# Recent Results on $^{155}$Lu, $^{156}$W & $^{156}$Ta:

## Correlation Analysis of Beta Decay and Low-Energy Conversion Electron Signals with an Implantation Detector

## (from fusion-evaporation reactions at JYFL)

Andy Briscoe

Active stoppers for decay experiments

# Outline

- Introduction
  – Experiment method for correlation analysis of fusion products (stable beams)
  – Specifics for β particles and conversion electrons
- Recent results from experiments with MARA
  i) $^{155}Lu$
  ii) $^{156}W$
  iii) $^{156}Ta$

- Summary

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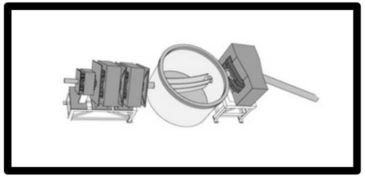
# Correlation of fusion products

implanting on junction side (X)
300 um thick (150 um, 700 um also commonly used)

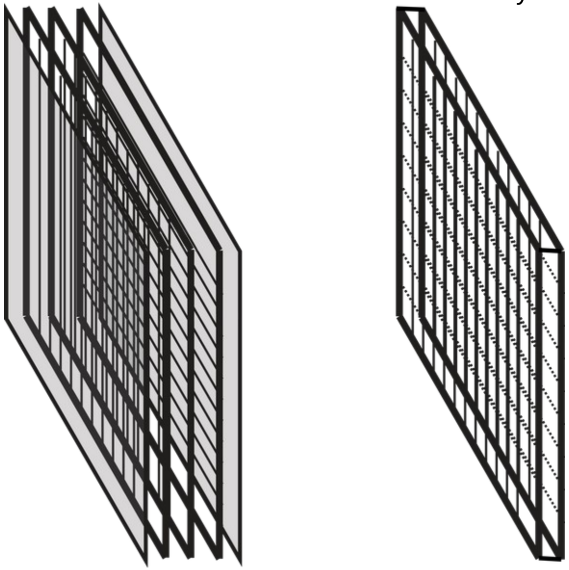
Target ($^{106}Cd$* or $^{102}Pd$*)



Beam (from Cyclotron, $^{58}Ni$*)

Recoil Separator (MARA)

Focus to transmission detector, position sensitive



MWPC (transmission detection)

DSSD (implantation detector)

TOF

40 cm

≈7 m

*for results shown today

**Correlations**

Trigger on DSSD for implantation-decay correlations

XY stips gives the pixel.

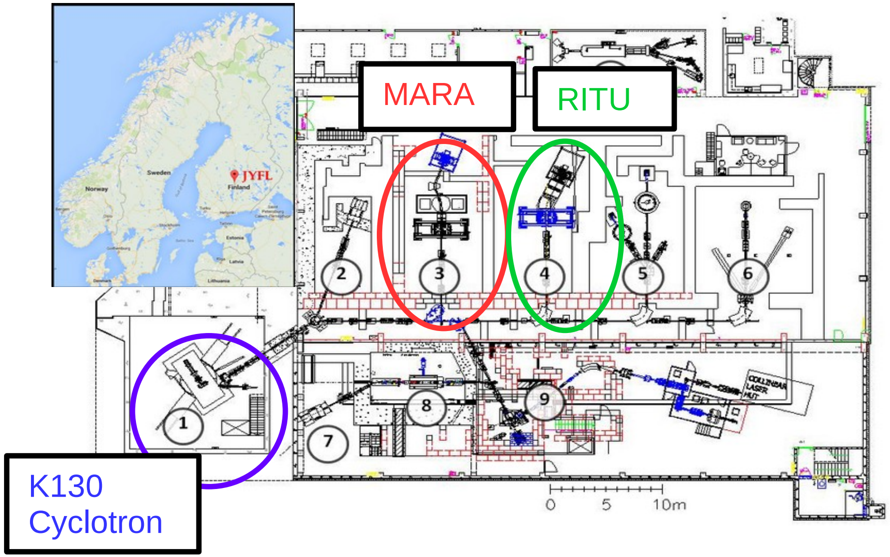
Single-pixel correlations

(simple)
R – α or p

(challenging)
R – β

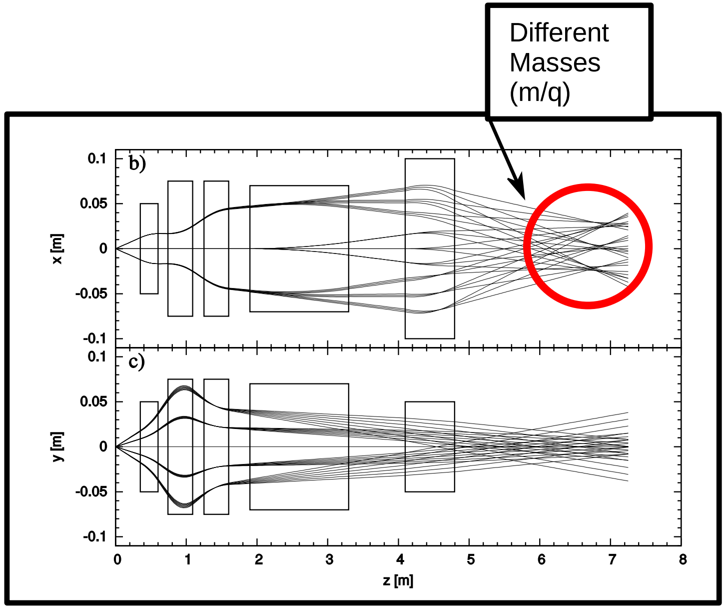
(less challenging)
R – β - α

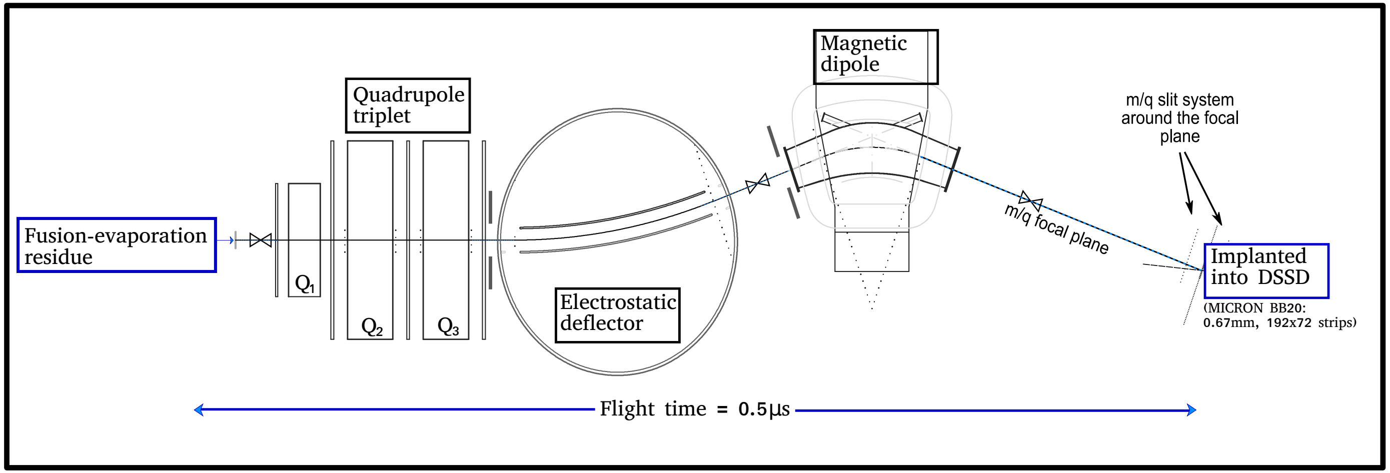
# Experimental with recoil separators at JYFL




$$E\rho_E = \frac{pv}{q} \approx \frac{2E_K}{q}$$

$$B\rho_B = \frac{p}{q} \approx \frac{\sqrt{2E_K m}}{q}$$

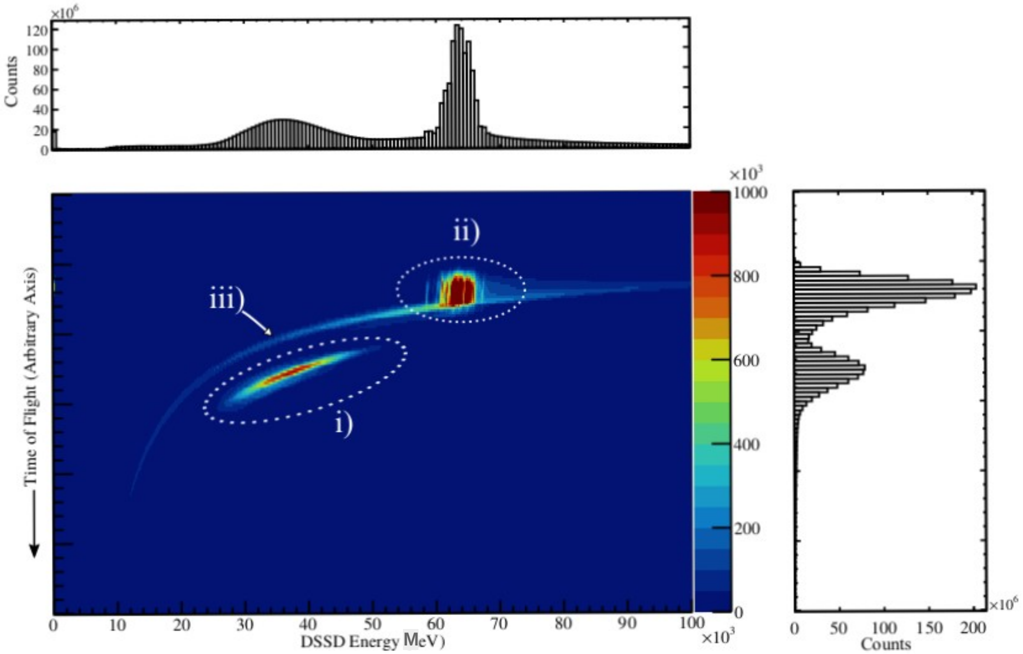



200 MeV Recoil => v/c = 0.05

Fusion-evaporation residues transported to focal plane for spectroscopy

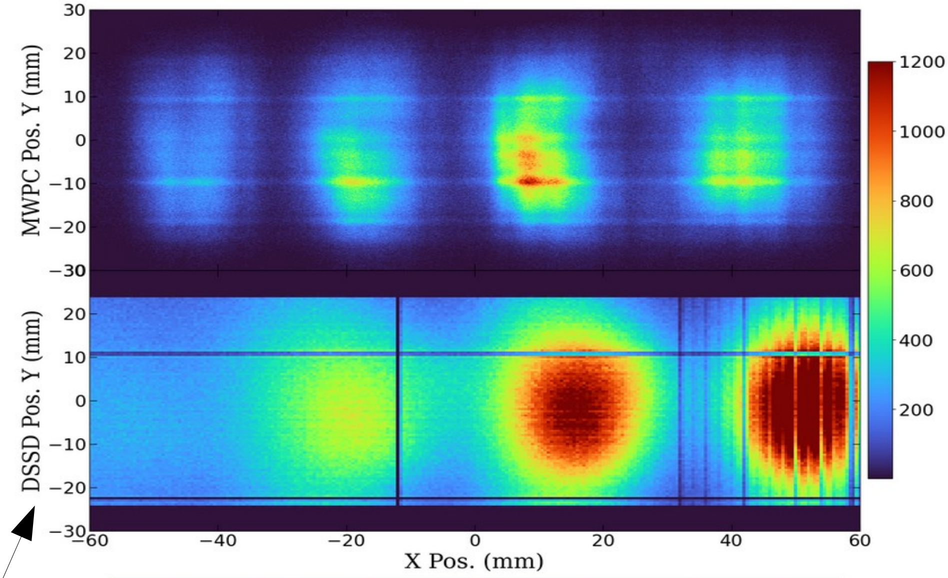
# Evaporation residue discrimination & MWPC DSSD phasespace

