Decay Spectroscopy of Deformed, Neutron-rich Nuclei at CARIBU@ANL

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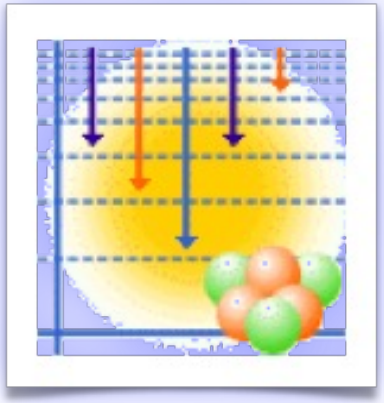
Outline

- Introduction
- Decay spectroscopy at CARIBU@ANL
- Results from recent campaigns in the A=100 (^{104}Nb) and A=160 (spin-trap isomers) mass regions
- Outlook – nuCARIBU & N=126 factory



CGS17, July 17-21, 2023, Grenoble, FRANCE

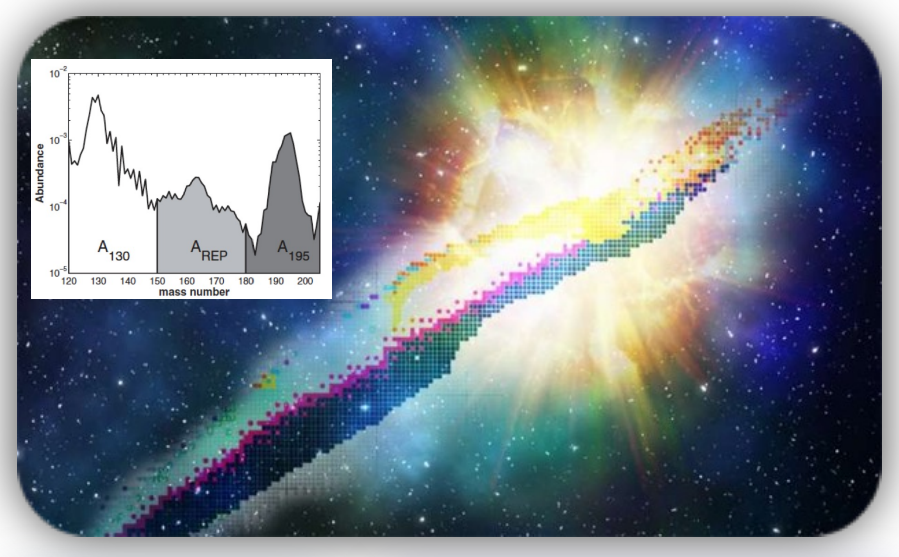
Introduction

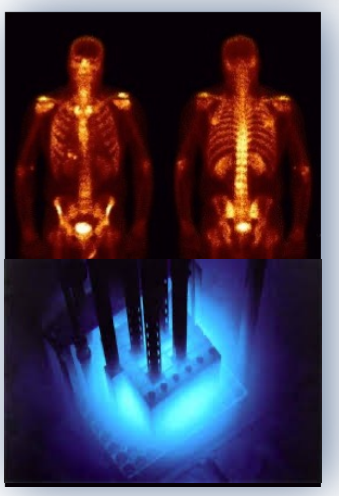
- Powerful Experimental Tool
  - Sensitive – reduced complexity
  - Selective – populates selected states
  - Versatile – various implementations

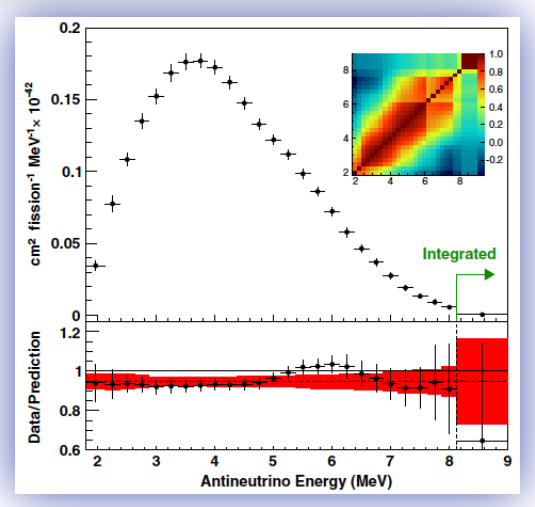
- Nuclear structure
  - single-particle structures
  - shape co-existence
  - configuration dependent residual interactions

- Nuclear Astrophysics
  - $T_{1/2}$, $J\pi$, E_x, P_{xn}, BR …

- Applications
  - Energy
  - Security
  - Nonproliferation
  - Nuclear Medicine
  - Fusion



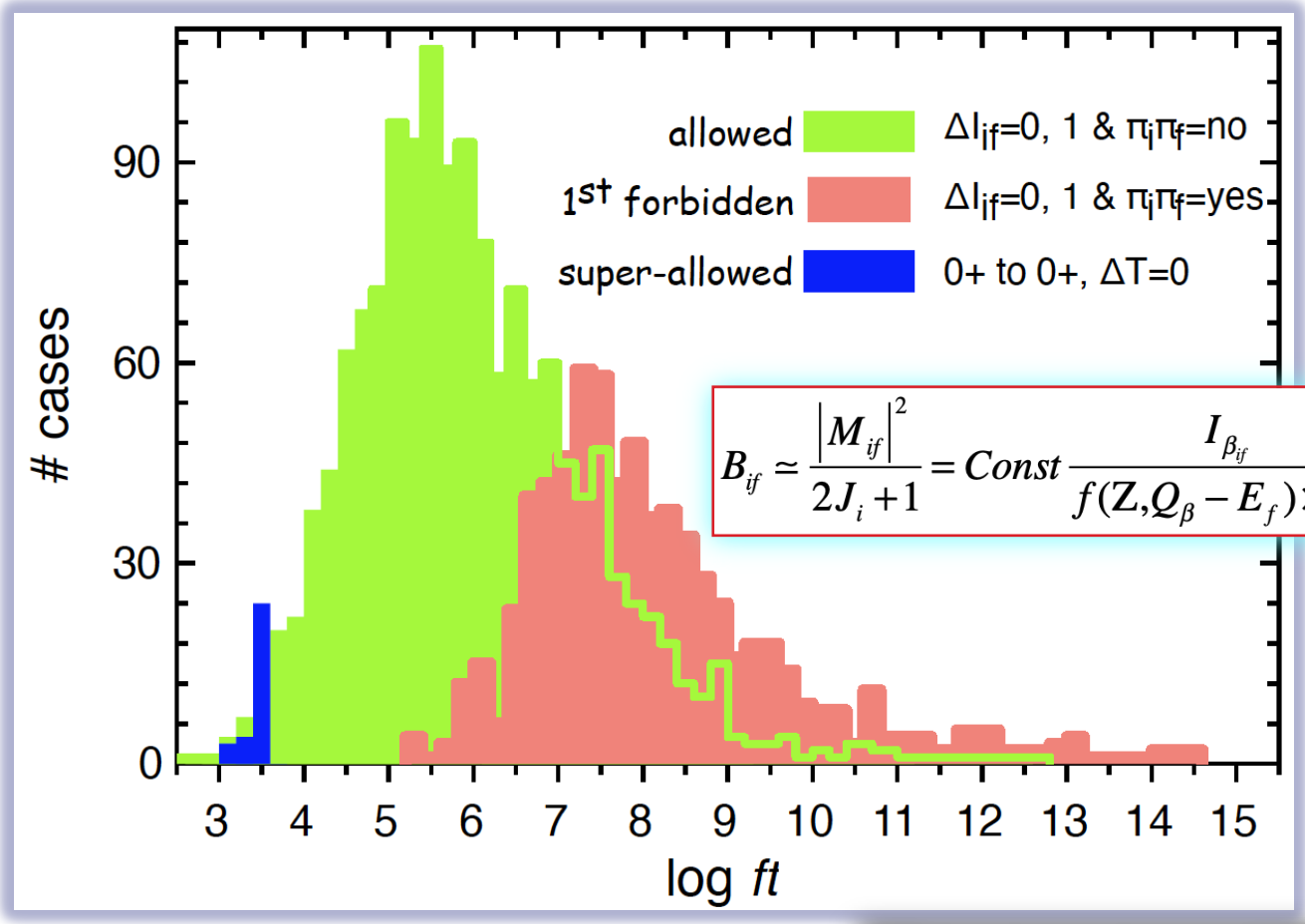




Contents lists available at ScienceDirect
Atomic Data and Nuclear Data Tables 152 (2023) 101584
Atomic Data and Nuclear Data Tables
journal homepage: www.elsevier.com/locate/adt

Systematics of log *ft* values for $\beta-$, and EC/$\beta+$ transitions

Steffen Turkat [a,*], Xavier Mougeot [b], Balraj Singh [c], Kai Zuber [a]

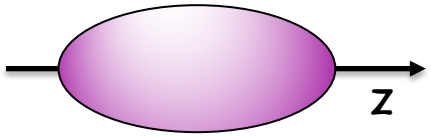


$$B_{if} \simeq \frac{|M_{if}|^2}{2J_i+1} = Const\,\frac{I_{\beta_{if}}}{f(Z,Q_\beta - E_f)\times T_{1/2}} = Const\,\frac{1}{ft}$$

☛ log *ft* (allowed) 3-13 -> hindrance of ~10^{10} → ☛ *l*-, isospin- or K-forbidden, or configuration hindered

Selection rules in β decay of deformed nuclei

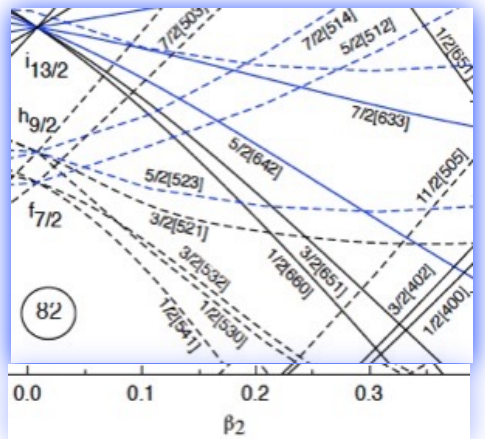
deformed nuclei – Nilsson model: $\Omega^{\pi}[Nn_z\Lambda]$; $\Lambda=\Omega \pm 1/2$



S.G. Nilsson, Dan. Mat. Fys. Medd. 29 (16) (1955)

ΔI=0, +/-1; $\pi_i.\pi_f$=NO (Allowed); $\pi_i.\pi_f$=YES (1st Forbidden)

