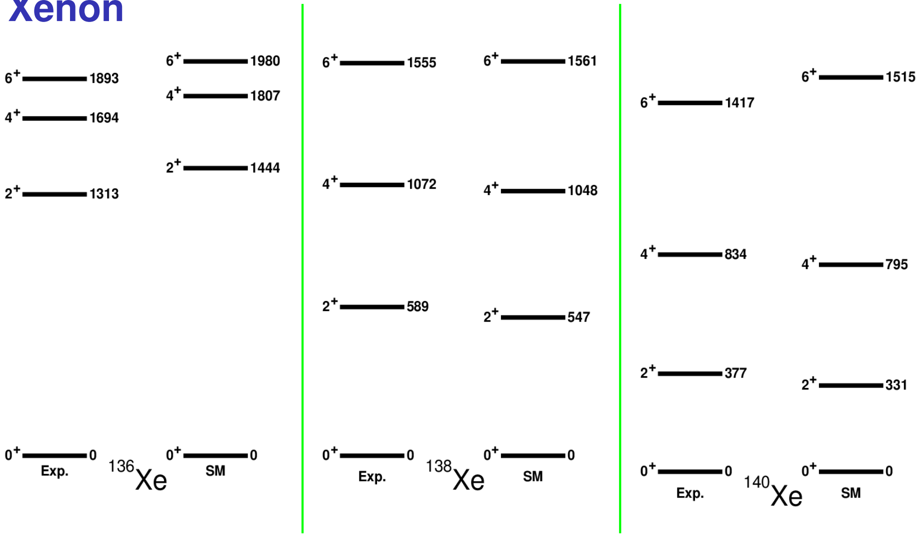
No sub-shell closure at N=90

Other Applications to the open n-p systems

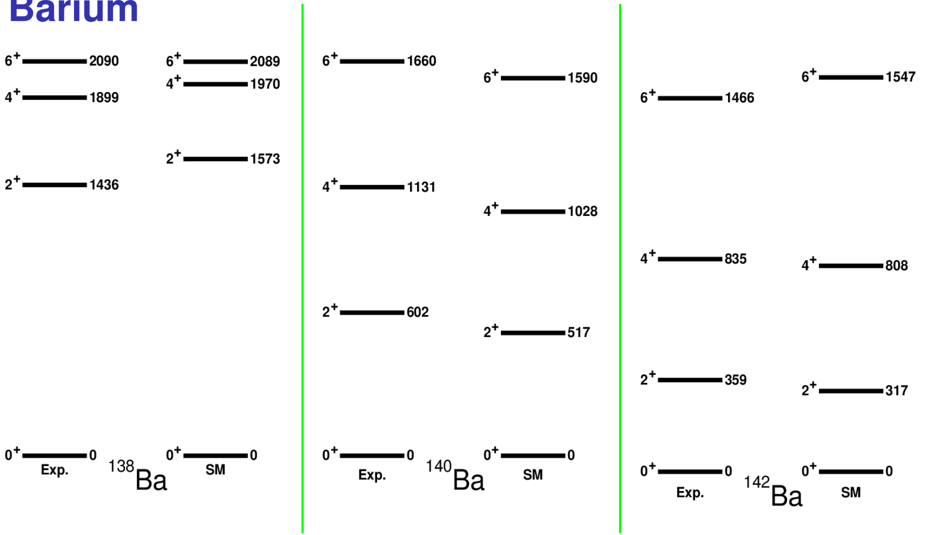
Tellerium


6+ 1691
4+ 1576
2+ 1279
0+ 0
Exp.
134Te
6+ 1879
4+ 1703
2+ 1352
0+ 0
SM
6+ 1383
4+ 1030
2+ 607
0+ 0
Exp.
136Te
6+ 1441
4+ 1080
2+ 605
0+ 0
SM
6+) 1440
4+) 904
2+) 443
0+ 0
Exp.
138Te
6+ 1492
4+ 856
2+ 429
0+ 0
SM

