Beta-decay spectroscopy of exotic nuclei around ^{132}Sn at ISOLDE

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Nuclear Tapas 2023
The shell model as a cornerstone of nuclear structure

Disclaimer

The talk is a selection of topics related to β-decay studies in the region around ^{135}Sn, mainly via gamma spectroscopy and fast-timing.

It does not deal with other population methods (i.e. fission), nor β-decay measurents using for instance total absorption or direct neutron detection.

gfn UCM Grupo de Física Nuclear
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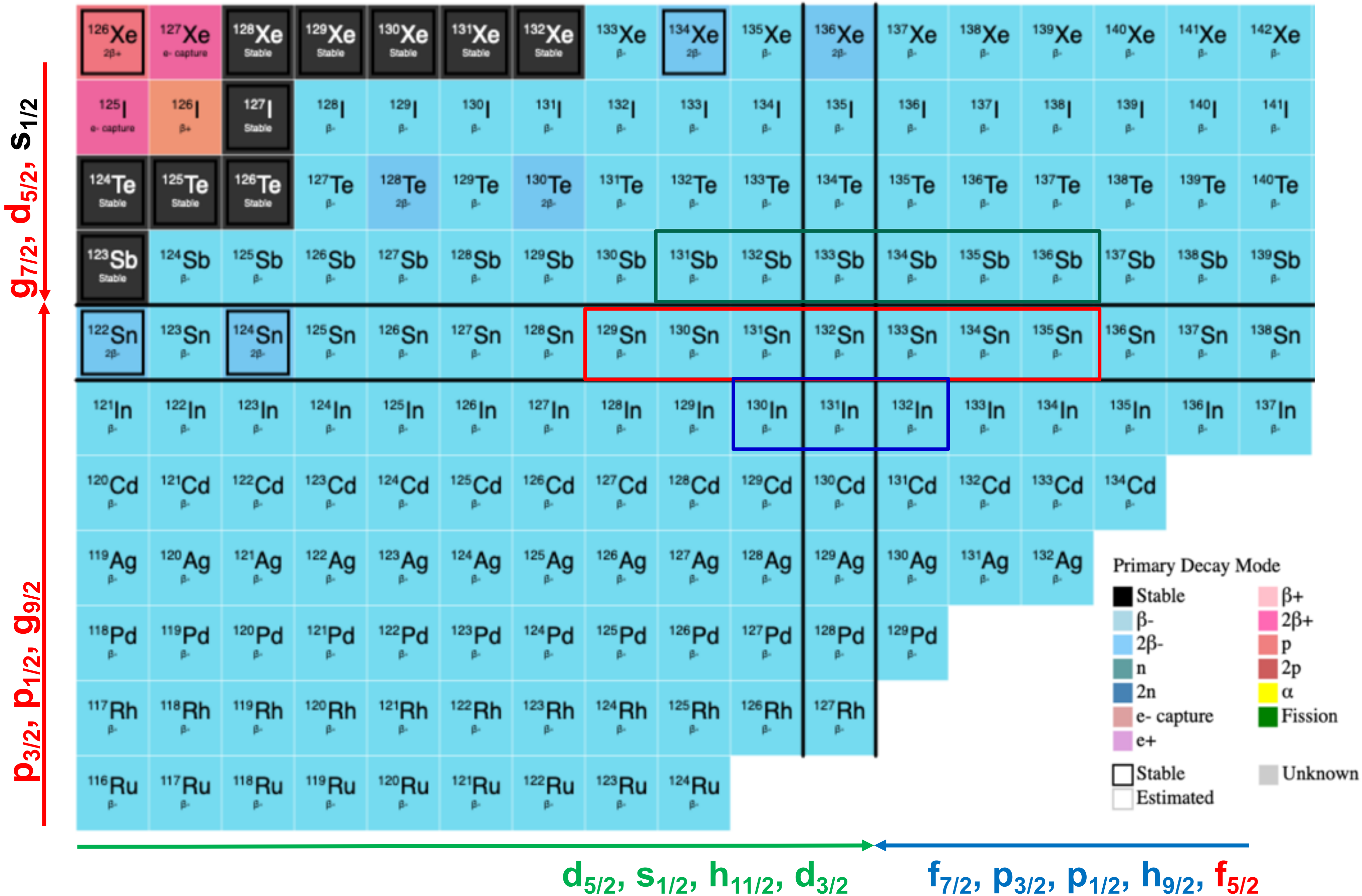
Region of interest



Why beta-decay

High $Q_ß$ values in the region

→ Access to a large decay windows

→ Energies above neutron separation energies above S_{2n} in some cases

Beta-decay selection rules

→ population of states via Gamow-Teller (GT) and first-forbidden (ff) transitions

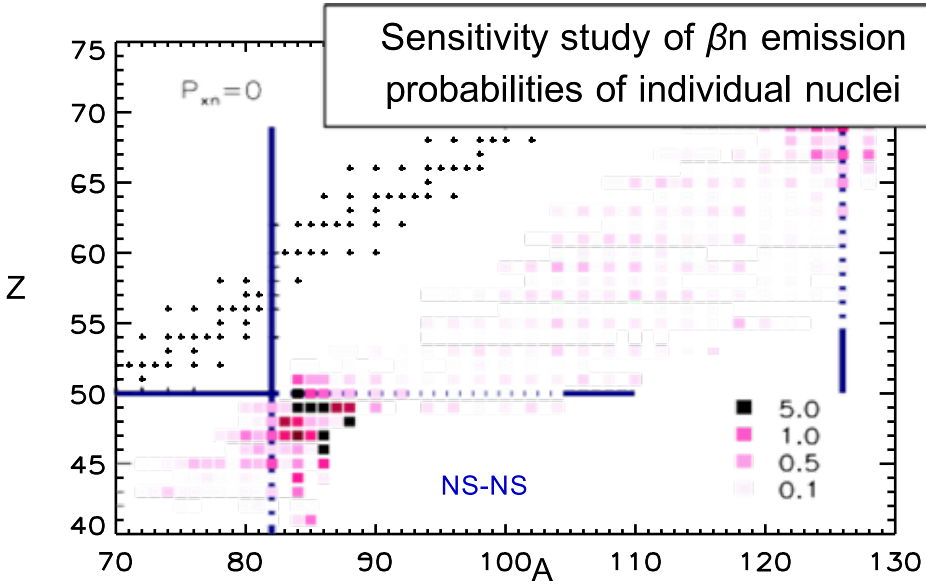
→ High-spin ß-decaying isomers populate different states

Access to different states in same nucleus, via ß/ß-n branches

Both details about structure and gross properties such as $T_{½}$ of ß-decaying states and P_{1n}, P_{2n} values

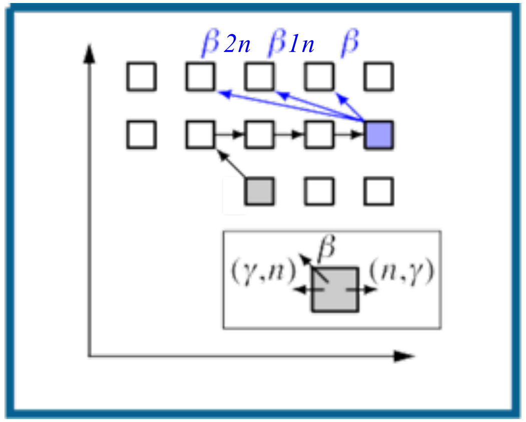
We can perform experiments addressing very exotic nuclei

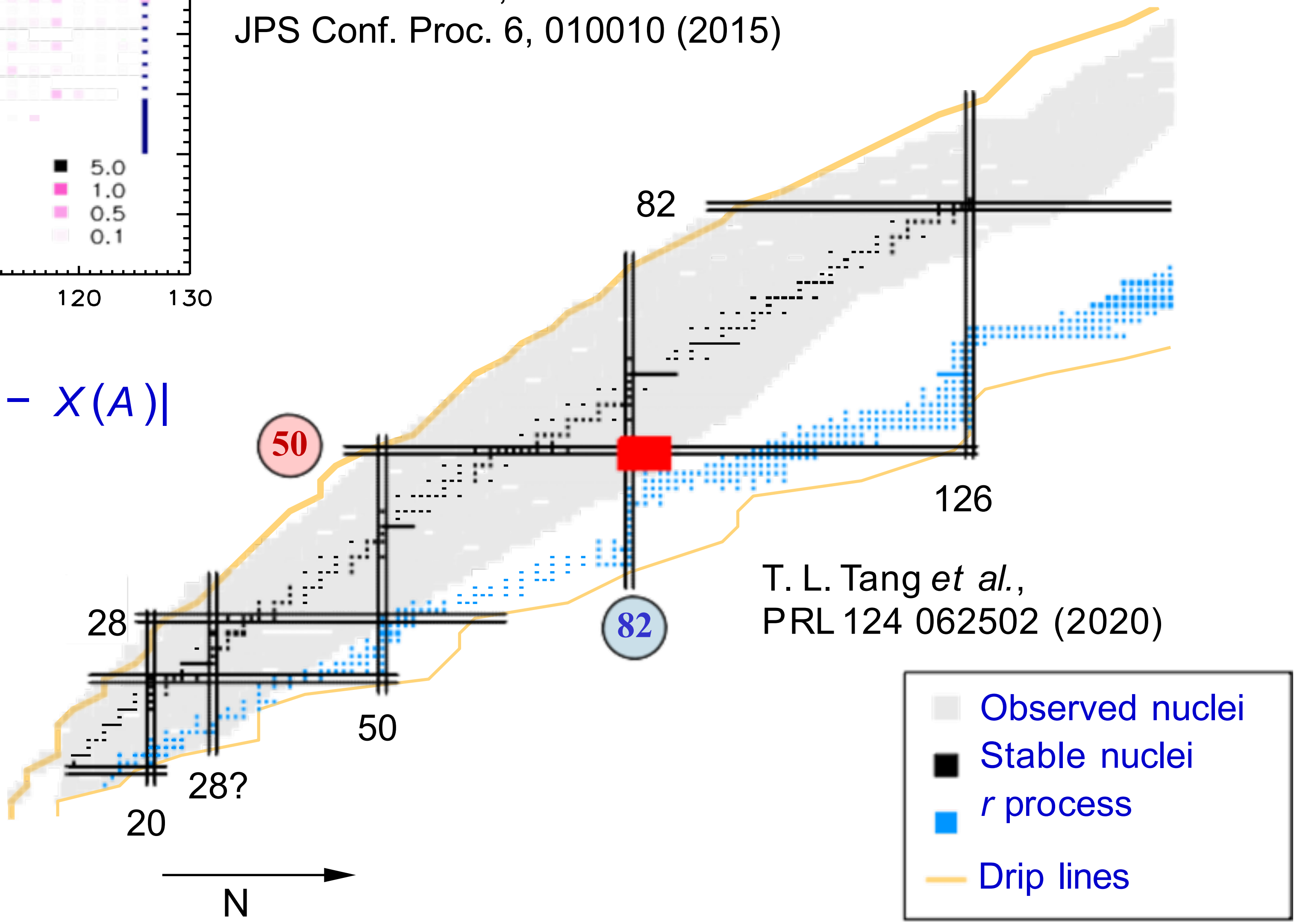
Proximity to the r-process path



R. Surman et al., JPS Conf. Proc. 6, 010010 (2015)

$$F = 100 \times \sum |X(A)_{P_{xn}=0} - X(A)|$$



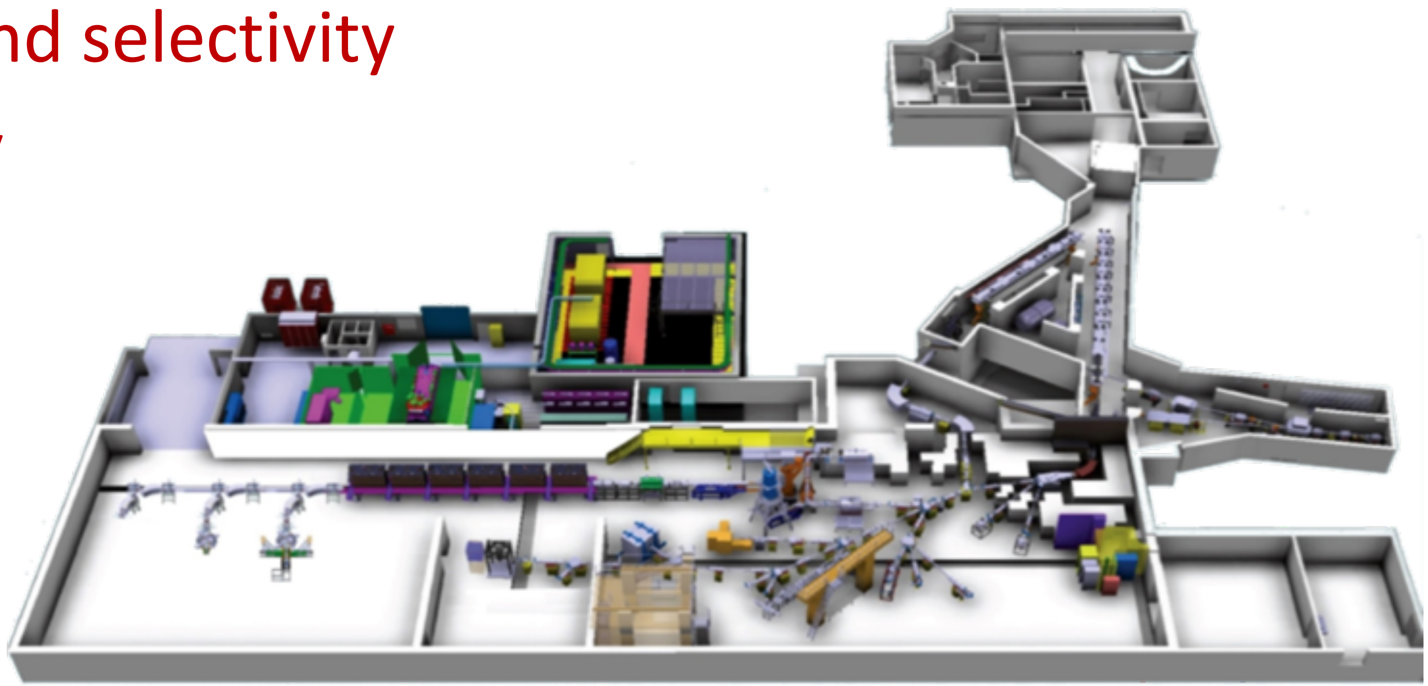


T. L. Tang *et al.*, PRL 124 062502 (2020)

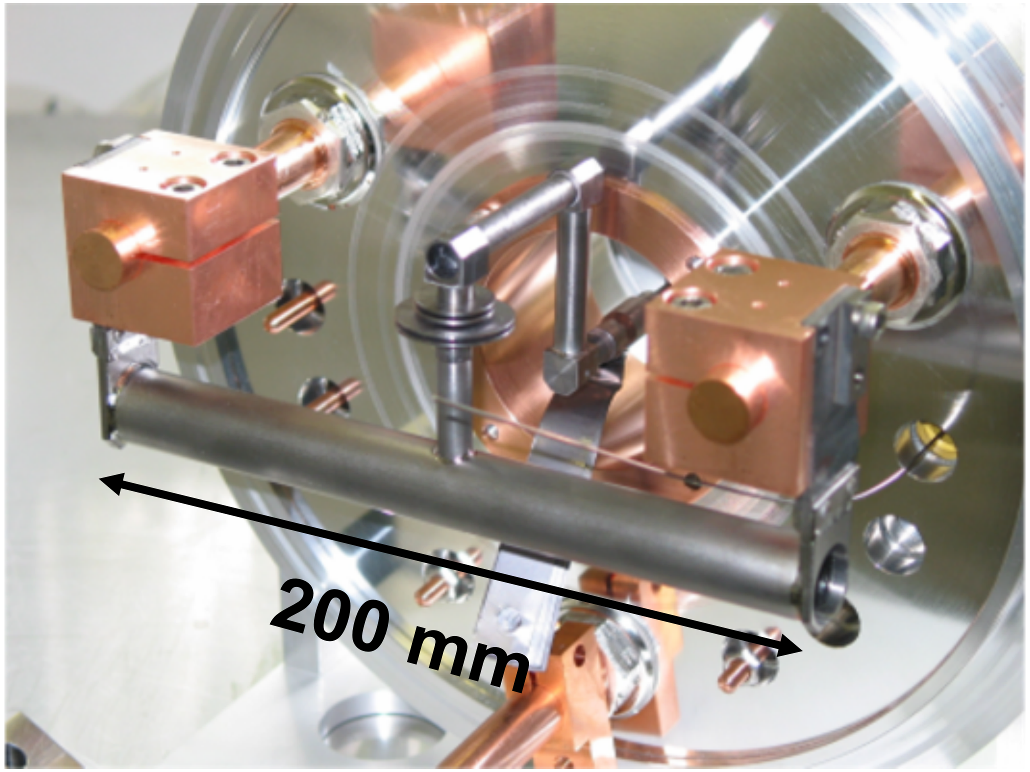
ISOLDE Experiments

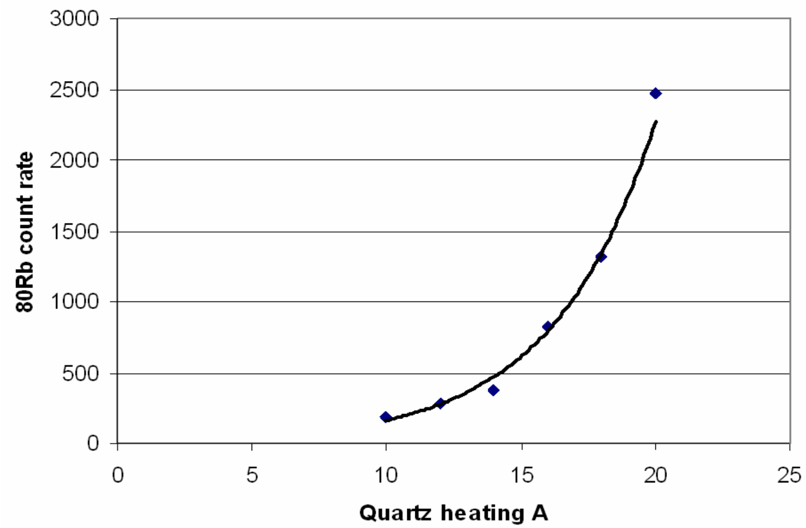
The ISOLDE facility provides unique capabilities to study nuclei populated in the β-decay of Cd, In, Sn.

