Nuclear moments of excited states in neutron rich Sn isotopes studied by on-line PAC

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Nuclear moments – Why?

Magnetic dipole and electric quadrupole moments

- ○ Sensitivity towards single-particle and collective properties of the nuclei

$$\vec{\mu}=\sum_{k=1}^{A} g_\ell^{(k)}\vec{\ell}^{(k)}+\sum_{k=1}^{A} g_s^{(k)}\vec{s}^{(k)}$$

$$2\,\mathrm{Q} = e^{\pi}\sum_{p=1}^{Z}\overline{(3z^2-r^2)} + e^{\nu}\sum_{n=1}^{N}\overline{(3z^2-r^2)}$$

Free-nucleon vs. effective g factors

$$g_s^\pi = 5.58 \qquad g_\ell^\pi = 1$$
$$g_s^\nu = -3.28 \qquad g_\ell^\nu = 0$$

$$g_s^\pi = 0.7 * g_s^\pi \qquad g_\ell^\pi = 1 + \Delta g^\pi$$
$$g_s^\nu = 0.7 * g_s^\nu \qquad g_\ell^\nu = \Delta g^\nu$$

Free-nucleon vs. effective charge

$$e^\pi = 1e$$
$$e^\nu = 0$$

$$e_{eff}^\pi = (1+\Delta e^\pi)e$$
$$e_{eff}^\nu = \Delta e^\nu\, e$$

- ✓ valence particle configuration;
- ✓ core polarization (M1 excitations);
- ✓ purity of the wave function

Single-particle case

$$Q_\mathrm{I} = \frac{2j+1-2n}{2j-1} Q_\mathrm{j}$$

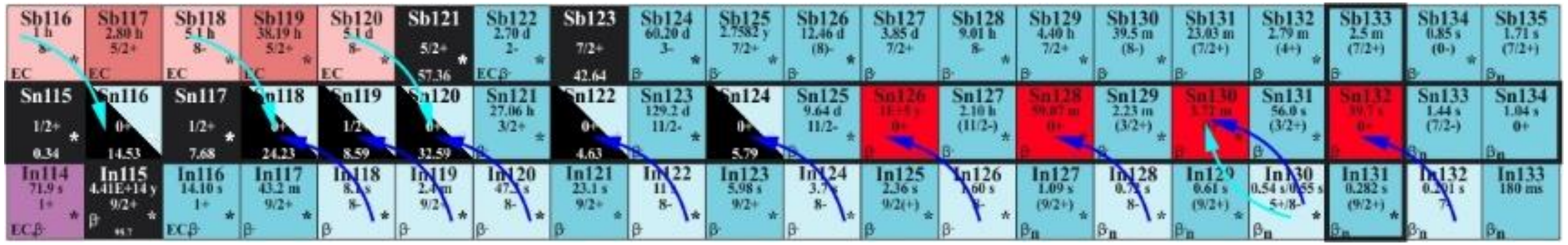
- ✓ valence orbital occupation n;
- ✓ collective properties;
- ✓ nuclear deformation

additivity rule

$$g = \frac{g_1+g_2}{2} + \frac{g_1-g_2}{2} * \frac{I_1(I_1+1)-I_2(I_2+1)}{I(I+1)}$$

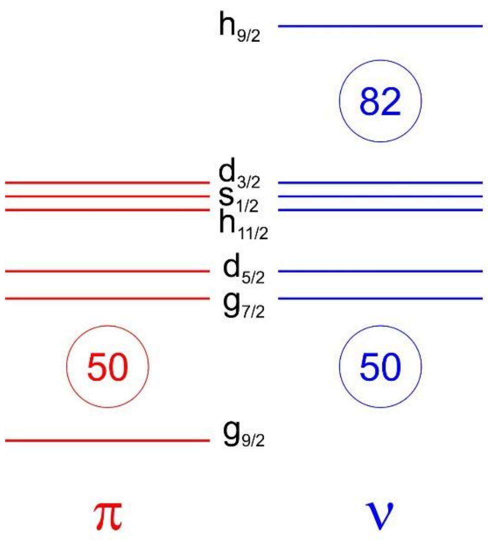
additivity: $I_1 \mathrm{x} I_2$ coupling,
simple addition if stretched

The area of the present proposal – neutron-rich Sn

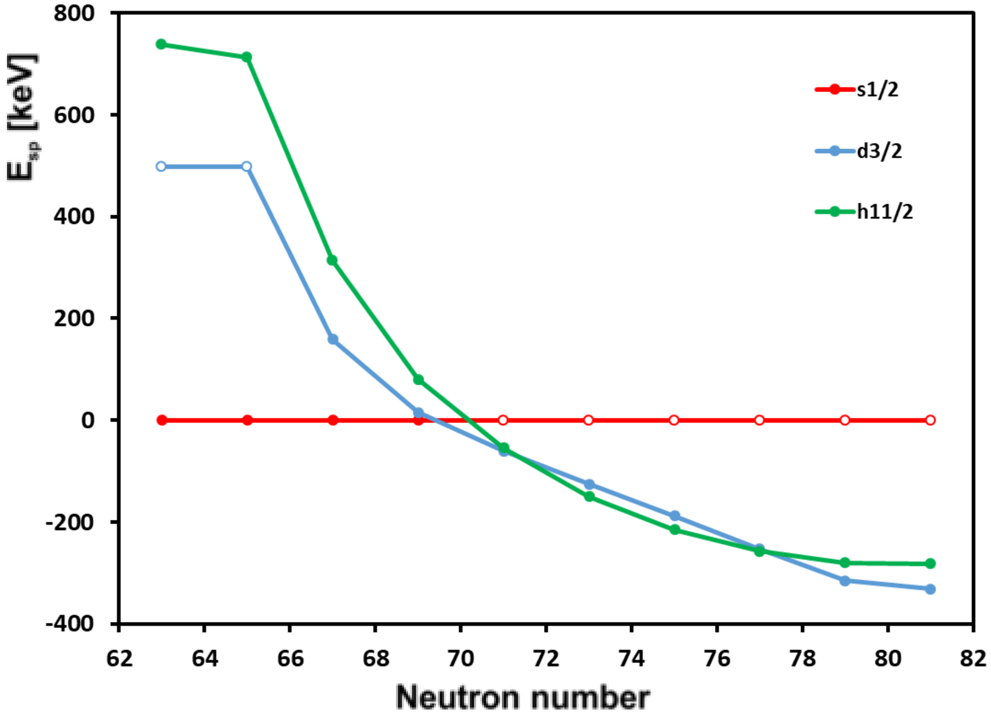


Sb116 1 h 8- EC	Sb117 2.80 h 5/2+ EC	Sb118 5.1 h 8- EC	Sb119 38.19 h 5/2+ EC	Sb120 5.1 d 8- EC	Sb121 5/2+ 57.36	Sb122 2.70 d 2- ECβ-	Sb123 7/2+ 42.64	Sb124 60.20 d 3- β-	Sb125 2.7582 y 7/2+ β-
Sn115 1/2+ 0.34	Sn116 0+ 14.53	Sn117 1/2+ 7.68	Sn118 0+ 24.23	Sn119 1/2+ 8.59	Sn120 0+ 32.59	Sn121 27.06 h 3/2+	Sn122 0+ 4.63	Sn123 129.2 d 11/2-	Sn124 0+ 5.79
In114 71.9 s 1+ ECβ-	In115 4.41E+14 y 9/2+ β- 95.7	In116 14.10 s 1+ ECβ-	In117 43.2 m 9/2+ β-	In118 8.5 s 8- β-	In119 2.4 m 9/2+ β-	In120 47.3 s 8- β-	In121 23.1 s 9/2+ β-	In122 11 8- β-	In123 5.98 s 9/2+ β-

Sb126 12.46 d (8)- β-	Sb127 3.85 d 7/2+ β-	Sb128 9.01 h 8- β-	Sb129 4.40 h 7/2+ β-	Sb130 39.5 m (8-) β-	Sb131 23.03 m (7/2+) β-	Sb132 2.79 m (4+) β-	Sb133 2.5 m (7/2+) β-	Sb134 0.85 s (0-) β-	Sb135 1.71 s (7/2+) βn
Sn125 9.64 d 11/2- β-	Sn126 1E+5 y 0+ β-	Sn127 2.10 h (11/2-) β-	Sn128 59.07 m 0+ β-	Sn129 2.23 m (3/2+) β-	Sn130 3.72 m β-	Sn131 56.0 s (3/2+) β-	Sn132 39.7 s 0+ β-	Sn133 1.44 s (7/2-) βn	Sn134 1.04 s 0+ βn
In124 3.7 s 8- β-	In125 2.36 s 9/2(+) β-	In126 1.60 s β-	In127 1.09 s (9/2+) βn	In128 0.72 s 8- βn	In129 0.61 s (9/2+) βn	In130 0.54 s/0.55 s 5+/8- βn	In131 0.282 s (9/2+) βn	In132 0.201 s 7- βn	In133 180 ms βn



Single-particle (hole) states in odd Sn

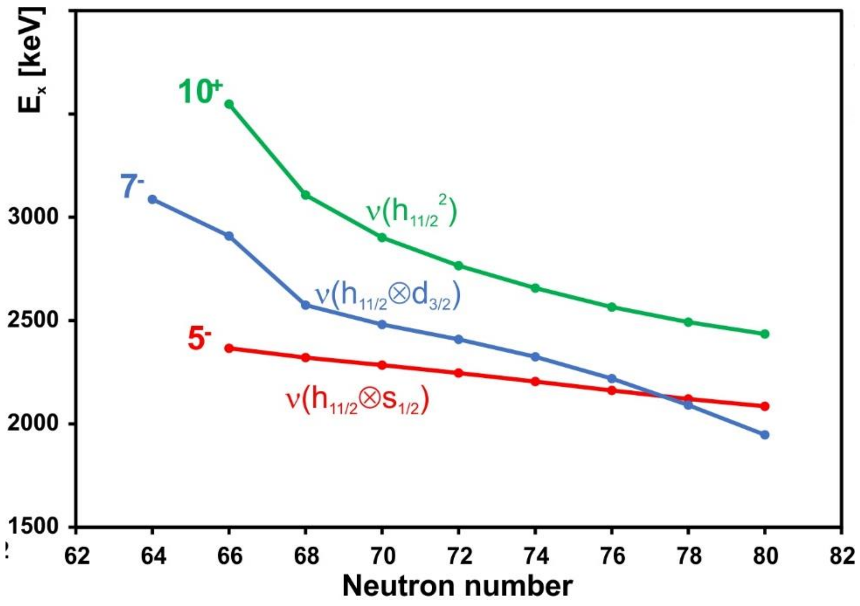


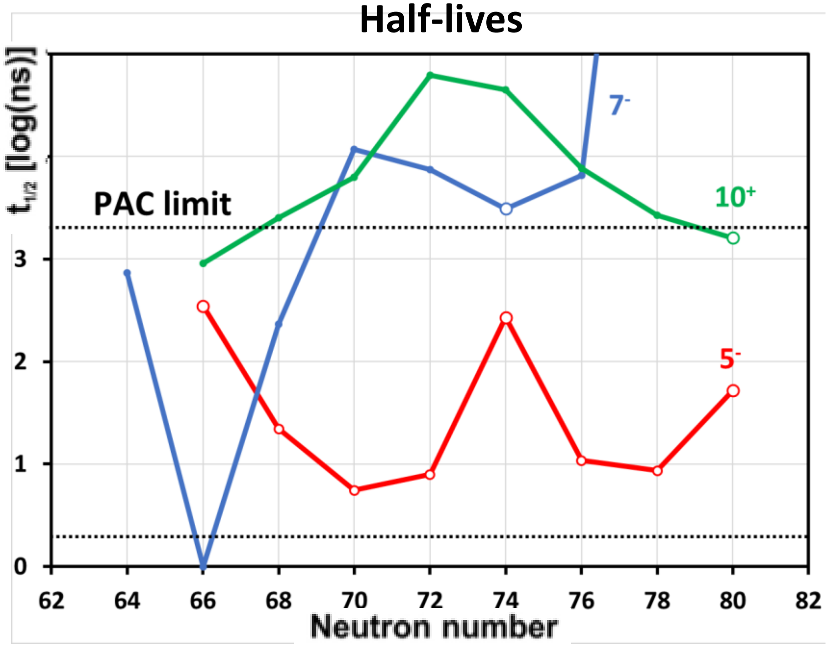
- Most **nuclear moments of the single-particle states** have been determined, primarily by COLLAPS [D.T. Yordanov et al., Comm. Phys. 3, 107 (2020)]