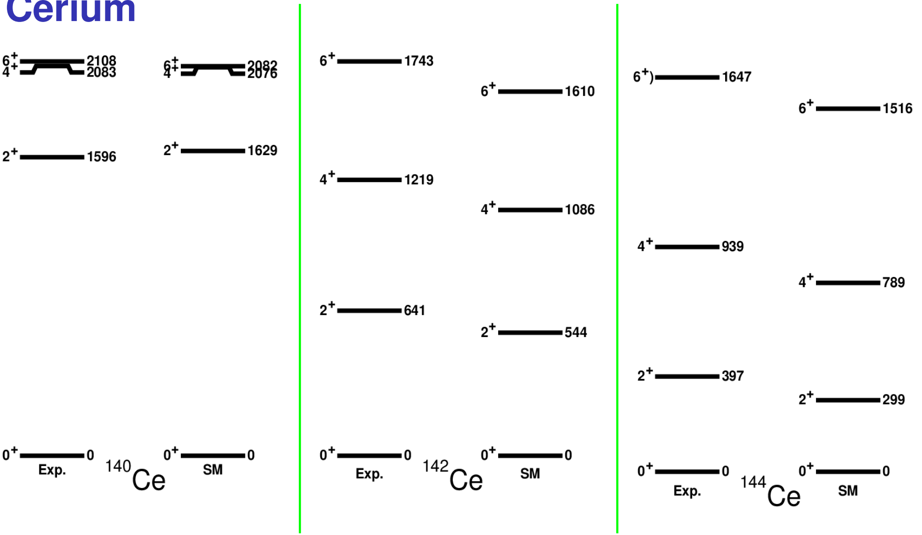
Xenon


6+ 1893
4+ 1694
2+ 1313
0+ 0
Exp.
136Xe
6+ 1980
4+ 1807
2+ 1444
0+ 0
SM
6+ 1555
4+ 1072
2+ 589
0+ 0
Exp.
138Xe
6+ 1561
4+ 1048
2+ 547
0+ 0
SM
6+ 1417
4+ 834
2+ 377
0+ 0
Exp.
140Xe
6+ 1515
4+ 795
2+ 331
0+ 0
SM

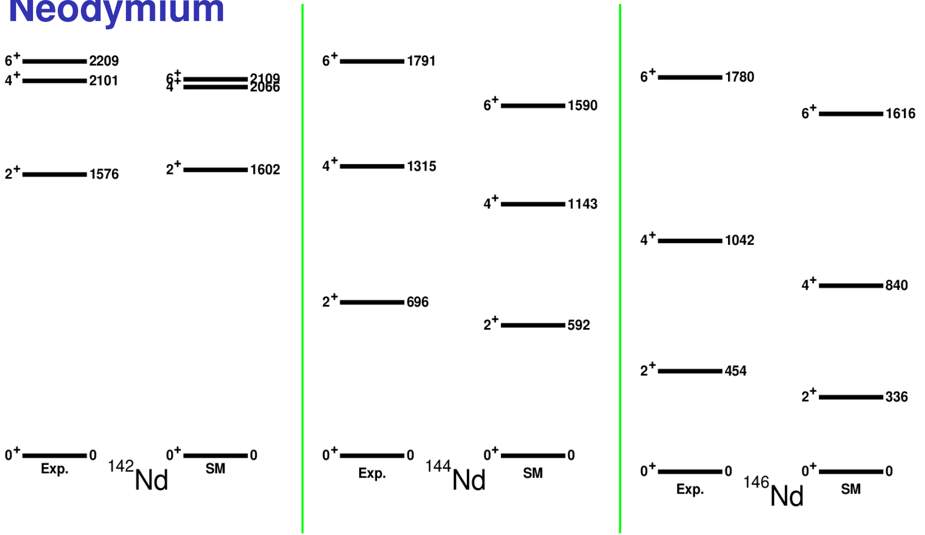
Barium


6+ 2090
4+ 1899
2+ 1436
0+ 0
Exp.
6+ 2089
4+ 1970
2+ 1573
0+ 0
SM
138Ba
6+ 1660
4+ 1131
2+ 602
0+ 0
Exp.
6+ 1590
4+ 1028
2+ 517
0+ 0
SM
140Ba
6+ 1466
4+ 835
2+ 359
0+ 0
Exp.
6+ 1547
4+ 808
2+ 317
0+ 0
SM
142Ba