G. Alaga, Phys. Rev. 100 (1955) 432



$\Delta\Omega = 0,+/-1$; $\Delta N=0=\Delta n_z=\Delta\Lambda=0$

$\Delta\Omega = 0,+/-1$; $\Delta N=0$ $\Delta n_z=\Delta\Lambda= 0,+/-1$

J. Fujita et al., Phys. Rev. C1, (1970) 2060

} Allowed Unhindered (AU)

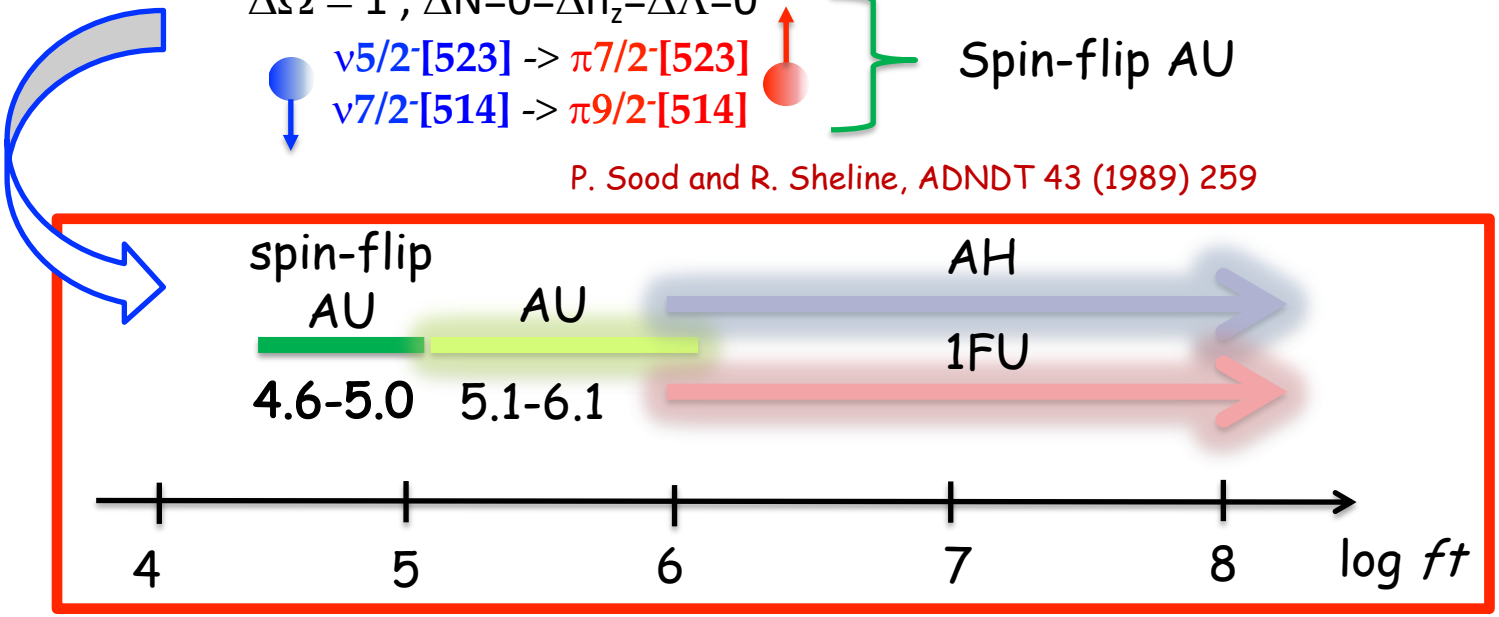
$\Delta\Omega = 1$; $\Delta N=0=\Delta n_z=\Delta\Lambda=0$

$\nu 5/2^-[523]$ -> $\pi 7/2^-[523]$

$\nu 7/2^-[514]$ -> $\pi 9/2^-[514]$

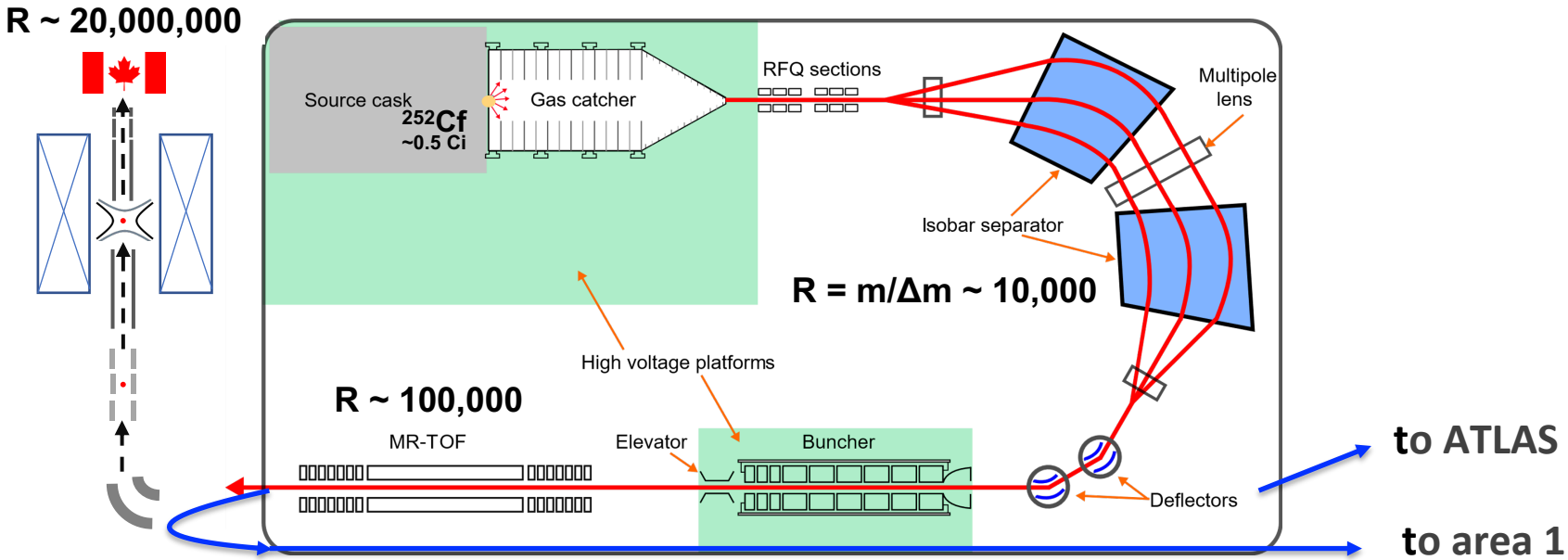
} Spin-flip AU

P. Sood and R. Sheline, ADNDT 43 (1989) 259

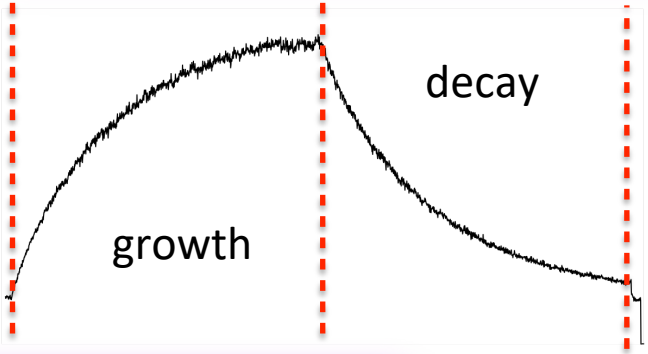


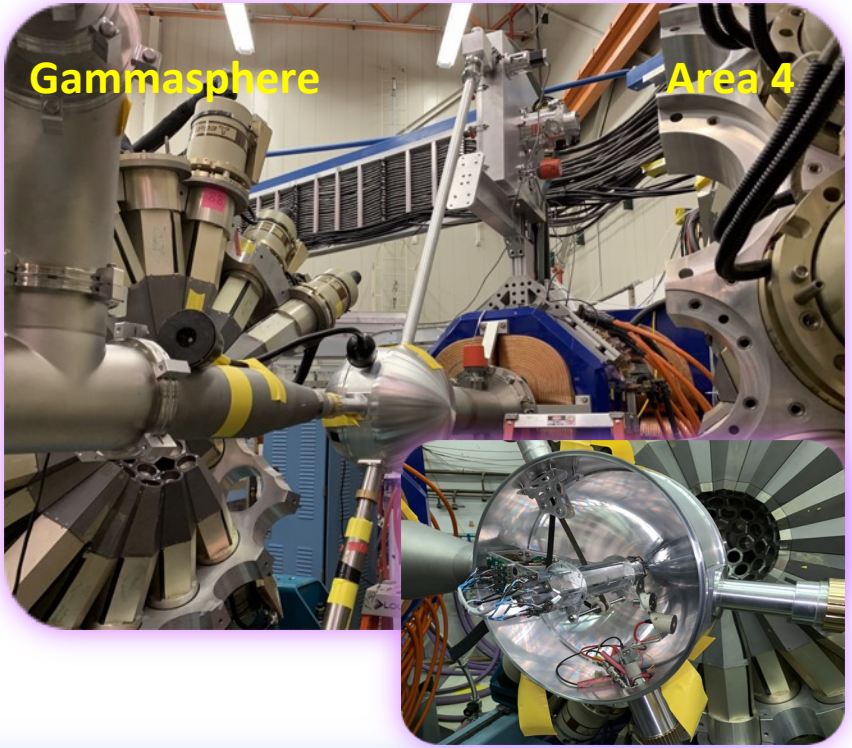
CARIBU @ ANL

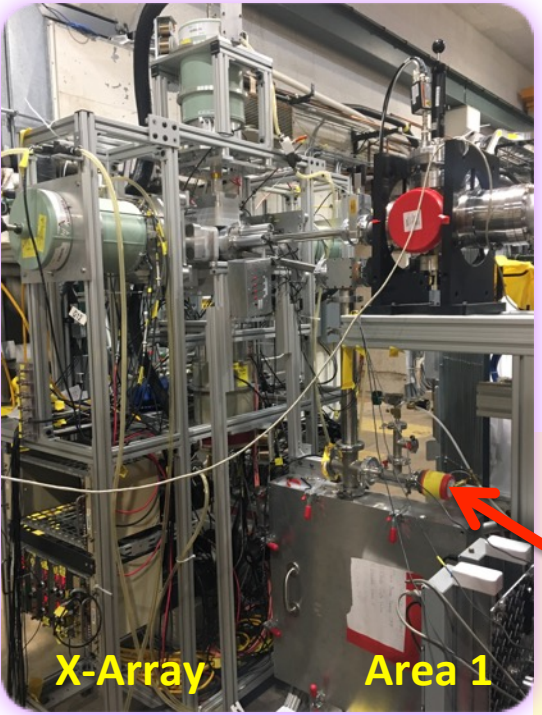

CPT


R ~ 20,000,000
Source cask
252Cf
~0.5 Ci
Gas catcher
RFQ sections
Multipole lens
Isobar separator
R = m/Δm ~ 10,000
High voltage platforms
R ~ 100,000
MR-TOF
Elevator
Buncher
Deflectors
to ATLAS
to area 1