- Neutron converter to suppress contaminants
- Fission induced on UC_x targets
- Molecular beams
- Transfer line to ionizer
- RILIS ionization and selectivity
- Isomer selectivity

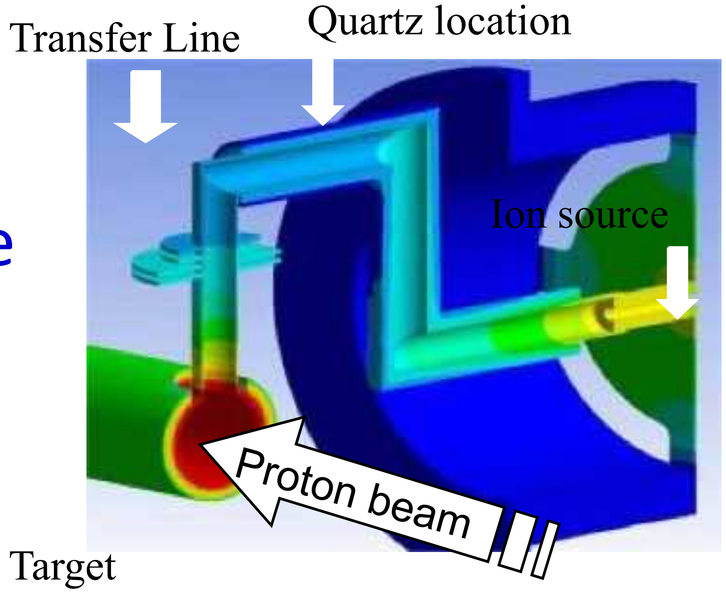


Cd: cooled transfer line





Heat transfer simulations



Temperature controlled quartz transfer line

[O. Arndt, E. Bouquerel, R. Catherall, C. Jost, K.-L. Kratz, U. Köster, J. Lettry, T. Stora, M. Turrión and the ISOLDE Collaboration]

RILIS ionization

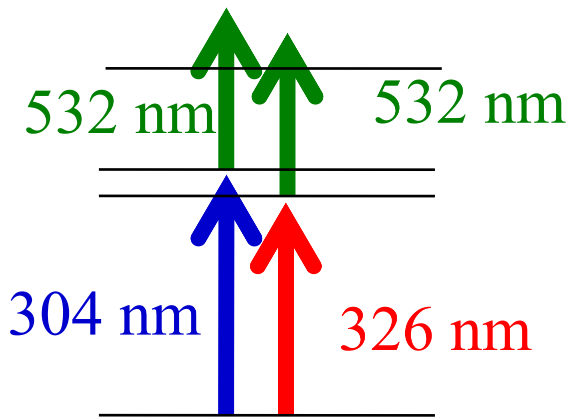
In: RILIS Ionization at ISOLDE

Resonant ionization of atomic structure.

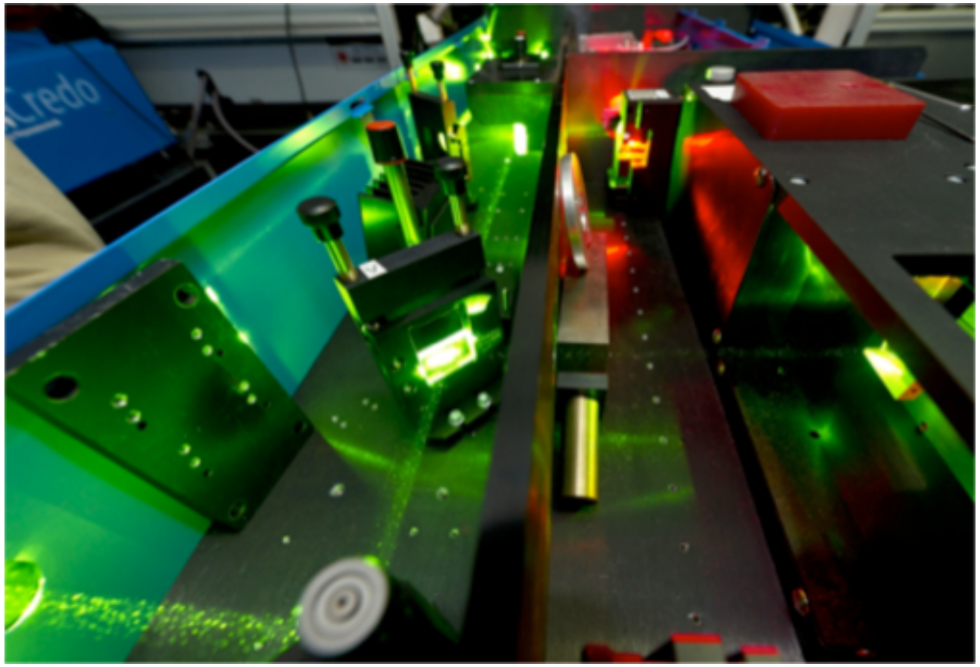
Highly selective ionization of desired isotope.

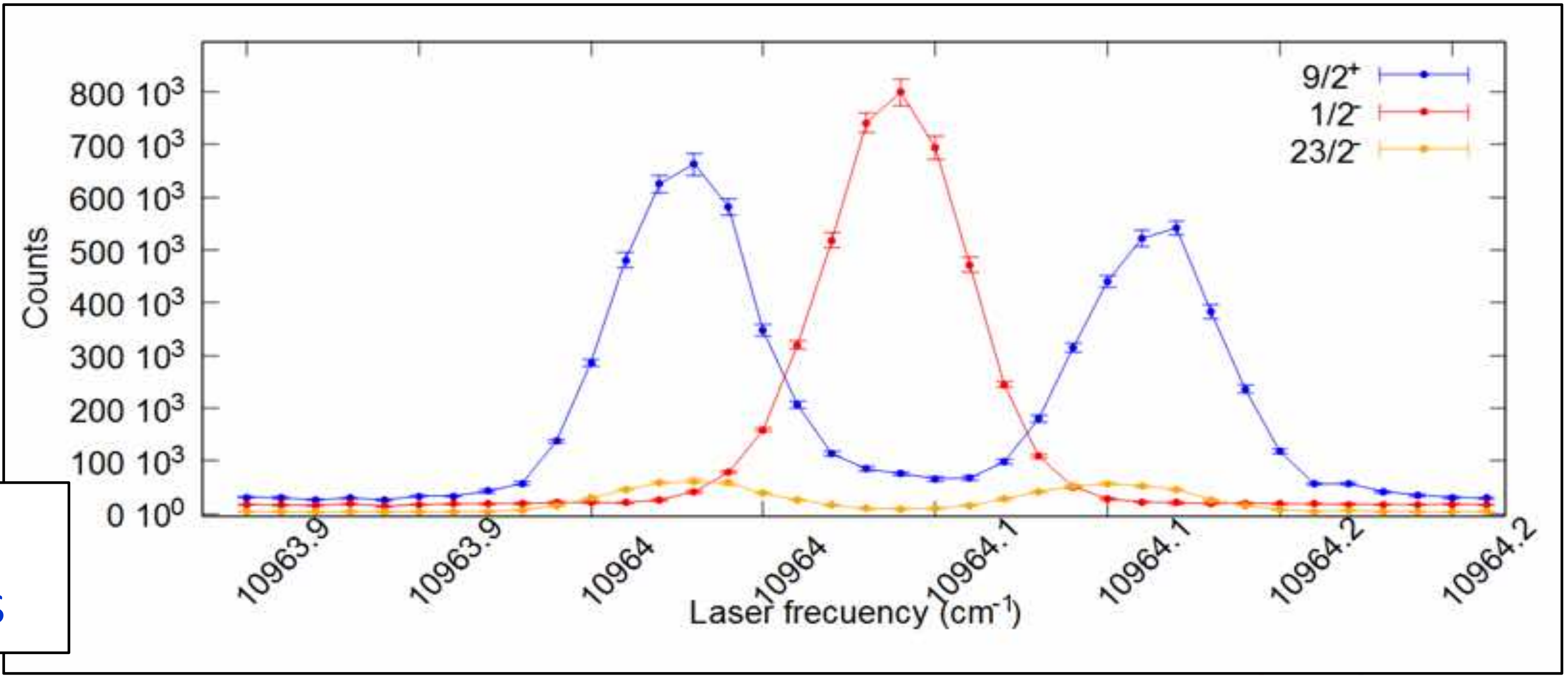
Hyperfine splitting gives the possibility to enhance nuclear isomeric states.

Isomerically-purified beams



V. Fedosseev et al.,
J. Phys. G44 (2017) 084006





RILIS scan for ^{129}In (^{131}In), monitored by decay γ-rays

Experiments at ISOLDE

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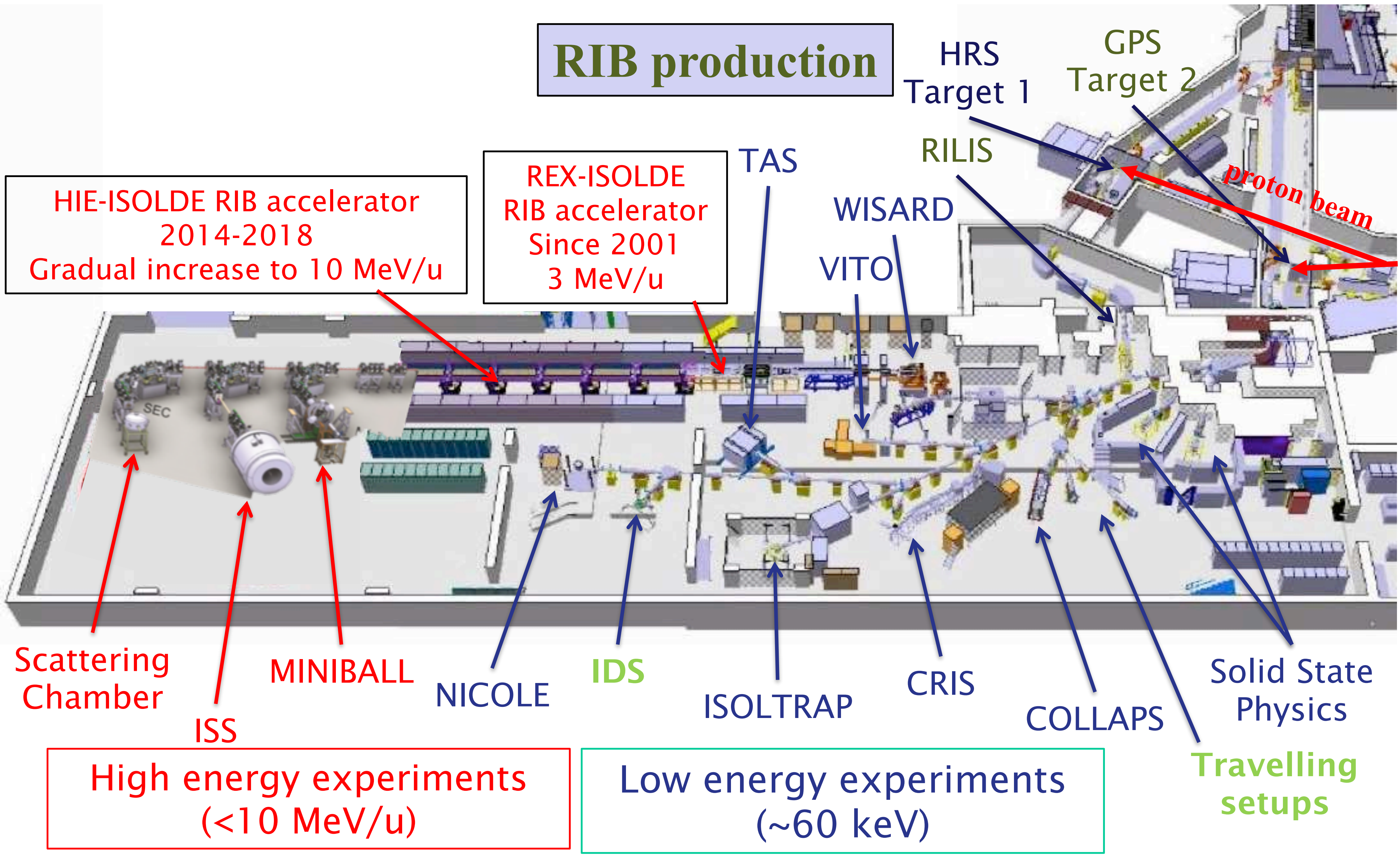

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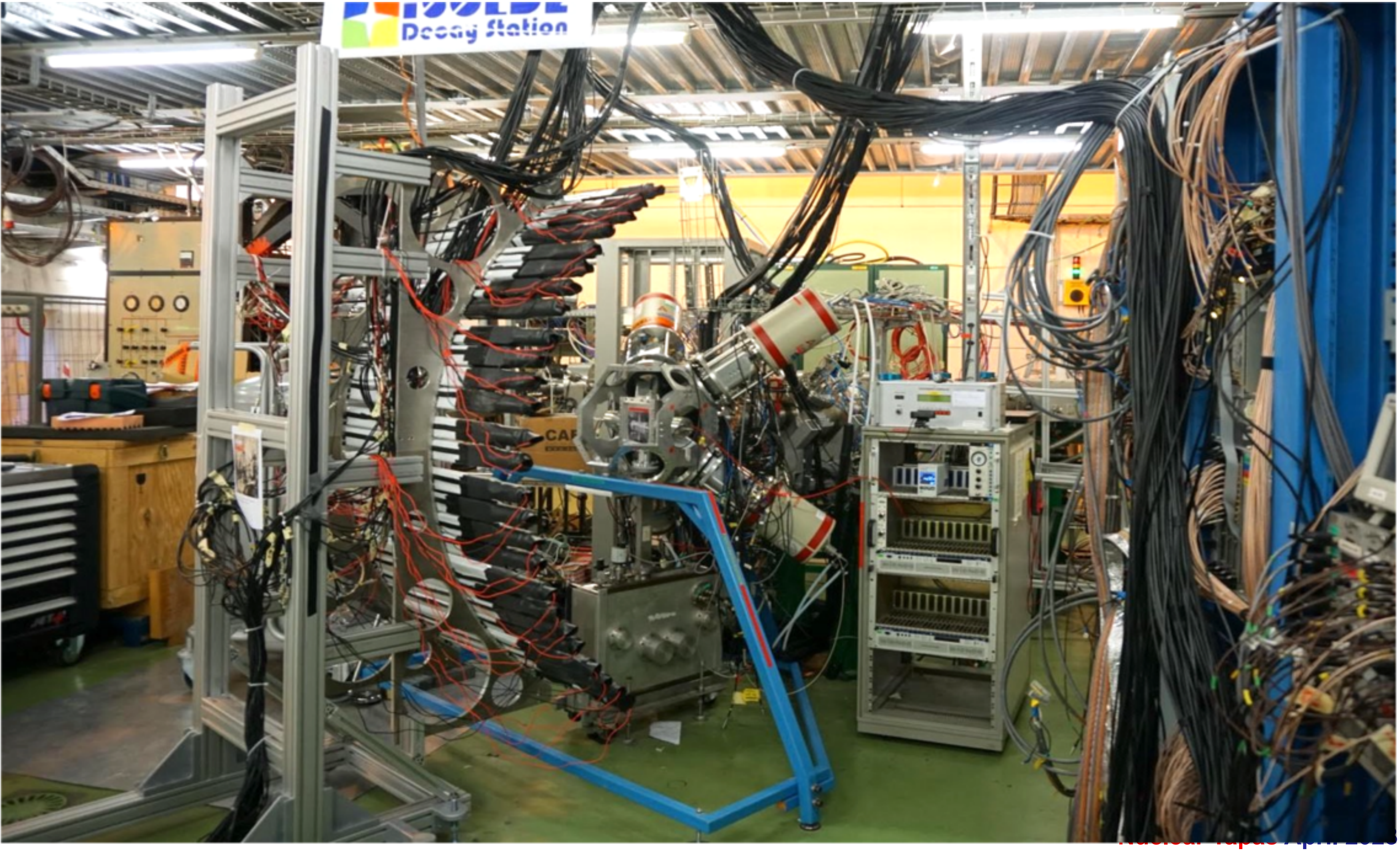
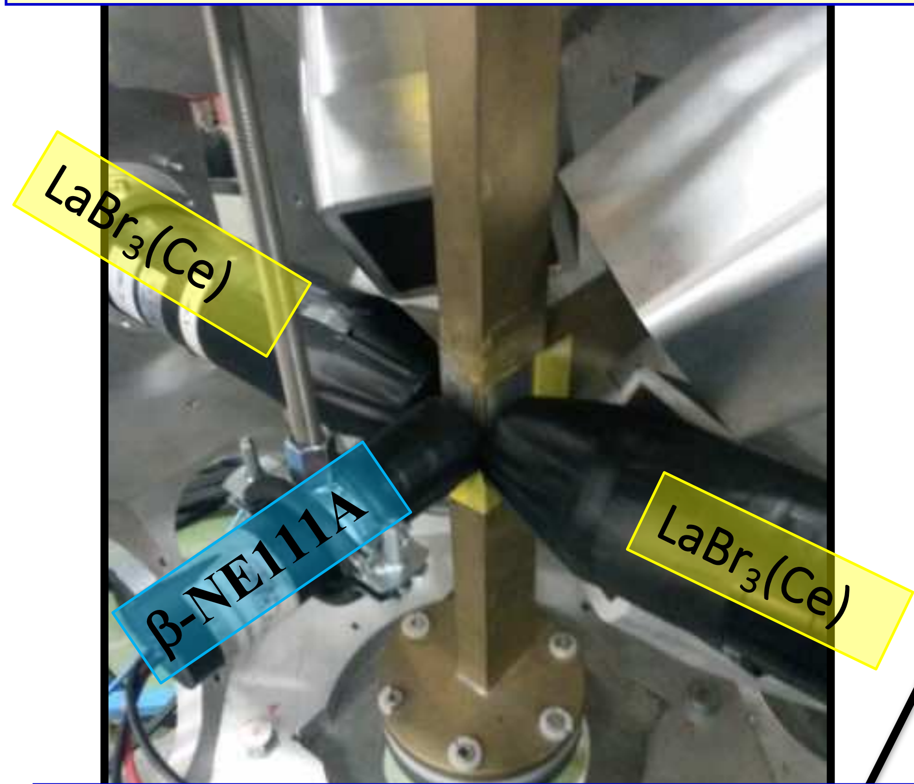
The ISOLDE Decay station

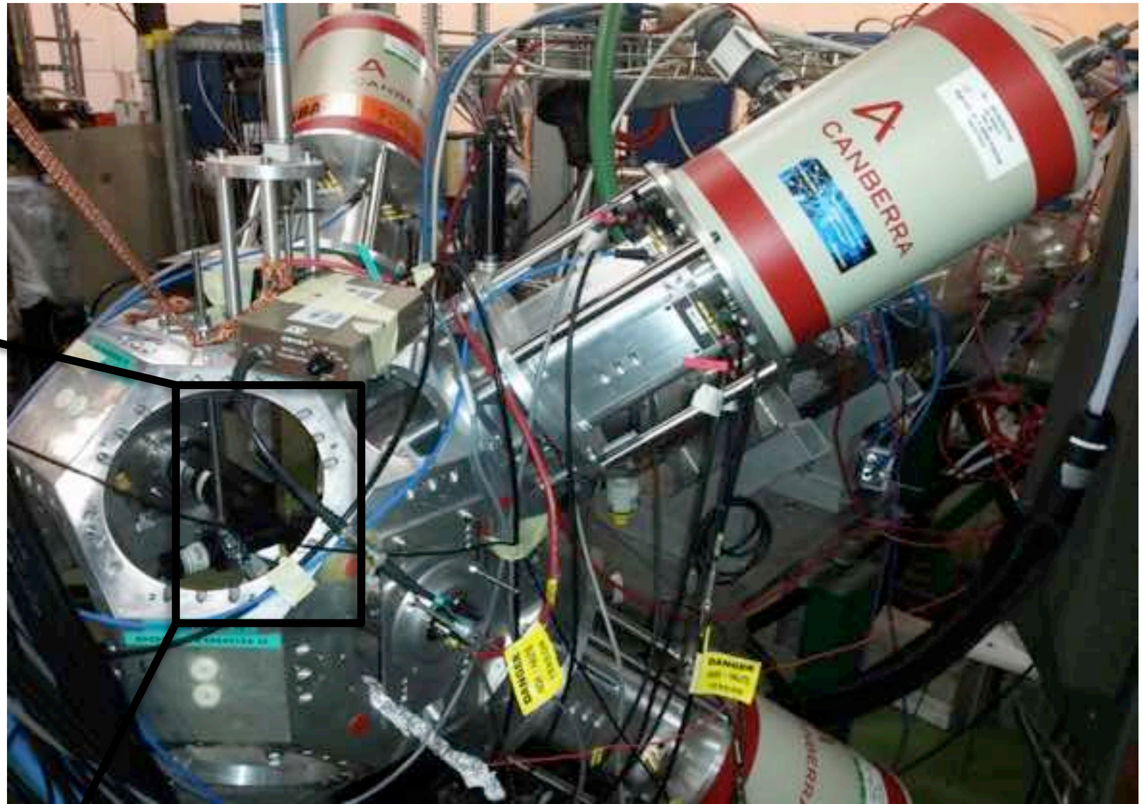


IDS: ß-decay setup at ISOLDE

- 4 or 6 Clover HPGe ~ 3.7% to 5.3% **eff**. @600keV
- 2 $LaBr_3(Ce)$ ~ 4% (2% each) @600keV (or up to 6 detectors)
- 1 Plastic Scintillator ~ 20% eff.
- DAQ – Digital system
- Analog TACs