Cerium


6+ 2108
4+ 2083
2+ 1596
0+ 0
Exp.
6+ 2082
4+ 2076
2+ 1629
0+ 0
SM
140Ce
6+ 1743
4+ 1219
2+ 641
0+ 0
Exp.
6+ 1610
4+ 1086
2+ 544
0+ 0
SM
142Ce
6+) 1647
4+ 939
2+ 397
0+ 0
Exp.
6+ 1516
4+ 789
2+ 299
0+ 0
SM
144Ce

Neodymium

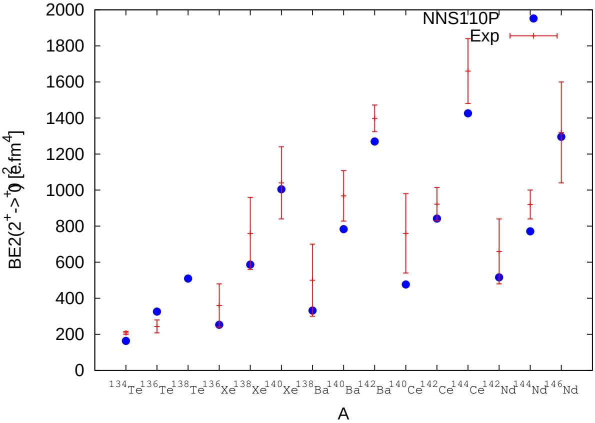


6+ 2209
4+ 2101
2+ 1576
0+ 0
Exp.
142Nd
6+ 2109
4+ 2066
2+ 1602
0+ 0
SM
6+ 1791
4+ 1315
2+ 696
0+ 0
Exp.
144Nd
6+ 1590
4+ 1143
2+ 592
0+ 0
SM
6+ 1780
4+ 1042
2+ 454
0+ 0
Exp.
146Nd
6+ 1616
4+ 840
2+ 336
0+ 0
SM

Collective properties

To be published

$B(E2, 2^+ \to 0^+)$



$e_{eff}(\pi) = 1.5e$
$e_{eff}(\nu) = 0.5e$

- ✓ B(E2) are reporduced with no explicit adjustement of the e_{eff}.
- ✓ BE2 in ^{136}Te is close to that ^{134}Te, so anomaly in ^{136}Te

Triaxiality

- $Q(2^+_\gamma) = -Q(2^+_{yrast})$.
- the presence of $B(E2, 2^+_\gamma \to 2^+_1)$ transition
- $Q(3^+) = 0$.
- strong $B(E2, 3^+ \to 2^+_2)$ transition

work under progress with Bounseng Bounthong using the deformed HF with constraints

	^{138}Te	^{140}Xe	^{142}Ba	^{144}Ce	^{146}Nd
$Q(2^+_1)e.fm^2$	-45.67	-62.64	-70.74	-75.24	-61.76
$Q(2^+_2)e.fm^2$	40.08	63.84	69.18	75.49	-60.92
$Q(3^+)e.fm^2$	-0.34	-1.31	-0.62	-0.79	-0.10
$B(2^+_2 \to 2^+_1)e^2.fm^4$	43	155	180	210	294
$B(3^+ \to 2^+_2)e^2.fm^4$	745	1911	2054	2569	2153
$Q_i(Q_0)$	157	220	248	262	248
$Q_i(B(E2))$	160	225	252	268	255
β	0.1	0.14	0.15	0.15	0.14

Conclusions-Perspectives

- ✓ Using NNS110P interaction, the agreement between the experience and calculated energy levels is improved.
- ✓ The pairing force must be reduced to reproduce the experimental transition rates in ^{136}Sn, leading to mixing seniority.
- ✓ The core excitations seem to have a negligible effect to the tin isotopes energies, confirming the strong magicity of ^{132}Sn
- ✓ ^{140}Sn doesn't exhibit the features of a doubly magic nucleus.
- ✓ The applications to other nuclei allowed us to test our interaction to differents systems.

Projects under progress

- Triaxiality in ^{140}Sm : in collaboration with Andreas Görgen, University of Oslo.
- Isomer in ^{140}Sb : in collaboration with Radomira Lozeva ; IPHC Strasbourg
- High spin states in ^{138}Te and ^{140}Xe : in collaboration with W.Urban,
- The deformation in the nuclei beyond ^{132}Sn with B.Bounthong.
- ...