- **μ for heavier $s_{1/2}$ not measurable !**

Subject of the present proposal: two-quasi-particle states

Probing the interaction between the **neutron** $h_{11/2}$, $d_{3/2}$ and $s_{1/2}$ orbitals **at Z=50**


Excitation energies


Half-lives

Our aim – **test nuclear coupling concept (the additivity rule) for a chain of semi-magic (Sn) nuclei, a textbook case ?**

The magnetic dipole and electric quadrupole moments of the 5^-, 7^- and 10^+ states in a chain of Sn isotopes would provide a very stringent test of the nuclear models and demonstrate simple textbook concepts of nuclear physics

→ does the **simple SM picture** work or what could we learn?

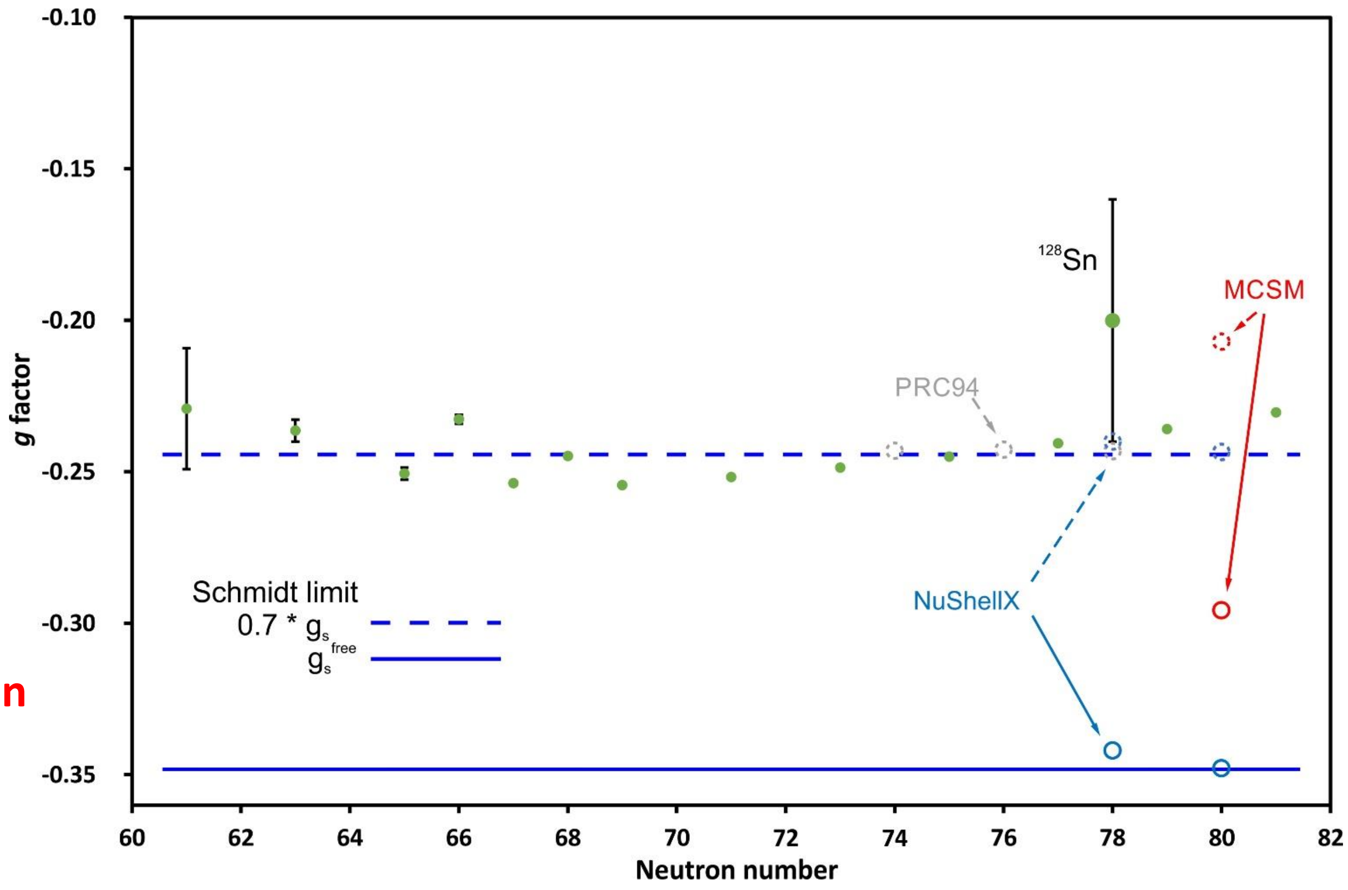
→ **indirect information on $s_{1/2}$ moments through 5^- states !**

Unexpected results from RIKEN on ^{130}Sn 10$^+$

- Gyromagnetic factors of the 11/2$^-$ states (also including the 10$^+$ in ^{116}Sn) are quasi constant over the large range of neutron numbers. The only exception 10$^+$ in ^{128}Sn (reported with a large error-bar). They are all very close to the effective Schmidt line ($g_s = 0.7*g_s^{free}$)

- Different theoretical calculations reproduce those, using effective g factors.

- **10$^+$ state in ^{130}Sn should have the most pure configuration** (high spin; no possible mixing below the shell closure)



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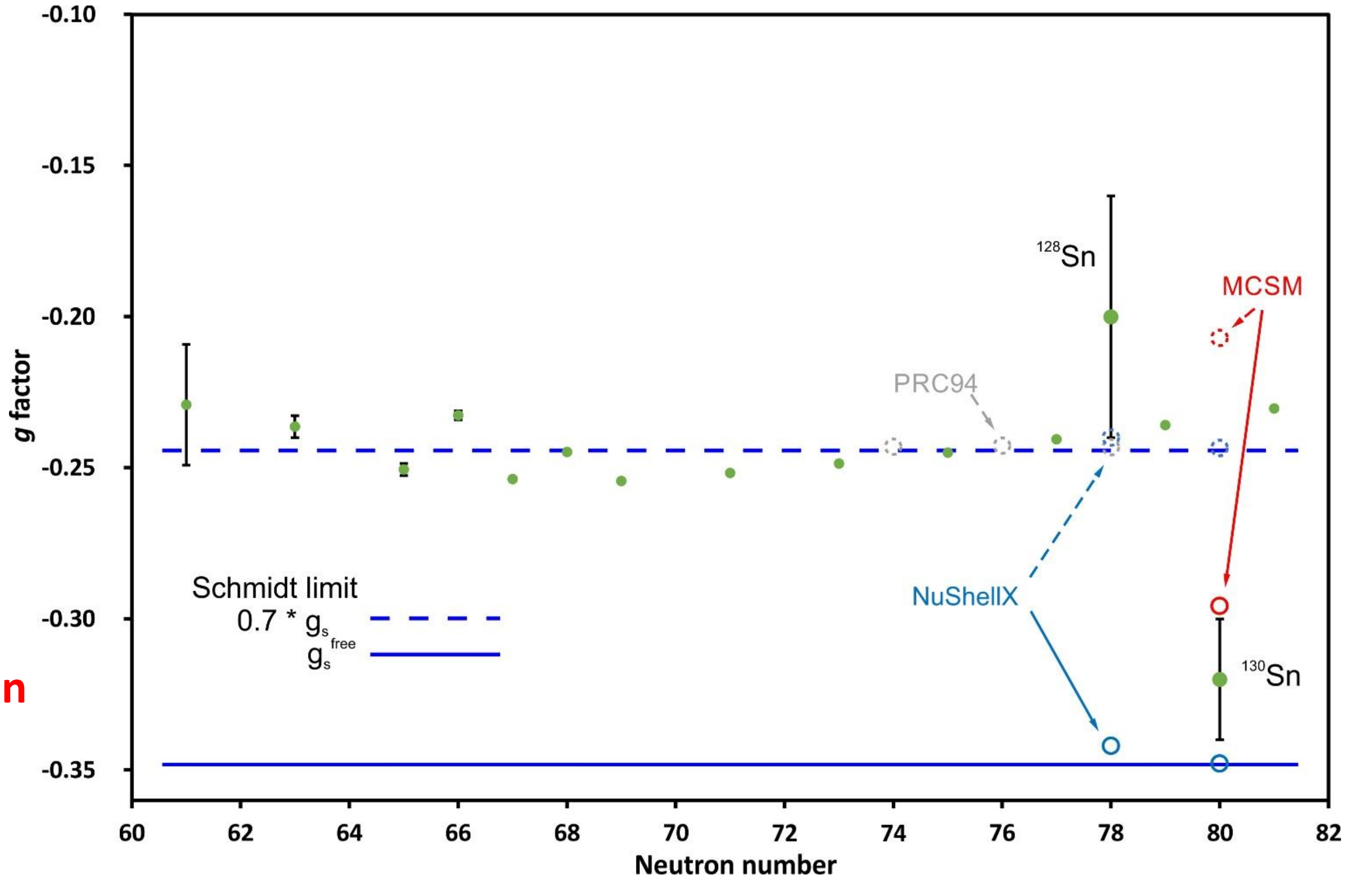
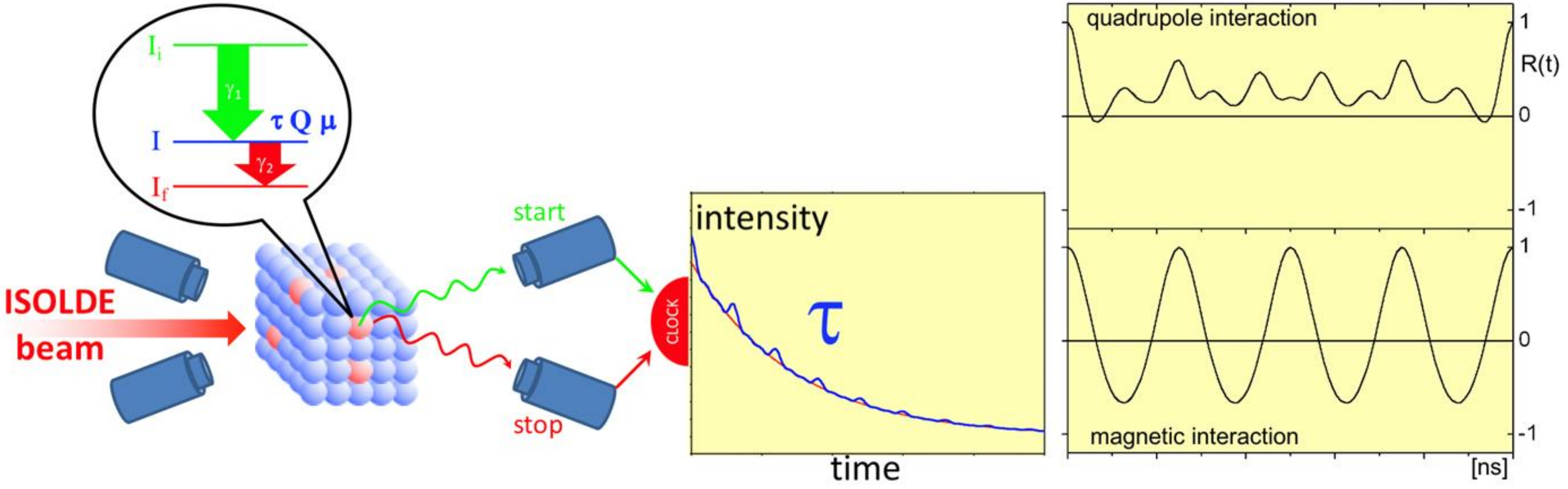