IDS + fast-timing





- Analog timing processing: ORTEC CFD and 3 TAC for fast-timing
- Digital DAQ **Nutaq / XIA Pixie**

- Movable tape system to remove activity

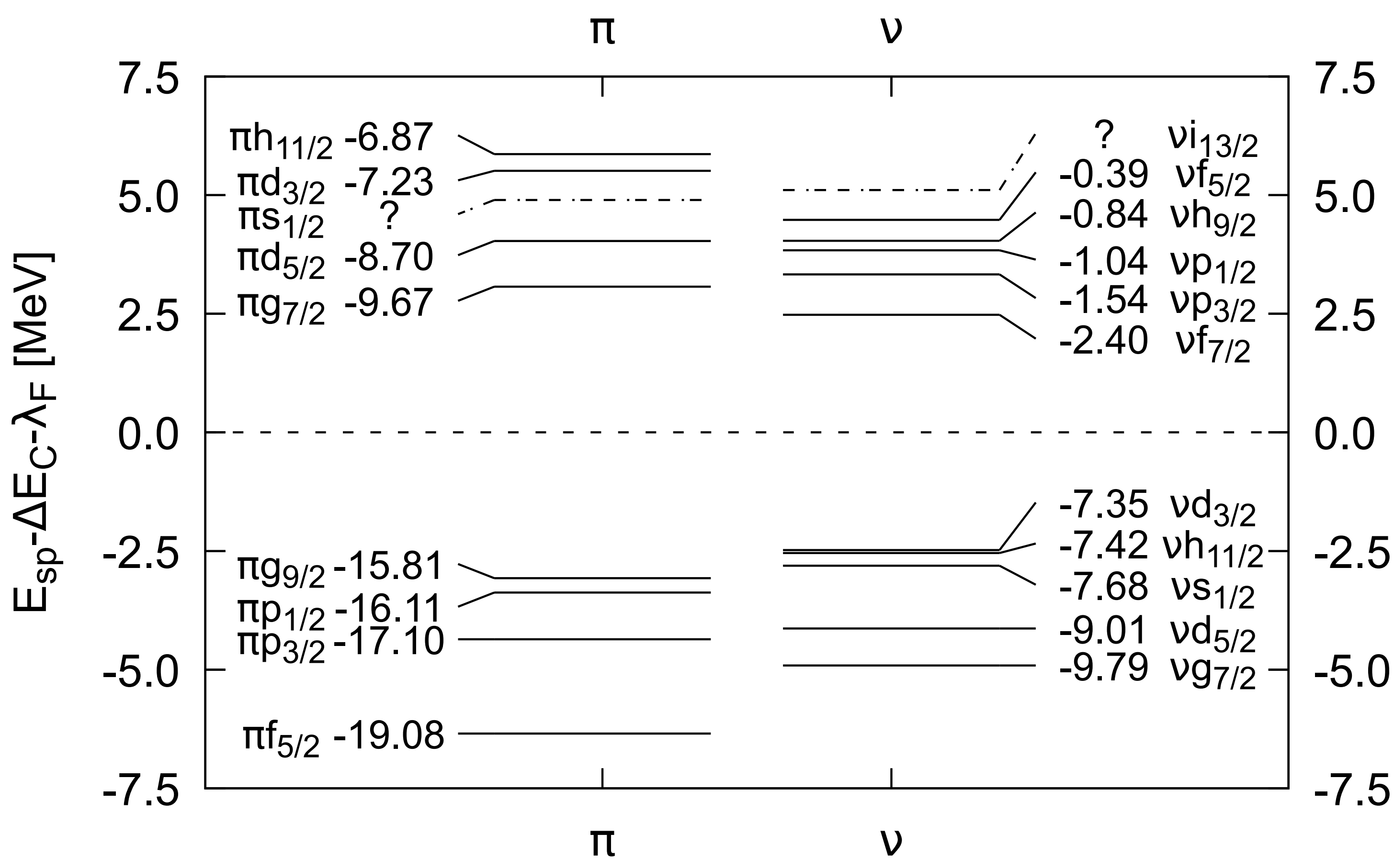
ISOLDE Decay Station

The strengths of beta-decay:

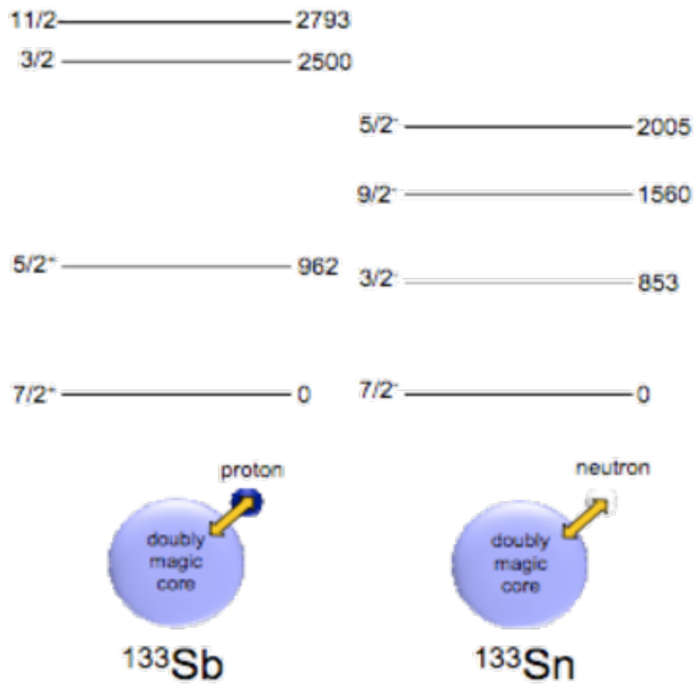
1. Single particle states
2. Core breaking states
3. Coupling of two neutrons
4. Competition of GT and ff transitions
5. Gamma emission from above S_n
6. Gross properties

Single particle states

Single particle energies



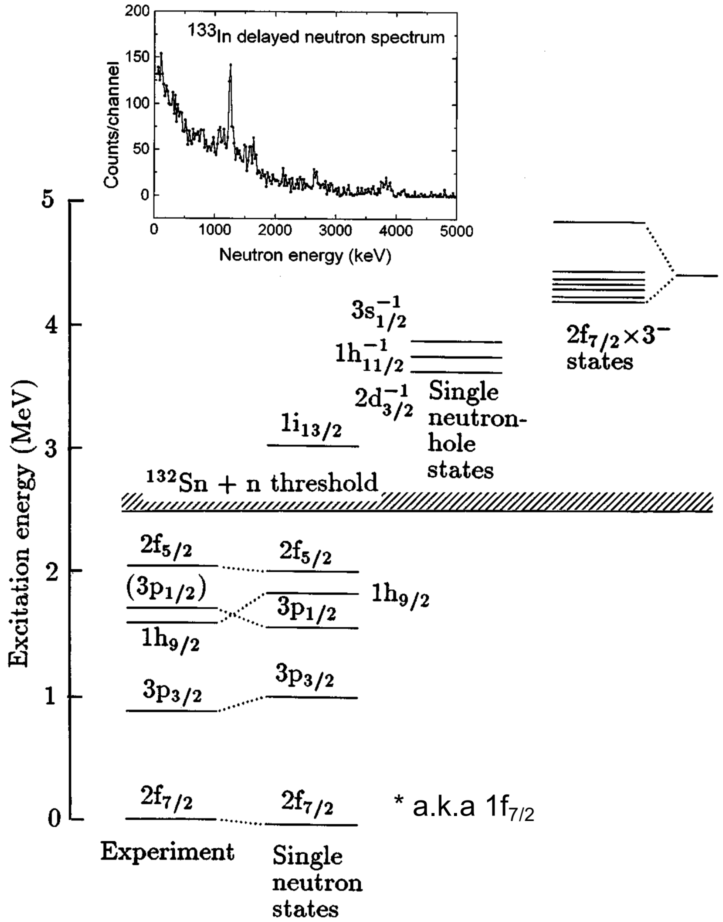
After H. Grawe, K. Langanke, and G. Martínez-Pinedo in Rep. Prog. Phys. 70, 1525 (2007).



^{131}Sb 3.23 MeV	^{132}Sb 5.55 MeV	^{133}Sb 4.01 MeV	^{134}Sb 8.51 MeV	^{135}Sb 8.04 MeV
^{130}Sn 2.15 MeV	^{131}Sn 4.72 MeV	^{132}Sn 3.09 MeV	^{133}Sn 8.05 MeV	^{134}Sn 7.59 MeV
^{129}In 7.75 MeV	^{130}In 10.25 MeV	^{131}In 9.24 MeV	^{132}In 14.14 MeV	^{133}In 13.41 MeV
^{128}Cd 6.9 MeV	^{129}Cd 9.78 MeV	^{130}Cd 8.77 MeV	^{131}Cd 12.81 MeV	^{132}Cd 12.15 MeV

^{133}Sn: single-particle states

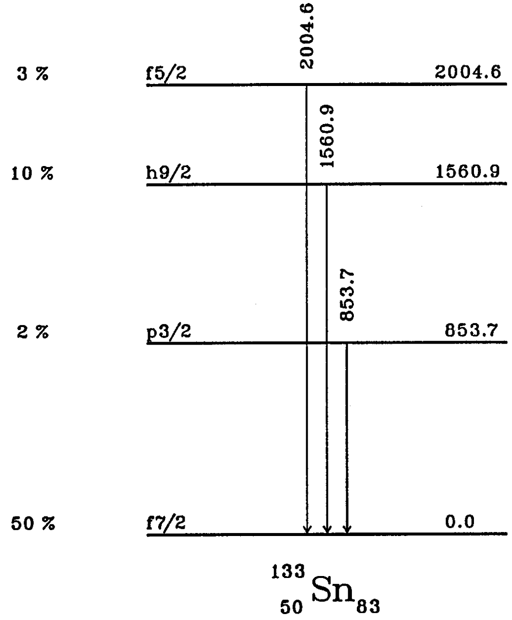
^{134}In ß-n decay



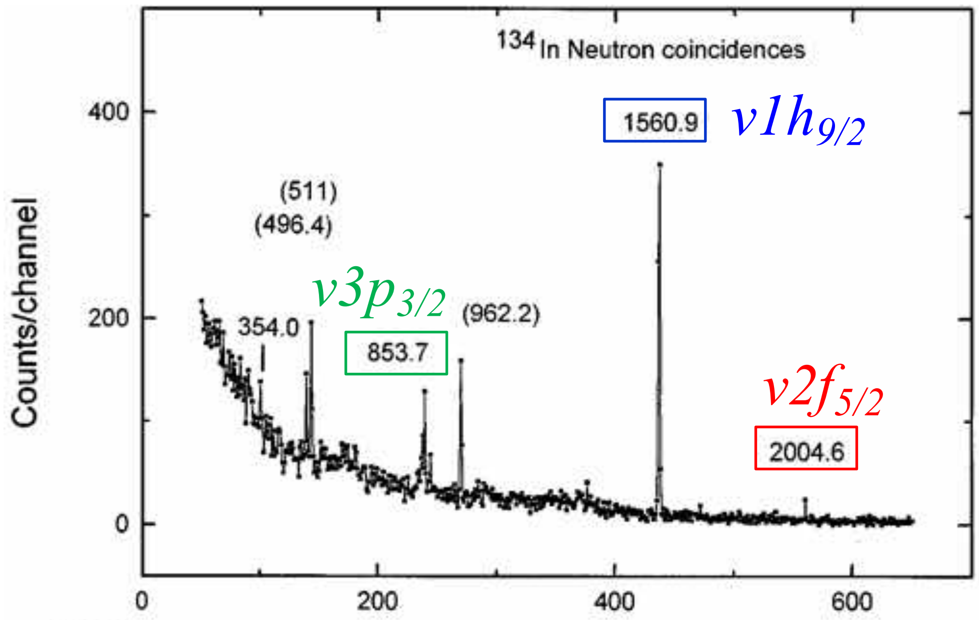
A comparison of the experimental results (left) with a *semiempirically adjusted Woods-Saxon* calculation of the ^{133}Sn sp states.

P. Hoff et al.,
PRL 77, 1020 (1996)

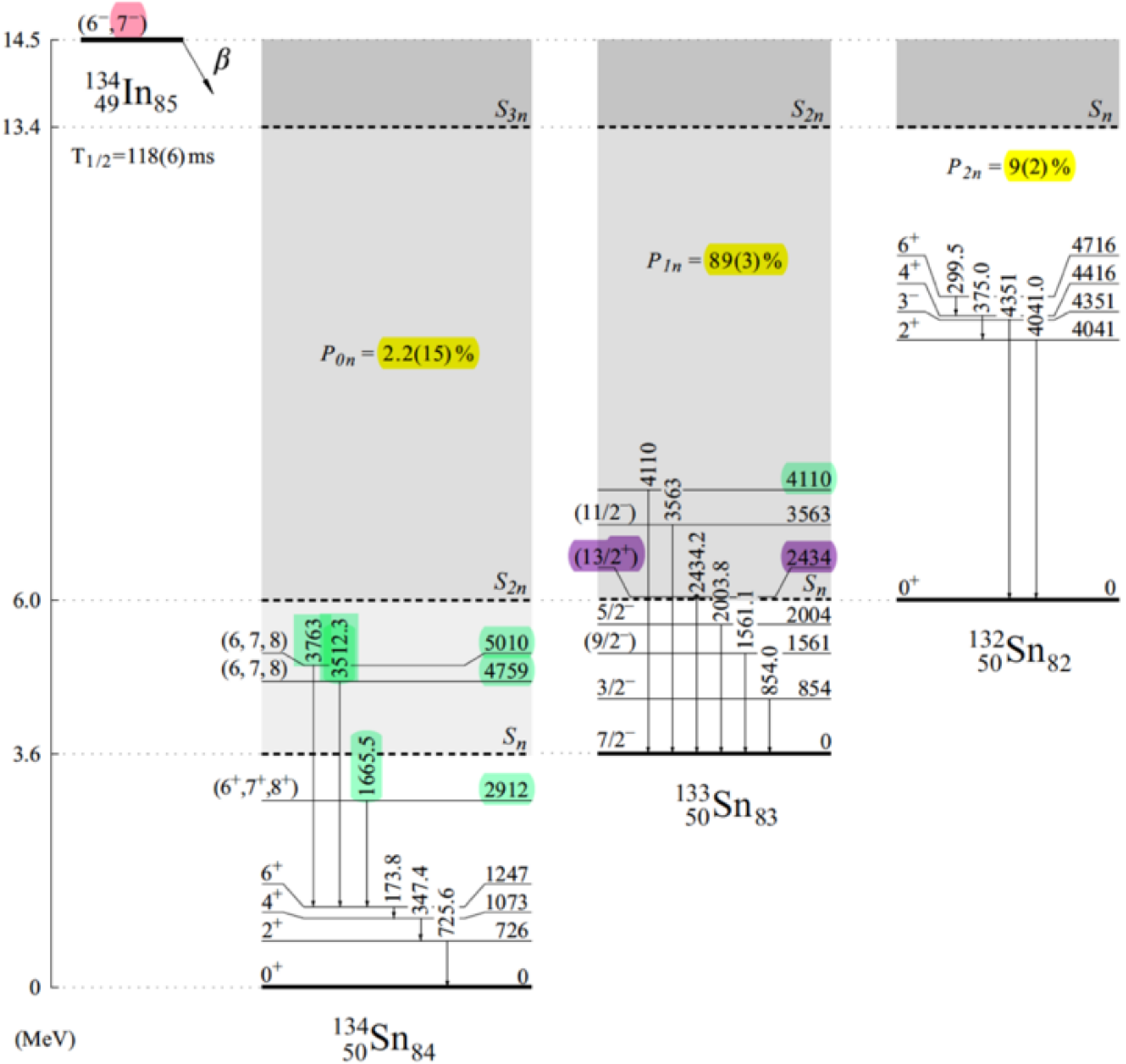
$P_n \approx 65\%$



^{134}In neutron coincidences



New decay scheme of ^{134}In



- β-decay and β2n-decay branches observed for the first time!
- Population of neutron-unbound states decaying via γ rays identified in ^{133}Sn and ^{134}Sn
- Apparent feeding in ^{134}Sn suggests a high g.s. ^{134}In spin value: **6⁻, 7⁻**
- Revised P_{1n}, P_{2n} values

Consistent with β-decay of ^{133}In, M. Piersa et al., PRC99 024304 (2019)

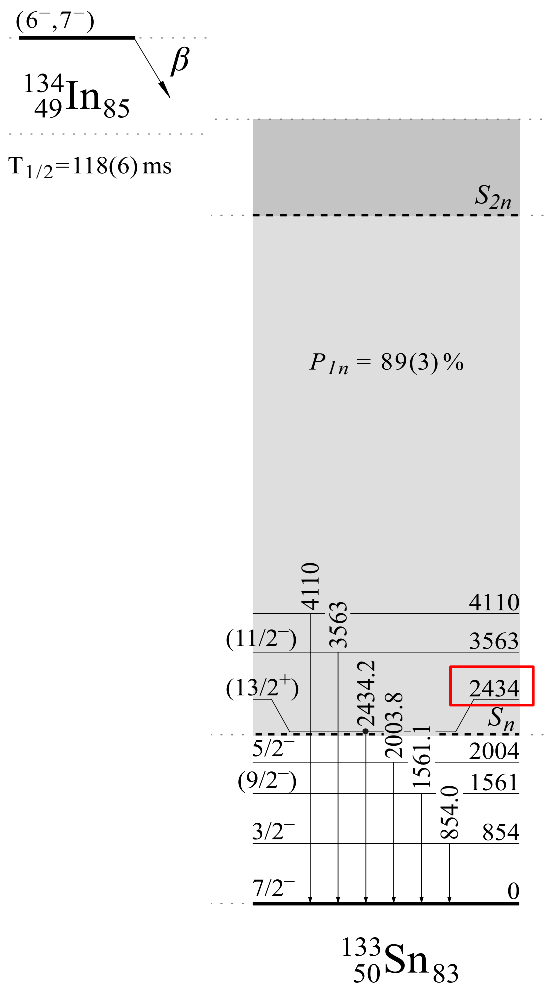
M. Piersa-Siłkowska et al., Phys. Rev. C 104, 044328 (2021)

