UNIVERSITY OF SURREY

University of Brighton

Isomeric Decays in Neutron-Rich ^{183,184}Hf isotopes Using the KISS facility

Nuclear Physics
Conference 2025

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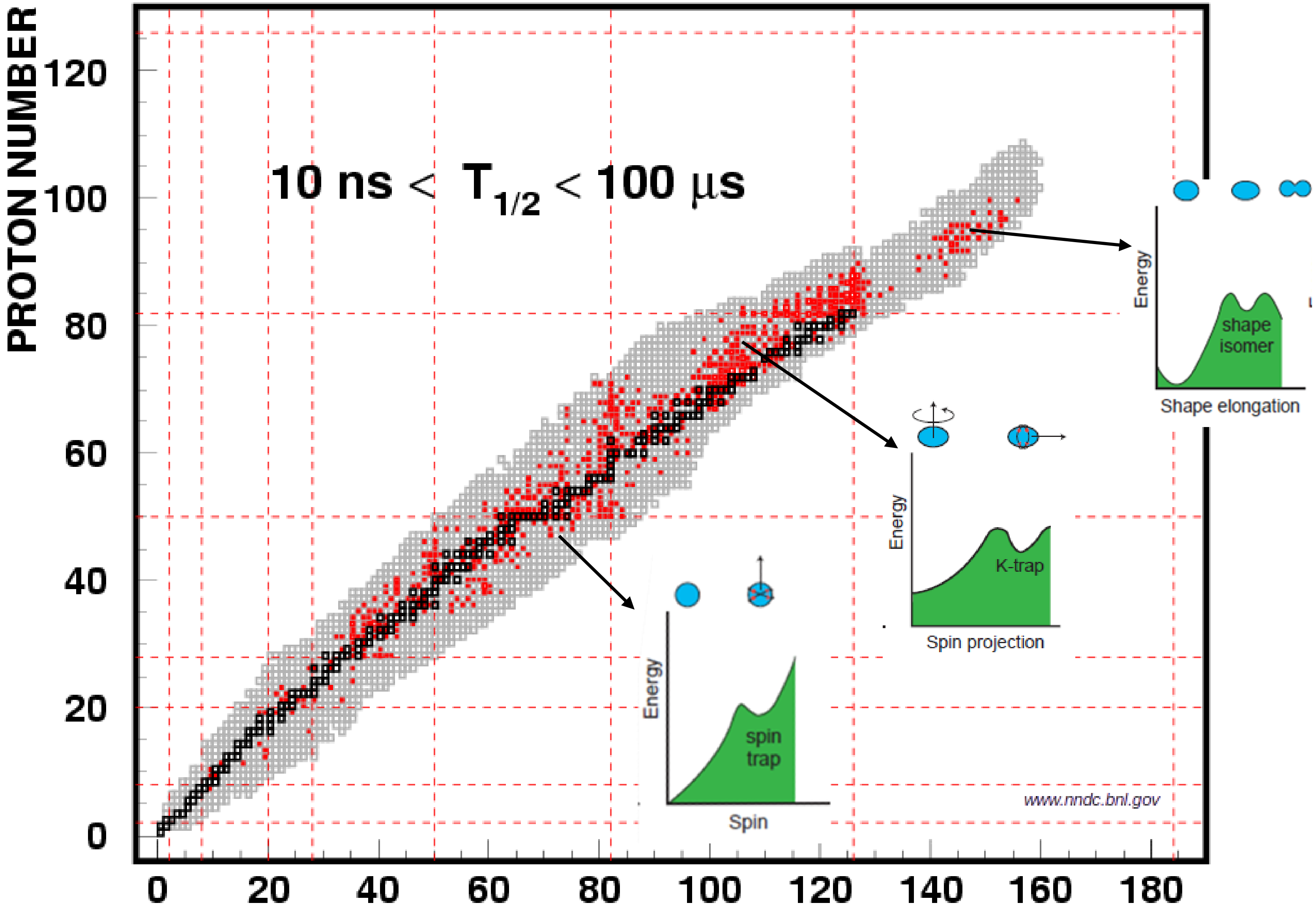
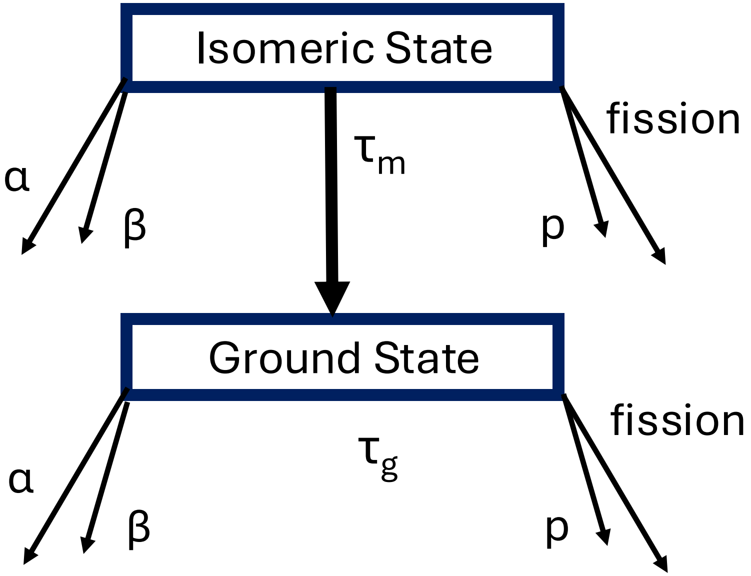
Introduction: Isomers





Isomeric State

α

β

τ_m

fission

p

Ground State

α

β

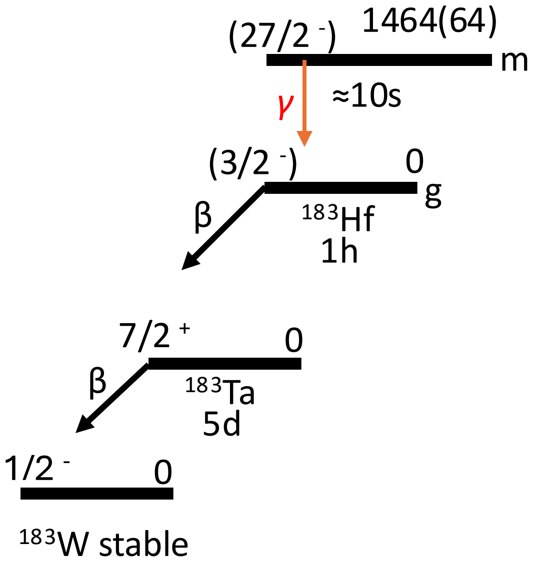
τ_g

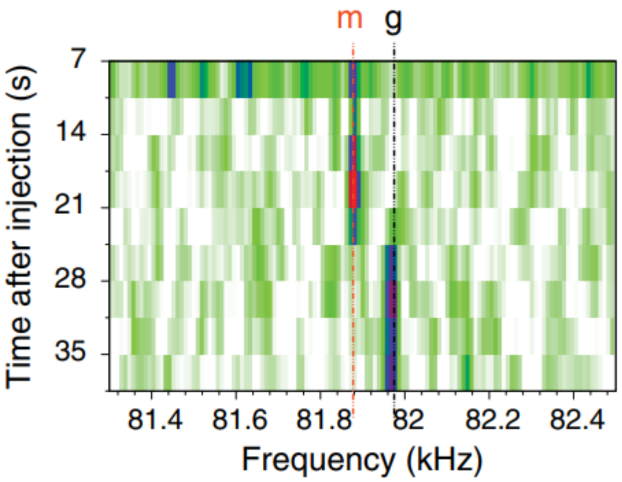
fission

p

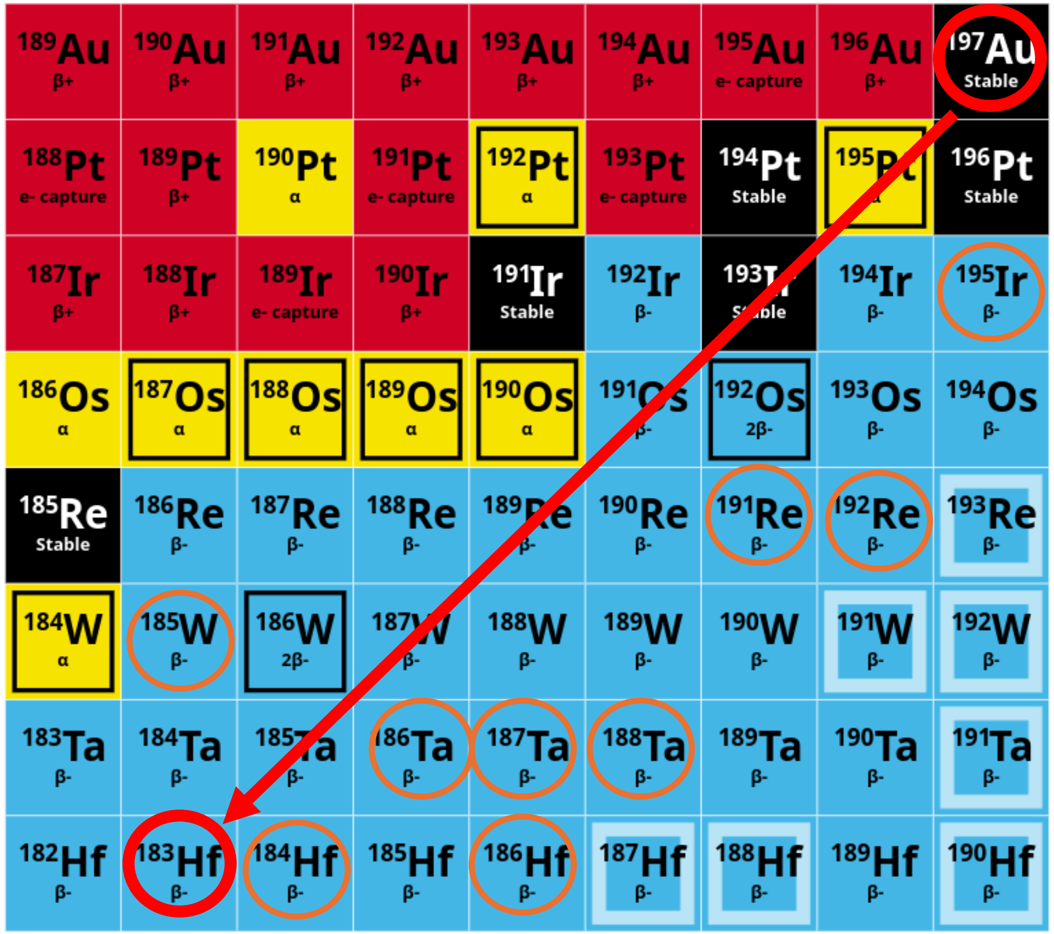
Adapted from H.J.Wollersheim., Physics with Exotic Nuclei Talk, 2016 ; P.M.Walker & G. Dracoulis, Nature . 399 (1999) 35.

A Known Example





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



^{189}Au β+	^{190}Au β+	^{191}Au β+	^{192}Au β+	^{193}Au β+	^{194}Au β+	^{195}Au e- capture	^{196}Au β+	^{197}Au Stable
^{188}Pt e- capture	^{189}Pt β+	^{190}Pt α	^{191}Pt e- capture	^{192}Pt α	^{193}Pt e- capture	^{194}Pt Stable	^{195}Pt α	^{196}Pt Stable
^{187}Ir β+	^{188}Ir β+	^{189}Ir e- capture	^{190}Ir β+	^{191}Ir Stable	^{192}Ir β-	^{193}Ir Stable	^{194}Ir β-	^{195}Ir β-
^{186}Os α	^{187}Os α	^{188}Os α	^{189}Os α	^{190}Os α	^{191}Os β-	^{192}Os 2β-	^{193}Os β-	^{194}Os β-
^{185}Re Stable	^{186}Re β-	^{187}Re β-	^{188}Re β-	^{189}Re β-	^{190}Re β-	^{191}Re β-	^{192}Re β-	^{193}Re β-
^{184}W α	^{185}W β-	^{186}W 2β-	^{187}W β-	^{188}W β-	^{189}W β-	^{190}W β-	^{191}W β-	^{192}W β-
^{183}Ta β-	^{184}Ta β-	^{185}Ta β-	^{186}Ta β-	^{187}Ta β-	^{188}Ta β-	^{189}Ta β-	^{190}Ta β-	^{191}Ta β-
^{182}Hf β-	^{183}Hf β-	^{184}Hf β-	^{185}Hf β-	^{186}Hf β-	^{187}Hf β-	^{188}Hf β-	^{189}Hf β-	^{190}Hf β-

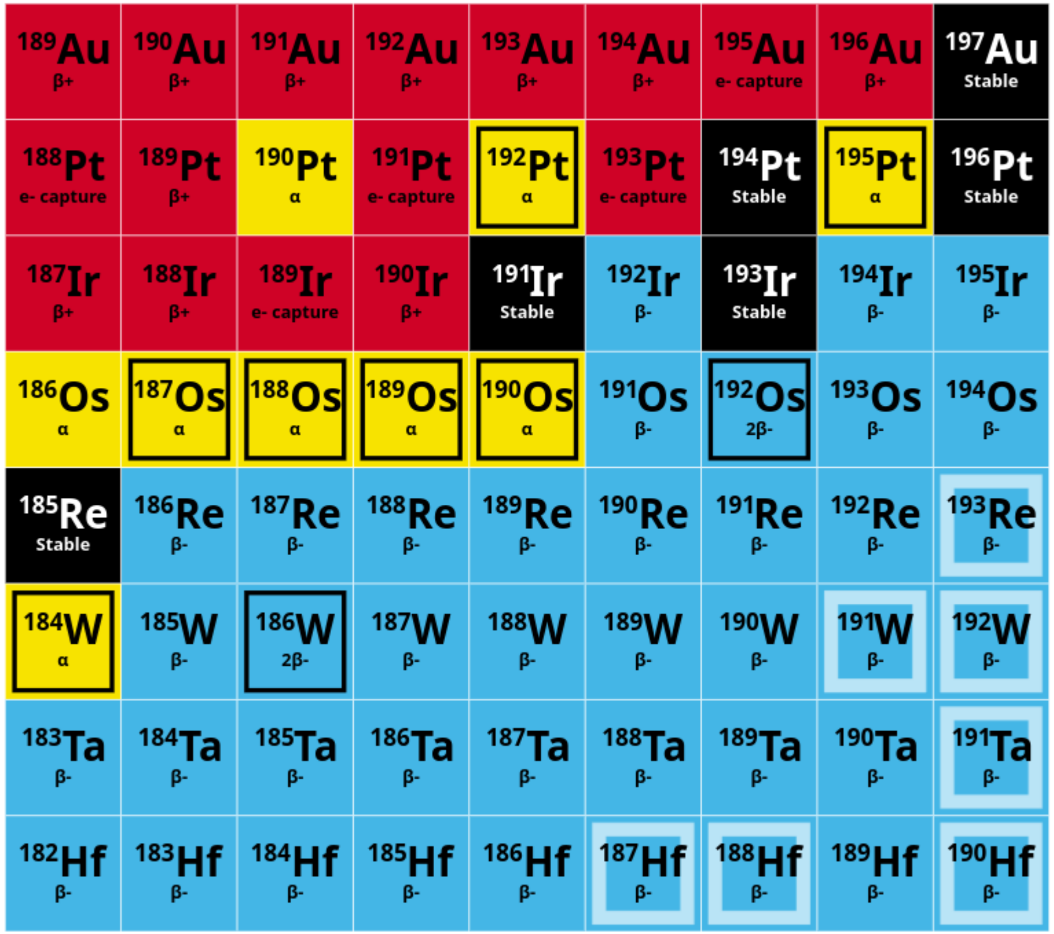
New Isomers $T_{1/2} > 1$s

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

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



^{189}Au β+	^{190}Au β+	^{191}Au β+	^{192}Au β+	^{193}Au β+	^{194}Au β+	^{195}Au e- capture	^{196}Au β+	^{197}Au Stable
^{188}Pt e- capture	^{189}Pt β+	^{190}Pt α	^{191}Pt e- capture	^{192}Pt α	^{193}Pt e- capture	^{194}Pt Stable	^{195}Pt α	^{196}Pt Stable
^{187}Ir β+	^{188}Ir β+	^{189}Ir e- capture	^{190}Ir β+	^{191}Ir Stable	^{192}Ir β-	^{193}Ir Stable	^{194}Ir β-	^{195}Ir β-
^{186}Os α	^{187}Os α	^{188}Os α	^{189}Os α	^{190}Os α	^{191}Os β-	^{192}Os 2β-	^{193}Os β-	^{194}Os β-
^{185}Re Stable	^{186}Re β-	^{187}Re β-	^{188}Re β-	^{189}Re β-	^{190}Re β-	^{191}Re β-	^{192}Re β-	^{193}Re β-
^{184}W α	^{185}W β-	^{186}W 2β-	^{187}W β-	^{188}W β-	^{189}W β-	^{190}W β-	^{191}W β-	^{192}W β-
^{183}Ta β-	^{184}Ta β-	^{185}Ta β-	^{186}Ta β-	^{187}Ta β-	^{188}Ta β-	^{189}Ta β-	^{190}Ta β-	^{191}Ta β-
^{182}Hf β-	^{183}Hf β-	^{184}Hf β-	^{185}Hf β-	^{186}Hf β-	^{187}Hf β-	^{188}Hf β-	^{189}Hf β-	^{190}Hf β-

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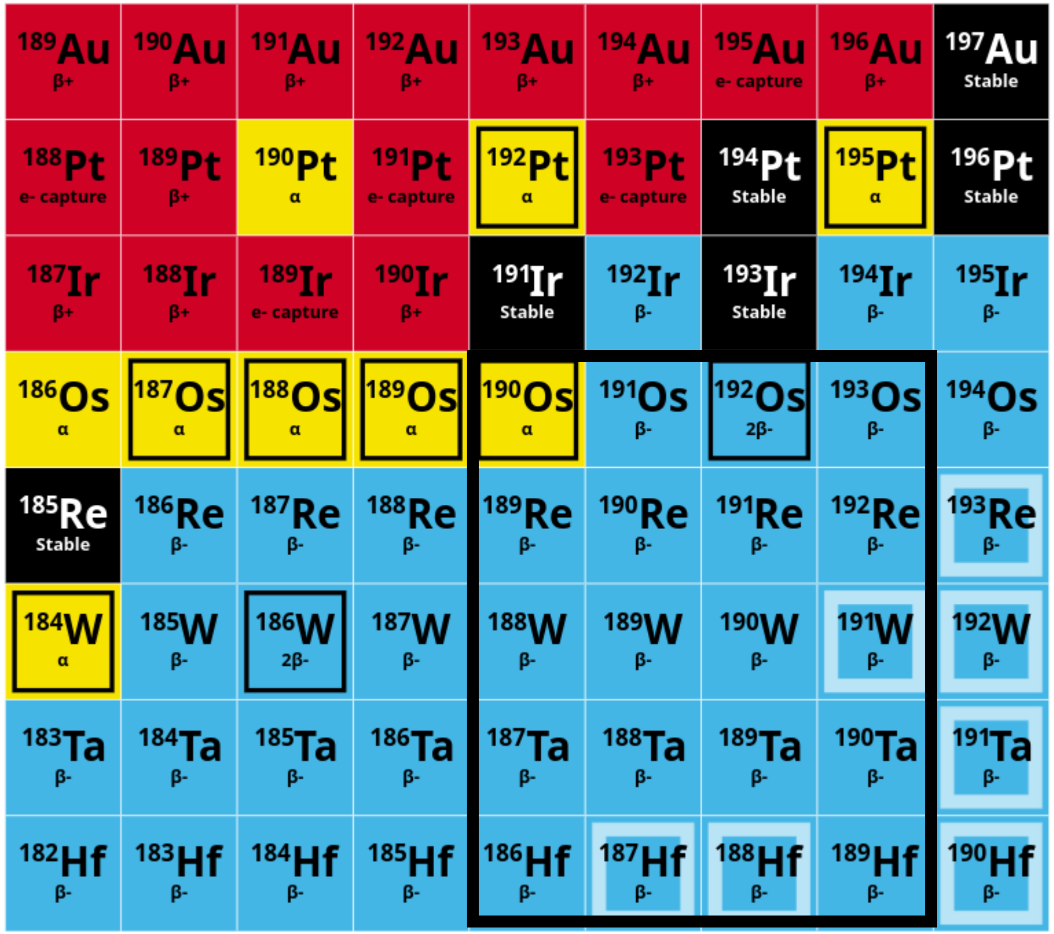

