UNIVERSITY OF SURREY

University of Brighton

Study of High-K Isomer Decays in Neutron-Rich ^{183,184}Hf isotopes Using the KISS Facility

22nd STFC Nuclear Physics Summer School

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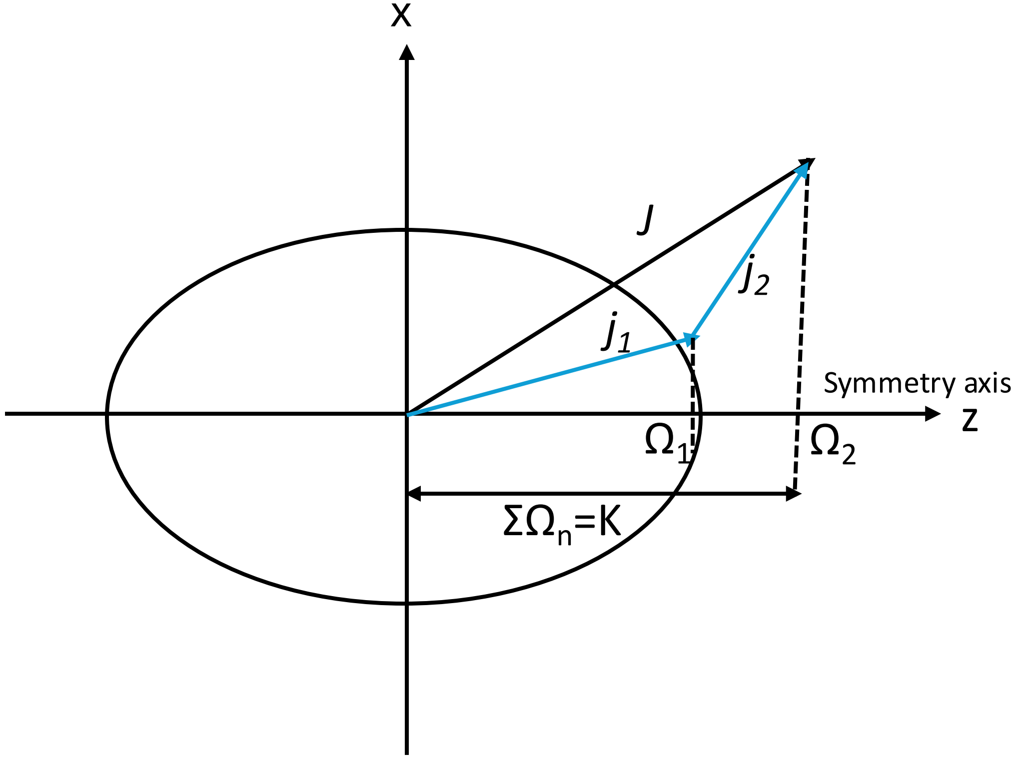
Introduction: K isomers



$|K_f - K_i| = |\Delta K| \leq \lambda$

K can only change by units up to multipolarity of the transition

$|\Delta K| - \lambda = v$

Larger changes in K result in hindered transition

- Individual nucleons have angular momentum, j, with projection Ω on the symmetry axis, and K is the sum of these Ω values.

Introduction: The Neutron-Rich Region

- Neutron rich nuclei in the mass 180-190 region:
  - Predicted to have longer half-lives[1].

[1]P.M.Walker *et al.* / Nature 399(1999)35;Hyp. Int. 135(2001)83

184Os 1.12e+13 y	185Os 92.95 d	186Os 2.00e+15 y	187Os Stable 1.97%	188Os Stable 13.24%	189Os Stable 16.15%	190Os Stable 26.26%
183Re 70d	184Re 35.43 d	185Re Stable	186Re 3.72d	187Re 4.12e+1	188Re 17.004h	189Re 24.2h
182W Stable	183W Stable	184W Stable	185W 74.9 d	186W stable	187W 23.8 h	188W 69.77 d
181Ta Stable	182Ta 114.804 d	183Ta 5.1 d	184Ta 8.7 h	185Ta 49.5 min	186Ta 10.5 min	187Ta 283s
180Hf Stable	181Hf 42.39 d	182Hf 8.9e+6 y	183Hf 1.019 h	184Hf 4.12h	185Hf 3.5 min	186Hf 2.6 min

Introduction: The Neutron-Rich Region

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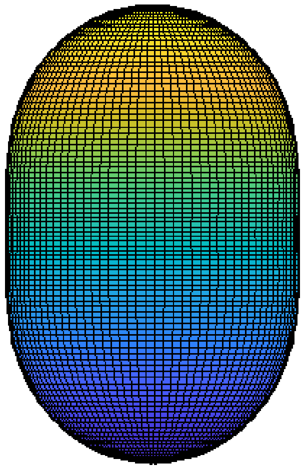
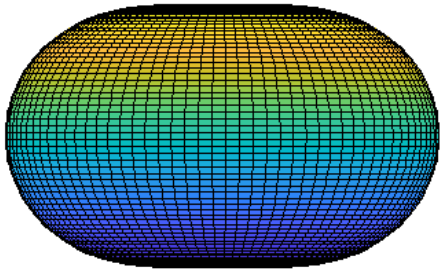
[2] F.R.Xu *et al.* / Phys. Rev. C 62(2000)014301



Prolate



Oblate

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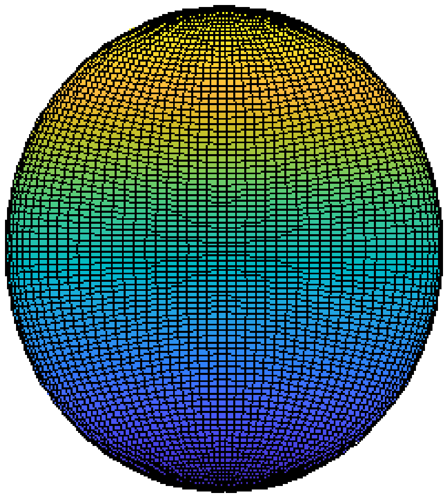
  - K mixing due to triaxiality may limit isomer half-lives, at least for Z > 73[3].



Triaxial

[1] P.M.Walker *et al.* / Nature 399(1999)35;Hyp. Int. 135(2001)83
[2] F.R.Xu *et al.* / Phys. Rev. C 62(2000)014301
[3] M.W.Reed *et al.* / Phys. Lett. B 752(2016)311

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- Challenges:
  - Neutron richness.
  - Refractory chemical properties of elements from hafnium to platinum.

184Os 1.12e+1 3 y	185Os 92.95 d	186Os 2.00e+1 5 y	187Os Stable 1.97%	188Os Stable 13.24%	189Os Stable 16.15%	190Os Stable 26.26%
183Re 70d	184Re 35.43 d	185Re Stable	186Re 3.72d	187Re 4.12e+1	188Re 17.004h	189Re 24.2h
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^{183}Hf and ^{184}Hf isomer spectroscopy at GSI

- During recent years, progress in this neutron-rich region includes the discovery of long-lived (seconds to minutes) isomers in ^{183}Hf, ^{184}Hf, and ^{187}Ta , with K values up to ~20ħ using the experimental storage ring (ESR) at GSI.

M.W.Reed *et al.* / Phys. Rev. Lett. 105 (2010) 172501; Phys. Rev. C 86 (2012) 054321.

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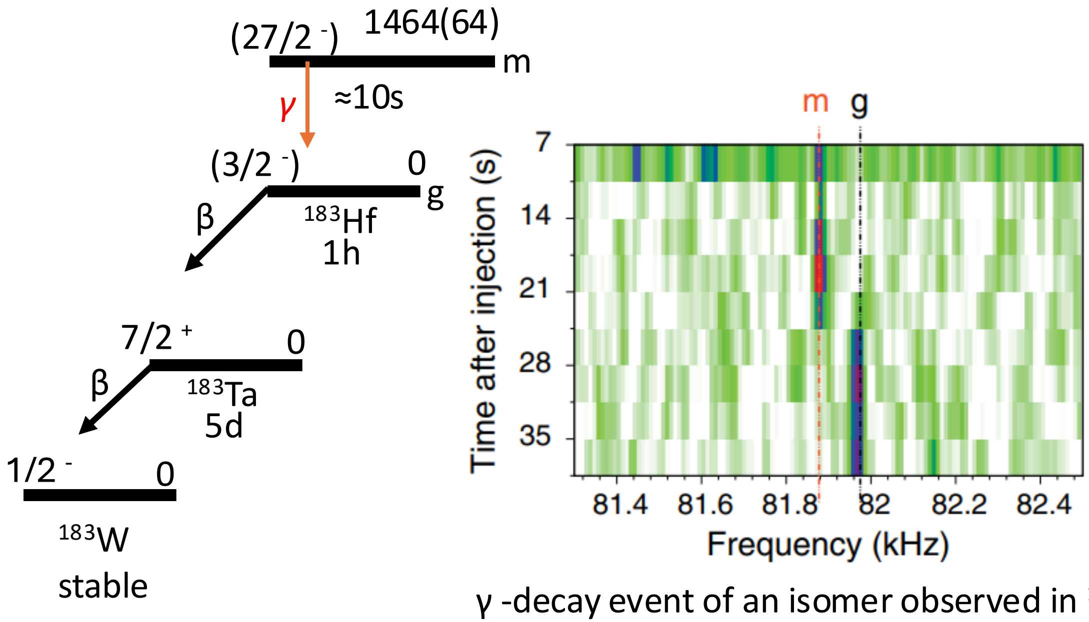

γ -decay event of an isomer observed in ^{183}Hf.

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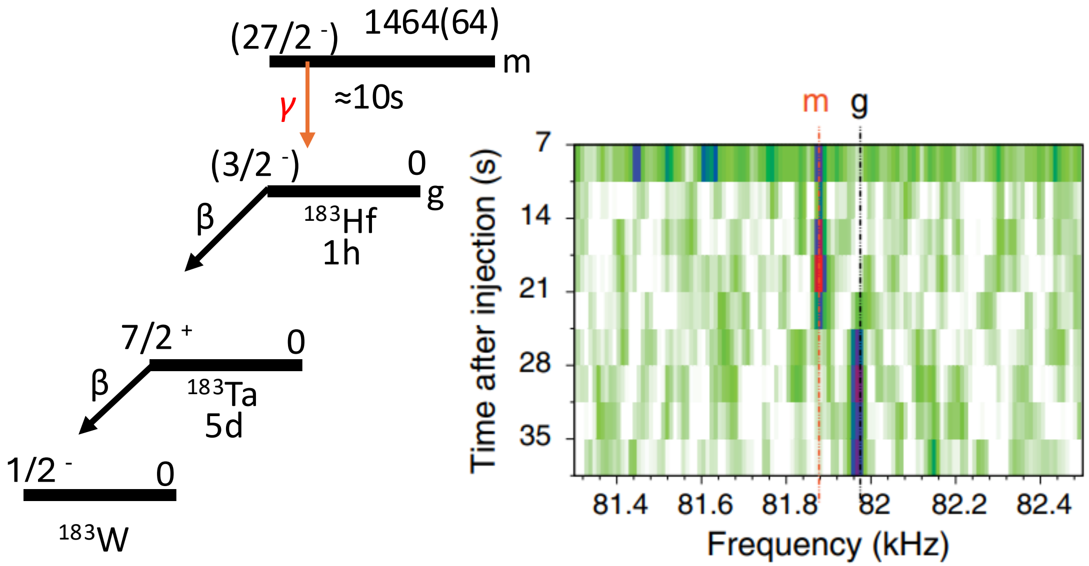