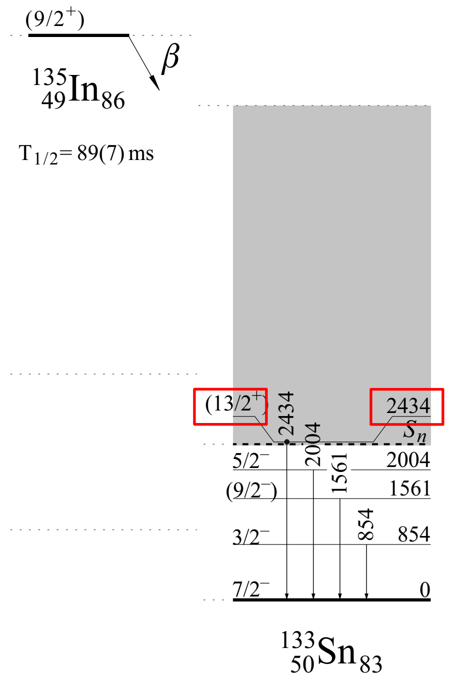
Search for the $\nu i_{13/2}$ state in ^{133}In in β decay

Estimated at around 2.5 Me Based on systematics and scaling of interactions

- E = 2700(200) keV [W. Urban et al., EPJA 5, 239 (1999)]
- E = 2511(80) keV [A. Korgul et al., PRC 91, 027303 (2015)]
- E = 2360–2600 keV [W. Reviol et al., PRC 94, 034309 (2016)]

2792-keV level suggested [J.M. Allmond et al., PRL112, 172701 (2014)]

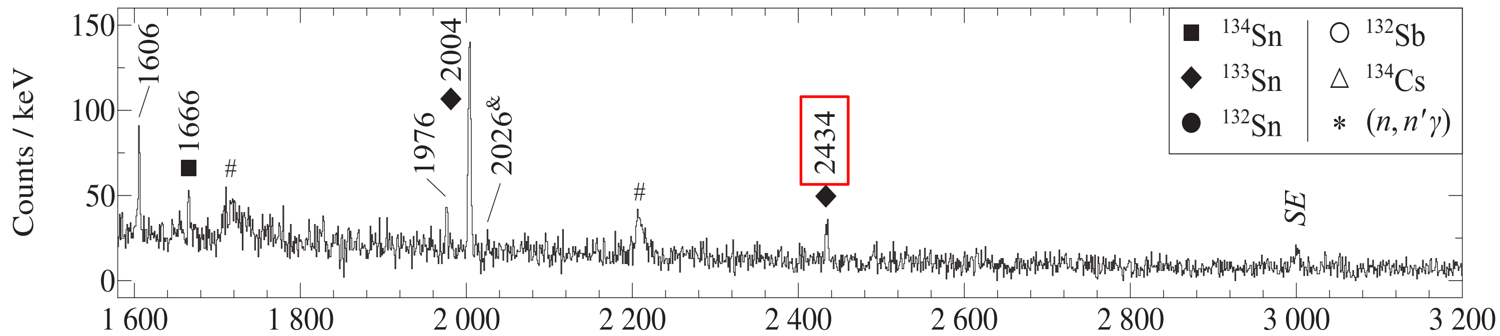




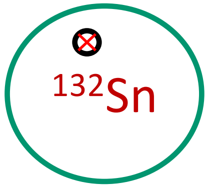
New candidate proposed based on the observation of a 2434-keV γ-ray in the β-n decay of ^{134}In and β-2n of ^{135}In

M. Piersa-Siłkowska et al.,
Phys. Rev. C 104, 044328 (2021)

β–γ coincidences, (0-400) ms



^{131}Sn: search for the $\upsilon h_{11/2}^{-1}$ single-hole state

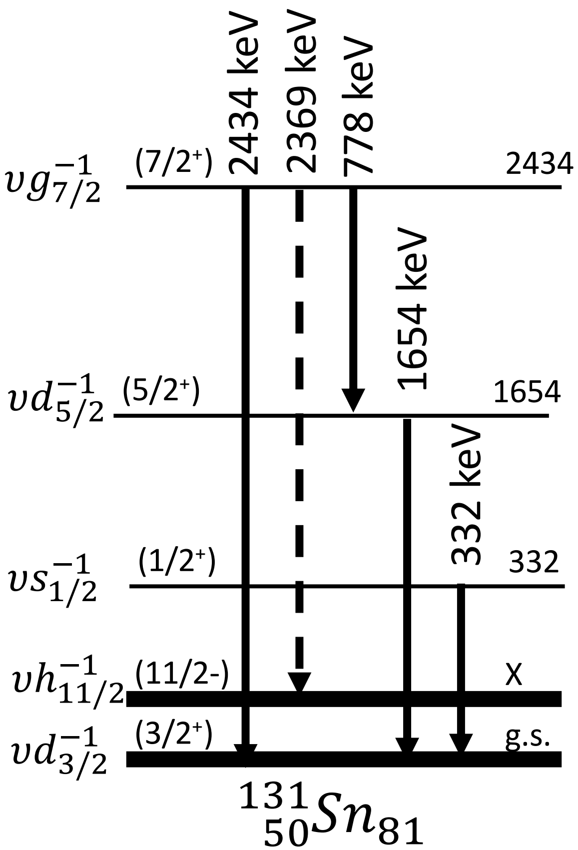


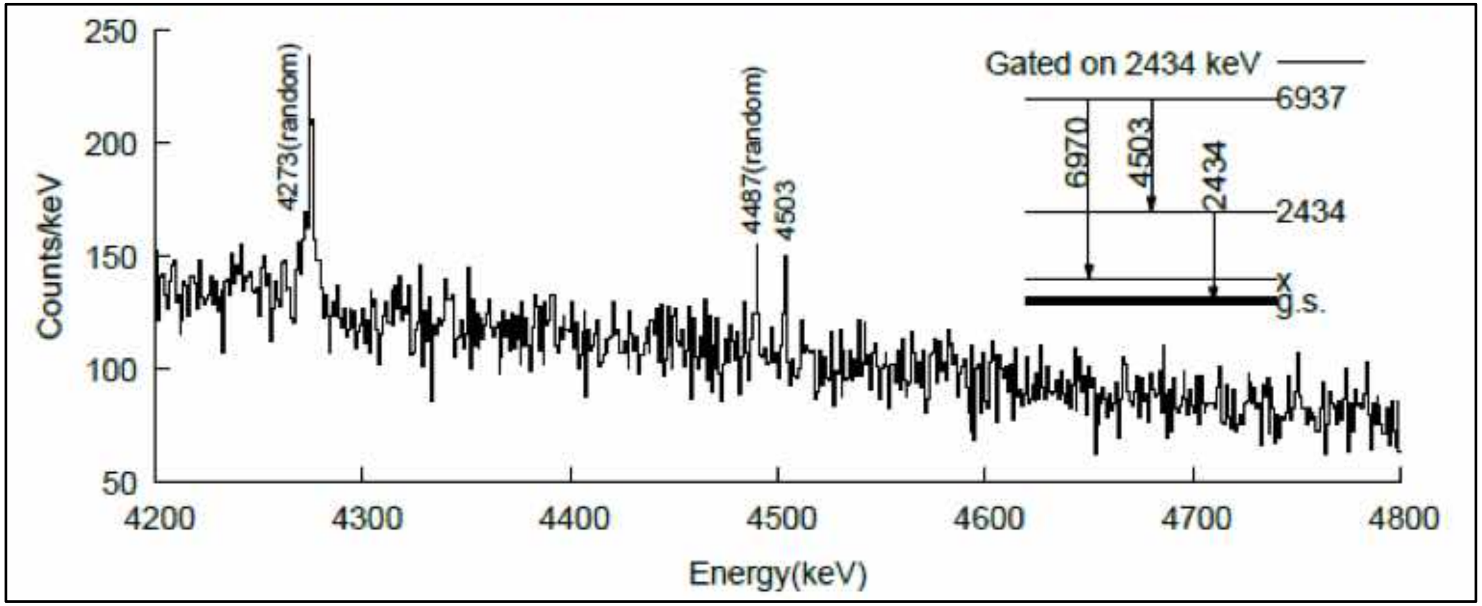
The precise E of the $\upsilon h_{(11/2)}^{-1}$ single-hole state still unconfirmed

Measured via Q_β energy differences in ^{131}Sn decay. E_x=69(14) keV

B. Fogelberg et al.

A More precise 65.1 keV energy was suggested from the 2369 keV transition (not confirmed by γγ coincidences).





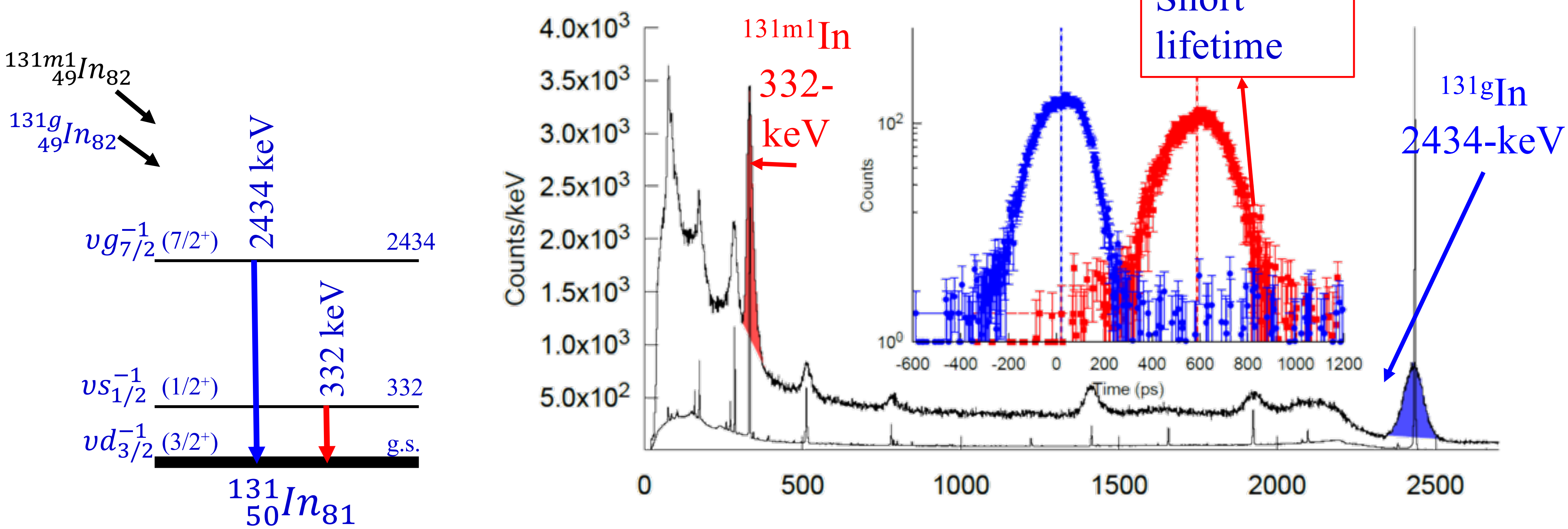
Confirmed the emission of the 2369-keV γ-ray in the ^{131g}In decay.

Tentative identification of a level decaying to both $\upsilon g_{7/2}^{-1}$ & $\upsilon h_{11/2}^{-1}$

J. Benito et al., Ph.D. Thesis 2020 and PRC to be submitted 2023

Addressing l-forbidden gamma transitions

The half life of the 332-keV $\nu s_{1/2}^{-1}$ state



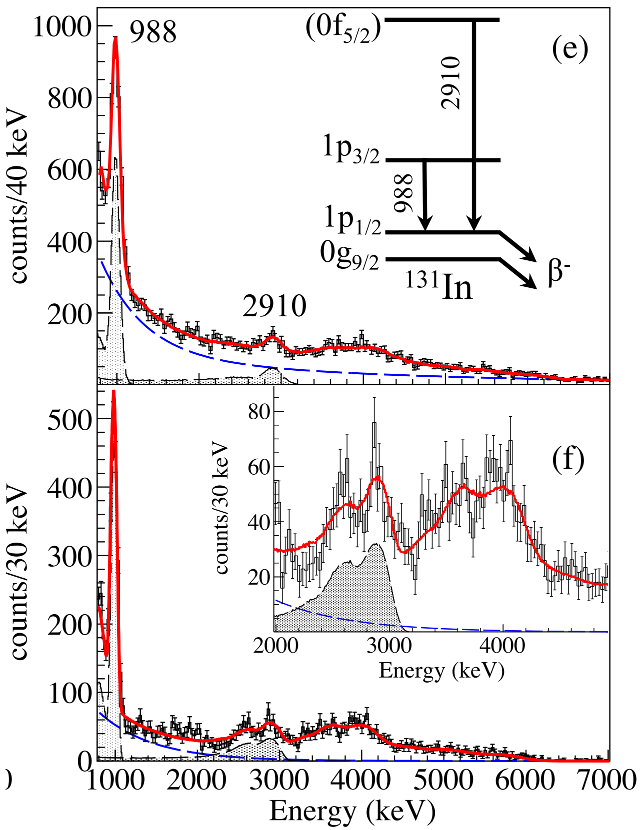
M1 transition (Δl=2): $\nu s_{1/2}^{-1} \longrightarrow \nu d_{3/2}^{-1}$, expected long

Measured half life of 20 ps

Similar to transition in ^{129}Sn [R. Liča, H. Mach et al., PRC 93, 044303 (2016)]

A slightly different from zero M1 effective operator for n holes greatly improves the agreement

^{131}In: the $\pi f_{5/2}$ state in the β decay of ^{131}Cd

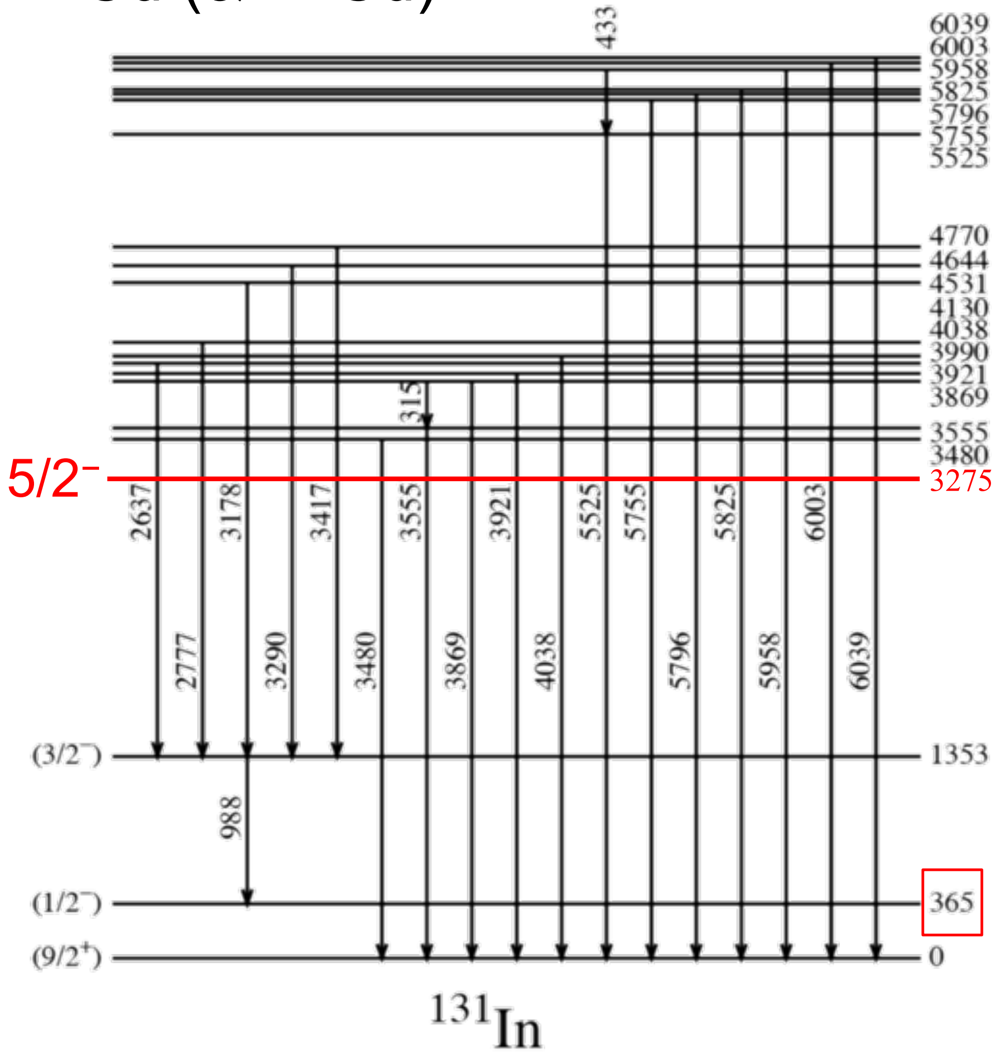


^{131}In: single hole nucleus

populated from ^{131}Cd (& ^{132}Cd)

ISOLDE IS684

V. Vaquero,
A. Jungclaus et al.,
PRL124, 022501
(2020)



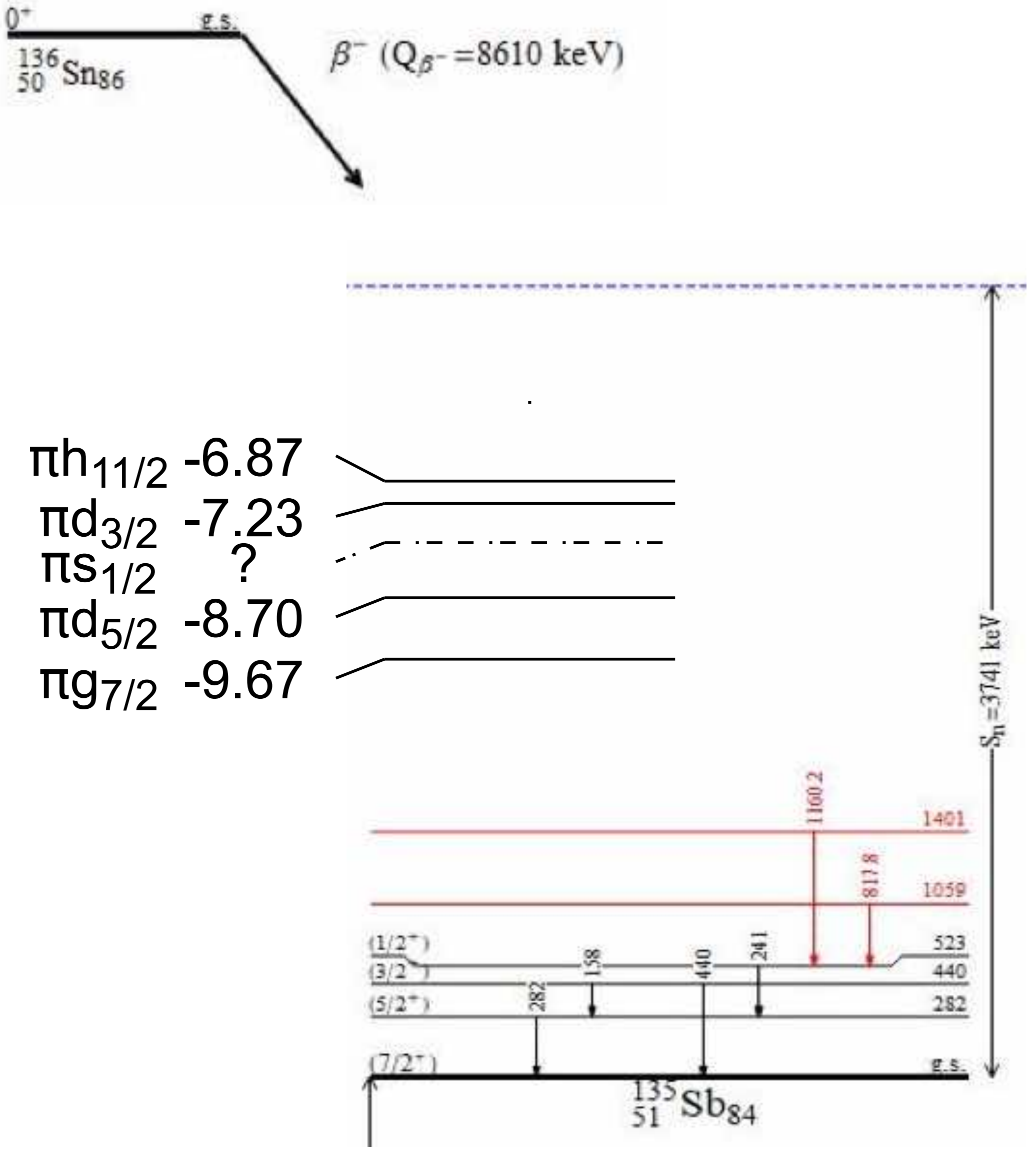
- $5/2^-$ level populated in β decay via $\nu 1f_{7/2} \rightarrow \pi 0f_{5/2}$ GT suppressed by $2\hbar\omega$
- populated directly (mixing) or indirectly
- main decay branch to the low-lying $1/2^-$ and weaker to g.s. and $3/2^-$

