Spectroscopy and shape change in neutron-rich Sr and Zr isotopes

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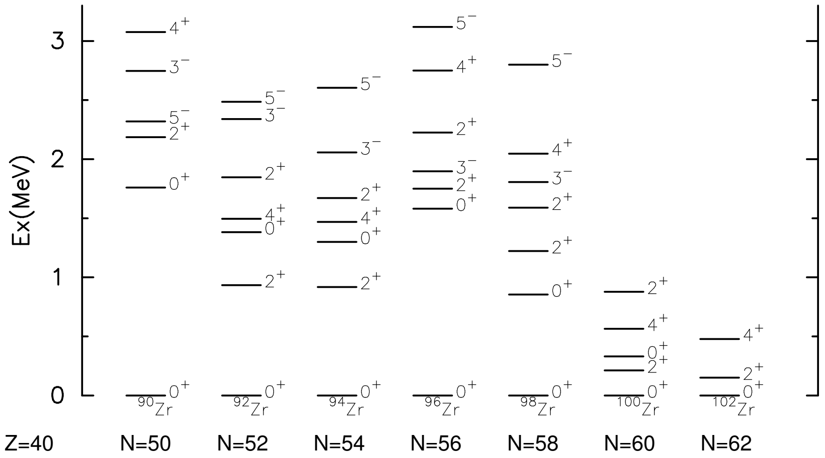
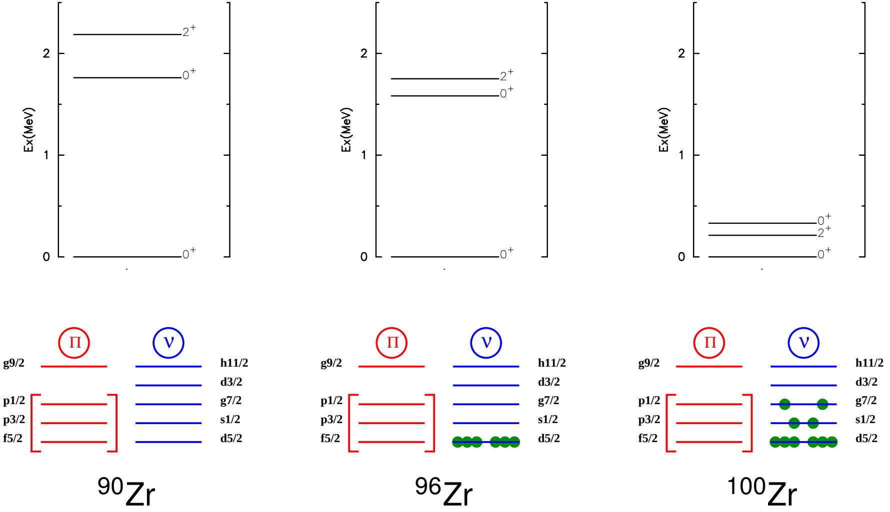
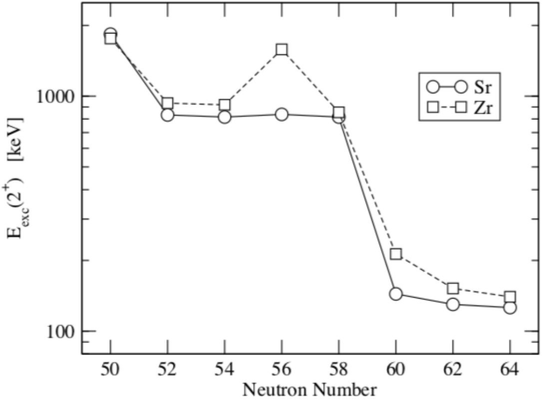
Introduction: Zr chain



Introduction: Zr chain



Introduction: Zr and Sr isotopes



The general many-body problem for fermions

The Schrödinger equation for a system of n particles each of mass m is:

$$\hat{H}|\Psi\rangle = E|\Psi\rangle, \tag{1}$$

$$H = \sum_{k=1}^{n}(T_k + U_k) + (\sum_{k<l}^{n} V_{kl} - \sum_{k=1}^{n} U_k) = H^0 + W \tag{2}$$

