Complete β-decay study of deformed, odd-odd ^{104,104m}Nb isomers

Soumen Nandi
Subatech (IMT Atlantique, CNRS/IN2P3, Nantes Université)

ISOL-France Workshop VI, May 27 – 29, 2024 @ IPHC

Outline

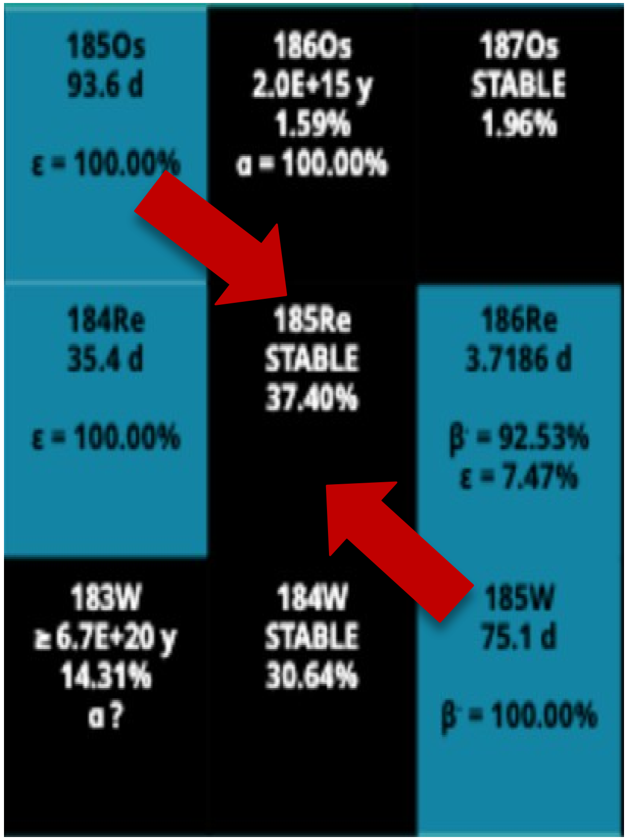
- Introduction
- Motivation
- β Decay of ^{104,104m}Nb
- Summary

Beta decay - Introduction

Beta decay: universal term for all weak-interaction transitions between two neighboring isobars

$\beta^+: p \rightarrow n + e^+ + \nu$

$EC: p + e^- \rightarrow n + \nu$



185Os 93.6 d ε = 100.00%	186Os 2.0E+15 y 1.59% α = 100.00%	187Os STABLE 1.96%
184Re 35.4 d ε = 100.00%	185Re STABLE 37.40%	186Re 3.7186 d β- = 92.53% ε = 7.47%
183W ≥ 6.7E+20 y 14.31% α ?	184W STABLE 30.64%	185W 75.1 d β- = 100.00%

$\beta^-: n \rightarrow p + e^- + \tilde{\nu}$

Classification of β decay:

$$\beta^- : n \longrightarrow p + e^- + \tilde{\nu}$$

$$\boxed{\Delta I = |I_i - I_f| = L_\beta + s_\beta}$$

$e^-\tilde{\nu}$
↑↓ Fermi
$s_\beta = 0$
$0^+ \to 0^+$

$e^-\tilde{\nu}$ $e^-\tilde{\nu}$
↑↑ or ↓↓ Gamow-Teller
$s_\beta = 1$
$1^+ \to 0^+$

Type of transition	Order of forbiddenness	ΔI	$\pi_i\pi_f$
Allowed		0,+1	+1
Forbidden unique	1	∓2	-1
	2	∓3	+1
	3	∓4	-1
	4	∓5	+1
	.	.	.
Forbidden	1	0, ∓1	-1
	2	∓2	+1
	3	∓3	-1
	4	∓4	+1
	.	.	.

transition probability

S_{if} - strength function

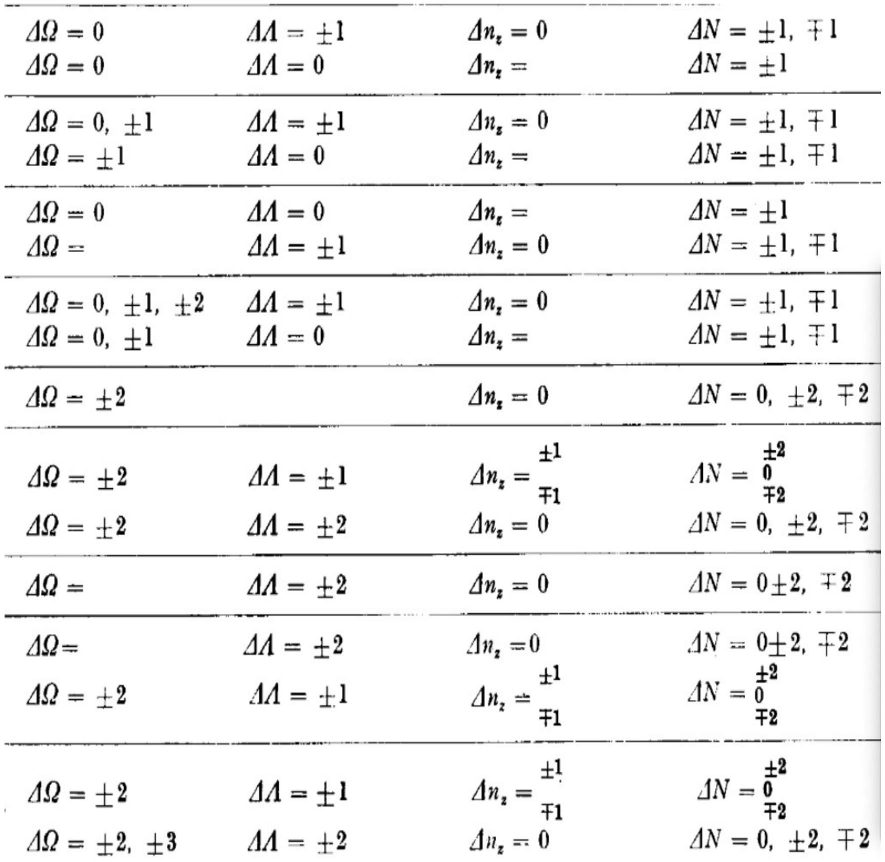
$$\boxed{B_{if}} \simeq \frac{\left|<\psi_f|\tau_k^\pm \quad or \quad \sigma\tau^\pm|\psi_i>\right|^2}{2J_i+1} = Const\boxed{\frac{I_{\beta_{if}}}{f(Z,Q_\beta - E_f)\times T_{1/2}}} = Const\frac{1}{ft} \Rightarrow t\ (T_{1/2}/I_\beta) \sim (1/Q_\beta^5)$$

f : energy and nuclear structure dependence of decay transition

Deformed β decay selection rules

Nuclear level in deformed nuclei represented by → $[Nn_z\Lambda\Omega]$

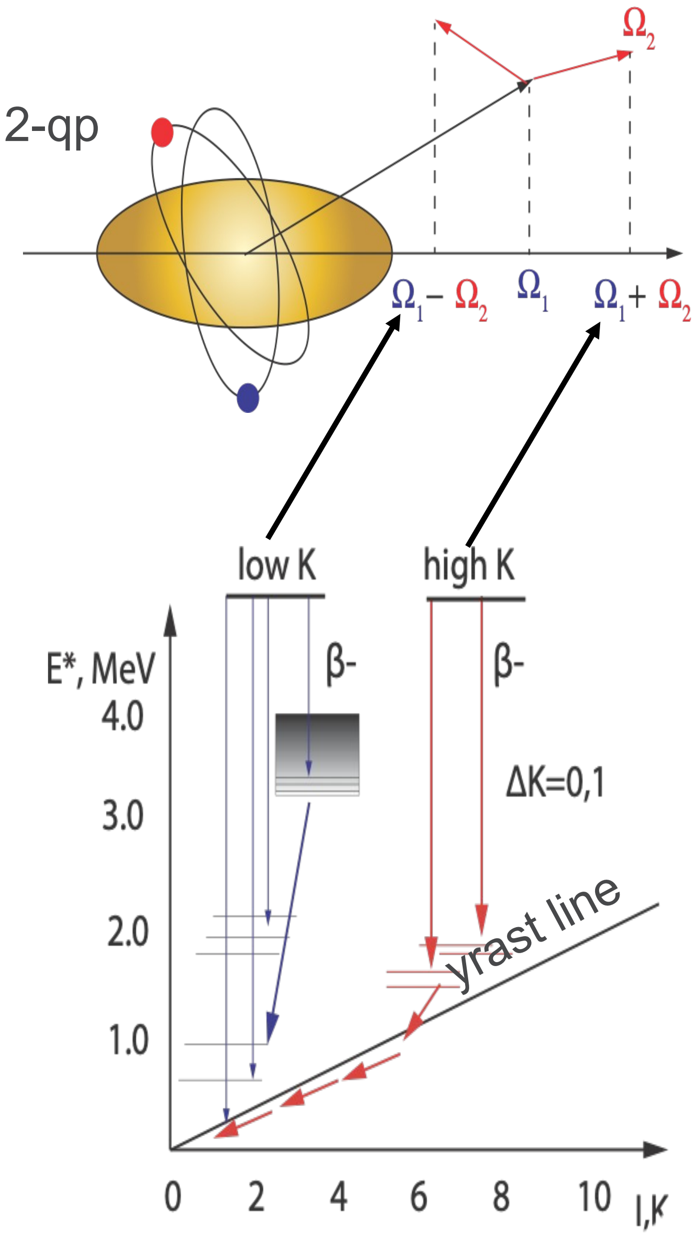
$\Delta N = \Delta n_z = \Delta\Lambda = 0$, $\Delta\Omega = 0, \pm 1$ $(4.9 < \log ft < 5.1)$ Allowed unhindered β decay