- A recent study at RIBF, RIKEN of the 10$^+$ isomer in ^{130}Sn indicates a g factor very close to the free Schmidt value. **Is this another example that the "effective values" are due to shortcomings in theory rather then having any robust physical meaning?** (*see e.g. P. Gysbers et al., Nature Physics 15, 428 (2019)*)
- **The unexpected RIKEN result** **(done with very poor statistics)** **needs reconfirmation beyond any doubts!**

The on-line PAC technique



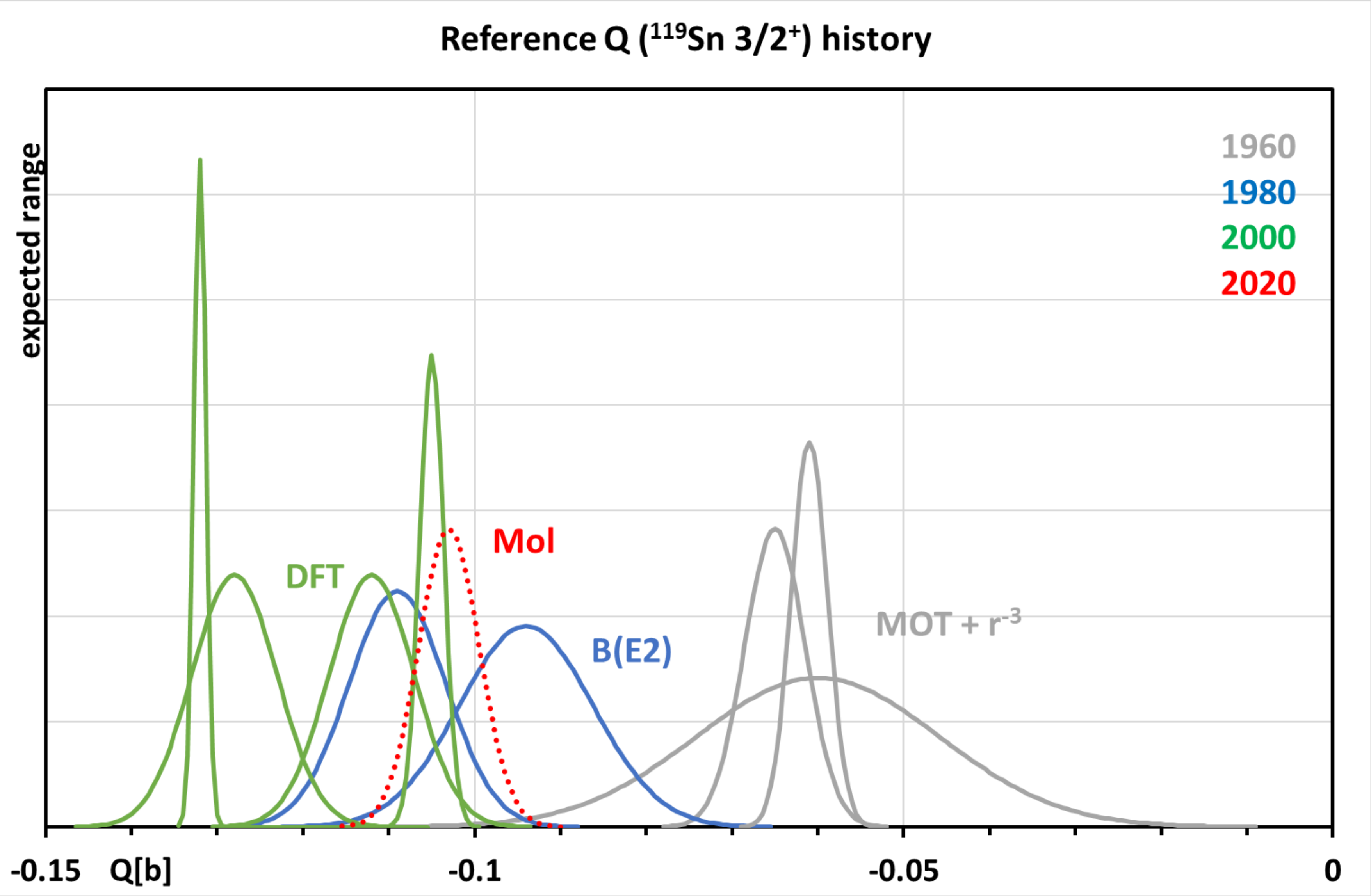
From the experimental perturbation pattern one extracts

$\nu_L = \mu / I \ast B / h$

Magnetic field B from external magnet or ferromagnetic solid

$\nu_Q = e\,Q \ast V_{zz} / h$

Electric field gradient Vzz in non-cubic solid (from theory!) or reference isotope



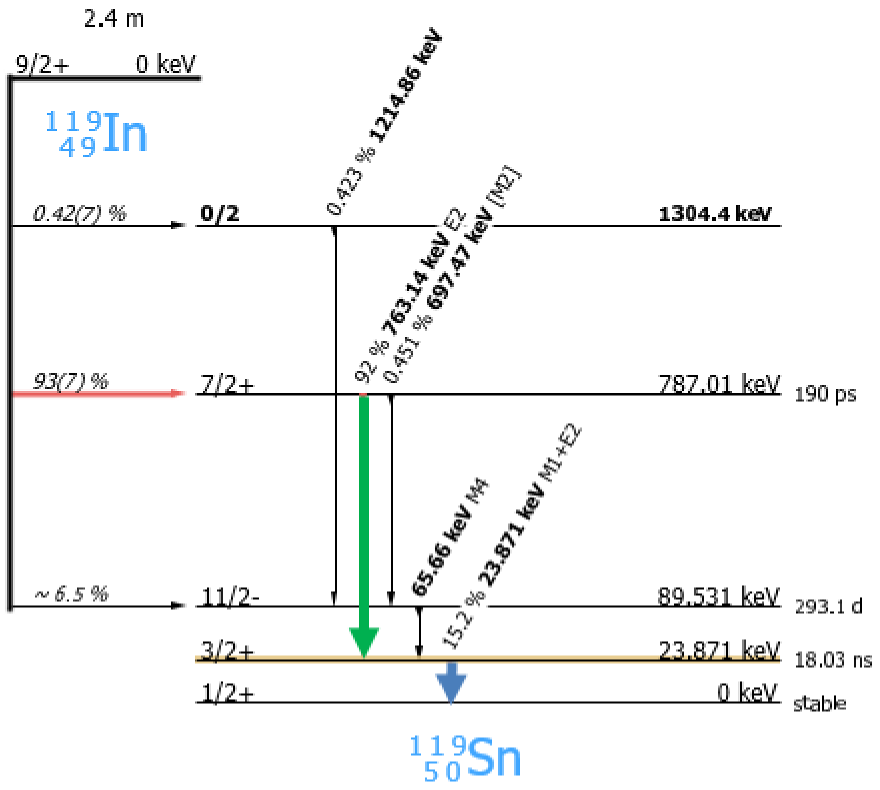
We shall clear up most of this mess !

