Perspectives for proton emitters and neutron-deficient refractory elements

Antoine de Roubin & Vladimir Manea

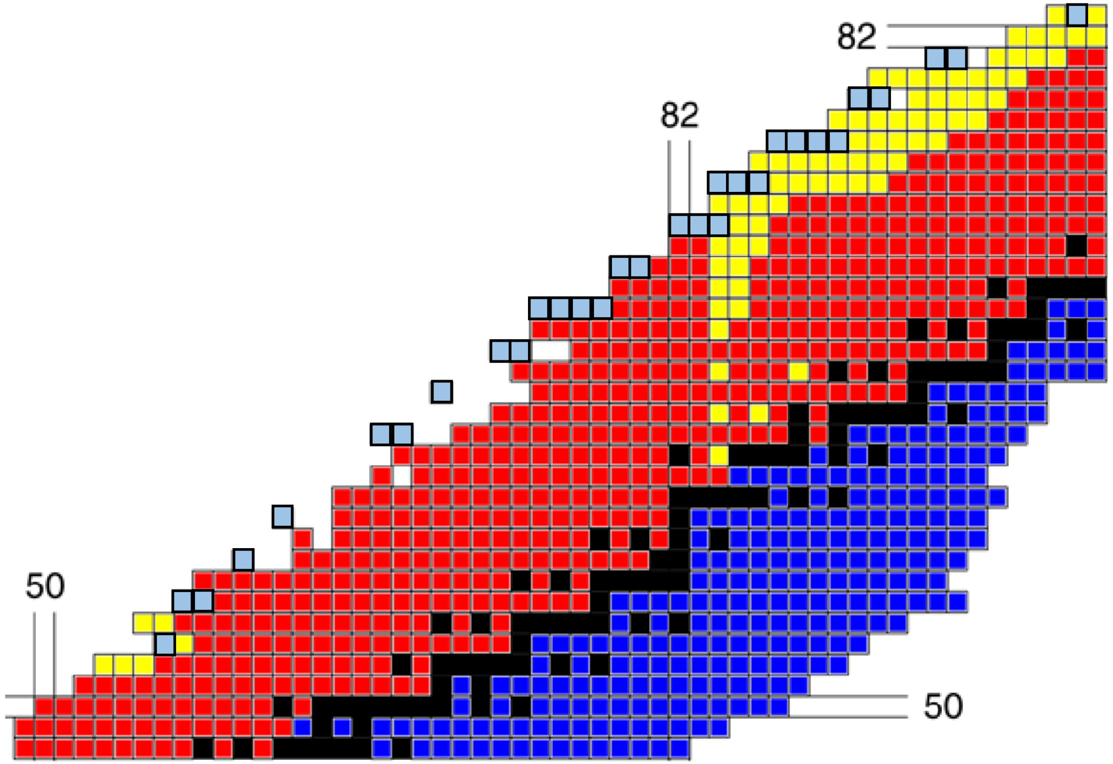
Proton radioactivity

- **Proton dripline:**
  - Nuclear interaction is not enough to bind nucleons together
  - Nucleons are bind by coulomb and centrifugal barrier

- **Proton radioactivity:**
  - Separation energy: $S_p < 0$
  - Proton travel through the barriers by quantum tunneling effect
  - The proton has a given half-live

- **Study of the nuclear structure beyond the dripline:**
  - Unique possibility to probe nuclear structure far from stability
  - Determination of individual states for protons and neutrons

- **$\sim$ 30 proton emitting nuclei are known with Z > 50:**
  - 20 proton emissions from long-lived excited states
  - From $^{109}_{53}\mathrm{I}$ (lightest) to $^{185}_{83}\mathrm{Bi}$ (heaviest)
  - For most of them the mass has not been measured directly
  - No laser spectroscopy has been done on them



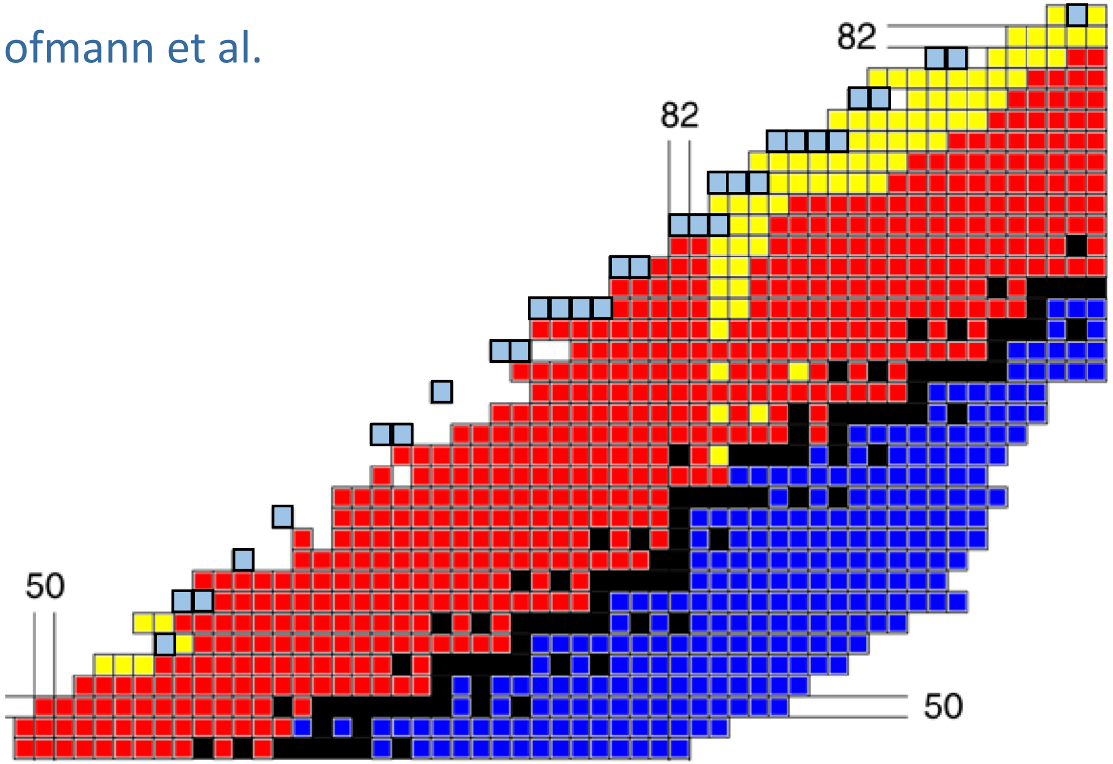
Proton radioactivity

- First clear evidence for proton emission with a measurable half-life:
  - $^{53}\text{Co}^{m}$ (I = 19^{-}) → ^{52}Fe

    J. Cerny, J. Esterl, R.A. Gough, R.G. Sextro, Phys. Lett. B33 (1970) 284.

- First proton emission from nuclei ground state discovered at GSI by Hofmann et al.
  - ^{151}Lu → ^{150}Yb

    S. Hofmann, et al., Z. Phys. A305 (1982) 111.



B. Blank, M.J.G. Borge / Progress in Particle and Nuclear Physics 60 (2008) 403–483

Characterization of the proton radioactivity

To fully characterize the proton radioactivity, one needs:

- Observation of the emitted proton
- The energy released in the decay Q_p
- The angular momentum carried by the proton I_p
- The probability to find the daughter nucleus in its ground state or in a low-lying excited state
  - This probability is the so-called fine structure effect of the proton emission
  - It depends strongly on the shape of the nucleus.

The proton radioactivity lifetime depends on these factors:

- Deformation
- Angular momentum of the emitted proton
- Residual interaction between valence proton and neutron
  - Especially in case of odd-odd nuclei

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Q_p released energy:
- Mass measurement

I_p angular momentum:
- Laser spectroscopy

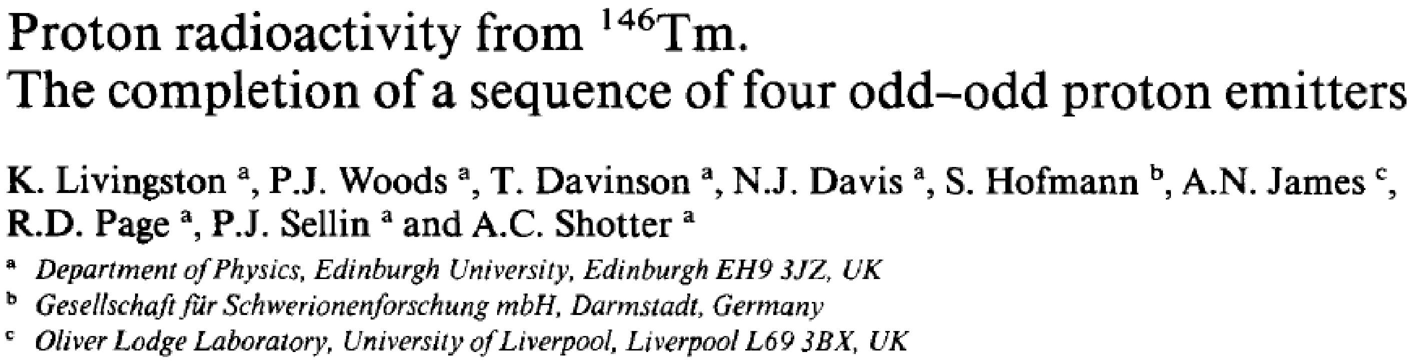
Nuclear deformation:
- Laser spectroscopy
- Mass spectrometry

Proton emitters accessible with S^3

		I S3 (A/Q=3)	AfterLEB	Fast LEB	I S3 (A/Q=7)	AfterLEB	After Fast LEB
108I	36ms	23	0,00	0,35	115	0,01	1,76
117La	23,5ms	4,45E+00	0,00	0,04	22,25	0,00	0,21
146Tm	68ms	120	0,36	3,12	600	1,80	15,59
151Lu	80,6ms	1,10E+03	3,37	28,68	5500	16,87	143,39
150Lu	45ms	160	0,06	2,97	800	0,32	14,87
166Ir	10,5ms	190	0,00	0,28	950	0,00	1,42