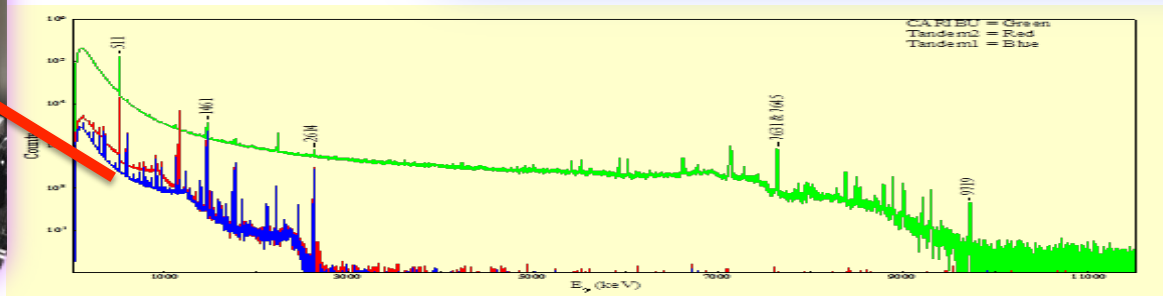
- direct implantation on the tape
- control the growth & decay times
  - selectivity by $T_{1/2}$
- β-γ-γ(t) coincidences







- **HEART** - HExagonal ARray for Triggering
  - ✓ 6 EJ-204 plastic scint. & 12 SiPM
  - ✓ ε_β~75% from β-γ singles & coin.
- powerful γ-γ-β-t coincidence device

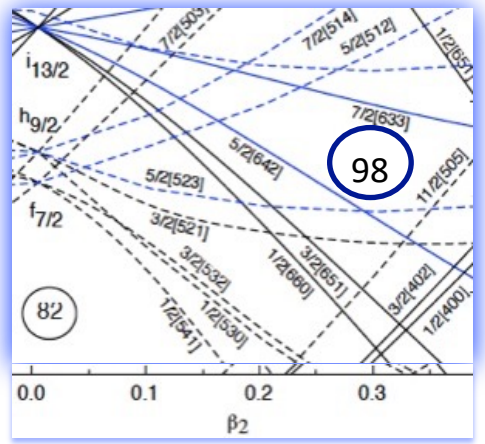


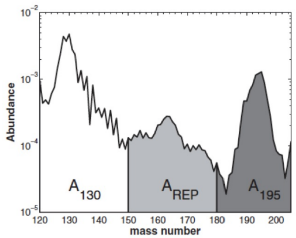
light rare-earth region

PHYSICAL REVIEW LETTERS **120**, 182502 (2018)

Masses and β-Decay Spectroscopy of Neutron-Rich Odd-Odd ^{160,162}Eu Nuclei: Evidence for a Subshell Gap with Large Deformation at $N = 98$

D. J. Hartley,[1] F. G. Kondev,[2] R. Orford,[2,3] J. A. Clark,[2,4] G. Savard,[2,5] A. D. Ayangeakaa,[2,*] S. Bottoni,[2,†] F. Buchinger,[3] M. T. Burkey,[2,5] M. P. Carpenter,[2] P. Copp,[2,6] D. A. Gorelov,[2,4] K. Hicks,[1] C. R. Hoffman,[2] C. Hu,[7] R. V. F. Janssens,[2,‡] J. W. Klimes,[2] T. Lauritsen,[2] J. Sethi,[2,8] D. Seweryniak,[2] K. S. Sharma,[9] H. Zhang,[7] S. Zhu,[2] and Y. Zhu[7]

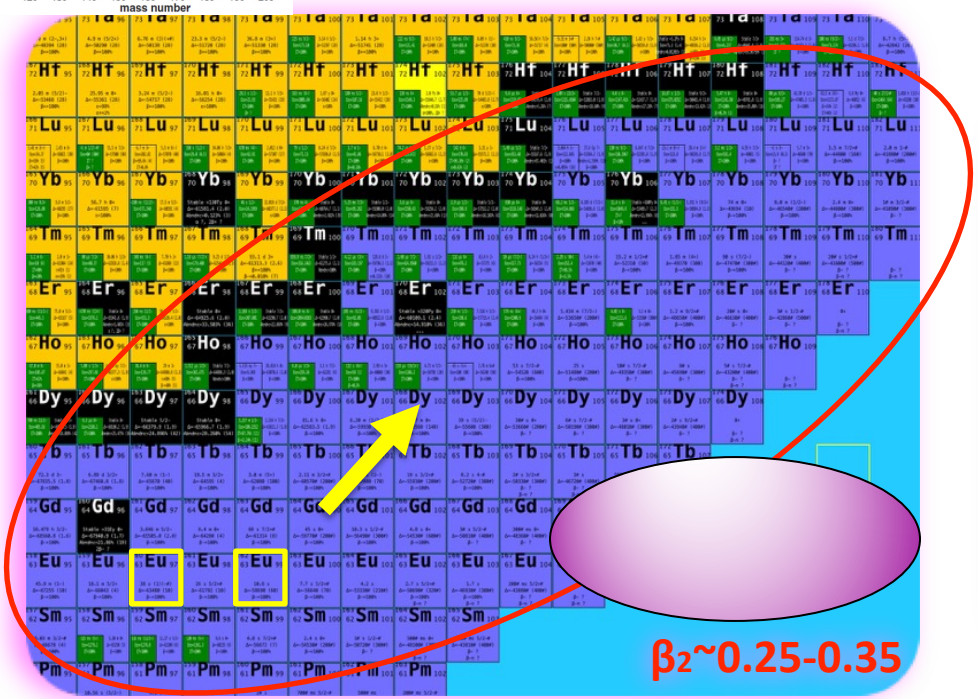




PHYSICAL REVIEW C **101**, 044301 (2020)

High-K, two-quasiparticle states in ^{160}Gd

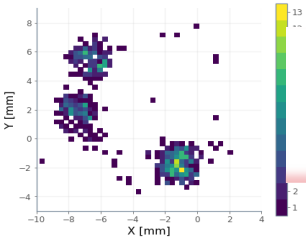
D. J. Hartley,[1] F. G. Kondev,[2] G. Savard,[2] J. A. Clark,[2] A. D. Ayangeakaa,[2,*] S. Bottoni,[2,†] M. P. Carpenter,[2] P. Copp,[2,3] K. Hicks,[1] C. R. Hoffman,[2] R. V. F. Janssens,[4,5] T. Lauritsen,[2] R. Orford,[6,‡] J. Sethi,[2,7] and S. Zhu[2,§]



light rare-earth region

- terra incognita - not easy to get there …
  - ✓ prompt-fission studies with GS - mostly along the yeast line …
  - ✓ in-flight fission & fragmentation (RIKEN) - beta-decay studies …
- well-deformed *n*-rich nuclei
- importance to nuclear structure & astrophysics (masses, $T_{1/2}$, P_n, etc.)