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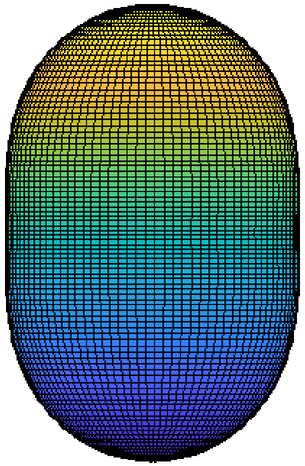
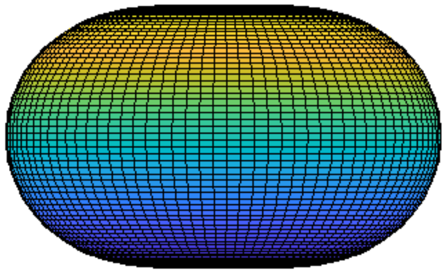
^{186}Os α	^{187}Os α	^{188}Os α	^{189}Os α	^{190}Os α	^{191}Os β-	^{192}Os 2β-	^{193}Os β-	^{194}Os β-
^{185}Re Stable	^{186}Re β-	^{187}Re β-	^{188}Re β-	^{189}Re β-	^{190}Re β-	^{191}Re β-	^{192}Re β-	^{193}Re β-
^{184}W α	^{185}W β-	^{186}W 2β-	^{187}W β-	^{188}W β-	^{189}W β-	^{190}W β-	^{191}W β-	^{192}W β-
^{183}Ta β-	^{184}Ta β-	^{185}Ta β-	^{186}Ta β-	^{187}Ta β-	^{188}Ta β-	^{189}Ta β-	^{190}Ta β-	^{191}Ta β-
^{182}Hf β-	^{183}Hf β-	^{184}Hf β-	^{185}Hf β-	^{186}Hf β-	^{187}Hf β-	^{188}Hf β-	^{189}Hf β-	^{190}Hf β-



Prolate



Oblate

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[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

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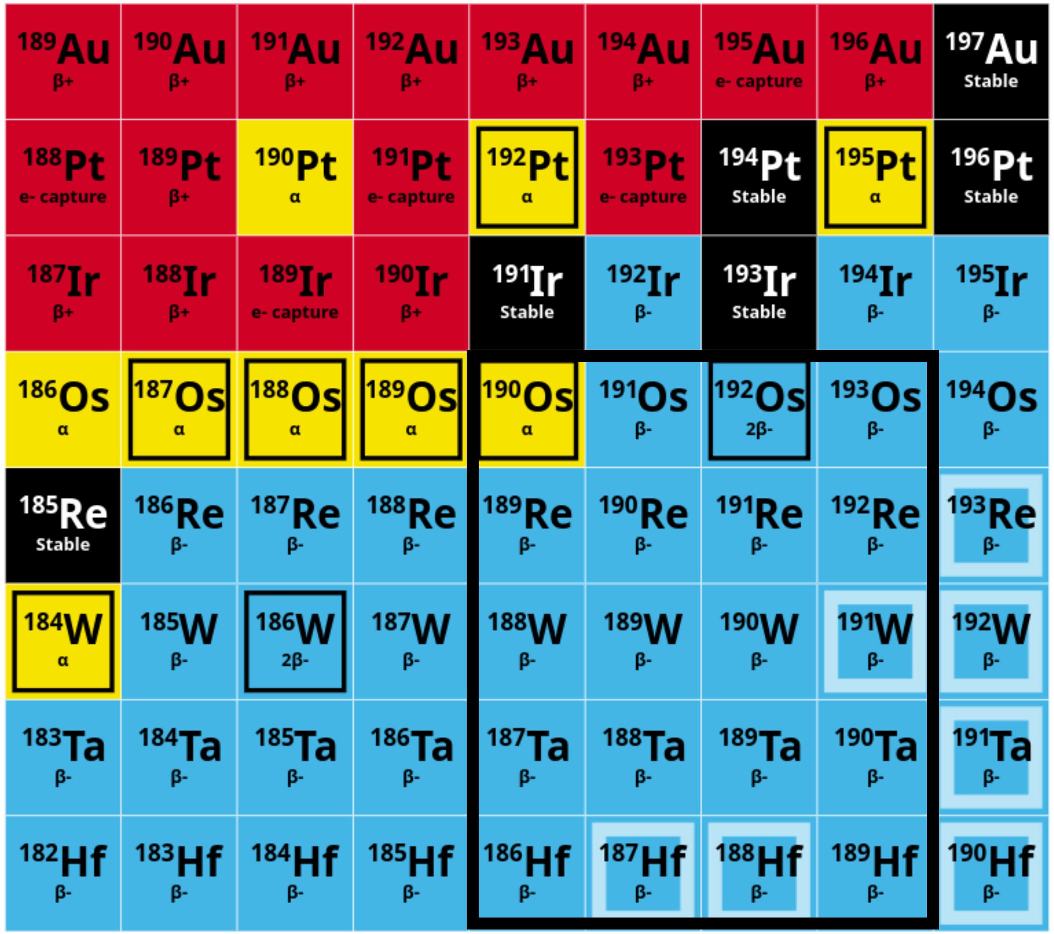
[2] F.R.Xu *et al.* / Phys. Rev. C 62(2000)014301

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



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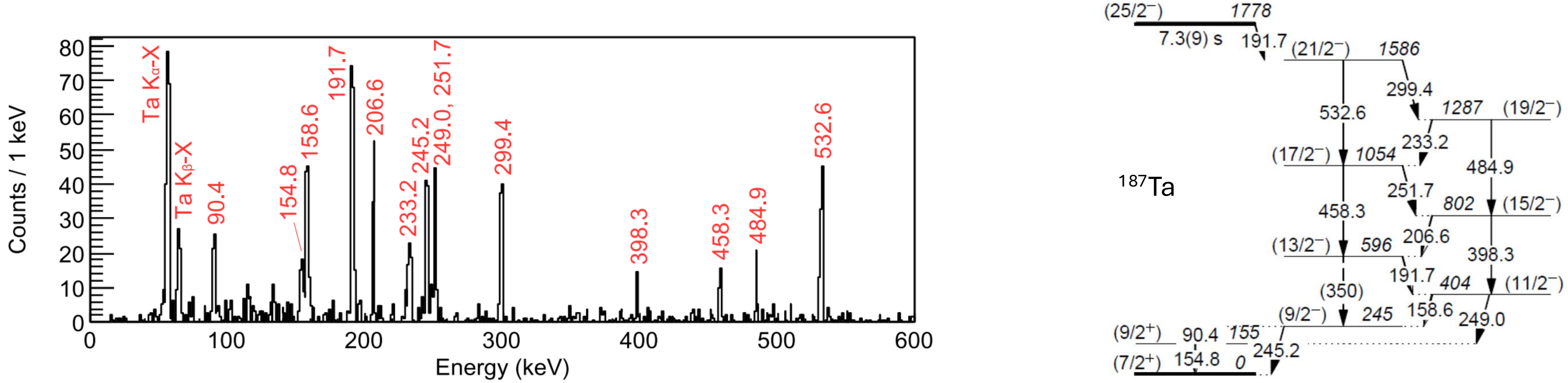
^{188}Pt e- capture	^{189}Pt β+	^{190}Pt α	^{191}Pt e- capture	^{192}Pt α	^{193}Pt e- capture	^{194}Pt Stable	^{195}Pt α	^{196}Pt Stable
^{187}Ir β+	^{188}Ir β+	^{189}Ir e- capture	^{190}Ir β+	^{191}Ir Stable	^{192}Ir β-	^{193}Ir Stable	^{194}Ir β-	^{195}Ir β-
^{186}Os α	^{187}Os α	^{188}Os α	^{189}Os α	^{190}Os α	^{191}Os β-	^{192}Os 2β-	^{193}Os β-	^{194}Os β-
^{185}Re Stable	^{186}Re β-	^{187}Re β-	^{188}Re β-	^{189}Re β-	^{190}Re β-	^{191}Re β-	^{192}Re β-	^{193}Re β-
^{184}W α	^{185}W β-	^{186}W 2β-	^{187}W β-	^{188}W β-	^{189}W β-	^{190}W β-	^{191}W β-	^{192}W β-
^{183}Ta β-	^{184}Ta β-	^{185}Ta β-	^{186}Ta β-	^{187}Ta β-	^{188}Ta β-	^{189}Ta β-	^{190}Ta β-	^{191}Ta β-
^{182}Hf β-	^{183}Hf β-	^{184}Hf β-	^{185}Hf β-	^{186}Hf β-	^{187}Hf β-	^{188}Hf β-	^{189}Hf β-	^{190}Hf β-

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 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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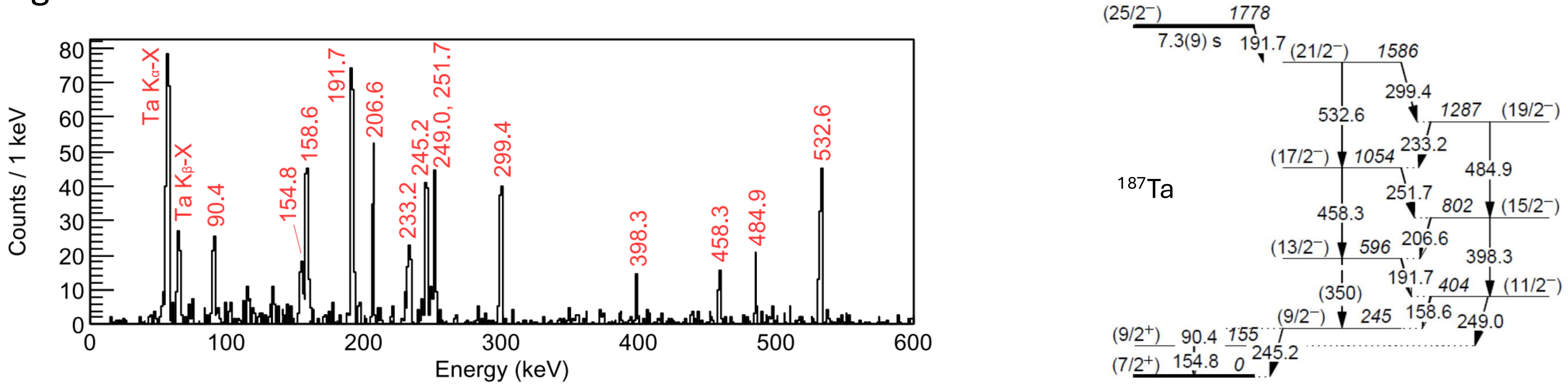
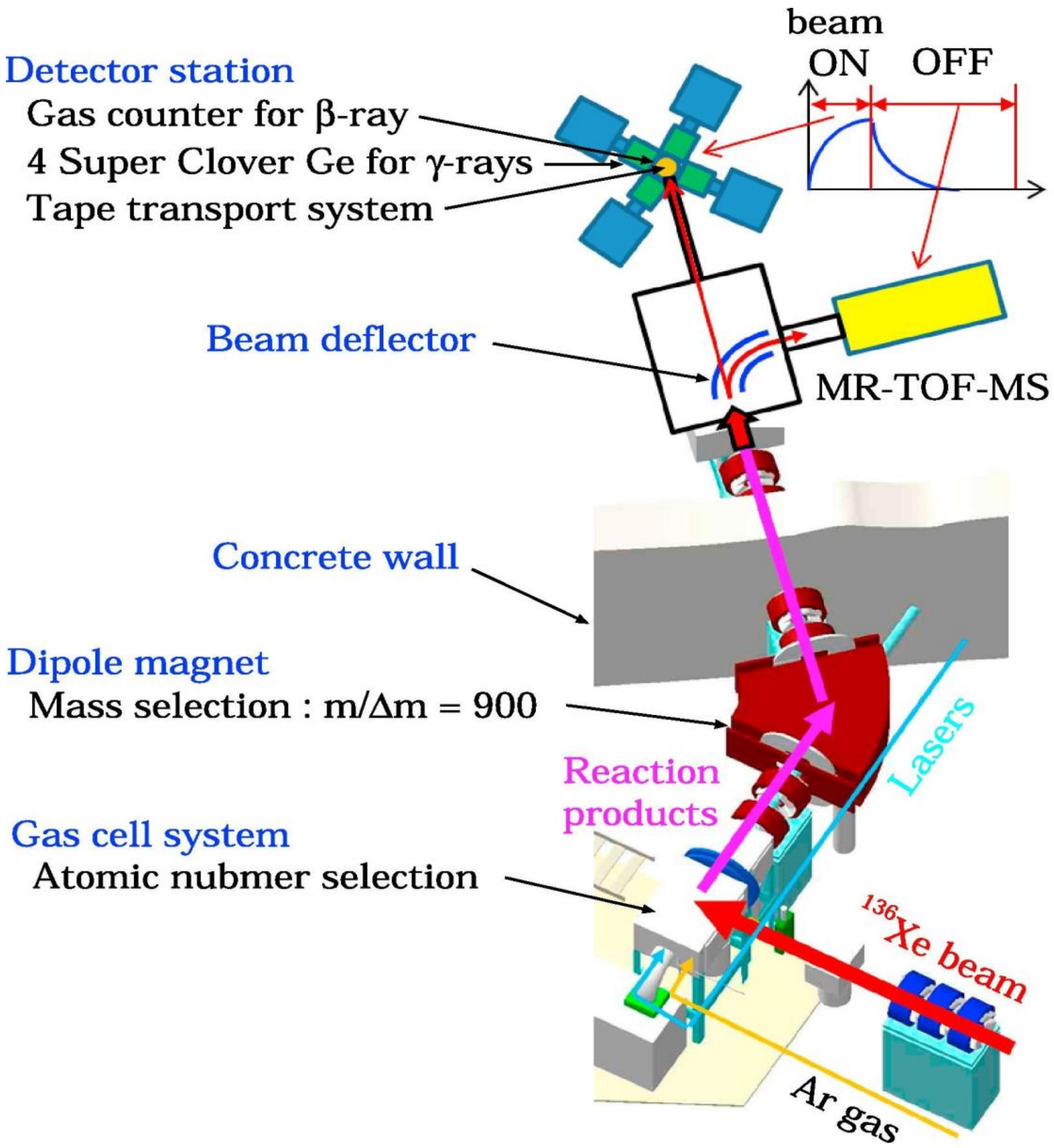


Summed γ-γ coincidence spectrum and the associated level scheme for ^{187}Ta obtained at KISS.

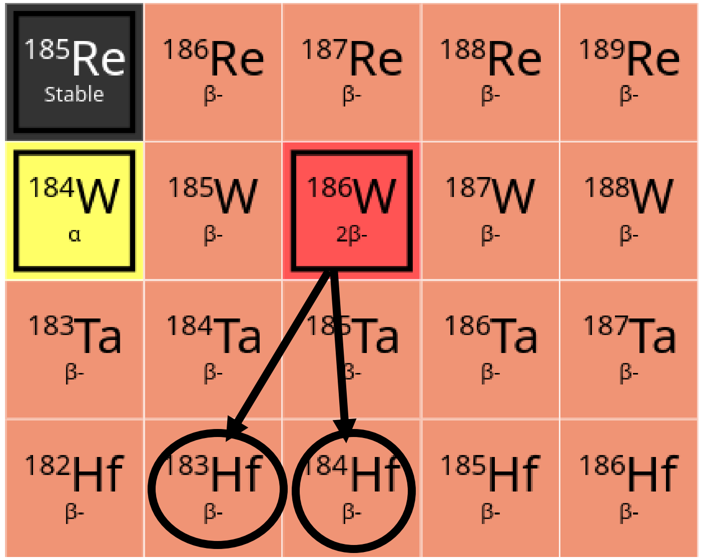
P.M.Walker *et al.* / Phys. Rev. Lett. 125 (2020) 192505

- 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



Y. Hirayama *et al.*, Nuclear spectroscopy of r-process nuclei using KEK Isotope Separation System; Nucl. Inst. Meth. B 463(2020)425-430



^{185}Re Stable	^{186}Re β-	^{187}Re β-	^{188}Re β-	^{189}Re β-
^{184}W α	^{185}W β-	^{186}W 2β-	^{187}W β-	^{188}W β-
^{183}Ta β-	^{184}Ta β-	^{185}Ta β-	^{186}Ta β-	^{187}Ta β-
^{182}Hf β-	^{183}Hf β-	^{184}Hf β-	^{185}Hf β-	^{186}Hf β-

Schematics of KISS for ^{136}Xe on ^{nat}W → ^{183,184}Hf with subsequent spectroscopy.

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 :

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

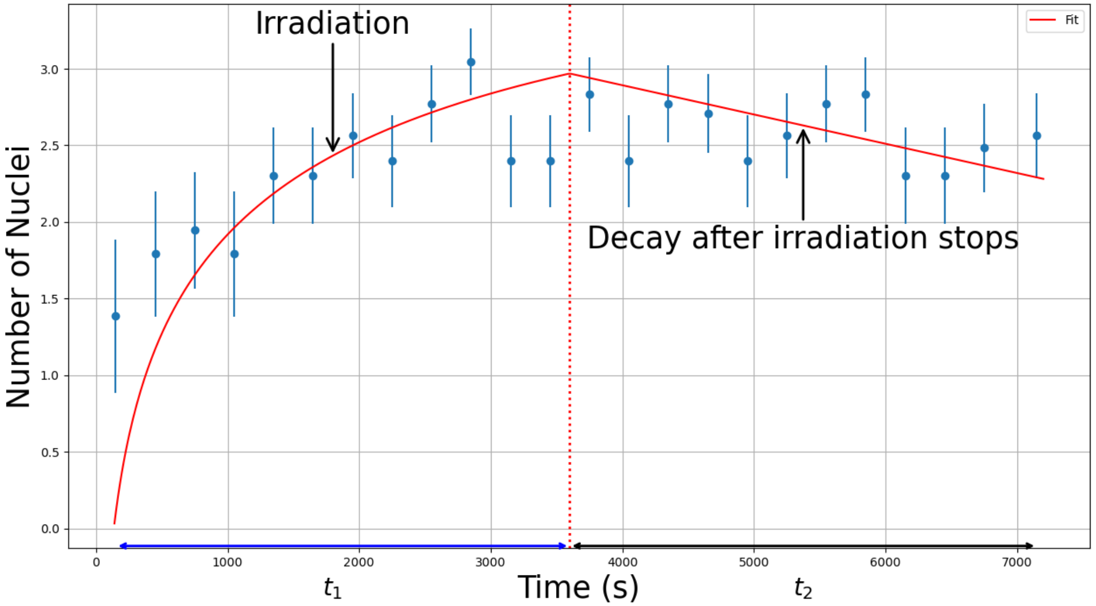
  - Here λ is the decay constant. Meanwhile, the number of nuclei that decayed in the time following irradiation (t_2) is calculated as:

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

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

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

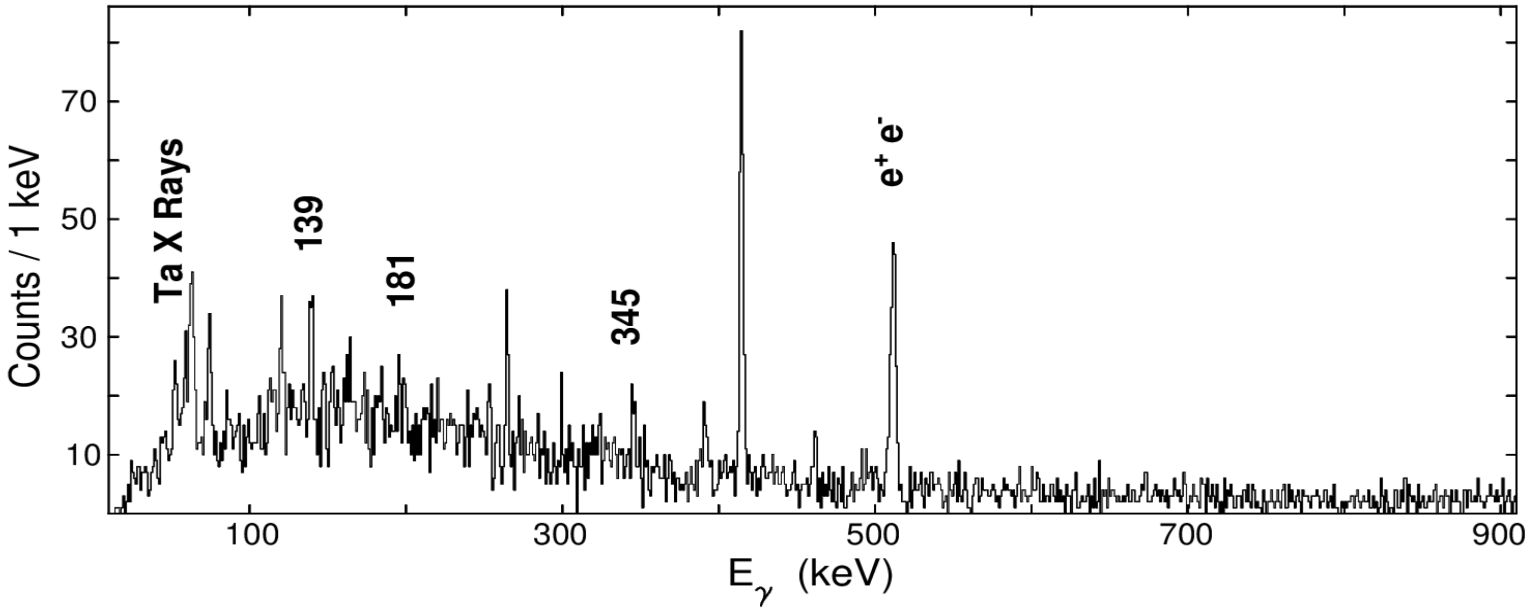
    Here, *N(T)* = $N(t_1)$ + $N(t_2)$, which is the total number of decays and is obtained through the weighted average of the number of decays of the transition in question

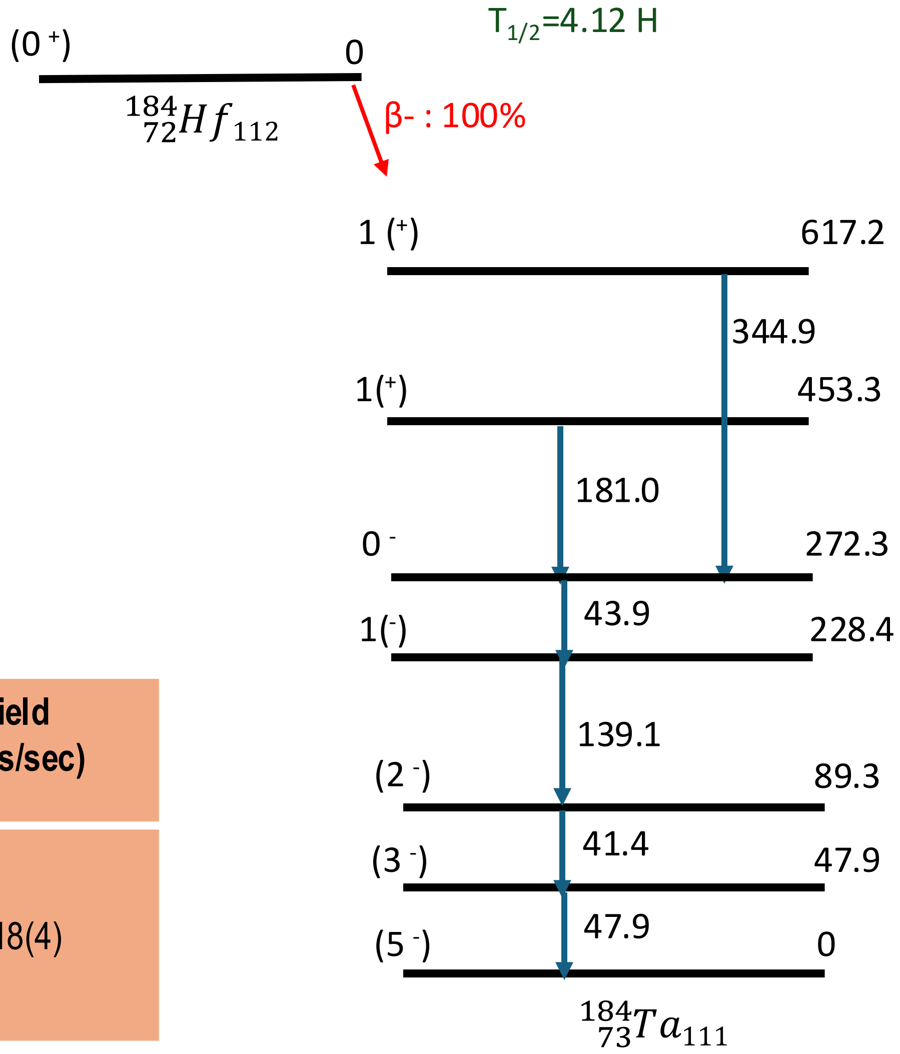


Number of nuclei during irradiation (1 hour of beam on) and decay (1 hour of beam off).

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)		

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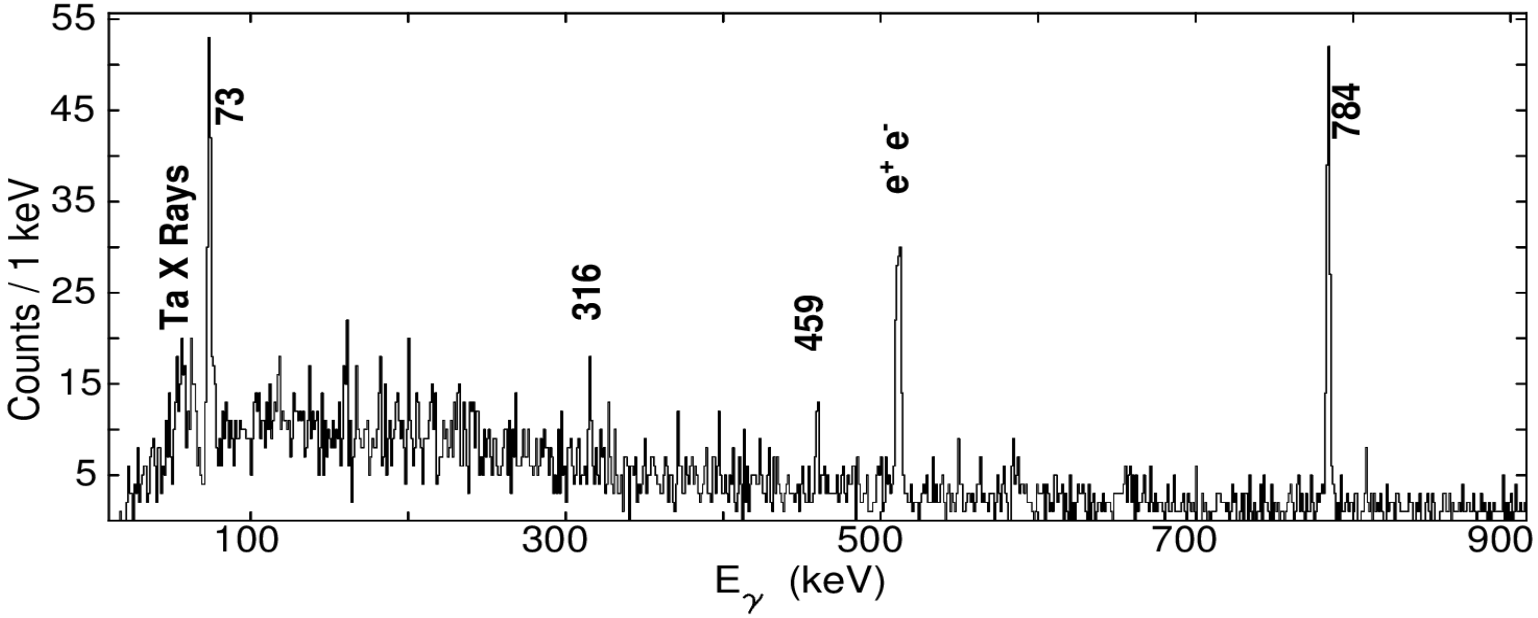
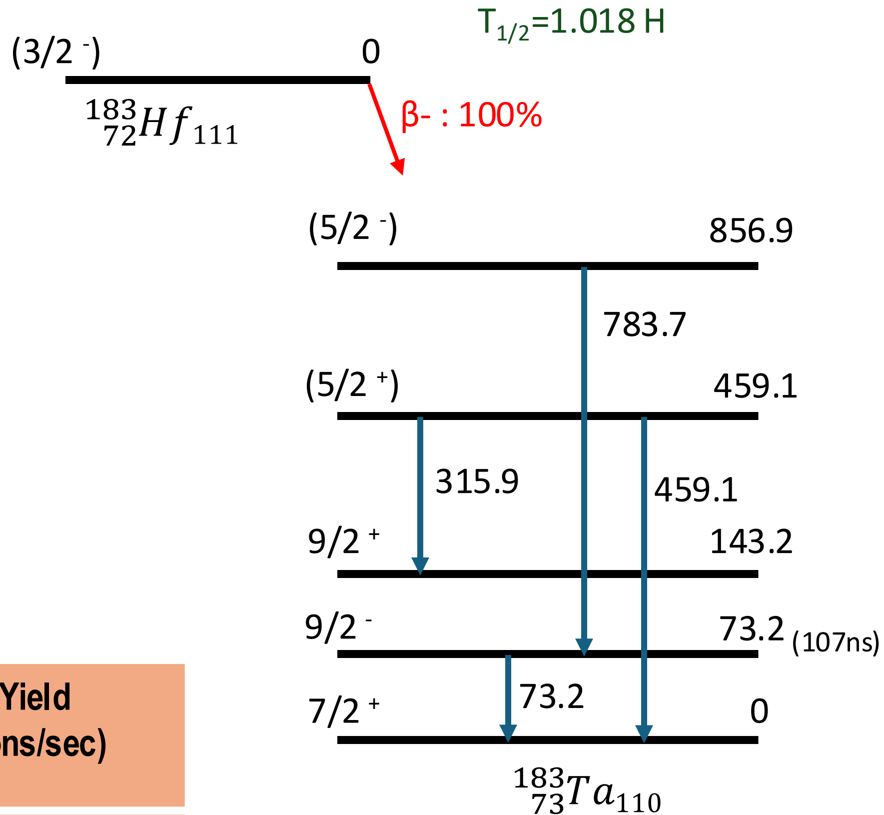
[1] https://www.nndc.bnl.gov/

Yield calculation of ^{183}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)
73.2(2)	110(15)	0.1370(14)	38.0(40)	5282(911)	1854(166)	0.81(7)
783.7(3)	134(14)	0.0900(9)	65.5(19)	5683(595)		

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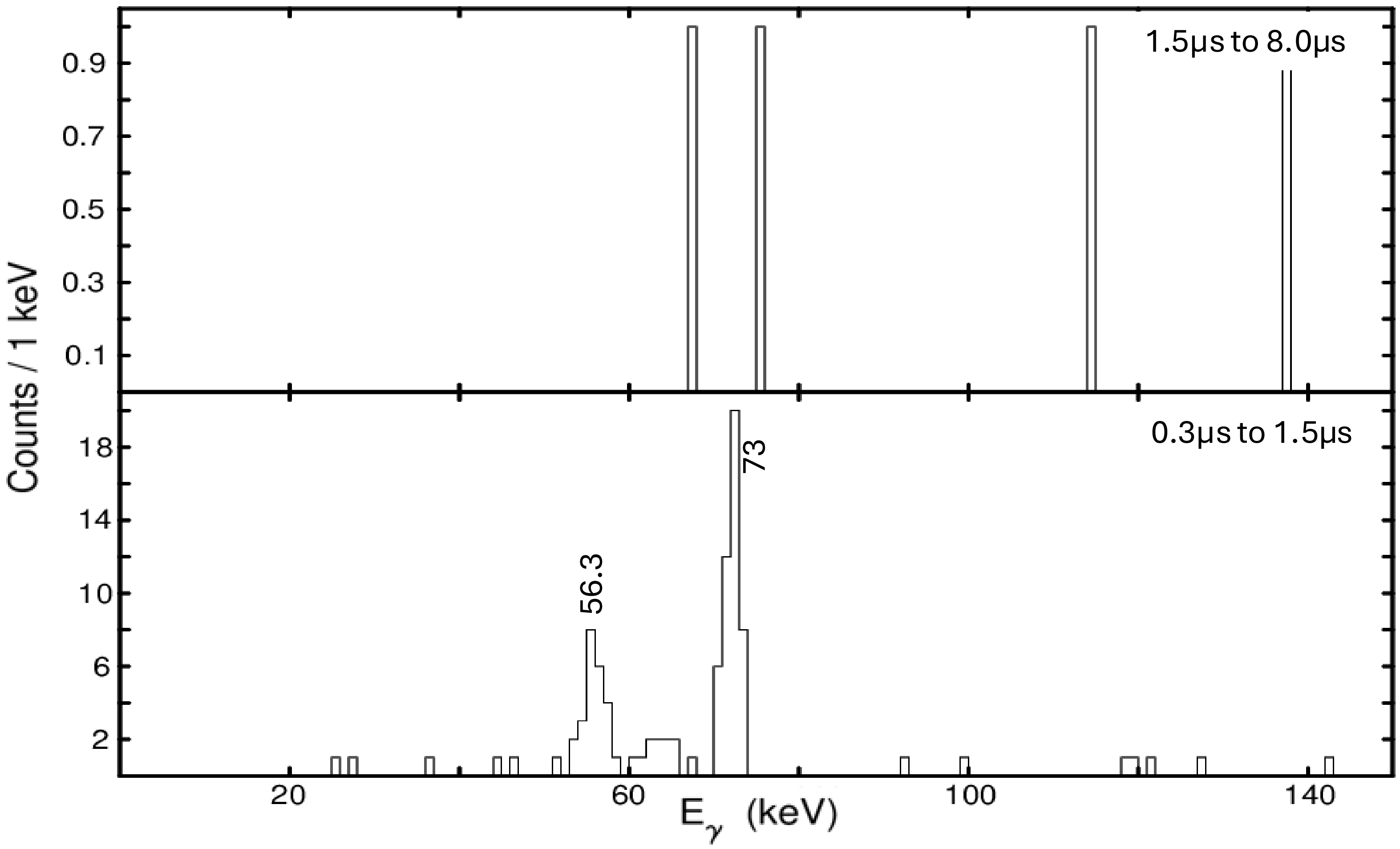
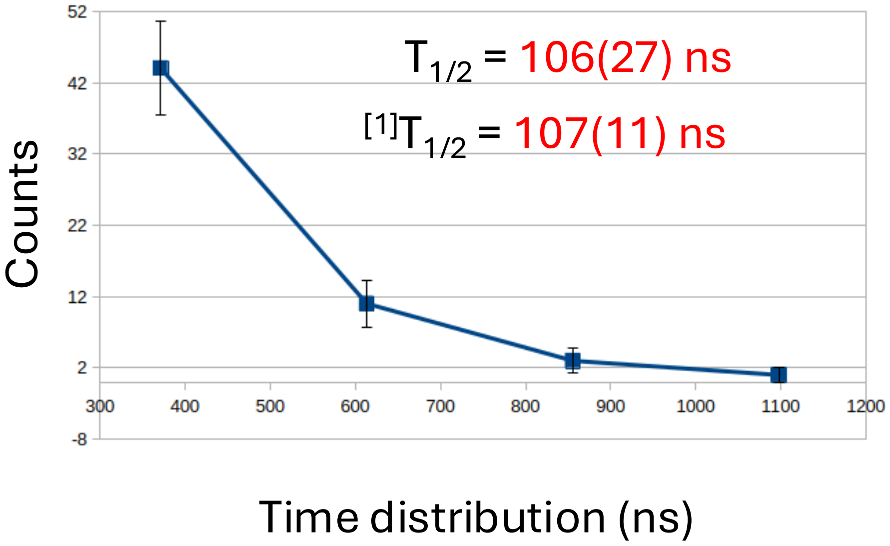
[1] https://www.nndc.bnl.gov/

Isomeric spectroscopy of ^{183}Hf g.s. β-decay to ^{183}Ta

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



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


$T_{1/2}$ = 106(27) ns

[1]$T_{1/2}$ = 107(11) ns

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

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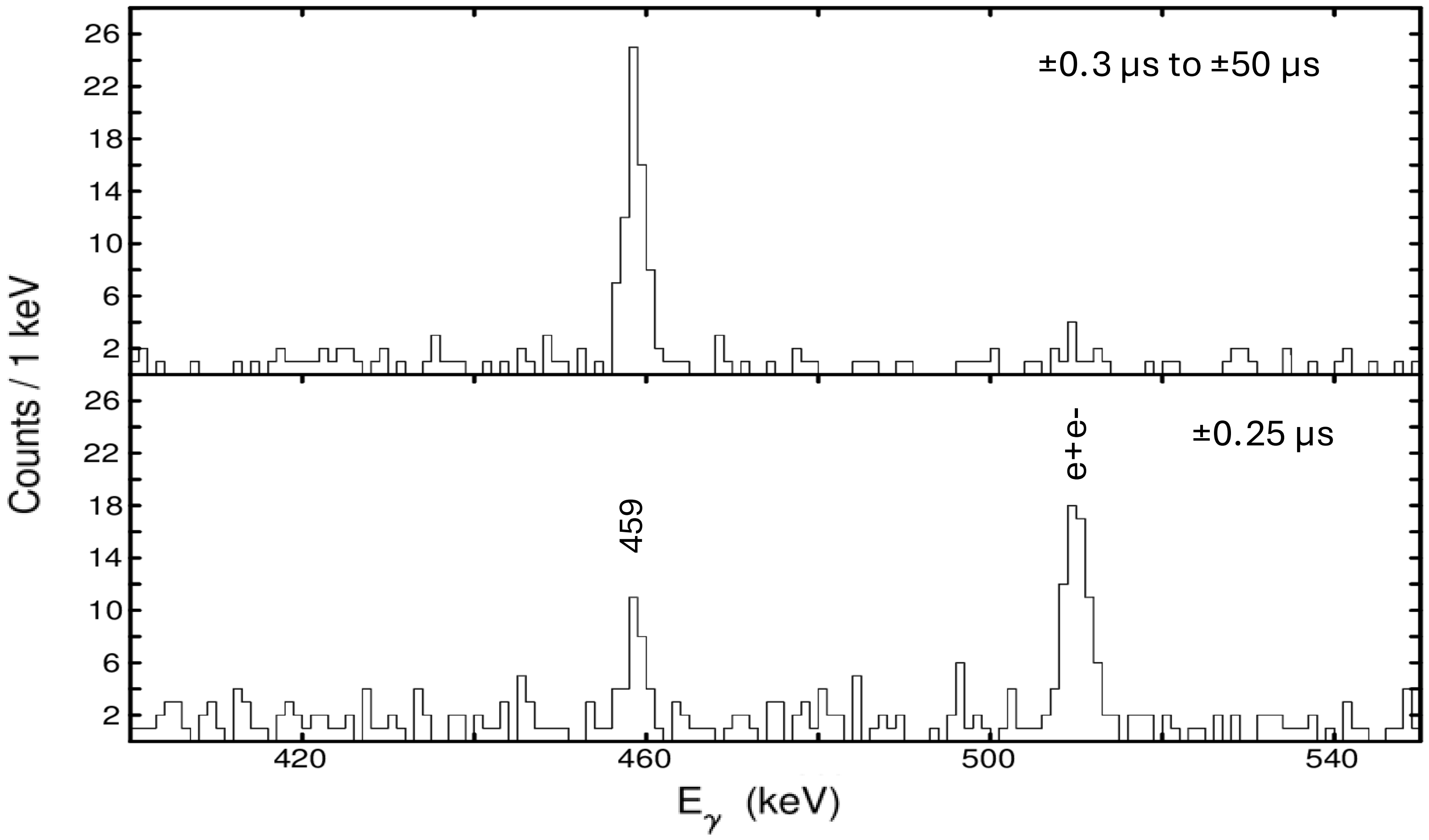
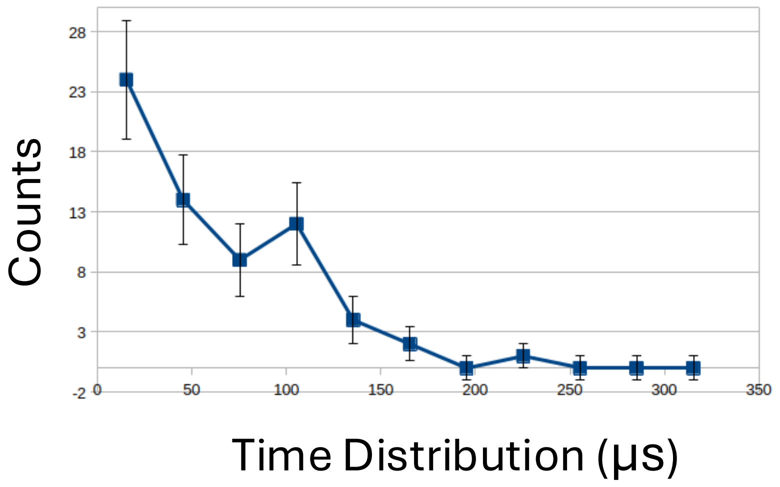
[1] https://www.nndc.bnl.gov/

Isomeric spectroscopy of ^{183}Hf g.s. β-decay to ^{183}Ta

Beam gated β-γ coincidence delayed spectra.