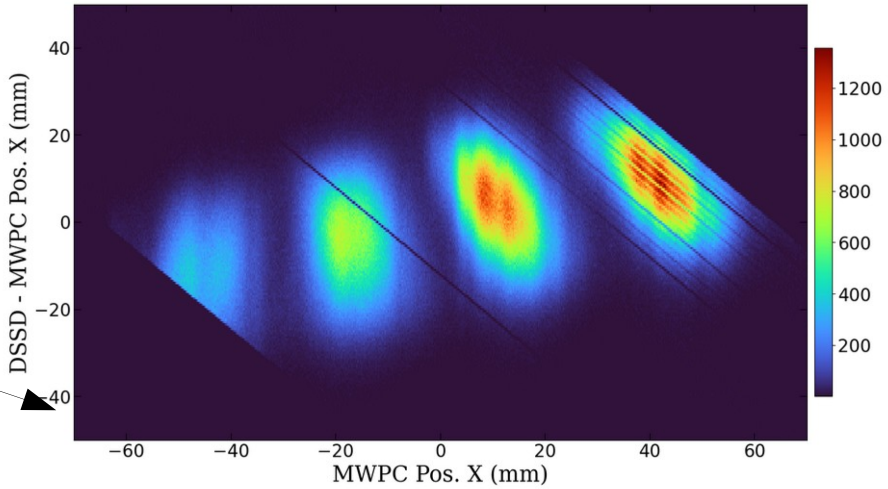



Recoils are discriminated by:

ToF between MWPC and DSSD
Characterstic implantation energy in Si

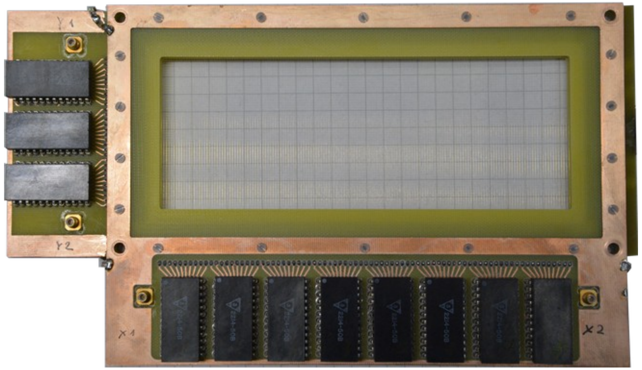
$^{155}$Lu α tagged,
4 charge states



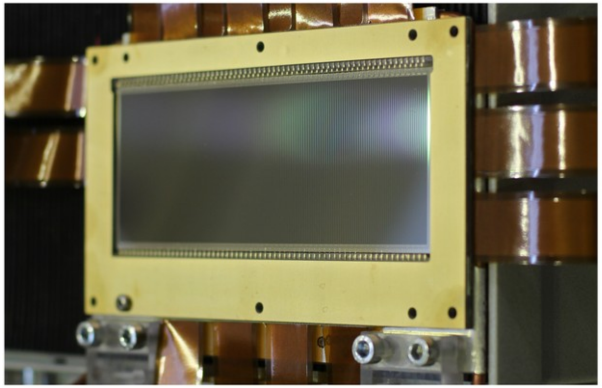
# Experimental techniques and apparatus: Focal-plane detectors

## Multi-wire proportional counter (MWPC)



Grid of 20 μm diameter gold-coated tungsten wires, provides (x,y) position of recoils

## Micron BB20 DSSD

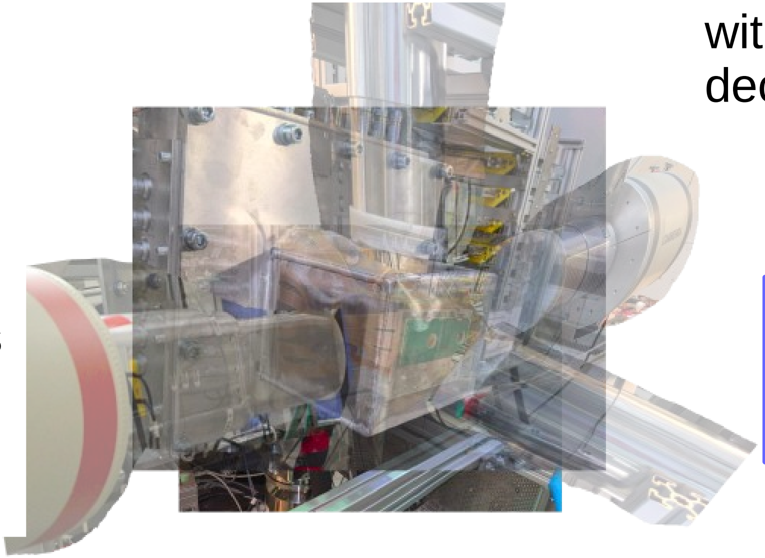


72 x 192 strips,
13,824 0.45 $mm^2$ pixels
300 um thick Si

Correlations of ɣ rays with implanted recoils or decays for around 50 us

## Ge detectors

3 BEGe & 1 Clover detectors outside chamber surrounding DSSD in close geometry.



All signals time stamped by a 100 MHz clock,
read out individually for correlation analysis

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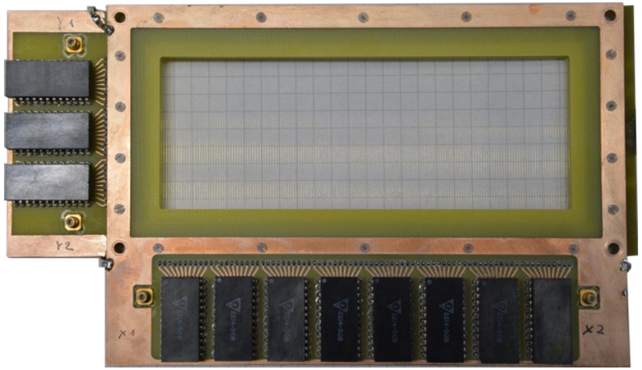

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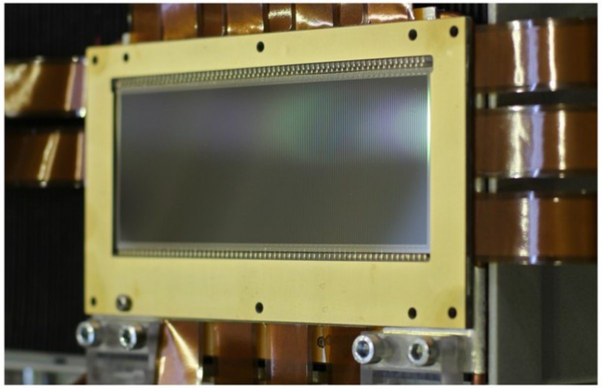

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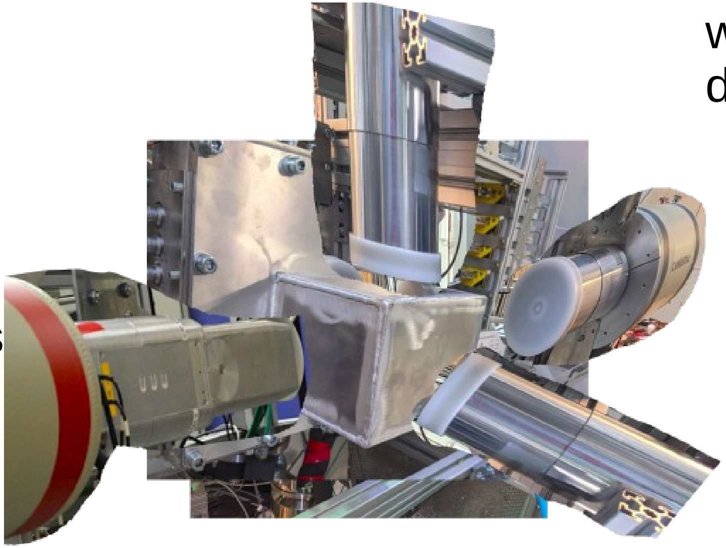

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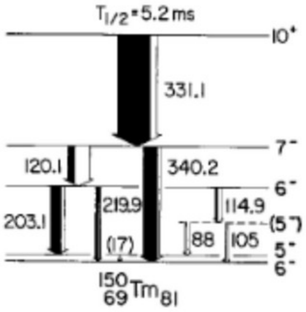
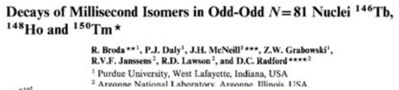
# DSSD Correlations & Calibration




Thresholds on DSSD low (≈60 keV) for possible conversion electrons & (limited) β signals

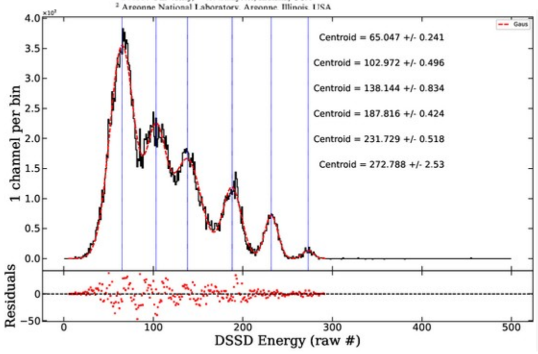
For measuring conversion electrons of implanted activity, good to have dedicated calibration.
External α source difficult due to dead layer.