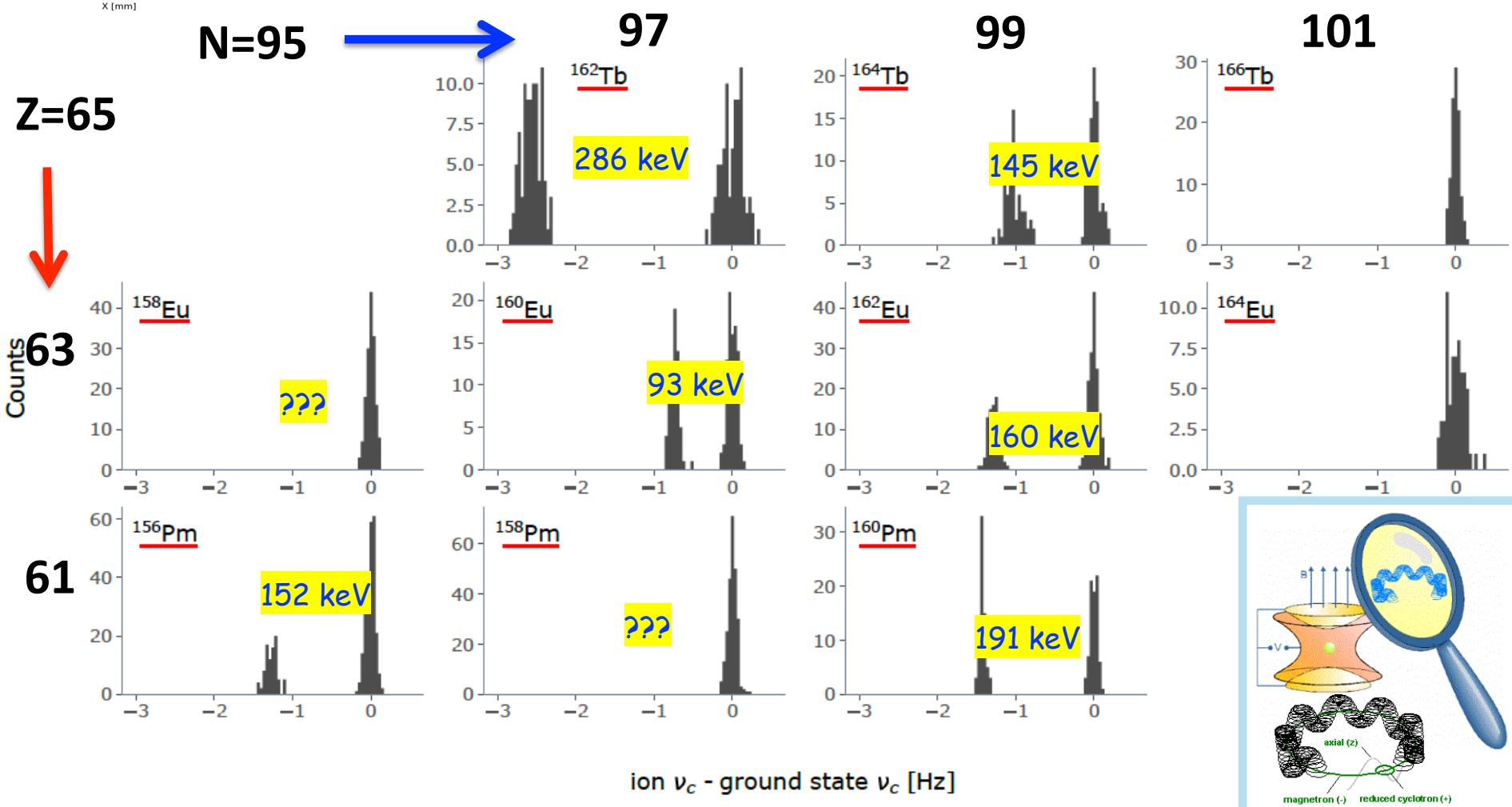
new spin-trap isomers - CPT@PI-ICR



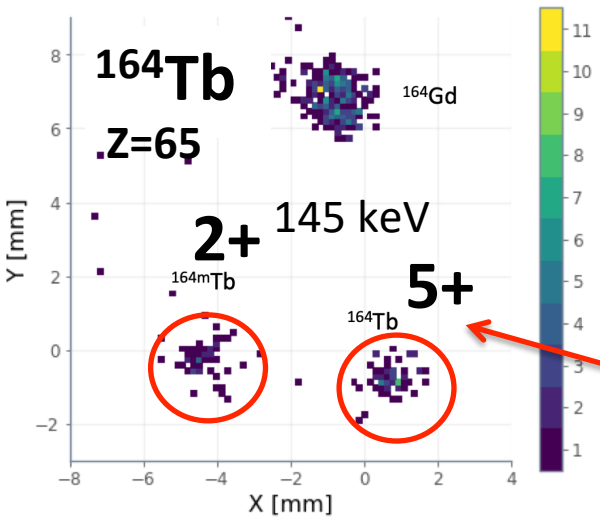
Physical Review C102, 011303(R) (2020)

Spin-trap isomers in deformed, odd-odd nuclei in the light rare-earth region near $N = 98$

R. Orford,[1,2,*] F. G. Kondev,[1] G. Savard,[1,3] J. A. Clark,[1,4] W. S. Porter,[1,†] D. Ray,[1,4] F. Buchinger,[2] M. T. Burkey,[1,3,‡] D. A. Gorelov,[1,4] D. J. Hartley,[5] J. W. Klimes,[1,§] K. S. Sharma,[4] A. A. Valverde,[1,4] and X. L. Yan[1,6]

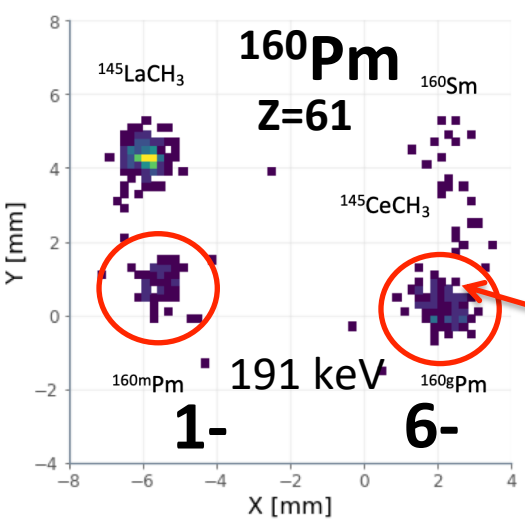


new spin-trap isomers – cont.



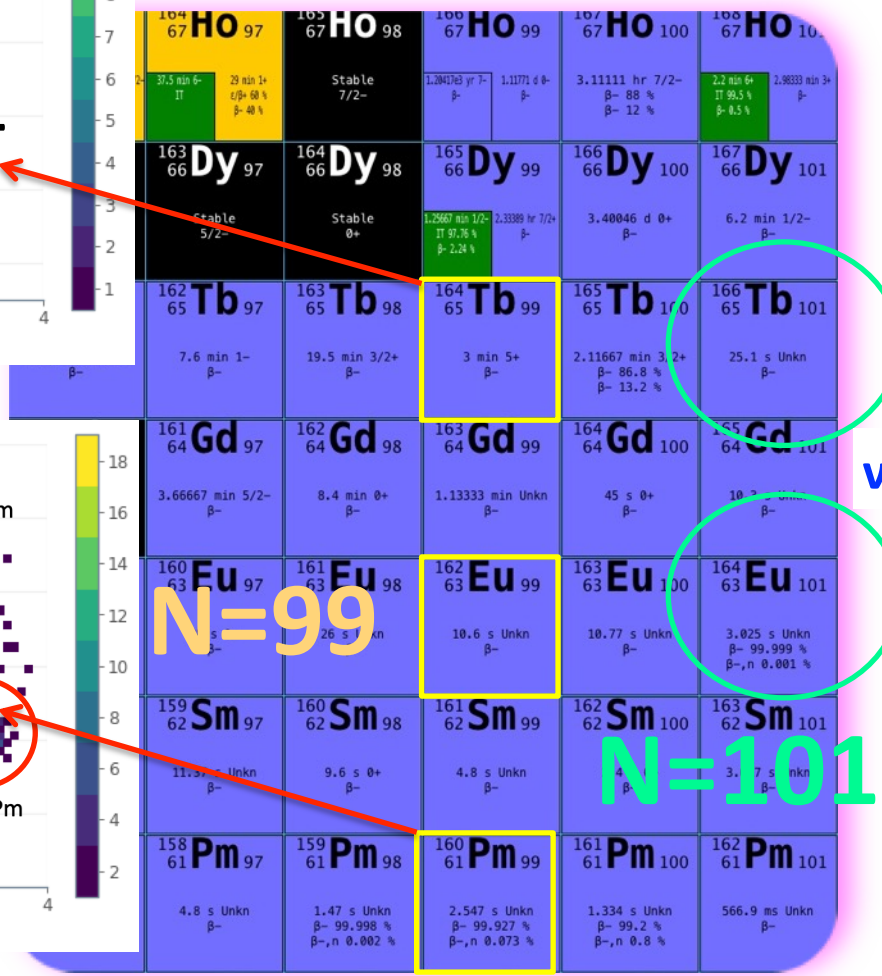
π3/2[411] ν7/2[633]

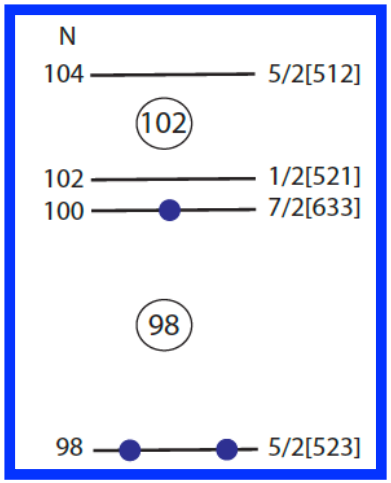
Kπ=2+ & 5+



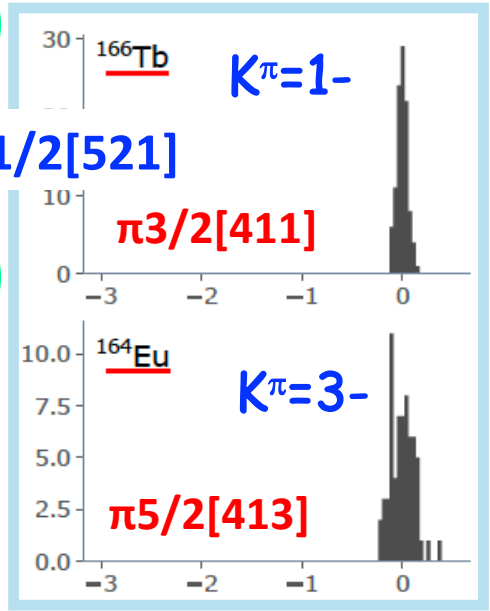
π5/2[532] ν7/2[633]

Kπ=1- & 6-





ν1/2[521]