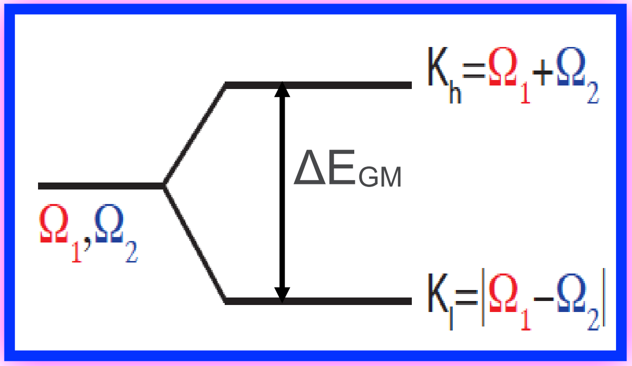


First forbidden	$\Delta\Omega = 0$	$\Delta\Lambda = \pm 1$	$\Delta n_z = 0$	$\Delta N = \pm 1, \mp 1$
	$\Delta\Omega = 0$	$\Delta\Lambda = 0$	$\Delta n_z =$	$\Delta N = \pm 1$
	$\Delta\Omega = 0, \pm 1$	$\Delta\Lambda = \pm 1$	$\Delta n_z = 0$	$\Delta N = \pm 1, \mp 1$
	$\Delta\Omega = \pm 1$	$\Delta\Lambda = 0$	$\Delta n_z =$	$\Delta N = \pm 1, \mp 1$
	$\Delta\Omega = 0$	$\Delta\Lambda = 0$	$\Delta n_z =$	$\Delta N = \pm 1$
	$\Delta\Omega =$	$\Delta\Lambda = \pm 1$	$\Delta n_z = 0$	$\Delta N = \pm 1, \mp 1$
	$\Delta\Omega = 0, \pm 1, \pm 2$	$\Delta\Lambda = \pm 1$	$\Delta n_z = 0$	$\Delta N = \pm 1, \mp 1$
	$\Delta\Omega = 0, \pm 1$	$\Delta\Lambda = 0$	$\Delta n_z =$	$\Delta N = \pm 1, \mp 1$
Second forbidden	$\Delta\Omega = \pm 2$		$\Delta n_z = 0$	$\Delta N = 0, \pm 2, \mp 2$
	$\Delta\Omega = \pm 2$	$\Delta\Lambda = \pm 1$	$\Delta n_z = \substack{\pm 1 \\ \mp 1}$	$\Delta N = \substack{\pm 2 \\ 0 \\ \mp 2}$
	$\Delta\Omega = \pm 2$	$\Delta\Lambda = \pm 2$	$\Delta n_z = 0$	$\Delta N = 0, \pm 2, \mp 2$
	$\Delta\Omega =$	$\Delta\Lambda = \pm 2$	$\Delta n_z = 0$	$\Delta N = 0 \pm 2, \mp 2$
	$\Delta\Omega =$	$\Delta\Lambda = \pm 2$	$\Delta n_z = 0$	$\Delta N = 0 \pm 2, \mp 2$
	$\Delta\Omega = \pm 2$	$\Delta\Lambda = \pm 1$	$\Delta n_z = \substack{\pm 1 \\ \mp 1}$	$\Delta N = \substack{\pm 2 \\ 0 \\ \mp 2}$
	$\Delta\Omega = \pm 2$	$\Delta\Lambda = \pm 1$	$\Delta n_z = \substack{\pm 1 \\ \mp 1}$	$\Delta N = \substack{\pm 2 \\ 0 \\ \mp 2}$
	$\Delta\Omega = \pm 2, \pm 3$	$\Delta\Lambda = \pm 2$	$\Delta n_z = 0$	$\Delta N = 0, \pm 2, \mp 2$

Alaga et al., Nucl.Phys. 625, (1957) **4**

Beta decay of deformed, odd-odd nuclei



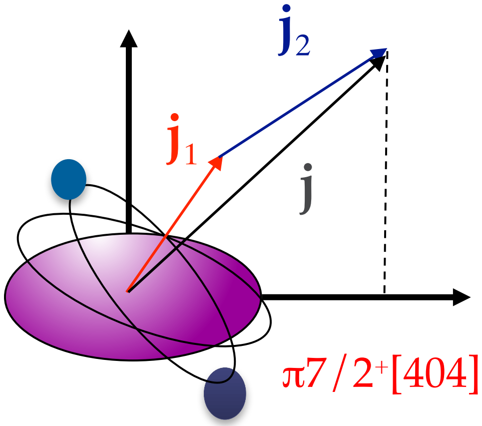


$$E= E_p+E_n+Vpn(GM\ shift)+(-1)^I B_{Newby(k=0)}$$

- **high-Ω** orbitals near both the **proton** & **neutron** Fermi surfaces favor the existence of β-decaying spin-trap isomers (low-K & high-K) – two distinctive decay patterns
- which states will be populated in the daughter nucleus depend not only on **the spin differences** (allowed, 1st forbidden, etc.), but also on the **K differences**, and the structure of parent and daughter states, e.g. **configuration changes ...**

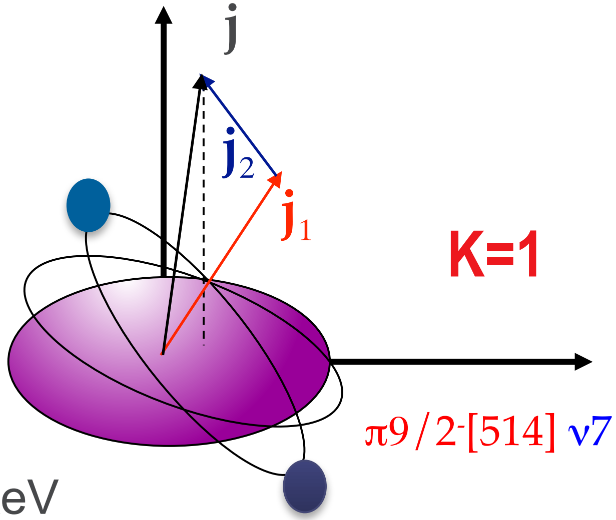
Beta decay of deformed odd-odd nuclei – cont.

^{178}Ta



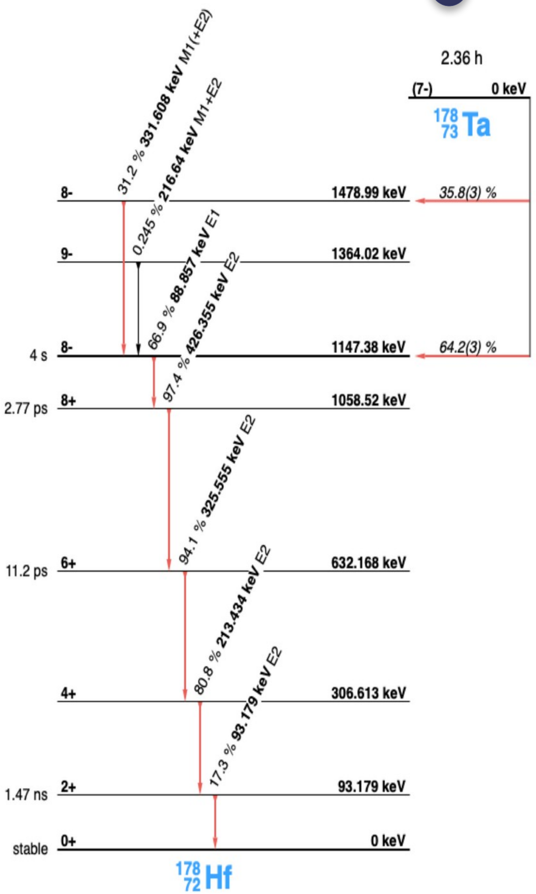
K=7

π7/2$^+$[404] ν7/2$^-$[514]