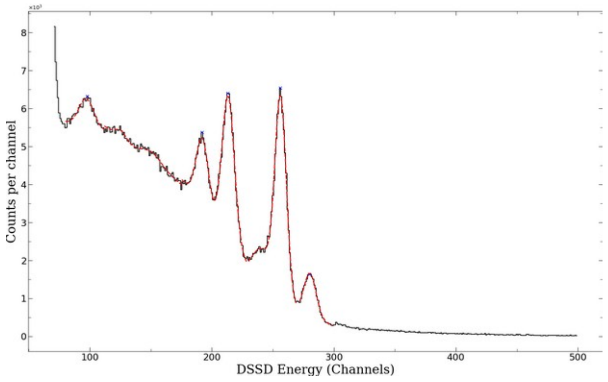
Strips matched with $^{133}$Ba source, calibrated with internal $^{150}$Tm conversion electrons produced within 1 shift overnight

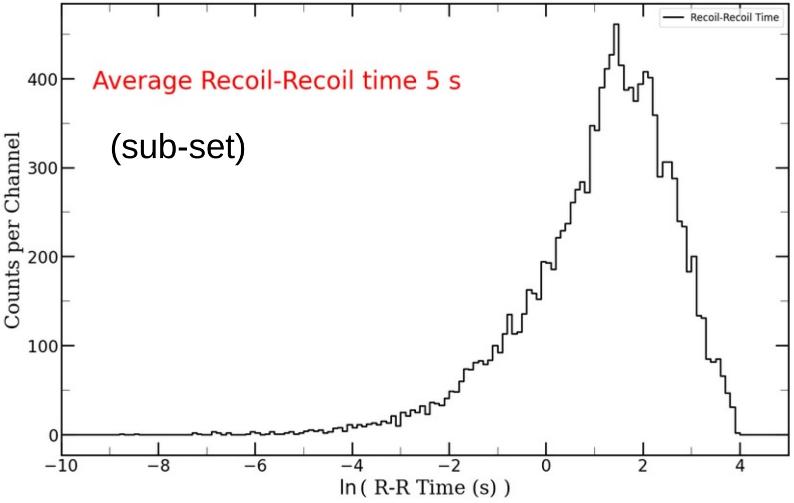


Decays of Millisecond Isomers in Odd-Odd $N=81$ Nuclei $^{146}$Tb, $^{148}$Ho and $^{150}$Tm *

R. Broda **[1], P.J. Daly[1], J.H. McNeill[1] ***, Z.W. Grabowski[1], R.V.F. Janssens[2], R.D. Lawson[2], and D.C. Radford ****[2]
[1] Purdue University, West Lafayette, Indiana, USA
[2] Argonne National Laboratory, Argonne, Illinois, USA



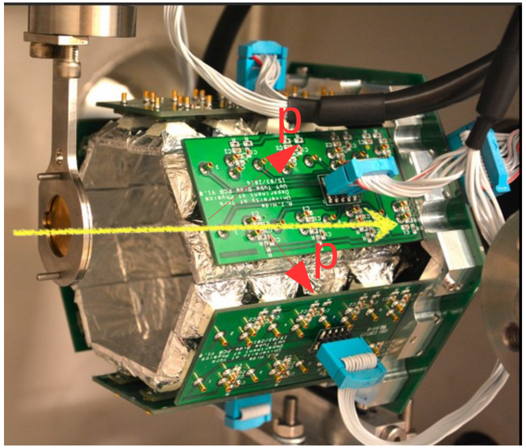



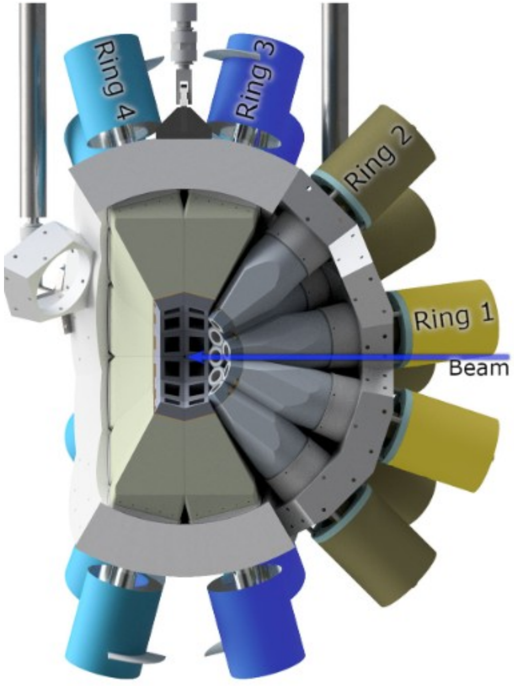

Random recoil rate (R -R) defines max correlation time.

Exponential distribution, average time 5 seconds. Can’t correlate well beyond this time after implantation.

# Ancillary detectors (others not mentioned)




**JYTube charged- particle detector**:120 2mm-thick plastic scintillators read out by SiPMs
Hexagonal cylinder geometry

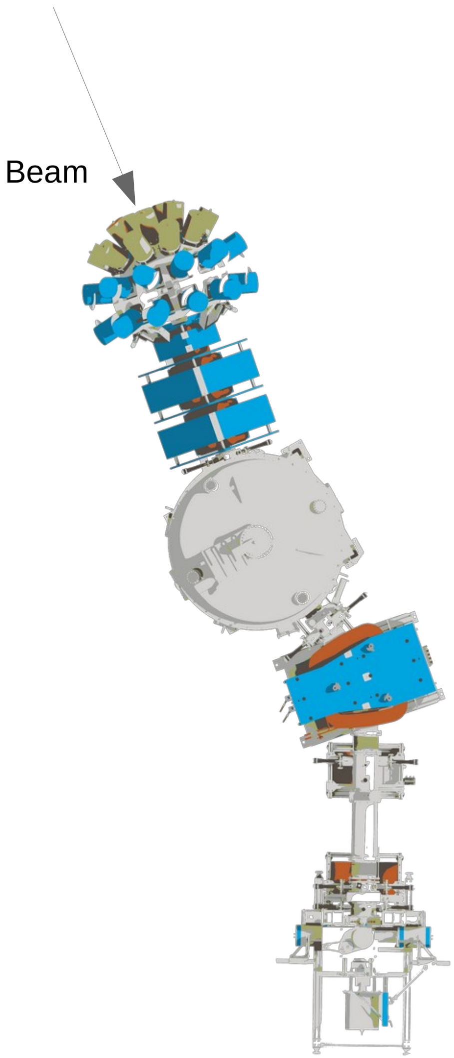



**JUROGAM3 Array**: 24 Clover and 16 Phase 1 Ge detectors, 4 angles

**The JUROGAM 3 spectrometer**

J. Pakarinen[1,a], J. Ojala[1], P. Ruotsalainen[1], H. Tann[1,2], H. Badran[1,4], T. Calverley[1,2], J. Hilton[1,2], T. Grahn[1], P. T. Greenlees[1], M. Hytönen[1], A. Illana[1], A. Kauppinen[1], M. Luoma[1,3], P. Papadakis[1,5], J. Partanen[1], K. Porras[1], M. Puskala[1], P. Rahkila[1], K. Ranttila[1], J. Sarén[1], M. Sandzelius[1], S. Szwec[1], J. Tuunanen[1], J. Uusitalo[1], G. Zimba[1]

Only 15 Phase 1s available for these experiments, Clovers on holiday in France..



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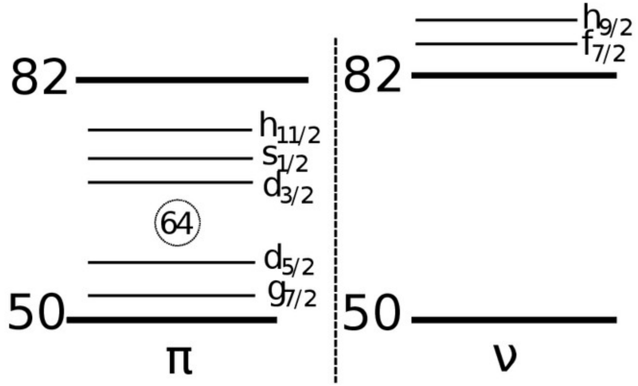
# Results : Region of interest & experimental details

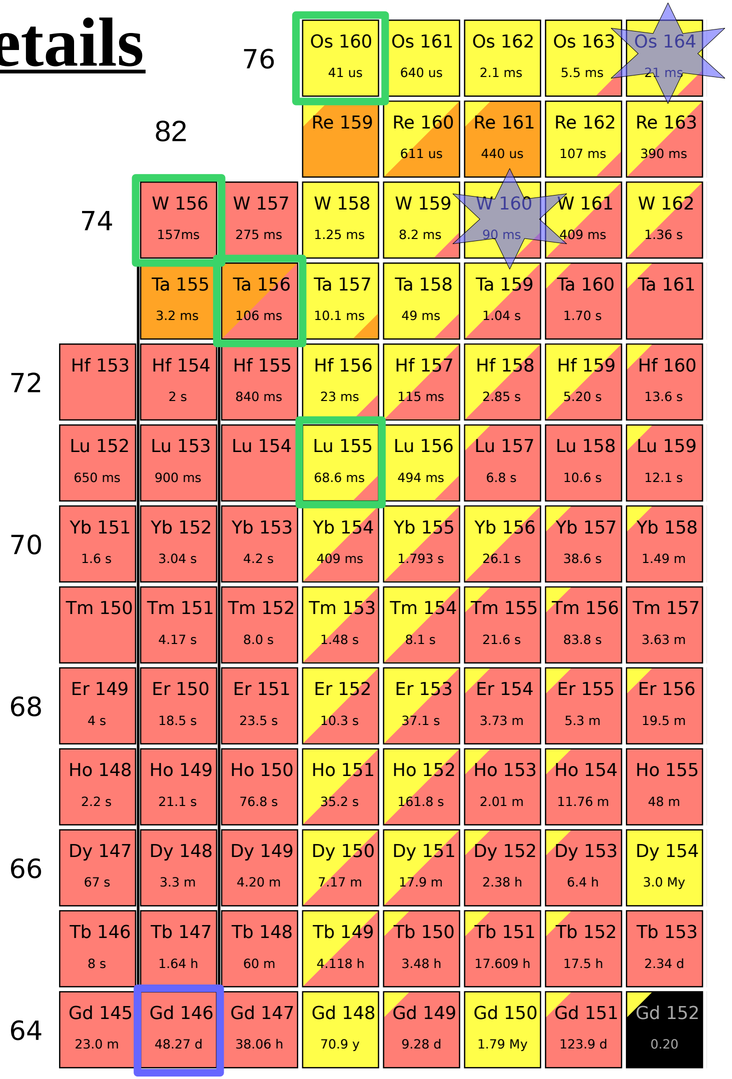
Two different experiments at Jyväskylä, main aims were to study to α/p emitters of neutron deficient nuclei around N = 82.