The standard solution of this problem is to solve first the simpler one

$$\hat{H}^0|\Phi_a\rangle = E_a^0|\Phi_a\rangle, \tag{3}$$

with

$$|\Phi_a\rangle = \Pi_{k=1}^{n}|\alpha_k\rangle = \phi_{\alpha_1}(\vec{r}_1)\phi_{\alpha_2}(\vec{r}_2)...\phi_{\alpha_n}(\vec{r}_n) \tag{4}$$

$$E_a^0 = \sum_{k=1}^{n}\varepsilon_{\alpha_k}. \tag{5}$$

The $|\alpha\rangle$ are solutions of the single-particle equation:

$$(T + U)|\alpha\rangle = \varepsilon_\alpha|\alpha\rangle \tag{6}$$

a- set of quantum numbers α_k, for example $|n_r, l, j, m_j\rangle$ in a spherical basis.

Shell-model approaches

- The wave-function of the ground state is expressed as a sum of the vacuum Φ_0 and particle-hole excitations build on this vacuum state

$$|\Psi_0\rangle = C_0|\Phi_0\rangle + \sum_{i\alpha} C_{i\alpha}|\Phi_{i\alpha}\rangle + C_{ij\alpha\beta}|\Phi_{ij\alpha\beta}\rangle + \cdots \quad (7)$$

where greek and latin symbols refer to particle and hole states, respectively. In short notation:

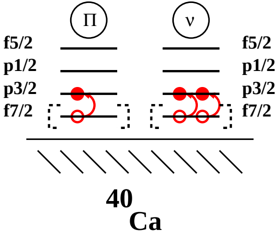
$$|\Psi_0\rangle = \sum_{ph} C_{ph}|\Phi_{ph}\rangle \quad (8)$$

- The equation for the energy reads

$$E = \langle\Psi_0|\hat{H}|\Psi_0\rangle = \sum_{pp'hh'} C^*_{p'h'}\langle\Phi_{p'h'}|\hat{H}|\Phi_{ph}\rangle C_{ph} \quad (9)$$

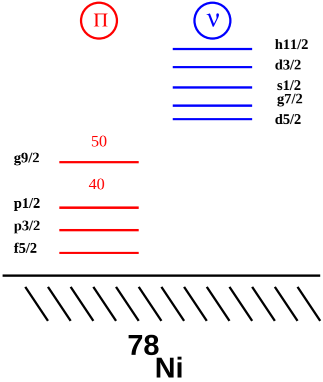
and it is solved by diagonalization.

- The vaccum for particle-hole excitations 1p-1h, 2p-2h,..., np-nh can be, e.g. the lowest-filling configuration (Slater determinant) outside a doubly-magic core.



- the problem solution is limited by computing capacities, i.e. the size of the matrix to diagonalize.

Nuclei above ^{78}Ni

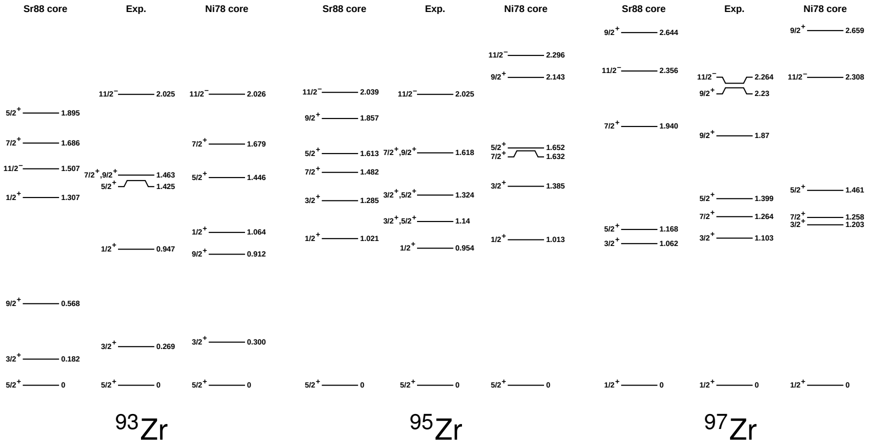


- Even-odd and odd-odd Br nuclei *PRC92 (2015) 014328, PRC94 (2016) 044328, PRC95 (2017) 024321, PRC100 (2019) 054331, PRC103 (2021) 034304*