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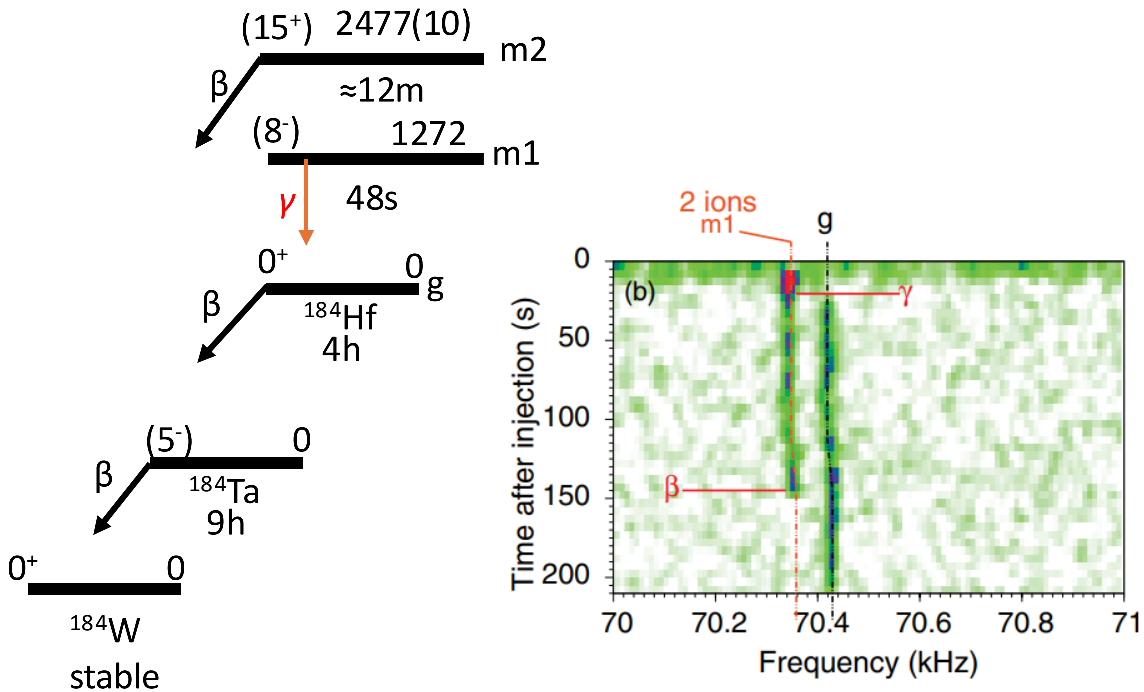
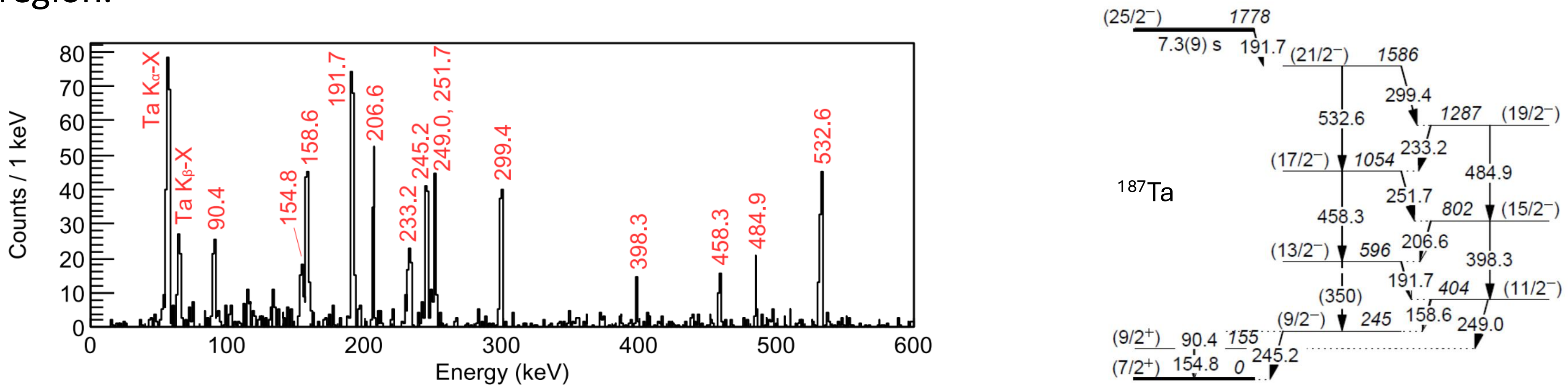


Two ^{184}Hf^{m1} ions were originally injected, however after the first ~10 s one ion γ decays into the ground state. Two minutes later, the second ion is lost from the ESR presumably as a β decay.

M.W.Reed *et al.* / Phys. Rev. Lett. 105 (2010) 172501; Phys. Rev. C 86 (2012) 054321.

Aim of the Experiment

- Using multi-nucleon transfer reactions, the KEK Isotope Separation System (KISS) facility in RIKEN, Japan, has developed a system for studying the spectroscopy of long-lived, high-K isomers in neutron rich mass region.



Summed γ-γ coincidence spectrum and the associated level scheme for ^{187}Ta obtained at KISS.

P.M.Walker *et al.* / Phys. Rev. Lett. 125 (2020) 192505

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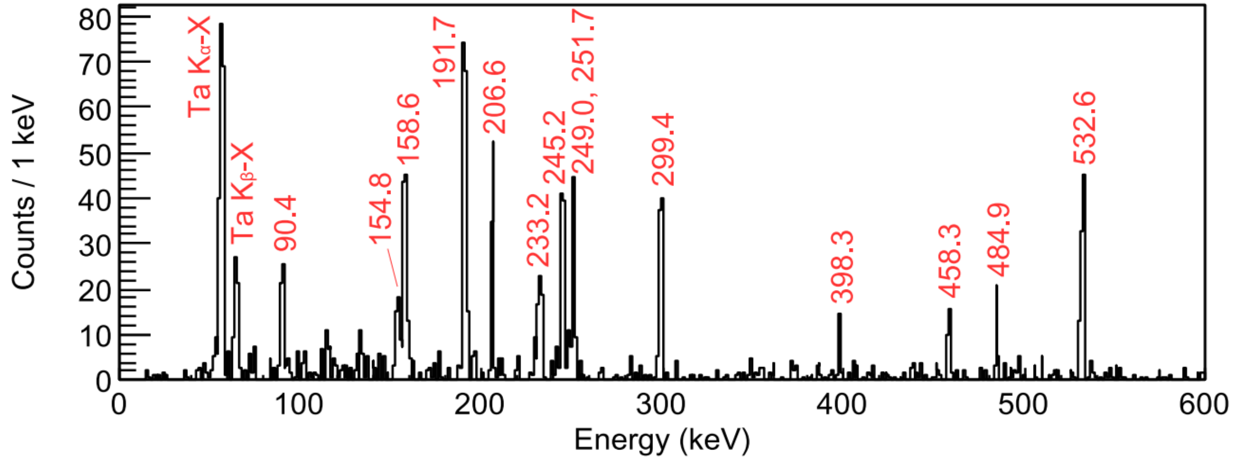

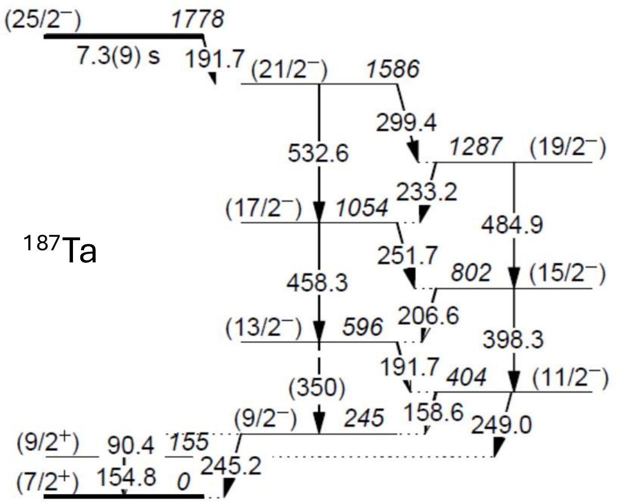

Summed γ-γ coincidence spectrum and the associated level scheme for ^{187}Ta obtained at KISS.

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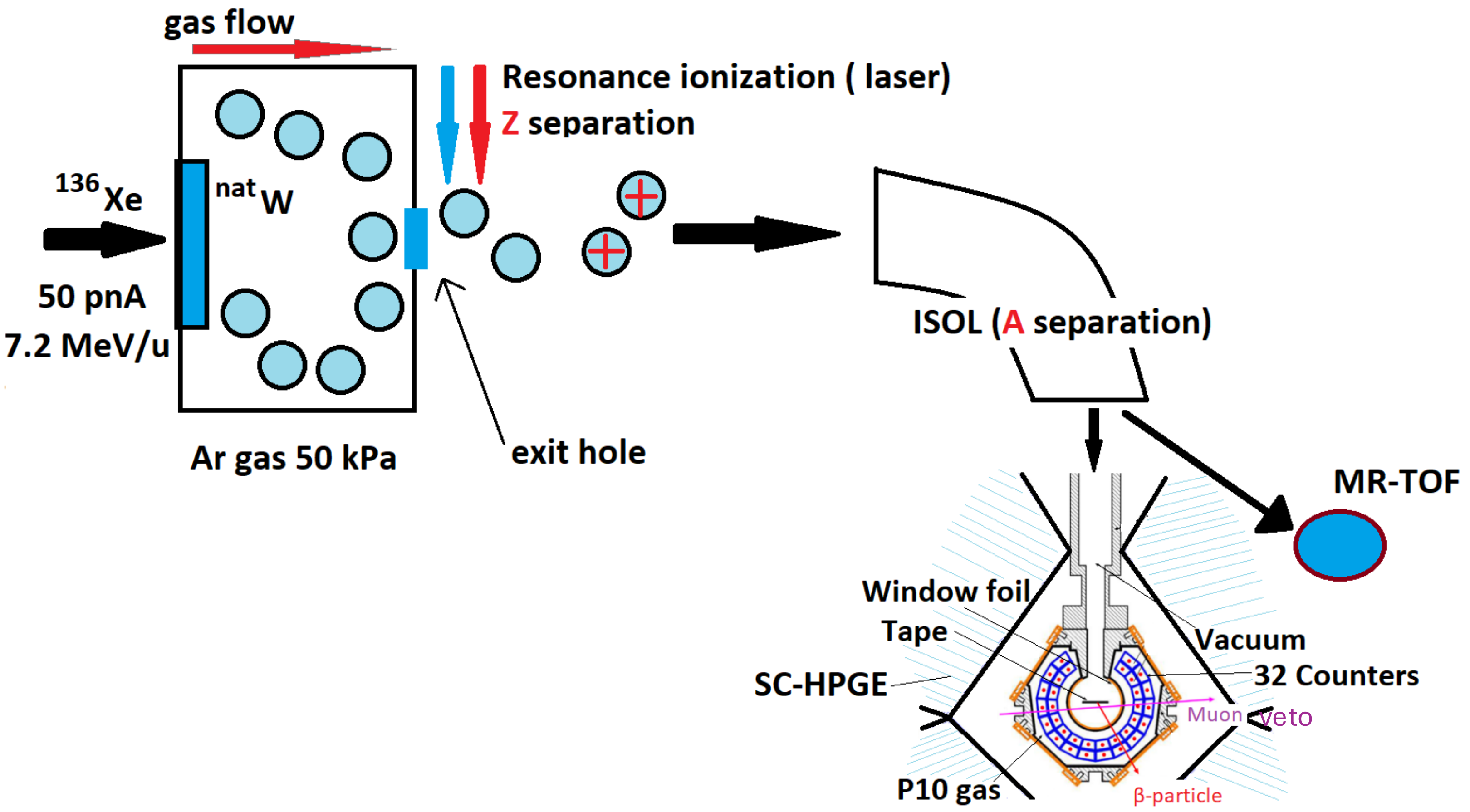
- The experiment aimed :
  - To make detailed spectroscopic studies of the long-lived isomers in ^{183}Hf and ^{184}Hf,
  - To learn about the favouring of high-K states,
  - To measure the β and γ-decay properties,
  - To investigate the sensitivity to shape changes.

The KISS Facility



185Re Stable 37.4%	186Re 3.72d	187Re 4.12e+10y 62.6%	188Re 17.004h β-=100%	189Re 24.2h β-=100%
184W Stable 30.64%	185W 74.9 d β-=100%	186W stable 28.43%	187W 23.8 h β-=100%	188W 69.77 d β-=100%
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182Hf 8.9e+6 y β-=100%	183Hf 1.019 h β-=100%	184Hf 4.12h β-=100%	185Hf 3.5 min β-=100%	186Hf 2.6 min β-=100%

Schematic for multi-nucleon transfer: ^{136}Xe on ^{nat}W → ^{183,184}Hf with subsequent spectroscopy (on right).

adapted from Jeong *et al.*, KEK Report 2010-2; Nucl. Inst. Meth. A 884(2018)1-10

Yield calculation of $^{183,184}Hf$

- Since the data for the experiment were accumulated throughout different time sequences, the determination of production yield became somewhat complex.
  - The number of nuclei that decayed during irradiation time (t_1) is determined as :

$$N(t_1) = Y\left[t_1 + \frac{e^{-\lambda t_1}}{\lambda} - \frac{1}{\lambda}\right]$$

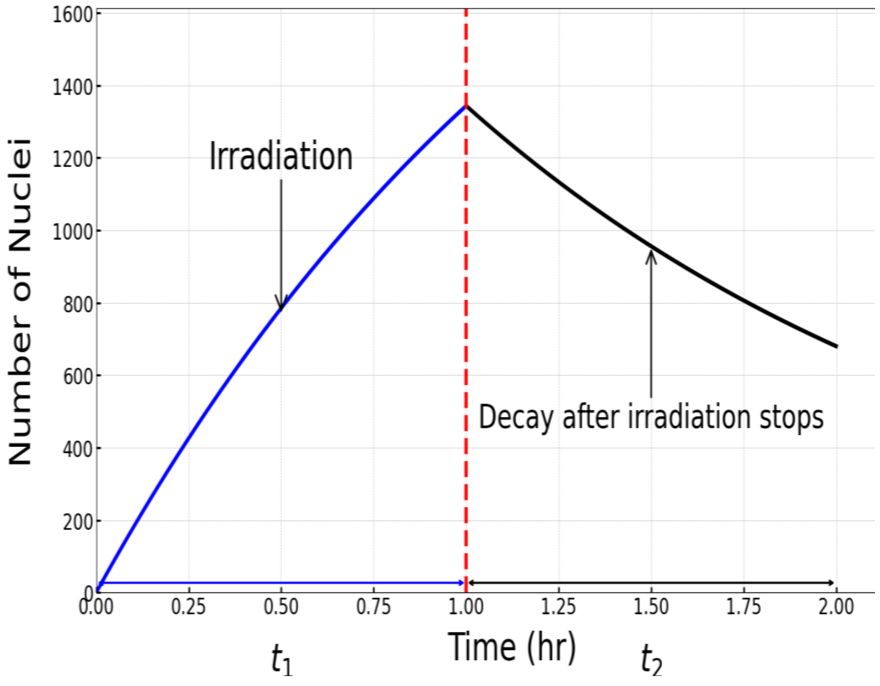
  - Here λ is the decay constant. Meanwhile, the number of nuclei that decayed in the time following irradiation (t_2) is calculated as:

$$N(t_2) = Y\left[\frac{1}{\lambda} - \frac{e^{-\lambda t_1}}{\lambda} - \frac{e^{-\lambda t_2}}{\lambda} + \frac{e^{-\lambda(t_1+t_2)}}{\lambda}\right]$$