$^{102}$Pd($^{58}$Ni,)$^{160}$W
305 MeV, 3-5 pnA, 273 hours (12 days), (had JUROGAM)
**$^{155}$Lu(3p2n) $^{156}$Ta(p3n)**

$^{106}$Cd($^{58}$Ni,4n), 310 MeV, 6.4 pnA, 292 hours (12 days)
**$^{160}$Os(4n) α ->$^{156}$W**




β & conversion electrons not primary aims of experiments, so their detection not optimised



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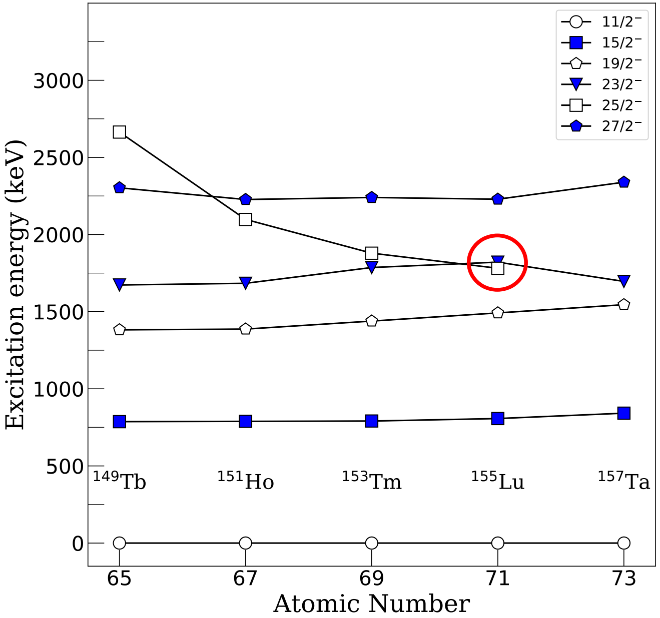
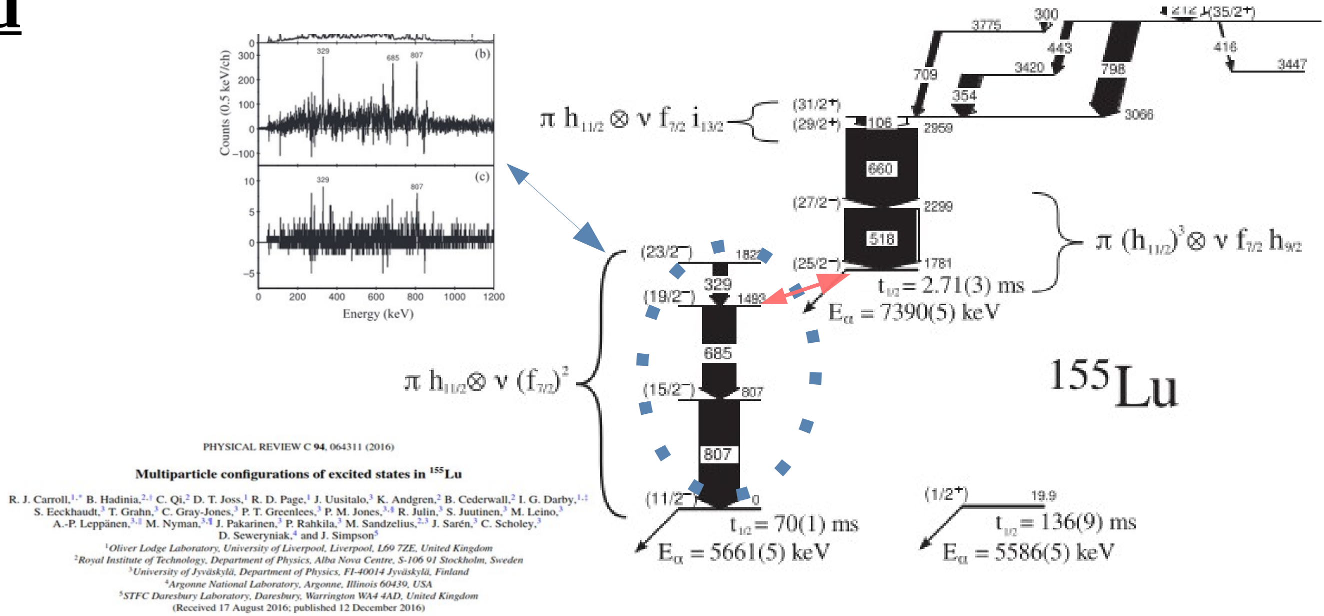
# Results $^{155}$Lu: Background




Spin-gap isomers in N = 84 isotones




**11/2⁻ -> 23/2⁻**
odd $\pi h_{11/2} \otimes (0^+,2^+,4^+,6^+)$ of $\nu(f_{7/2})^2$

**25/2-** $(\pi h_{11/2})^3 \otimes \nu f_{7/2} h_{9/2}$

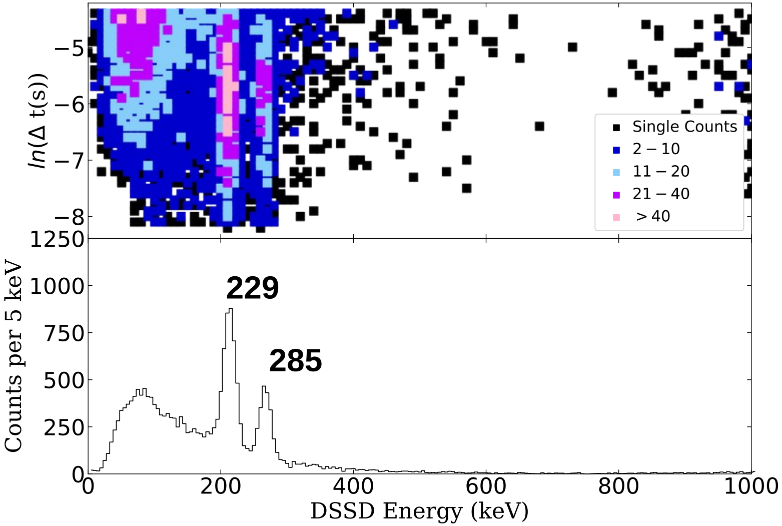
Excitation energy known difference in alpha decays. Assumed $b_\alpha$ = 100 %.

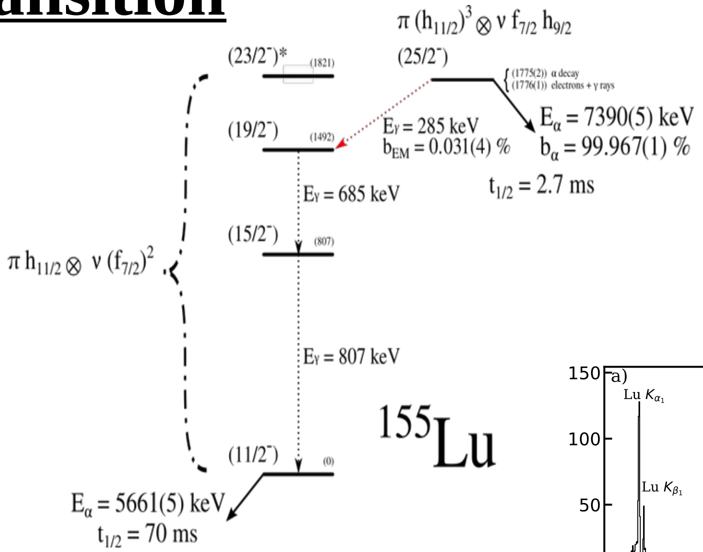
Competing EM transition 25/2⁻ → 19/2⁻ would be at least an M3, & decay with $t_{1/2}$=2.71 ms.

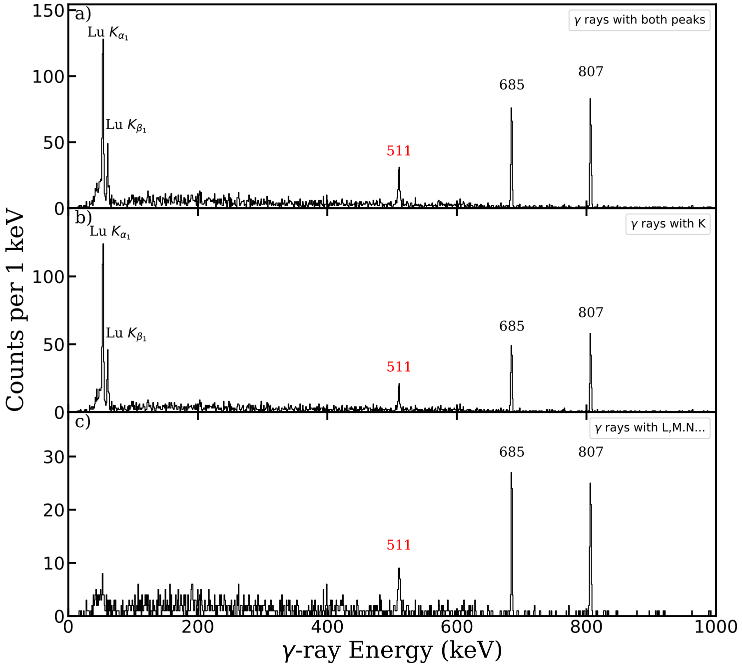
Hopeless to correlate γ rays on this time scale.
Conversion electrons after implantation?

# Results $^{155m}$Lu: Internal transition

## Recoil – c.e. - $^{155}$Lu ($h_{11/2}$) α




Correlations of decays before $h_{11/2}$ reveal K and L conversion of a single transition.

$25/2^{-} \rightarrow 19/2^{-}$

Ratio of $25/2^{-}$ α to electrons calculated ɣ rays gives **branch (%)**

# Results $^{155}$Lu: branch & strength

**Recoil – c.e. - $^{155}$Lu (h11/2) α**

**|**

**(807 or 685 keV)ɣ**

Gating on ɣ-rays “prompt” with conversion electrons results in clean electron spectrum. Measurement of K- and L(MM)-conversion ratio allows multipolarity to be deduced.

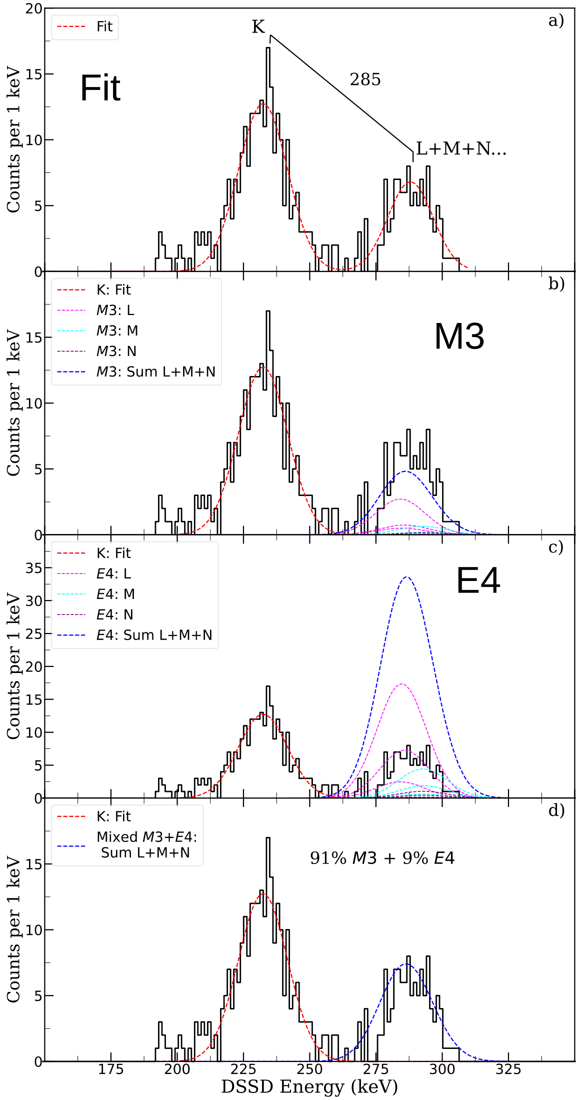
The branching ratio and multipolarites allows us to extract transitions strengths.