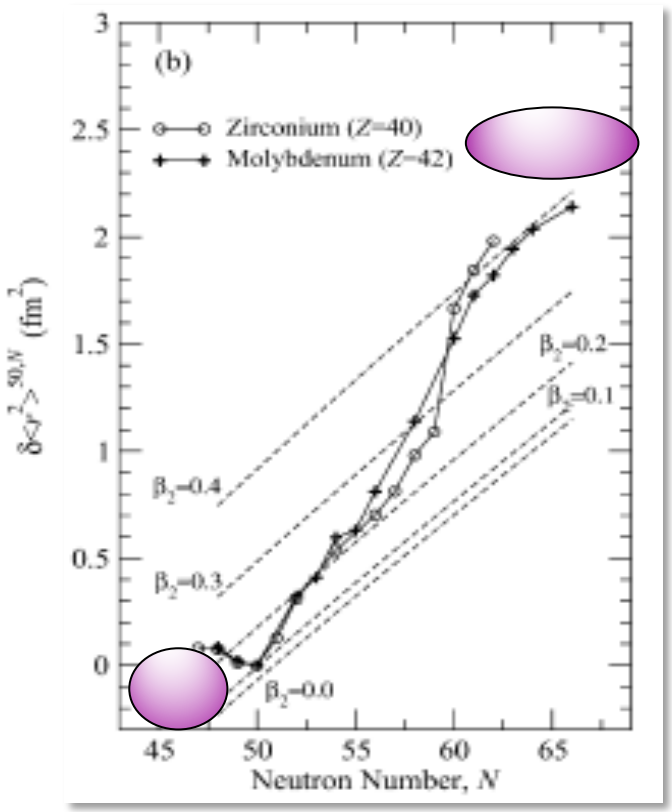


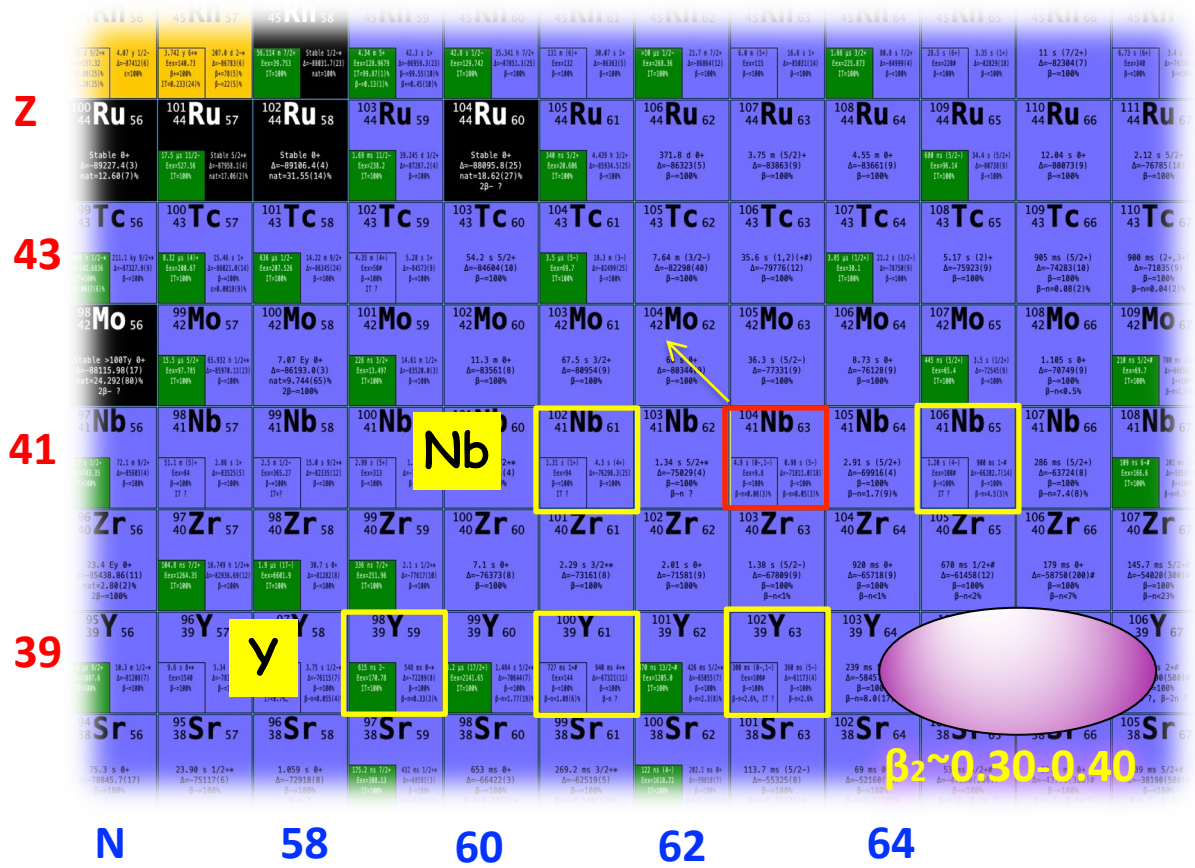
R. Orford et al., PRC102, 011303(R) (2020)

deformed A=100 region

⇒ evolution of shapes from spherical to well deformed
⇒ great examples of shape coexistence
⇒ applications – anti-neutrino spectra reconstructions

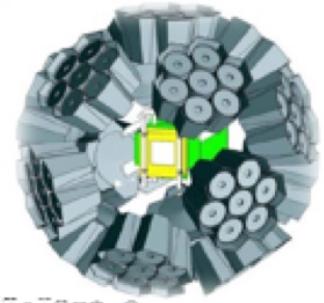
⇒ data on the neutron-rich side are still sparse
⇒ existence of isomers (odd-odd nuclei) - needs characterization

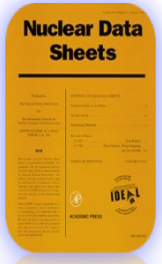


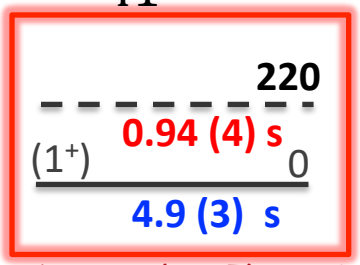


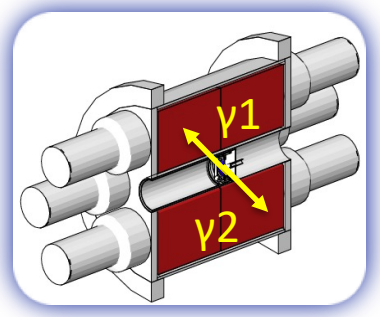
Charlwood et al., Phys. Lett. B 674, (2009) 23

$^{104}_{41}Nb^{63}$



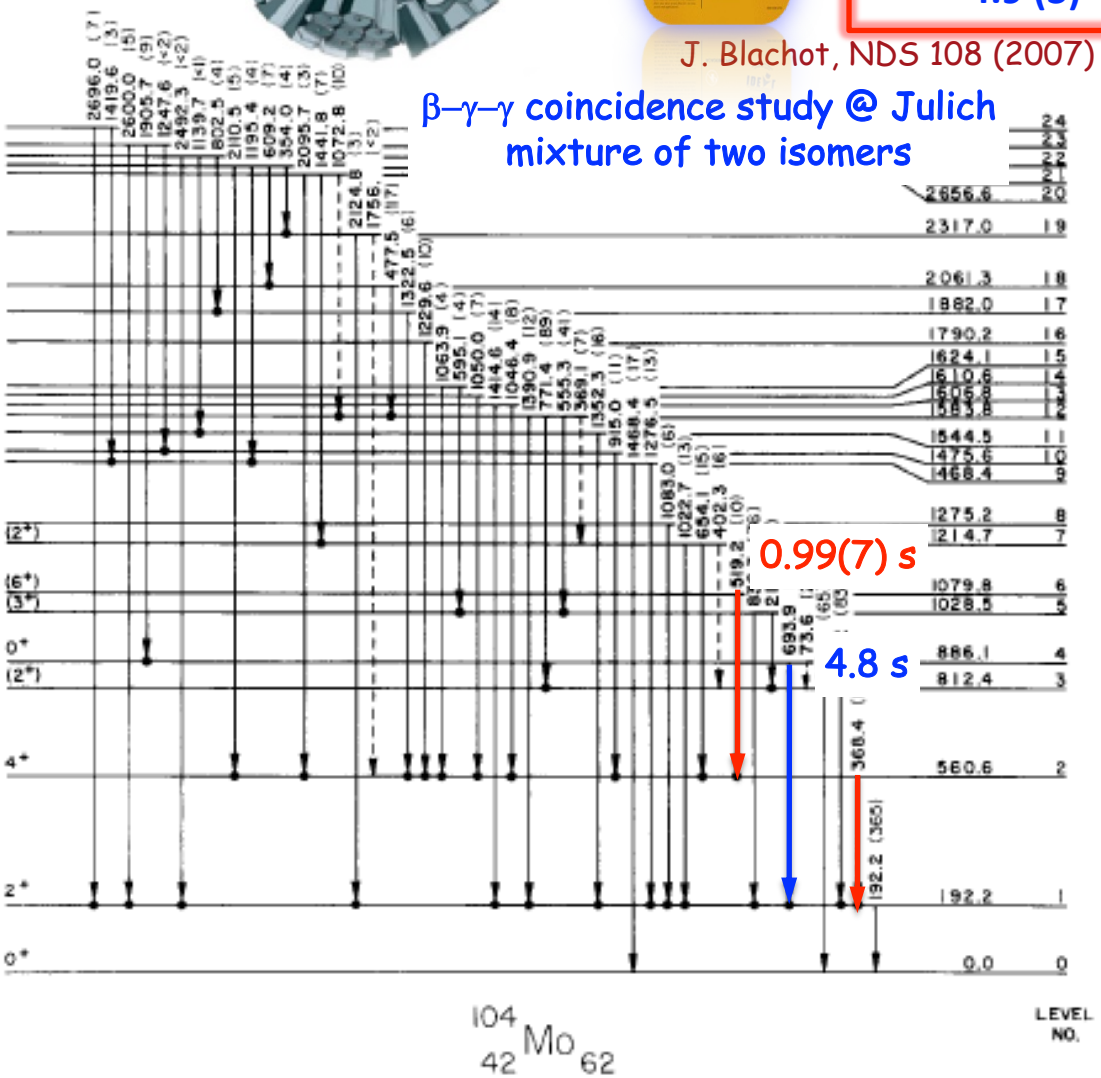






J. Blachot, NDS 108 (2007) 2035

β–γ–γ coincidence study @ Julich
mixture of two isomers



0.99 s state & TAGS @ MSU
direct feeding feeding to 0+ & 4+?

Energy (keV)		Intensity (%)	Error (±)	Energy (keV)	Intensity (%)	Error (±)
0	0+	5.6	1.3	3050	0	
192		0		3130	0	
561	4+	2.9	0.6	3210	1.4	0.4
812		2.2	0.7	3290	0	
886		0		3370	0	
1028		0		3450	0	
1080		0		3530	0	
1215		0		3630	0.87	0.14
1275		0.02	0.06	3730	0	
1469		0.4	0.3	3830	0	
1475		1.7	0.4	3930	0	
1545		0		4030	1.65	0.23
1583		1.9	0.3	4130	0.0	0.3
1607		0		4230	3.4	0.5
1611		0		4330	0.00	0.21
1624		0.3	0.3	4430	0	
1790		1.0	0.3	4530	0.00	0.08
1882		0		4730	2.3	0.3
2061		28.8	1.5	4930	0.84	0.21
2317		0		5130	0.40	0.11
2656		17.5	1.5	5330	1.0	0.3
2671		1.3	1.0	5530	0.7	0.3
2685		4.6	0.7	5730	0.8	0.3
2792		3.6	0.8	5930	0.6	0.5
2888		0		6030	0.02	0.07
2890		3.9	0.6	6530	1.6	0.3
2970		7.4	1.1	7030	2.2	0.5

B. Kern et al., Z. Phys. A306 (1982) 161

J. Gombas et al., Phys. Rev. C103 (2021) 035803

0.94 (4) s 215(120)