Interaction: based on realistic TBME, monopoles corrected. Proven successful and predictive in a large number of applications:

- Structure, mixed symmetry states in Zr isotopes, shell evolution between ^{91}Zr and ^{101}Sn *PRC79 (2009) 064310*
- Collectivity of $N = 52, 54$ nuclei*PRC88 (2013) 034327, PRC92 (2015) 034305, PRC92 (2015) 064322, PRC96 (2017) 011301R, PRC95 (2017) 051302R*
- 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, PRC93 (2016) 034318*
- 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, MSS of ^{86,88}Kr, ^{88}Sr *PRC 80 (2014) 064305, PRC94 (2016) 054323*
- Neutron-rich Cd isotopes *PRC79 (2009) 011301R, PRC82 (2010) 034323*

Results: odd Zr isotopes N=51-57

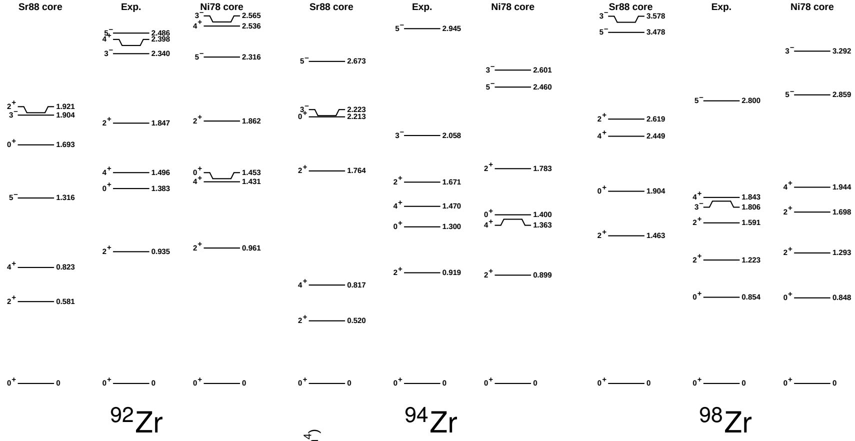


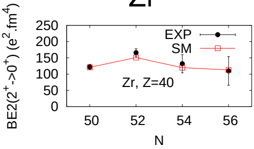
PHYSICAL REVIEW C **79**, 064310 (2009)

Shell model description of zirconium isotopes

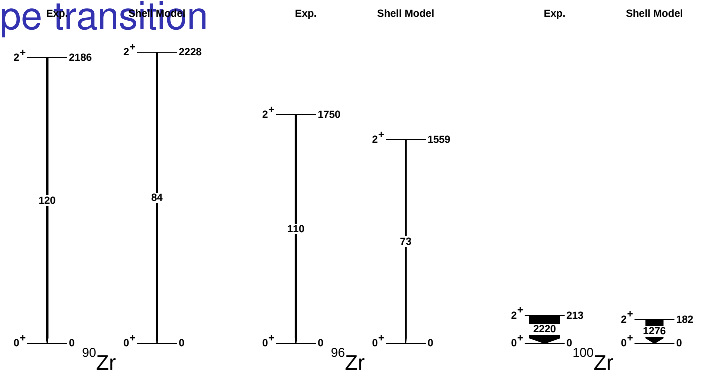
K. Sieja,[1,2] F. Nowacki,[3] K. Langanke,[2,4] and G. Martínez-Pinedo[1]
[1]*GSI-Helmholtzzentrum für Schwerionenforschung mbH., Planckstrasse 1, D-64-220 Darmstadt, Germany*
[2]*Institut für Kernphysik, Technische Universität Darmstadt, D-64289 Darmstadt, Germany*
[3]*Institute Pluridisciplinaire Hubert Curien, 23 rue du Loess, Strasbourg, France*