  - In our current analysis, we have calculated yields for run files having t_1=t_2=T. This results in total yield being:

$$Y = \frac{N(T)}{T - \frac{e^{-\lambda T}}{\lambda} + \frac{e^{-2\lambda T}}{\lambda}}$$

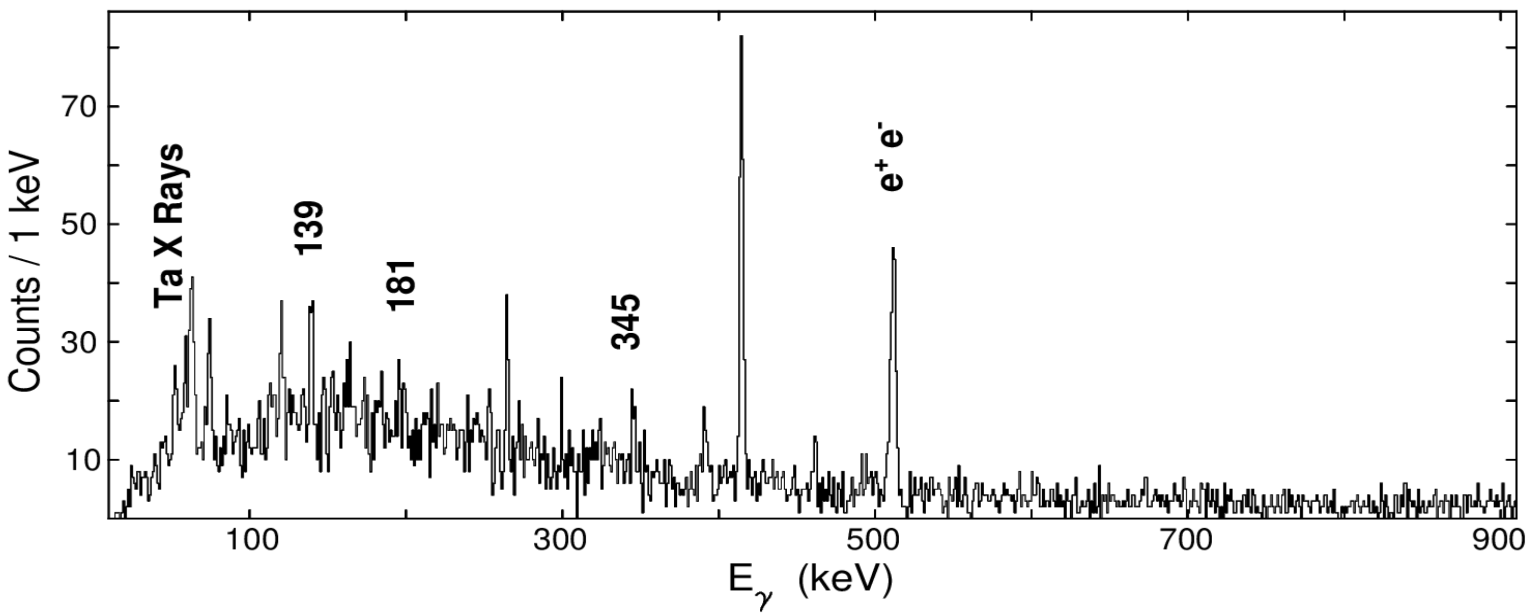
Here, *N(T)* = $N(t_1)$ + $N(t_2)$, which is the total number of decays and is obtained through the weighted average of the number of decays of the transition in question

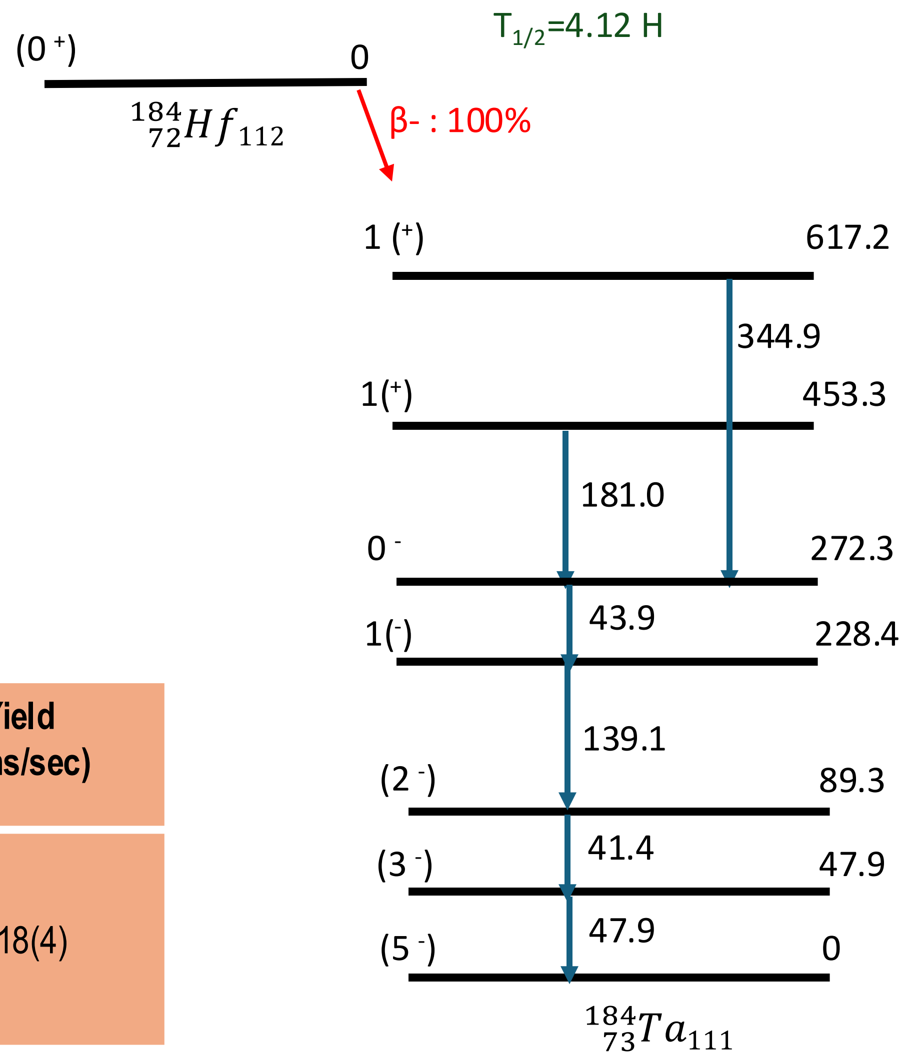


Schematic illustration of number of nuclei during irradiation (1 hour of beam on) and decay (1 hour of beam off) considering $T_{1/2}$ = 1.018 hr and yield as 1852 ions/hr.

Yield calculation of ^{184}Hf

β-γ coincidence spectra.





E_γ (keV)	A_γ	ε_γ	I_γ From [1]	N(T)	Wt. N(T) (per run)	Yield (ions/sec)
139.1(2)	47(15)	0.1690(17)	46.0(70)	1511(534)	1614(377)	0.18(4)
344.9(2)	31(8)	0.1290(13)	35.0(60)	1716(532)		

[1]https://www.nndc.bnl.gov/

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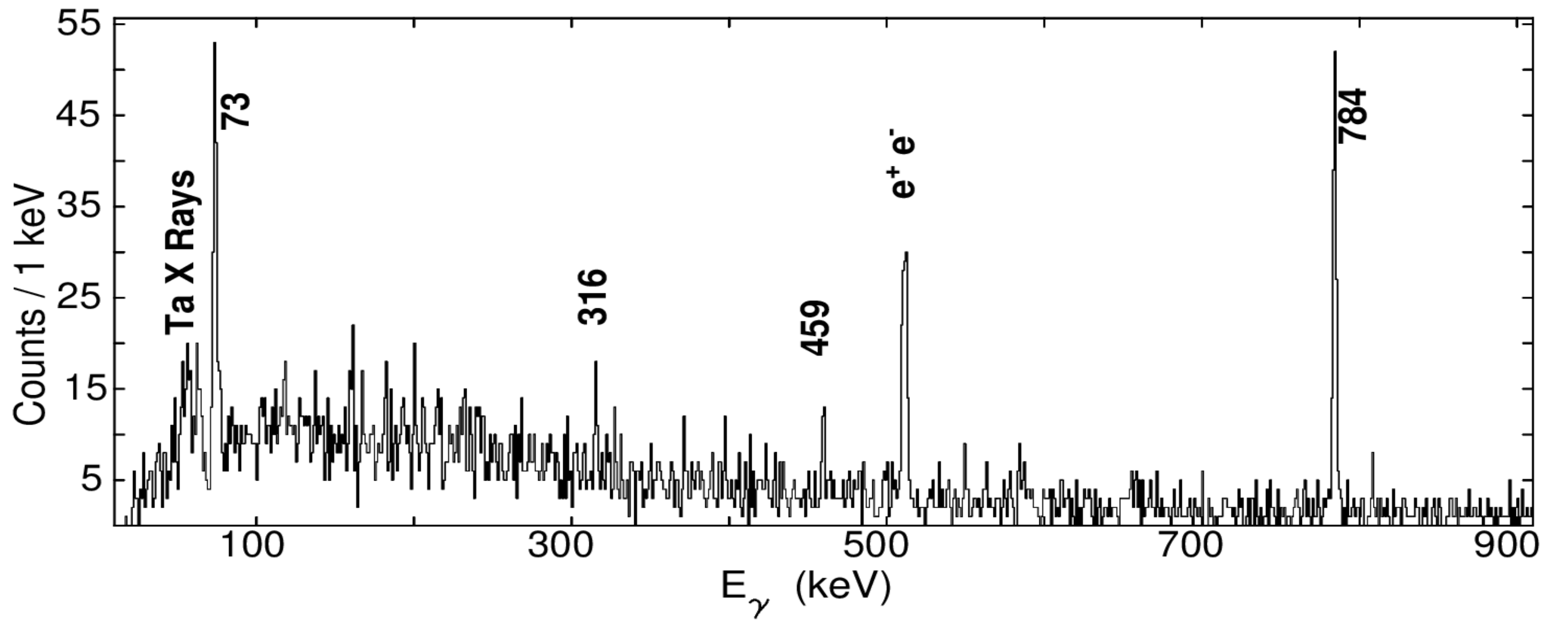
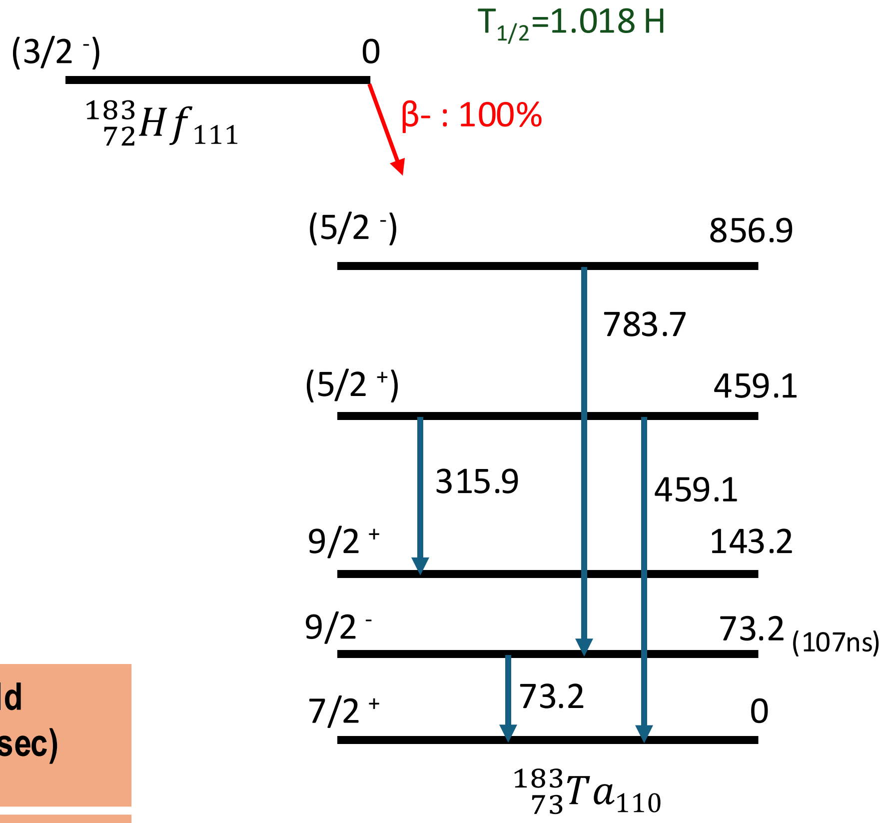
β-γ coincidence spectra.