K=1

π9/2$^-$[514] ν7/2$^-$[514]



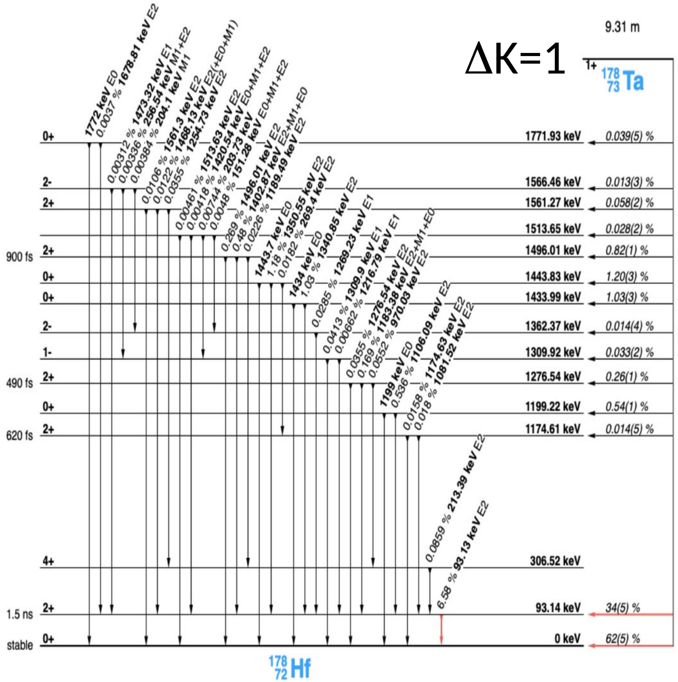
ΔK=1

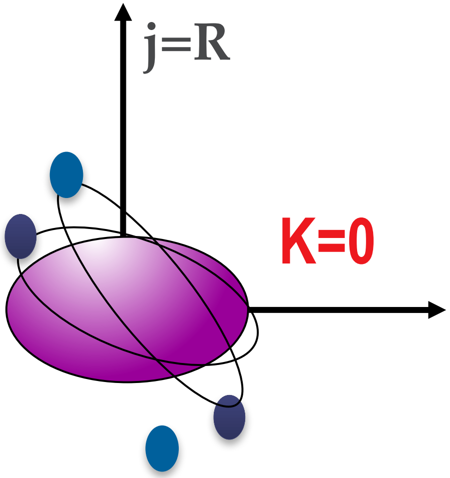
π7/2$^+$[404] π9/2$^-$[514]

log *ft* =4.8

Q$_{EC}$=1837 keV

ΔK=1



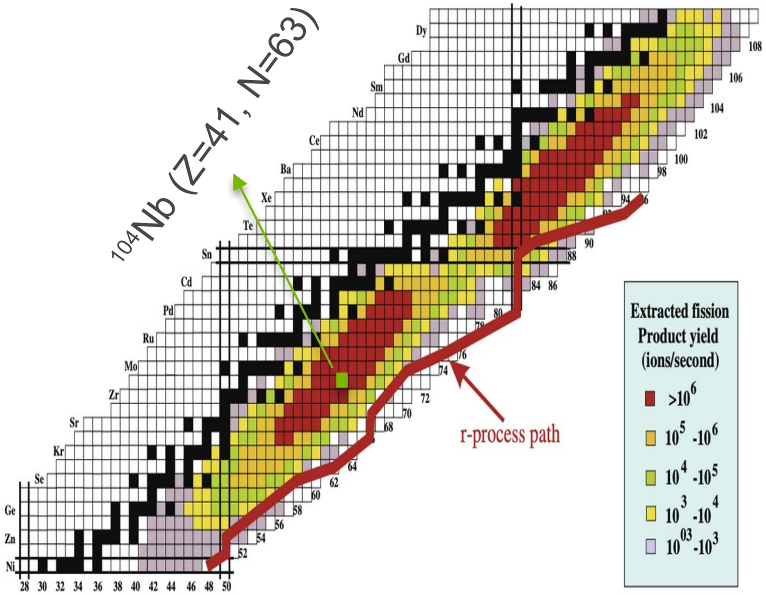


K=0

ν7/2$^-$**[514]** -> π9/2$^-$**[514]**

log *ft* =4.7

Motivations



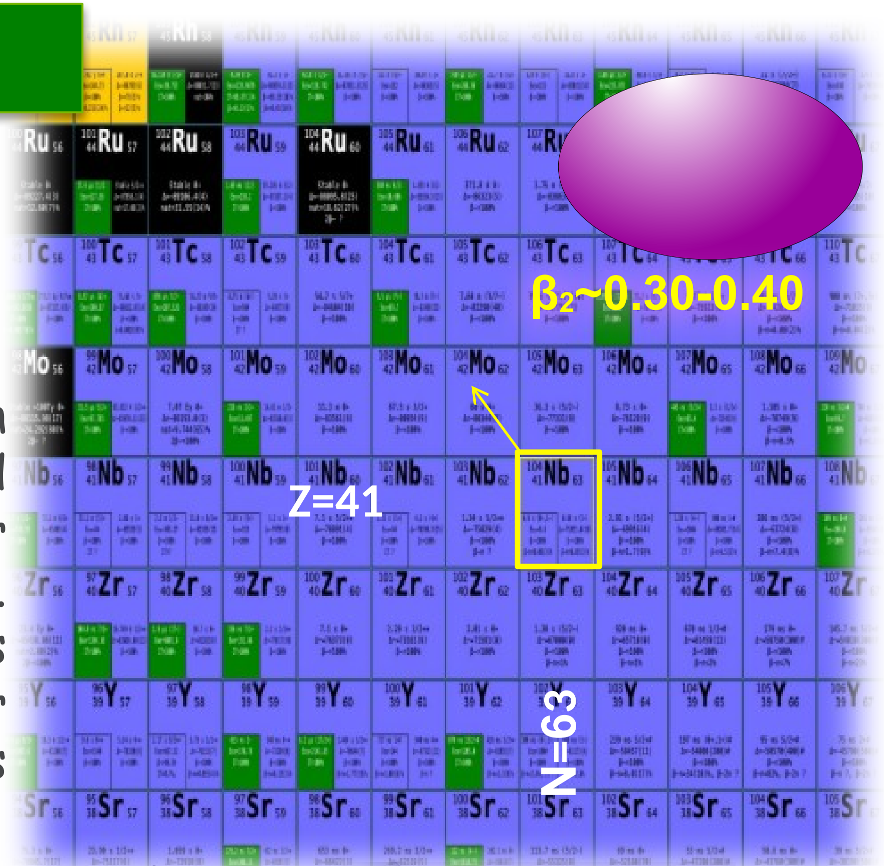
Accessible region in CARIBU

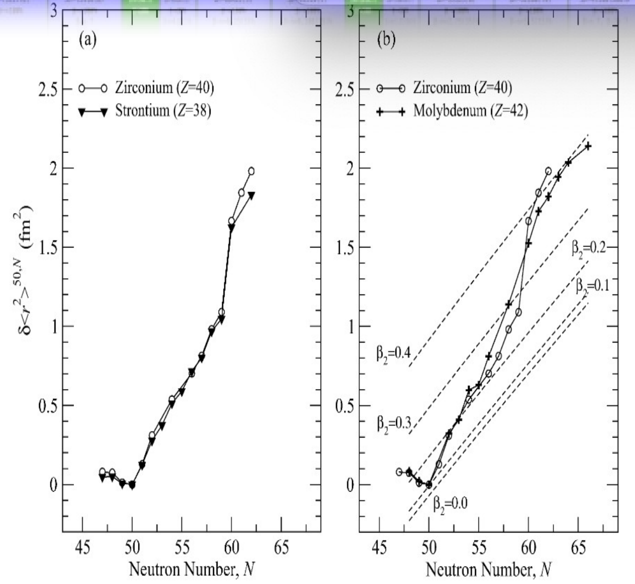
- The difficulty in accessing the nuclei in neutron rich A~100 has not allowed sufficient information to be gathered to support or refute this scenario.

- Knowledge on the properties of this nuclei are critical for the astrophysical implications in the r-process.
- The β-decay properties are important to the application and predict the reactor antineutrino spectra and decay heat of nuclear reactor.

A~100 deformed region

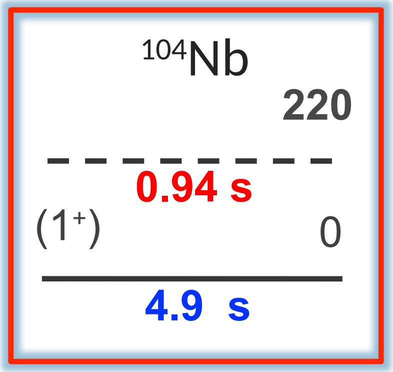
- The neutron rich A~100 lie in a region between the major shell gap of 28<Z<50 and 50<N<82 and shows sudden change in nuclear shape at N=60 for Sr and Zr isotopes. Whereas the change in shape for Mo is gradual at N=60. Therefore, the nuclear structure information in this region has significant importance.
- Deformed neutron rich odd-odd nuclei has also multiple beta decay states e.g Y, Nb based on different configuration. But the experimental data is very scarce.