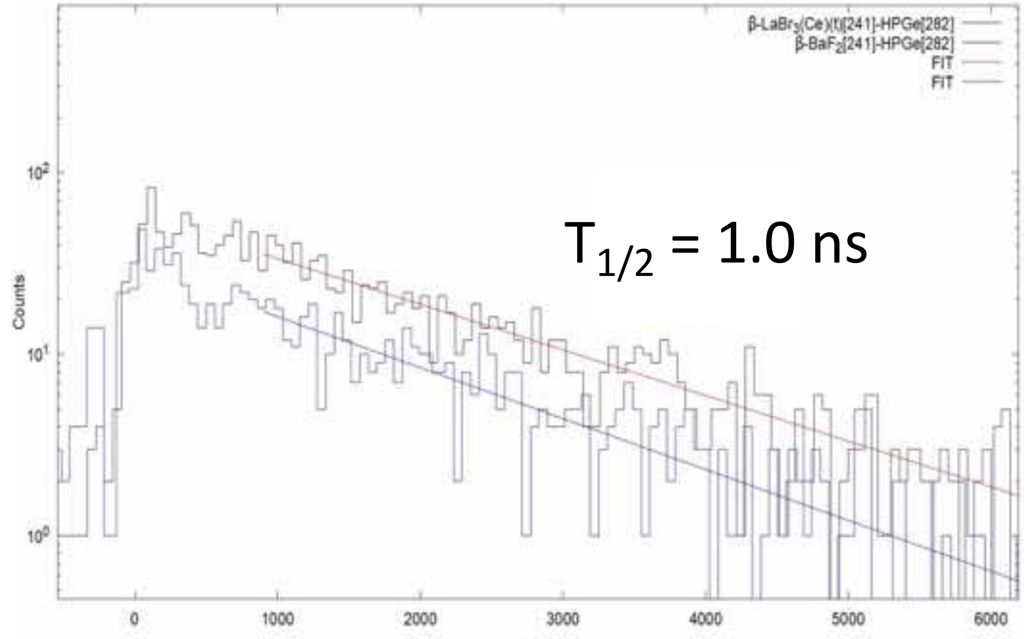
J. Taprogge, A. Jungclaus et al.,
EPJ A52, 347 (2016)

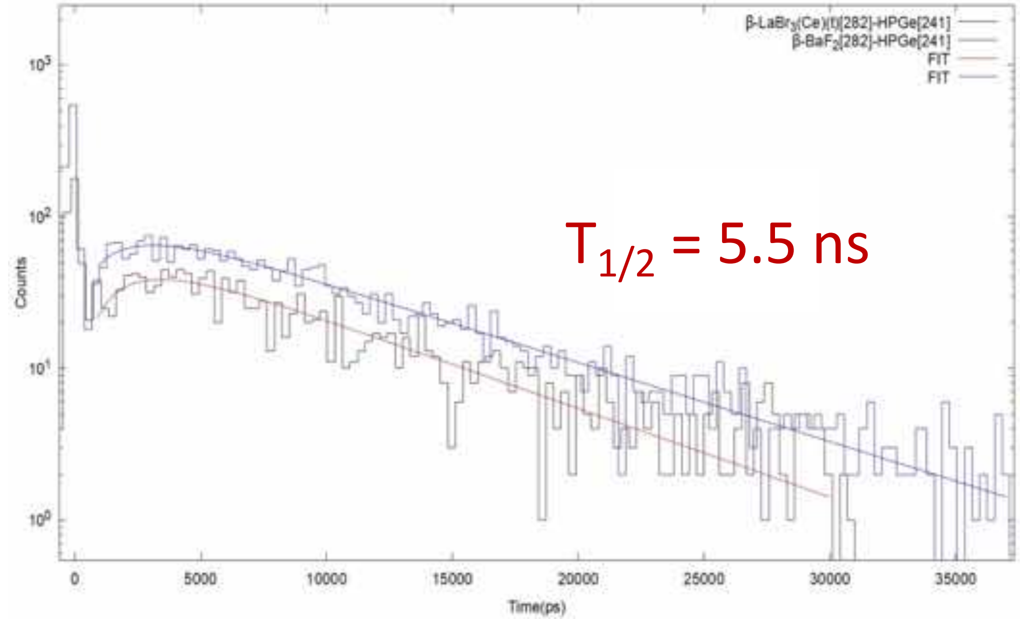
^{135}Sb: lifetimes of s.p. states

^{135}Sb: ^{132}Sn + 1p + 2n

ATD βγγ(t) fast-timing





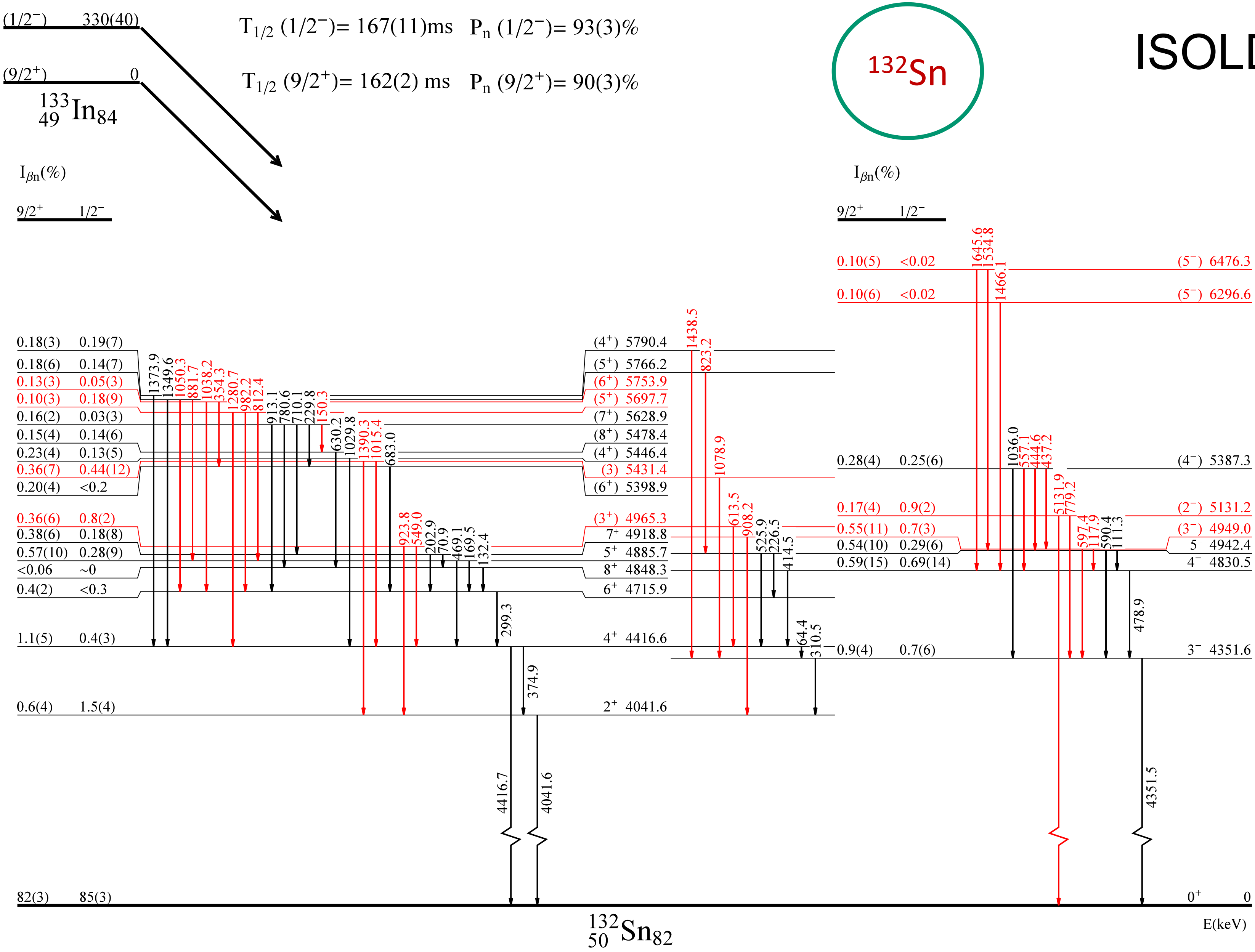


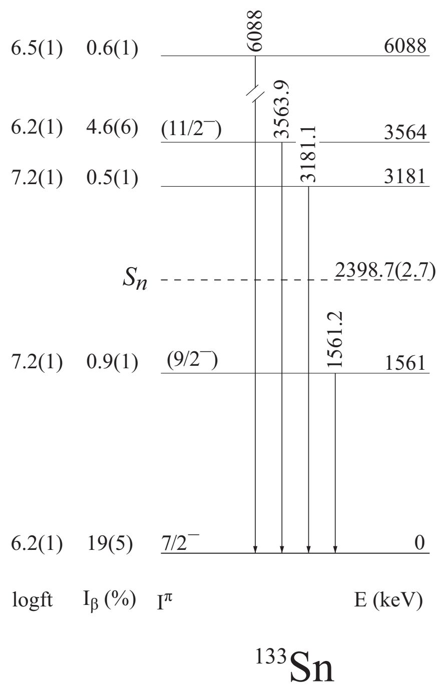
M. Llanos et al., in preparation

Breaking of the core

Available information on ^{132}Sn

ISOLDE IS610

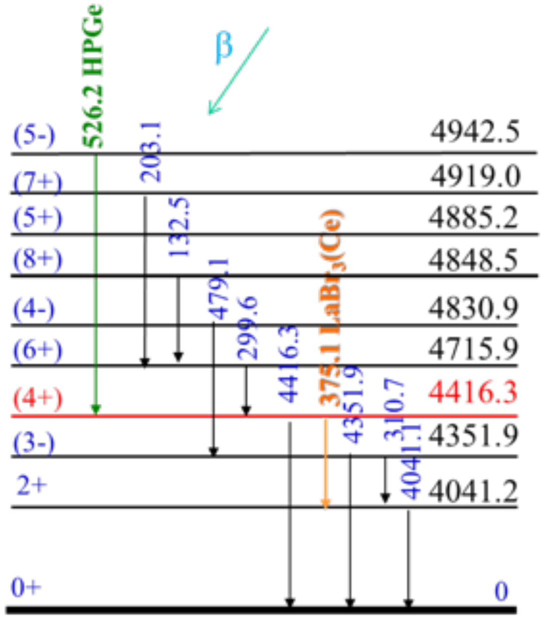


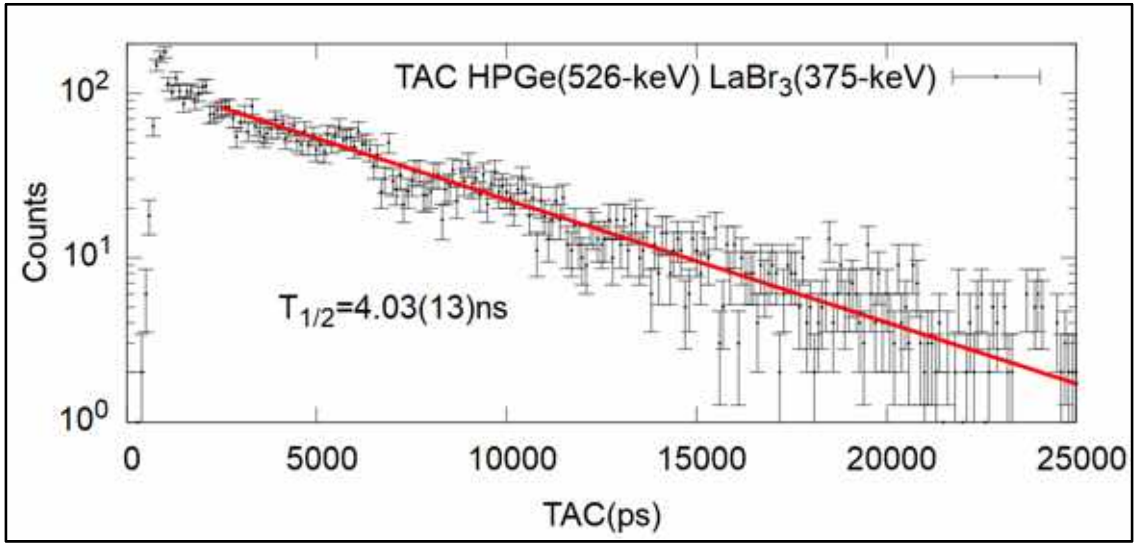


M. Piersa et al., PRC 99, 024304 (2019)

J. Benito et al., Phys. Rev. C102, 014328 (2020)

Complete lifetime investigation in ^{132}Sn





E_i (keV)	Config$_i$	J_i^Π	$T_{1/2}$	$T_{1/2}$ (literature)	E_f (keV)	Config$_f$	J_f^Π	E_γ (keV)	$X\lambda$	$B(X\lambda)$ (W.u.)
4351.6	Octupole vibration	3^-	<5 ps	<5 ps [18]	0	g.s.	0^+	4351.5	E3[c]	>7.1
				$3.4(^{+20}_{-9})$ ps [45][b]	4041.6	$\nu f_{7/2}h_{11/2}^{-1}$	2^+	310.5	E1[c]	$>1.2\times10^{-4}$
4416.6	$\nu f_{7/2}h_{11/2}^{-1}$	4^+	3.99(2) ns	3.95(13) ns [18]	0	g.s.	0^+	4416.7	E4	7.7(4)
					4041.6	$\nu f_{7/2}h_{11/2}^{-1}$	2^+	374.9	E2[c]	0.40(2)
					4351.6	Octupole vibration	3^-	64.4	E1	$2.57(13)\times10^{-6}$
4715.9	$\nu f_{7/2}h_{11/2}^{-1}$	6^+	21.3(4) ns	20.1(5) ns [18]	4416.6	$\nu f_{7/2}h_{11/2}^{-1}$	4^+	299.3	E2[c]	0.268(6)
4830.5	$\nu f_{7/2}d_{3/2}^{-1}$	4^-	27(2) ps	26(5) ps [18][a]	4351.6	Octupole vibration	3^-	478.9	M1[c]	$7.3(5)\times10^{-3}$
					4416.6	$\nu f_{7/2}h_{11/2}^{-1}$	4^+	414.5	E1	$2.3(3)\times10^{-6}$
4848.3	$\nu f_{7/2}h_{11/2}^{-1}$	8^+	2.108(14) μs	2.080(17) μs [3]	4715.9	$\nu f_{7/2}h_{11/2}^{-1}$	6^+	132.4	E2[c]	0.1039(14)
4885.7	$\nu f_{7/2}h_{11/2}^{-1}$	5^+	<30 ps	<40 ps [18]	4416.6	$\nu f_{7/2}h_{11/2}^{-1}$	4^+	469.1	M1	$>6.5\times10^{-3}$
									E2	>19
					4715.9	$\nu f_{7/2}h_{11/2}^{-1}$	6^+	169.5	M1	$>4.6\times10^{-3}$
									E2	>94
4918.8	$\nu f_{7/2}h_{11/2}^{-1}$	7^+	104(4) ps	62(7) ps [18][a]	4715.9	$\nu f_{7/2}h_{11/2}^{-1}$	6^+	202.9	M1	$1.74(9)\times10^{-2}$
					4848.3	$\nu f_{7/2}h_{11/2}^{-1}$	8^+	70.9	M1	$\boxed{6.0(7)\times10^{-2}}$

J. Benito et al., PRC 102, 014328 (2020)

$B(M1;\, 7^+ - 8^+)_{th} = 0.012\ \mu_N$

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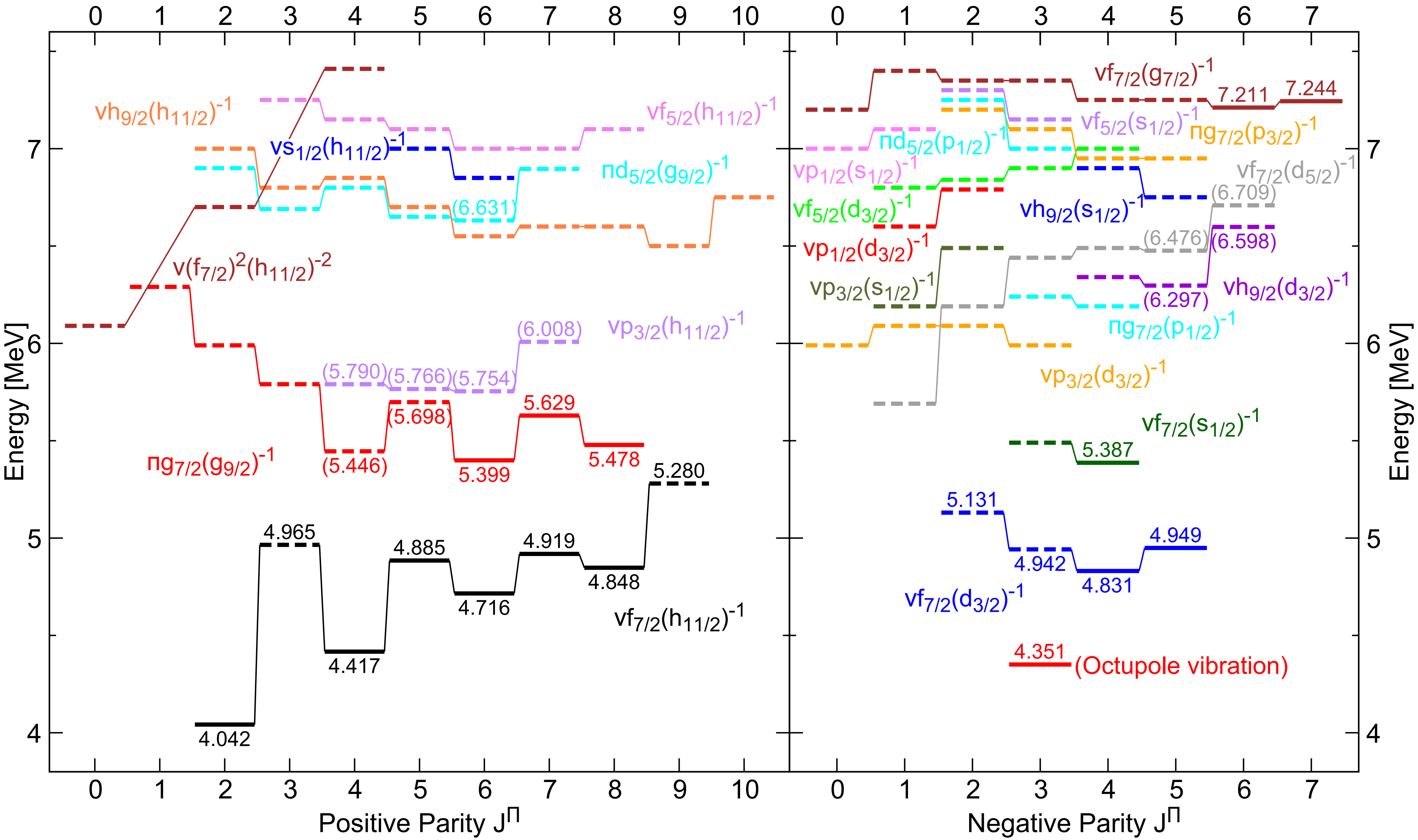
Particle-hole multiplets