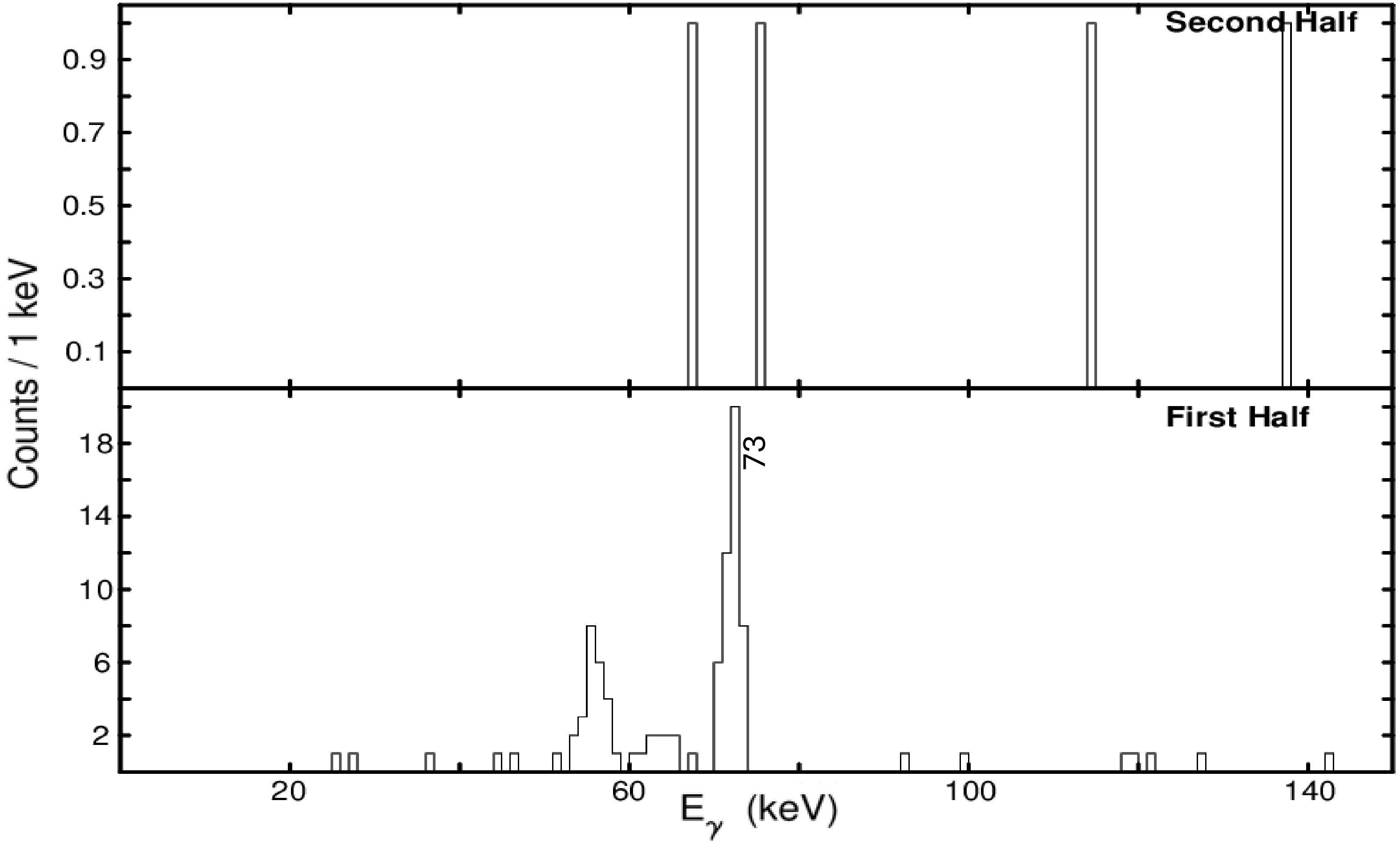


E_γ (keV)	A_γ	ε_γ	I_γ From [1]	N(T)	Wt. N(T) (per run)	Yield (ions/sec)
73.16(2)	110(15)	0.1370(14)	38.0(40)	5282(911)	1854(166)	0.81(7)
783.73(3)	134(14)	0.0900(9)	65.5(19)	5683(595)		

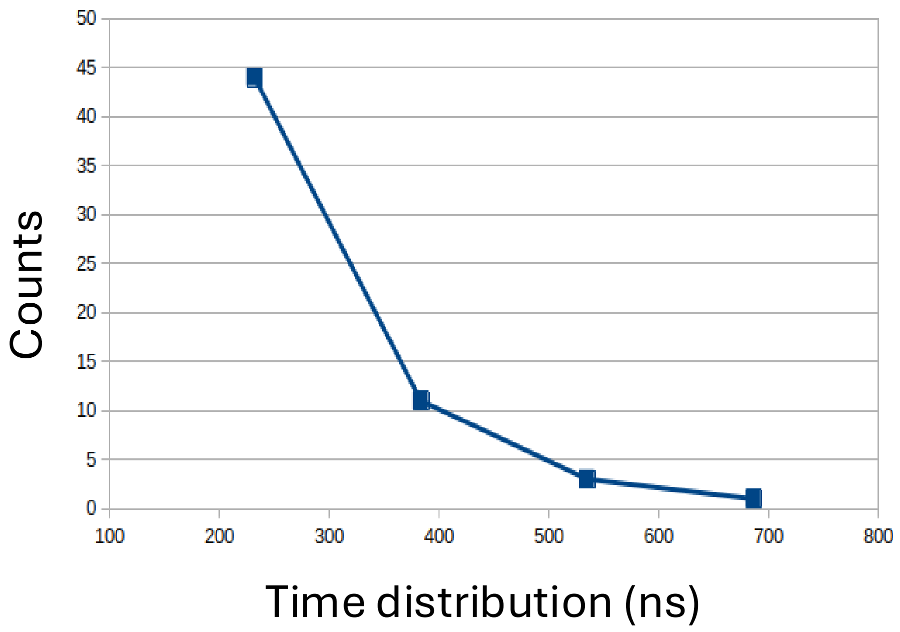
[1]https://www.nndc.bnl.gov/

Preliminary Isomeric spectroscopy of ^{183}Hf

β-γ coincidence delayed spectra gated over β-γ time.



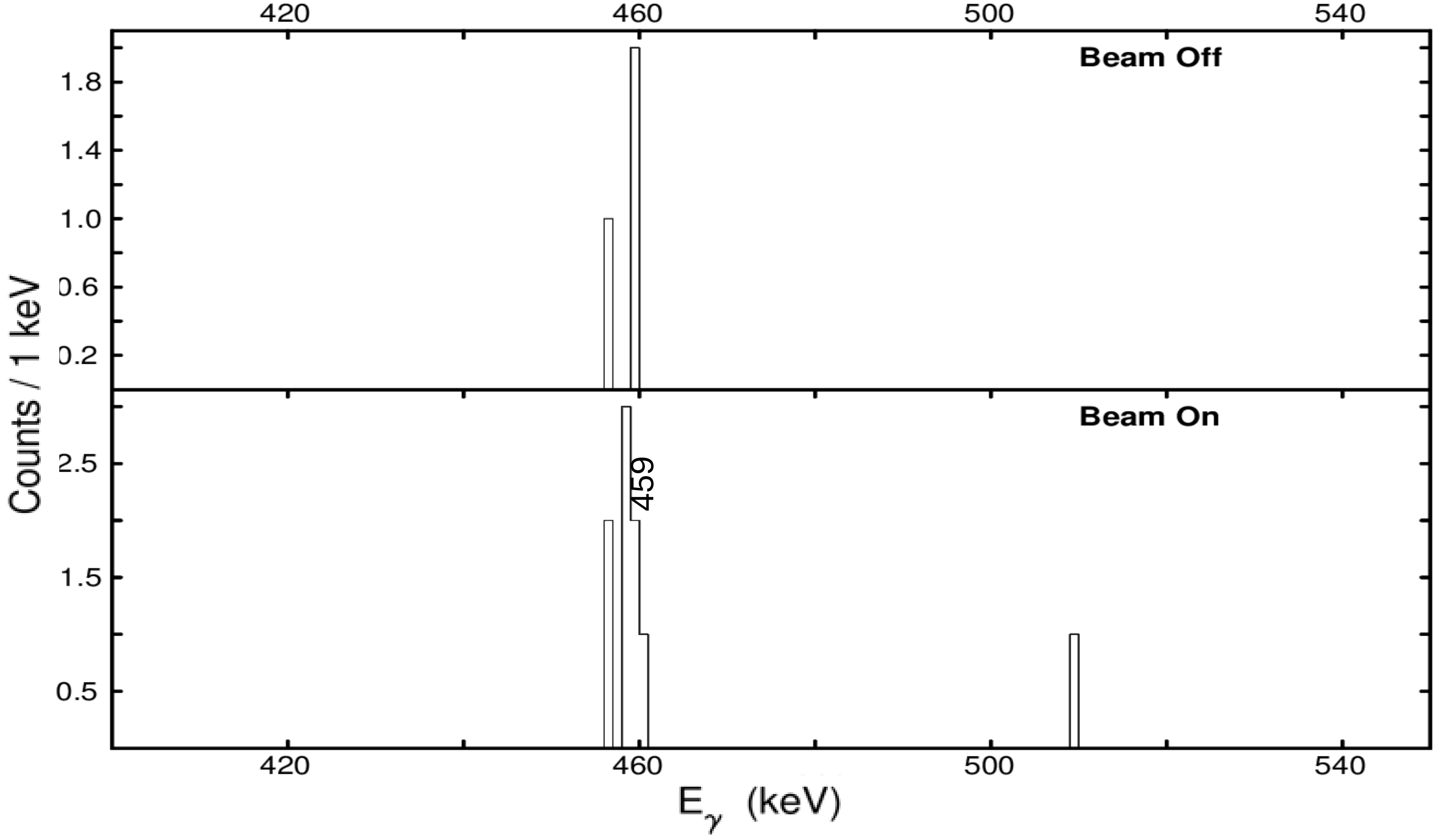
Peak areas at 73 keV in ^{183}Hf run files added together

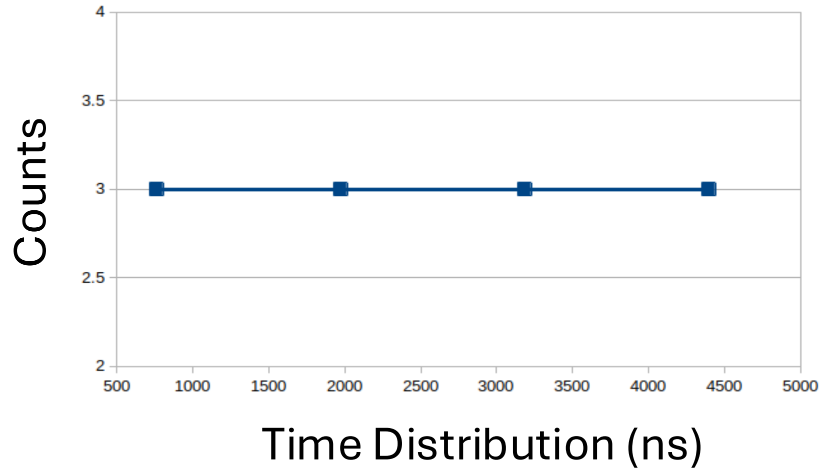


Comparing peak areas at 73 keV after dividing the first half of the beam gated β-γ coincidence delayed spectra into smaller time intervals.

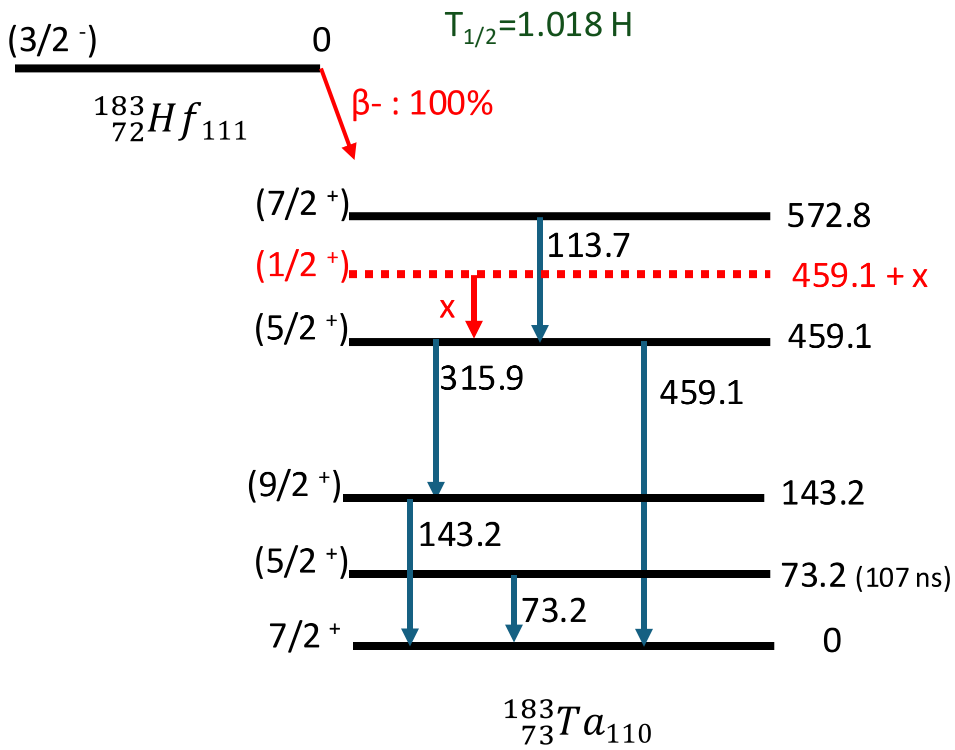
Preliminary Isomeric spectroscopy of ^{183}Hf

Beam gated β-γ coincidence delayed spectra.