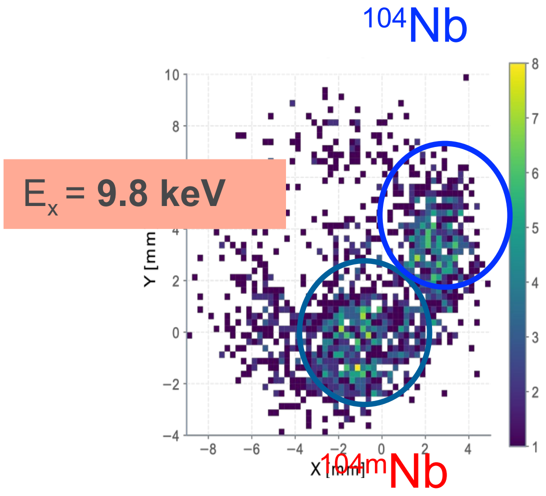


Charlwood et al., Phys. Lett. B 674, (2009) 23-27

Previously known information's on ^{104}Nb



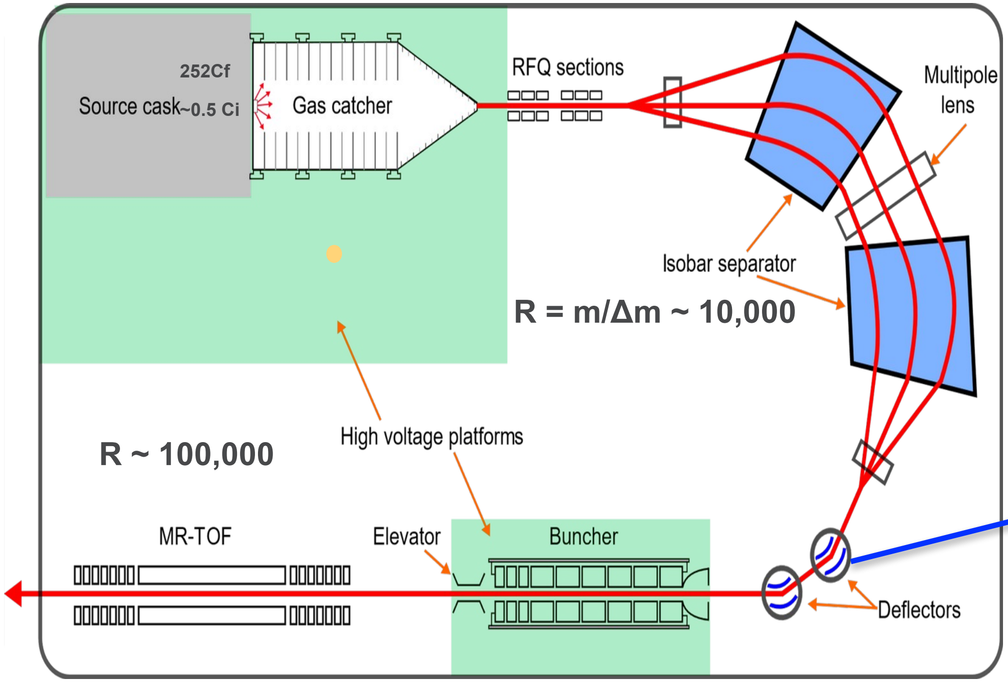
J. Blachot, NDS 108 (2007) 2035



R. Orford, PhD thesis 2021

- Two β decay states present in ^{104}Nb nucleus with different half life values.
- Separation between two β decay state was 220 keV from the β decay end point energy measurement.
- There is no experimental data based on the high spin β decay state in NDS.
- Recent TAGS measurement was done by MSU group for this high spin β decay state.
- On the other hand, a mass measurement (CPT) shows the separation between two β decay state is 9.8 keV