Courtesy of L. Caceres

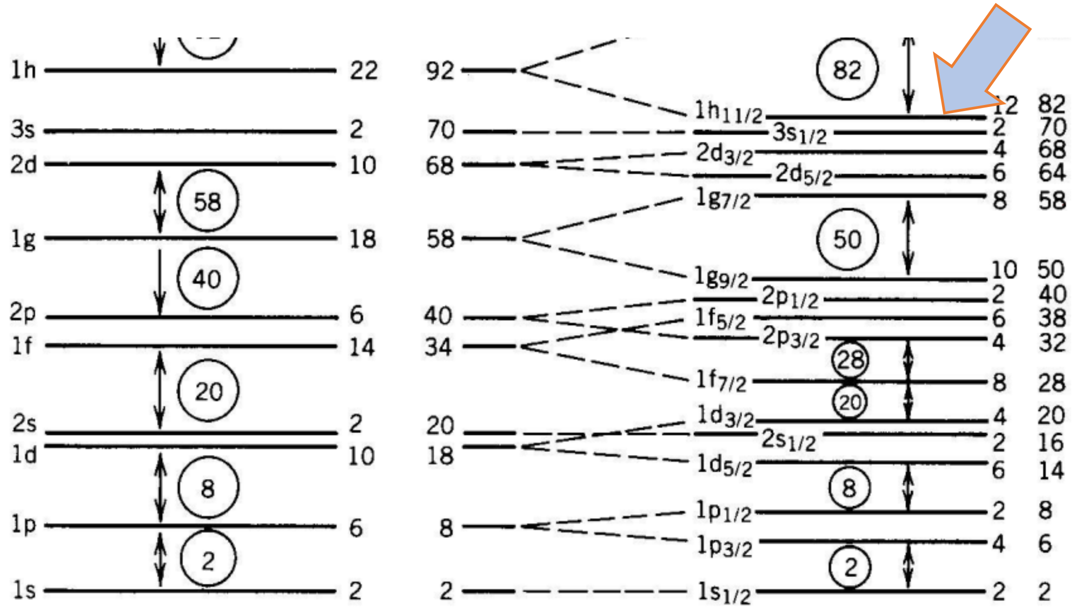
^{146}Tm proton emission observation (1993)

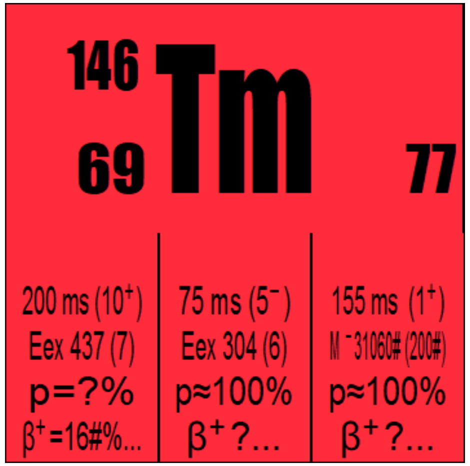


Proton radioactivity from ^{146}Tm.
The completion of a sequence of four odd–odd proton emitters

K. Livingston [a], P.J. Woods [a], T. Davinson [a], N.J. Davis [a], S. Hofmann [b], A.N. James [c],
R.D. Page [a], P.J. Sellin [a] and A.C. Shotter [a]

[a] *Department of Physics, Edinburgh University, Edinburgh EH9 3JZ, UK*
[b] *Gesellschaft für Schwerionenforschung mbH, Darmstadt, Germany*
[c] *Oliver Lodge Laboratory, University of Liverpool, Liverpool L69 3BX, UK*





$^{146}_{69}$Tm 77

200 ms (10^+)	75 ms (5^-)	155 ms (1^+)
Eex 437 (7)	Eex 304 (6)	M −31060# (200#)
p=?%	p≈100%	p≈100%
β^+=16#%...	β^+?...	β^+?...

Produced via: ^{92}Mo(^{58}Ni, p3n)
Q_1 = 1127(5) keV
Q_2 = 1197(5) keV

To determin the proton orbital:

The theoretical spectroscopic factor:

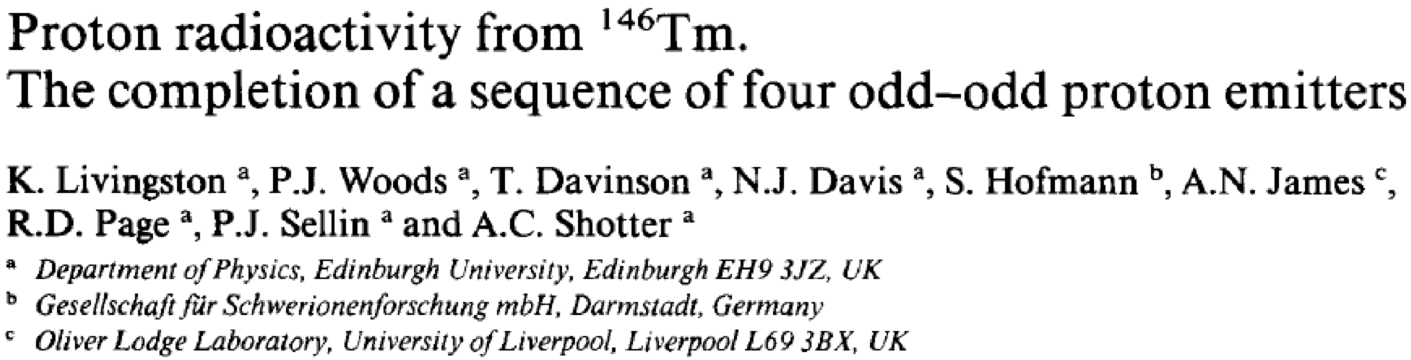
$$S_p^{th} = (2I_i + 1)^{-1} \langle I_i \| a^\dagger(j) \| I_f \rangle^2$$

The experimental spectroscopic factor:

$$S_p^{exp} = \frac{T_{1/2}^{calc}}{T_{1/2}^{exp}}$$

$T_{1/2}^{exp}$ is the total half-life divided by the fraction of the decay that goes by proton emission

^{146}Tm proton emission observation



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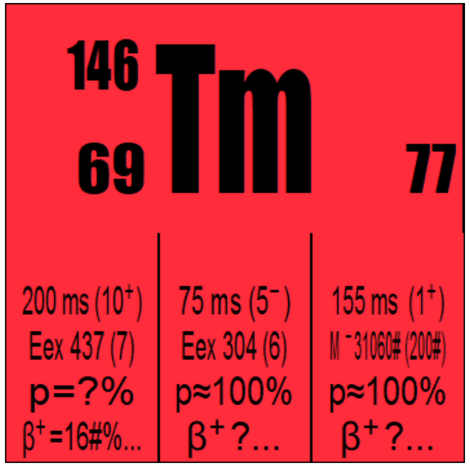

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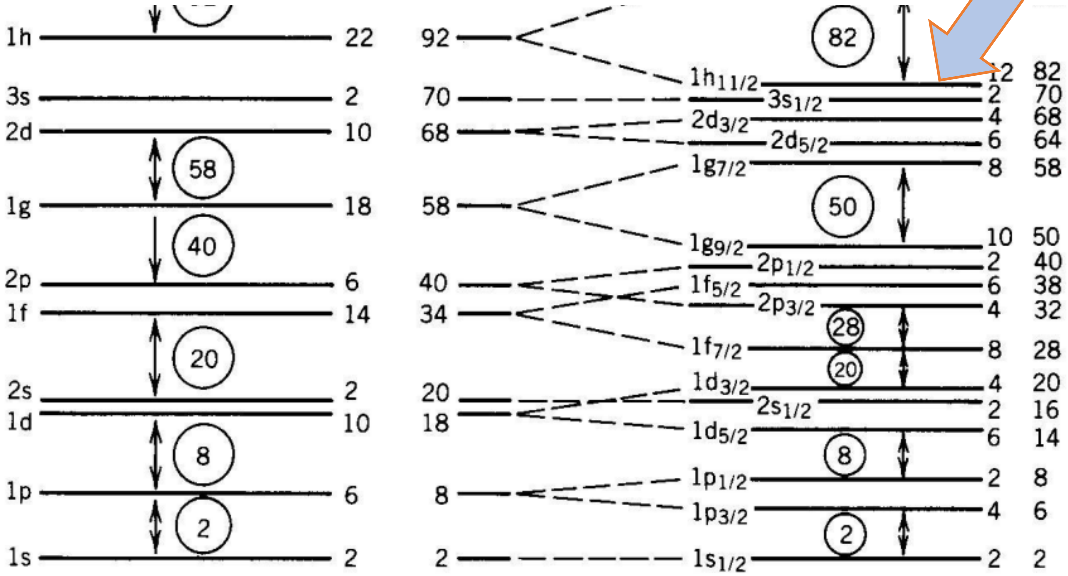
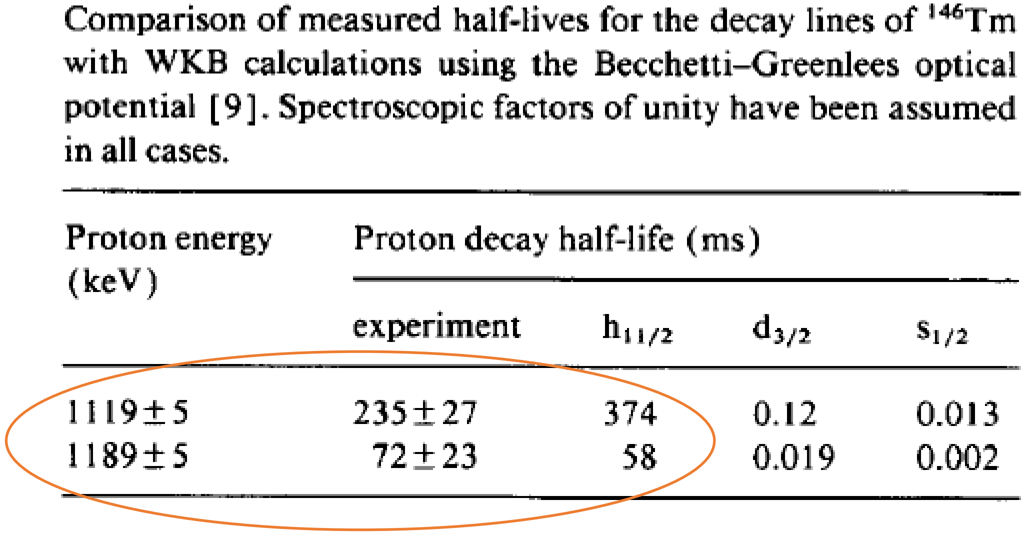
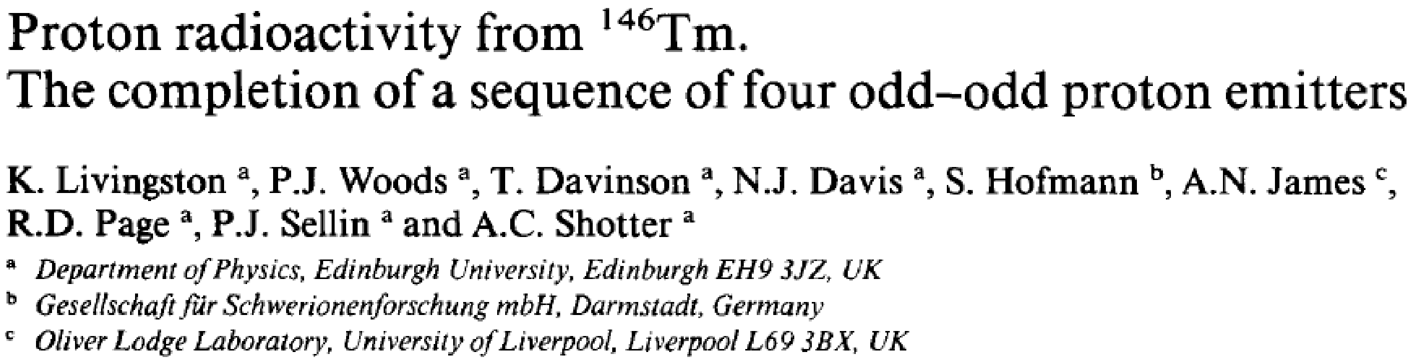