M. Graefenstedt et al., Z. Phys. 327 (1987) 383

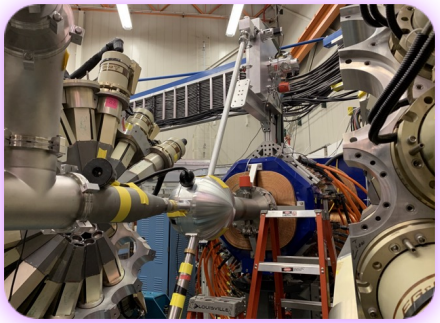
(1^+) 0

4.9(3) s

J. Blachot, NDS 108 (2007) 2035

^{104}Nb

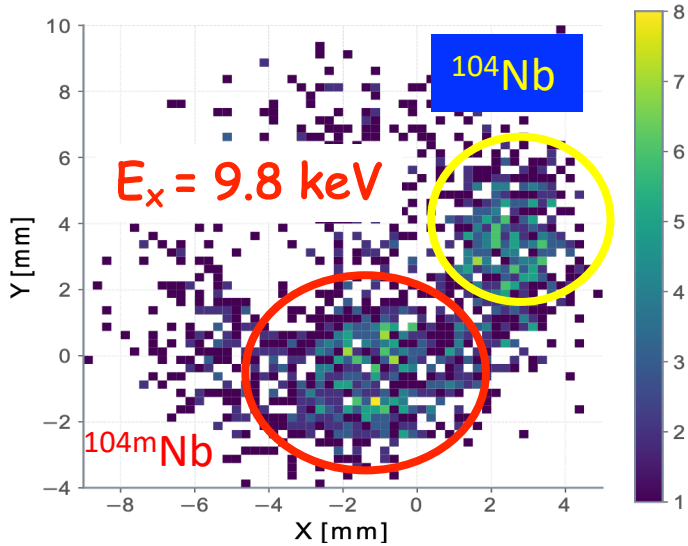
CARIBU@Gammasphere



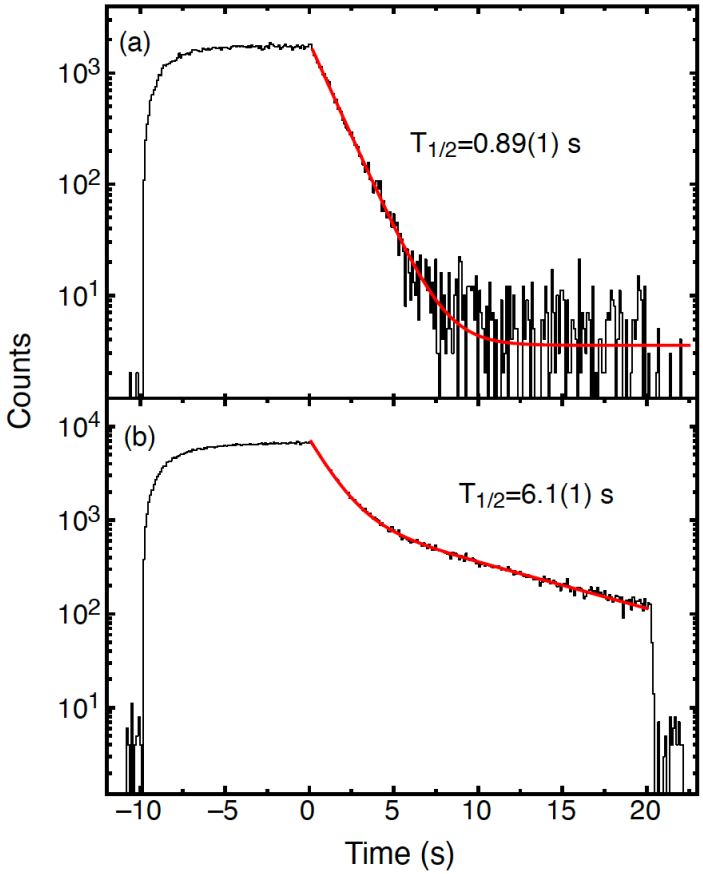
tape cycles

10s/20s
10s/40s

CPT@PI-ICR

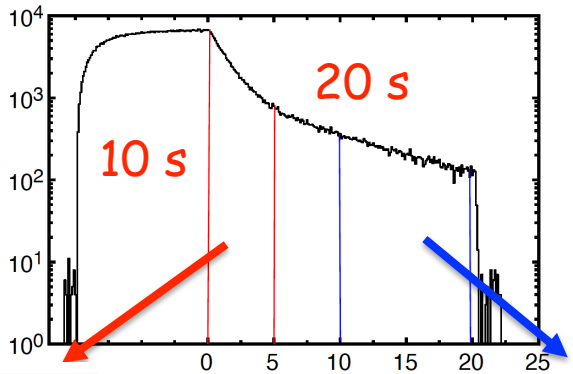


R. Orford, PhD thesis 2021



S. Nandi et al., to be published

^{104}Nb



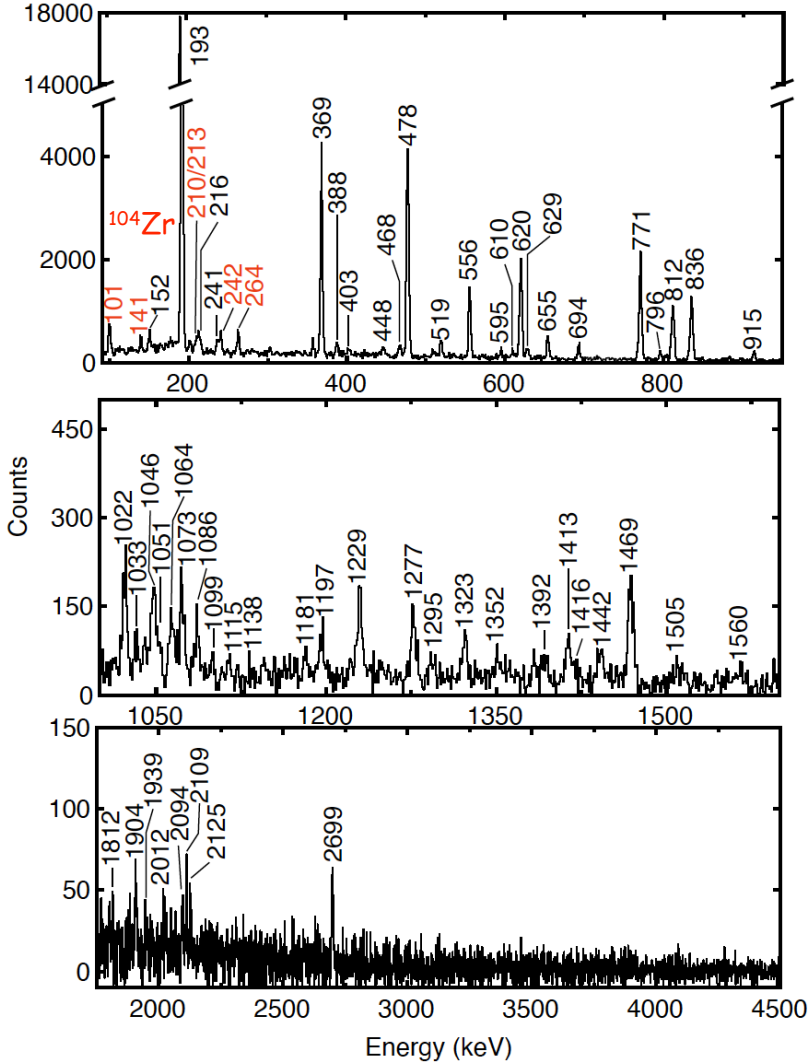
long-lived daughter (^{104}Mo) and grand- daughter (^{104}Tc) decays subtracted from 10s/40 s data