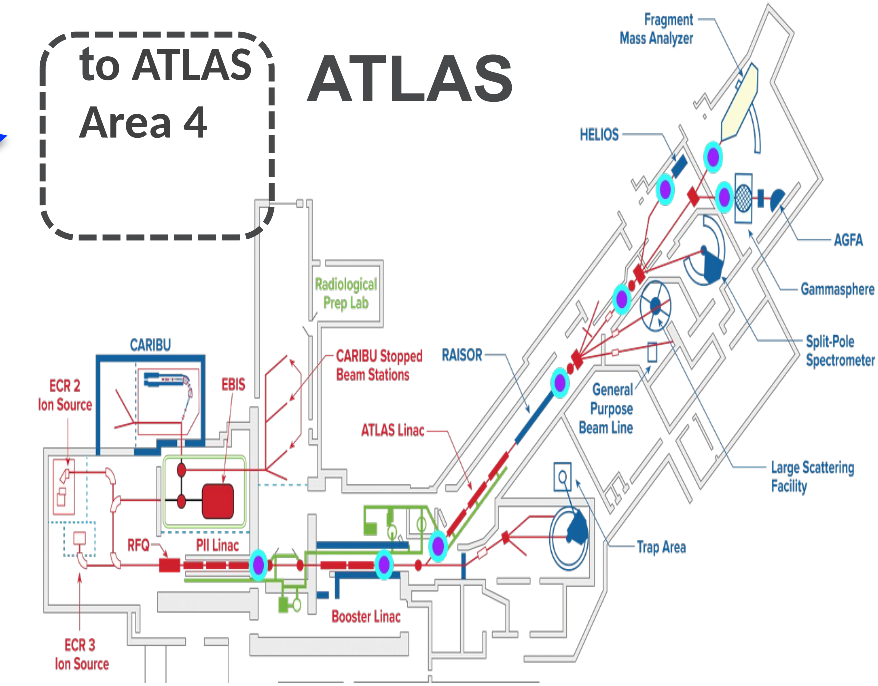
Decay Spectroscopy @ ANL



Schematic presentation of CARIBU

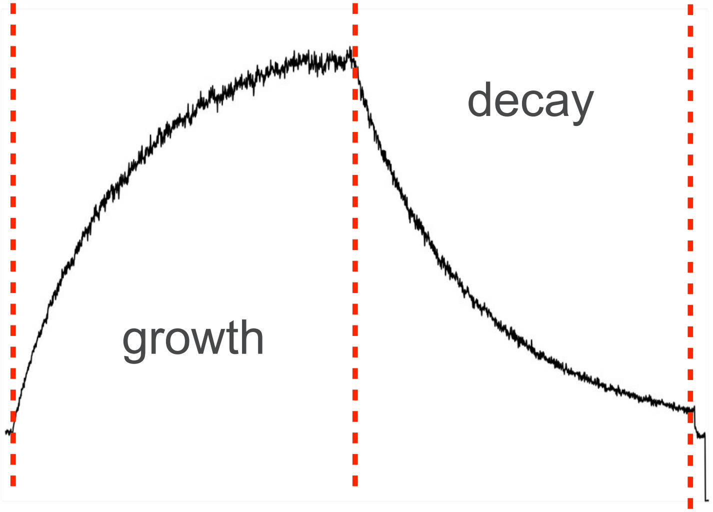
to ATLAS Area 4

ATLAS

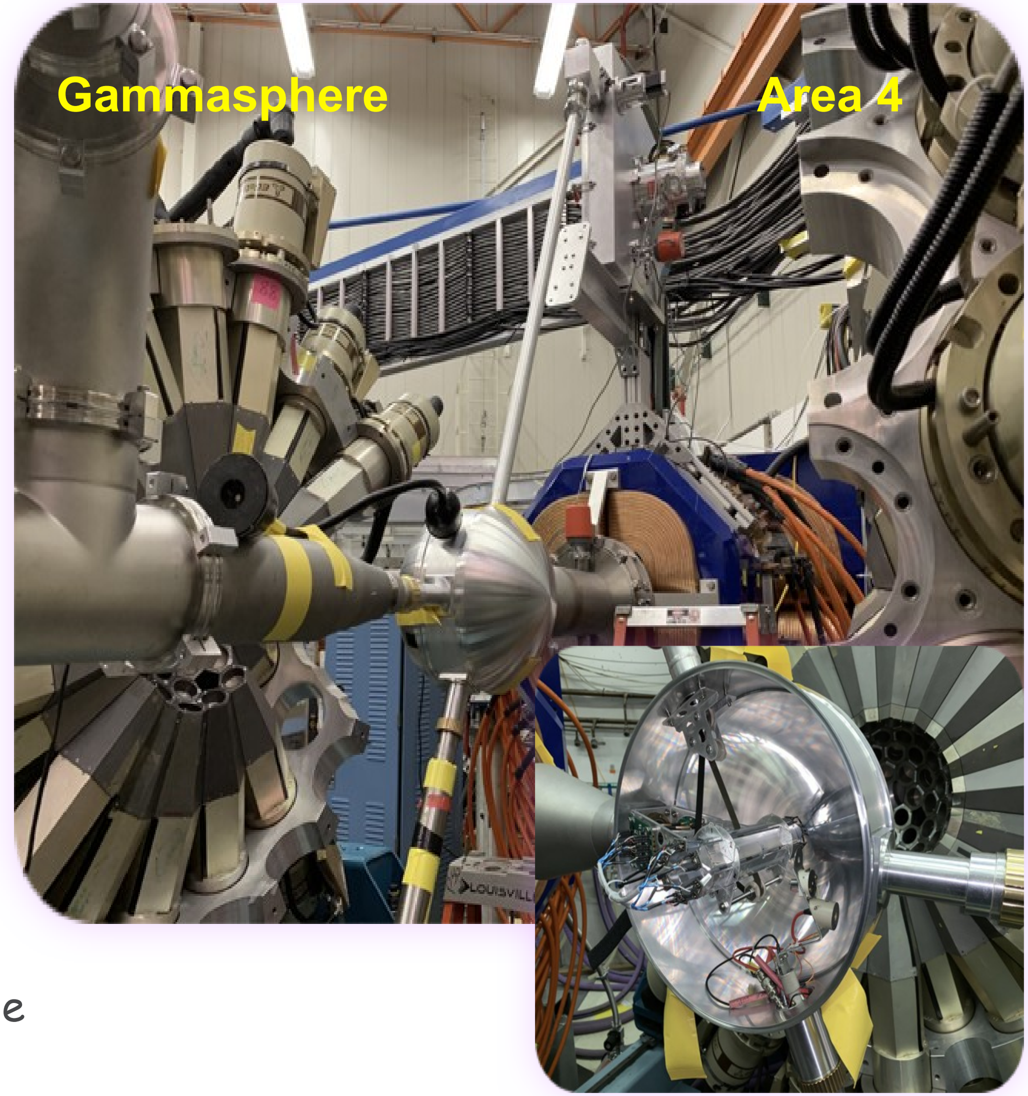


New β-decay station @ ANL

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

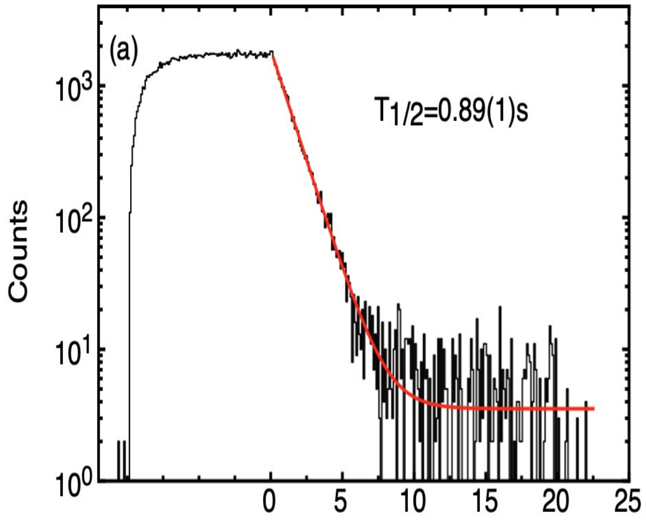


- The data are collected in two different tape cycle modes 10/20s and 10/40s.
- 10/40s cycle is considered to get daughter and grand-daughter decay of ^{104}Nb.

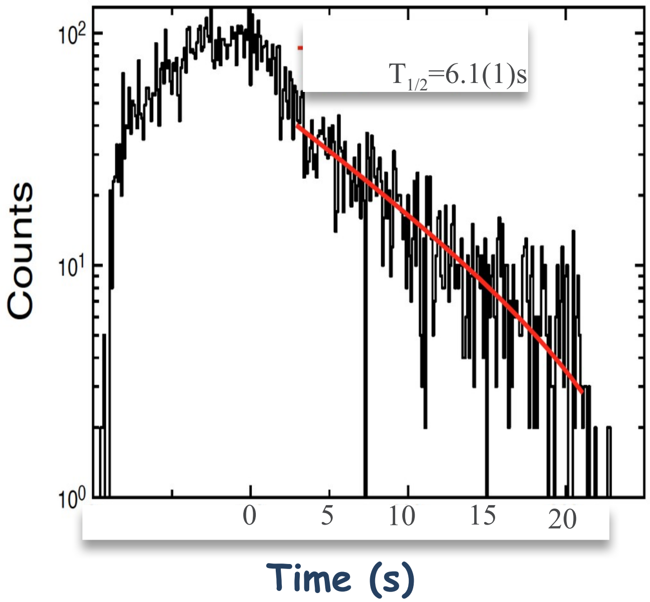


- **HEART – Hexagonal Array for Tiggering**
- **6 EJ-204 plastic scint.**
- E_β~ 75% **from β–γ singles & coin.**
- **Powerful γ–γ–β-t coincidence device**

Measurement of Half-life ($T_{1/2}$) values



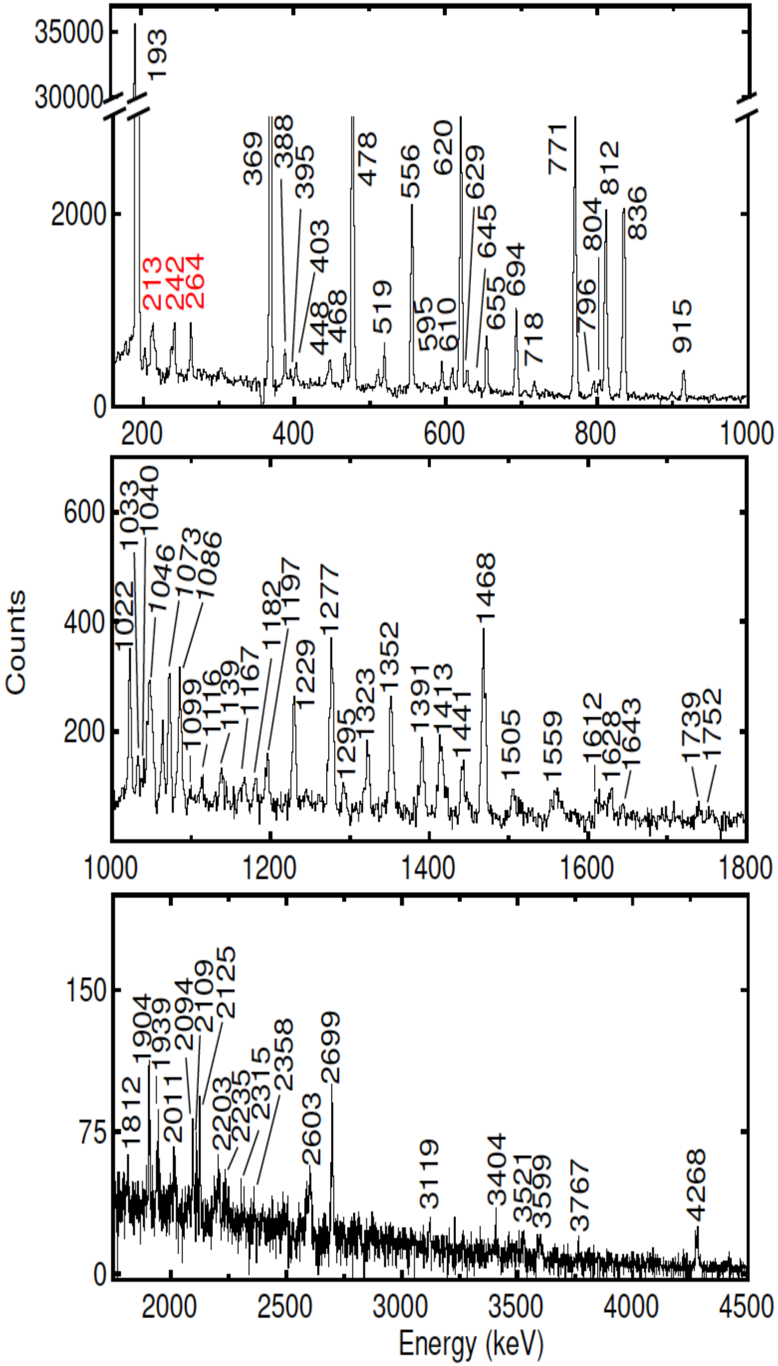
- Time spectrum gate by 478+771 keV transition.
- $T_{1/2}$ value obtained with better precision using single exponential decay curve fit.
- Populate high spin levels