Comparison of measured half-lives for the decay lines of ^{146}Tm with WKB calculations using the Becchetti–Greenlees optical potential [9]. Spectroscopic factors of unity have been assumed in all cases.

Proton energy (keV)	Proton decay half-life (ms)			
	experiment	$h_{11/2}$	$d_{3/2}$	$s_{1/2}$
1119±5	235±27	374	0.12	0.013
1189±5	72±23	58	0.019	0.002

^{146}Tm proton emission observation



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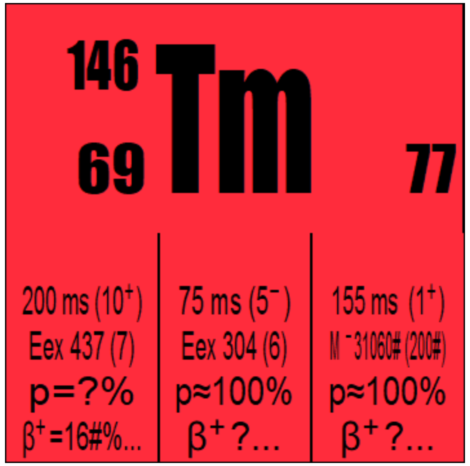

146 Tm
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Produced via: ^{92}Mo(^{58}Ni, p3n)
Q_1 = 1127(5) keV
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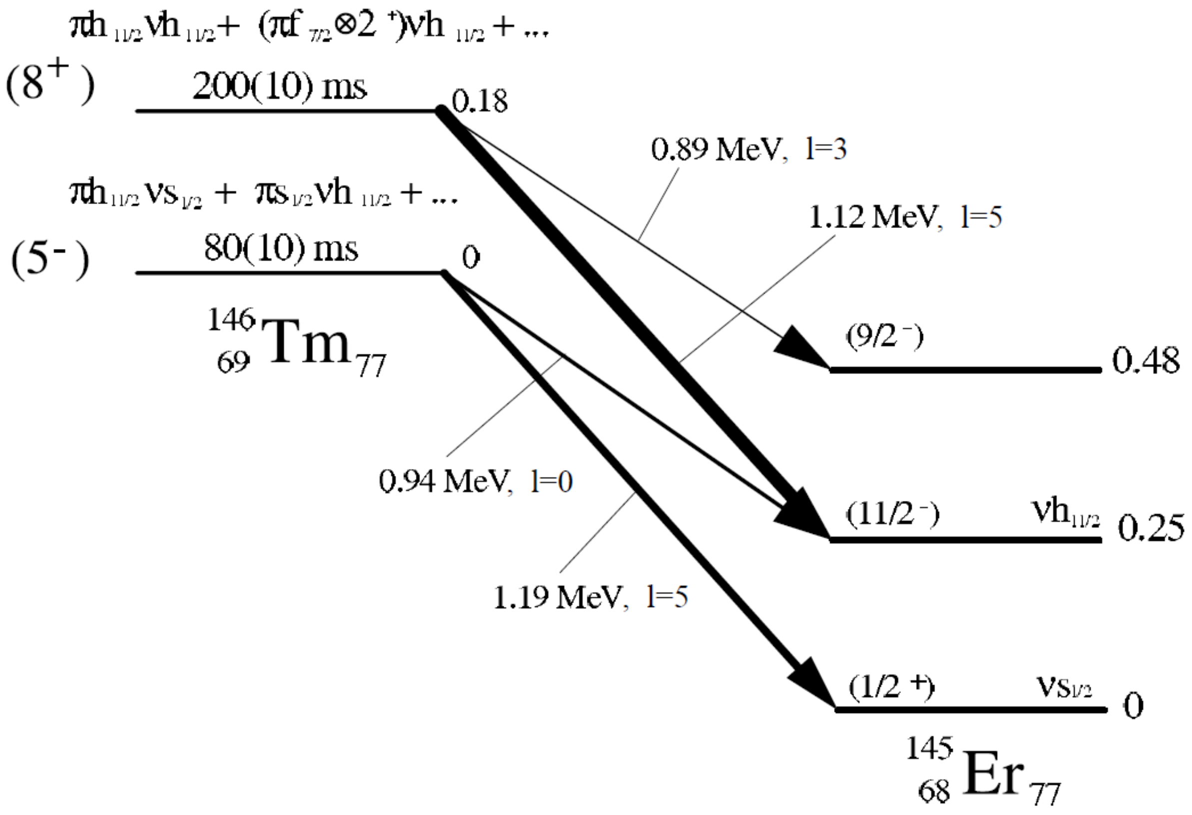
- “The proton emitting states and the proton transition rates are well reproduced assuming simple spherical shell model states […]”
- “This behavior is not reproduced in other known region of p emission around $Z = 53 - 55$ where discrepancies have been attributed to the onset of deformation”
- “It is important to establish new examples of proton emission in the linking region from $Z = 57 - 67$”
- “This region is expected to be highly deformed and offers the prospect of a systematic investigation of the effect of deformation on the proton decay process”

^{146}Tm proton emission observation

PHYSICAL REVIEW C **68**, 034330 (2003)

Neutron single-particle states populated via proton emission from ^{146}Tm and ^{150}Lu

T. N. Ginter,[1,2,3,4,*] J. C. Batchelder,[3] C. R. Bingham,[5,6] C. J. Gross,[6] R. Grzywacz,[5,6,7] J. H. Hamilton,[1] Z. Janas,[7] M. Karny,[5,7] A. Piechaczek,[8] A. V. Ramayya,[1] K. P. Rykaczewski,[6] W. B. Walters,[9] and E. F. Zganjar[8]



- More proton lines were identified
- The observed decay pattern has been interpreted by using spherical estimates of emission probabilities
- The first observation of fine structure in proton emission from an odd-odd nucleus

^{146}Tm proton emission observation

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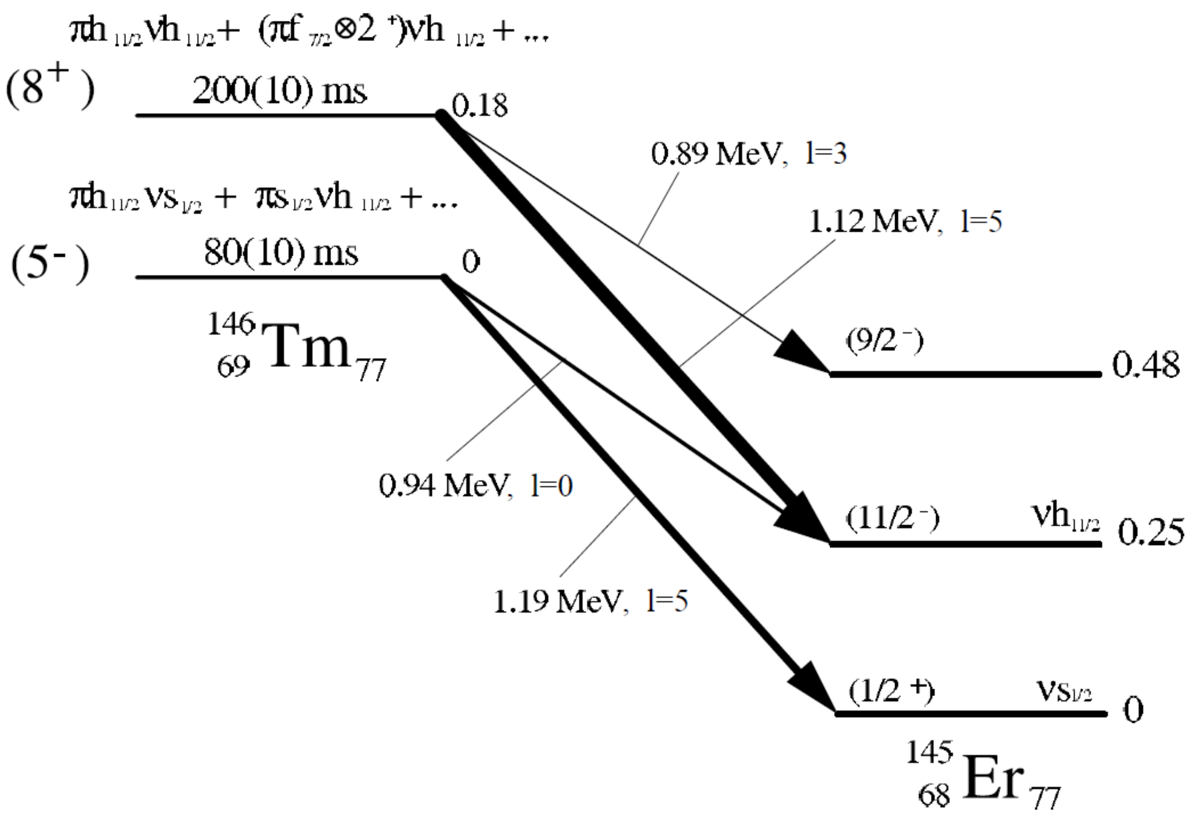
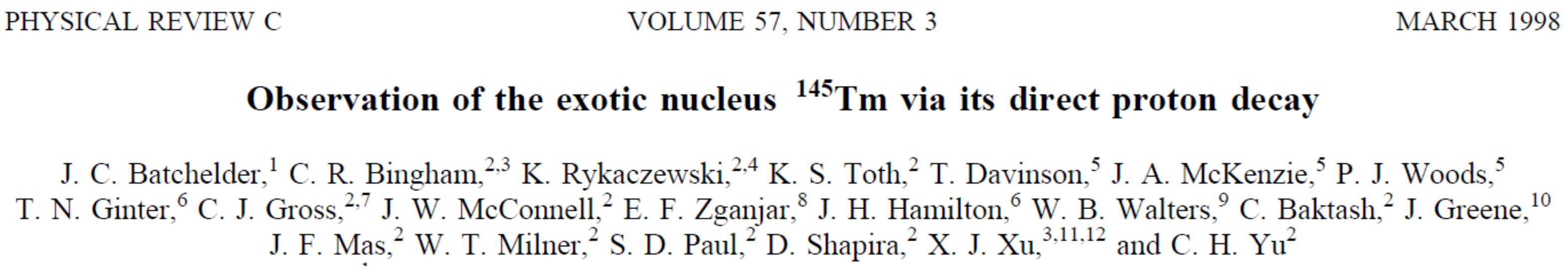


- Demonstrates for the first time that a proton radioactivity can be used to probe the neutron single particle level structure in the daughter nucleus.