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

	I_γ(%) From [1]	Normalised I_γ(%)
Old Intensity	30(1)	9(4)
New Intensity		33(6)
±0.25 μs		9(3)
±0.3 μs to ±50 μs		24(4)

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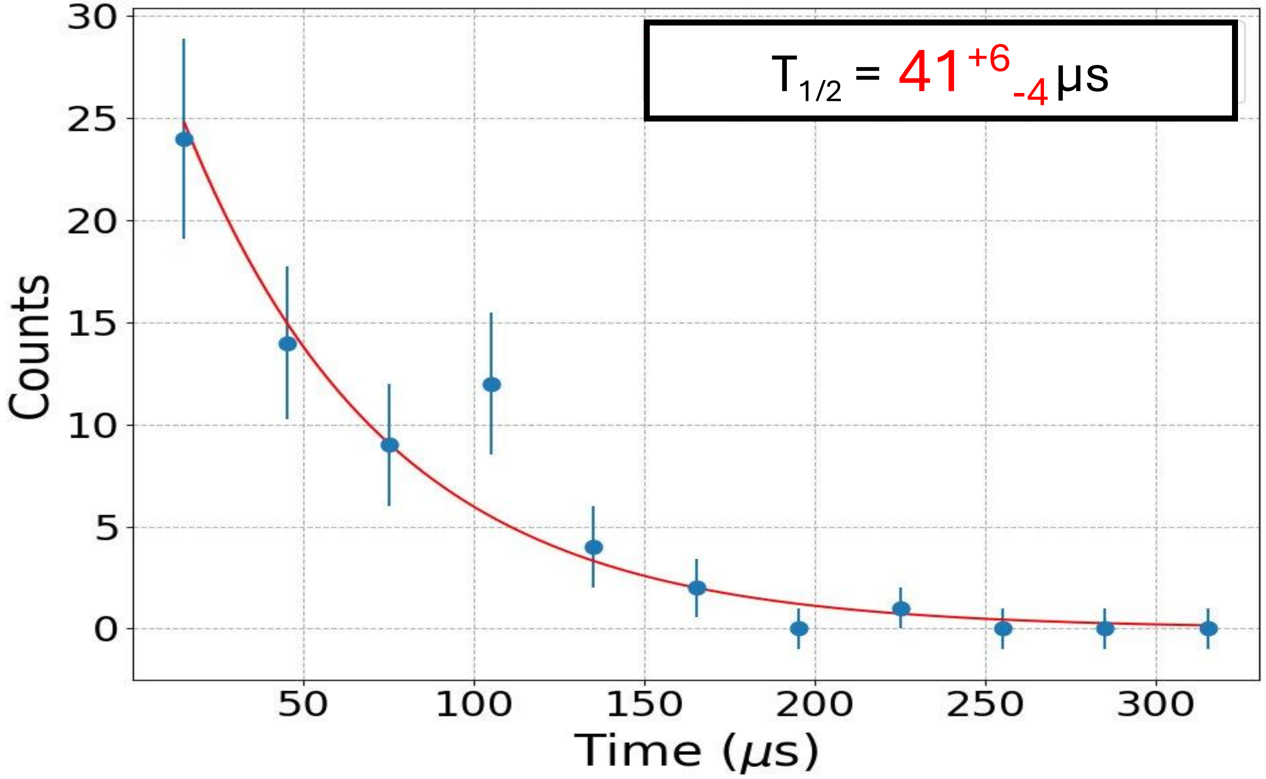
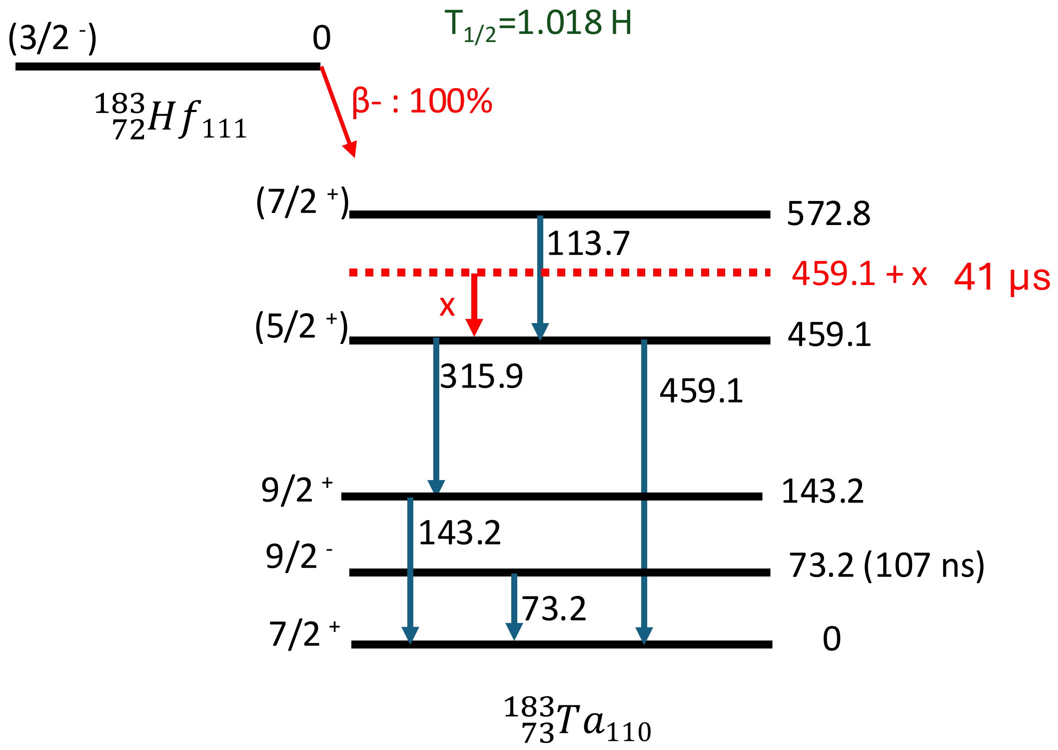
[1] https://www.nndc.bnl.gov/

Isomeric spectroscopy of ^{183}Hf g.s. β-decay to ^{183}Ta





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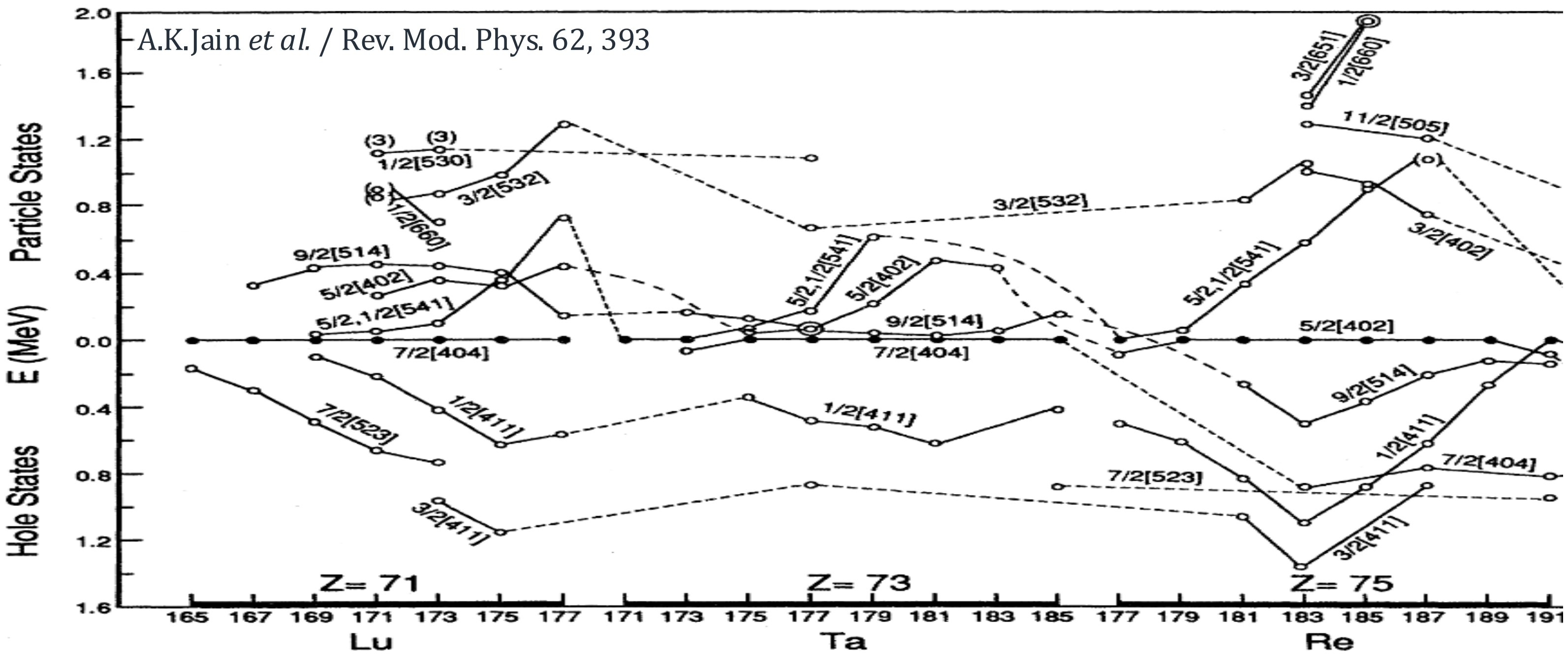
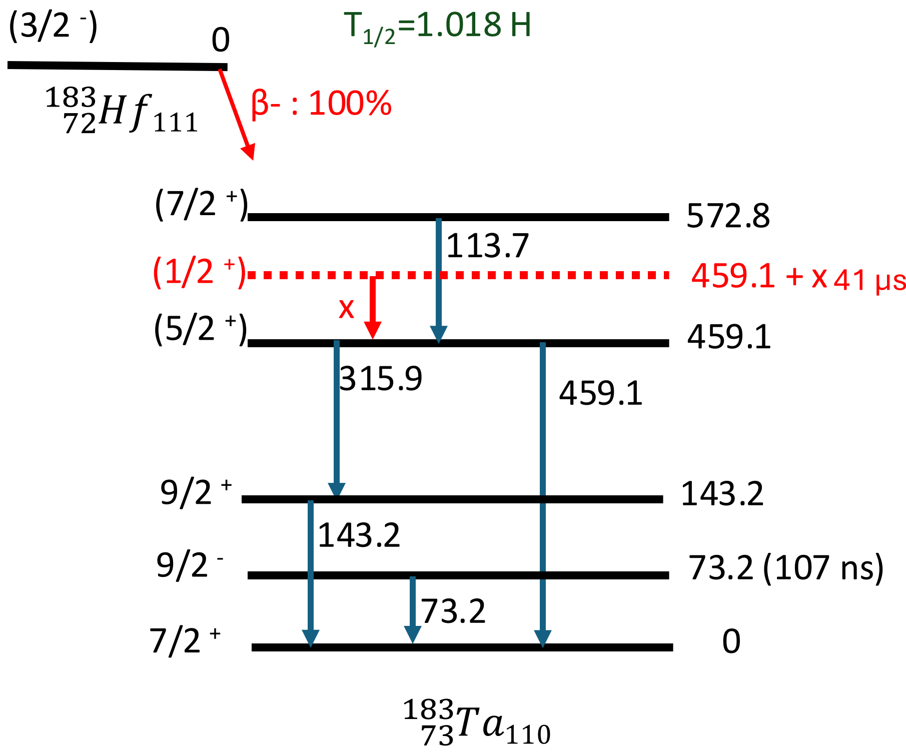

A.K.Jain *et al.* / Rev. Mod. Phys. 62, 393



Nucleus	$J_i^\pi \to J_f^\pi$	$E_{\rm level}$ (keV)	$T_{1/2}$	E_γ (keV)
^{177}Lu[1]	$1/2^+[411] \to 5/2^+[402]$	569.6721(5)	155(7) μs	111.715(1)
^{177}Ta[1]	$1/2^+[411] \to 5/2^+[402]$	487.63(6)	26(3) ns	417.16(5)
^{179}Ta[1]	$1/2^+[411] \to 5/2^+[402]$	520.23(18)	0.28(8) μs	281.69(16)
^{181}Ta[1]	$1/2^+[411] \to 5/2^+[402]$	615.19(3)	18(1) μs	133.027(18)
^{183}Ta	$1/2^+[411] \to 5/2^+[402]$	459.1+x	41(7) μs	<100
^{177}Re[1]	$1/2^+[411] \to 5/2^+[402]$	495.73(15)		411.0(2)
^{183}Re[1]	$1/2^+[411] \to 5/2^+[402]$	878.92(5)		878.91(5)
^{187}Re[1]	$1/2^+[411] \to 5/2^+[402]$	625.516(8)	540(11) ps	625.52(1)

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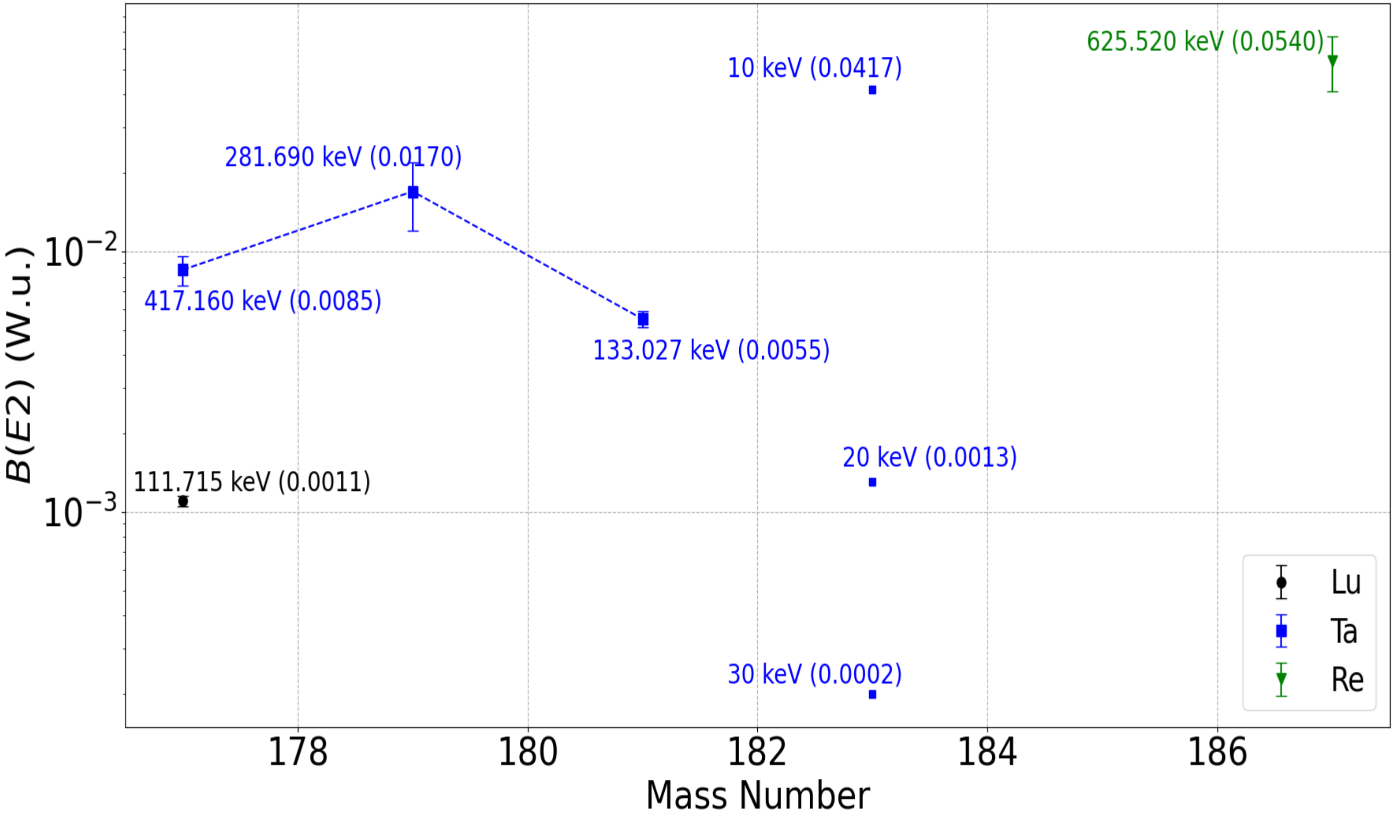
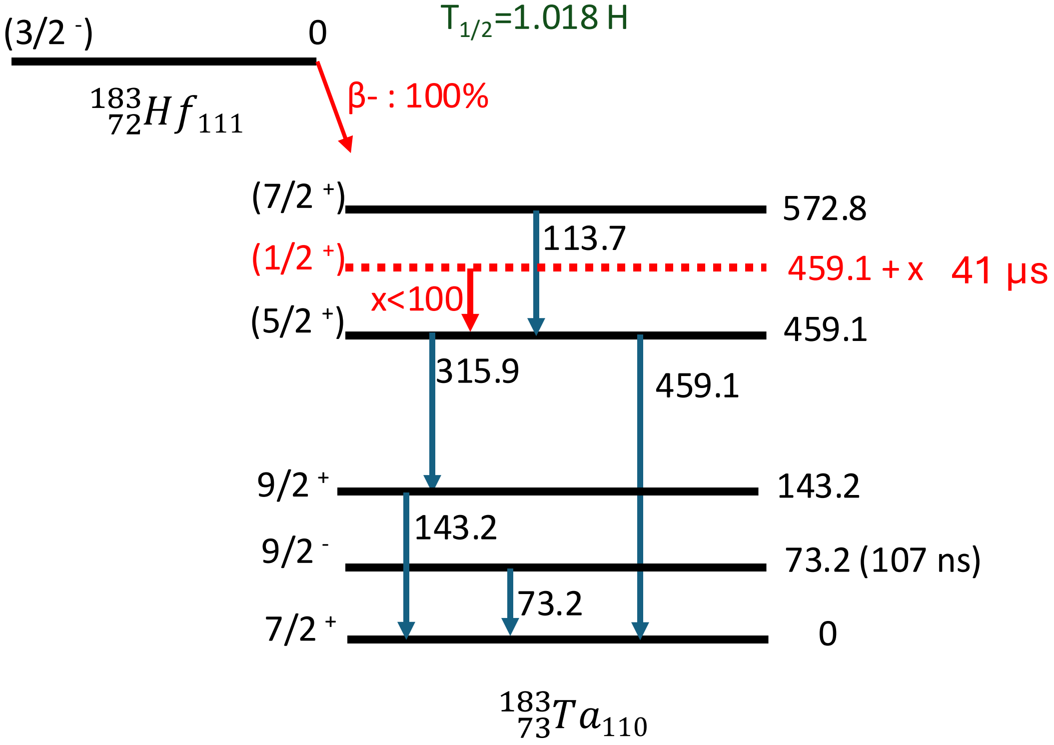
[1] https://www.nndc.bnl.gov/