- Time spectrum gate by 1277 +1352 keV transition.
- $T_{1/2}$ value modified using single exponential decay curve fit.
- Populate low spin levels

High spin β decay state in ^{104m}Nb (Short lived)

- The complete β decay scheme based on the high spin β decay state in ^{104}Nb has been reported for the first time in this work .
- Different β-gated, Eγ-Eγ coincidence matrix was utilized to build the decay schemes of ^{104}Nb. The total counts of 3.8×10^6 has been reported from β gated γ singles spectrum.
- β gated singles with a time gate of 0 to 5 s mostly contains γ rays from short lived isomeric state in ^{104}Nb.
- Daughter and grand daughter contribution has been subtracted from 10/40s data

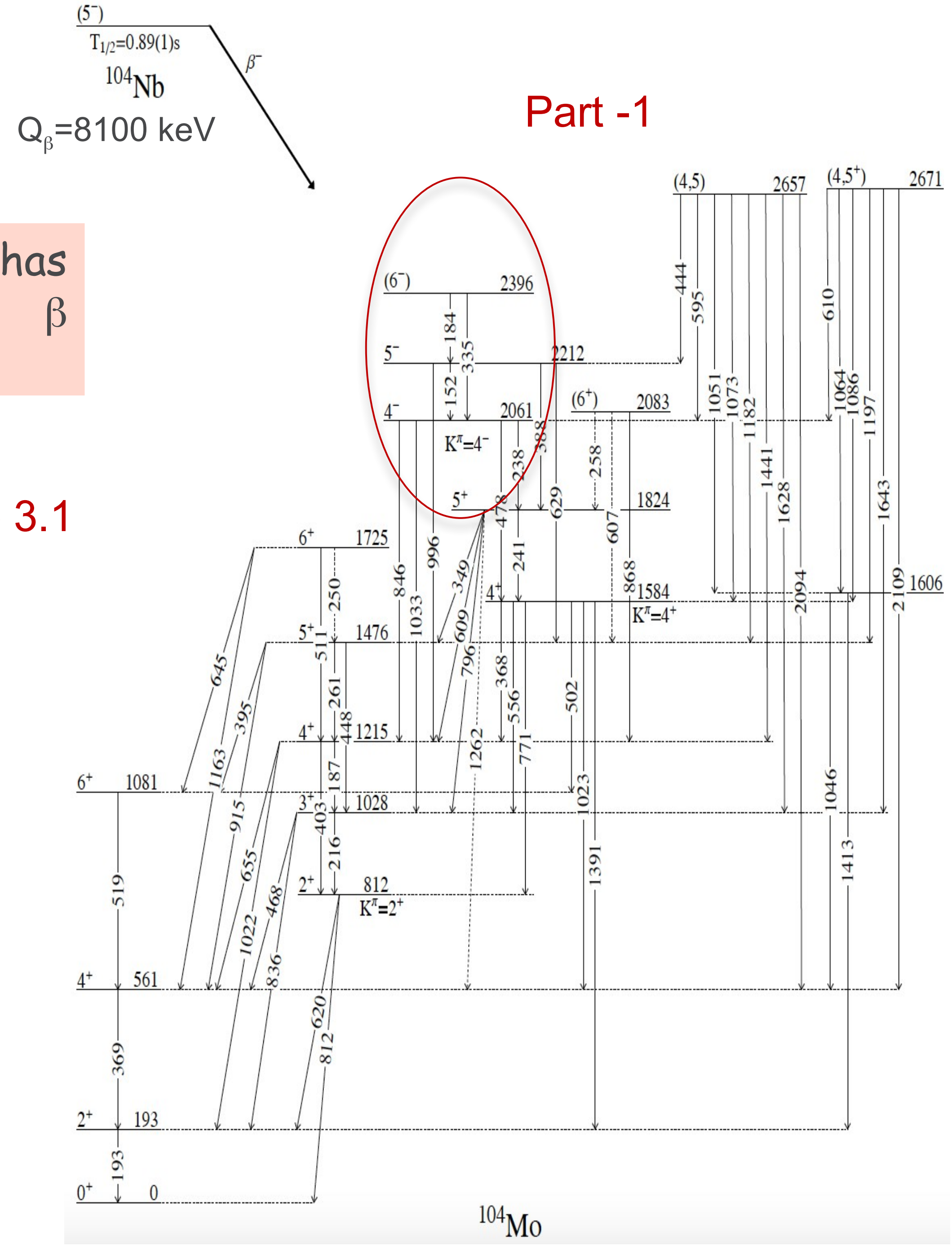


- New decay scheme from ^{104m}Nb β decay state.

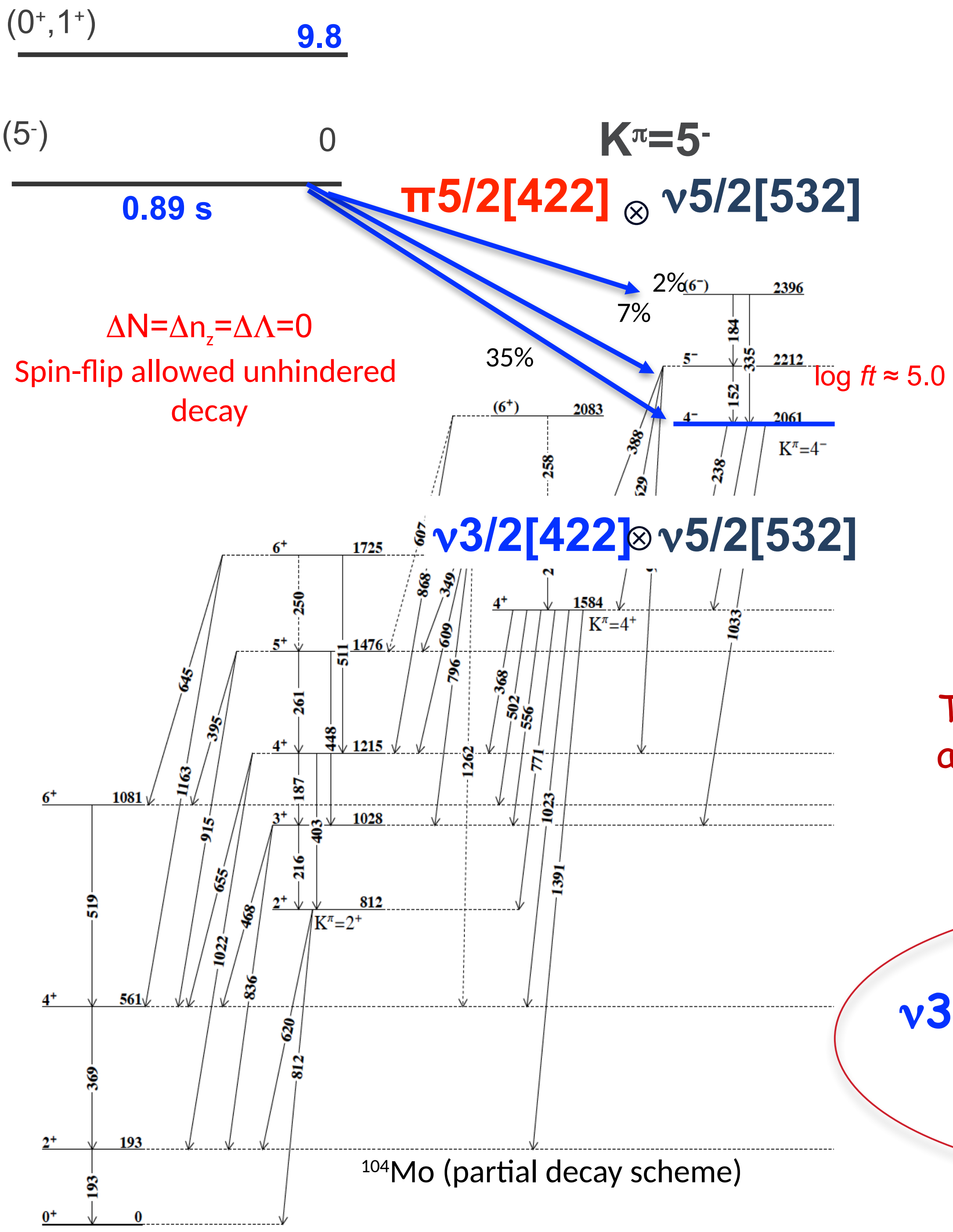
- 2061 keV level has predominant β feeding

Observed levels up to 3.1 MeV

Part -1



^{104}Nb



$K^{\pi}=5^{-}$

$\pi 5/2[422] \otimes \nu 5/2[532]$

$\Delta N=\Delta n_z=\Delta\Lambda=0$

Spin-flip allowed unhindered decay

$\nu 3/2[422] \otimes \nu 5/2[532]$

log *ft* ≈ 5.0

^{104}Mo (partial decay scheme)