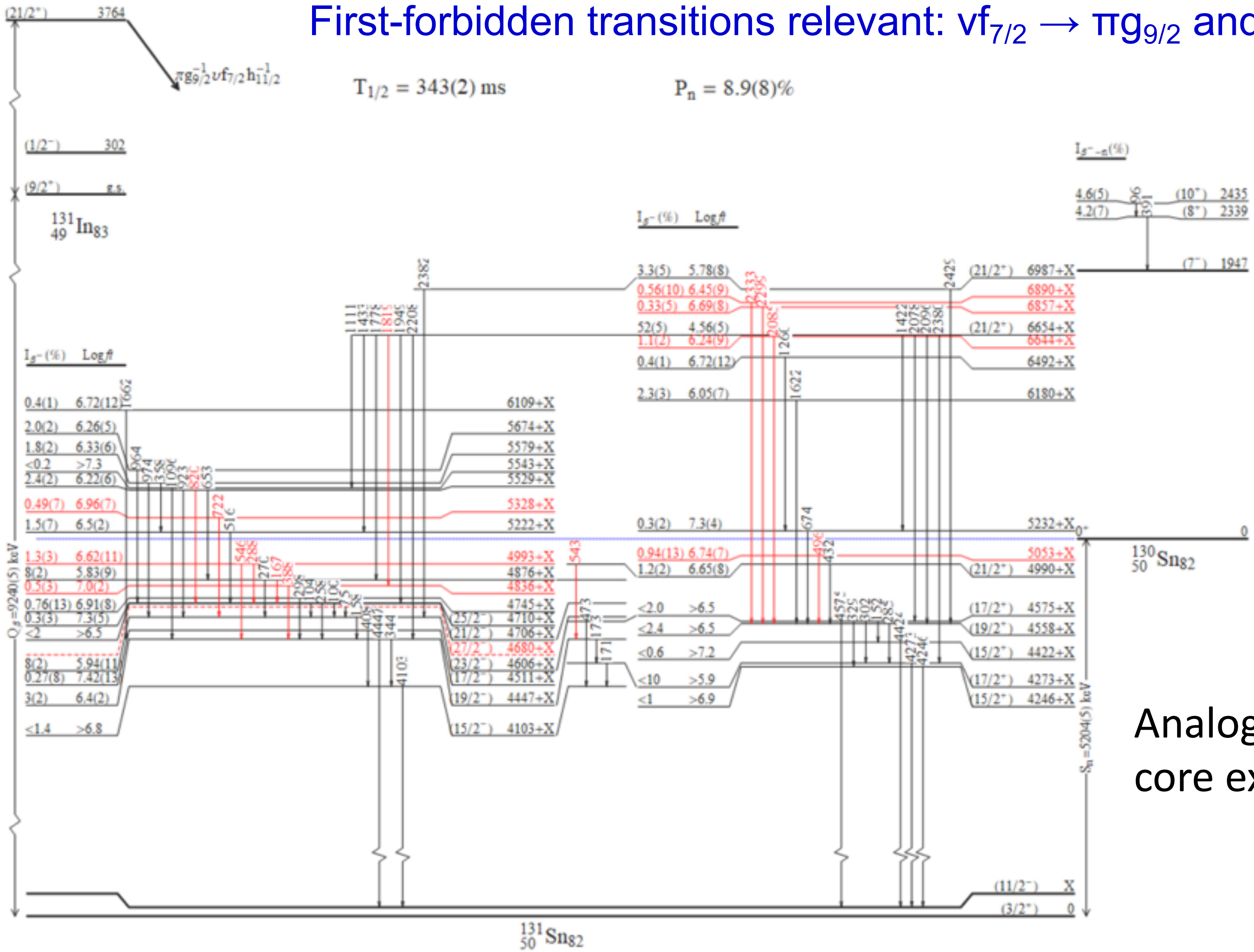


J. Benito et al., PRC 102, 014328 (2020)

Similarity to the structure of ^{131}Sn

GT transition involves $\nu g_{7/2} \rightarrow \pi g_{9/2}$

First-forbidden transitions relevant: $\nu f_{7/2} \rightarrow \pi g_{9/2}$ and $\nu h_{11/2} \rightarrow \pi g_{9/2}$



Analogy to ^{132}In --> ^{132}Sn core excitations (shell gap)

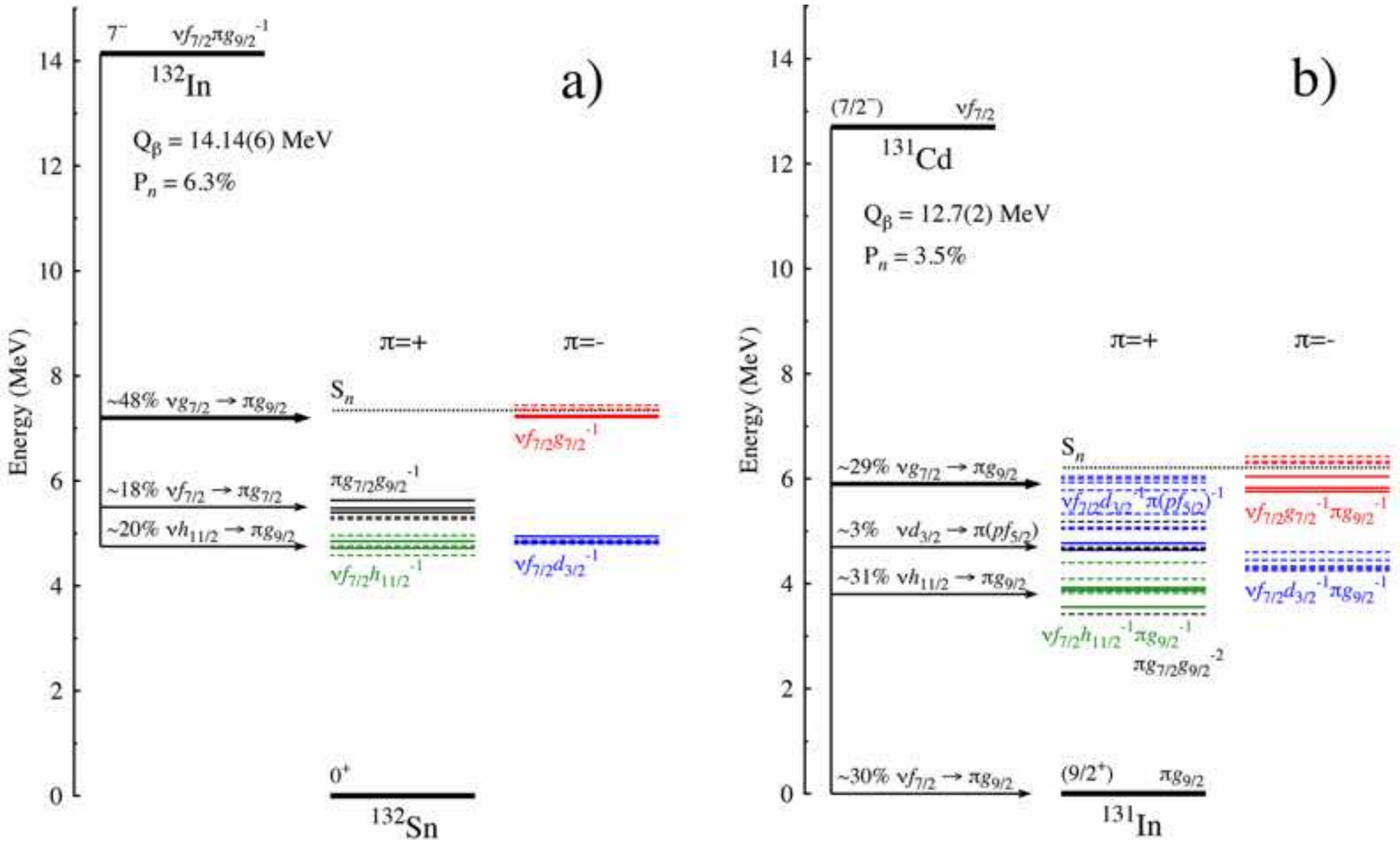
J. Benito et al., to be submitted to PRC

Investigation of the structure of ^{131}In

Proposal to measure core-excited states arising from many of the allowed multiplets, similar to other nuclei such as ^{132}Sn

Neutron proton-hole configurations coupled to the $\pi g_{9/2}$ (or *pf*) hole

Lifetimes of the high-lying core excited states in ^{131}In: electromagnetic transition rates help identify the configurations



Complementary study from ^{132}Cd 0^+ g.s., large P_n value

J. Taprogge et al., Eur. Phys. J. A 52, 347 (2016)

Coupling of two neutrons

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

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

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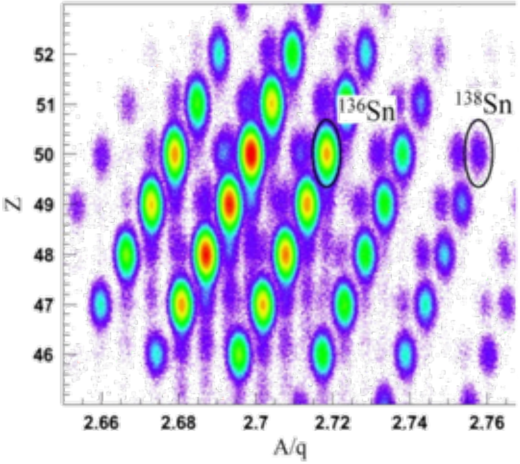
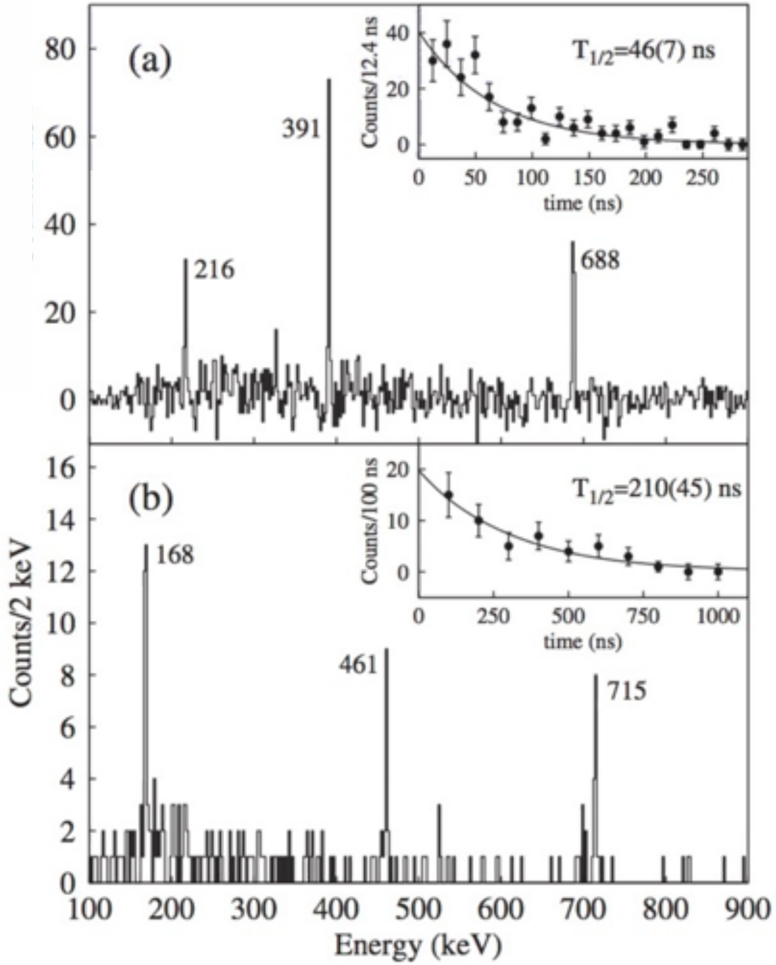
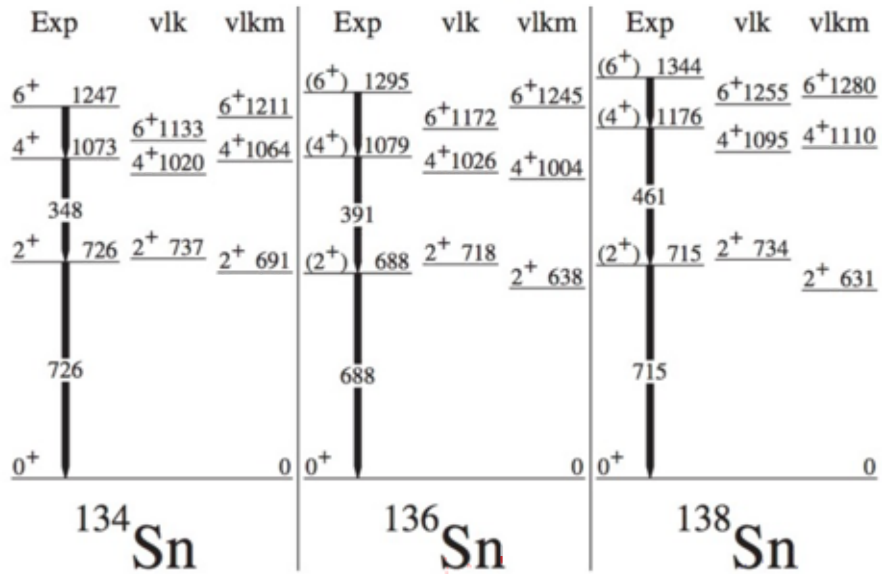
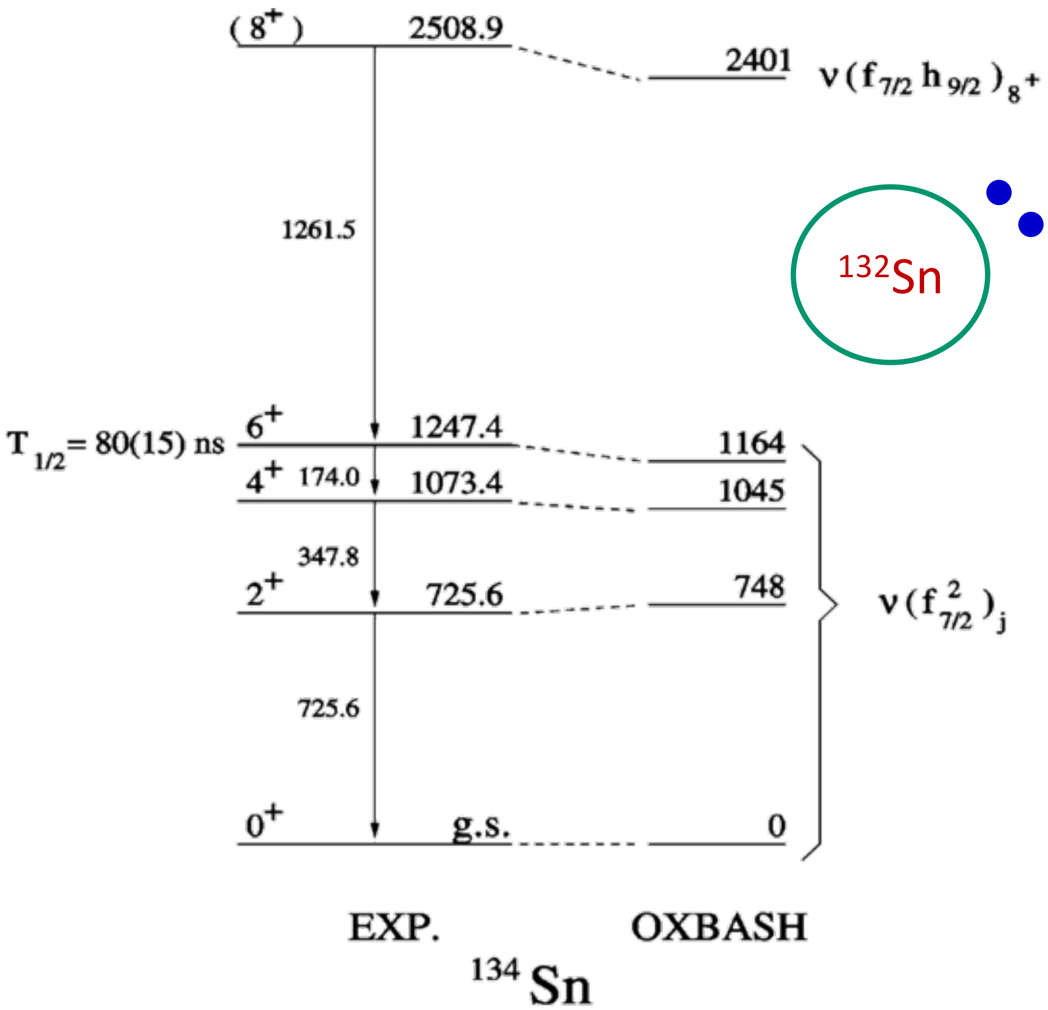
- Three delayed γ rays each from $^{136;138}Sn$ have been observed.
- 6^+ isomer, $(f_{7/2})^2$, seniority-2 coupling scheme.
- Realistic interactions do not reproduce the experimentally determined $B(E2; 6^+ \rightarrow 4^+)$ value of ^{136}Sn, even when core excitations are included.
- An empirical modification of $\nu(f_{7/2})^2$ matrix elements, equivalent to reduced pairing, improves the description
- **Neutron-neutron** part of realistic interactions used in shell-model calculations off stability