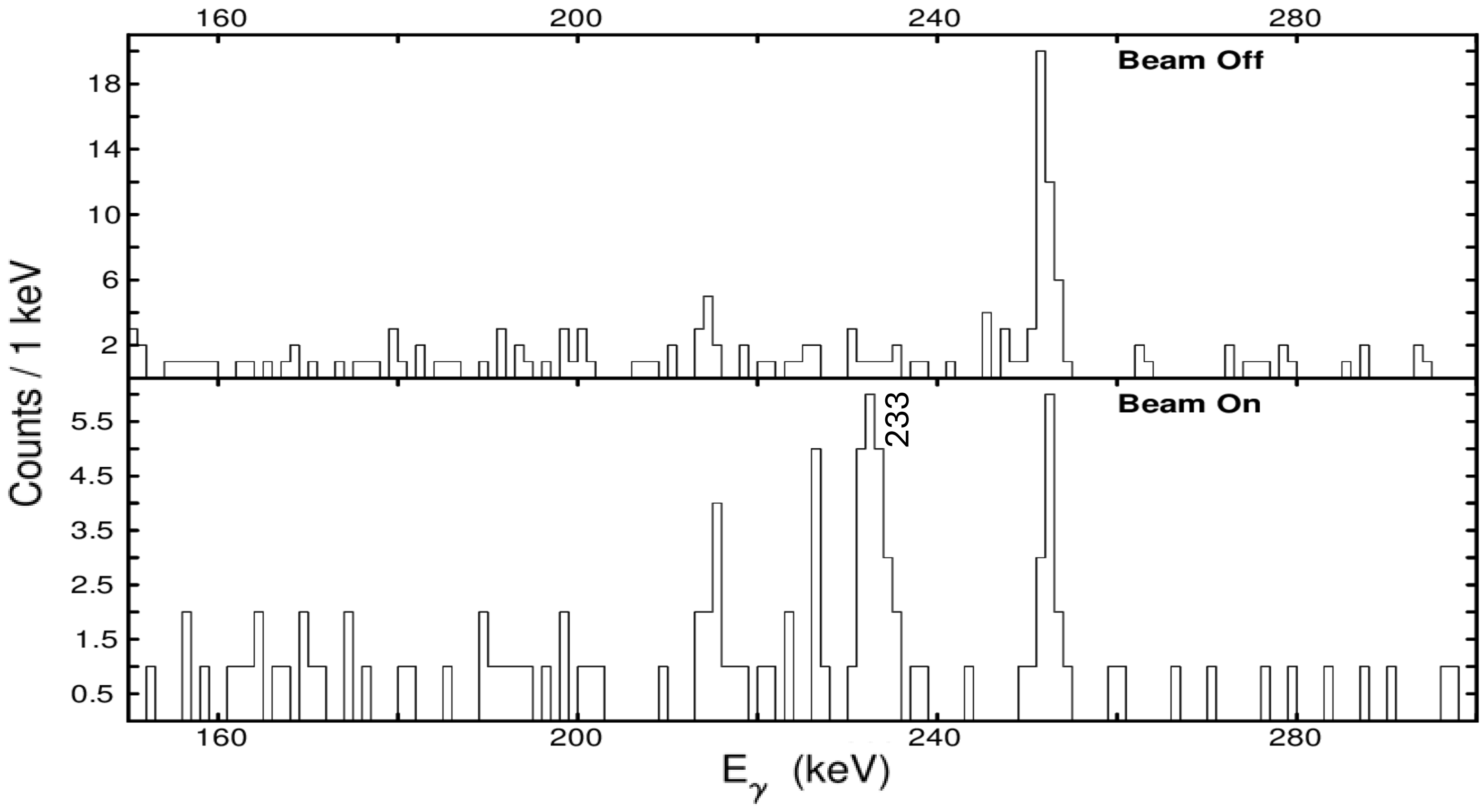


Peak areas at 459 keV in ^{183}Hf run files added together

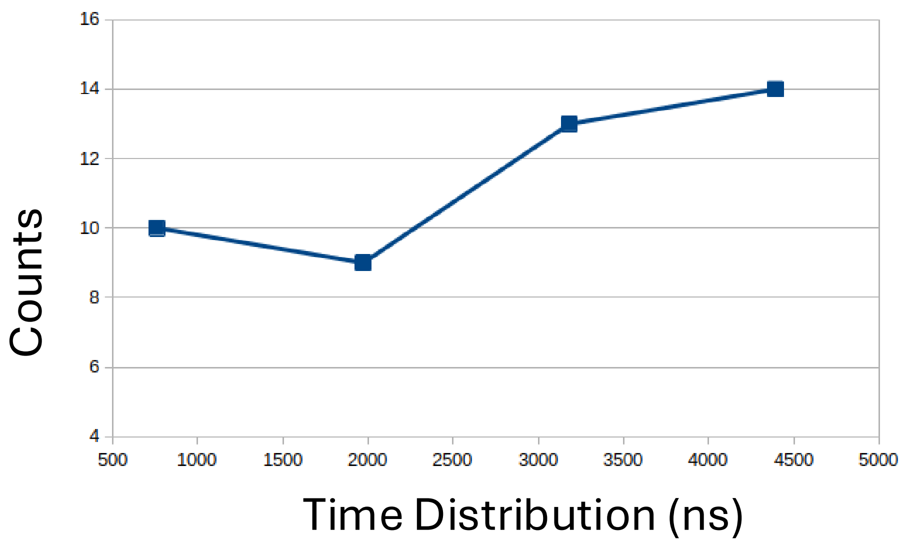


Preliminary Isomeric spectroscopy of ^{184}Hf

Beam gated β-γ coincidence delayed spectra.



Peak areas at 233 keV in ^{184}Hf run files added together



Comparing peak areas at 233 keV after dividing the beam on period of beam gated β-γ coincidence delayed spectra into smaller time intervals.

Summary

- The experiment expected production rate was 1.5pps for ^{183}Hf [0.81(7)] and ^{184}Hf [0.18(4)]. But current calculation indicate significant lower yields, but it is worth noting that despite lower yields, it was for the first time that such isotopes have been produced using the KISS facility.

- the "new" isomer populated in ^{183}Hf ground-state beta decay (involving 459 keV gamma decay). There could well be a $1/2^+$[411] state just above the $5/2^+$ 459 keV level in ^{183}Ta, which would decay by an E2 transition to the $5/2^+$ state.

- The "new" isomer that seems to be populated in ^{184}Hf isomeric decay (233 keV gamma decay) still needs work.

Collaborators

Y. Hirayama, Y.X. Watanabe, P. Schury, S.Kimura, M. Wada

A.Takamine, J.Yap

H. Watanabe, J. Chen

G. Lane

F.G. Kondev

Y. Litvinov

S. Doshi, A.M.Bruce

S. Pascu, Zs. Podolyák, P. M. Walker, G. Bartram, G. Hudson-Chang, V.Chandrakumar

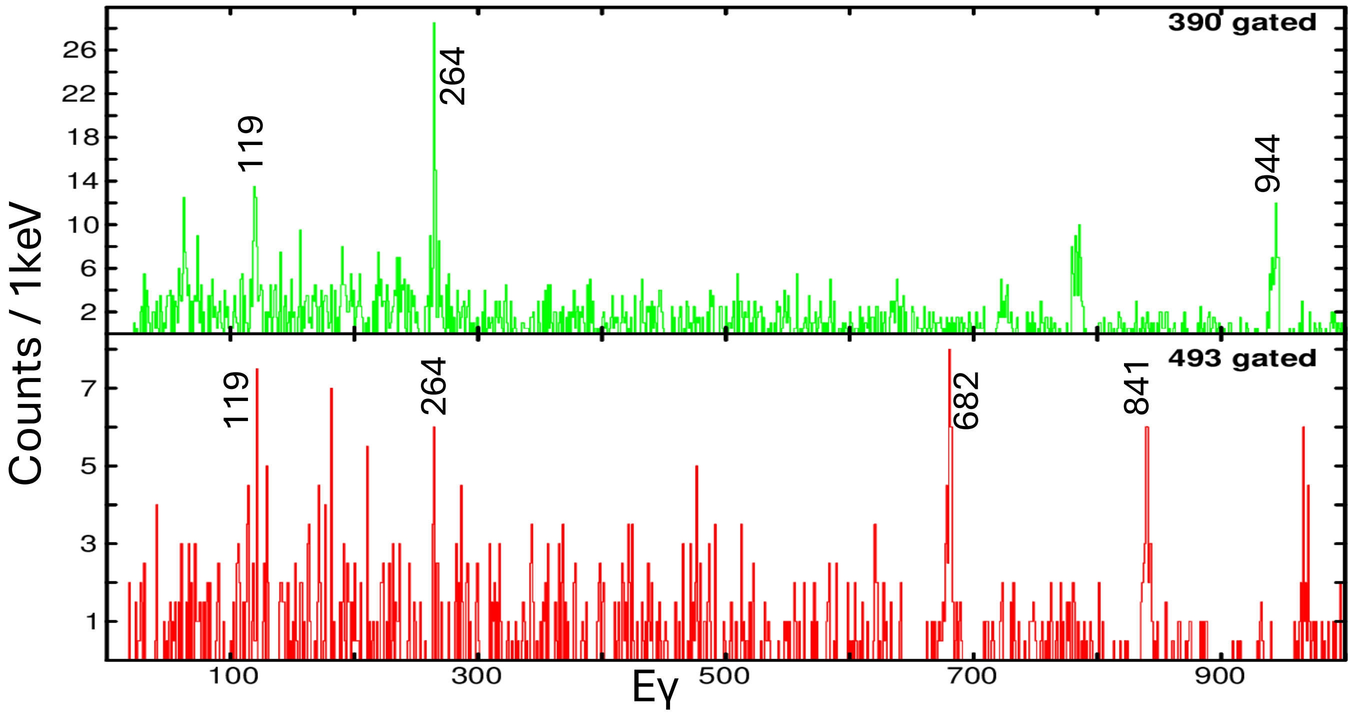
J.Cubiss

S. Dutt, S. Guo, G. Li, J.Gada, Z. Liu, P. Ma

Thank You For Listening !

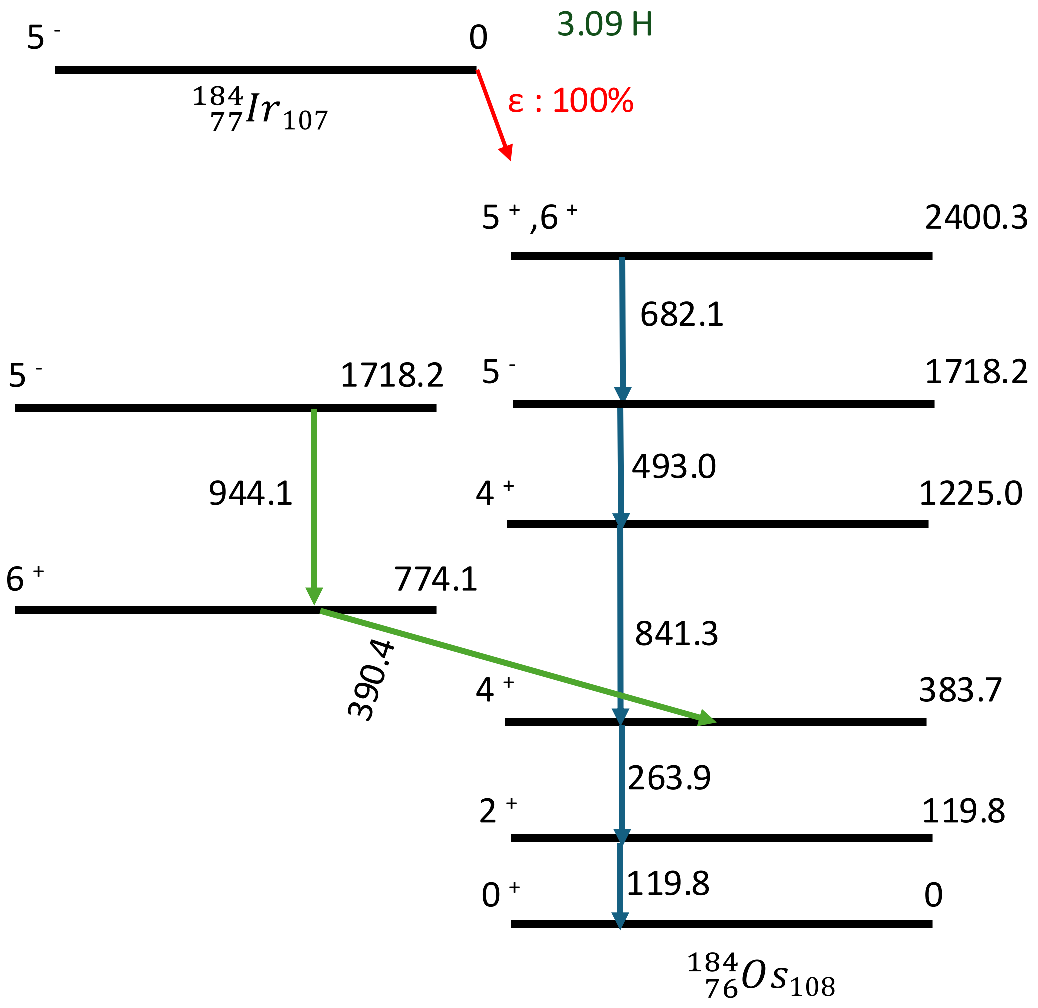
Additional Slides

Intensity calculation of ^{184}Os



Gating on 494		
E_γ (keV)	I_γ% From [1]	Norm. I_γ%
119.8	100	55(22)
263.9	100	64(31)
841.3	100	117(45)
682.1	146	146(55)

Gating on 390		
E_γ (keV)	I_γ% From [1]	Norm. I_γ%
119.8	46	38(11)
263.9	46	43(12)
944.1	46	46(15)



Missing intensity of 459

Decay for 3 run files of 1hr/1hr										
Energy	Intensity (%)	Error	Efficiency	Error (1% of eff)	Area	Error	Calculated Intensity	Error	Normalized Intensity	Error
459.1	29.8	0.9	0.113	0.001	22	9	195	80	9	4

~30 counts in the ground state, and about 1/3 of these are visible within the time spectra up to 5 μs, it implies that the remaining 2/3 (70%) are outside this time range.