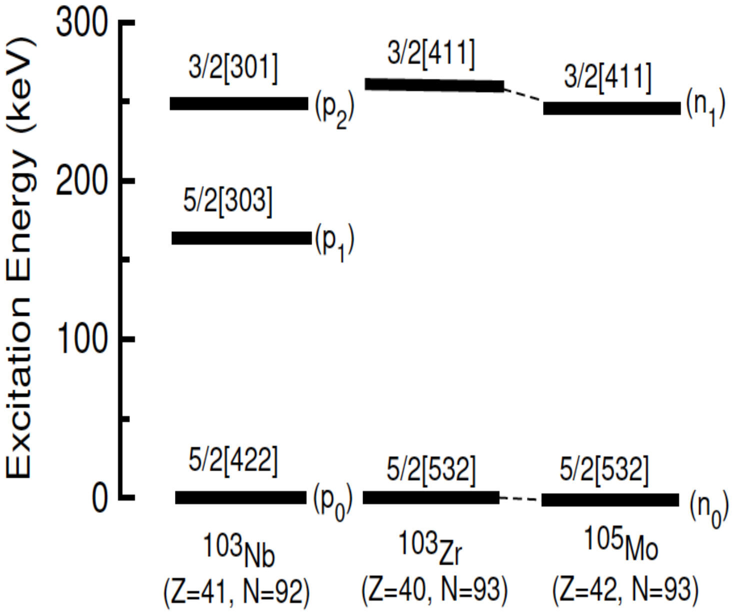
- Spin and parity of $K^{\pi}=4^{-}$ band are adopted from Phys. Rev. C 104, 064318, (2021).
- The 4^{-} state in $K^{\pi}=4^{-}$ band has maximum β-feeding intensity.
- Direct β-feeding intensity at (6-) state in $K^{\pi}=4^{-}$ band also justifies the spin and parity of the high spin β decay state in ^{104}Nb as (5^{-}).

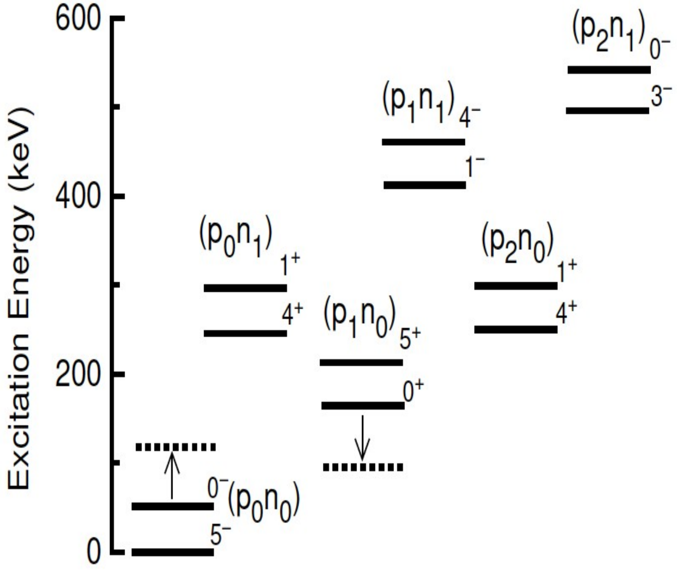
The configuration of $K^{\pi}=4^{-}$ band has been assigned from the experimental g_k-g_R value.

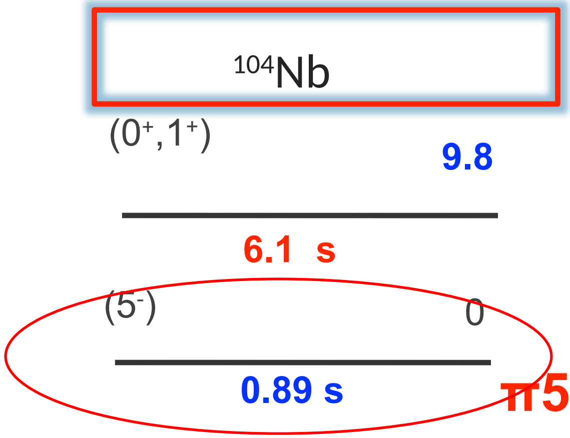
$\nu 3/2[422] \rightarrow \pi 5/2[422]$

log *ft* ≈ 5.0

Configuration of high spin β decaying state in ^{104}Nb







^{104}Nb

$(0^+,1^+)$ **9.8**

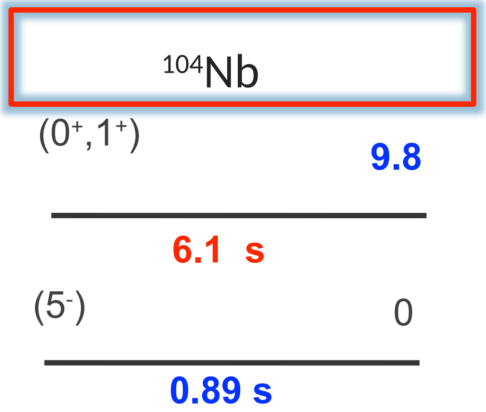
6.1 s

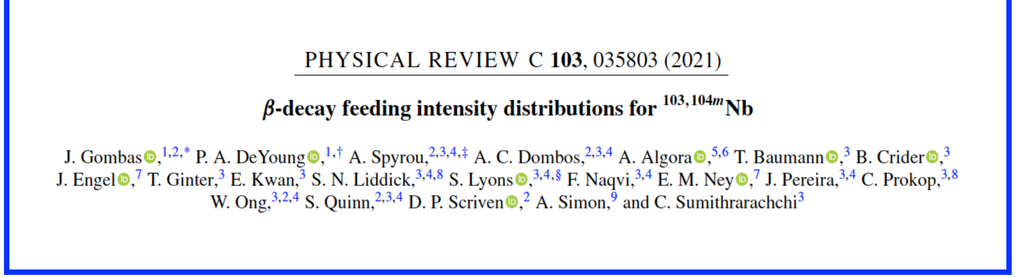
(5^-) 0

0.89 s

$K^\pi=5^-$

$\pi5/2[422] \otimes \nu5/2[532]$





PHYSICAL REVIEW C **103**, 035803 (2021)

β-decay feeding intensity distributions for ^{103,104m}Nb

J. Gombas,[1,2,*] P. A. DeYoung,[1,†] A. Spyrou,[2,3,4,‡] A. C. Dombos,[2,3,4] A. Algora,[5,6] T. Baumann,[3] B. Crider,[3] J. Engel,[7] T. Ginter,[3] E. Kwan,[3] S. N. Liddick,[3,4,8] S. Lyons,[3,4,§] F. Naqvi,[3,4] E. M. Ney,[7] J. Pereira,[3,4] C. Prokop,[3,8] W. Ong,[3,2,4] S. Quinn,[2,3,4] D. P. Scriven,[2] A. Simon,[9] and C. Sumithrarachchi[3]

TAGS measurement using SUN at NSCL/MSU

- ^{104m}Nb is associated with 0.9 s the decaying state
- no decay scheme was established
- data discrepancy & different interpretation