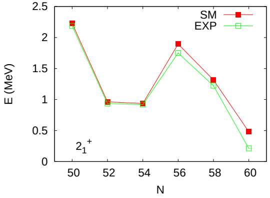
Results: even Zr isotopes N=50-58

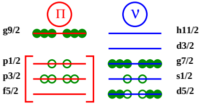




Shape transition



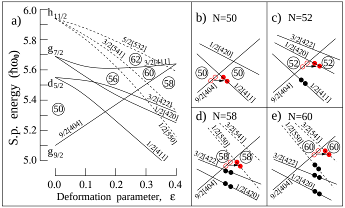




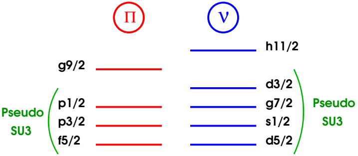
☞prolate configuration $\beta = 0.26$

Origin of deformation

- Spin-Orbit Partners mechanism: strong interaction between $\pi g_{9/2}$ protons and $\nu g_{7/2}$ neutrons
  P. Federman and S. Pitel, Phys. Rev. C20 (1979) 820
- Increased role of the neutrons from the extruder $\nu g_{9/2}$ orbital
  W. Urban et al., Phys. Rev. C102 (2020) 064321



- increased role of the intruder orbitals $\pi d_{5/2}$ and $\nu f_{7/2}$
  PRC79 (2009) 064310



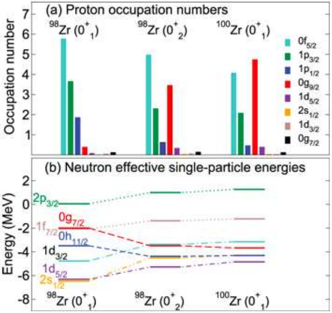
1. two pseudo-SU3 blocks: $B(E2;2^+ \rightarrow 0^+)$=770e^{2}fm^4
2. adding $\pi d_{5/2}$ orbital to form an extra symmetry block: $B(E2;2^+ \rightarrow 0^+)$=2200e^{2}fm^4
3. adding also $\nu f_{7/2}$ orbital to form another extra symmetry block: $B(E2;2^+ \rightarrow 0^+)$=3500e^{2}fm^4

EXP=2220e^{2}fm^4

☞extension of the model space necessary

MCSM in Zr and Sr isotopes

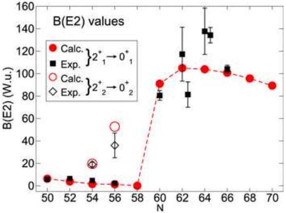
with MC and variational basis optimization procedure, problem equivalent to diagonalization of 10^{23} SD (current diagonalization limit 10^{11})



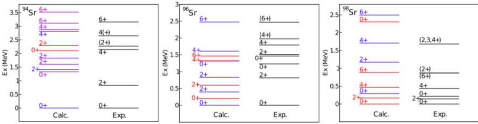
☞consistent with earlier SM suggestions

T. Togashi et al., PRL117 (2016) 172502

E2 transitions in Zr isotopes



Spectra of Sr isotopes



Sr isotopes

A lot of new experimental studies were performed in recent years in Sr isotopes:

- Coulex of $^{96-98}$Sr at REX-ISOLDE
  E. Clement et al. Phys. Rev. Lett. 116 (2016) 022701
  -5DCH calculations with Gogny forces
- (d,p) reactions on $^{94-96}$Sr from TRIUMF
  S. Cruz et al., Phys. Lett. B786 (2018) 94; PRC100 (2019) 054321; PRC102 (2020) 024335
  -restricted SM calculations
- Lifetime measurements in $^{94-98}$Sr
  J.M. Regis et al., PRC95 (2017) 054319
  -MCSM calculations