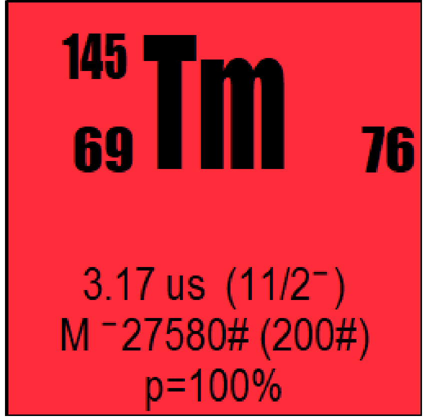
^{145}Tm proton emission observation



PHYSICAL REVIEW C VOLUME 57, NUMBER 3 MARCH 1998

Observation of the exotic nucleus ^{145}Tm via its direct proton decay

J. C. Batchelder,[1] C. R. Bingham,[2,3] K. Rykaczewski,[2,4] K. S. Toth,[2] T. Davinson,[5] J. A. McKenzie,[5] P. J. Woods,[5] T. N. Ginter,[6] C. J. Gross,[2,7] J. W. McConnell,[2] E. F. Zganjar,[8] J. H. Hamilton,[6] W. B. Walters,[9] C. Baktash,[2] J. Greene,[10] J. F. Mas,[2] W. T. Milner,[2] S. D. Paul,[2] D. Shapira,[2] X. J. Xu,[3,11,12] and C. H. Yu[2]



145 Tm 69 76

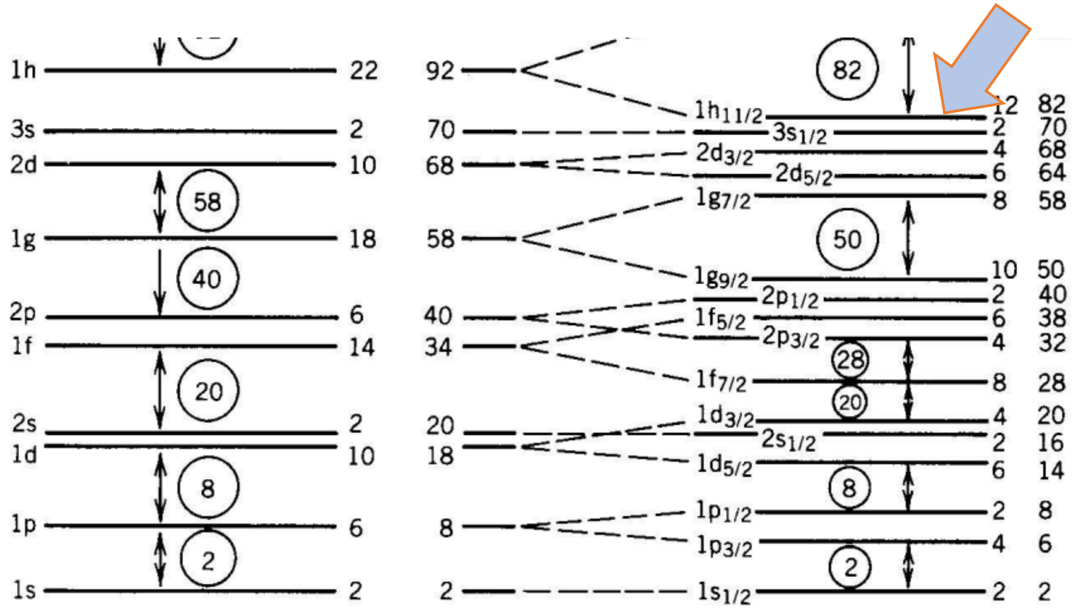
3.17 us (11/2⁻)

M ⁻27580# (200#)

p=100%

Produced via: ^{92}Mo(^{58}Ni, p4n)

Q = 1.728(10) keV



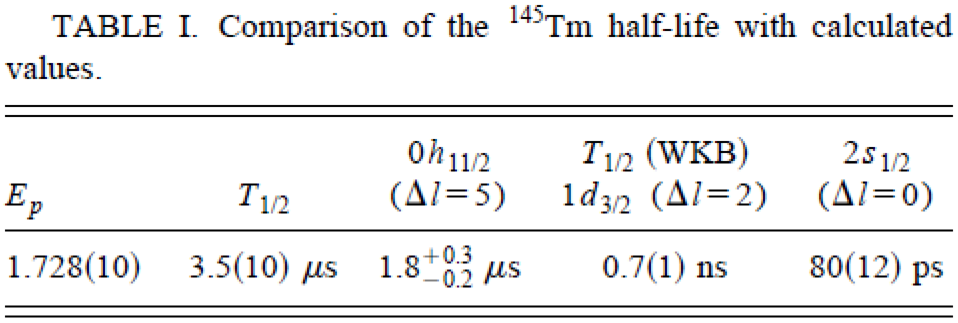
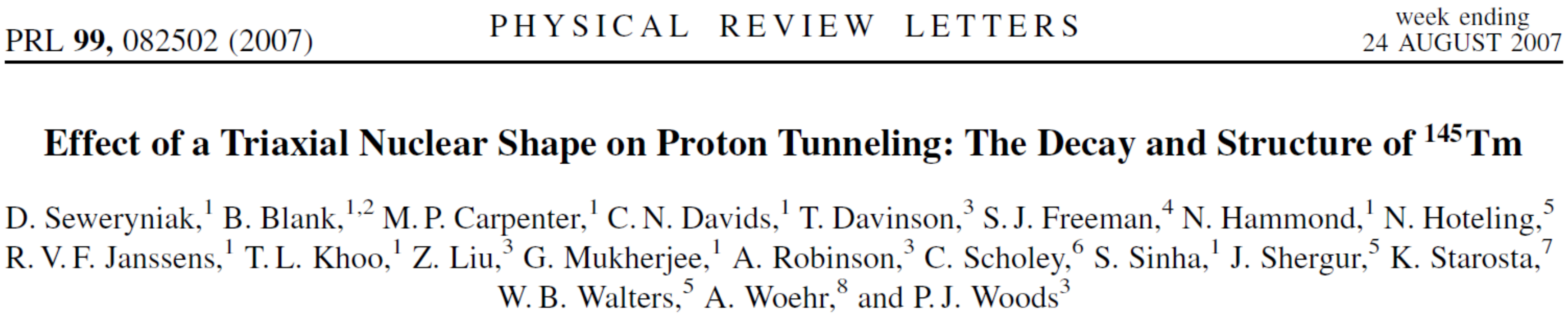


TABLE I. Comparison of the ^{145}Tm half-life with calculated values.

E_p	$T_{1/2}$	$0h_{11/2}$ ($\Delta l=5$)	$T_{1/2}$ (WKB) $1d_{3/2}$ ($\Delta l=2$)	$2s_{1/2}$ ($\Delta l=0$)
1.728(10)	3.5(10) μs	$1.8^{+0.3}_{-0.2}$ μs	0.7(1) ns	80(12) ps

- The experimental spectroscopic factor and an $0h_{11/2}$ orbital assignment are consistent with an overall spherical description.
- However, the best decay energy is predicted by a formula that includes significant deformation

^{145}Tm proton emission observation



PRL **99,** 082502 (2007) PHYSICAL REVIEW LETTERS week ending 24 AUGUST 2007

Effect of a Triaxial Nuclear Shape on Proton Tunneling: The Decay and Structure of ^{145}Tm

D. Seweryniak,[1] B. Blank,[1,2] M. P. Carpenter,[1] C. N. Davids,[1] T. Davinson,[3] S. J. Freeman,[4] N. Hammond,[1] N. Hoteling,[5] R. V. F. Janssens,[1] T. L. Khoo,[1] Z. Liu,[3] G. Mukherjee,[1] A. Robinson,[3] C. Scholey,[6] S. Sinha,[1] J. Shergur,[5] K. Starosta,[7] W. B. Walters,[5] A. Woehr,[8] and P. J. Woods[3]

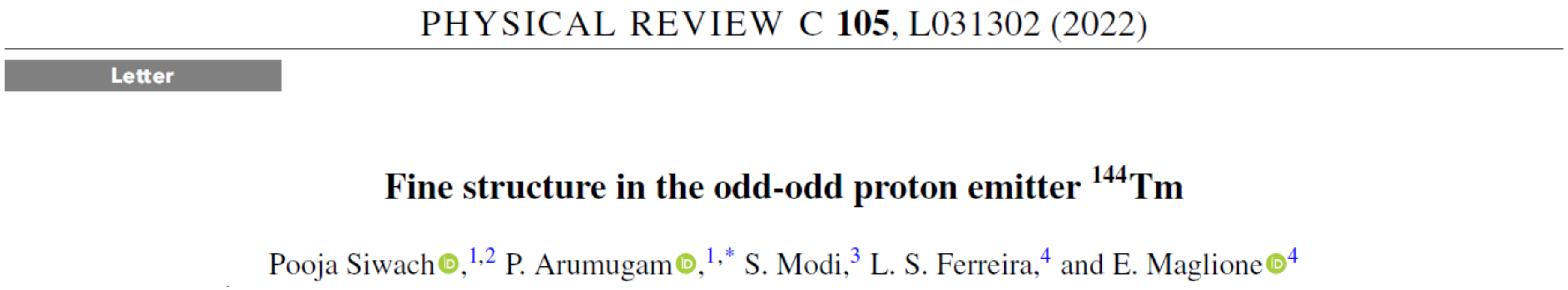
Islands of triaxiality:

- Specific combinations of single-particle orbitals near the Fermi surface can lead to triaxial shapes
- One of the islands corresponds to the *N* = 76, 77, 78 isotones above the *Z* = 50 proton shell in the vicinity of the proton drip line
    - Near the 145Tm proton emitter.