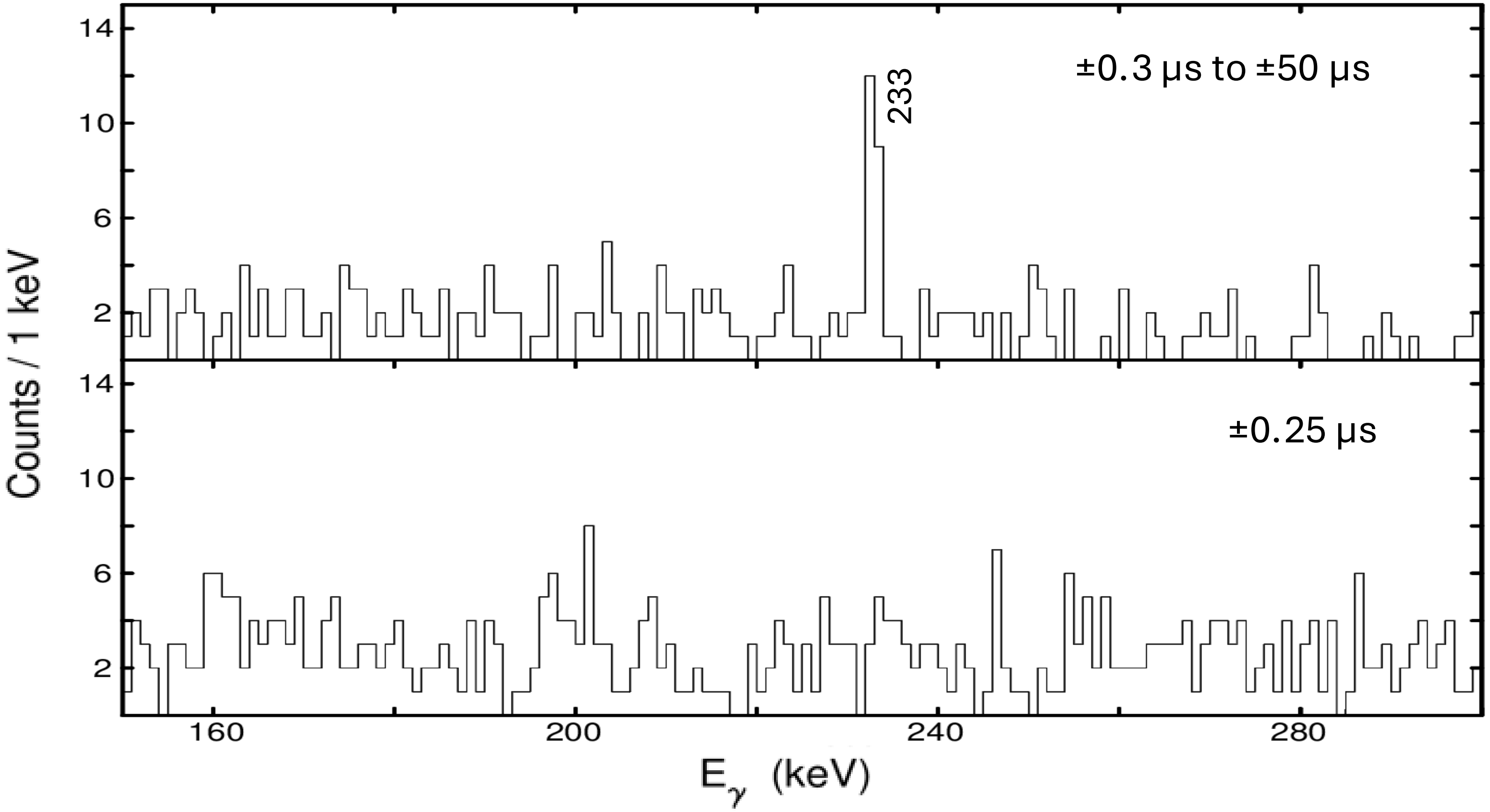
Isomeric spectroscopy of ^{183}Hf g.s. β-decay to ^{183}Ta

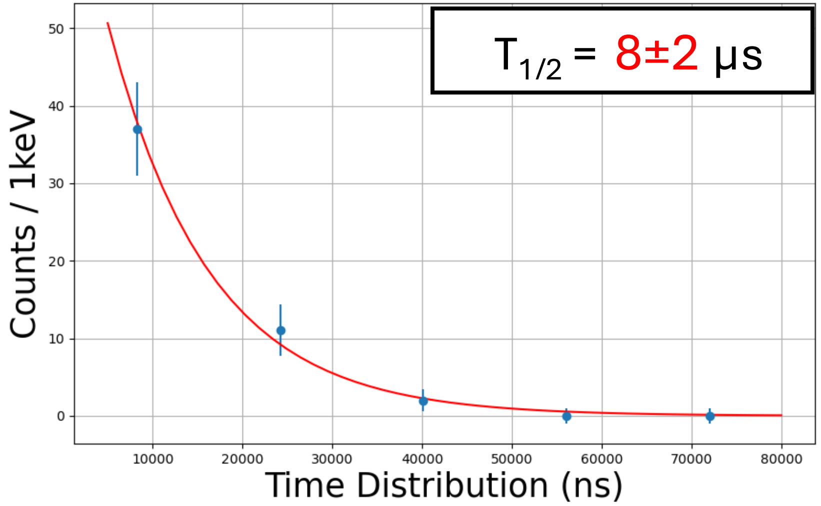




Preliminary Isomeric spectroscopy of ^{184}Hf g.s β-decay to ^{184}Ta

Beam gated β-γ coincidence delayed spectra.





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). This is 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.

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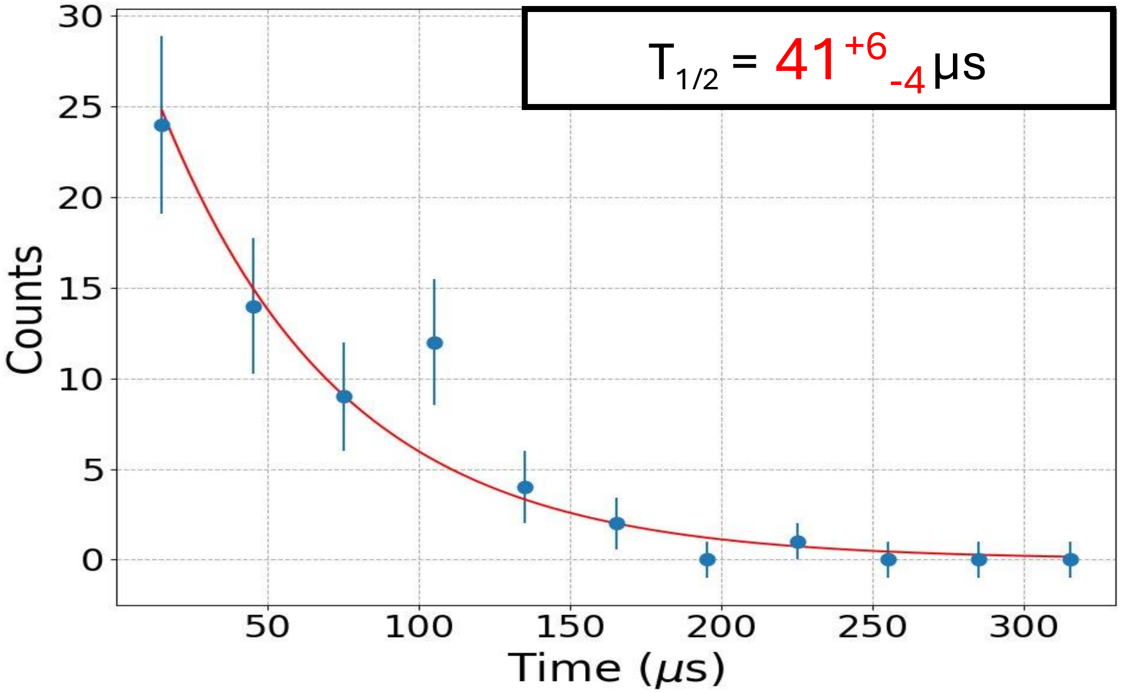
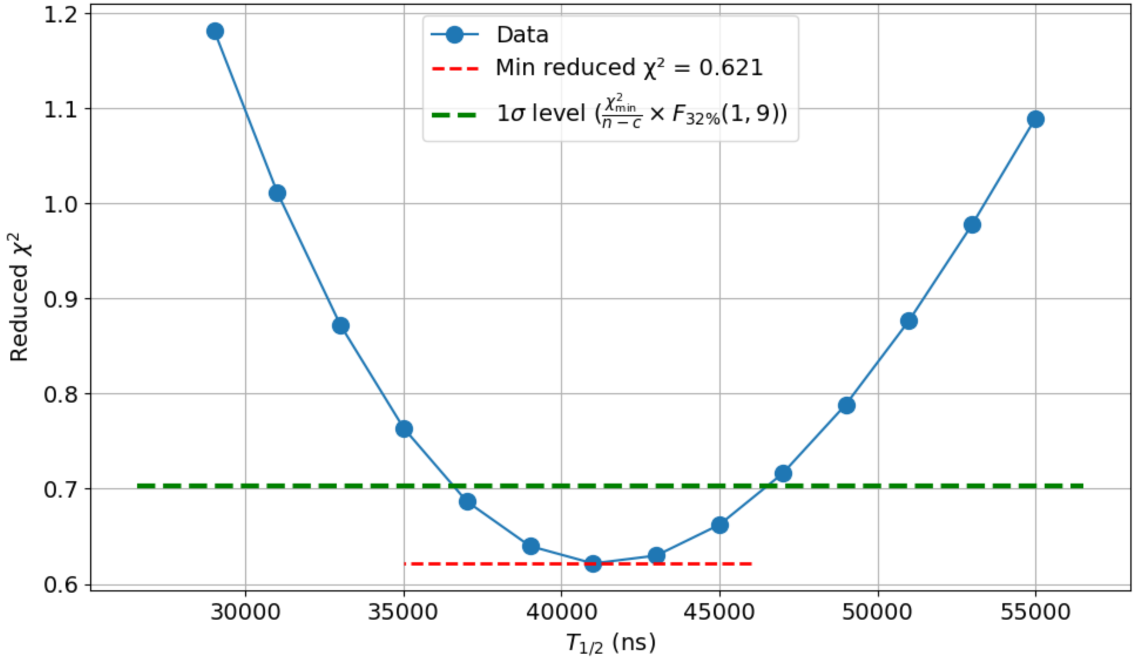
Thank You For Listening !

Additional Slides

Plotting Reduced χ^2 vs $T_{1/2}$

To get errors: 32% confidence level is considered with F-distribution factor



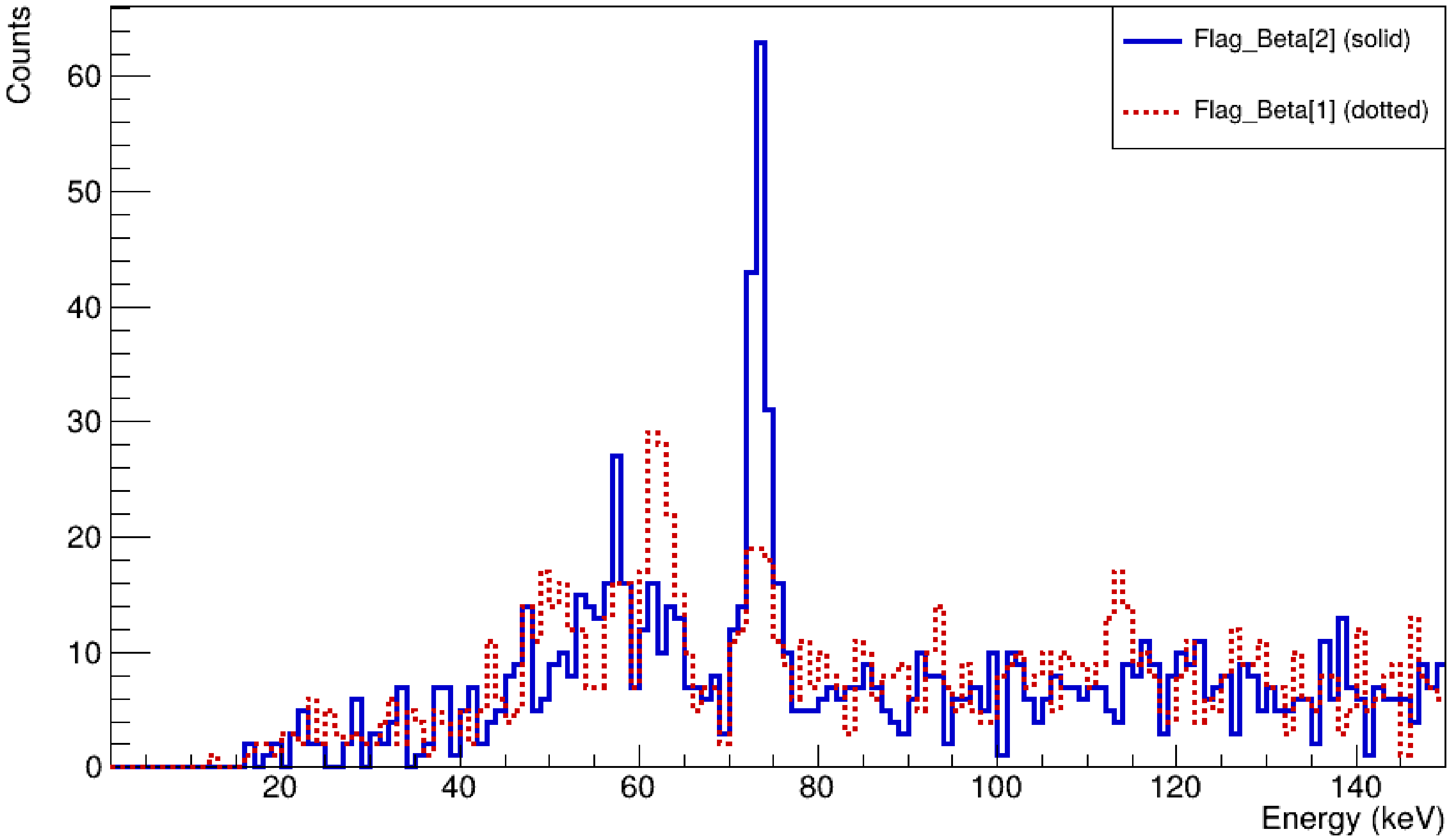


$T_{1/2} = 41^{+6}_{-4}$ μs

X-ray analysis for ^{183}Hf 1hr run files

K X-ray energies (keV)

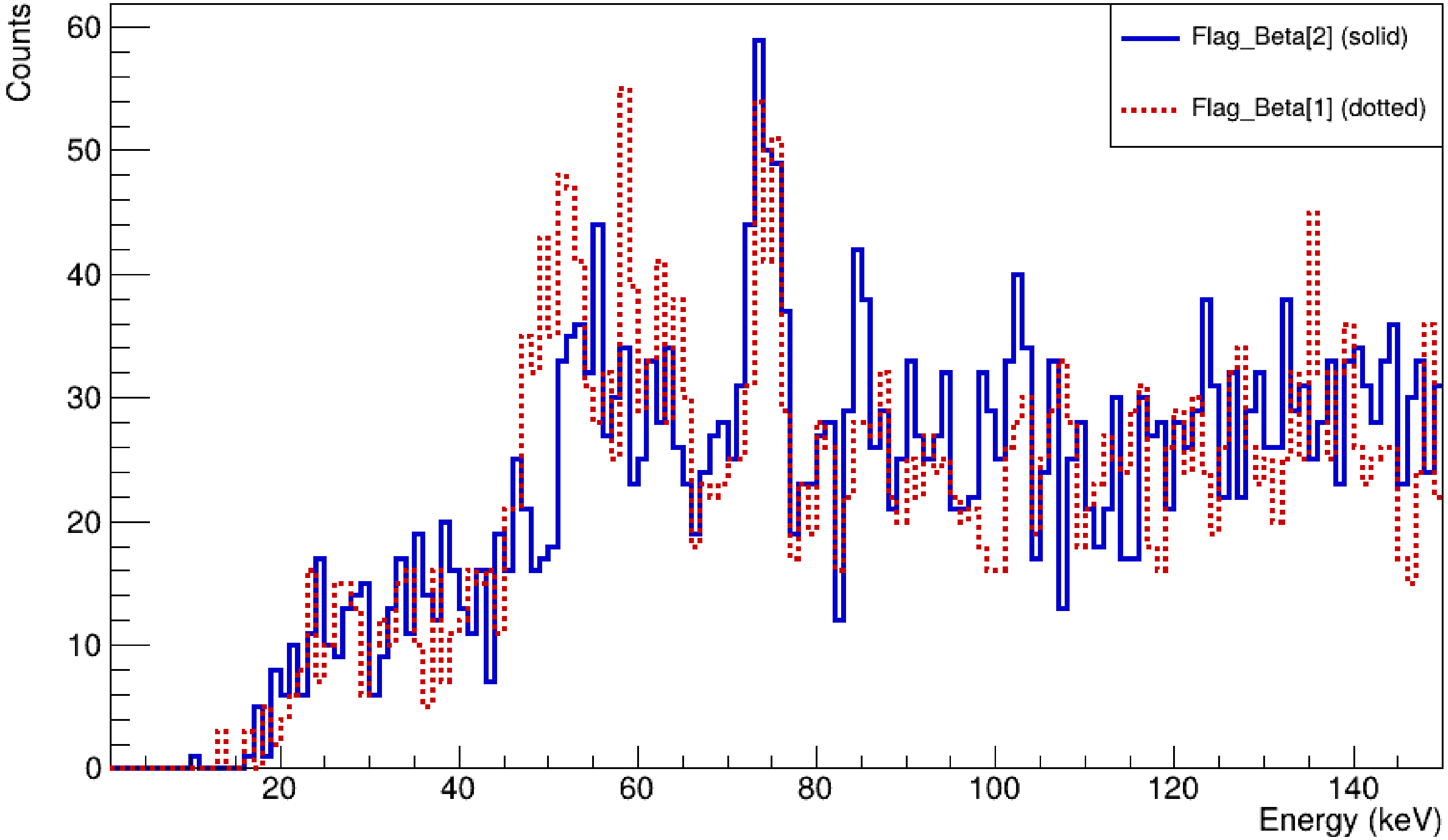
Z	α2	α1	β1	β2
71 Lu:	53.0	54.1	61.2	63.0
72 Hf:	54.6	55.8	63.2	65.0
73 Ta:	56.3	57.5	65.2	67.0
74 W:	58.0	59.3	67.2	69.1
75 Re:	59.7	61.1	69.2	71.2
76 Os:	61.5	63.0	71.3	73.4
77 Ir:	63.3	64.9	73.5	75.6
78 Pt:	65.1	66.8	75.7	77.9
79 Au:	67.0	68.8	77.9	80.2
80 Hg:	68.9	70.8	80.2	82.5
81 Tl:	70.8	72.9	82.5	84.9
82 Pb:	72.8	75.0	84.8	87.3



X-ray analysis for ^{183}Hf 5min run files

K X-ray energies (keV)