Weiskopf estimates : **428 ms and 7300 s and M3 and E4.**

Results in:
**B(M3) = 0.063 W.u.**
**B(E4) = 60 W.u.**

M3 is hindered consistent with other known single-particle states in in region.

Such enhancement of B(E4) potentially surprising.



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  ii)**$^{156}$W**

  iii)$^{156}$Ta
- (if time) Simulation insights
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# Results $^{156}$W: Background

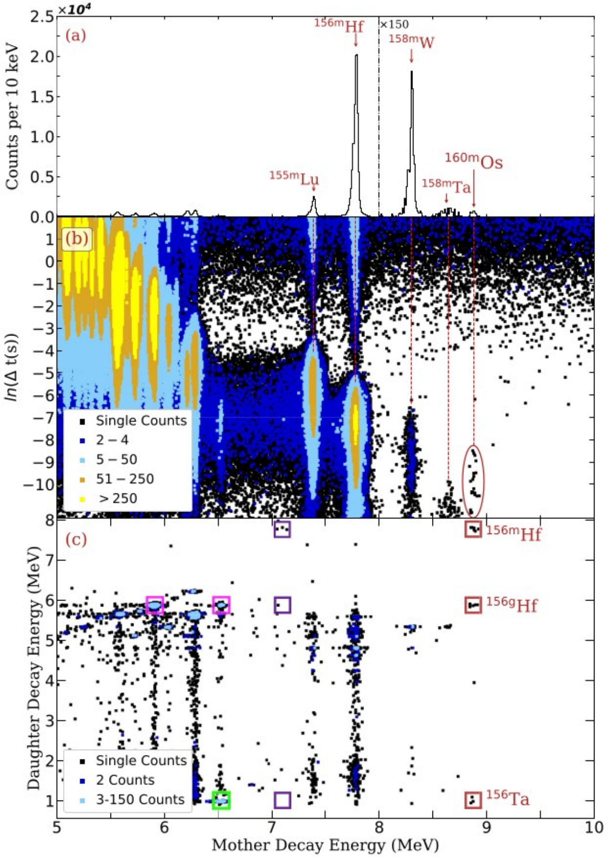
$^{156}$W (N = 82) was expected to β decay.

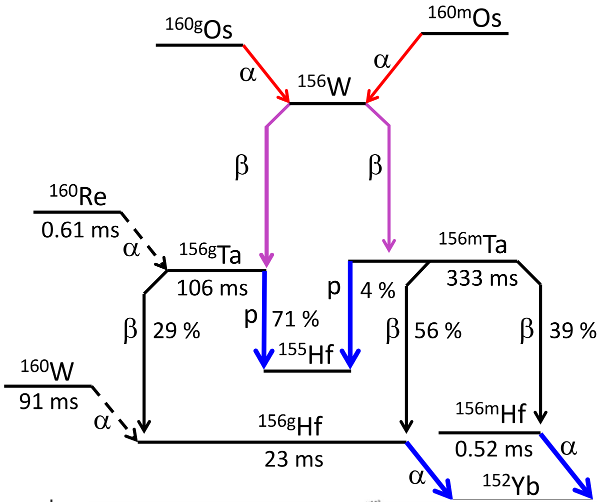
Low cross section (few counts), only way to measure is to populate via $^{160}$Os.

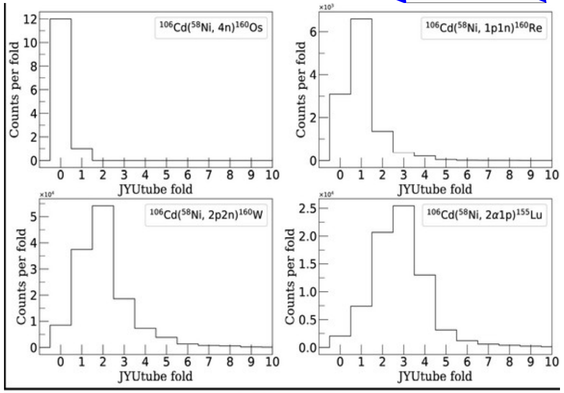
Managed to produce & measure both α-decaying states $^{160}$Os.

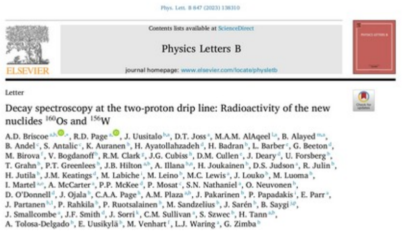
Eventually feed both α-decaying states in $^{156}$Hf, and both proton-decaying states in $^{156}$Ta.
(main aim of experiment)

Clean correlations allowed us to study the β-decay properties of $^{156}$W for the first time.




Two ways to measure this half-life:
1. Time difference between $^{160}$Os α and $^{156m}$Hf α, $^{156}$Ta p, **not $^{156g}$Hf α**
2. Time difference between $^{160}$Os α and $^{156}$W β

# Results $^{156}$W: Chains

1) $^{156}$**W** $t_{1/2}$**= 153 (+64 -39) ms,** after correcting for unambigous intervening decays.

2)

3)

$^{a}$ α decay of $^{156}$Hf ground state
$^{b}$ α decay of $^{156}$Hf isomeric state
$^{c}$ proton decay of $^{156}$Ta ground state
$^{d}$ proton decay of $^{156}$Ta isomeric state
$^{e}$ α decay of $^{152}$Er
$^{f}$ α decay of $^{155}$Lu
$^{g}$ β decay of $^{156}$W feeding $^{156}$Ta ground state
$^{h}$ β decay of $^{156}$W feeding $^{156}$Ta isomeric state
$^{i}$ β decay of $^{156}$Ta isomeric state

| Chain # | $E_1$ (keV) | $t_1$ (μs) | $E_2$ (keV) | $t_2$ (ms) | $E_3$ (keV) | $t_3$ (ms) | $E_4$ (keV) | $t_4$ (ms) | $E_5$ (keV) | $t_5$ (ms) | JYTube Fold |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 8911 | 27 | 5886$^{a}$ | 1285 | - | - | - | - | - | - | 0 |
| 2 | 8894 | 31 | 472$^{h}$ | 43 | 165$^{i}$ | 1498 | 5883$^{a}$ | 55 | 4820$^{e}$ | 1139 | 0 |
| 3 | 8868 | 31 | 180$^{i}$ | 1605 | 7801$^{b}$ | 1 | - | - | - | - | 0 |
| 4 | 8878 | 205 | 1016$^{c}$ | 256 | - | - | - | - | - | - | 1 |
| 5 | 8850 | 15 | 341$^{h}$ | 256 | 5904$^{a}$ | 1285 | - | - | - | - | 0 |
| 6 | 8888 | 28 | 156$^{h}$ | 28 | 7741$^{b}$ | 923 | - | - | - | - | 0 |
| 7 | 8891 | 166 | 867$^{h}$ | 314 | 7716$^{b}$ | 48 | - | - | - | - | 0 |
| 8 | 8852 | 14 | 218$^{h}$ | 108 | 7811$^{b}$ | 662 | - | - | - | - | 0 |
| 9 | 8847 | 102 | 5839$^{a}$ | 864 | - | - | - | - | - | - | 0 |
| 10 | 8888 | 181 | 204$^{h}$ | 712 | 7791$^{b}$ | 307 | 1345 | 314 | - | - | 0 |
| 11 | 8929 | 27 | 245$^{h}$ | 48 | 7765$^{b}$ | 578 | - | - | - | - | 0 |
| 12 | 8851 | 52 | 425$^{g}$ | 312 | 974$^{c}$ | 226 | 215 | 840 | - | - | 0 |
| 13 | 8871 | 57 | 5864$^{a}$ | 800 | - | - | - | - | - | - | 0 |
| 14 | 8856 | 13 | 1131$^{d}$ | 916 | 5577$^{f}$ | 1096 | | | | | 1 |
| 15 | 7108 | 112 | 878$^{h}$ | 88 | 7812$^{b}$ | 70 | - | - | - | | 0 |
| 16 | 7069 | 105 | 5879$^{a}$ | 489 | - | - | - | - | - | - | 0 |
| 17 | 7144 | 13 | 7756$^{b}$ | 82 | 1871 | 1414 | 4815$^{e}$ | 4721 | - | - | 0 |
| 18 | 7049 | 364 | 7767$^{b}$ | 481 | - | - | - | - | - | - | 1 |

β-particle detection efficiency in single pixel ≈ 5-20%

# Results $^{156}$W: Chains

1) $^{156}$**W** $t_{1/2}$**= 153 (+64 -39) ms**, after correcting for unambigous intervening decays.

2) $^{156}$**W** $t_{1/2}$**= 147 (+73 -36) ms,** direct β detection

3) Can combine unique data for improved precision:
$^{156}$**W** $t_{1/2}$**= 157 (+57 -34) ms**

Values compare well with **predicted value of 130 ms [P. Möller, M.R. Mumpower et al.]**

$^a$ α decay of $^{156}$Hf ground state
$^b$ α decay of $^{156}$Hf isomeric state
$^c$ proton decay of $^{156}$Ta ground state
$^d$ proton decay of $^{156}$Ta isomeric state
$^e$ α decay of $^{152}$Er
$^f$ α decay of $^{155}$Lu
$^g$ β decay of $^{156}$W feeding $^{156}$Ta ground state
$^h$ β decay of $^{156}$W feeding $^{156}$Ta isomeric state
$^i$ β decay of $^{156}$Ta isomeric state

| Chain # | $E_1$ (keV) | $t_1$ (μs) | $E_2$ (keV) | $t_2$ (ms) | $E_3$ (keV) | $t_3$ (ms) | $E_4$ (keV) | $t_4$ (ms) | $E_5$ (keV) | $t_5$ (ms) | JYTube Fold |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 8911 | 27 | $5886^a$ | 1285 | - | - | - | - | - | - | 0 |
| 2 | 8894 | 31 | $472^h$ | 43 | $165^i$ | 1498 | $5883^a$ | 55 | $4820^e$ | 1139 | 0 |
| 3 | 8868 | 31 | $180^i$ | 1605 | $7801^b$ | 1 | - | - | - | - | 0 |
| 4 | 8878 | 205 | $1016^c$ | 256 | - | - | - | - | - | - | 1 |
| 5 | 8850 | 15 | $341^h$ | 256 | $5904^a$ | 1285 | - | - | - | - | 0 |
| 6 | 8888 | 28 | $156^h$ | 28 | $7741^b$ | 923 | - | - | - | - | 0 |
| 7 | 8891 | 166 | $867^h$ | 314 | $7716^b$ | 48 | - | - | - | - | 0 |
| 8 | 8852 | 14 | $218^h$ | 108 | $7811^b$ | 662 | - | - | - | - | 0 |
| 9 | 8847 | 102 | $5839^a$ | 864 | - | - | - | - | - | - | 0 |
| 10 | 8888 | 181 | $204^h$ | 712 | $7791^b$ | 307 | 1345 | 314 | - | - | 0 |
| 11 | 8929 | 27 | $245^h$ | 48 | $7765^b$ | 578 | - | - | - | - | 0 |
| 12 | 8851 | 52 | $425^g$ | 312 | $974^c$ | 226 | 215 | 840 | - | - | 0 |
| 13 | 8871 | 57 | $5864^a$ | 800 | - | - | - | - | - | - | 0 |
| 14 | 8856 | 13 | $1131^d$ | 916 | $5577^f$ | 1096 | | | | | 1 |
| 15 | 7108 | 112 | $878^h$ | 88 | $7812^b$ | 70 | - | - | - | | 0 |
| 16 | 7069 | 105 | $5879^a$ | 489 | - | - | - | - | - | - | 0 |
| 17 | 7144 | 13 | $7756^b$ | 82 | 1871 | 1414 | $4815^e$ | 4721 | - | - | 0 |
| 18 | 7049 | 364 | $7767^b$ | 481 | - | - | - | - | - | - | 1 |