- The proton emission can be used as a probe of triaxial shapes.
- Comparison between the particle-rotor model and the measured level energies suggests that an asymmetry parameter $\gamma \sim 20°$ fits the data best.

P. Moller *et al.*, Phys. Rev. Lett. **97**, 162502 (2006).

^{144}Tm proton emission observation



PHYSICAL REVIEW C **105**, L031302 (2022)

Letter

Fine structure in the odd-odd proton emitter ^{144}Tm

Pooja Siwach,[1,2] P. Arumugam,[1,*] S. Modi,[3] L. S. Ferreira,[4] and E. Maglione[4]

The fine structure in 144Tm:

- Studied within the nonadiabatic quasiparticle approach.
- ^{144}Tm is found to be highly triaxial with $\gamma \sim 30°$

Among around 30 known proton emitters in the region $50 < Z < 82$, fine structure is exhibited by:

- ^{131}Eu
- ^{141}Ho
- ^{144,145,146}Tm

- Microscopic-macroscopic calculations involve several parameters to be tuned
- Makes them unreliable in drip-line nuclei due to lack of data
- Necessity to probe the nuclear structure properties of the drip-line

^{150,151}Lu proton emitters

PHYSICAL REVIEW C **68**, 034330 (2003)

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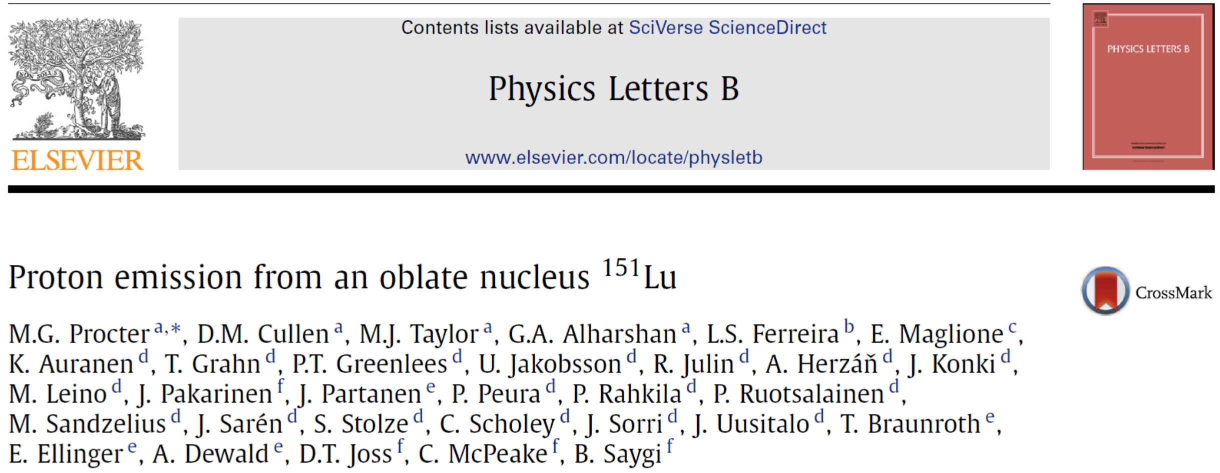
- In ^{150m,gs}Lu no evidence for fine structure in the proton emission was found



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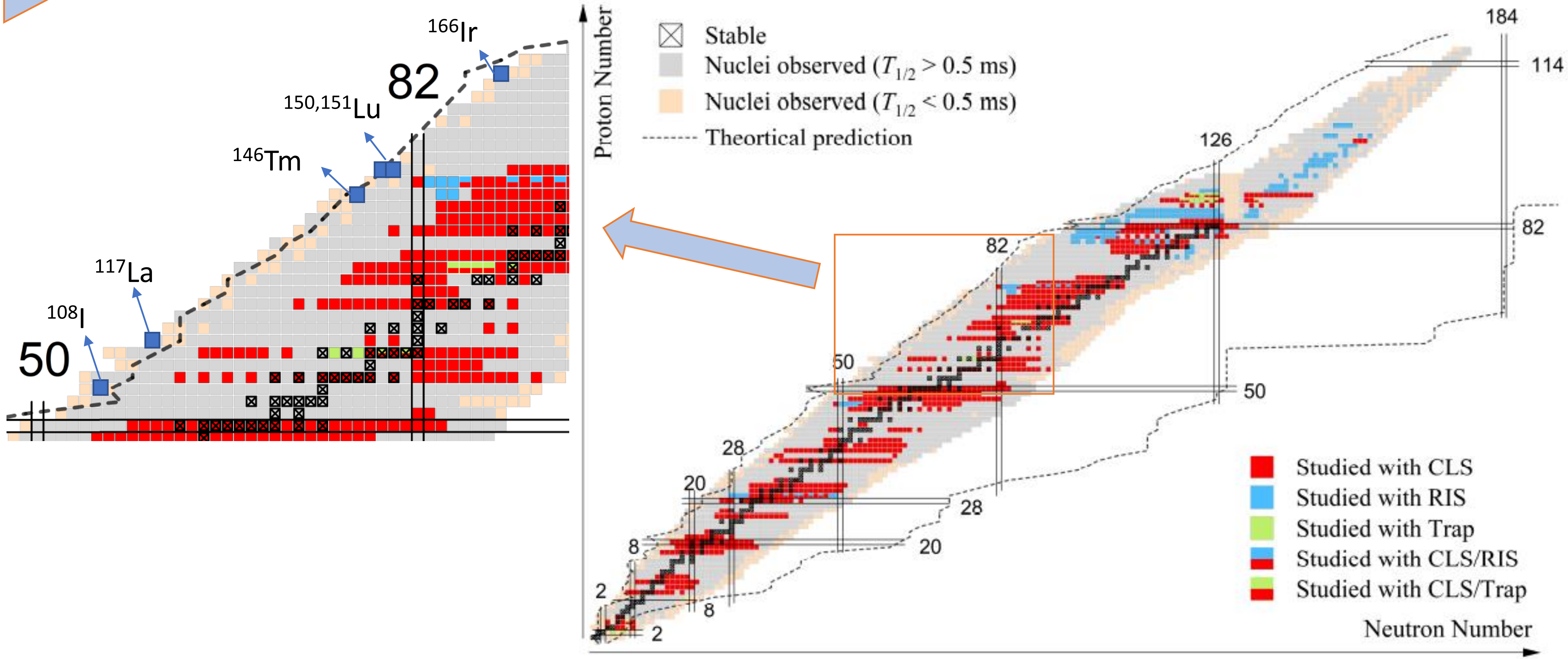
Proton emission from an oblate nucleus ^{151}Lu

M.G. Procter[a,*], D.M. Cullen[a], M.J. Taylor[a], G.A. Alharshan[a], L.S. Ferreira[b], E. Maglione[c], K. Auranen[d], T. Grahn[d], P.T. Greenlees[d], U. Jakobsson[d], R. Julin[d], A. Herzáň[d], J. Konki[d], M. Leino[d], J. Pakarinen[f], J. Partanen[e], P. Peura[d], P. Rahkila[d], P. Ruotsalainen[d], M. Sandzelius[d], J. Sarén[d], S. Stolze[d], C. Scholey[d], J. Sorri[d], J. Uusitalo[d], T. Braunroth[e], E. Ellinger[e], A. Dewald[e], D.T. Joss[f], C. McPeake[f], B. Saygi[f]

- The proton emitting ground state in ^{151}Lu is found to be oblate
- With a deformation $\beta = -0.11^{+0.02}_{-0.05}$
- Best evidence to date for proton emission from an oblate nucleus.

Laser spectroscopy beyond the *p*-dripline



X.F. Yang, S.J. Wang, S.G. Wilkins et al., Laser spectroscopy for the study of exotic nuclei, Progress in Particle and Nuclear Physics (2022)
doi: https://doi.org/10.1016/j.ppnp.2022.104005.

Status of laser spectroscopy in Tm and Lu isotopes

Tm isotopic chain:

- Latest measurements from 2000 down to ^{153}Tm
- No fundamental properties are known below ^{153}Tm
- Nuclear spins are assigned only tentatively
- Laser spectroscopy will enable these to be established unambiguously

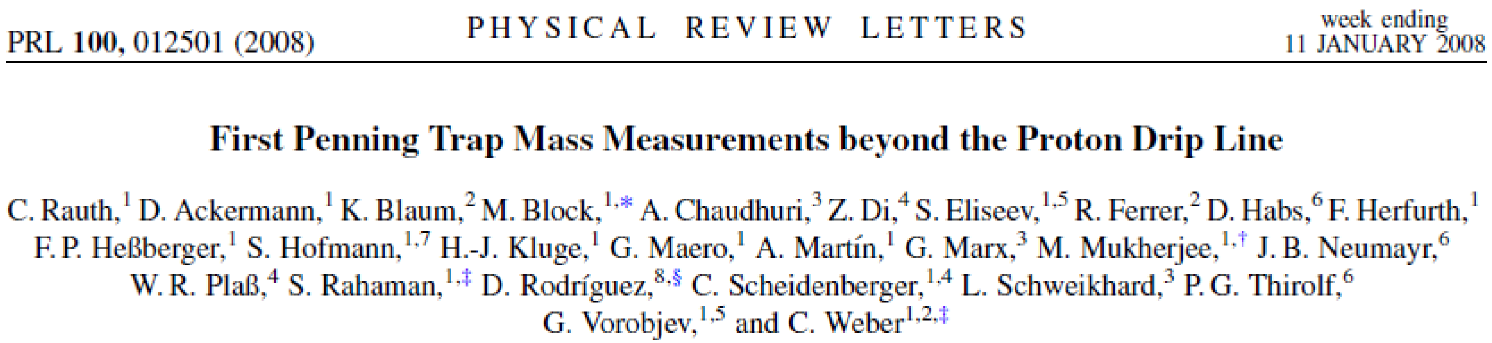
Lu isotopic chain:

- Measurements only extend as far down as ^{161}Lu
- No such measurements in the wider region extend below the N = 82 shell closure

- To date, no laser spectroscopy has been performed on a proton emitting nuclei !
- What is the charge radius evolution ?
- The spatial extent of the proton distribution is expected to increase
  - Depends on the angular momentum occupied by the unstable proton and S_p

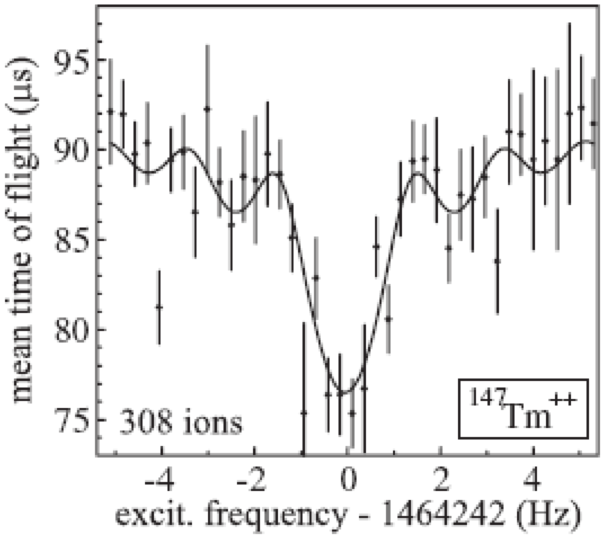
A.E. Barzakh, *et al.,* Phys. Rev. C **61**, 034304 (2000)
U. Georg, *et al.,* Eur. Phys. J. A **3,** 225 (1998)

Mass spectrometry beyond the *p*-dripline


PRL **100,** 012501 (2008) PHYSICAL REVIEW LETTERS week ending 11 JANUARY 2008

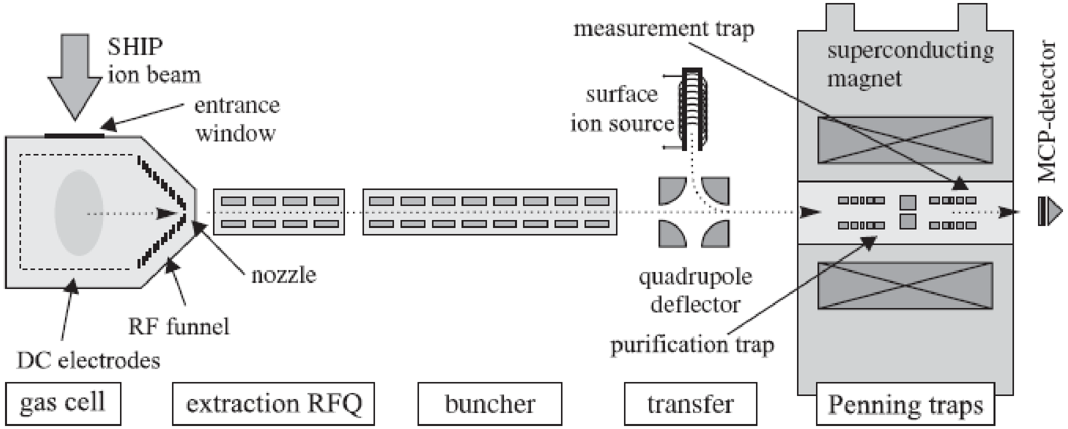
First Penning Trap Mass Measurements beyond the Proton Drip Line

C. Rauth,[1] D. Ackermann,[1] K. Blaum,[2] M. Block,[1,*] A. Chaudhuri,[3] Z. Di,[4] S. Eliseev,[1,5] R. Ferrer,[2] D. Habs,[6] F. Herfurth,[1] F. P. Heßberger,[1] S. Hofmann,[1,7] H.-J. Kluge,[1] G. Maero,[1] A. Martín,[1] G. Marx,[3] M. Mukherjee,[1,†] J. B. Neumayr,[6] W. R. Plaß,[4] S. Rahaman,[1,‡] D. Rodríguez,[8,§] C. Scheidenberger,[1,4] L. Schweikhard,[3] P. G. Thirolf,[6] G. Vorobjev,[1,5] and C. Weber[1,2,‡]

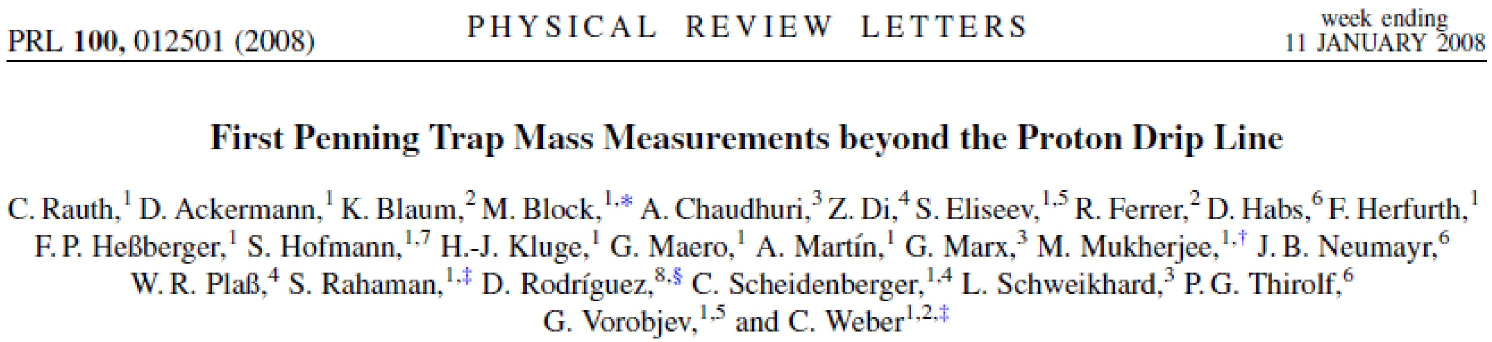


- Direct mass measurement of proton emitting nuclei:
  - To test mass models
  - To study competition between α decay and proton emission (also β for some cases)
  - To determine the proton drip line location

- First direct mass measurement of a proton emitter nuclei
  - $^{147}_{69}Tm$ at SHIPTRAP



Status of mass spectrometry in Tm and Lu isotopes



PRL **100**, 012501 (2008) PHYSICAL REVIEW LETTERS week ending 11 JANUARY 2008

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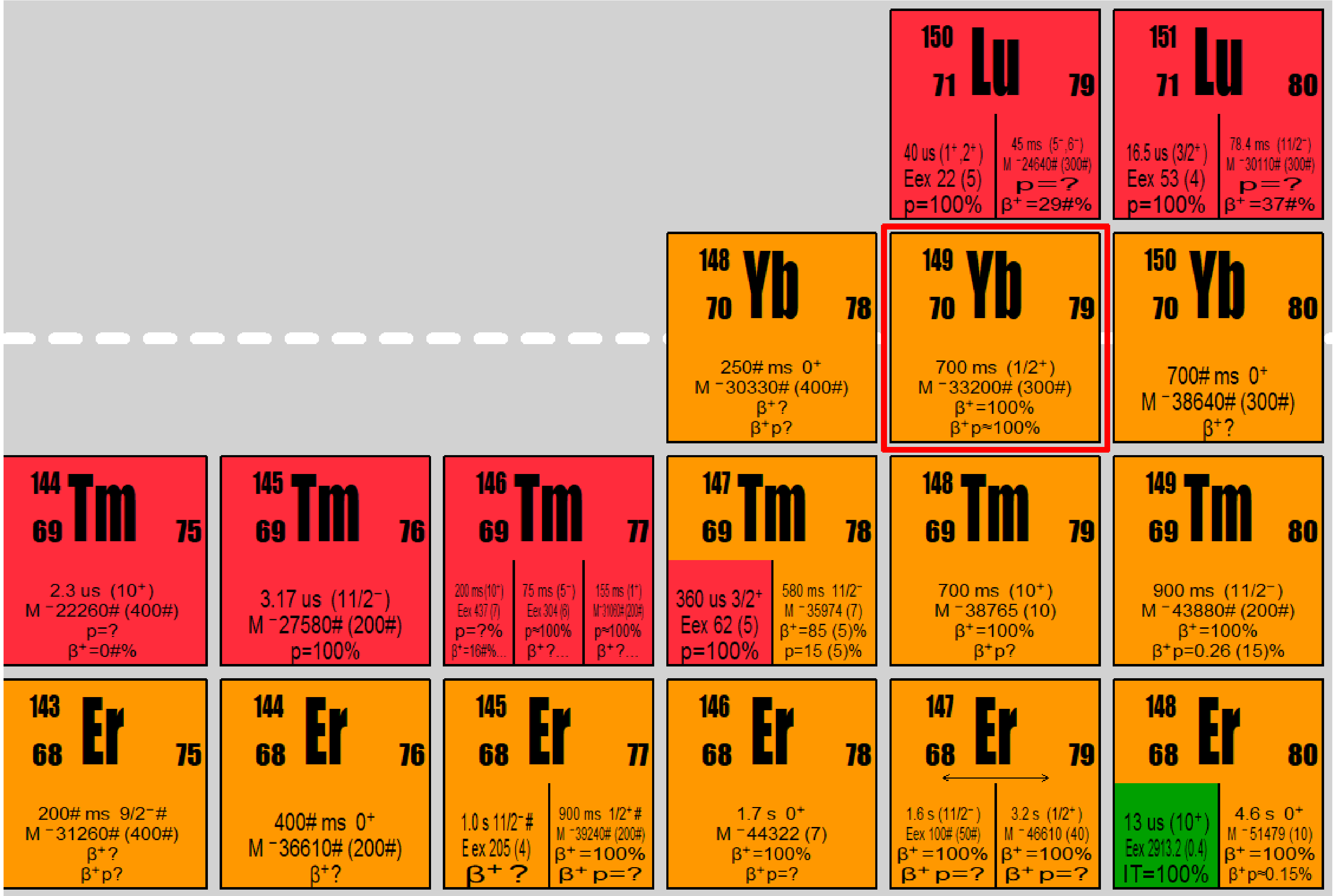
G. Vorobjev,[1,5] and C. Weber[1,2,‡]

- No mass measurement cross the N = 82 shell except ^{147,148}Tm at SHIPTRAP
- From direct mass measurement we can derived the proton separation energies and compared to predictions from mass formulas.
- The new values of the proton separation energies are used to determine the location of the proton drip-line more accurately.