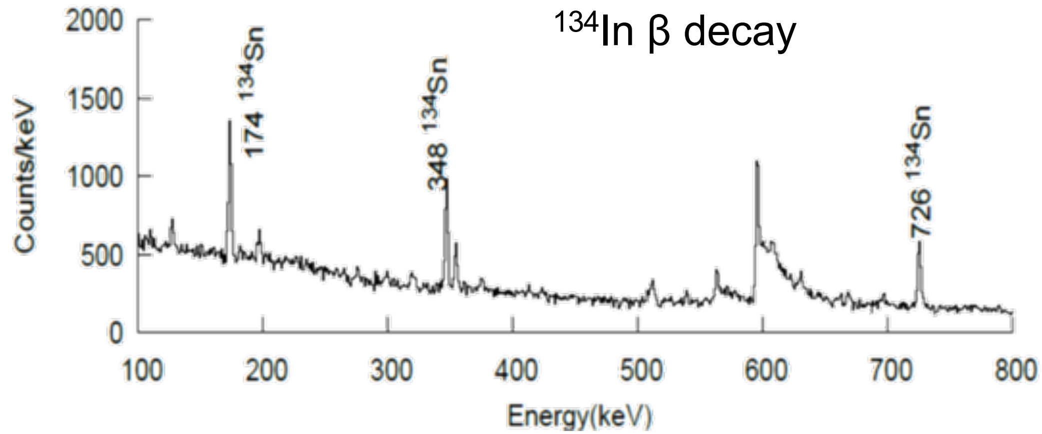


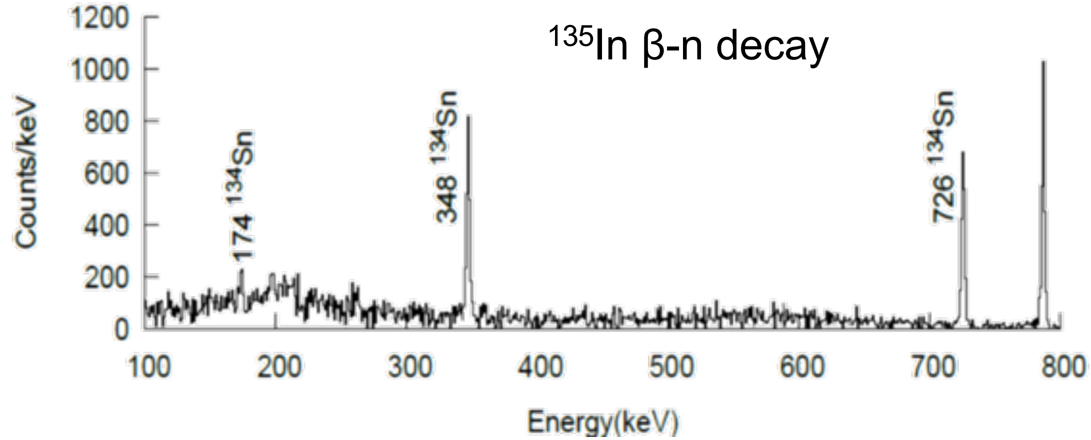




Lifetime measurements for ^{134}Sn



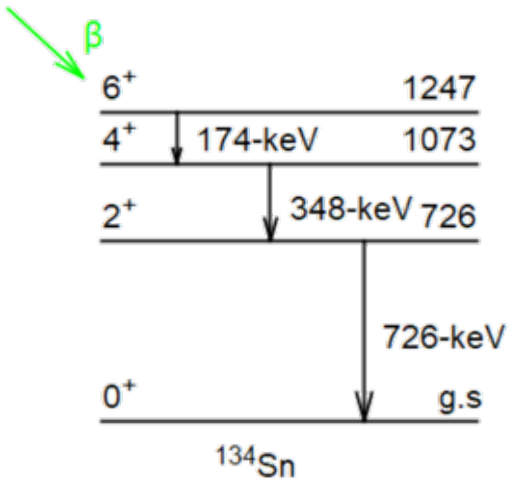




^{248}Cm spontaneous fission [A. Korgul et al., EPJ A7, 167 (2000)] Gammasphere

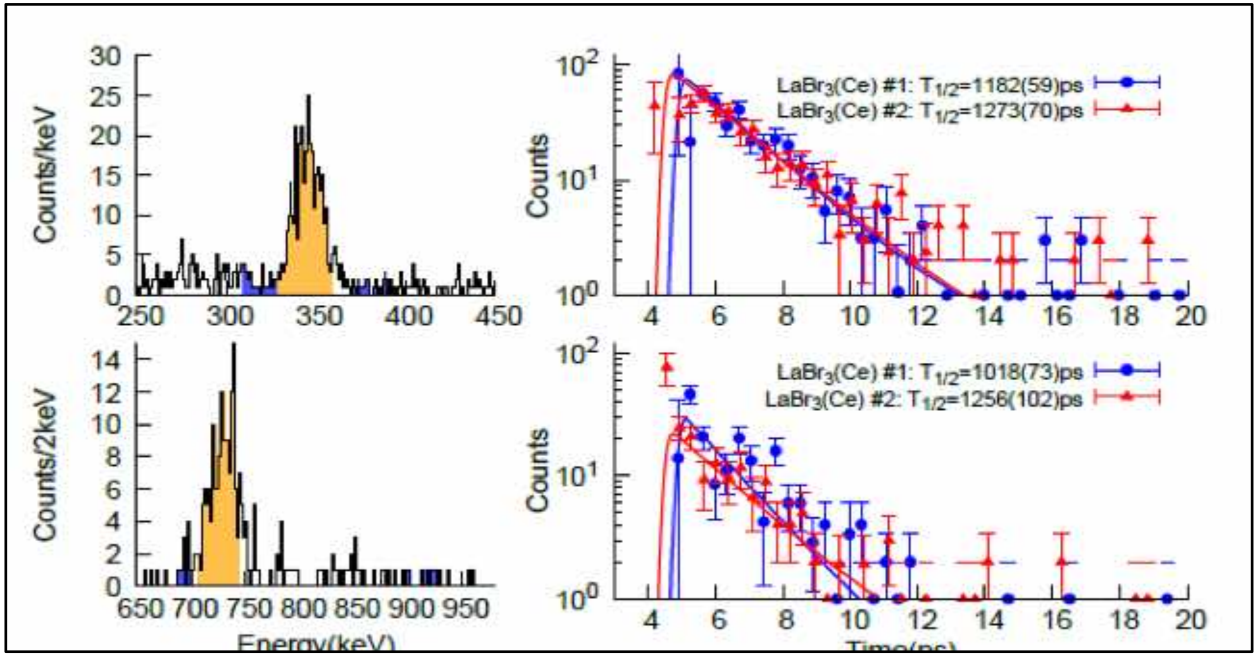
Coulomb Excitation [J. Beene et al., Nuclear Physics A746, 471 (2004)]   Deduced $T_{1/2}$ = 49(7) ps

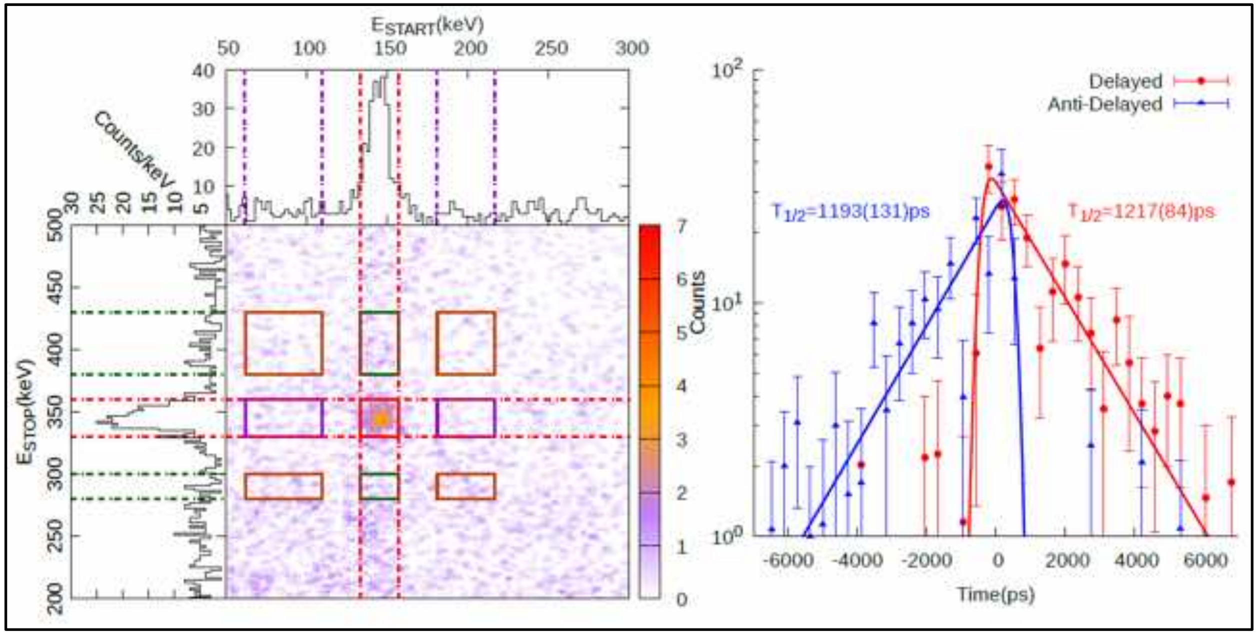
Lifetime measurements for ^{134}Sn



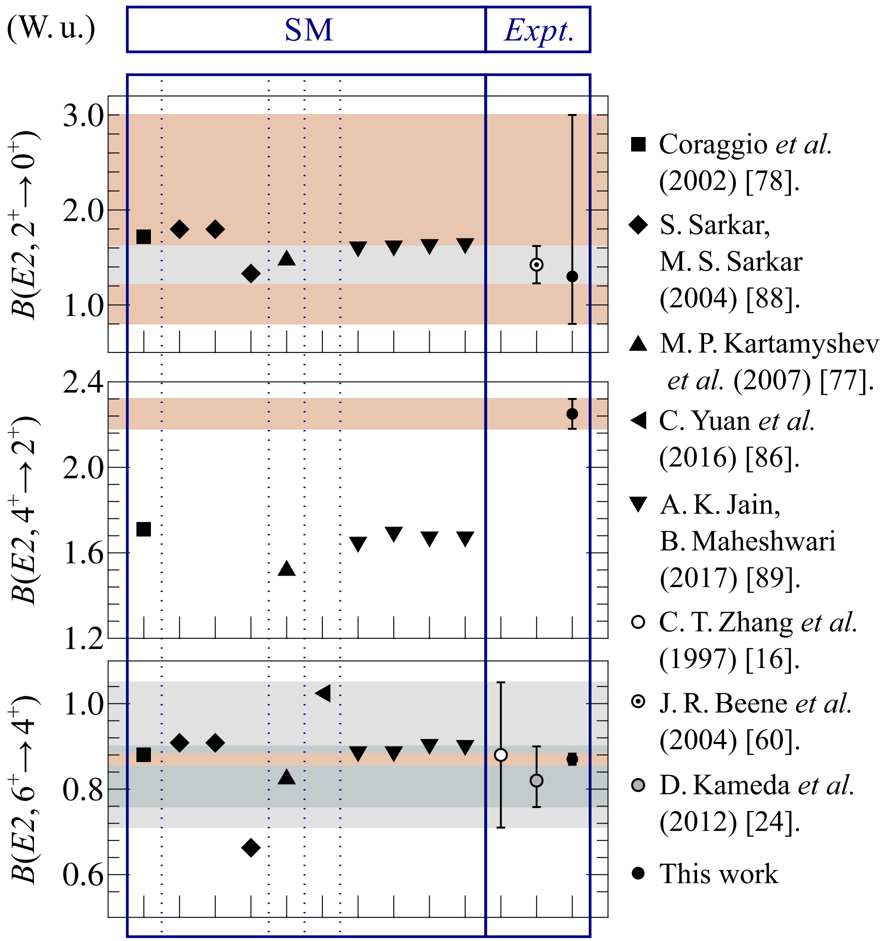
$J_I \rightarrow J_F$	E (keV)	$T_{1/2}$	B(E2) W.u.
$6^+ \rightarrow 4^+$	174	81.7(12) ns	0.97(7)
$4^+ \rightarrow 2^+$	348	1.18(4) ns	2.19(7)
$2^+ \rightarrow 0^+$	726	53(30) ps	1.3(7)

J. Benito et al.





Lifetime measurement of the 4^+ state in ^{134}Sn

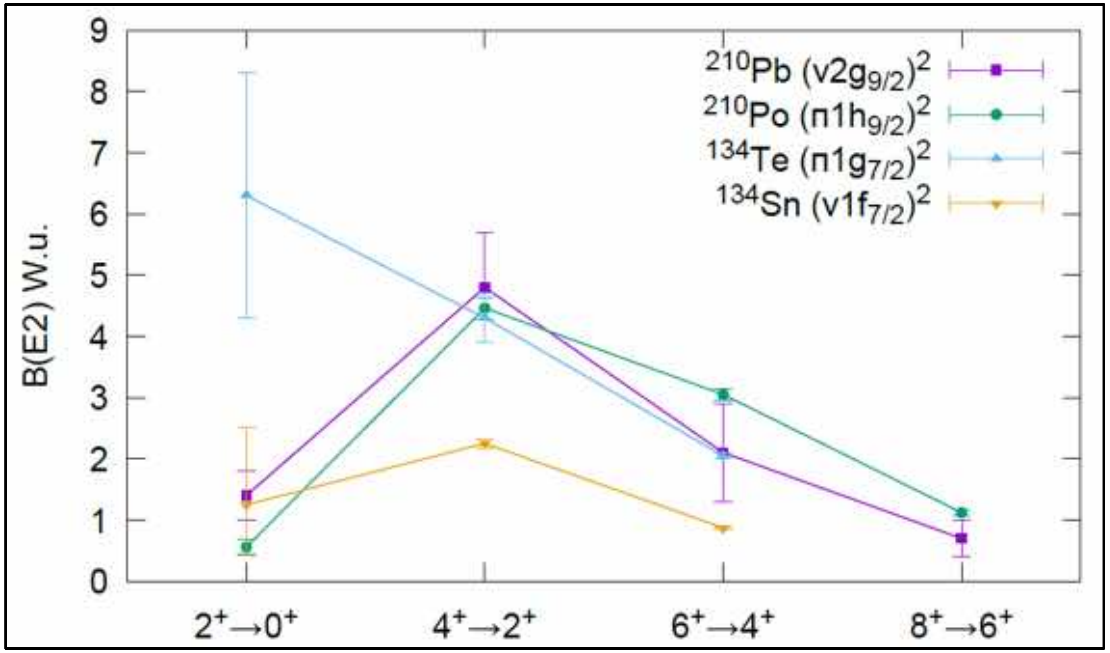


M. Piersa-Siłkowska, A. Korgul, **J. Benito**, LMF et al., PRC104, 044328 (2021)

Complete set of lifetimes for the states of the $\nu(f_{7/2})^2$ configuration

First measurements for the lifetime of the1073-keV (4^+) state

Unexpectedly large B(E2; $4^+ \to 2^+$) ?



Coraggio: SM CD-Bonn, ^{132}Sn core + valence neutrons (6)
Sarkar: SM modified empirical CW5082 from ^{208}Pb – drastic change of proton effective charge
Kartamyshev + Hjorth-Jensen: SM effective 2-body int., 6 orbitals, assess pairing
Yuan: SM jj46 Hamiltonian, 4 p and 6 n valence orbits in the Z = 28 − 50 and N = 82–126 major shells
Jain: SM renormalized CD-Bonn, ad-hoc TBME modified (4 versions)

Analogy to N=82

A. Korgul et al.,
Eur. Phys. J. A 32, 25–29 (2007)

Jan Blomqvist (1932-2022)

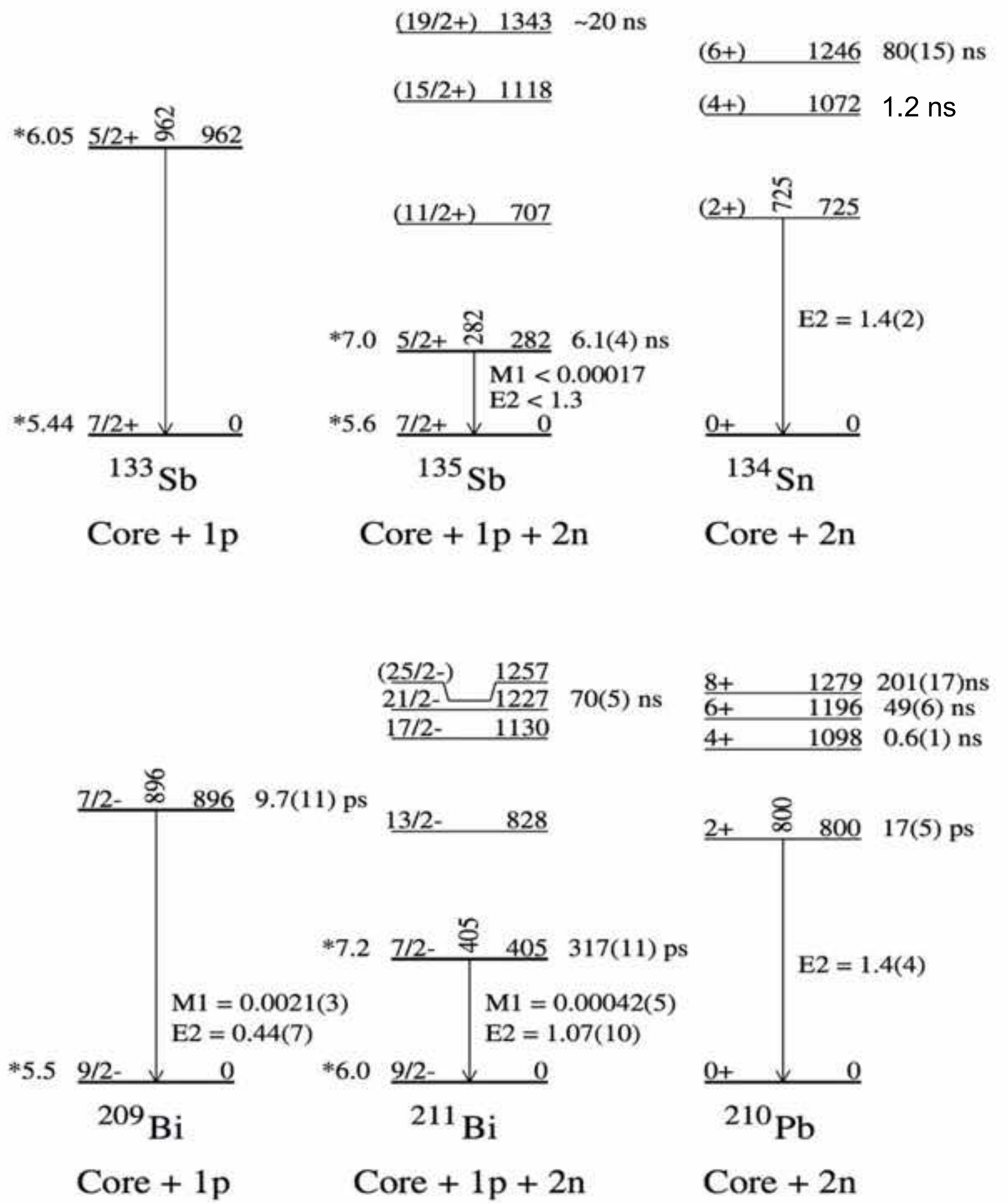
Realistic interactions used in shell-model calculations far from stability