Using the decay law, we get $0.7 = e^{-\lambda \cdot 5\ \mu s}$

Upon solving this, we'll have $\lambda = 7.1340 \times 10^4\ s^{-1}$

$T_{1/2} = \ln 2/\lambda = 9.72\ \mu s$

and mean lifetime = $1/\lambda = 14.1\ \mu s$.

Calculating the Weisskopf transition probability, giving transition rate

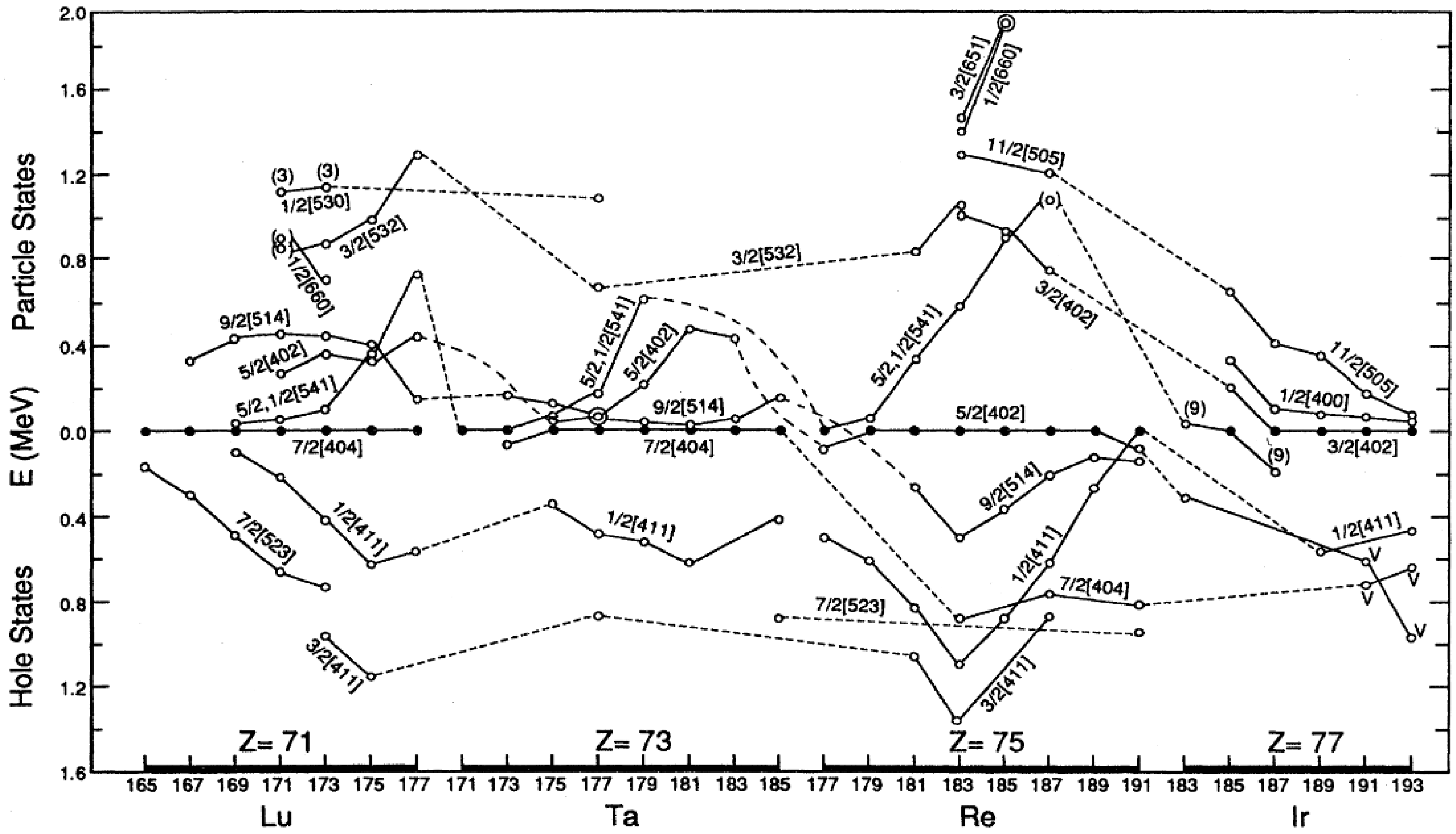
= 7.3* 10^7 * (183)^(4/3) * (0.063)^5 = $7.527 \times 10^4\ s^{-1}$,

resulting in a $T_{1/2} = 9.21\ \mu s$ and

a mean lifetime = 13.28 μs.

Confirming a low energy (not known) E2 transition.

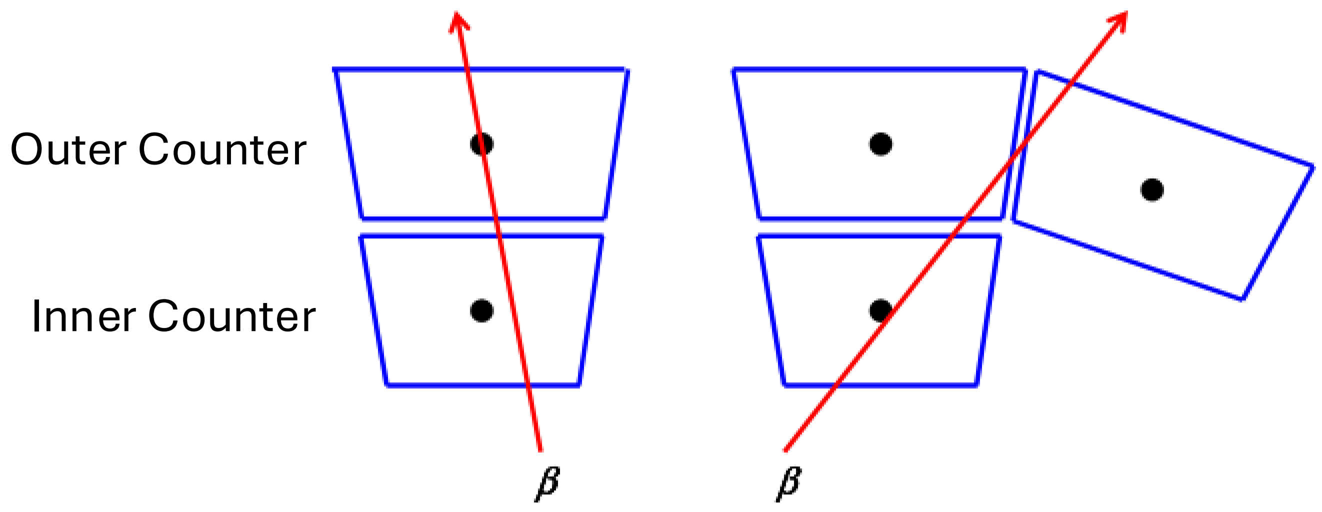
Nilsson Diagram



A.K.Jain *et al.* / Rev. Mod. Phys. 62, 393

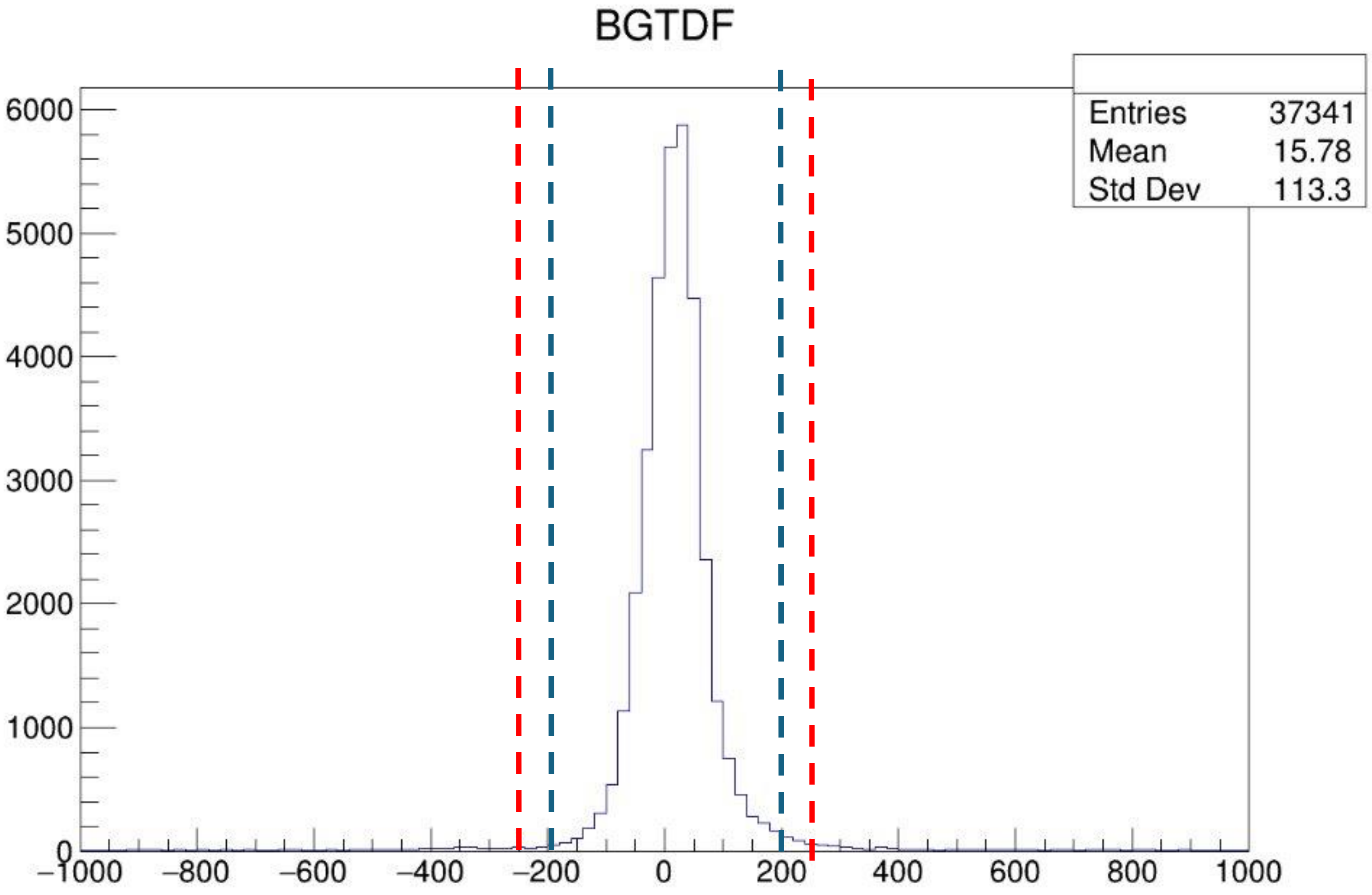
Mystery of M =0 to M=5

- M=0: self ADC and TDC gate.
- Internal conversion electrons, having a typical maximum energy of ∼100 keV, are completely stopped in the inner counters. As such, produces M = 1 events in the inner counters.
- When one telescope (inner + outer counter) is fired then it is considered as M=2.
- When one telescope and an adjacent outer counter is fired is M=3.
- When one telescope and an adjacent inner counter is fired is M=4.
- M=5: is a dummy.



(a) $M = 2$. (b) $M = 3$.