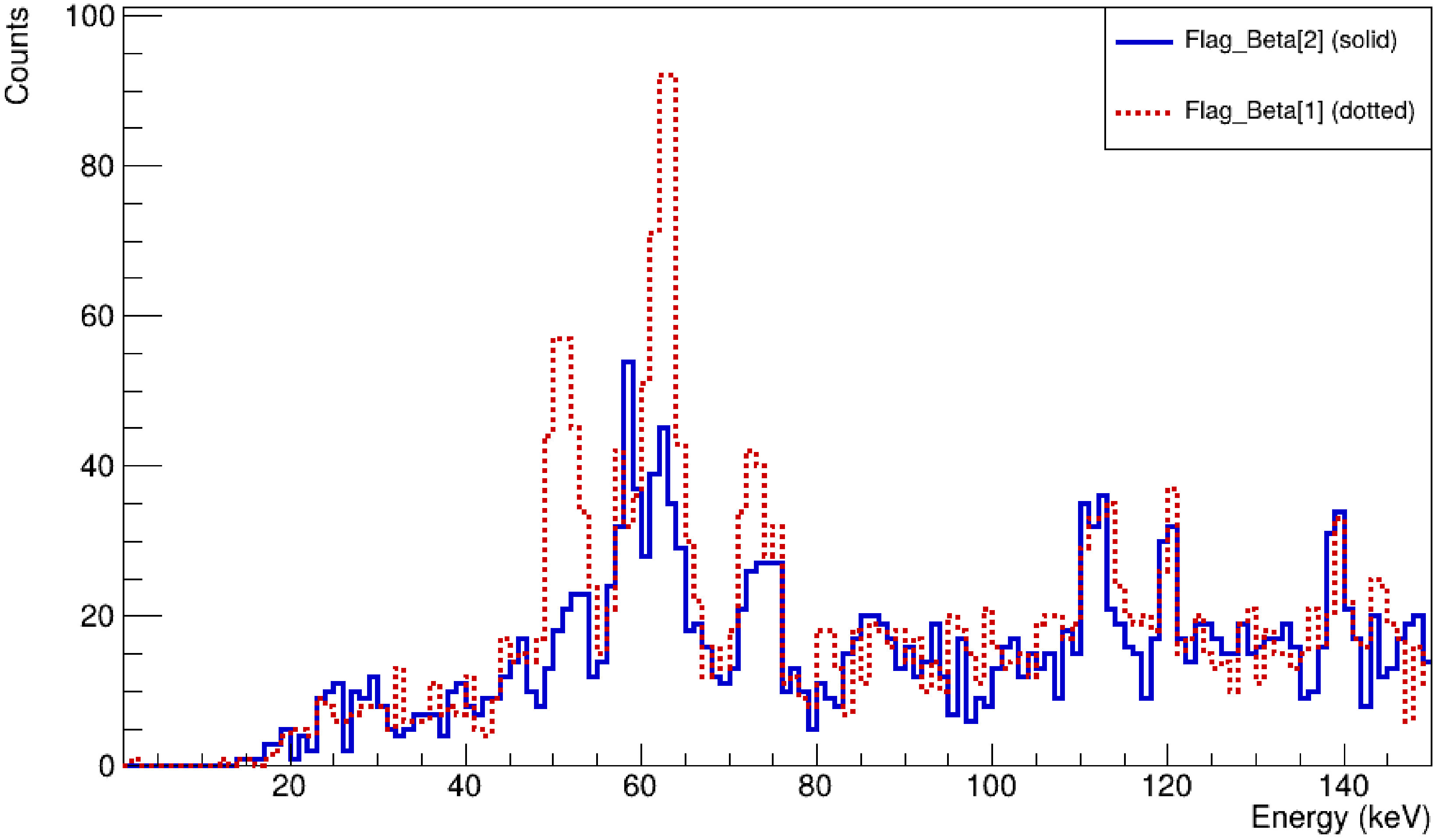
Z	α2	α1	β1	β2
71 Lu:	53.0	54.1	61.2	63.0
72 Hf:	54.6	55.8	63.2	65.0
73 Ta:	56.3	57.5	65.2	67.0
74 W:	58.0	59.3	67.2	69.1
75 Re:	59.7	61.1	69.2	71.2
76 Os:	61.5	63.0	71.3	73.4
77 Ir:	63.3	64.9	73.5	75.6
78 Pt:	65.1	66.8	75.7	77.9
79 Au:	67.0	68.8	77.9	80.2
80 Hg:	68.9	70.8	80.2	82.5
81 Tl:	70.8	72.9	82.5	84.9
82 Pb:	72.8	75.0	84.8	87.3



X-ray analysis for ^{184}Hf 4hr run files

K X-ray energies (keV)

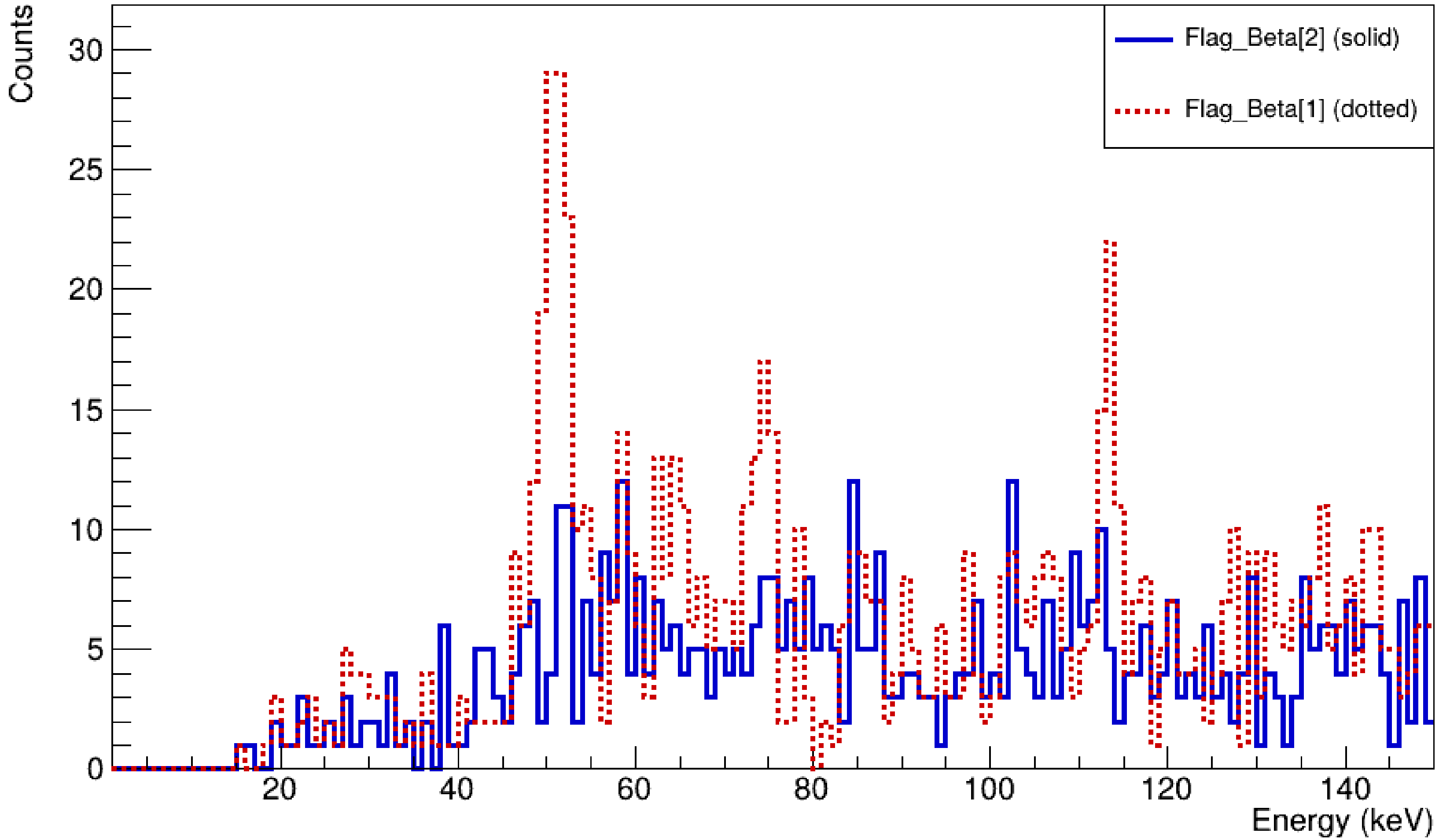
Z	α2	α1	β1	β2
71 Lu:	53.0	54.1	61.2	63.0
72 Hf:	54.6	55.8	63.2	65.0
73 Ta:	56.3	57.5	65.2	67.0
74 W:	58.0	59.3	67.2	69.1
75 Re:	59.7	61.1	69.2	71.2
76 Os:	61.5	63.0	71.3	73.4
77 Ir:	63.3	64.9	73.5	75.6
78 Pt:	65.1	66.8	75.7	77.9
79 Au:	67.0	68.8	77.9	80.2
80 Hg:	68.9	70.8	80.2	82.5
81 Tl:	70.8	72.9	82.5	84.9
82 Pb:	72.8	75.0	84.8	87.3



X-ray analysis for ^{184}Hf 20min run files

K X-ray energies (keV)

Z	α2	α1	β1	β2
71 Lu:	53.0	54.1	61.2	63.0
72 Hf:	54.6	55.8	63.2	65.0
73 Ta:	56.3	57.5	65.2	67.0
74 W:	58.0	59.3	67.2	69.1
75 Re:	59.7	61.1	69.2	71.2
76 Os:	61.5	63.0	71.3	73.4
77 Ir:	63.3	64.9	73.5	75.6
78 Pt:	65.1	66.8	75.7	77.9
79 Au:	67.0	68.8	77.9	80.2
80 Hg:	68.9	70.8	80.2	82.5
81 Tl:	70.8	72.9	82.5	84.9
82 Pb:	72.8	75.0	84.8	87.3

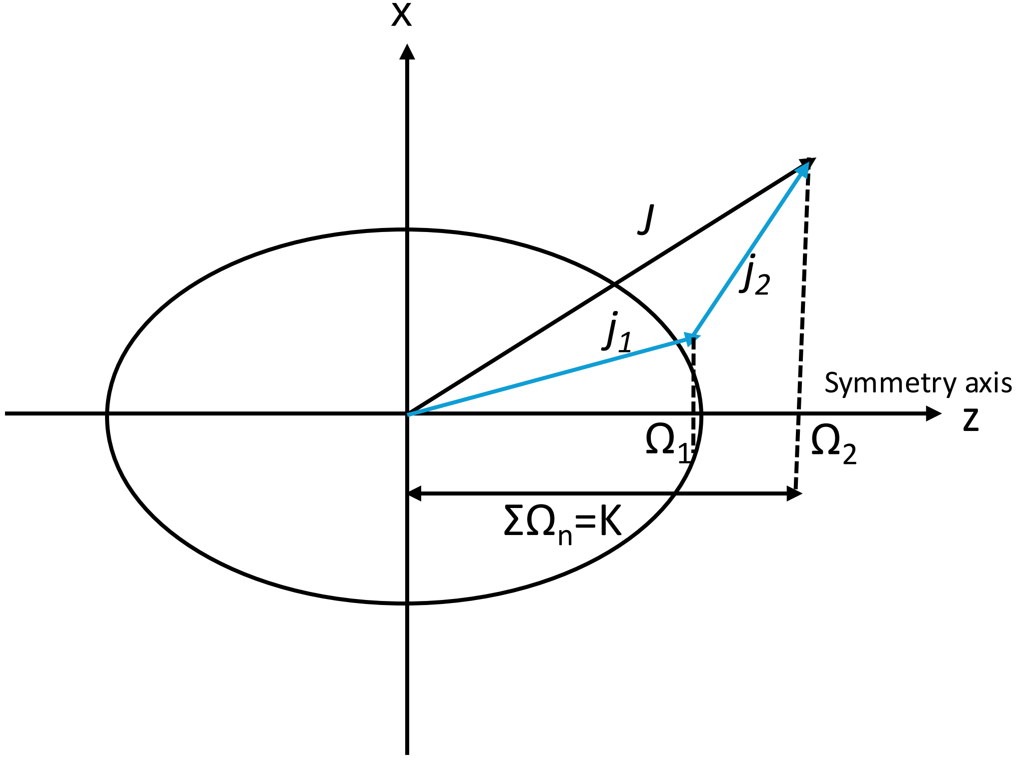


Missing intensity of 459

Old intensities by normalizing using Iγ of 783.7 keV						
Energy	Intensity (%)	Error	Area	Error	Normalized Intensity	Error
73.2	38	4	110	15	35	6
459.1	29.8	0.9	22	9	9	4
783.7	65.5	1.9	134	14	65	10

New intensities obtained by normalizing using Iγ of 783.7 keV						
Energy	Intensity (%)	Error	Area	Error	Normalized Intensity	Error
73.2	38	4	127	13	40	7
459.1	29.8	0.9	85	11	33	6
783.7	65.5	1.9	134	15	65	10

Introduction: K isomers



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

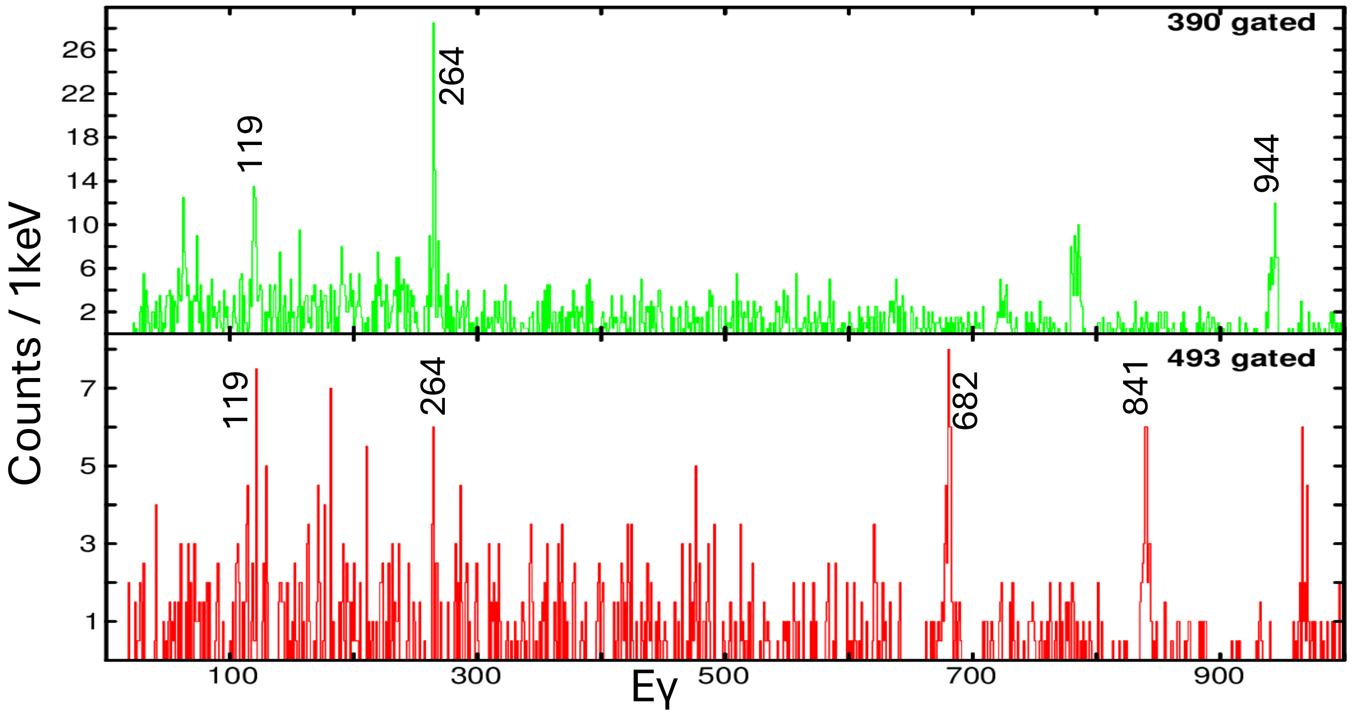
K can only change by units up to multipolarity of the transition

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

Larger changes in K result in hindered transition

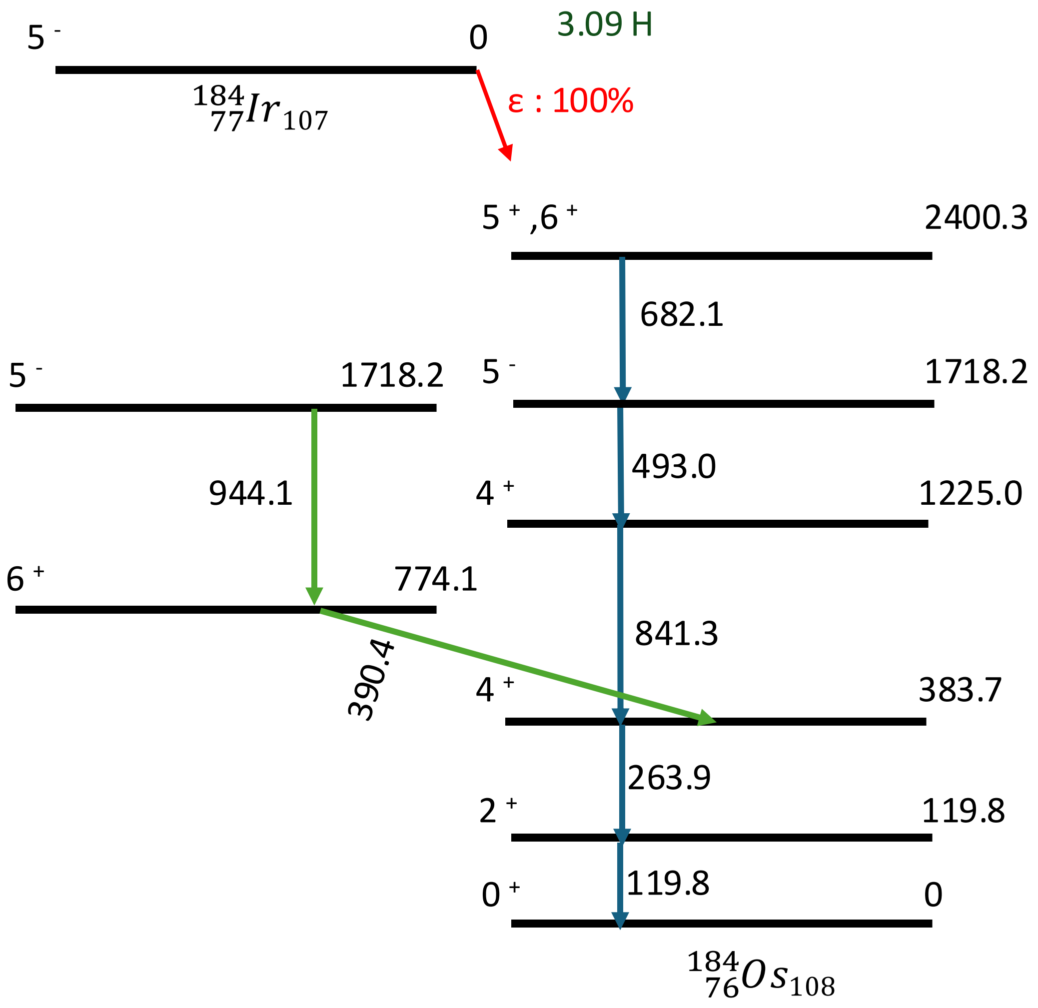
- Individual nucleons have angular momentum, j, with projection Ω on the symmetry axis, and K is the sum of these Ω values.