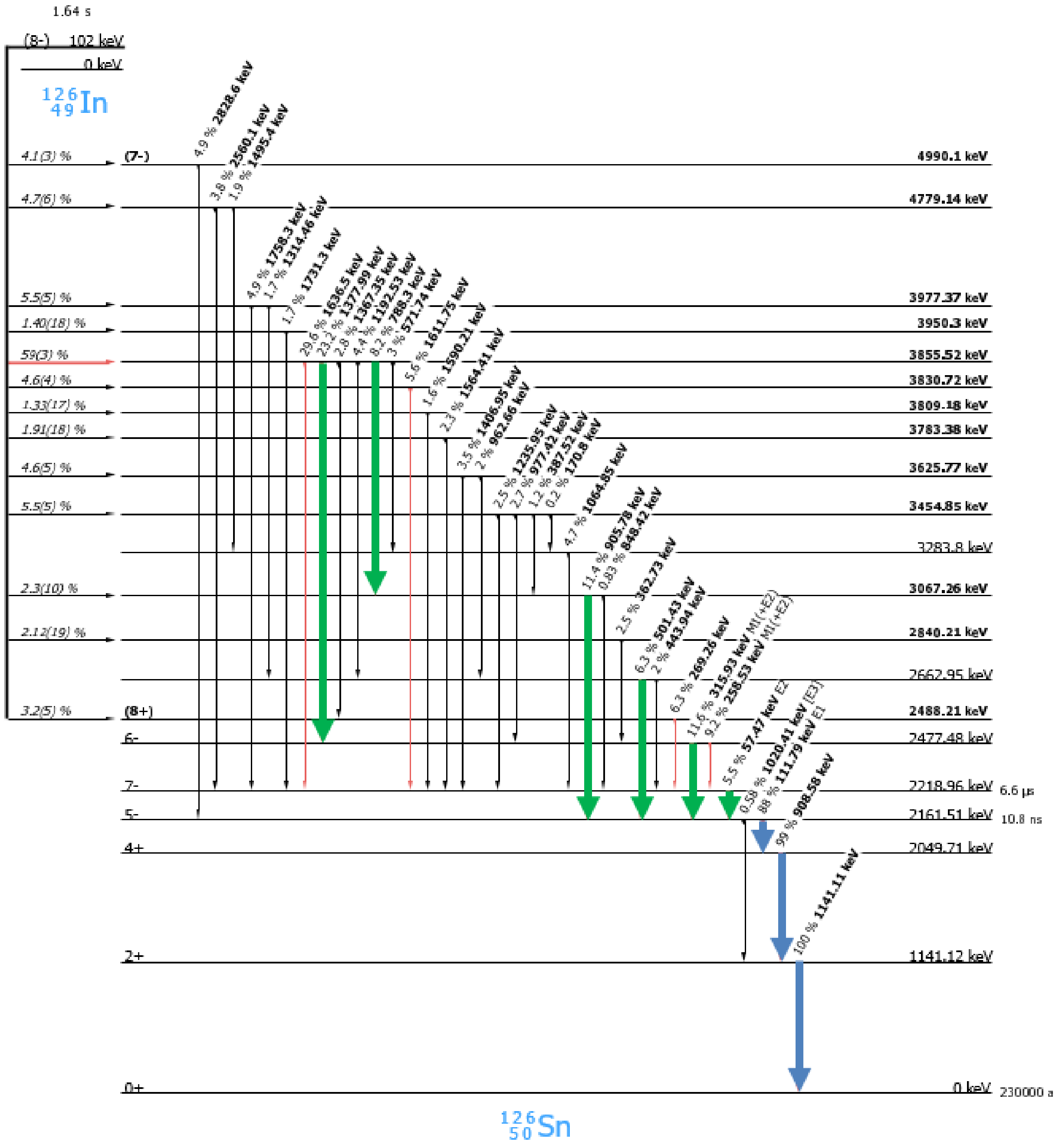
Complex decay scheme

requires multi-dimensional on-line storage and off-line analysis

Simple decay scheme

for testing of target materials and effects of implantation damage





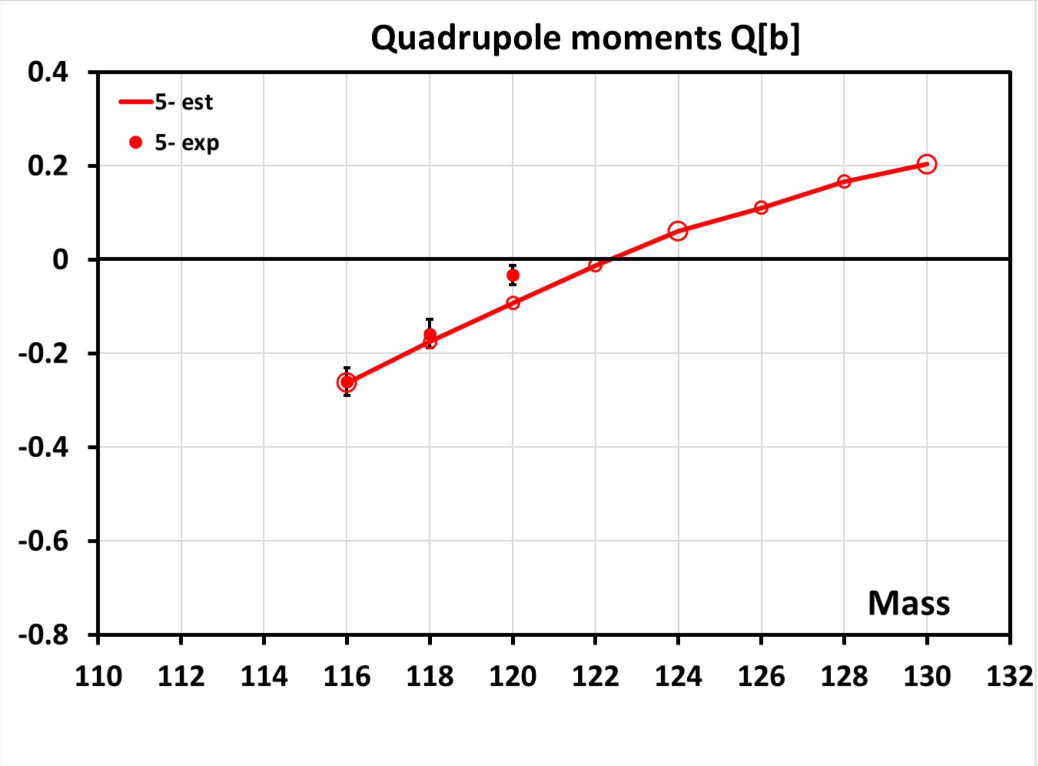
The test program using $^{119}\mathrm{In} \rightarrow {}^{119}\mathrm{Sn}\ 3/2^+$

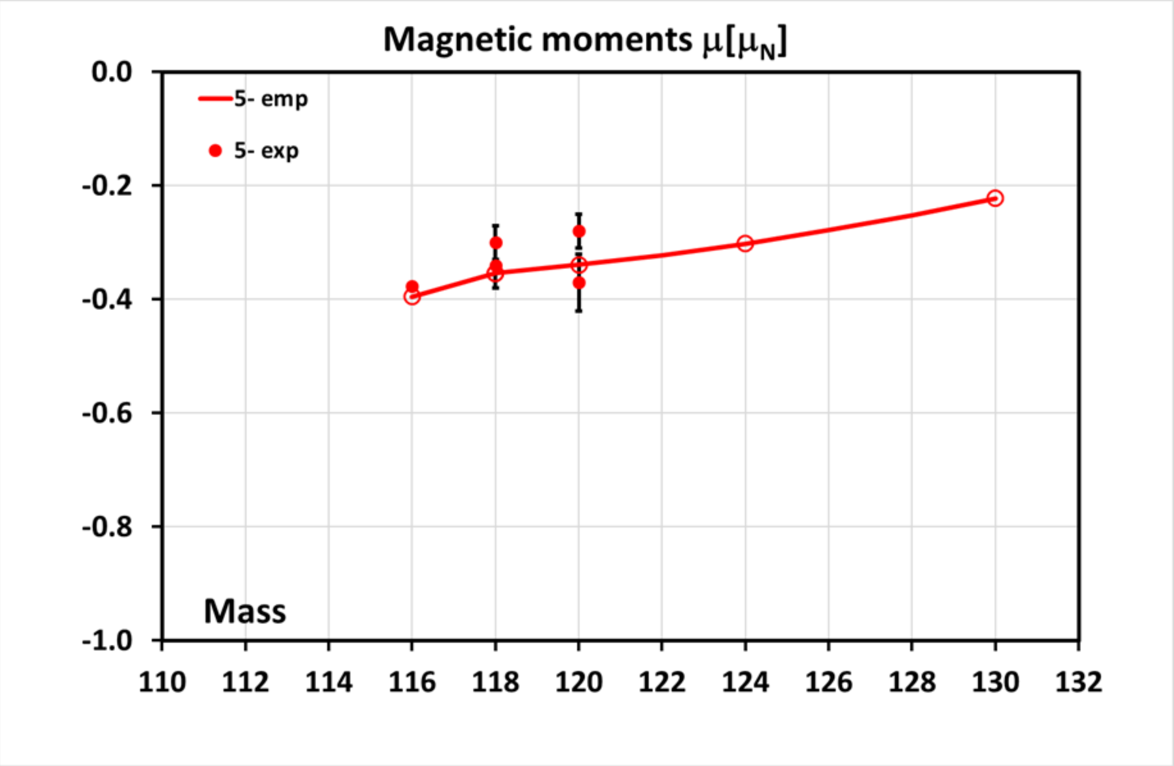
Experiment:	Purpose:
Test indium implantation into Zn single crystal, study damage effect as function of temperature	Find optimal temperature for on-line experiments with 5^- states
Measure precision value for QI at one optimal T	Find Q ratio to ^{116}Sn 5^-
Test indium implantation into graphite or alternatives S, Se	Find optimal matrix for short-lived 5^- cases
Check effect of implantation damage in Fe at RT	Understand origin of spectral damping

The 5^- states

Quadrupole moments expected identical to $11/2^-$ state in $^{A+1}$Sn

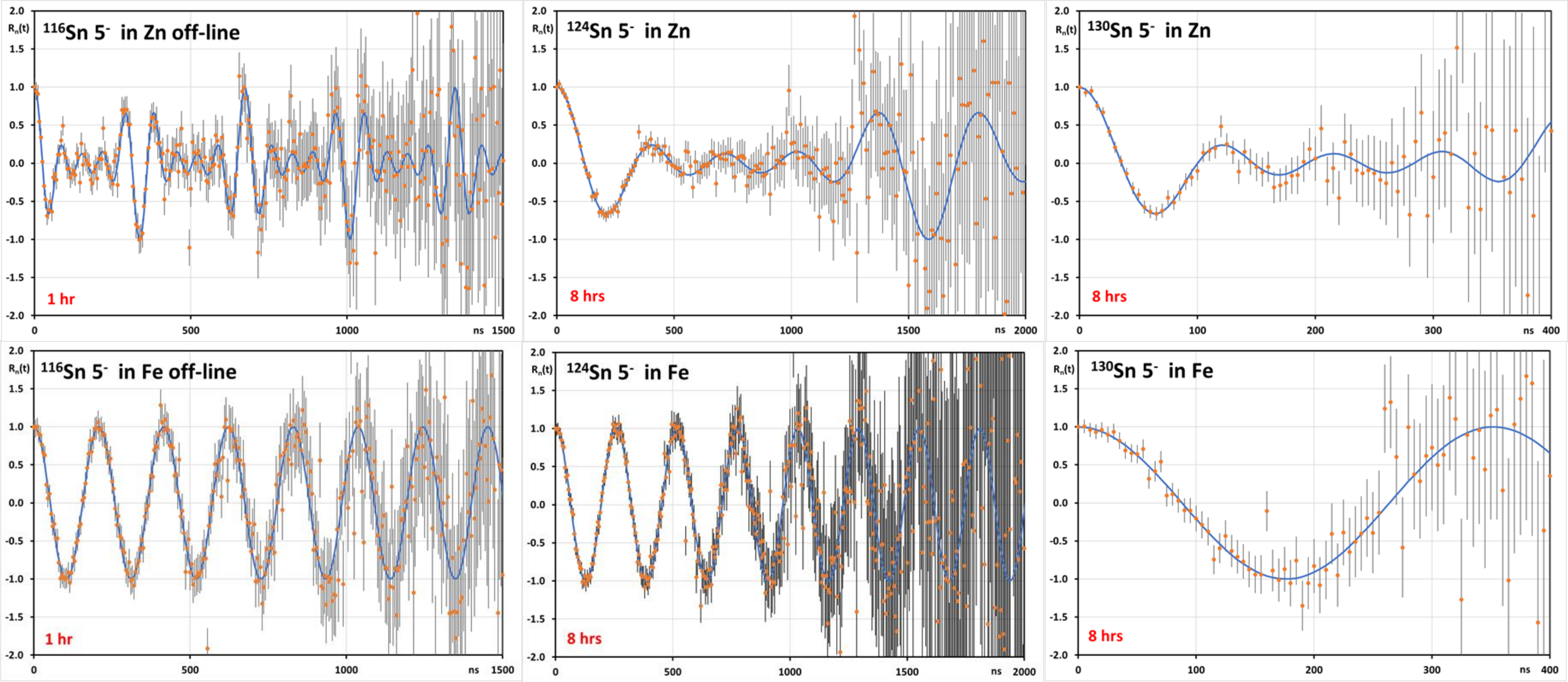
Magnetic moments as coupling of $\mu(11/2^-)$ and $\mu(1/2^+)$ in $^{A+1}$Sn





Simulated spectra for long-lived 5^- states

note different running times!