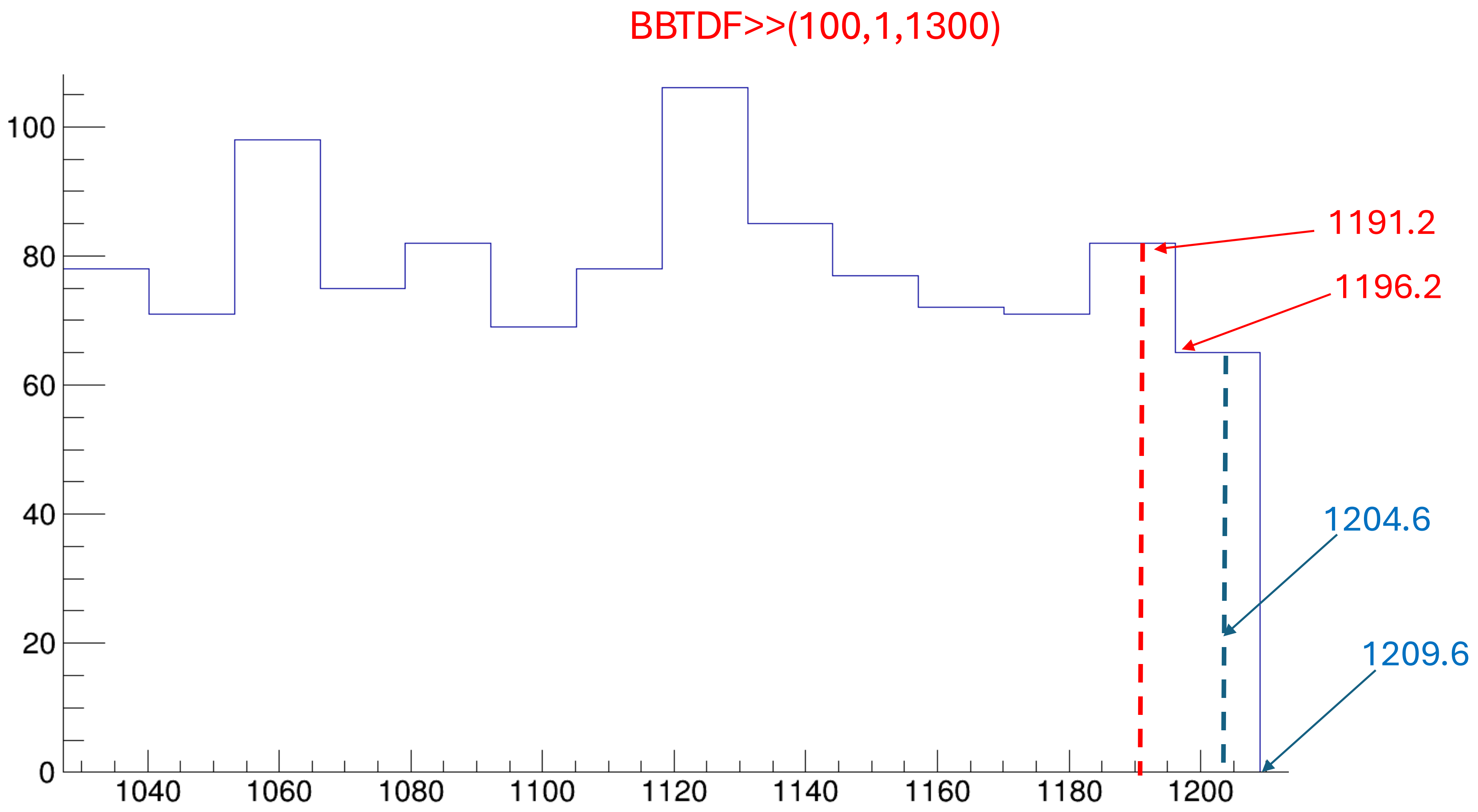
Defining Prompt and Delay through β-γTime Difference



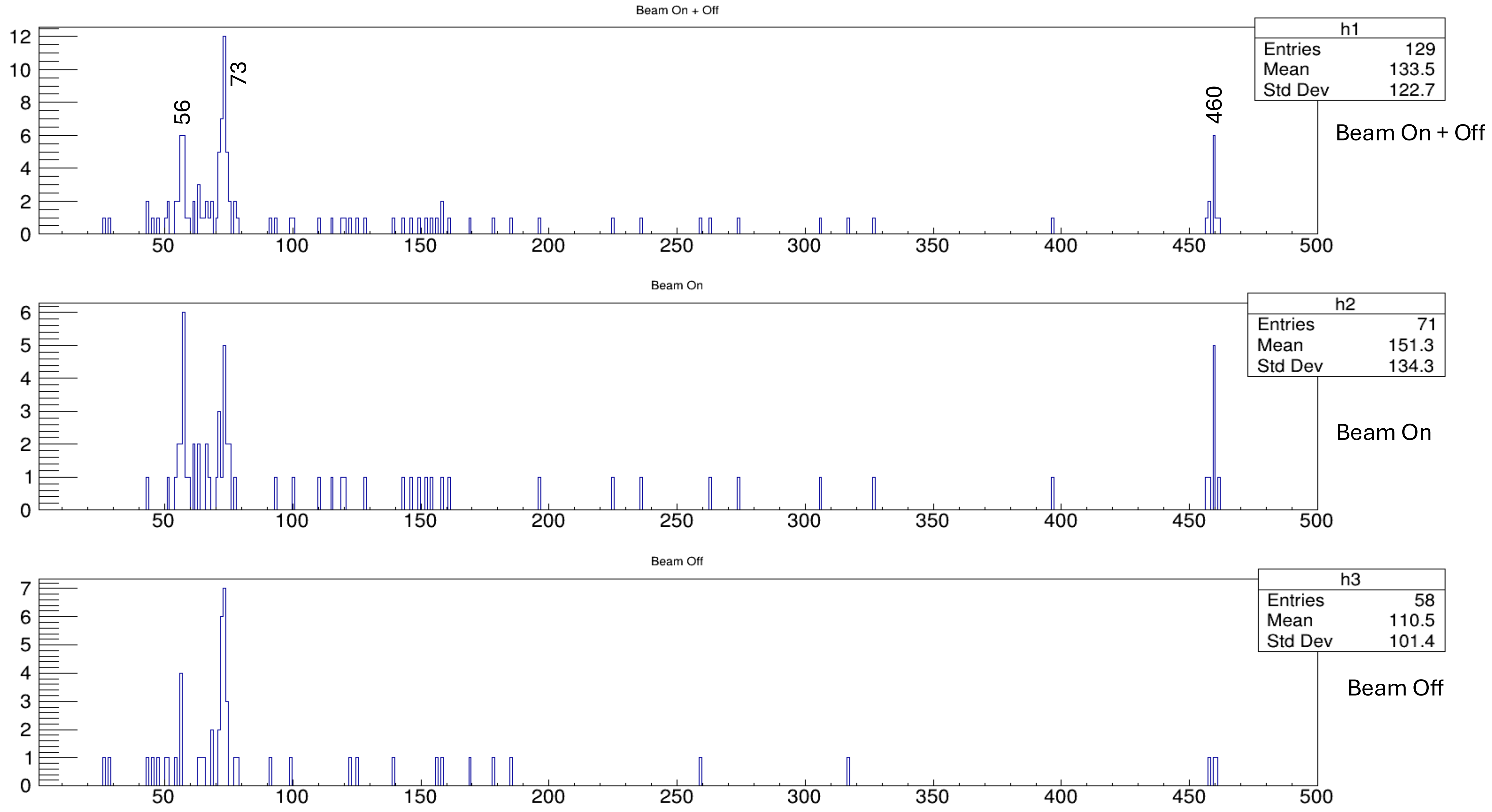
-8000 -250 +250 +8000

Delayed Prompt Delayed

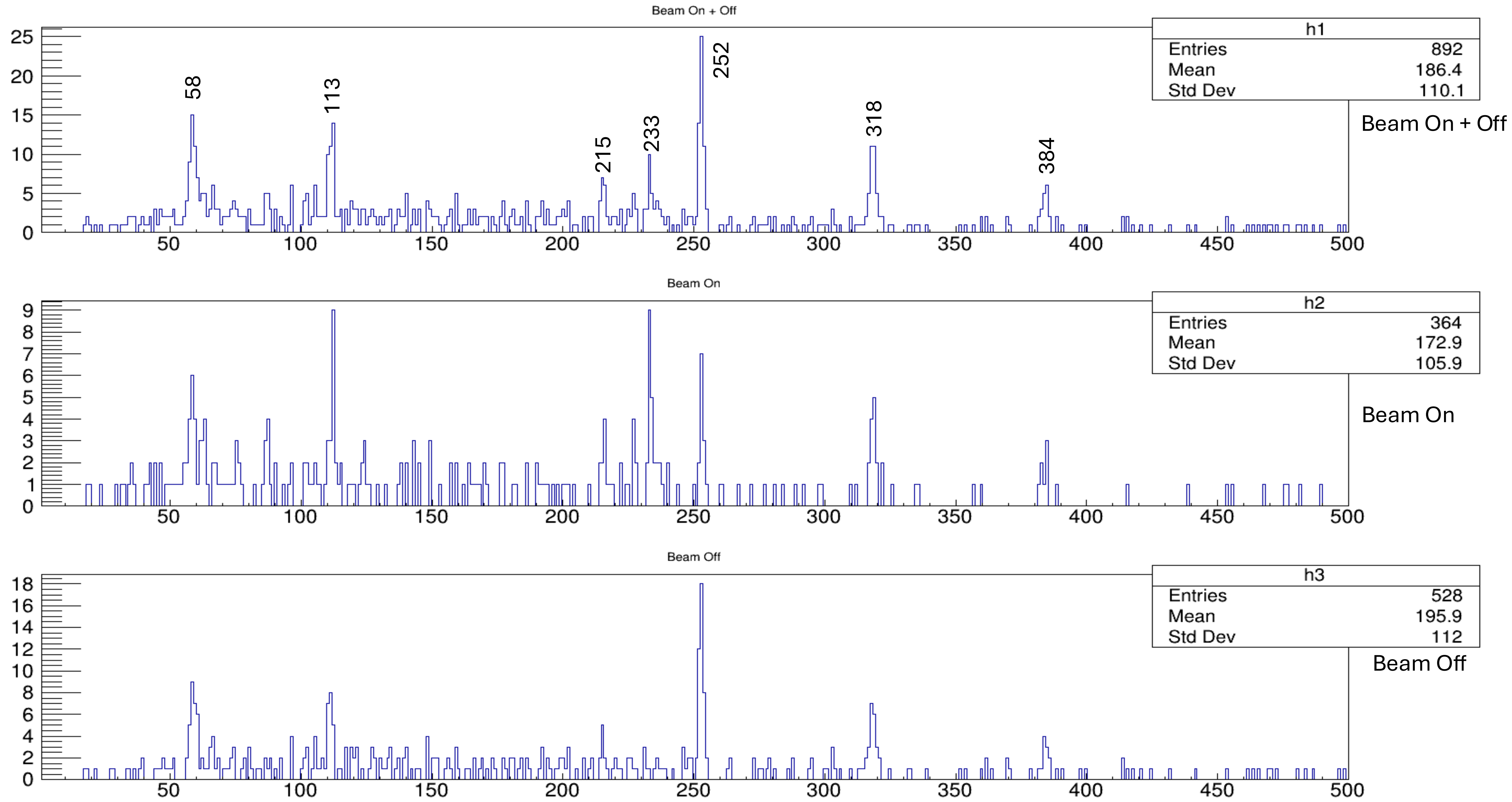
Looking for activity curve from BBTDF in 184Hf 20min/5sec run file