Nuclear deformation and fine structure in the p-emission



				150 Lu 71 79 40 us $(1^+,2^+)$ Eex 22 (5) p=100% 45 ms $(5^-,6^-)$ M $^-$24640# (300#) p=? β^+=29#%	151 Lu 71 80 16.5 us $(3/2^+)$ Eex 53 (4) p=100% 78.4 ms $(11/2^-)$ M $^-$30110# (300#) p=? β^+=37#%
			148 Yb 70 78 250# ms 0^+ M $^-$30330# (400#) β^+? β^+p?	149 Yb 70 79 700 ms $(1/2^+)$ M $^-$33200# (300#) β^+=100% β^+p≈100%	150 Yb 70 80 700# ms 0^+ M $^-$38640# (300#) β^+?
144 Tm 69 75 2.3 us (10^+) M $^-$22260# (400#) p=? β^+=0#%	145 Tm 69 76 3.17 us $(11/2^-)$ M $^-$27580# (200#) p=100%	146 Tm 69 77 200 ms (10^+) Eex 437 (7) p=?% β^+=16#%… 75 ms (5^-) Eex 304 (6) p≈100% β^+?… 155 ms (1^+) M $^-$31060# (200#) p≈100% β^+?…	147 Tm 69 78 360 us $3/2^+$ Eex 62 (5) p=100% 580 ms $11/2^-$ M $^-$35974 (7) β^+=85 (5)% p=15 (5)%	148 Tm 69 79 700 ms (10^+) M $^-$38765 (10) β^+=100% β^+p?	149 Tm 69 80 900 ms $(11/2^-)$ M $^-$43880# (200#) β^+=100% β^+p=0.26 (15)%
143 Er 68 75 200# ms $9/2^-$# M $^-$31260# (400#) β^+? β^+p?	144 Er 68 76 400# ms 0^+ M $^-$36610# (200#) β^+?	145 Er 68 77 1.0 s $11/2^-$# E ex 205 (4) β^+? 900 ms $1/2^+$# M $^-$39240# (200#) β^+=100% β^+p=?	146 Er 68 78 1.7 s 0^+ M $^-$44322 (7) β^+=100% β^+p=?	147 Er 68 79 1.6 s $(11/2^-)$ Eex 100# (50#) β^+=100% β^+p=? 3.2 s $(1/2^+)$ M $^-$46610 (40) β^+=100% β^+p=?	148 Er 68 80 13 us (10^+) Eex 2913.2 (0.4) IT=100% 4.6 s 0^+ M $^-$51479 (10) β^+=100% β^+p≈0.15%

Proton emitters accessible with S^3

		I S3 (A/Q=3)	AfterLEB	Fast LEB	I S3 (A/Q=7)	AfterLEB	After Fast LEB
108I	36ms	23	0,00	0,35	115	0,01	1,76
117La	23,5ms	4,45E+00	0,00	0,04	22,25	0,00	0,21
146Tm	80ms	120	0,36	3,12	600	1,80	15,59
151Lu	80,6ms	1,10E+03	3,37	28,68	5500	16,87	143,39
150Lu	45ms	160	0,06	2,97	800	0,32	14,87
166Ir	10,5ms	190	0,00	0,28	950	0,00	1,42

Courtesy of L. Caceres

- ^{108}I → end of the rp-process (*K. Auranen et al., PLB, **792**, 187 (2019)*)
- ^{117}La → strongly deformed nuclei, $\beta \sim 0.3°$ (*F. Soramel et al., Phys. Rev. C **63**, 031304(R) (2001)*)
- ^{166}Ir → competition between α and p decay (*C.N. Davids et al., Phys. Rev. C **55**, 2255 (1997)*)

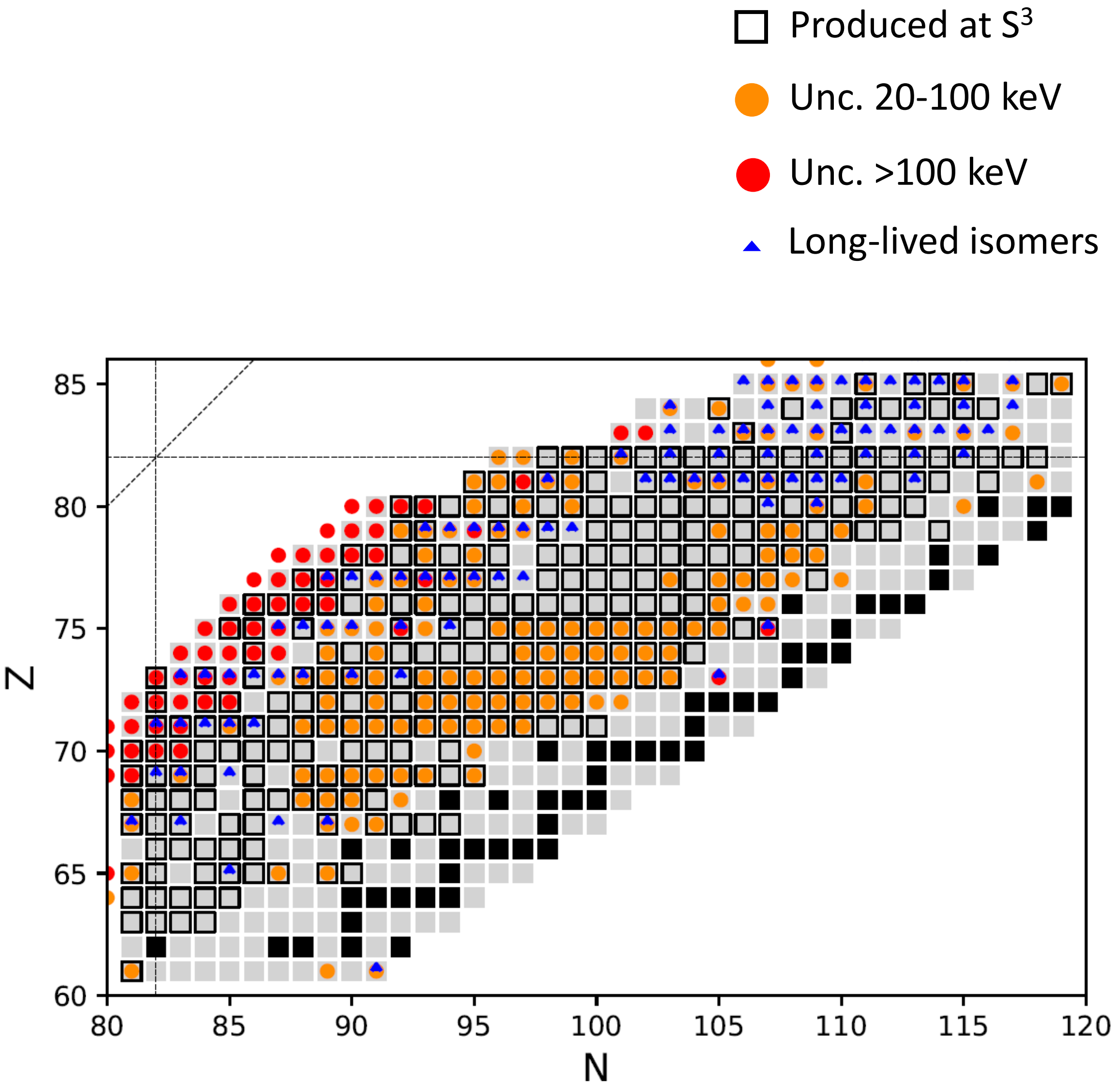
Courtesy V. Manea

Mass measurements of heavy elements with $70 < Z < 82$

- ❑ Many masses in the region measured by storage ring mass spectrometry or linked by Q_α (uncertainties 30 keV or above).
  - ○ Opportunity for (high precision) mass spectrometry with Penning traps.

- ❑ Many low-lying isomers especially in the odd-Z chains:
  - ○ Opportunity for (high-resolution) mass spectrometry with Penning traps and trap-assisted decay spectroscopy.

- ❑ Many of the elements inaccessible from thick-target facilities.



https://u.ganil-spiral2.eu/chartbeams/
M. Wang et al., Chinese Phys. C 45, 030003 (2021)
T. Radon et al., Nucl. Phys. A 677, 75-99 (2000)
Yu. A. Litvinov et al., Nucl. Phys. A 756 3–38 (2005)