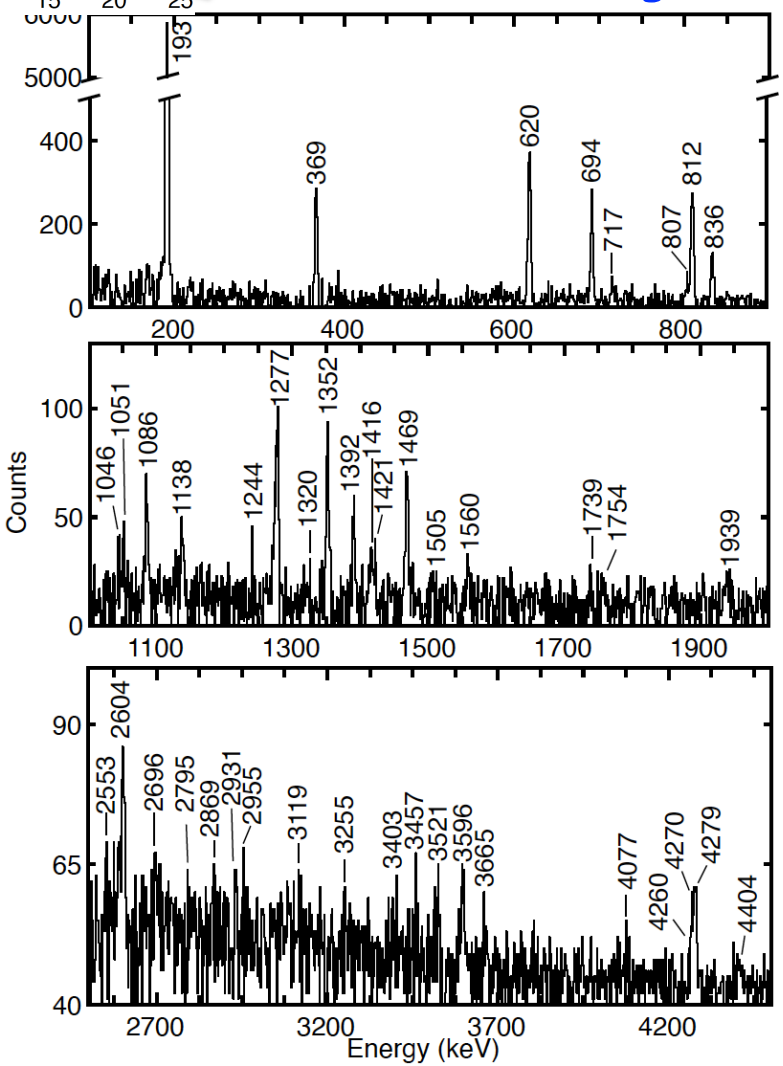
34 levels
93 gammas

$T_{1/2}$=0.89 s
0-5 s

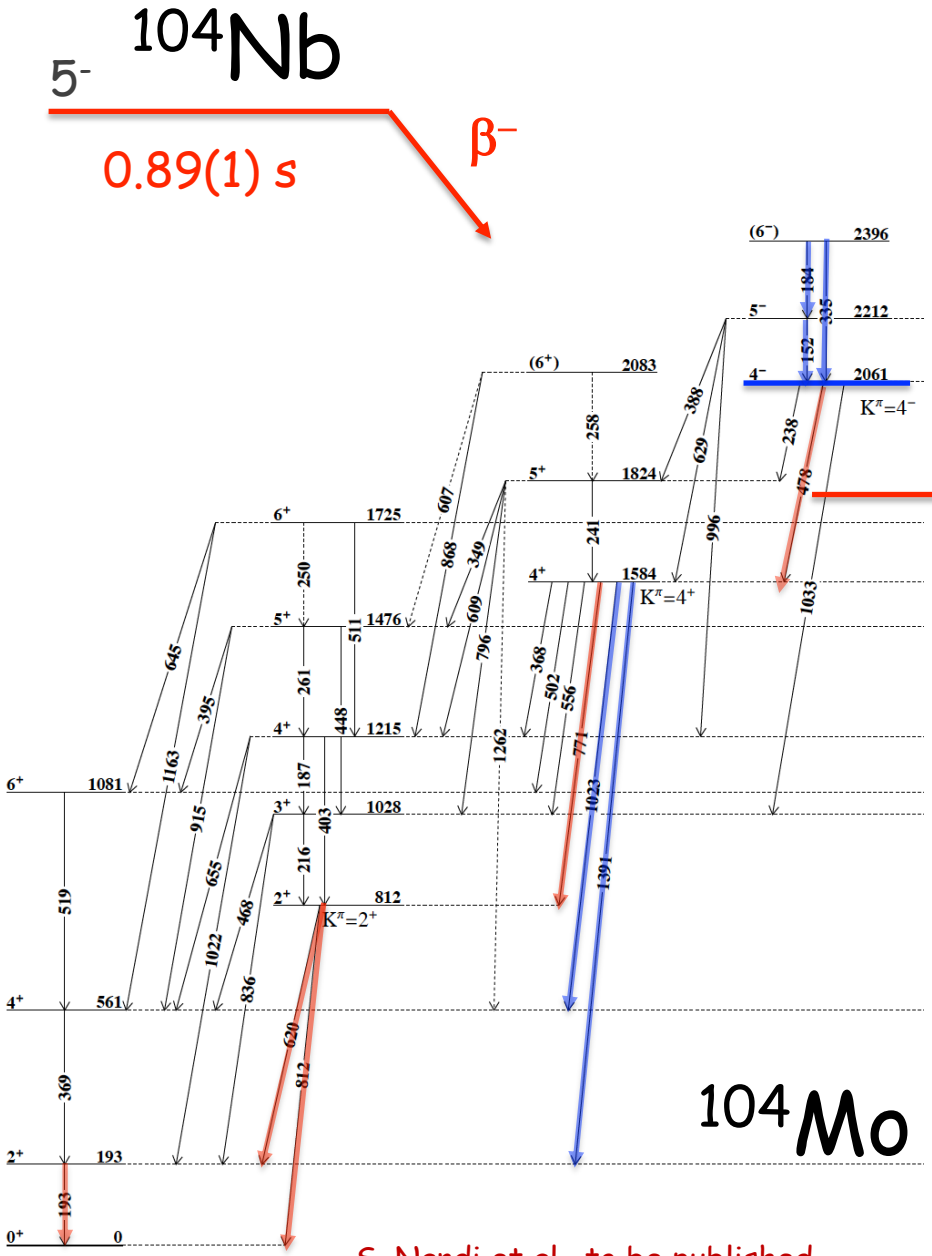
$T_{1/2}$=6.1 s
10-20 s

66 levels
94 gammas

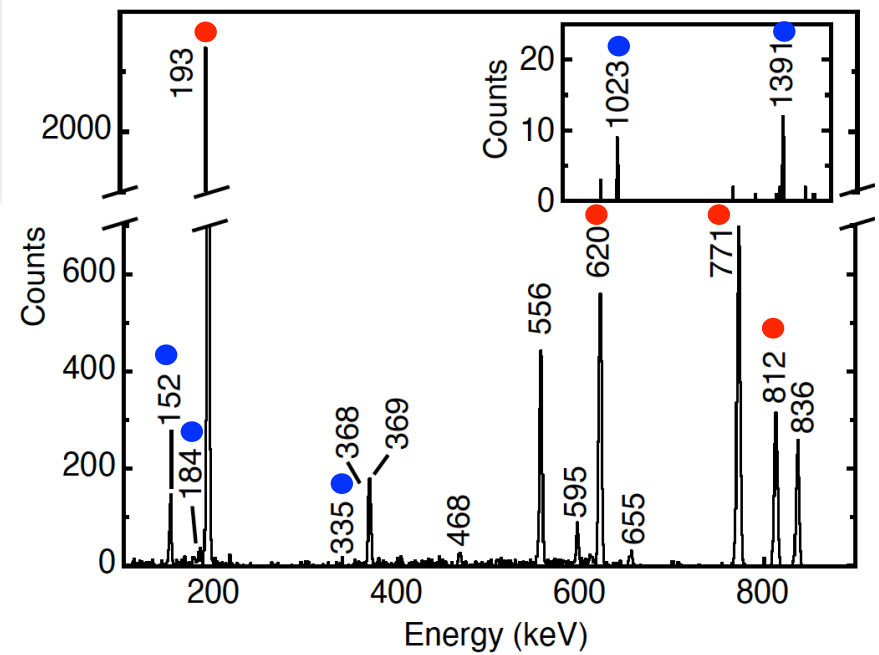




beta-gamma-gamma coincidences

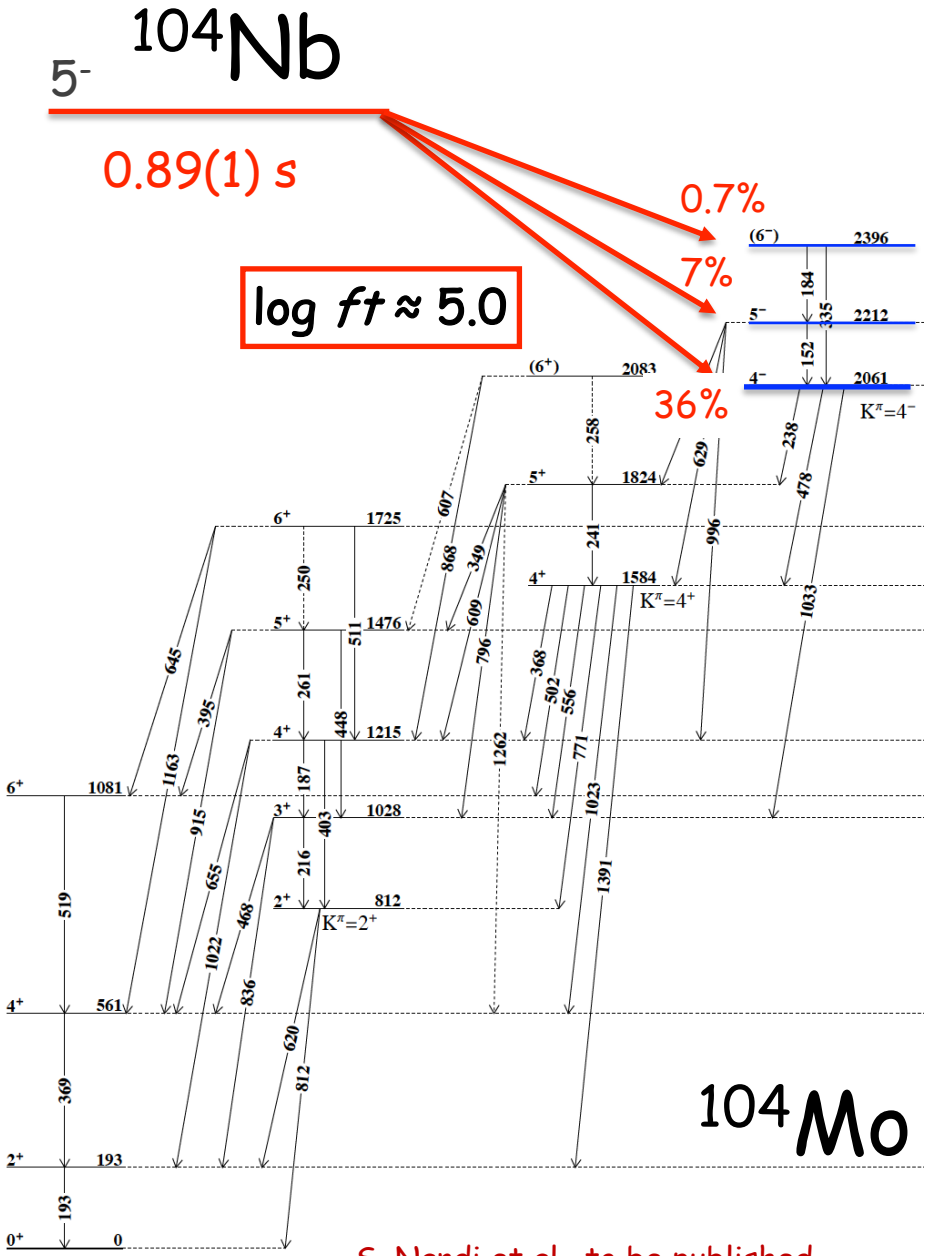


gate 478-keV



S. Nandi et al., to be published

- population of If=4⁻, 5⁻ and 6⁻ in the daughter -> Ii = 5



S. Nandi et al., to be published

Kπ=5-: π5/2[422] ν5/2[532]

spin-flip AU

Kπ=4-: ν3/2[422] ν5/2[532]

- Iπ=4-, 2061-keV and Iπ=5-, 2212-keV levels in ^{104}Mo from γγ(θ) in ^{252}Cf SF

B.M. Musangu et al., Phys. Rev. C104 (2021) 064318

- Kπ=4-: |gK-gR|exp = 0.3 (1)

⇒ ν3/2[422] ν5/2[532] -0.4
⇒ ν3/2[422] ν5/2[532] -0.8
⇒ π3/2[501] π5/2[422] +1.4

observed levels up to 5.7 MeV

^{104m}Nb

(1+)