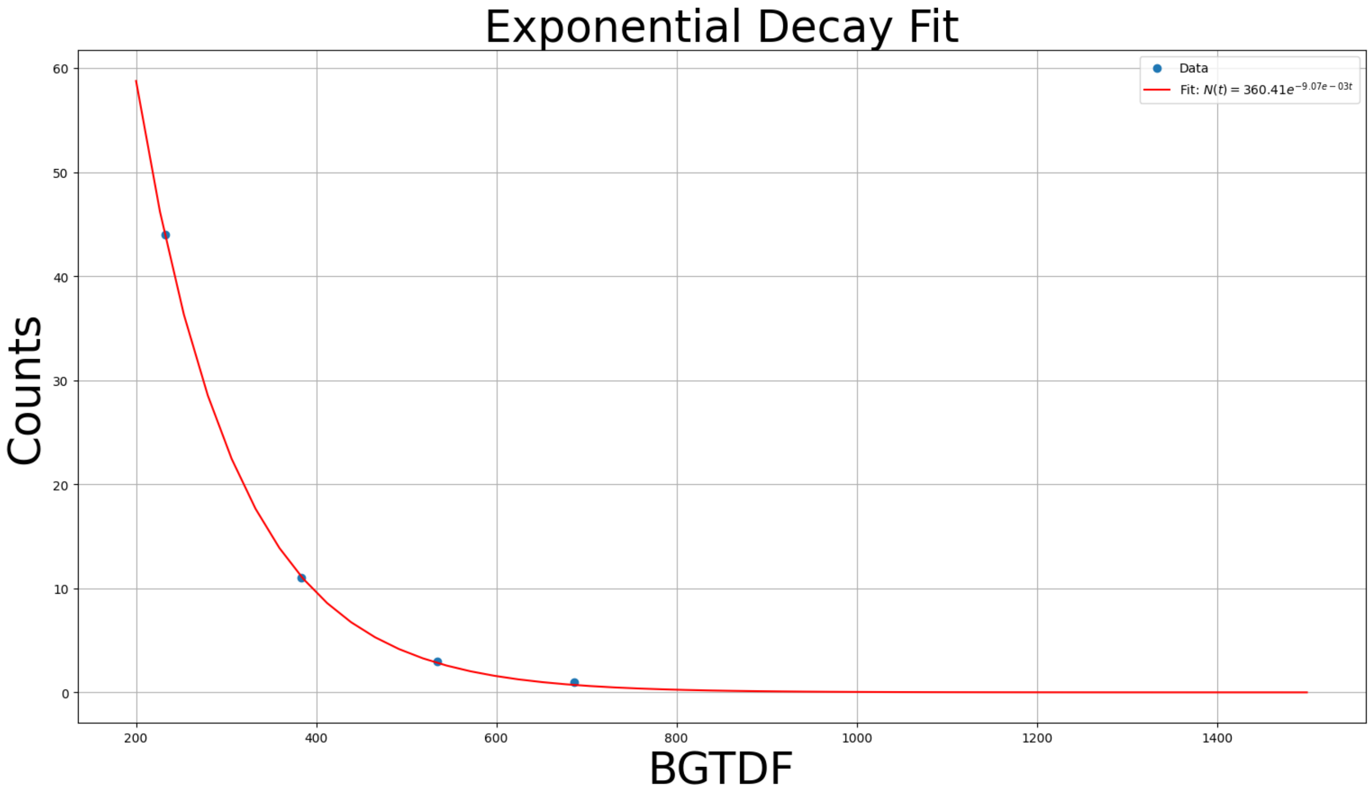
Delayed Spectra of ^{183}Hf



Delayed Spectra of ^{184}Hf



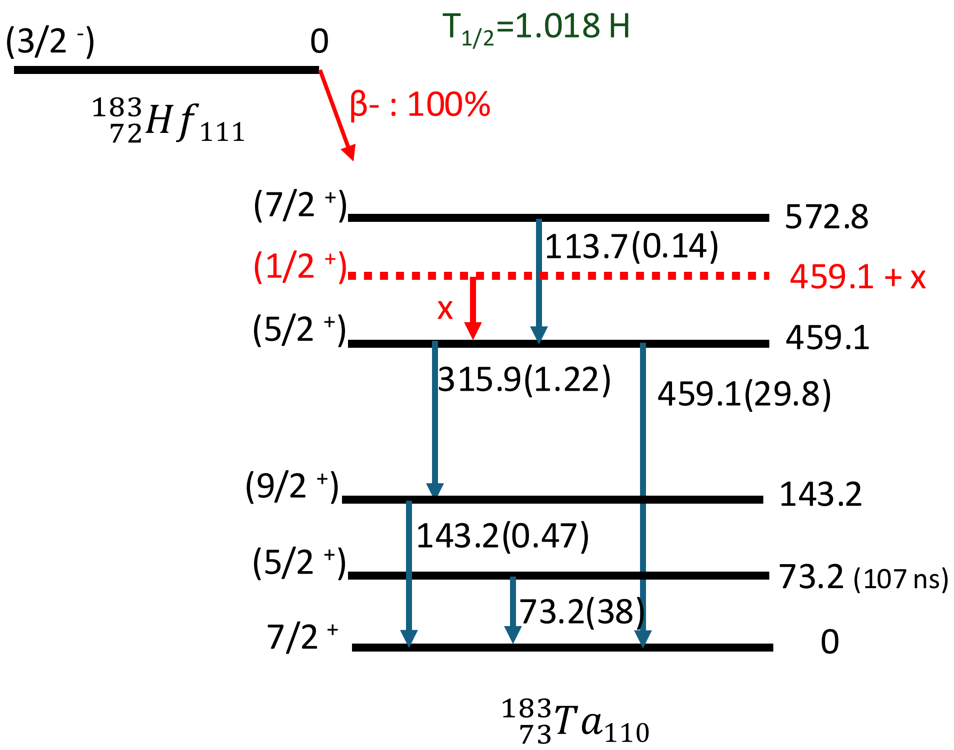
Half Life Calculation of 73 keV

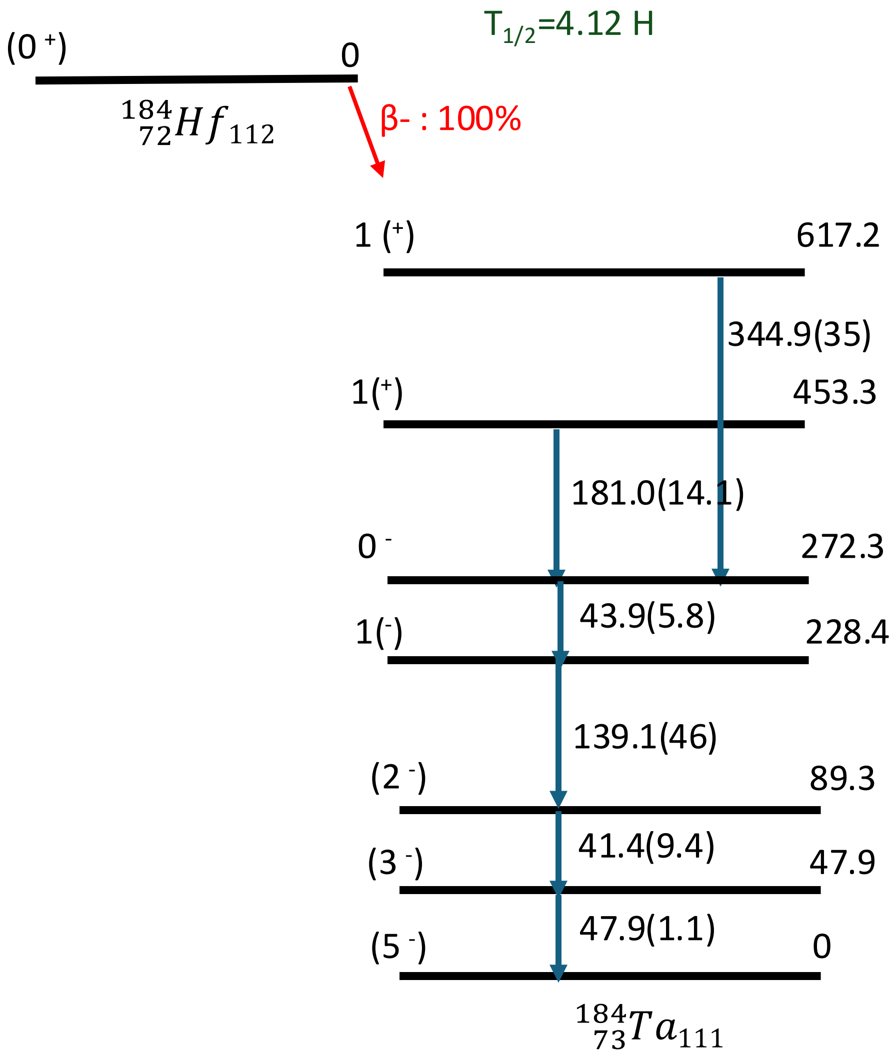


$\lambda = 9.07 \times 10^{-3}\ \text{sec}^{-1}$

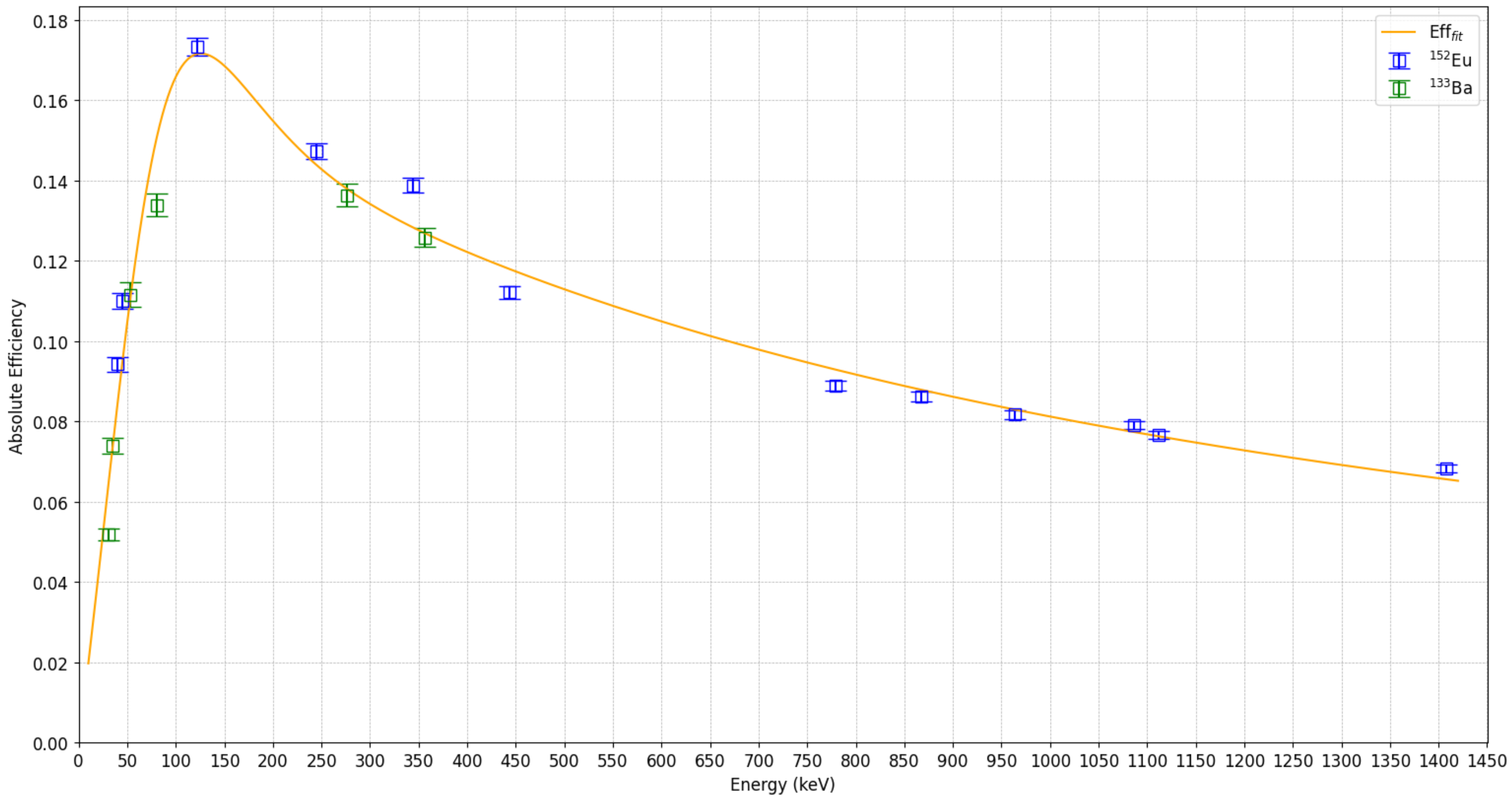
$T_{1/2} = 76.43$ nano sec

^{183,184}Hf Decay Plots



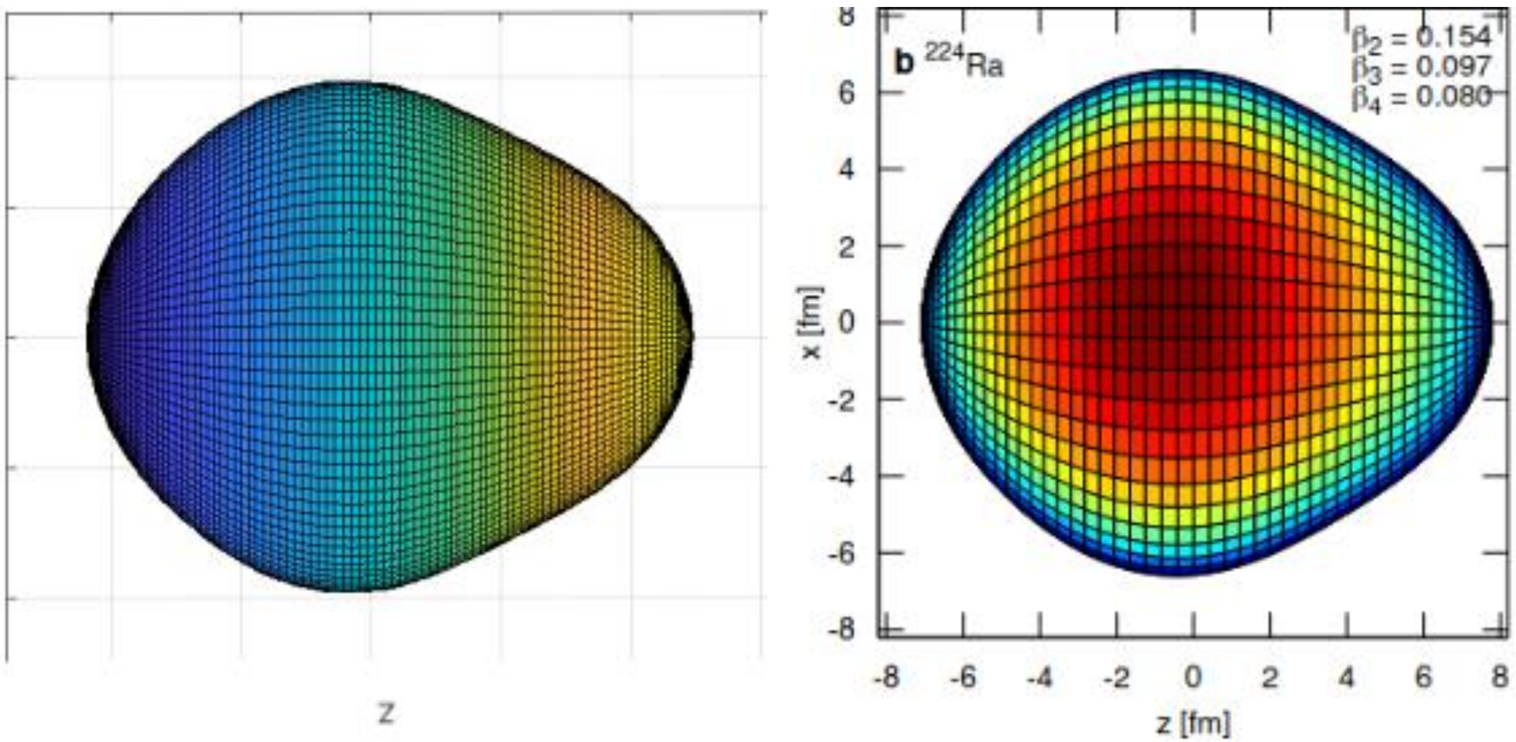


Efficiency



Eff$_{fit}$
^{152}Eu
^{133}Ba
Absolute Efficiency
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
0.18
0 50 100 150 200 250 300 350 400 450 500 550 600 650 700 750 800 850 900 950 1000 1050 1100 1150 1200 1250 1300 1350 1400 1450
Energy (keV)

Nuclear Deformation



L. P. Gaffney et al. Nature, 497, 2013.

$$R(\theta,\phi) = R_{\text{av}}\left(1 + \sum_{\lambda=0}^{\infty}\sum_{\mu=-\lambda}^{\lambda} \alpha_{\lambda,\mu} Y_{\lambda,\mu}(\theta,\phi)\right)$$

Nuclear Deformation