β-particle detection efficiency in single pixel ≈ 5-20%

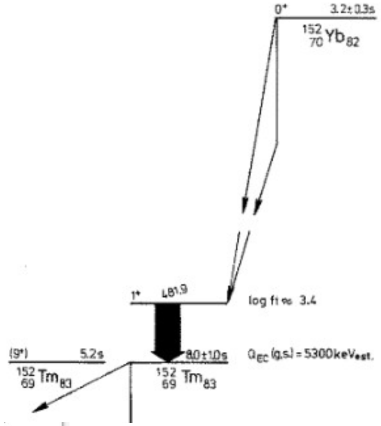
Detected in 9 / 18 chains (50%). Why do we see many apparent β signals?

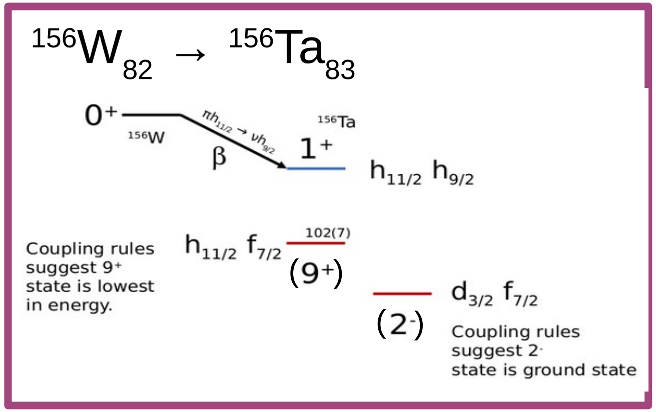
# Results $^{156}$W: Feeding

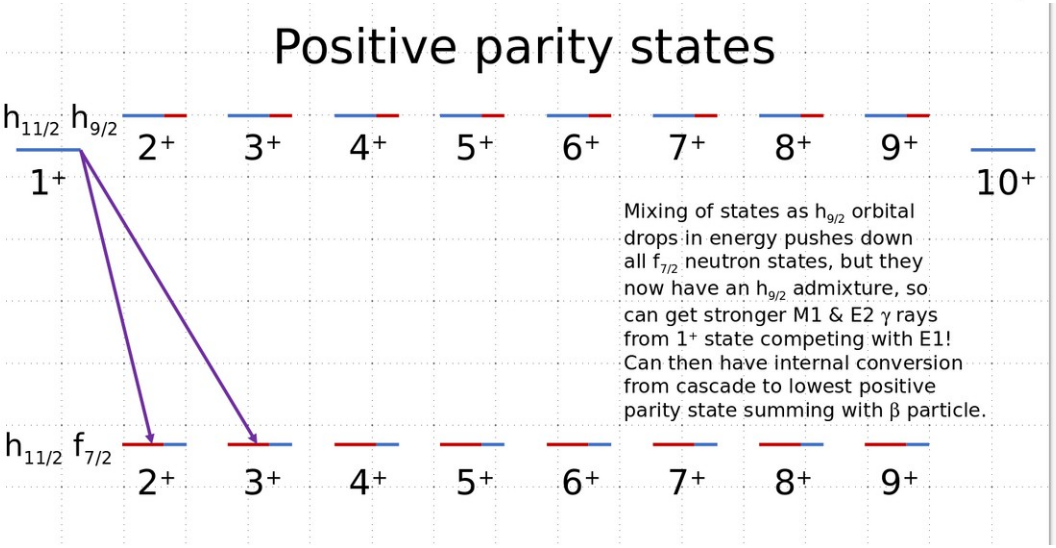
β decay feeding of N = 82 isotones dominates by favoured Gamov teller spin-flip transitions.

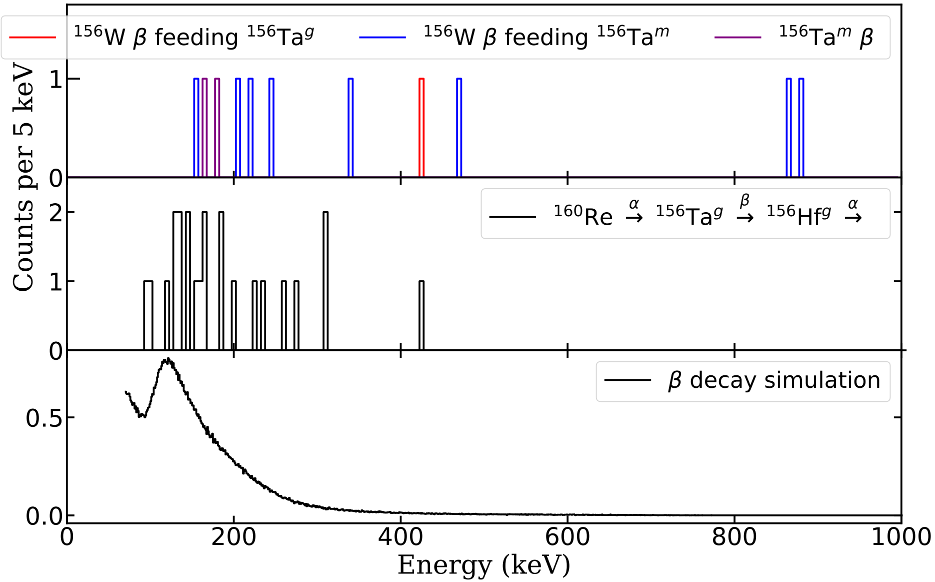
$\pi h_{11/2} \rightarrow \nu h_{9/2}$

All lighter N = 82 isotones,
2- state exclusively fed via E1 from 1⁺.
We see feeding to both states



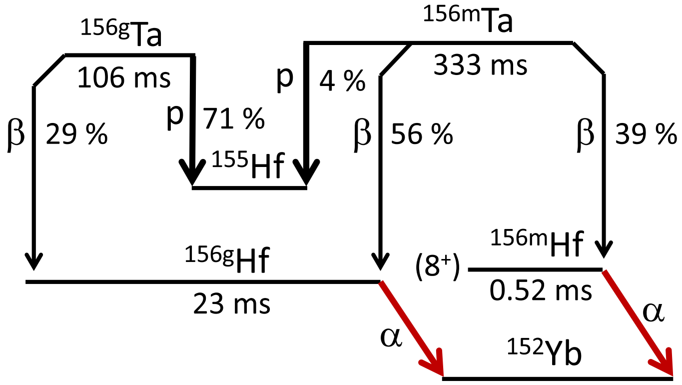

Cascade of highly converted γ rays through positive parity multiplet, low energy electrons sum to give signals!

$Q_\beta$ predicted 8.82 MeV

# Outline

- Introduction – Experiment method for correlation analysis of fusion products (stable beams)
- Specifics for β particles and conversion electrons
- **Recent results with of with experiments with MARA**
  **i)** $^{155}$Lu
  ii)$^{156}$W
  iii)**$^{156}$Ta**
- Summary

# Results $^{156}$Ta: Background



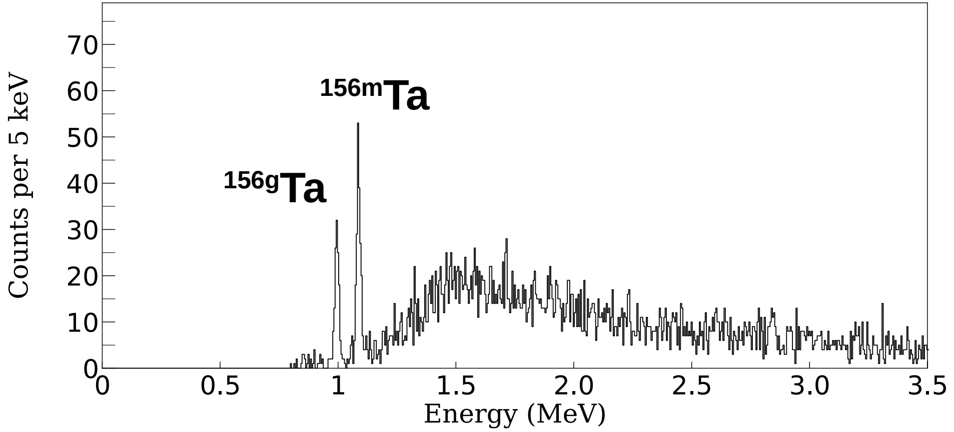

$^{156}$Ta is first dominant Ta proton emitter (3% branch in $^{157}$Ta)

2 states known. Proton emission $Q_p$ and (partial) $t_{1/2}$ shows that proton is emitted from $\boldsymbol{\pi d_{3/2}}$ and $\boldsymbol{\pi h_{11/2}}$ orbitals for ground state & isomeric state.

Interpreted as :

ground state: $\pi d_{3/2} \otimes \pi f_{7/2}$ , $J^\pi$=($2^-$ to $4^-$), coupling rules: $2^-$

isomeric state: $\pi h_{11/2} \otimes \pi f_{7/2}$ , $J^\pi$=($9^+$ to $2^+$) coupling rules: $9^+$



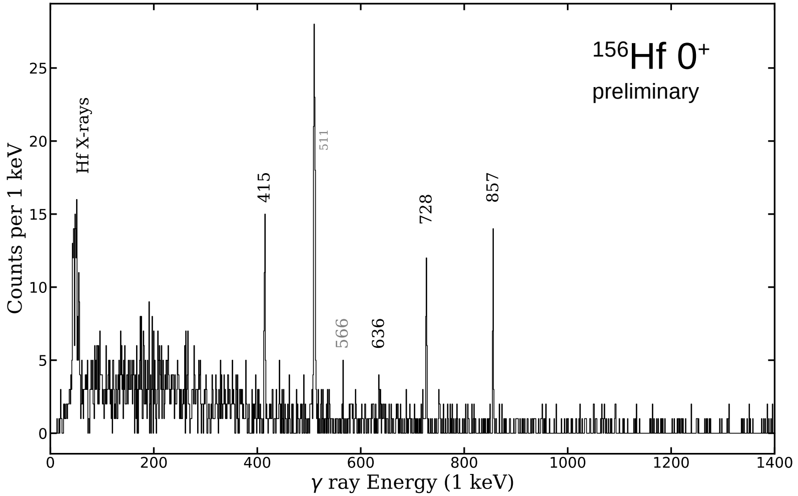

States fed by β decay carry information on $J^\pi$ of the proton/β emitting states.