The off-line program for 5^- states with Sb sources

using 4-5 existing PAC spectrometers of solid-state collaboration

QI (temperature) for ^{116}Sn in Zn after annealing (at least 2 points)

QI for ^{116}Sn in In for precise Vzz

QI for ^{118}Sn in Zn for precise Q

Test implantation of ^{118}Sb into graphite

QI for ^{120}Sn in graphite to obtain Q

MI at RT for ^{116}Sn in Fe after annealing for precise B_{hf}

MI for ^{116}Sn in Ni at 200C

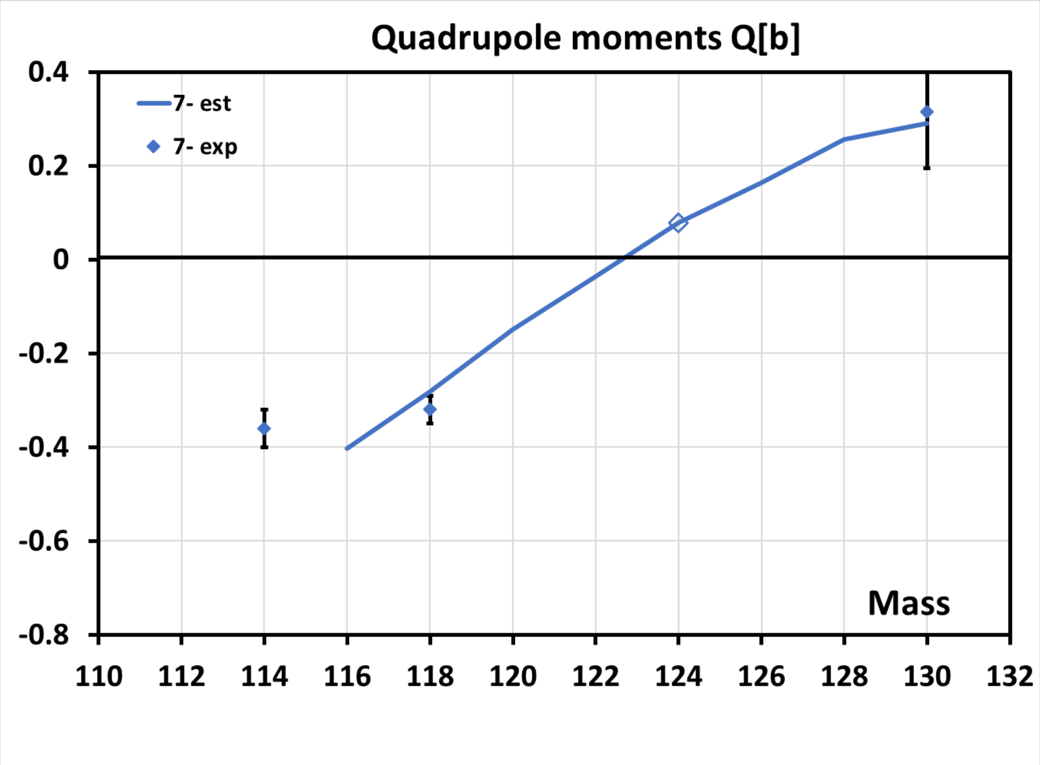
MI for ^{118}Sn in Fe for precise μ

Test implantation of ^{118}Sb into Gd

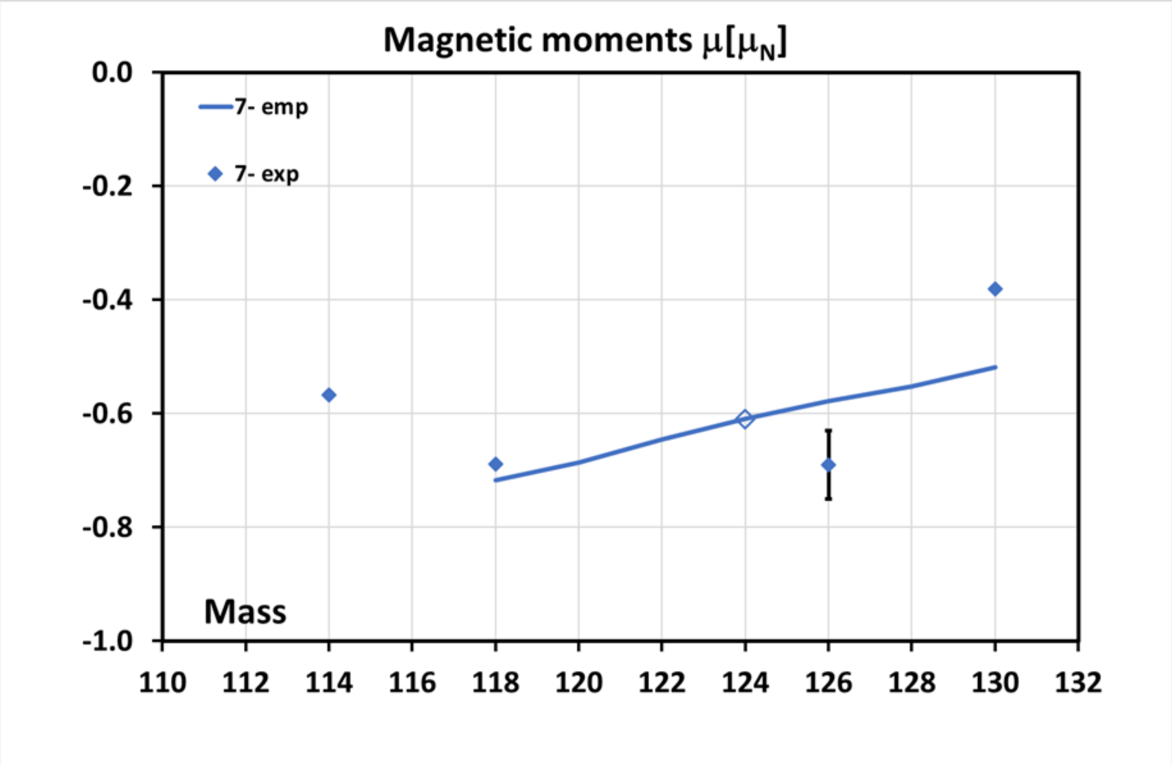
MI for ^{120}Sn in Gd to obtain μ

The 7^- states

Quadrupole moments as coupling of $Q(11/2^-)$ and $Q(3/2^+)$ in ^{A+1}Sn

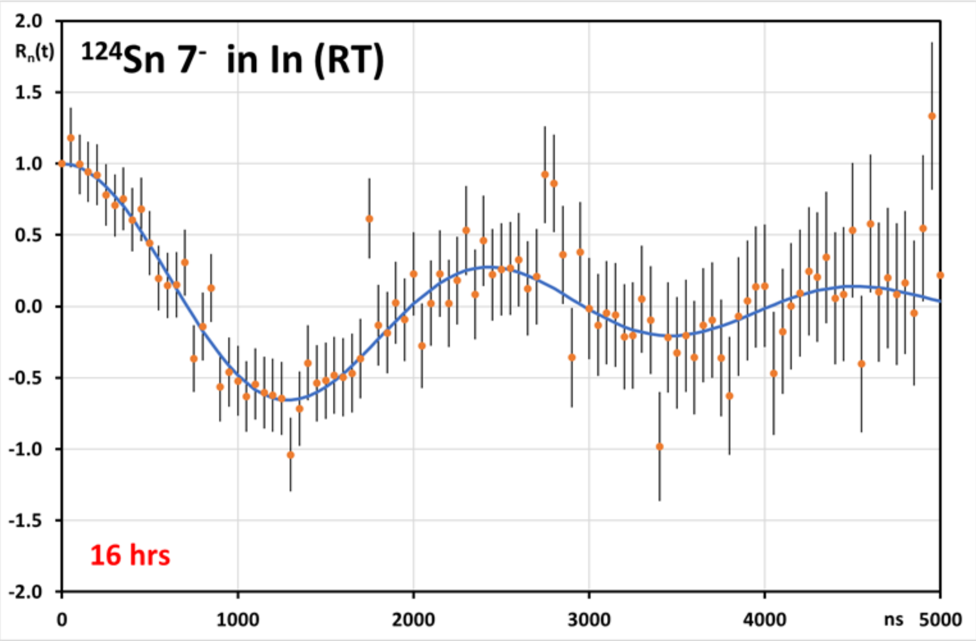


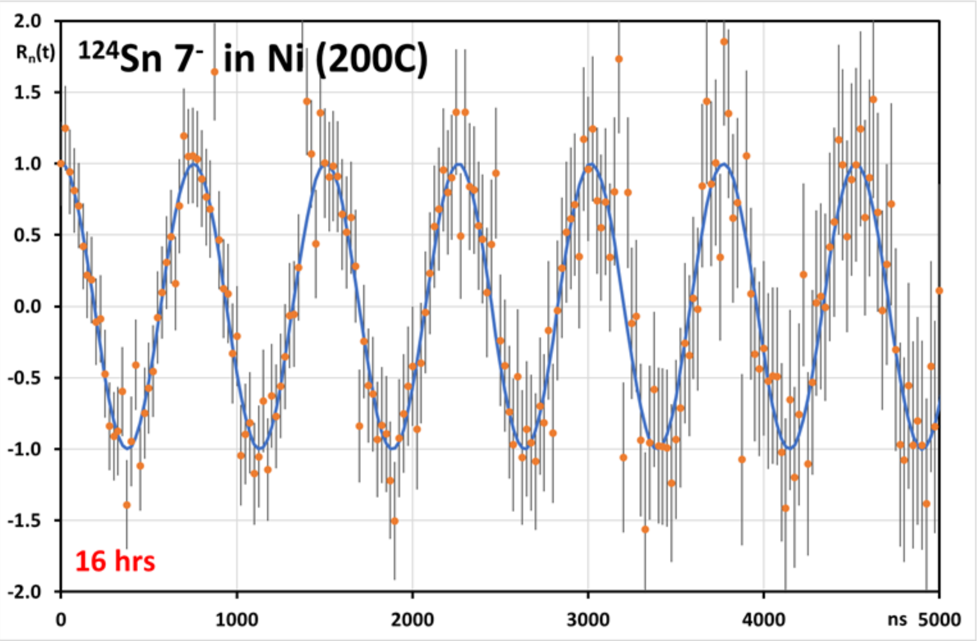
Magnetic moments as coupling of $\mu(11/2^-)$ and $\mu(3/2^+)$ in ^{A+1}Sn