Intensity calculation of ^{184}Os

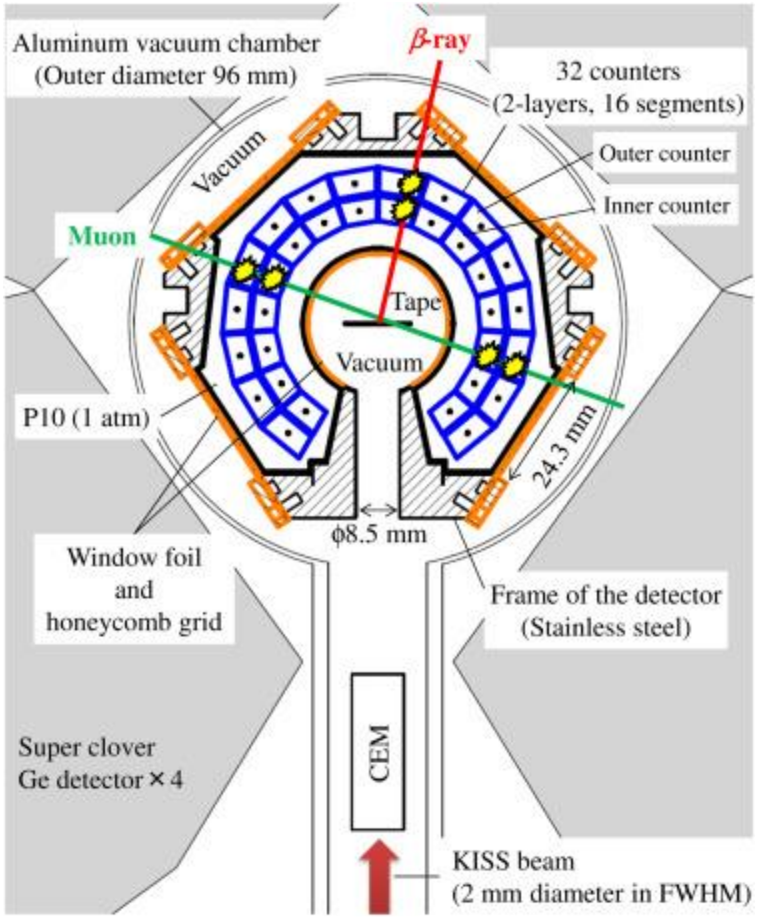


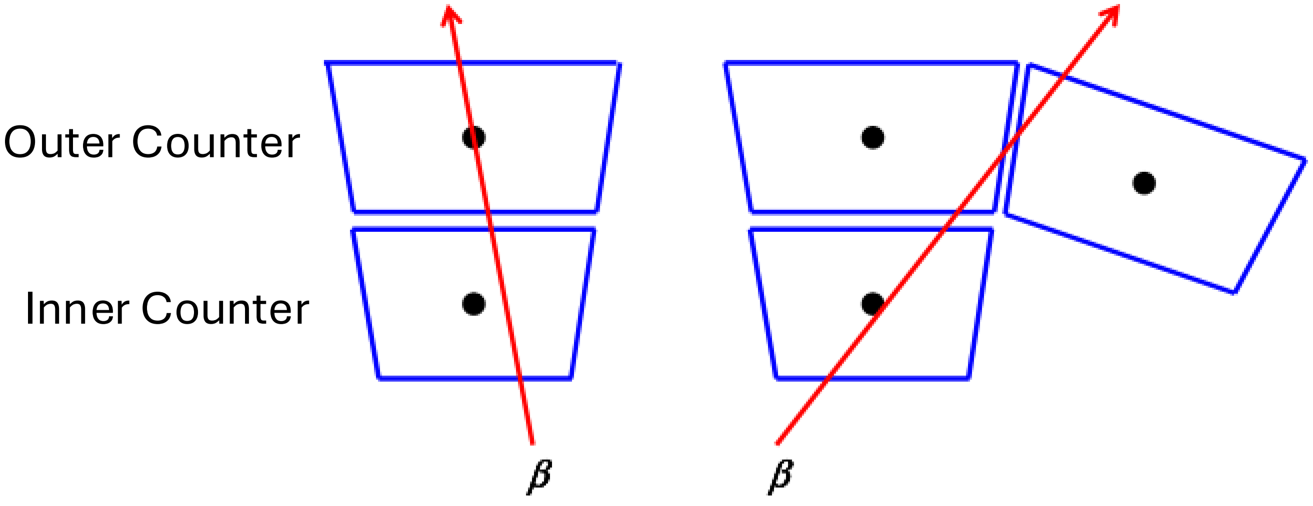
Gating on 494		
E_γ (keV)	I_γ% From [1]	Norm. I_γ%
119.8	100	55(22)
263.9	100	64(31)
841.3	100	117(45)
682.1	146	146(55)

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)



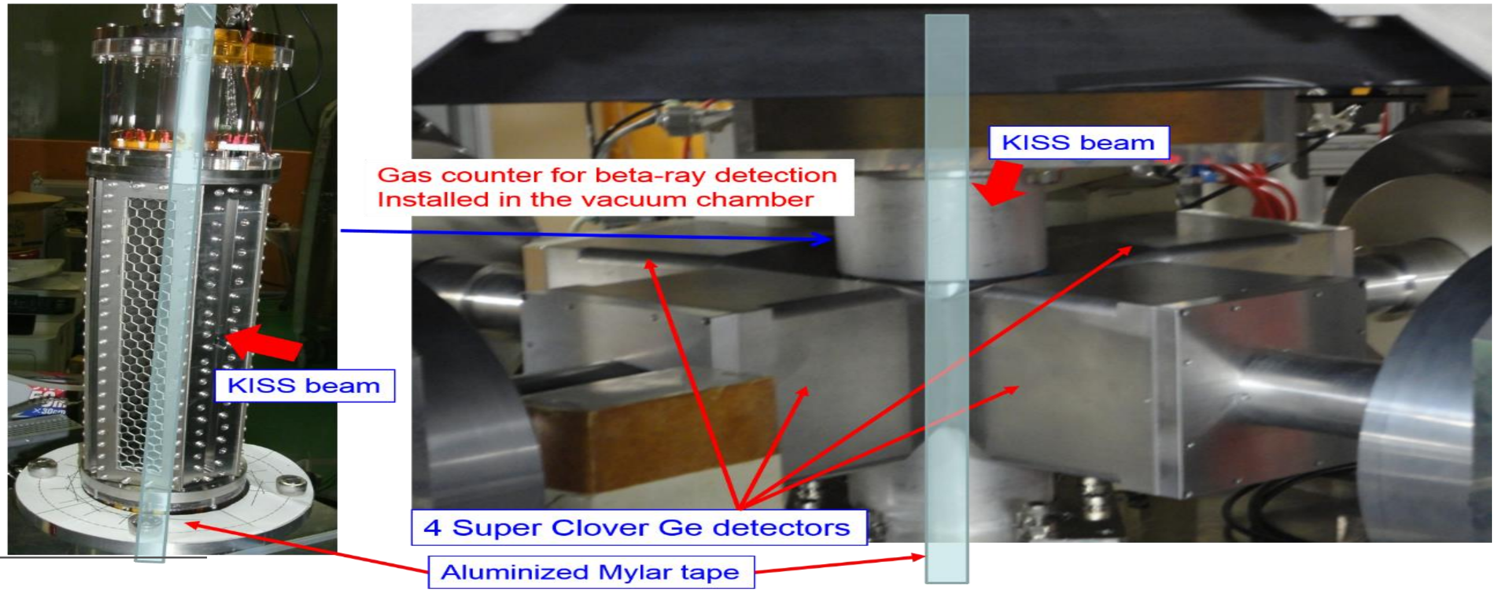
MSPGC





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

Low-background and highly efficient
Gas counter for beta-ray detection

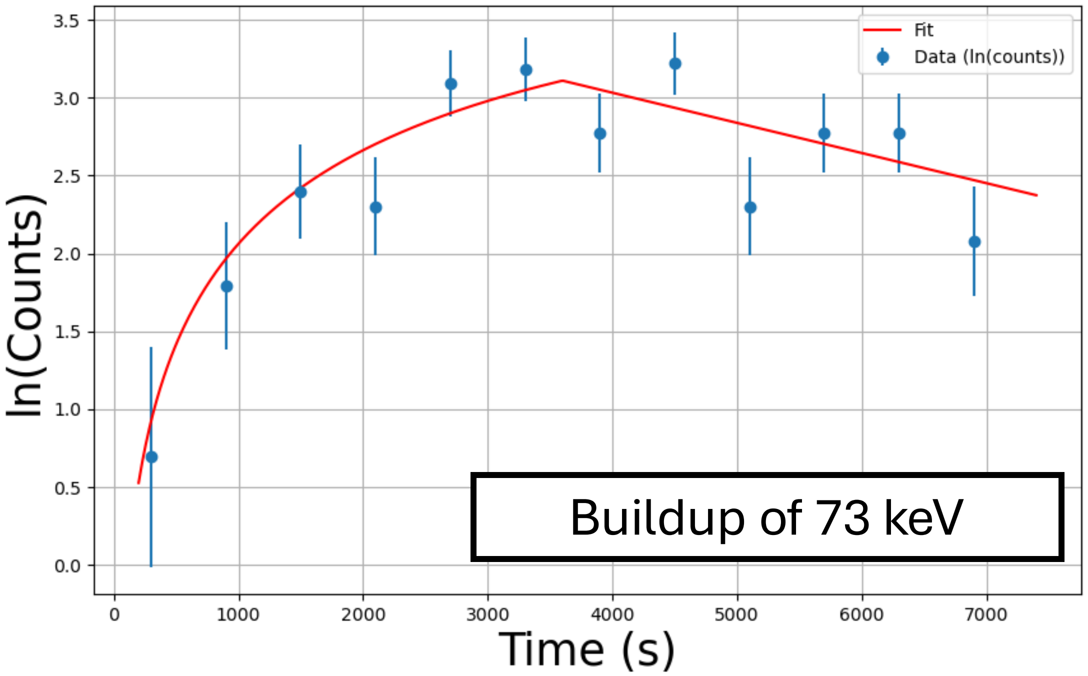


M.Mukai *et al.* / NIM . A. 884 (2018) 01689002

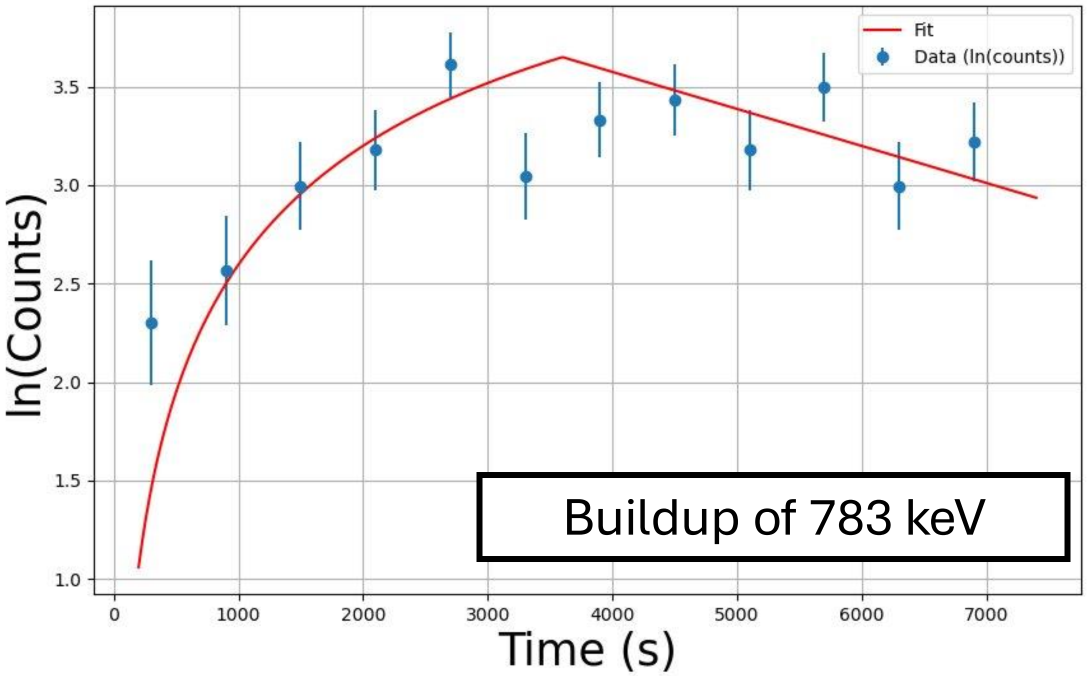
Getting Half-life of ^{183}Hf g.s. using build up equation

Fitting peaks, where implantation period is fitted using: $N(t) = Y/\lambda * (1 - \exp(-\lambda * t))$

And decay period is fitted using: $N(t) = [A/\lambda * (1 - \exp(-\lambda * t1))] * \exp(-\lambda * (t2))$



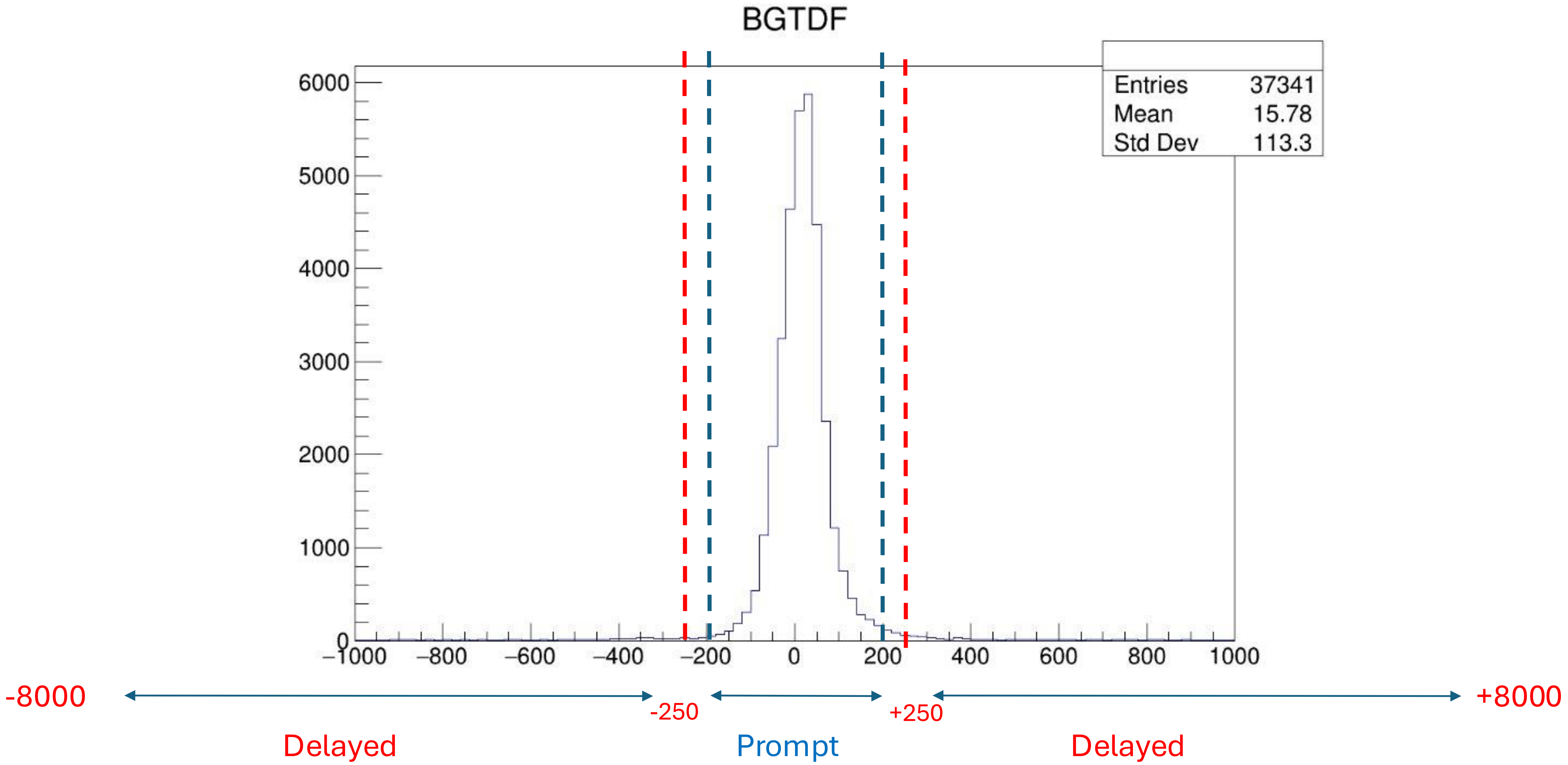
Buildup of 73 keV



Buildup of 783 keV

E_γ (keV)	$T_{1/2}$ hr	wt. $T_{1/2}$ hr
73.2(2)	1.008(0.218)	1.004(0.179)
783.7(3)	0.994(0.313)	