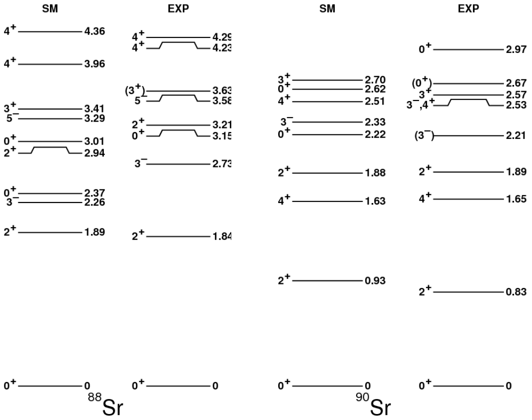
New data from the EXILL campaign:

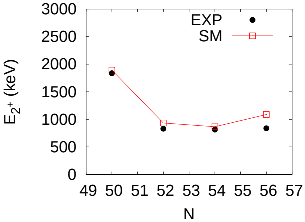
- ^{90,92,94,96}Sr, 23 new levels, 30 new decays, 57 parity/spin assignements
- reliable assignements of spin/parity
- identification of the key collective excitations

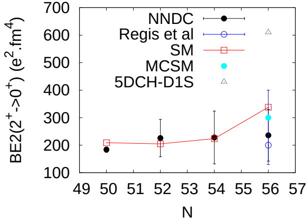
W. Urban, KS et al., *Structure of even-even Sr isotopes with* $50 \leq N \leq 58$, in preparation.

KS, *Single-particle and collective structures in neutron-rich Sr isotopes towards the* $N = 60$ *shape transition*, in preparation.

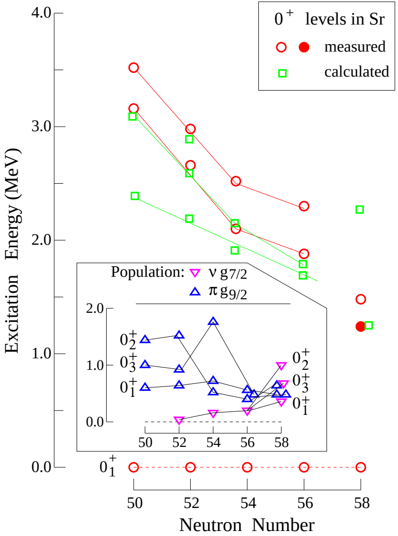
Light Sr isotopes



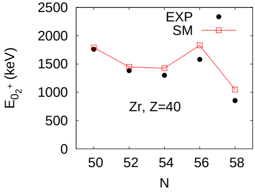




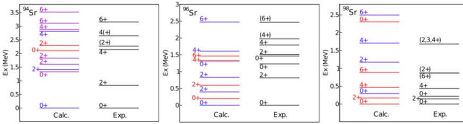
Systematics of the 0^+ excitations



First excited 0^+ in zirconium isotopes



Spectra of Sr isotopes from MCSM

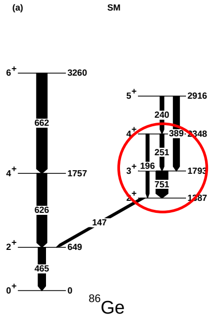


Is it experiment or theory?

Non-axiality around ^{78}Ni core

Suggestion from SM and GCM-Gogny models: triaxial bands close to the core in N=52,54 Se and Ge

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



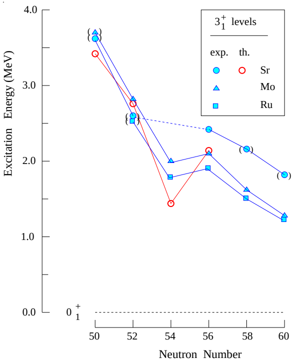
confirmed in recent experiments

Phys. Rev. C92 (2015) 034305;

Phys. Rev. C92 (2015) 064322;

Phys. Rev. C96 (2017) 011301R

What about Sr isotopes?



A γ band ($K = 2$), apart of a characteristic level sequence, has $Q(2^+_\gamma) = -Q(2^+_\gamma)$ and $Q(3^+) \sim 0$.