6.1 (1) s

Q(β⁻)=8.5 MeV

β⁻

6.1 < **log *ft*** < 7.5

- levels with I=0+ & 2+ in ^{104}Mo
- mult=1-2 g-ray cascades

low-K, $|\Omega_n - \Omega_p|$ state
J=(1)

log *ft* -> Ah or 1Fu

7.2

6.8

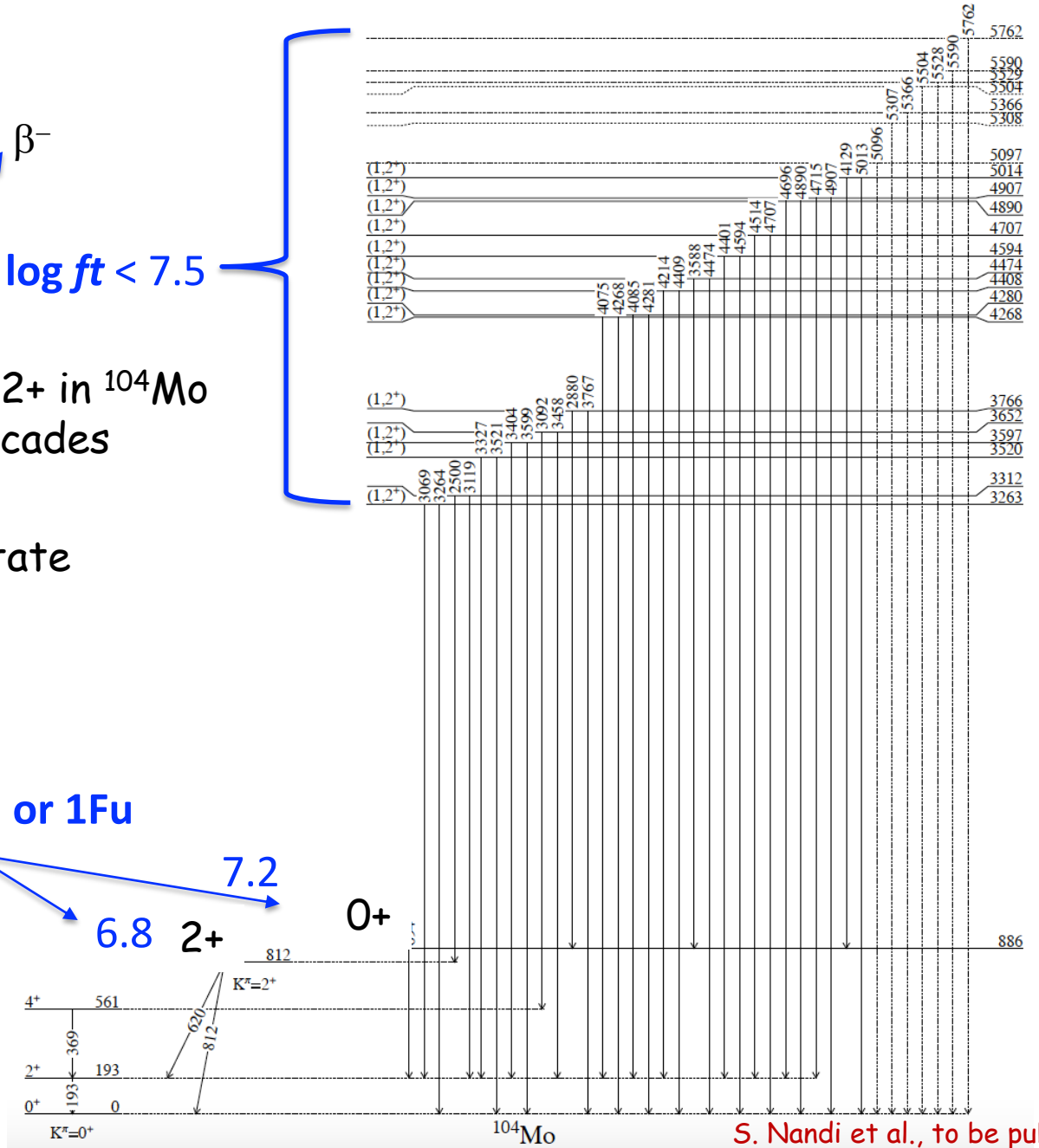
2+

0+

^{104}Mo

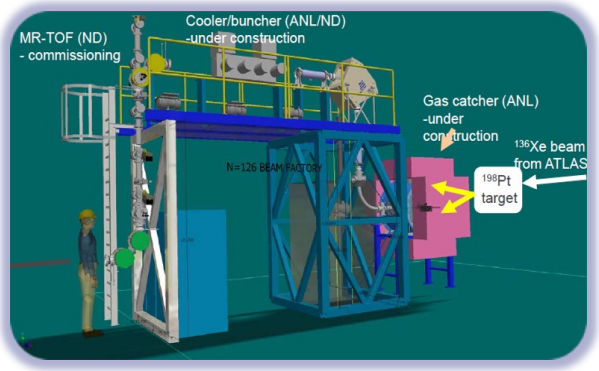
>7.0

>7.3

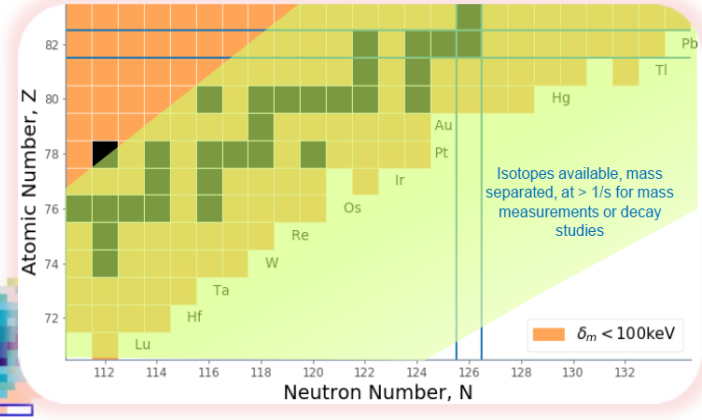


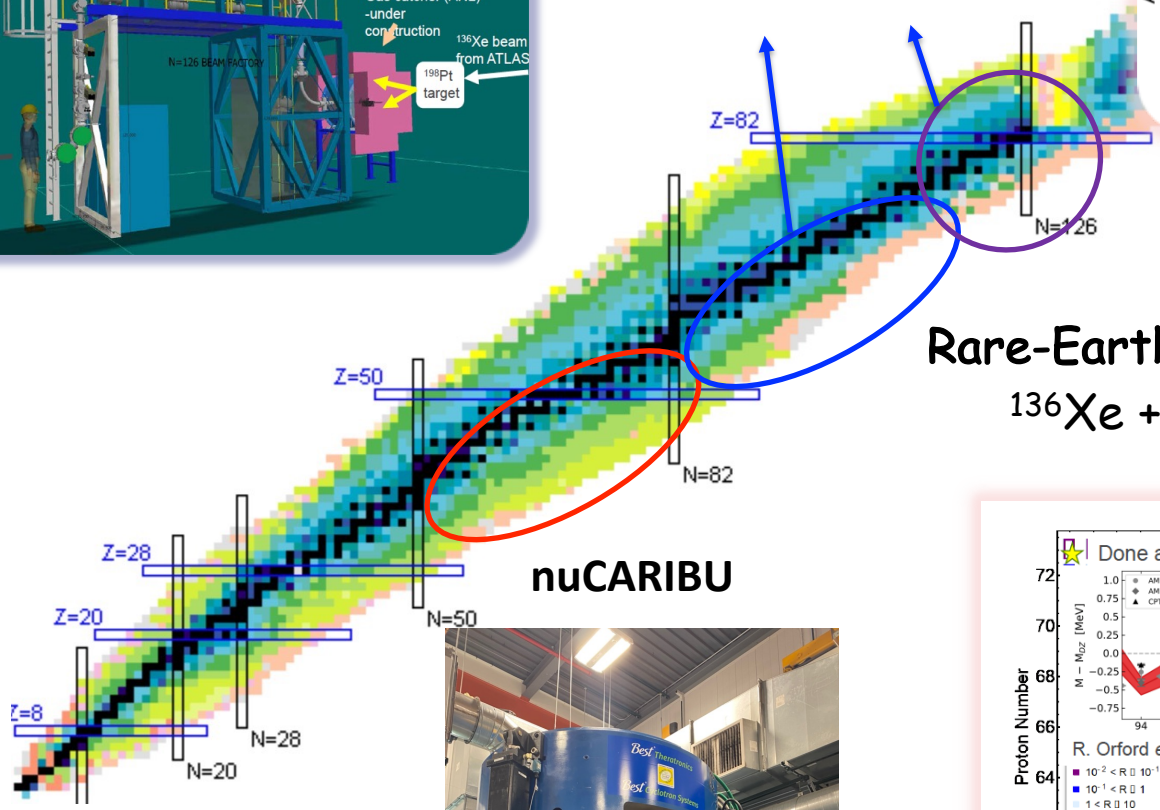
S. Nandi et al., to be published

Outlook



multi-nucleon transfer reactions



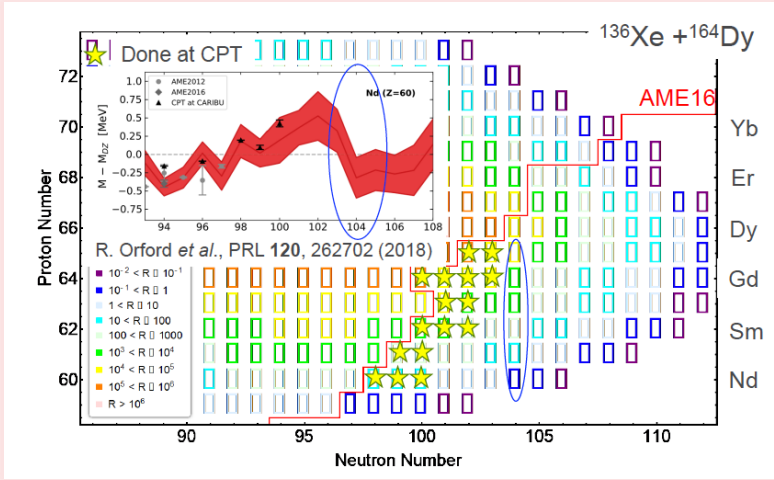


N=126 FACTORY

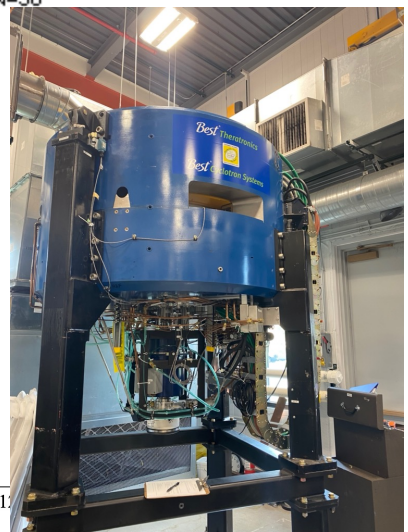
$^{136}Xe + ^{198}Pt$

Rare-Earth FACTORY

$^{136}Xe + ^{164}Dy$



nuCARIBU



$p + ^{6,7}Li$

6 MeV@0.5 mA

Best Cyclotron Systems

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