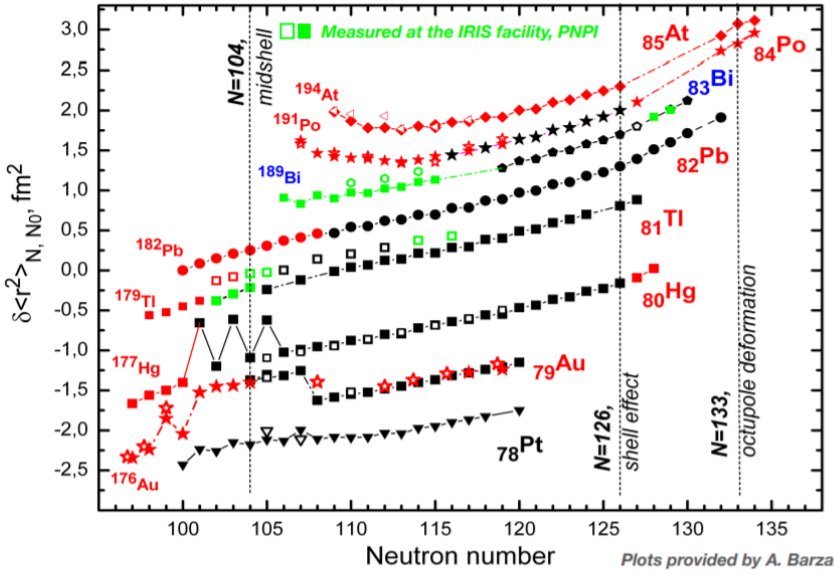
Courtesy V. Manea

Mass measurements of heavy elements with 70 < Z < 82

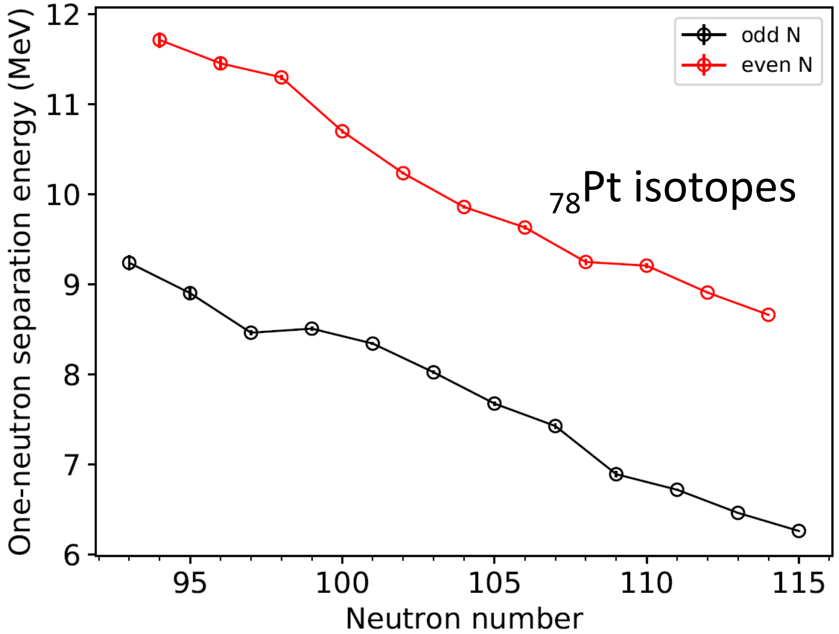
- Ground-state charge radii exhibit spectacular variations around neutron midshell in the $_{79}$Au and $_{80}$Hg isotopic chains.
  - Sudden return to sphericity at N = 98-100
  - Charge radii « inflation » present also in the $_{78}$Pt chain
  - Almost terra incognita below Z = 78 (for the ground-state trends)

- Complementary effect in binding energies is very subtle:
  - Only clearly visibile in <u>**one**-</u>neutron separation energies
  - Odd-N and even-N values behave differently
    - ➢ Interplay between deformation and pairing

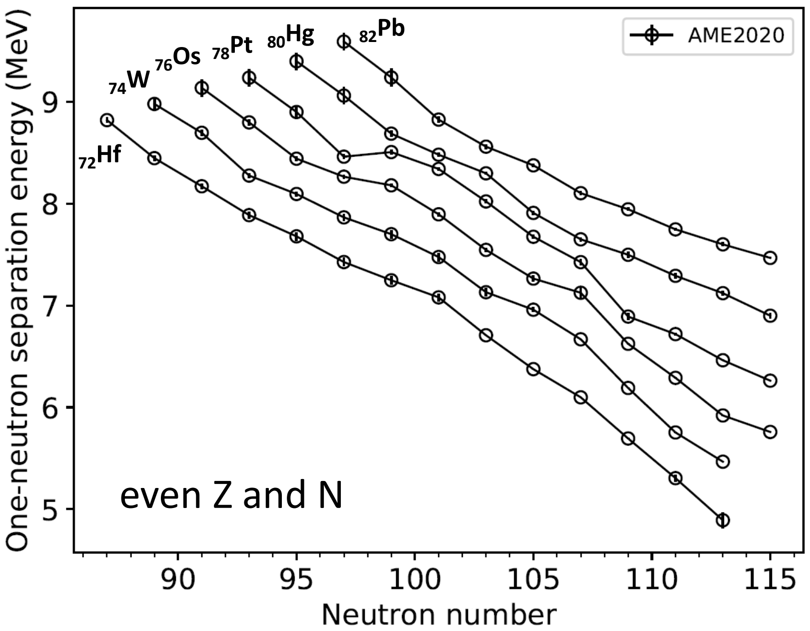
J. Cubiss et al., Phys. Rev. Lett. 131, 202501 (2023)



Plots provided by A. Barzakh (PNPI)



M. Wang et al., Chinese Phys. C 45, 030003 (2021)



Courtesy V. Manea

Mass measurements of heavy elements with 70 < Z < 82

J. Cubiss et al., Phys. Rev. Lett. 131, 202501 (2023)

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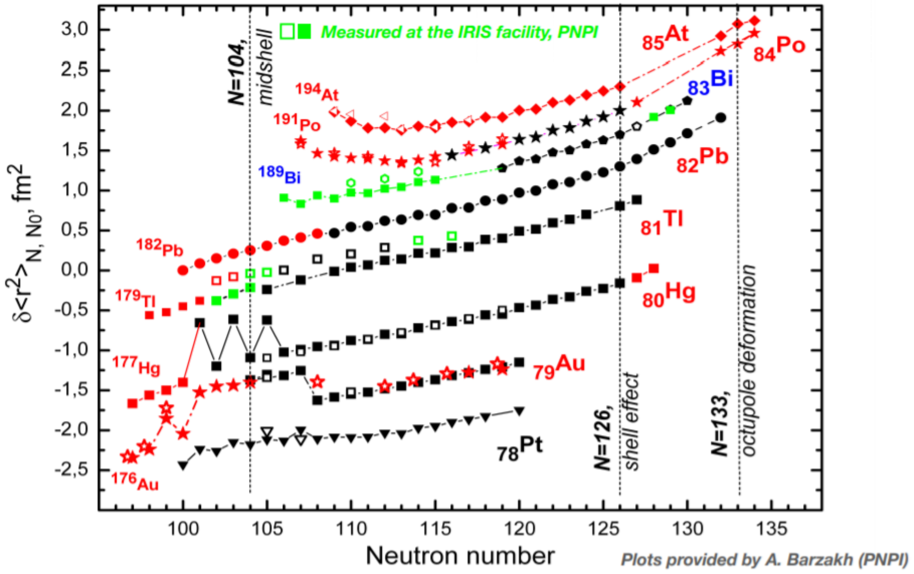


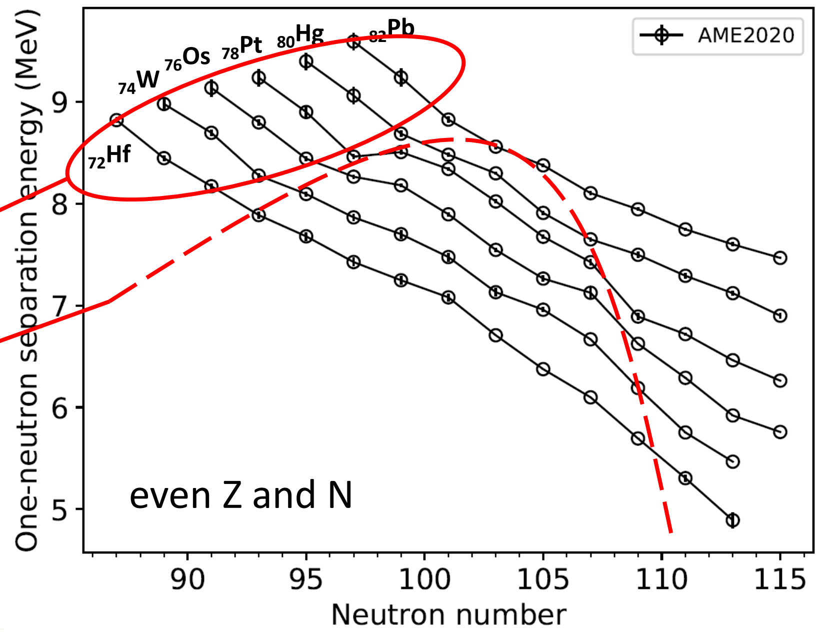
Plots provided by A. Barzakh (PNPI)

- ☐ Questions to pursue through mass masurements (and complementary laser spectroscopy):

Q1: Study the trends of binding energies up to the dripline

Q2: Map the boundary of the region of strong deformation

Correlate the picture with the trends of isomeric states



M. Wang et al., Chinese Phys. C 45, 030003 (2021)

Thank you for your attention !!!

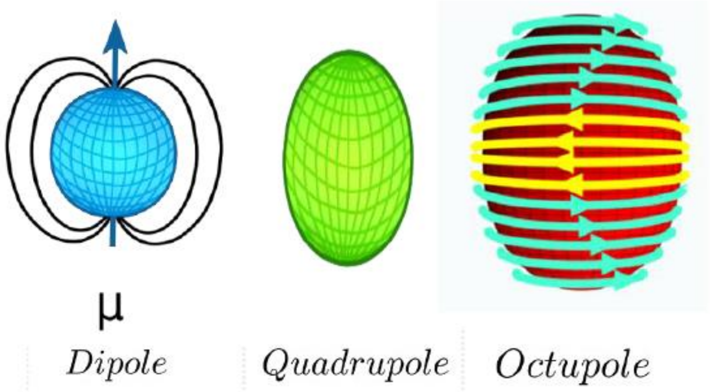
And thanks to Vladimir for the slides !

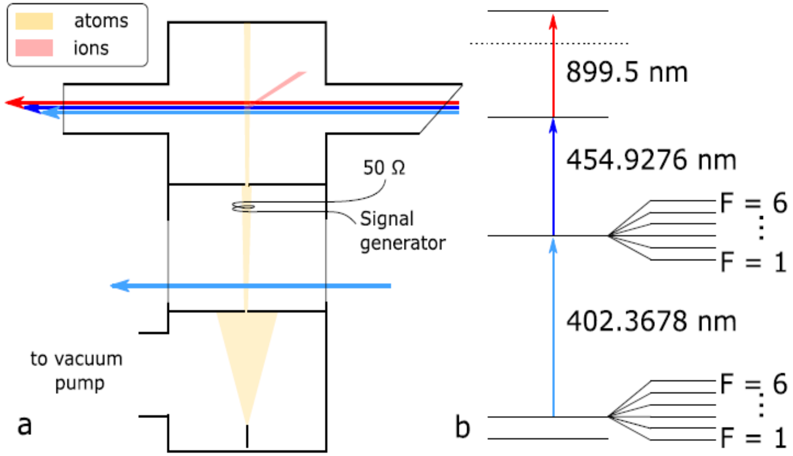
S^3 Low Energy Branch (S^3-LEB)

RF spectroscopy at S^3-LEB – colaboration with KU Leuven

- Future upgrade planned
- Laser-radiofrequency double-resonance spectroscopy
  - Laser are used for state preparation and readout
  - Spectroscopy is preformed using an RF excitation

  - **See R.P. de Groote presentation on Thursday at 2pm !!**





R.P. de Groote *et al.*, PLB **827**, 136930 (2022)