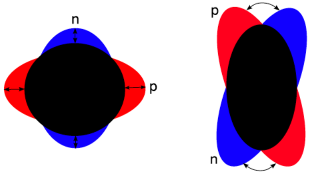
This is not true for $^{88-90,94}$Sr. **But in ^{92}Sr:**

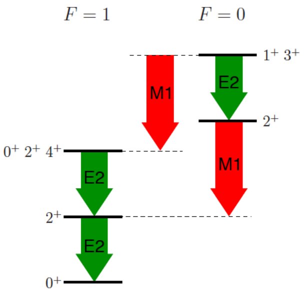
$Q(2^+_2) = 24.8e^2.fm^2$

$Q(2^+_1) = -16.5e^2.fm^2$

$Q(3^+) = 1.89e^2.fm^2$

Mixed-symmetry states

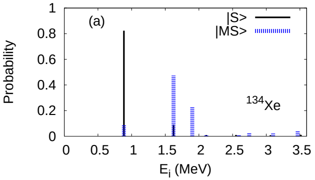




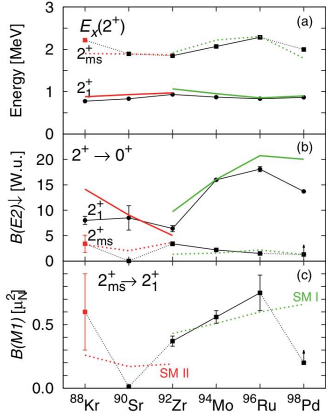
F-spin: concept of isospin extended to proton and neutron bosons
maximum F : state is fully symmetric (FS)
nonmaximum F: state is said to have a mixed-symmetry (MS)
signature: strong $M1$ decay between 2_1^+ and MS $\langle 2^+_{MS} | T(M1) | 2_1^+ \rangle \sim 1\mu_N$

K. Sieja et al., Description of proton-neutron mixed-symmetry states near ^{132}Sn within a realistic LSSM, PRC80 (2009) 054311

Q-phonon scheme:
$|2_1^+\rangle = Q_{\mathrm{S}} |0_1^+\rangle$
$|2^+_{\mathrm{MS}}\rangle = Q_{\mathrm{MS}} |0_1^+\rangle$
$Q_{\mathrm{S}} = Q_p + Q_n$
$Q_{\mathrm{MS}} = Q_p - \alpha Q_n$



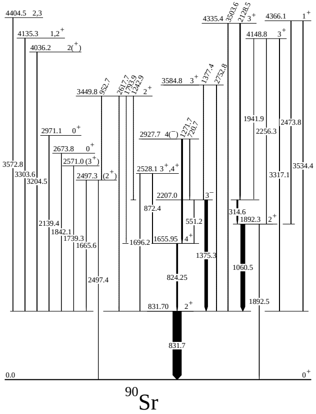
MS states in N=52 isotones



K. Moschner et al., PRC94 (2016) 054323

B(XL) in ^{92}Zr

N	Transition	exp	SM
52	$B(E2;2^+_1 \rightarrow 0^+_1)$	$164e^2fm^4$	$151e^2fm^4$
	$B(E2;2^+_1 \rightarrow 0^+_2)$	$71e^2fm^4$	$50e^2fm^4$
	$B(E2;2^+_2 \rightarrow 0^+_1)$	$84e^2fm^4$	$100e^2fm^4$
	$B(M1;2^+_2 \rightarrow 2^+_1)$	$0.37(4)\mu_N^2$	$0.21\mu_N^2$
	$B(M1;2^+_3 \rightarrow 2^+_1)$	$\leq 0.024\mu_N^2$	$0.06\mu_N^2$

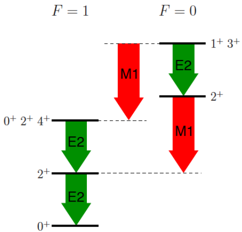


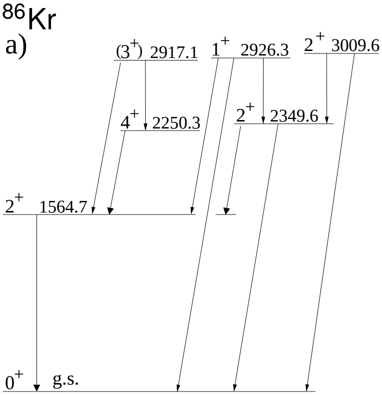
What become MS states at N=50?