Simulated spectra for long-lived 7^- state in ^{124}Sn

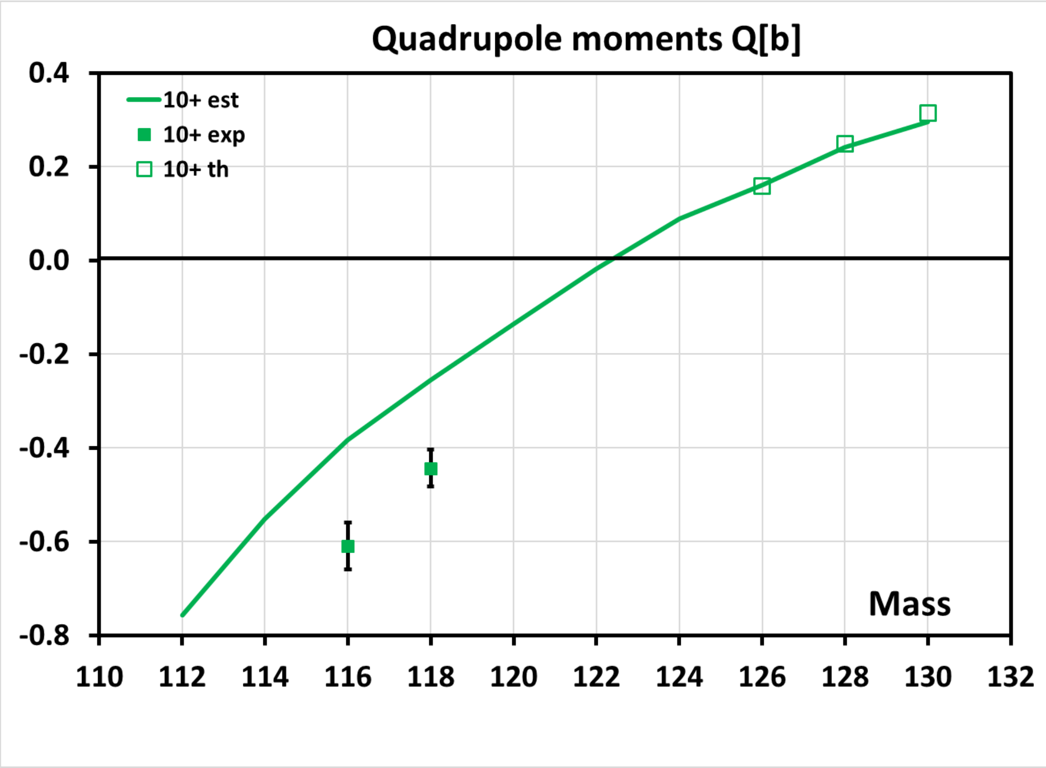
A fortunate case: Due to small Q expected and favorable decay characteristics PAC feasible in spite of long $t_{1/2}$ (3.1 μs)





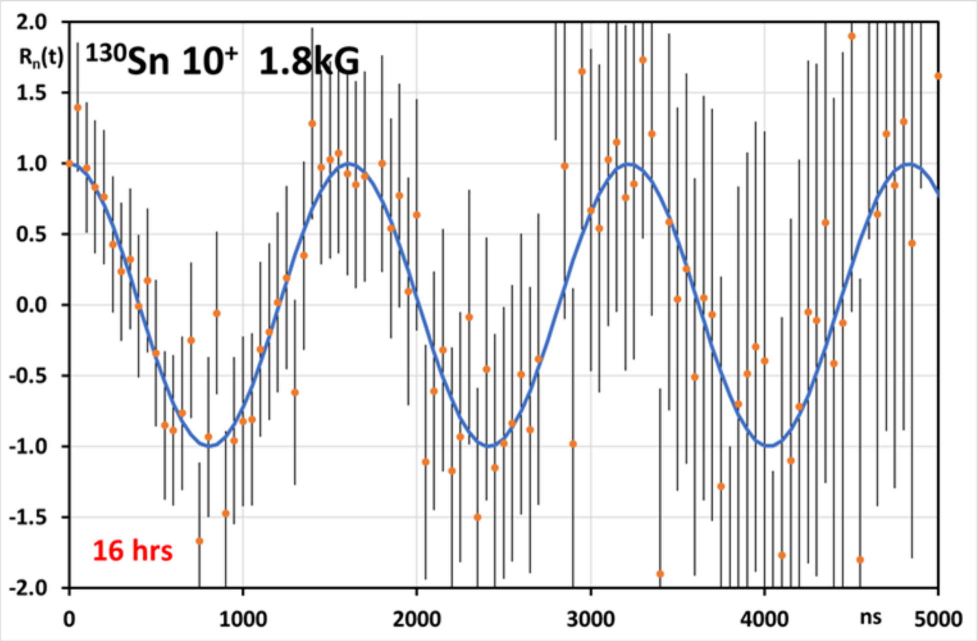
10^+ state in ^{130}Sn

- **Should have a very pure $h_{11/2}{}^2$ configuration**
  Also 8^+ state will be virtually pure $h_{11/2}{}^2$
- B(E2) will give the most precise value for Q
- Thus: Measuring QI (in In) for **new reference!**
- However: Difficult to estimate run time
- Therefore: Postpone until after MI experiment!



Check of preliminary RIKEN results for μ:

Simulated spectrum for measurement in magnet



Acceptable accuracy reachable!

Required beamtimes

On-line

ISOLDE beam, UC/RILIS					State of interest			Experiment		
	Ip	t1/2 [s]	Approx. int. [at/μC]	Required int. [at/sec]		Ip	t1/2 [ns]	measure	host	shifts
^{119}In	$9/2^+$	144	$4x10^7$	$2x10^6$	^{119}Sn	$3/2^+$	18	Q, μ	Zn,C,S,Fe	3
^{118m}In	8^-	8.1	$5x10^7$	$1x10^6$	^{118}Sn	5-	22	Q	C	1
^{120m}In	8^-	47.3	$5x10^7$	$1x10^6$	^{120}Sn	5-	5.5	Q	C	1
^{122m}In	8-	11	$2x10^8$	$1x10^6$	^{122}Sn	5-	7.9	Q	C	1
^{124m}In	8^-	3.7	$4x10^7$	$1x10^6$	^{124}Sn	5^-	270	Q, μ	Zn,Fe	2
^{126m}In	8^-	1.6	$7x10^6$	$1x10^6$	^{126}Sn	5^-	11	Q	C	1
^{128m}In	8^-	0.72	$3x10^6$	$1x10^6$	^{128}Sn	5^-	8.6	Q	C	1
^{130m}In	5^+	0.54	$1x10^5$	$2x10^5$	^{130}Sn	5^-	52	Q, μ	Zn,Fe	4
^{132}In	7^-	0.2	$1x10^4$	$4x10^4$	^{132}Sn	6^+	21.3	μ	Fe	2
^{124m}In	8^-	3.7	$4x10^7$	$5x10^5$	^{124}Sn	7^-	3100	Q, μ	In,Ni	4
^{130m}In	10^-	0.55	$1x10^5$	$2x10^5$	^{130}Sn	10^+	1610	μ	Cu	3

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Off-line

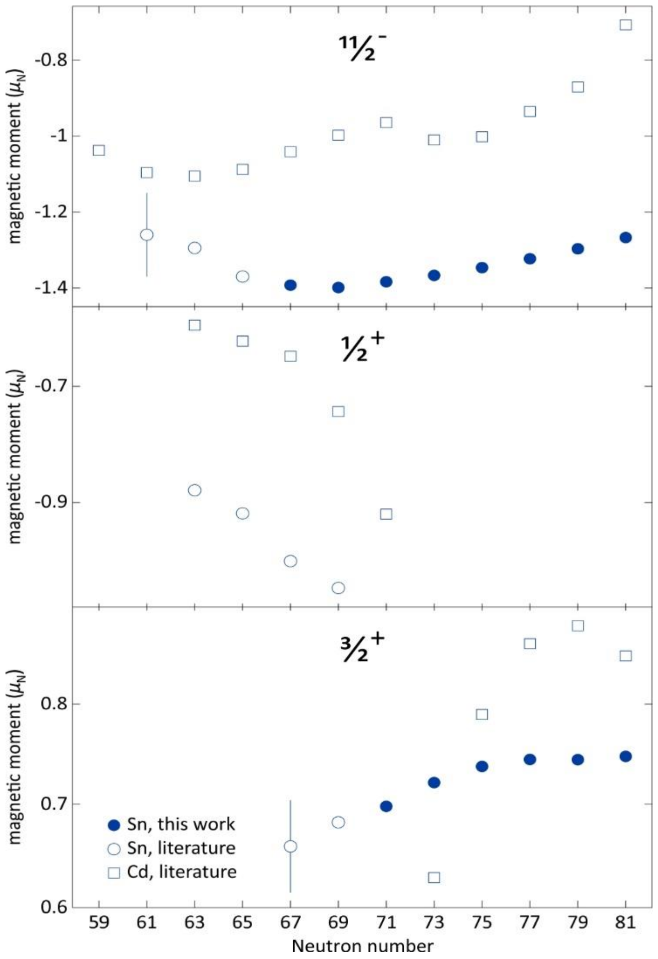
^{116m}Sb	8^-	1h	$5x10^7$	$2x10^{10a)}$	^{116}Sn	5^-	320	Q, μ	Zn,In,Fe,Ni	2
^{118m}Sb	8^-	5.1h	$1x10^8$	$4x10^{10a)}$	^{118}Sn	5^-	22	Q, μ	Zn,C,Fe,Gd	1
^{120}Sb	8^-	5.8d	$2x10^8$	$2x10^{11a)}$	^{120}Sn	5^-	8	Q	C,Gd	1

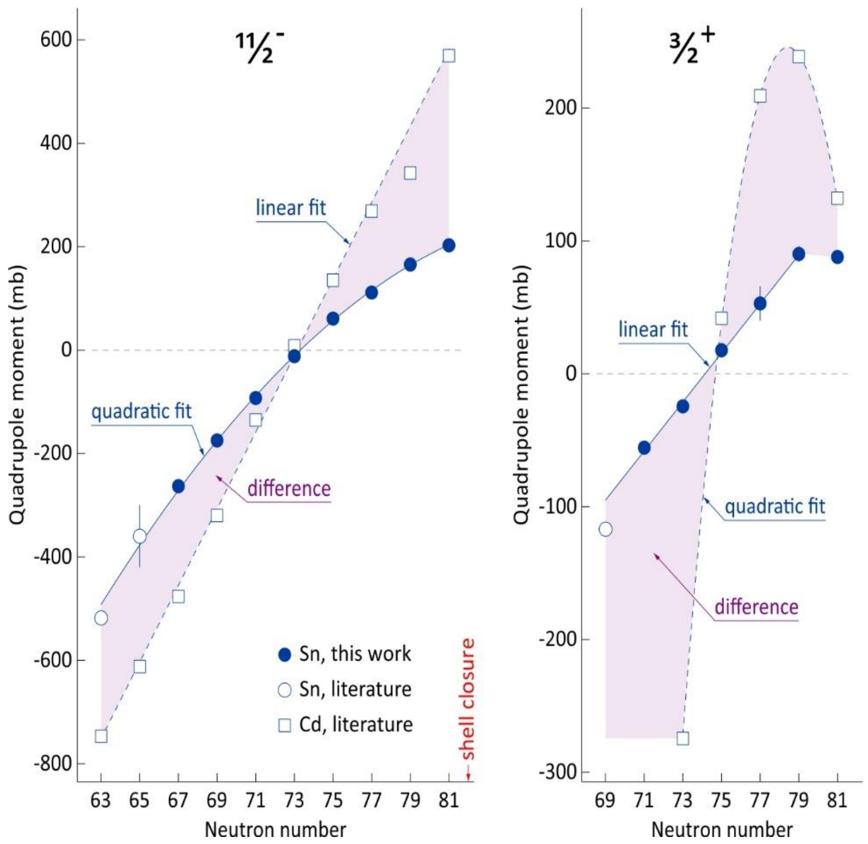
4

Slides for discussion

Sn results from COLLAPS

- Recent results from laser spectroscopy of odd-mass Sn isotopes from COLLAPS: ***D.T. Yordanov et al., Comm. Phys. 3, 107 (2020)*** – magnetic and quadrupole moments and r.m.s. radii for odd-mass Sn isotopes