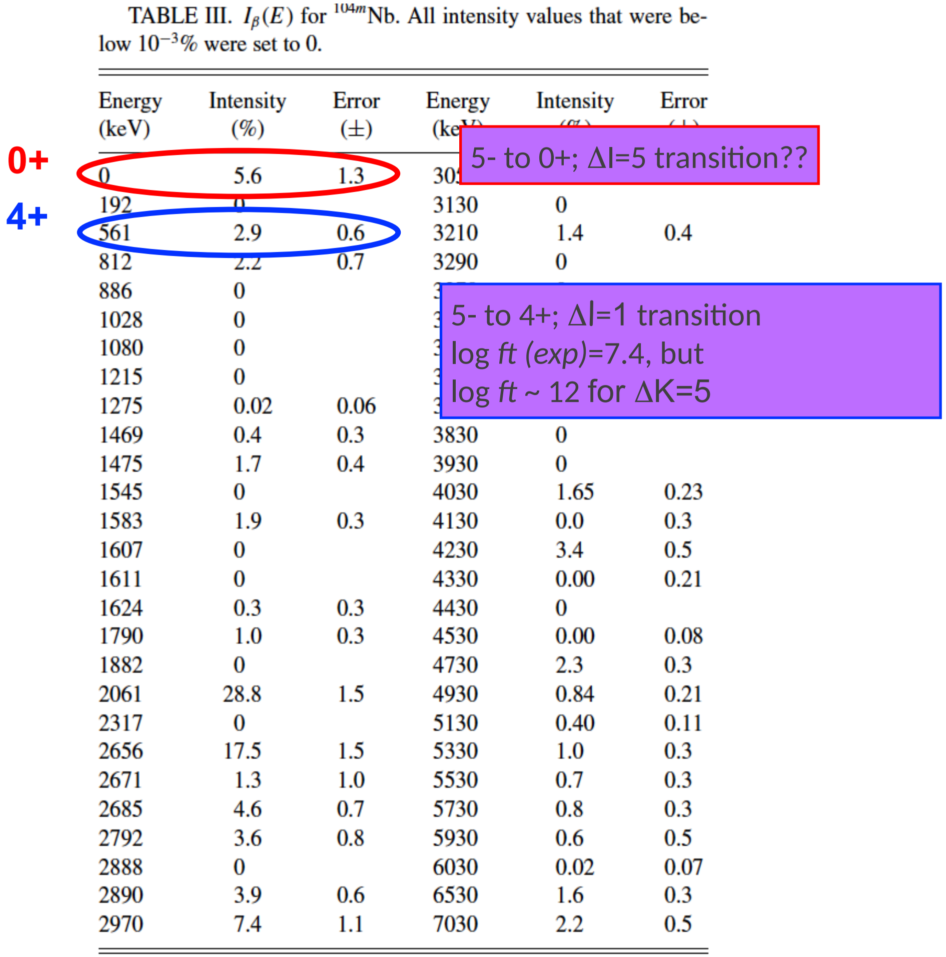


TABLE III. $I_\beta(E)$ for ^{104m}Nb. All intensity values that were below 10^{-3}% were set to 0.

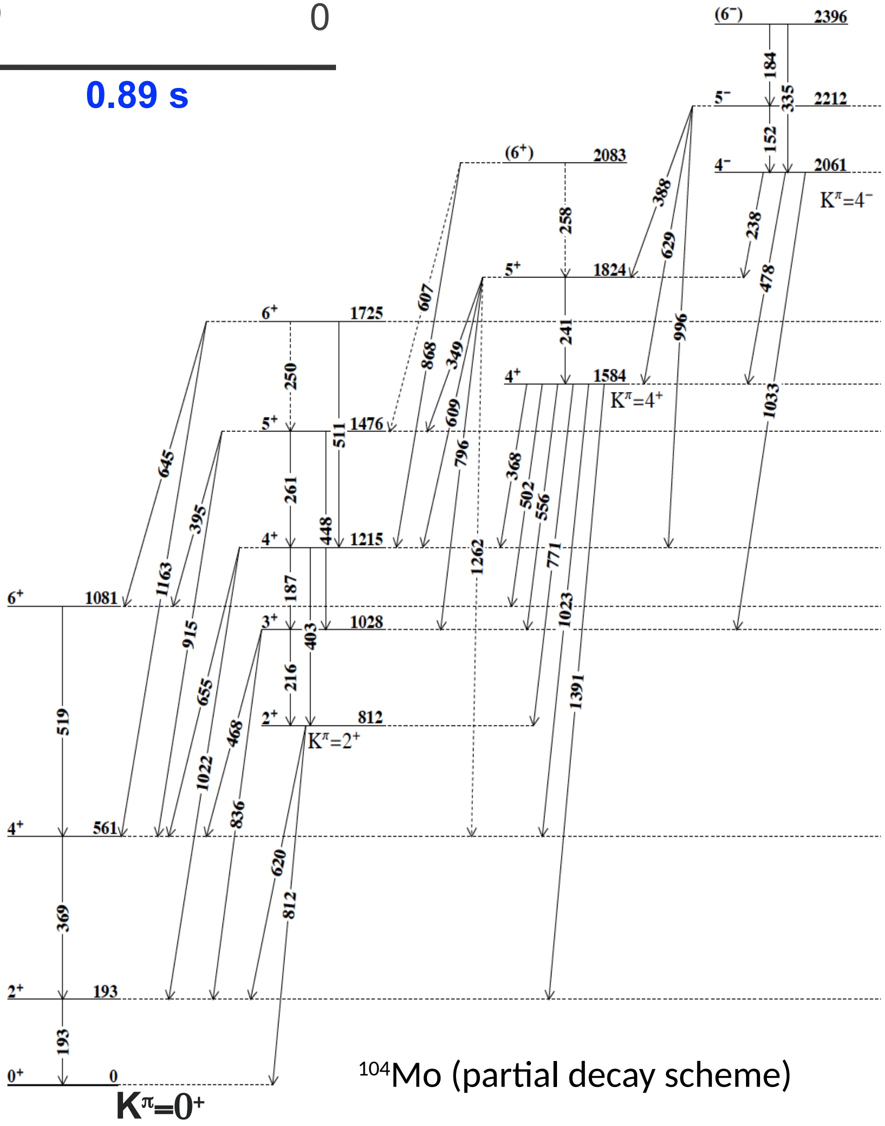
Energy (keV)	Intensity (%)	Error (±)	Energy (keV)	Intensity (%)	Error (±)
0	5.6	1.3	305		
192	0		3130	0	
561	2.9	0.6	3210	1.4	0.4
812	2.2	0.7	3290	0	
886	0		3		
1028	0		3		
1080	0		3		
1215	0		3		
1275	0.02	0.06	3		
1469	0.4	0.3	3830	0	
1475	1.7	0.4	3930	0	
1545	0		4030	1.65	0.23
1583	1.9	0.3	4130	0.0	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

0+

4+

5- to 0+; ΔI=5 transition??

5- to 4+; ΔI=1 transition
log *ft (exp)*=7.4, but
log *ft* ~ 12 for ΔK=5



^{104}Mo (partial decay scheme)

Summary

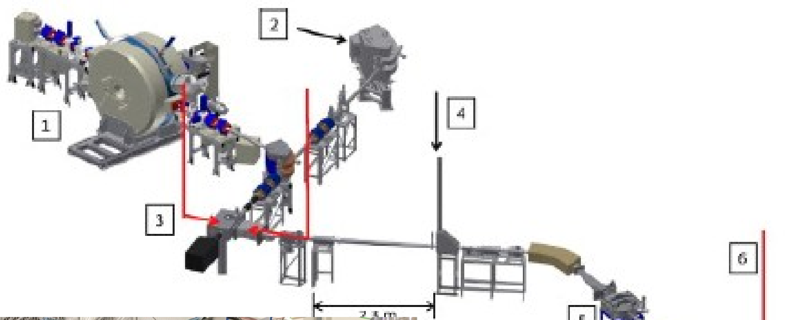
^{104m}Nb

- The spin and parity of the parent β decay scheme has been reported as (5^-).
- Half-life value of the β decaying state has been modified with better precession.
- A new configuration of ν3/2[422] ⊗ ν5/2[532] has been assigned to the 2061 keV level.
- Spin flip unhindered β decay has been observed for the first time in A~100 region which follows deformed β decay selection rules.
- A new comprehensive decay scheme has been reported for the first time.

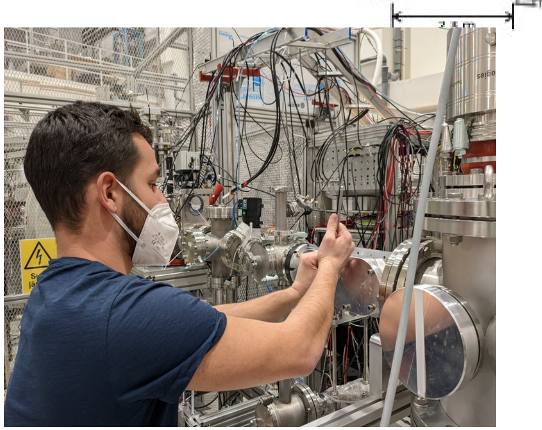

Thank You

TAGS 2022

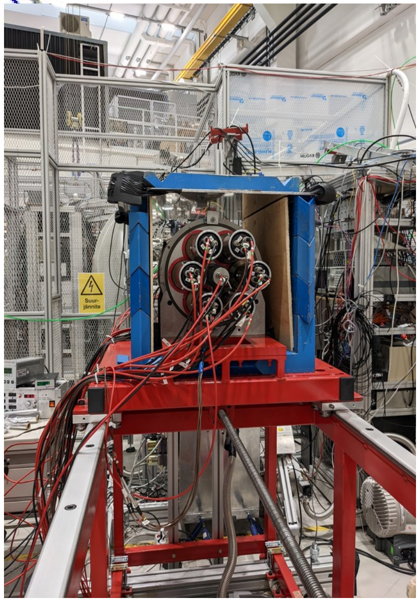
- **TAGS campaign @IGISOL (Jyväskylä) in Sept. 2022:**



  - **Nantes-Valencia proposal:** Reactor Antineutrinos & Decay Heat, and Nuclear Structure and Astrophysics
  - **First TAGS experiment with Faster DAQ**
  - **ROCINANTE Spectrometer (12 BaF_2)**
  - **Very successful: 17 nuclei**



1 PhD student:
J. Pépin (Valencia - Nantes)



Analysis on-going (J. Pépin, S. Nandi et al.)