B(XL) in ^{86}Kr

N	Transition	SM
50	$B(E2;2^+_1 \rightarrow 0^+_1)$	$190e^2fm^4$
	$B(E2;2^+_2 \rightarrow 0^+_1)$	$18e^2fm^4$
	$B(M1;2^+_2 \rightarrow 2^+_1)$	$0.25\mu_N^2$

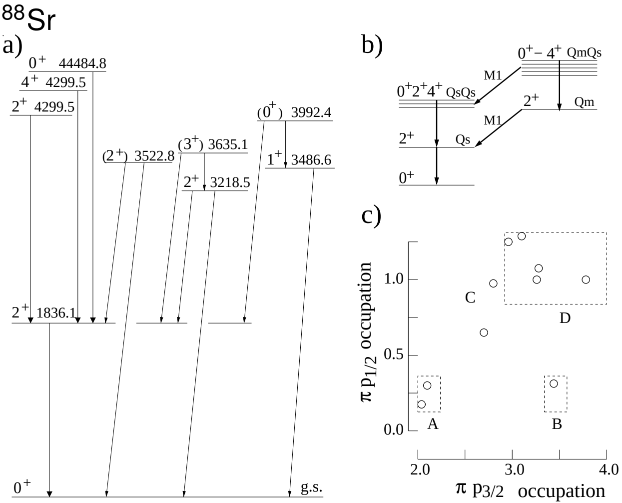
☞Strong *M*1 transitions between $f_{5/2}$ and $p_{3/2}$ orbitals





W. Urban et al. PRC94 (2016) 044328

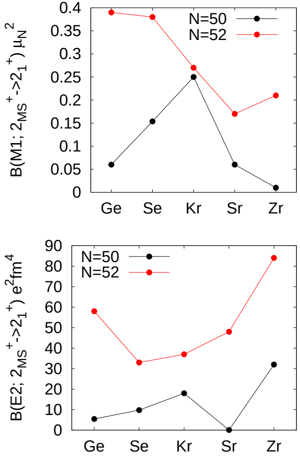
What become MS states at N=50?



Systematics at N=50,52

B(XL) in ^{88,90}Sr

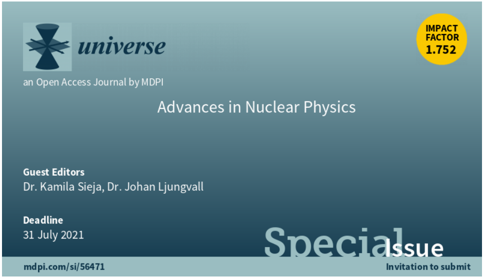
N	Transition	SM
50	$B(E2;2_1^+ \to 0_1^+)$	$209e^2fm^4$
	$B(E2;2_2^+ \to 0_1^+)$	$0.1e^2fm^4$
	$B(M1;2_2^+ \to 2_1^+)$	$0.06\mu_N^2$
52	$B(E2;2_1^+ \to 0_1^+)$	$205e^2fm^4$
	$B(E2;2_2^+ \to 0_1^+)$	$48e^2fm^4$
	$B(M1;2_2^+ \to 2_1^+)$	$0.17\mu_N^2$



Conclusions

- Understanding of the nature of low-energy excitations around ^{78}Ni
- Mixed-symmetry states: what they really are?
- Tracking evolution of single-particle excitations in the region
- Need experimental data: less exotic nuclei, better probes

Advances in Nuclear Physics



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-review, regular, communication
-deadline end of 2021 (progressive publication before the deadline)