Defining Prompt and Delay through β-γTime Difference

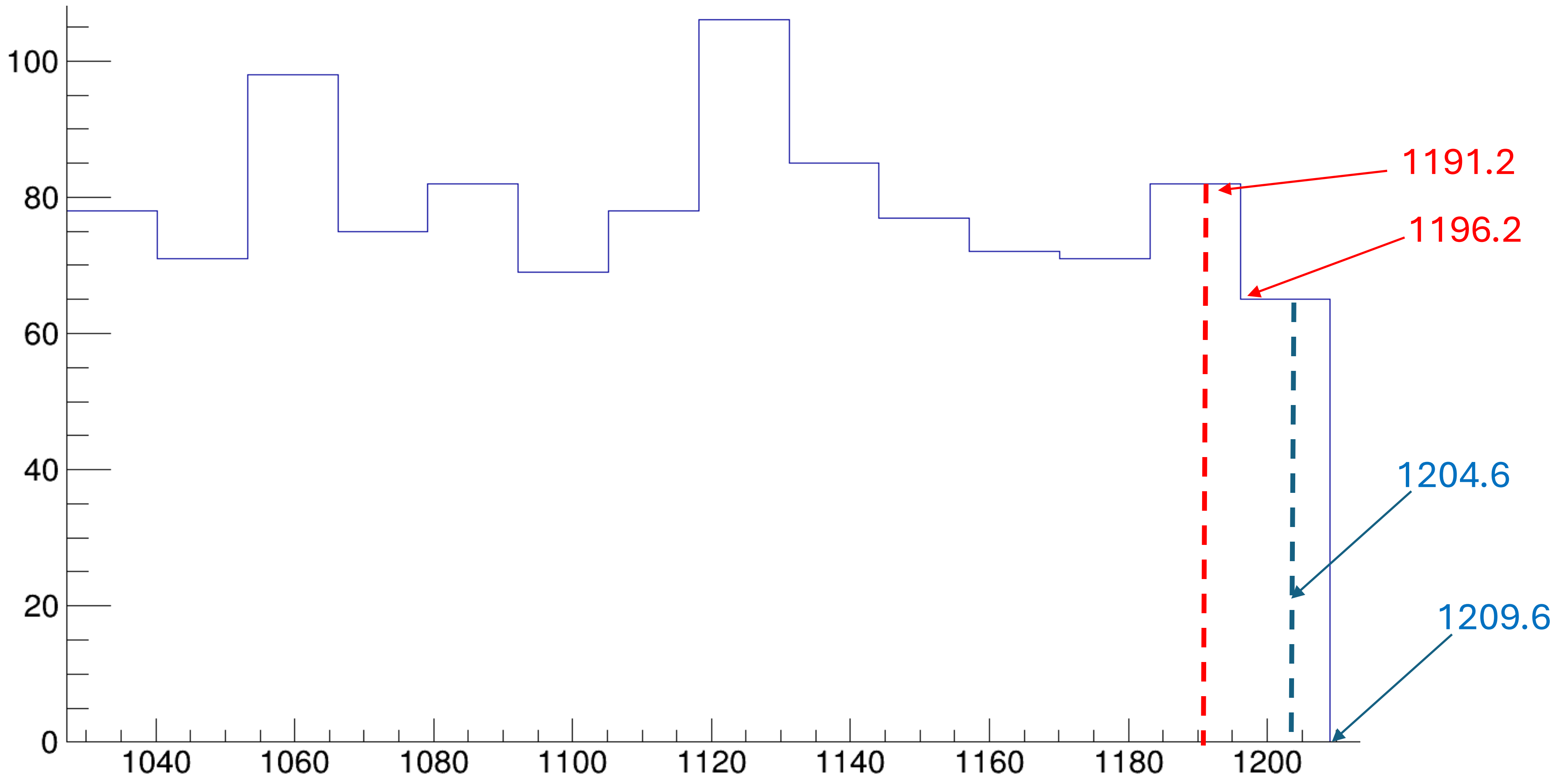


-8000 -250 +250 +8000

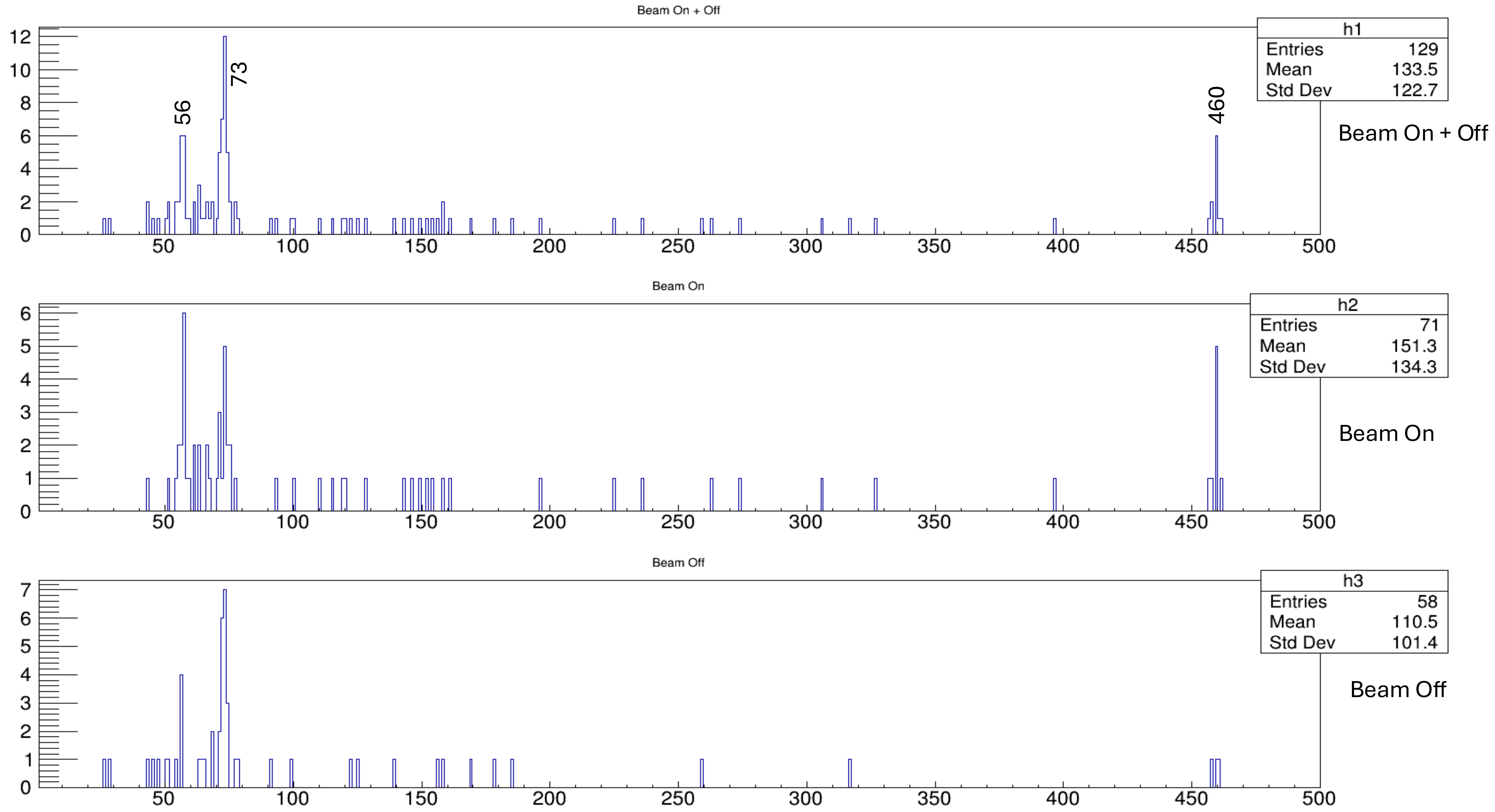
Delayed Prompt Delayed

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

BBTDF>>(100,1,1300)



Delayed Spectra of ^{183}Hf

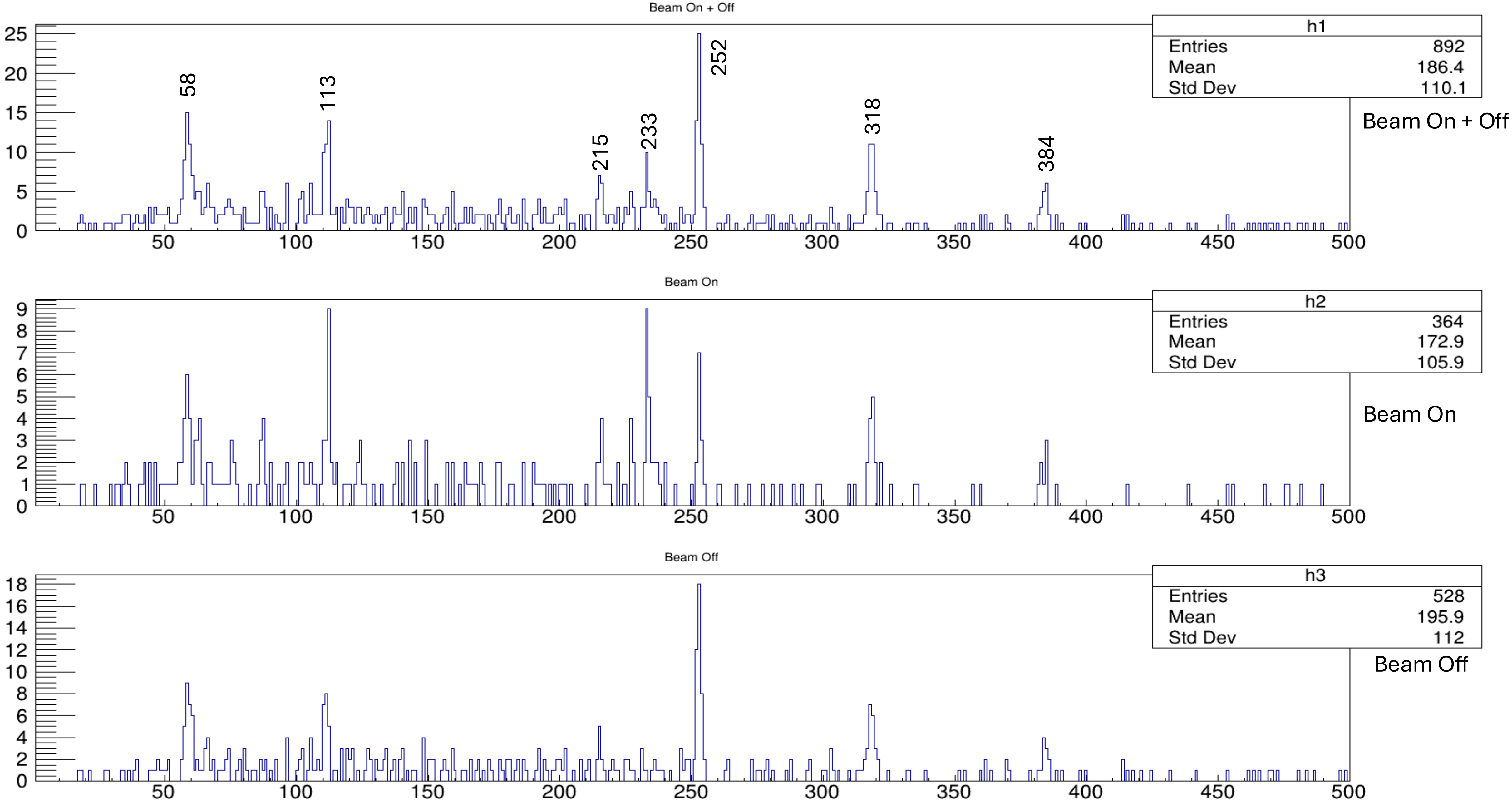


Beam On + Off

Beam On

Beam Off

Delayed Spectra of ^{184}Hf

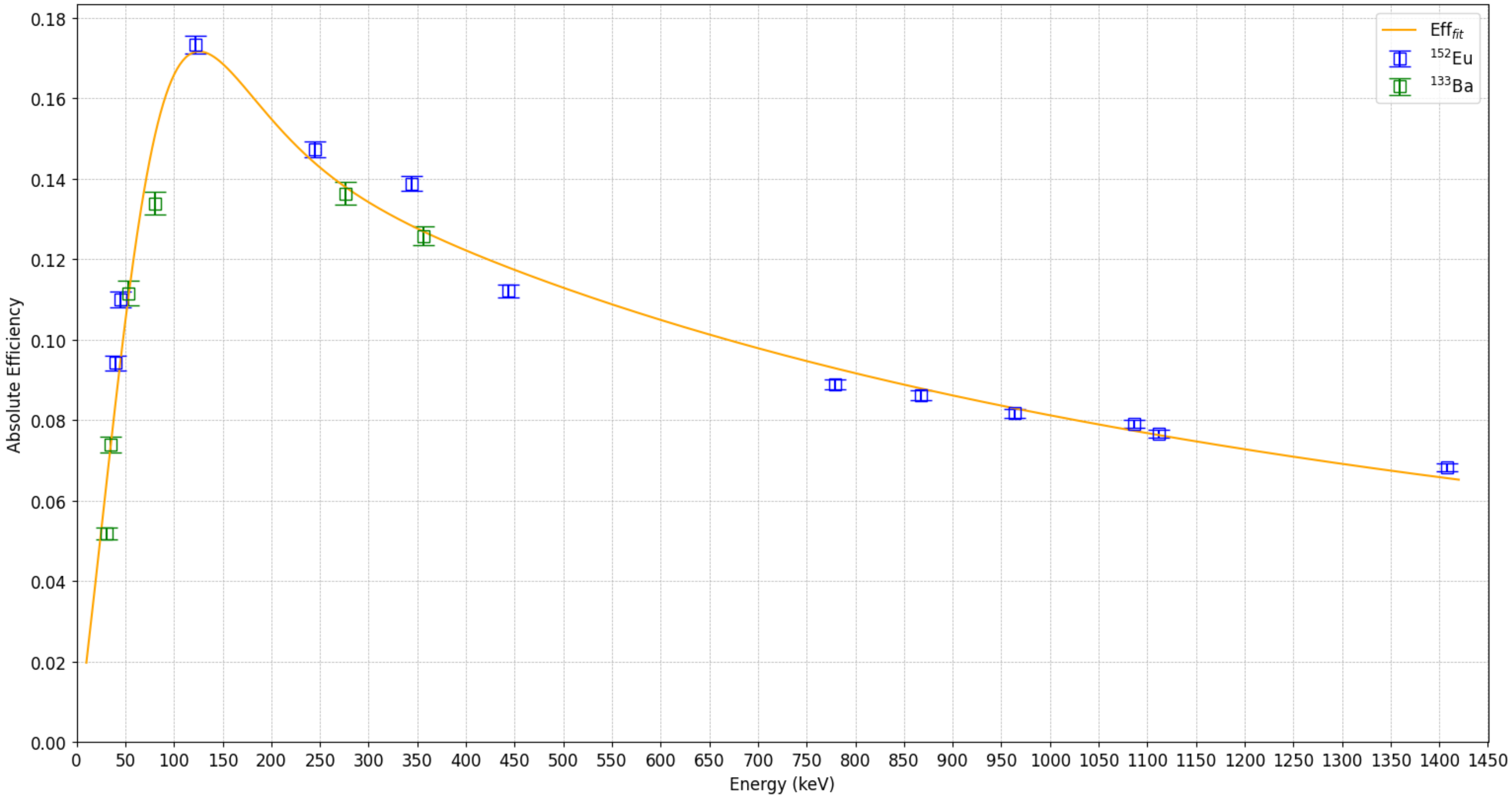


Beam On + Off

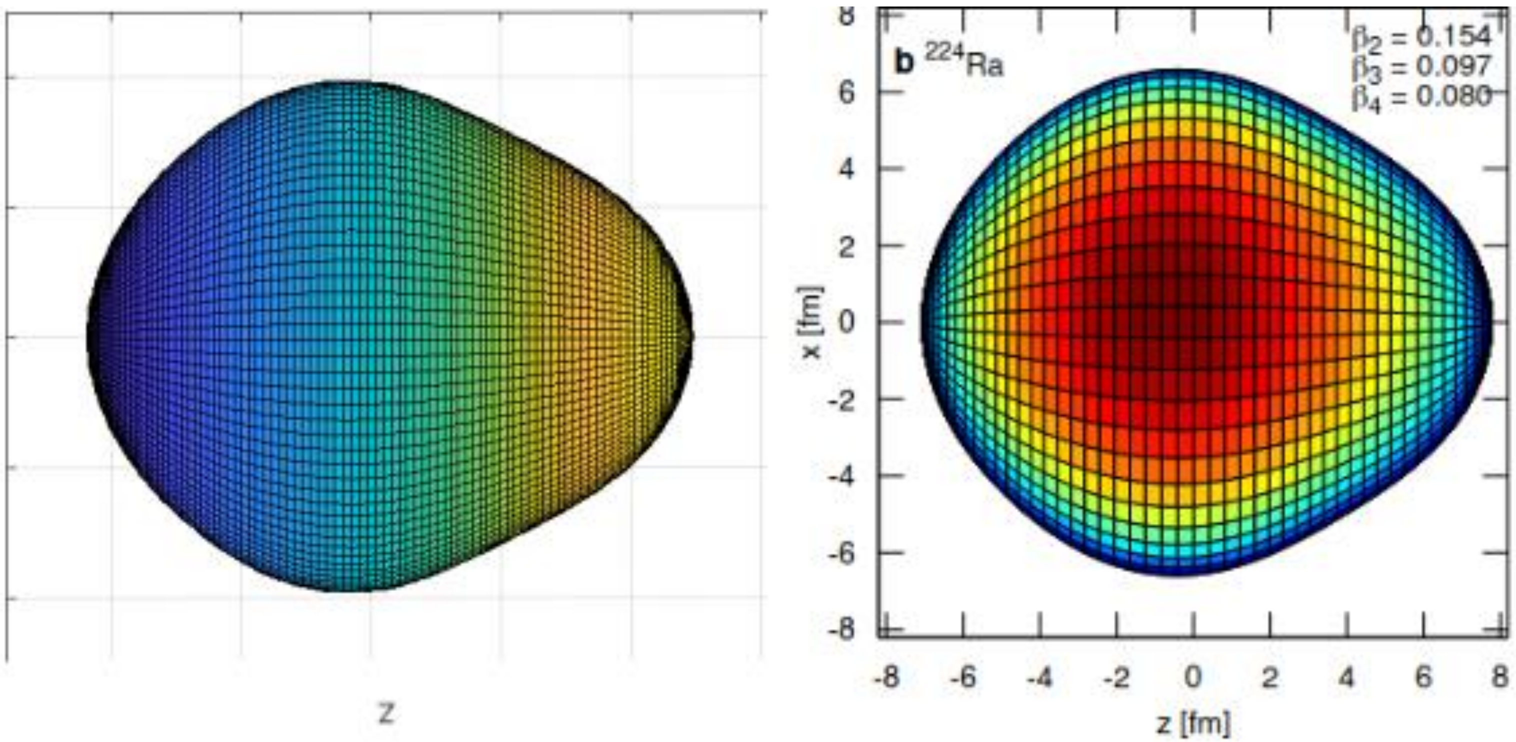
Beam On

Beam Off

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
Energy (keV)
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

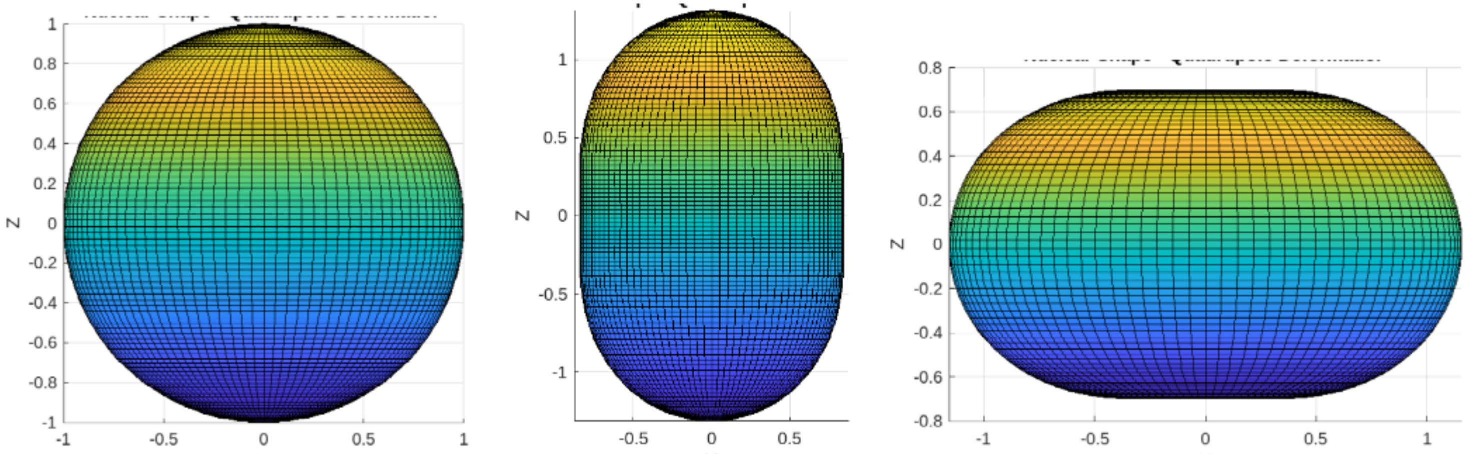
Nuclear Deformation



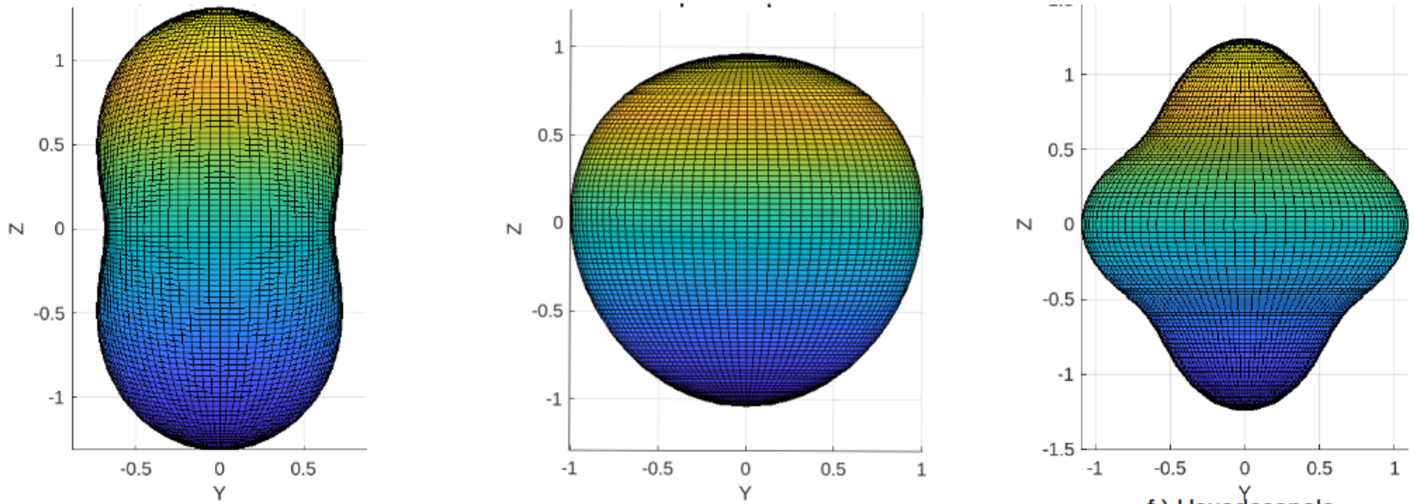
L. P. Gaffney et al. Nature, 497, 2013.

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

Nuclear Deformation



a.) Spherical b.) Prolate c.) Oblate



d.) Triaxial e.) Octupole f.) Hexadecapole