- Effect of pairing
- NN interaction for large number of particles

Other nuclei around ^{132}Sn

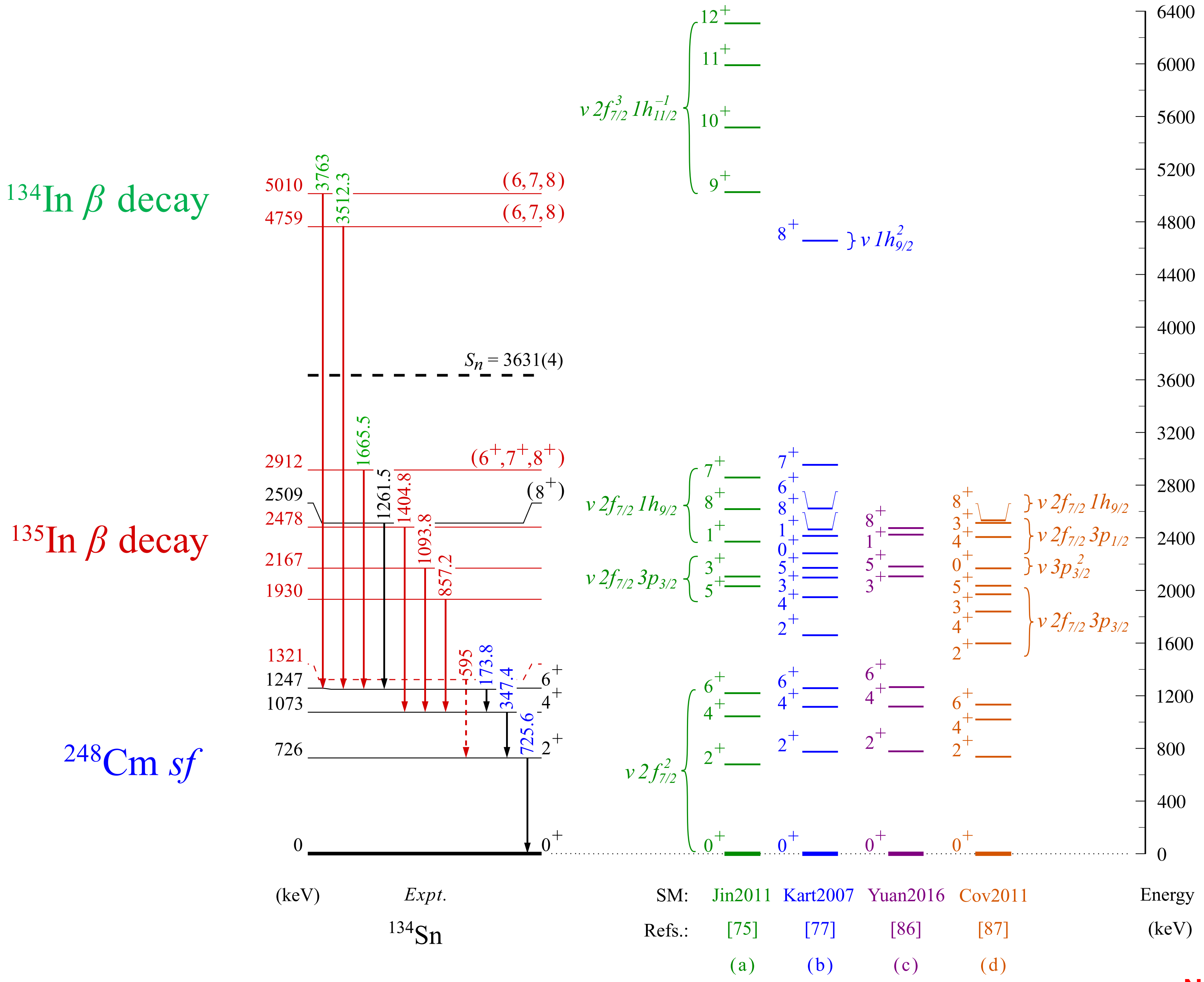
Odd nuclei are also relevant

- Coupling of few particles / holes
- Single particle configurations



L.M. Fraile

First β-decay spectroscopy of ^{135}In



Jin: SM extended paring-plus-quadrupole model with monopole corrections (core excitations)

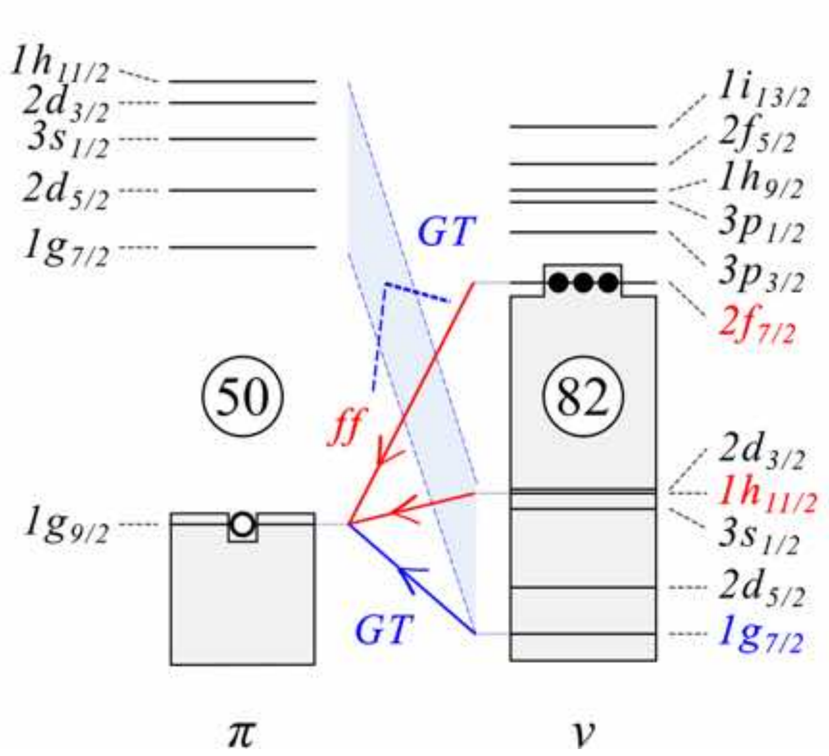
Kartamyshev

Yuan

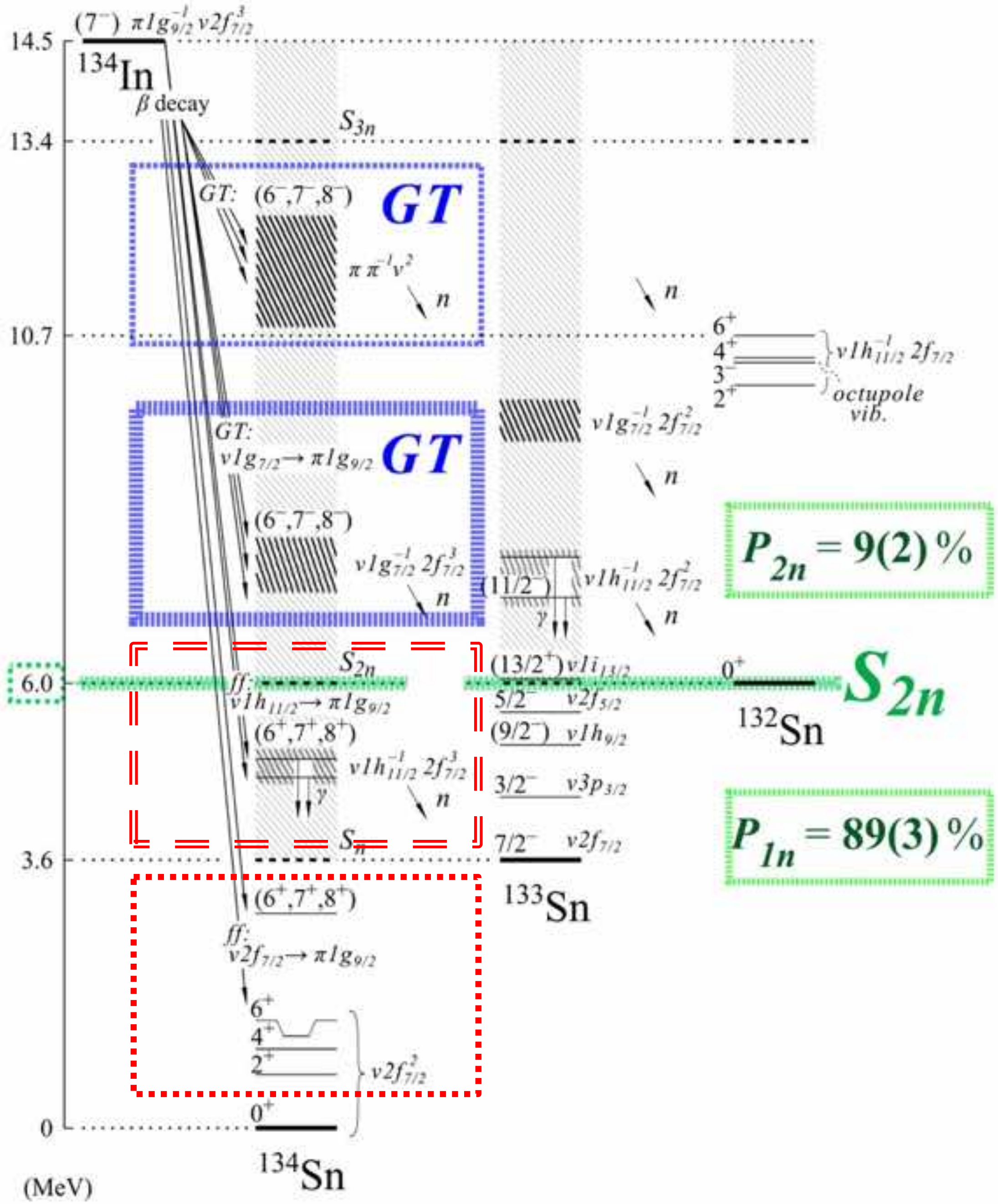
Covello: SM CD-Bonn, V_{low-k} , 6 orbitals

Competition of GT and ff transitions

Gamow-Teller and 1st forbidden transitions

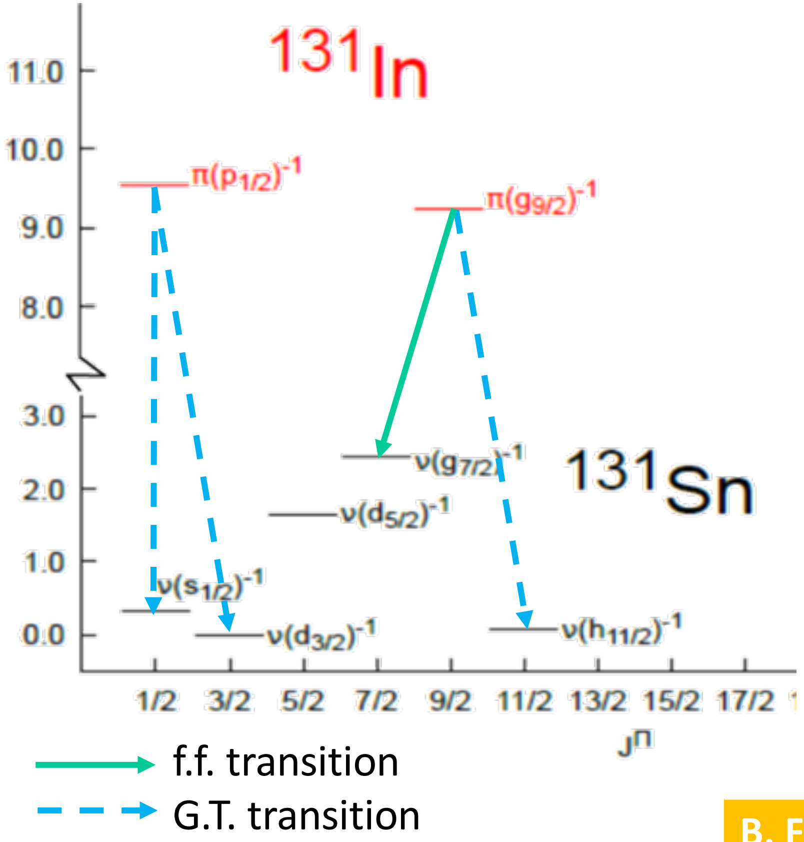


M. Piersa-Siłkowska, PRC104, 044328 (2021)



^{134}In β decay

^{131}In isomer selectivity



Isomer selective study makes it possible to revise I_β and log*ft* values.

Previous studies show a discrepancy between the log*ft* values for the three ff transitions in the ^{131}In β-decay

The previous discrepancy disappears

J. Benito et al., to be submitted

			B. Fogelberg et al.		R. Dunlop et al.		This work	
Transitions		E level	Iβ(%)	Log (ft)	I_β(%)	Log (ft)	I_β(%)	Log (ft)
$\pi g_{9/2}^{-1} \rightarrow \upsilon g_{7/2}^{-1}$	G.T.	2434	90	4.4	84.2(22)	4.4	66(11)	4.5(2)
$\pi g_{9/2}^{-1} \rightarrow \upsilon h_{11/2}^{-1}$	f.f	X	<20	>5.6	$5(^{+15}_{-5})$	6.2	25(6)	5.5(2)
$\pi p_{1/2}^{-1} \rightarrow \upsilon d_{3/2}^{-1}$	f.f	g.s.	~95	5.1	68.1(22)	5.2	54(7)	5.34(13)
$\pi p_{1/2}^{-1} \rightarrow \upsilon s_{1/2}^{-1}$	f.f.	332	3.5	6.5	27.8(7)	5.5	42(7)	5.40(4)

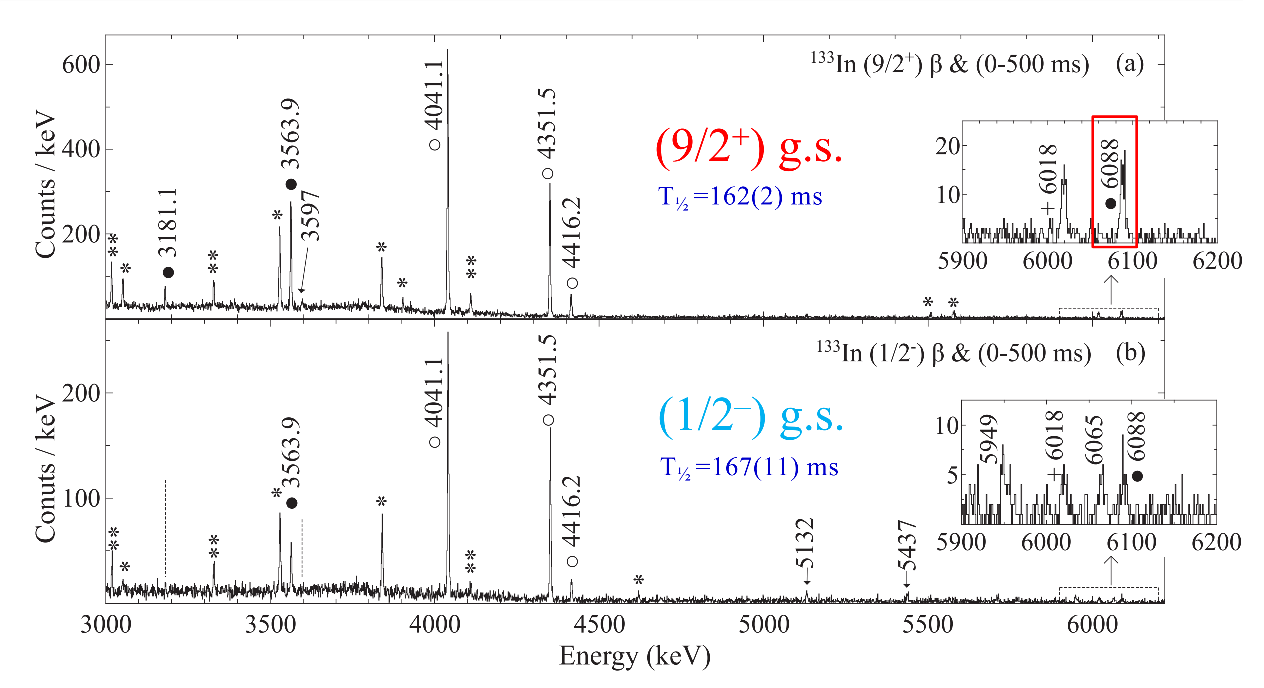
Population of neutron-unbound states in ^{133}Sn

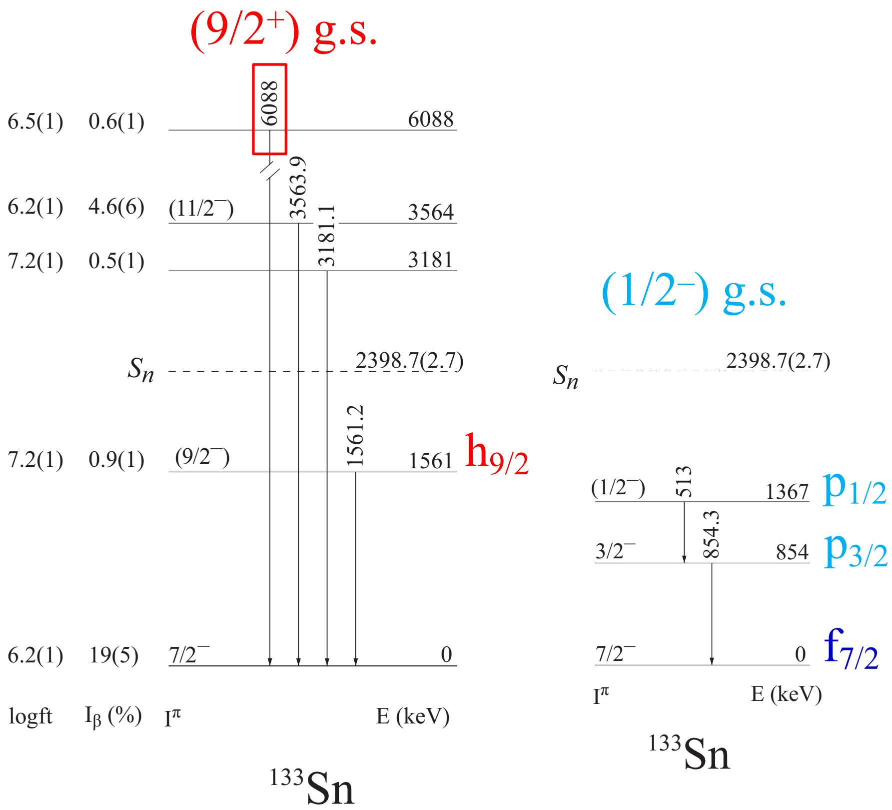
Isomer selective decay from ^{133}In

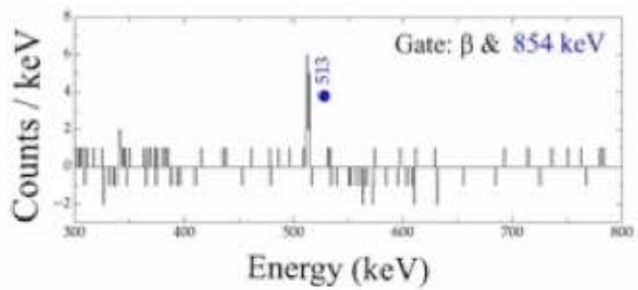
Population of states via ff transitions

Competition of gamma and neutron decay --> gamma-ray emission above S_n

M. Piersa, A. Korgul, LMF, J. Benito et al., Phys Rev C99, 024304 (2019).







513-keV line, reported by K. L. Jones et al., Nature 465, 454 (2010)

Summary

Summary

Beta-decay spectroscopy is a powerful tool to study the exotic region around ^{132}Sn including

- → Beta-decay via GT and ff transitions
- → Gross properties such as decay lifetimes and (indirectly) neutron emission probabilities
- → Competition of gamma emission for neutron unbound states
- → Single particle features
- → Nucleon (neutron) pairs
- → Core-breaking states

ISOLDE/CERN offers excellent options for this kind of measurements

Collaboration

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IDS collaboration

ISOLDE Physics group and technical teams

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THANK YOU!