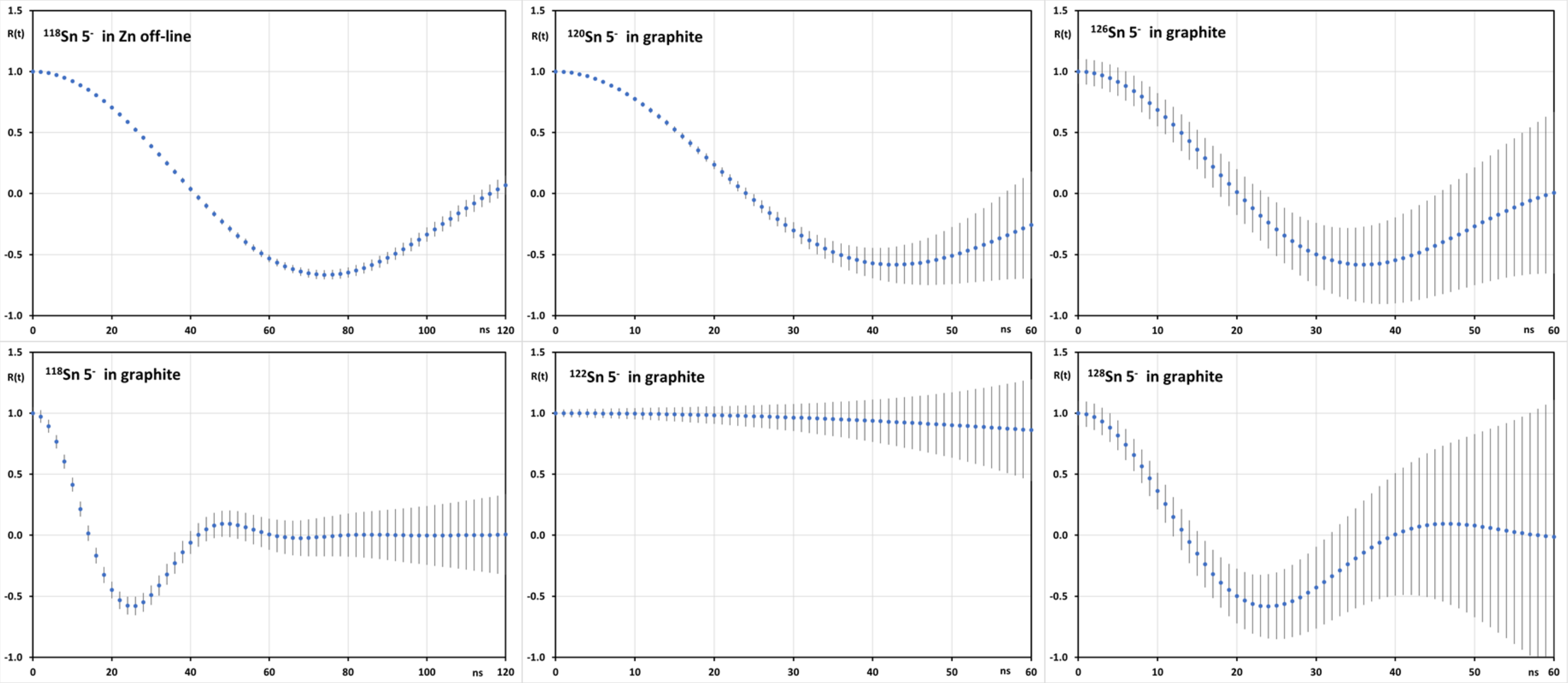




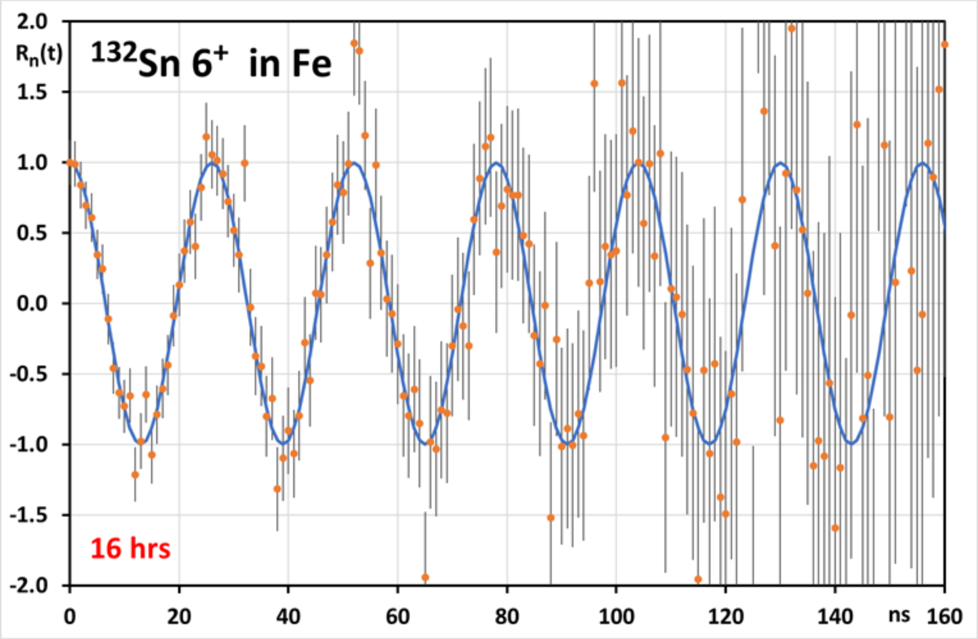
- The magnetic and the quadrupole **moments of the s.p. states** have been determined!

- Our aim – **test the additivity rule for a chain of semi-magic (Sn) nuclei** → does the **simple SM picture** work or what could it teach us?

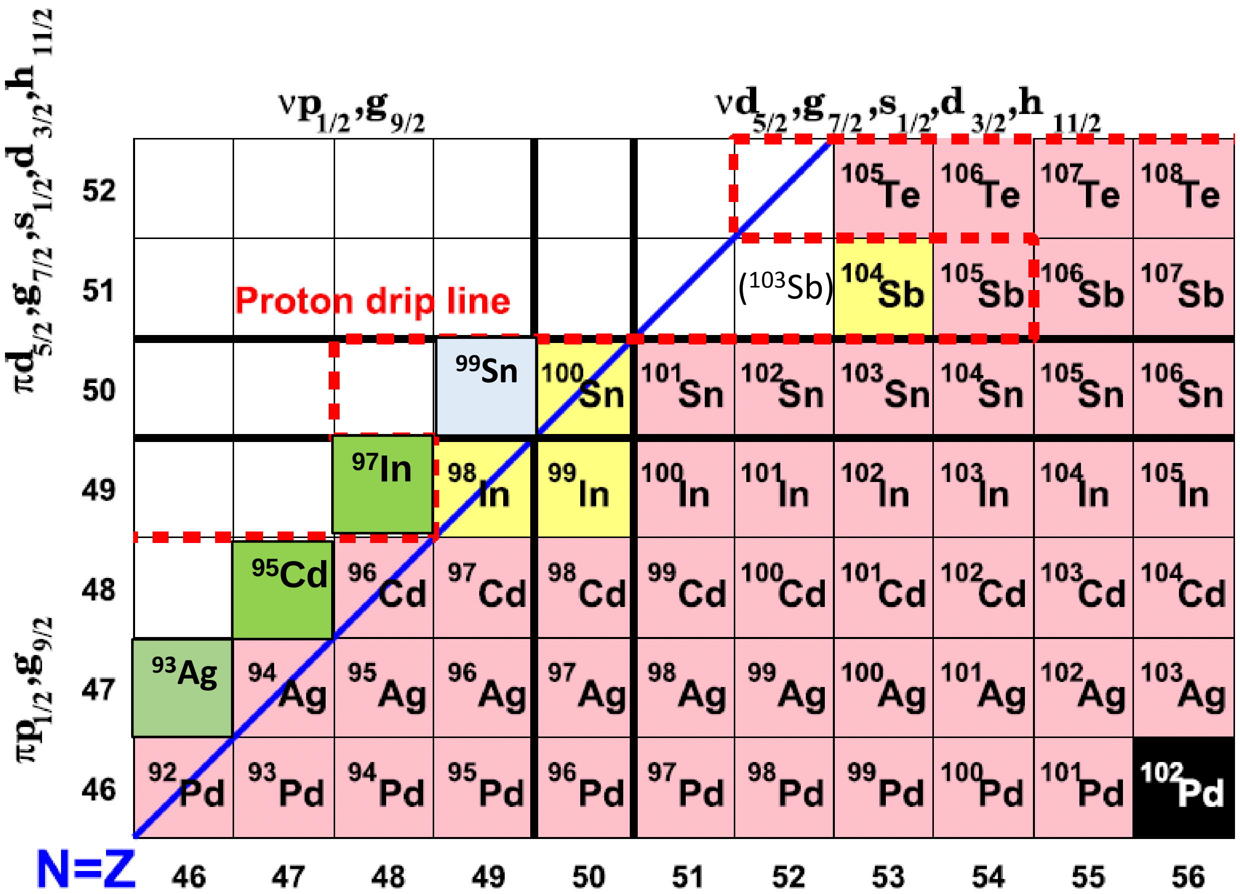
Expected spectra for short-lived 5^- states



Simulated spectrum for 6$^+$ state in ^{132}Sn



Gamow-Teller β decay of ^{100}Sn (Z,N=50)



	46	47	48	49	50	51	52	53	54	55	56
52								^{105}Te	^{106}Te	^{107}Te	^{108}Te
51							(^{103}Sb)	^{104}Sb	^{105}Sb	^{106}Sb	^{107}Sb
50				^{99}Sn	^{100}Sn	^{101}Sn	^{102}Sn	^{103}Sn	^{104}Sn	^{105}Sn	^{106}Sn
49			^{97}In	^{98}In	^{99}In	^{100}In	^{101}In	^{102}In	^{103}In	^{104}In	^{105}In
48		^{95}Cd	^{96}Cd	^{97}Cd	^{98}Cd	^{99}Cd	^{100}Cd	^{101}Cd	^{102}Cd	^{103}Cd	^{104}Cd
47	^{93}Ag	^{94}Ag	^{95}Ag	^{96}Ag	^{97}Ag	^{98}Ag	^{99}Ag	^{100}Ag	^{101}Ag	^{102}Ag	^{103}Ag
46	^{92}Pd	^{93}Pd	^{94}Pd	^{95}Pd	^{96}Pd	^{97}Pd	^{98}Pd	^{99}Pd	^{100}Pd	^{101}Pd	^{102}Pd