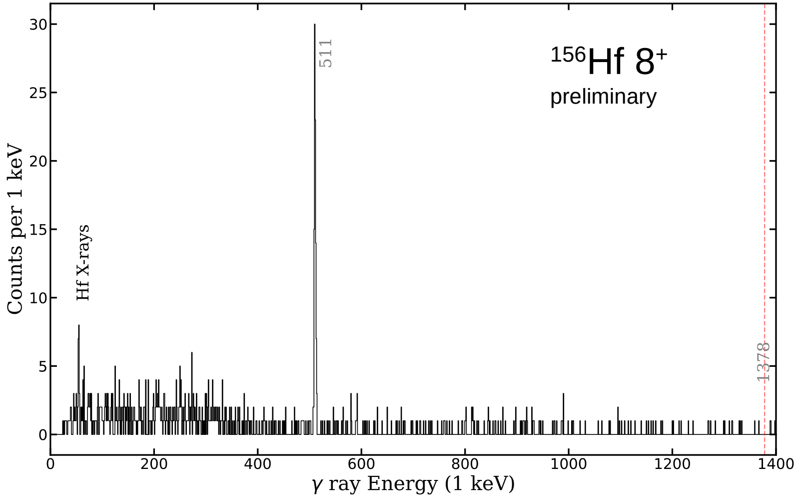
**Search for ɣ rays at FP for:**

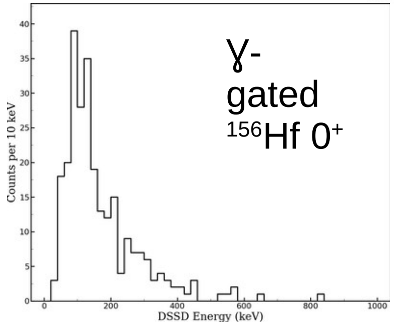
**R-$^{156g/m}$Ta (β) -$^{156g/m}$Hf (α)**

# Results $^{156}$Ta: Results

R-$^{156g/m}$Ta(β)-$^{156g/m}$Hf(α)



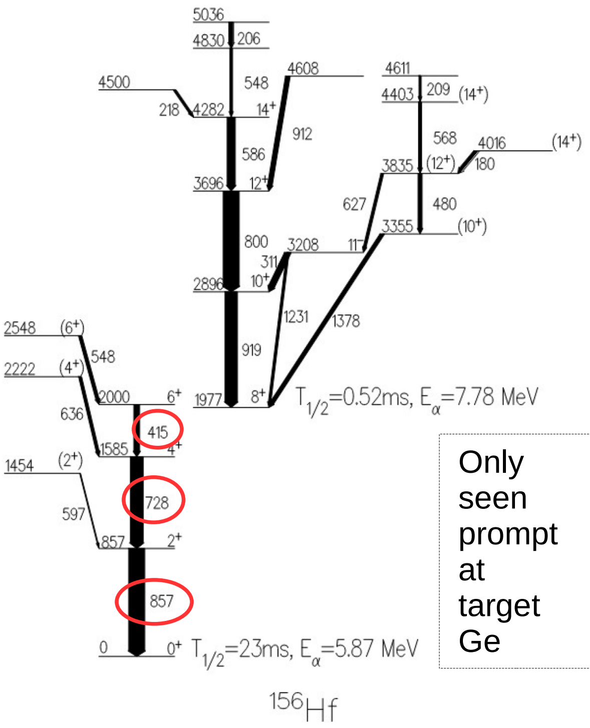




PHYSICAL REVIEW C **71**, 054319 (2005)

**Multiparticle configurations in $N = 84$ isotones located at the proton drip line**

D. Seweryniak,[1,2] J. Uusitalo,[1] P. Bhattacharyya,[3] M. P. Carpenter,[1] J. A. Cizewski,[1,4] K. Y. Ding,[4,*] C. N. Davids,[1] N. Fotiades,[4,†] R. V. F. Janssens,[1] T. Lauritsen,[1] C. J. Lister,[1] A. O. Macchiavelli,[5] D. Nisius,[1] P. Reiter,[1] W. B. Walters,[2] and P. J. Woods[6]




Only seen prompt at target Ge

Intensities of ɣ rays coincident with β particles that feed 0$^+$ α-decaying state in $^{156}$Hf not quite consistent with suggested spins of (9$^+$) and (2-)

Not quite enough stats for ɣɣ coincidences

Recoil-β time difference may give extra information on feeding..

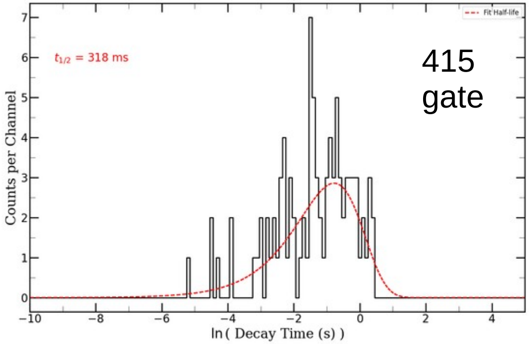
# Results $^{156}$Ta: Results

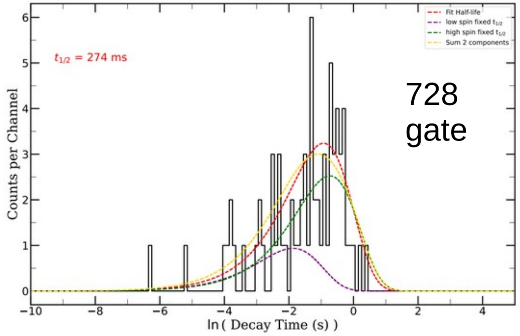
Time difference between recoil implant & β-ɣ allows measurement of the half-lives of the states feeding.
(discuss these)

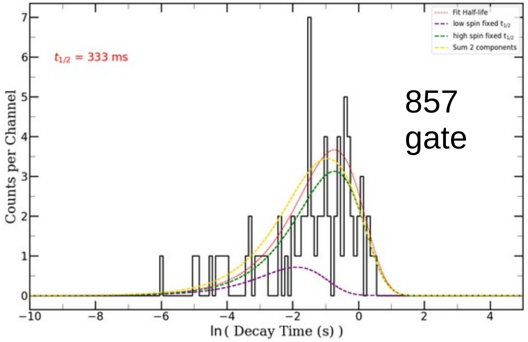
**$^{156m}$Ta at potential $7^+$ assignment**.
Similar observed in $^{154}$Lu (K.S. Vierinen, Phys. Rev. C 38 (1988)).

$^{156g}$Ta could be feeding both $4^+$ and $2^+$, work in progress to what we can assign here ($2^-$ or $4^-$).

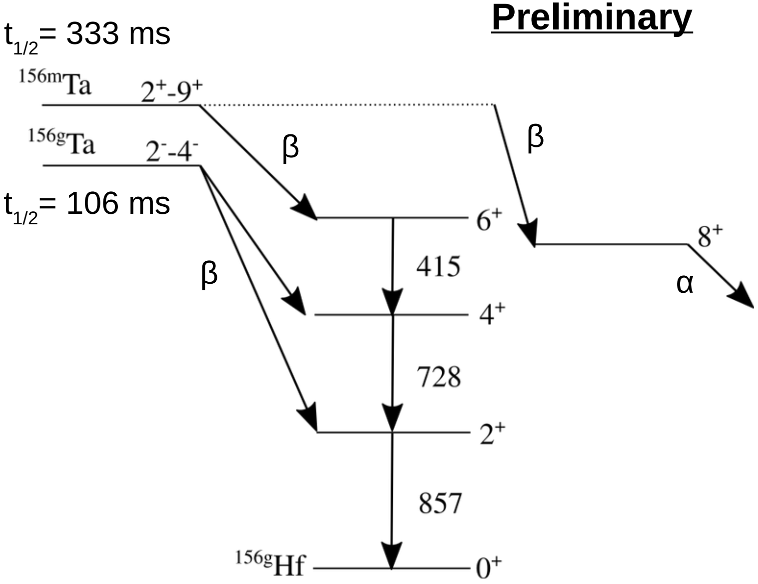
Can be used as a tag for an in-beam study for the firs time..

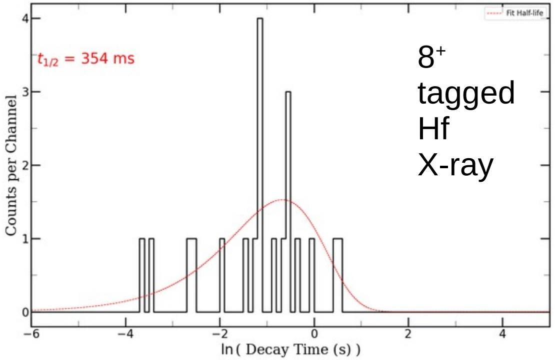



**Preliminary**



# Outline

- Introduction – Experiment method for correlation analysis of fusion products (stable beams)
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- Recent results with of with experiments with MARA

  i) $^{155}$Lu

  ii)$^{156}$W

  iii)$^{156}$Ta
- **Summary**

# Conlusion/Summary

$^{155}$Lu : sensitive to a weak conversion electron branch in this isomeric state, mixed M3/E4.

$^{156}$W: change in behaviour of β decay feeding with respect to lighter N= 82 isotones. Low energy conversion electrons within multiplet enhances sensitivity to β decays.