D. Lubos *et al.*, Phys Rev. Lett. 122, 222502 (2019)
P. Gysbers *et al.*, Nature Physics 15, 428 (2019)

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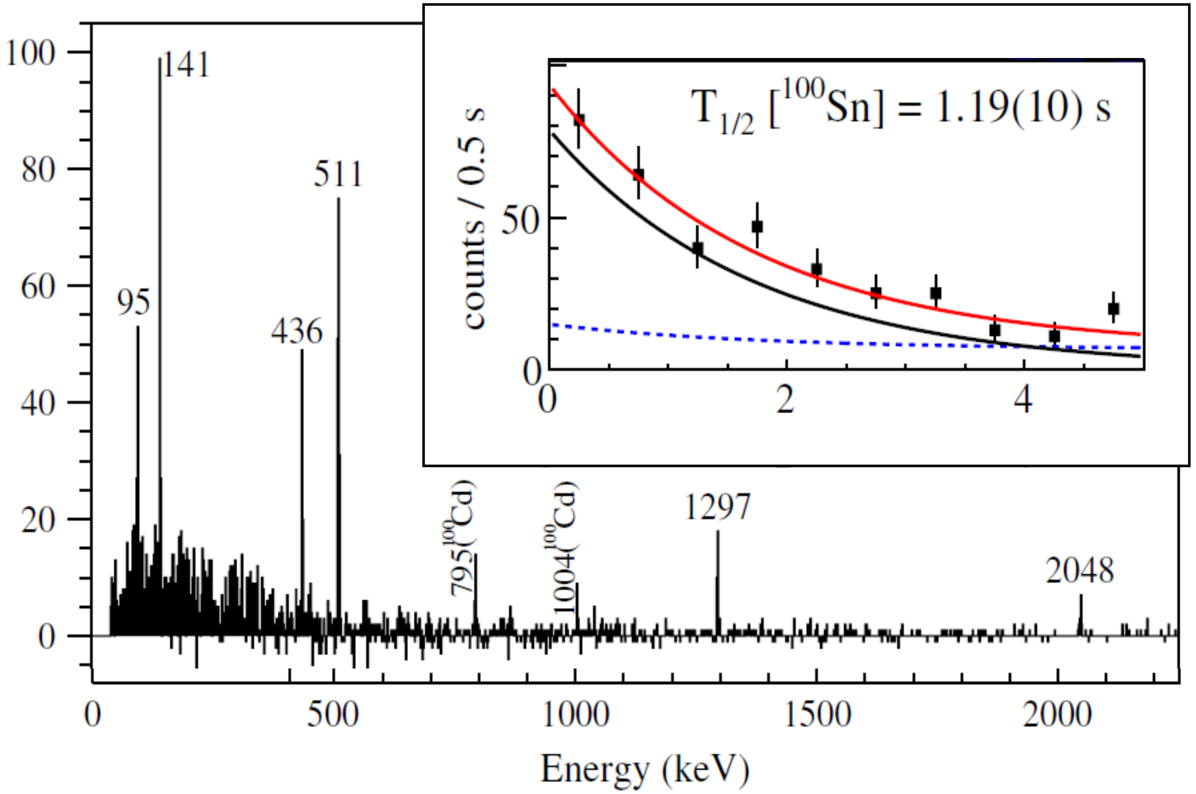

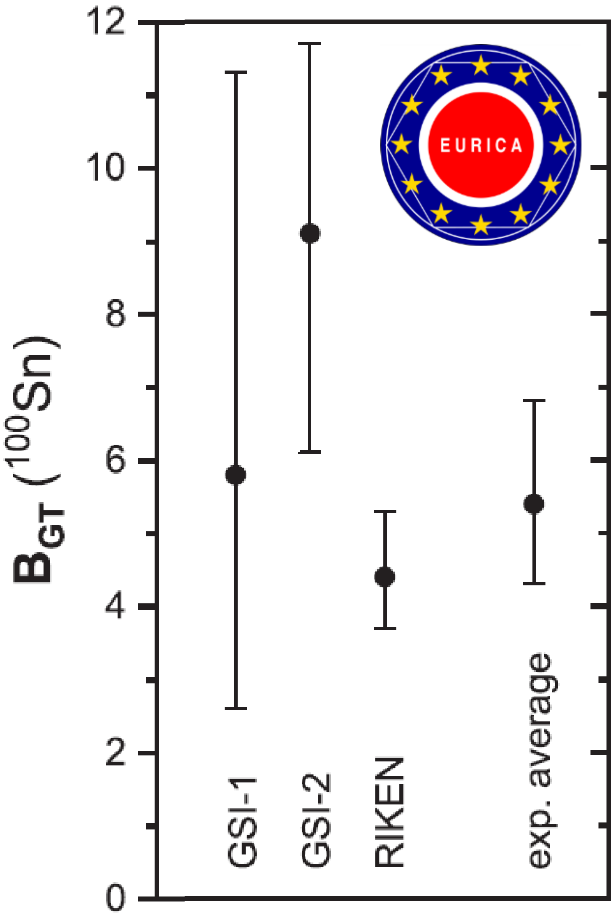

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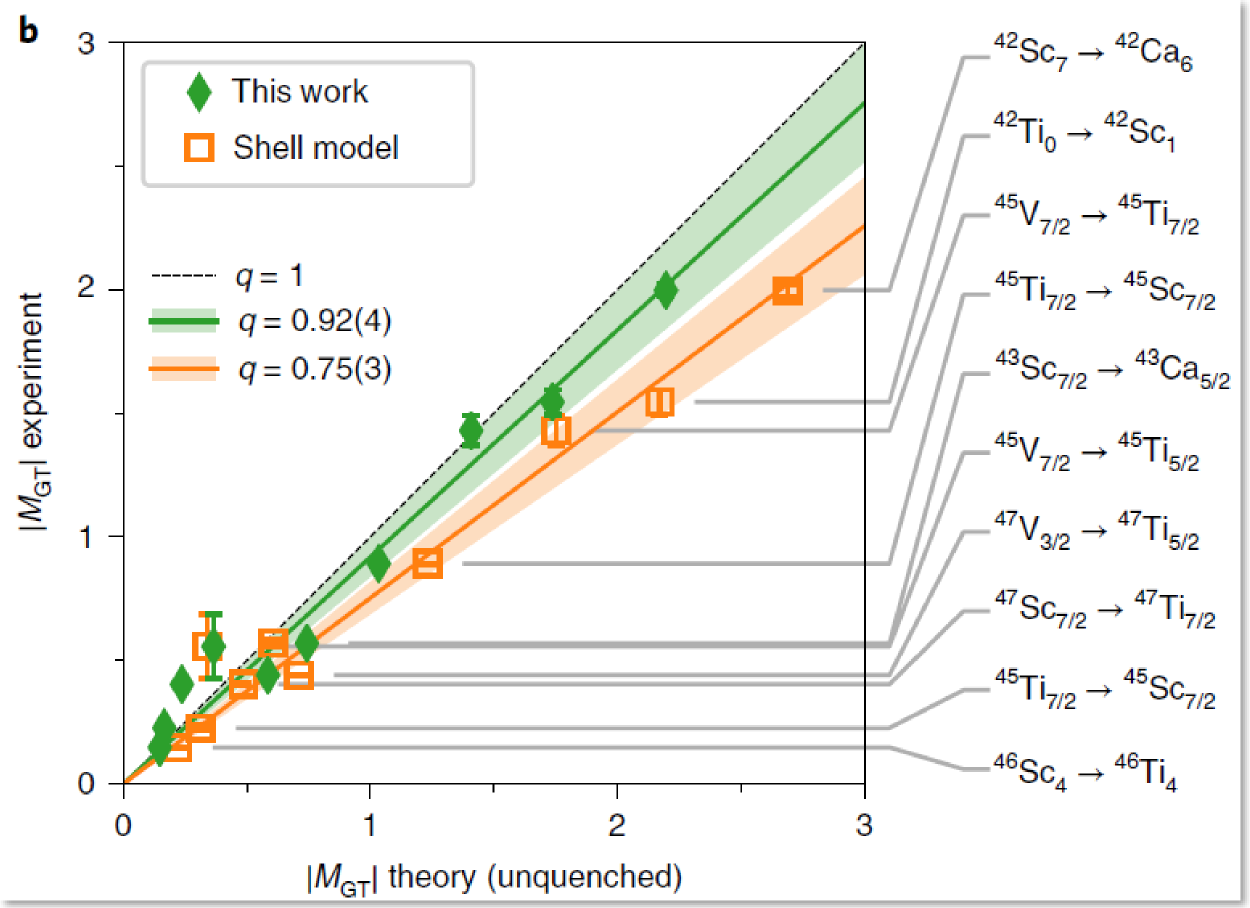
- Discrepancy between exp. and theoretical β decay rates, g_A (1,27) quenched ~ 0.75 (e.g. Towner “Quenching of spin matrix elements in nuclei” Phys. Rep. 155 (1987)), *is without first-principle explanation*
- Combining EFT of the strong and the weak forces with quantum many-body techniques explains the discrepancy



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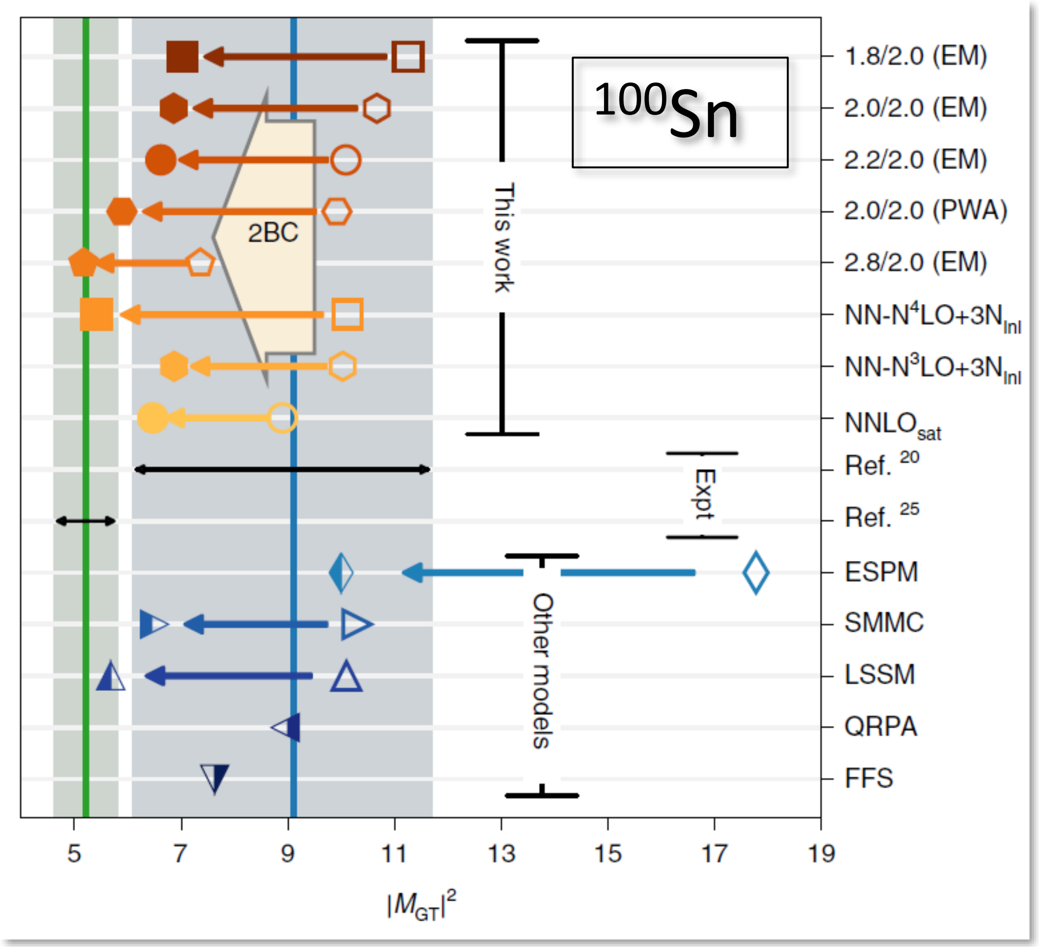

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