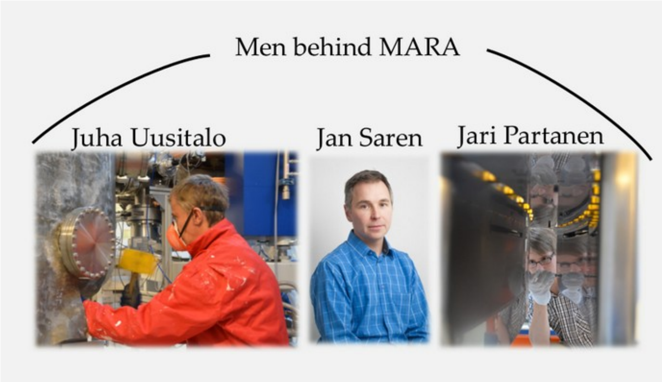
$^{156}$Ta: (preliminary) β-ɣ analysis should allow assignment of $J^{\pi}$

Further studies in this region would be benefit from dedicated β tracking instrumentation :)

# thanks for listening!

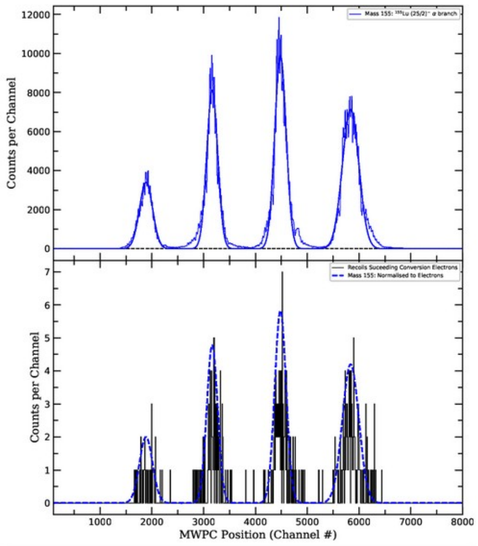
And to my collaborators

A.D. Briscoe [a,b,*], R.D. Page [a], J. Uusitalo [b,a], D.T. Joss [a], M.A.M. AlAqeel [l,a], B. Alayed [m,a], B. Andel [c], S. Antalic [c], K. Auranen [b], H. Ayatollahzadeh [d], H. Badran [b], L. Barber [e], G. Beeton [d], M. Birova [f], V. Bogdanoff [b], R.M. Clark [g], J.G. Cubiss [h], D.M. Cullen [e], J. Deary [d], U. Forsberg [b], T. Grahn [b], P.T. Greenlees [b], J.B. Hilton [a,b], A. Illana [b,n], H. Joukainen [b], D.S. Judson [a], R. Julin [b], H. Jutila [b], J.M. Keatings [d], M. Labiche [i], M. Leino [b], M.C. Lewis [a], J. Louko [b], M. Luoma [b], I. Martel [a,o], A. McCarter [a], P.P. McKee [d], P. Mosat [c], S.N. Nathaniel [a], O. Neuvonen [b], D. O'Donnell [d], J. Ojala [b], C.A.A. Page [h], A.M. Plaza [a,b], J. Pakarinen [b], P. Papadakis [i], E. Parr [a], J. Partanen [b,1], P. Rahkila [b], P. Ruotsalainen [b], M. Sandzelius [b], J. Sarén [b], B. Saygi [j,p], J. Smallcombe [a], J.F. Smith [d], J. Sorri [k], C.M. Sullivan [a], S. Szwec [b], H. Tann [a,b], A. Tolosa-Delgado [b], E. Uusikylä [b], M. Venhart [f], L.J. Waring [a], G. Zimba [b]

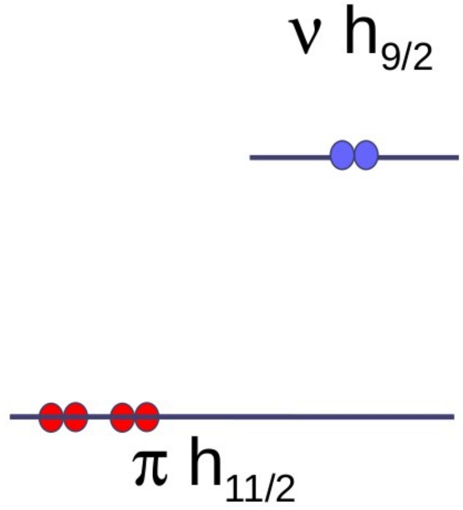


# Back up slides next

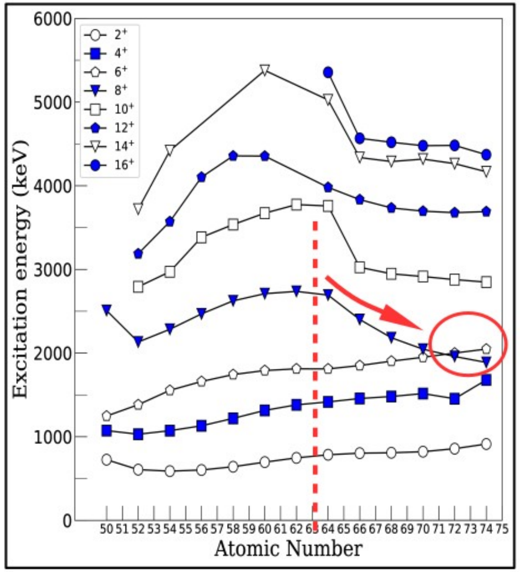
# Back up: $^{155}$Lu

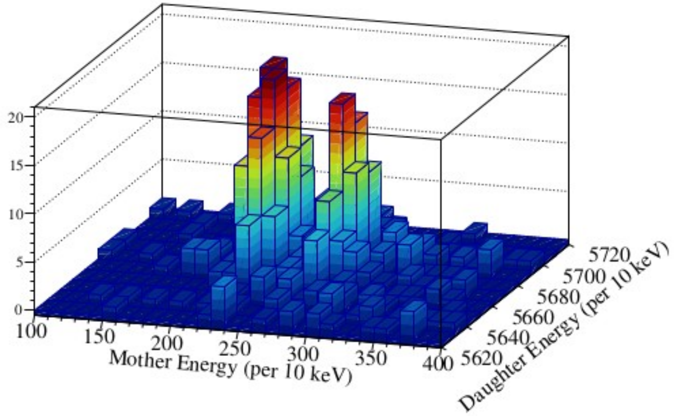



## Experimental Motivation



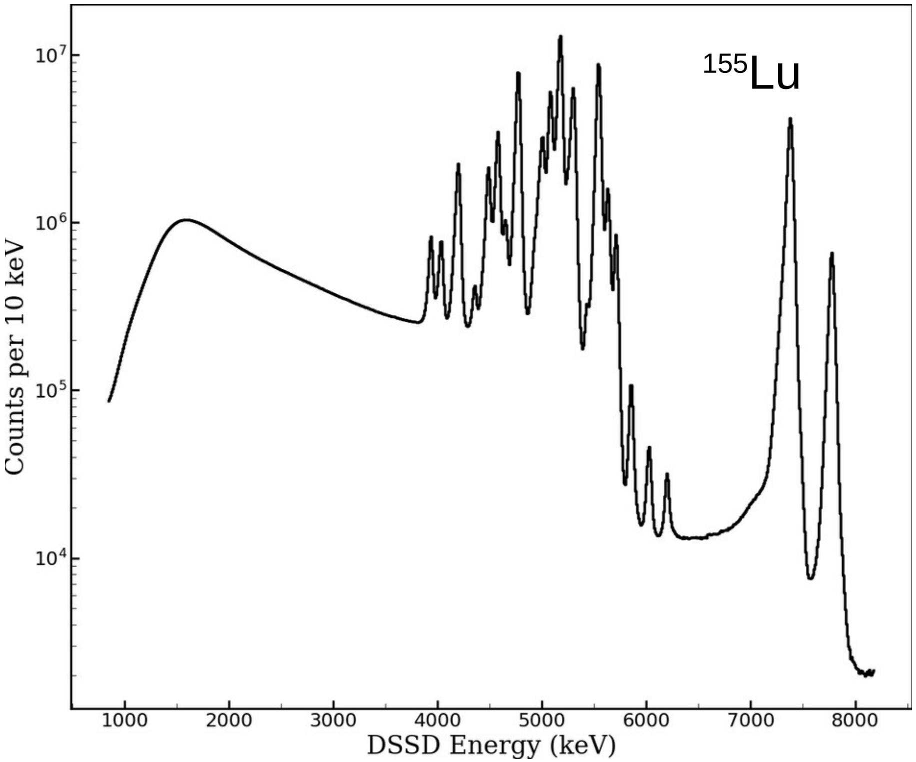

Valence orbitals above doubly magic $^{146}$Gd



# Back up: $^{155}$Lu

$^{155}$Lu alpha spectrum.



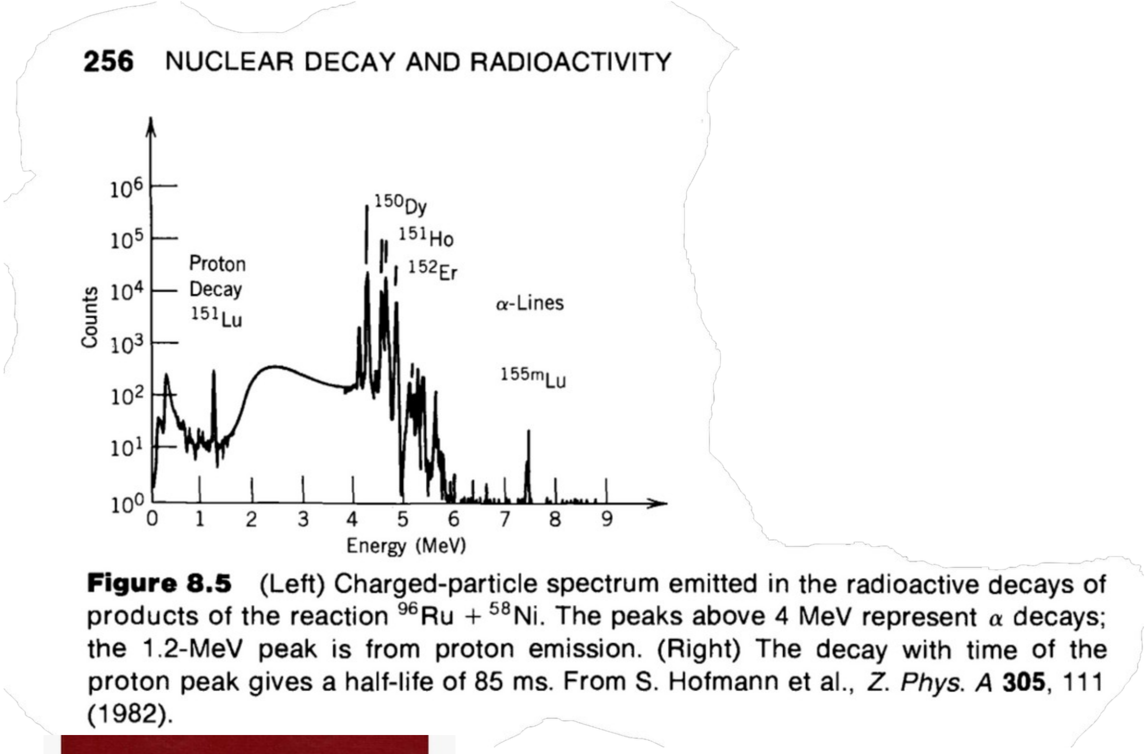
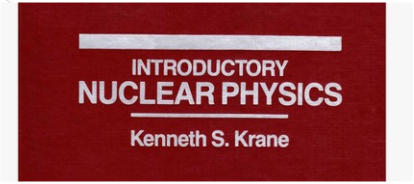






**Figure 8.5** (Left) Charged-particle spectrum emitted in the radioactive decays of products of the reaction $^{96}Ru + ^{58}Ni$. The peaks above 4 MeV represent $\alpha$ decays; the 1.2-MeV peak is from proton emission. (Right) The decay with time of the proton peak gives a half-life of 85 ms. From S. Hofmann et al., *Z. Phys. A* **305**, 111 (1982).




Contaminants of heavier Ni in target