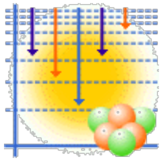
Argonne NATIONAL LABORATORY

Decay Data - Experiment



Filip G. Kondev
kondev@anl.gov

- ❑ decay data are very rich source of nuclear structure information & are of importance to many other areas
  - ✓ nuclear structure – often offer the best quantities, because the complexity of spectra is reduced
  - ✓ astrophysics – especially on the "r-process" side – neutron-rich nuclei
  - ✓ atomic masses – proton-rich ($Q\alpha$ & Qp); neutron-rich ($Q\beta-$)
  - ✓ applications of nuclear science

Plan

- will cover in somewhat details experimental α and β decays

- isomer decays – lectures by Prof. P. Reagan

Atomic Data and Nuclear Data Tables 103–104 (2015) 50–105

Configurations and hindered decays of *K* isomers in deformed nuclei with A > 100

F.G. Kondev[a,*], G.D. Dracoulis[b,1], T. Kibédi[b]

IOP Publishing

Rep. Prog. Phys. **79** 07630

Review of metastable states in heavy nuclei

G D Dracoulis[1,4], P M Walker[2] and F G Kondev[3]

Introduction

Experimental Decay Data

- experimental results obtained following α–, β^--, β^+, EC, IT, p, cluster, etc. decay processes

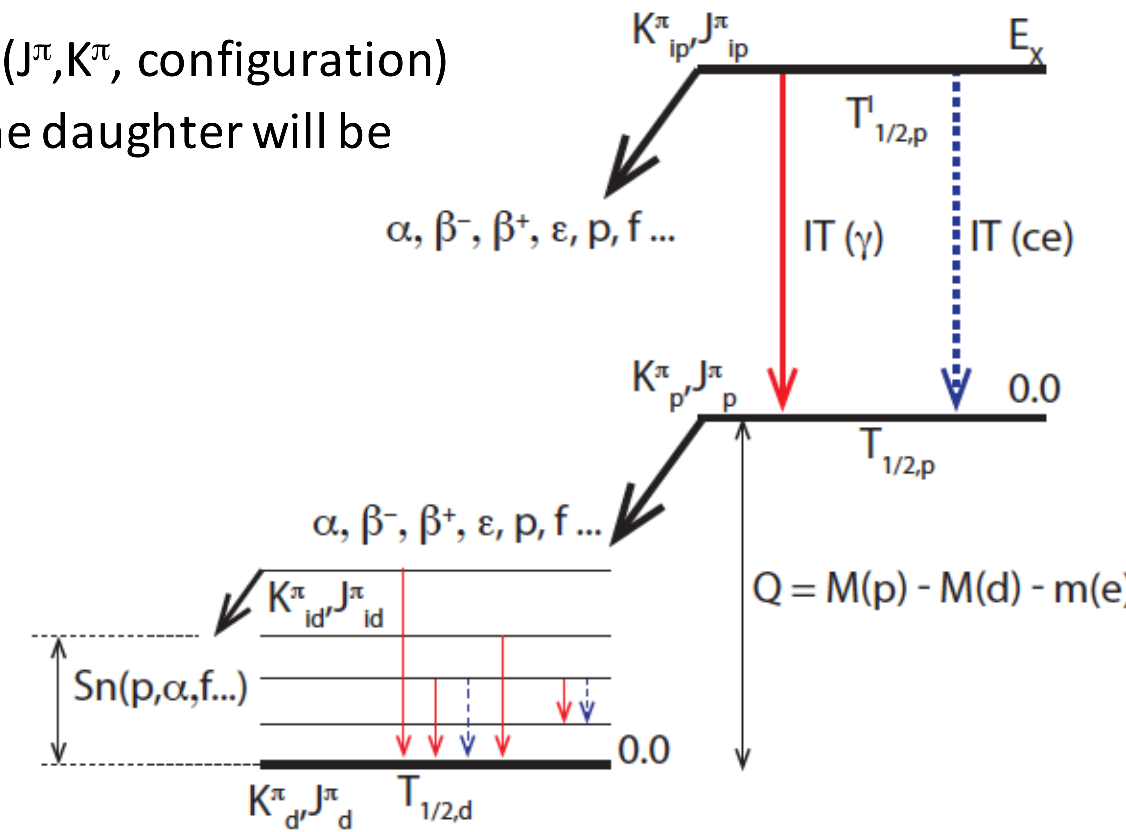
Evaluated Decay Data

- recommended (best) values for nuclear levels and decay radiation properties, deduced by the evaluator using all available experimental data & theoretical calculations (e.g. electron conversion coefficients)

Myth: decay data evaluation deals only with decay data – many properties come from other decays and reactions (adopted level properties), e.g. Eγ, Iγ, MR, ICC, …

Introduction – cont.

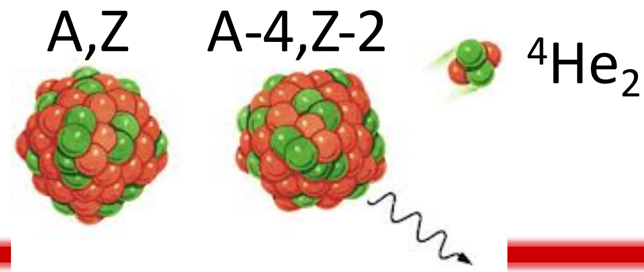
- structure of the parent state (J^{π},K^{π}, configuration)
  - ✓ controls which states of the daughter will be populated



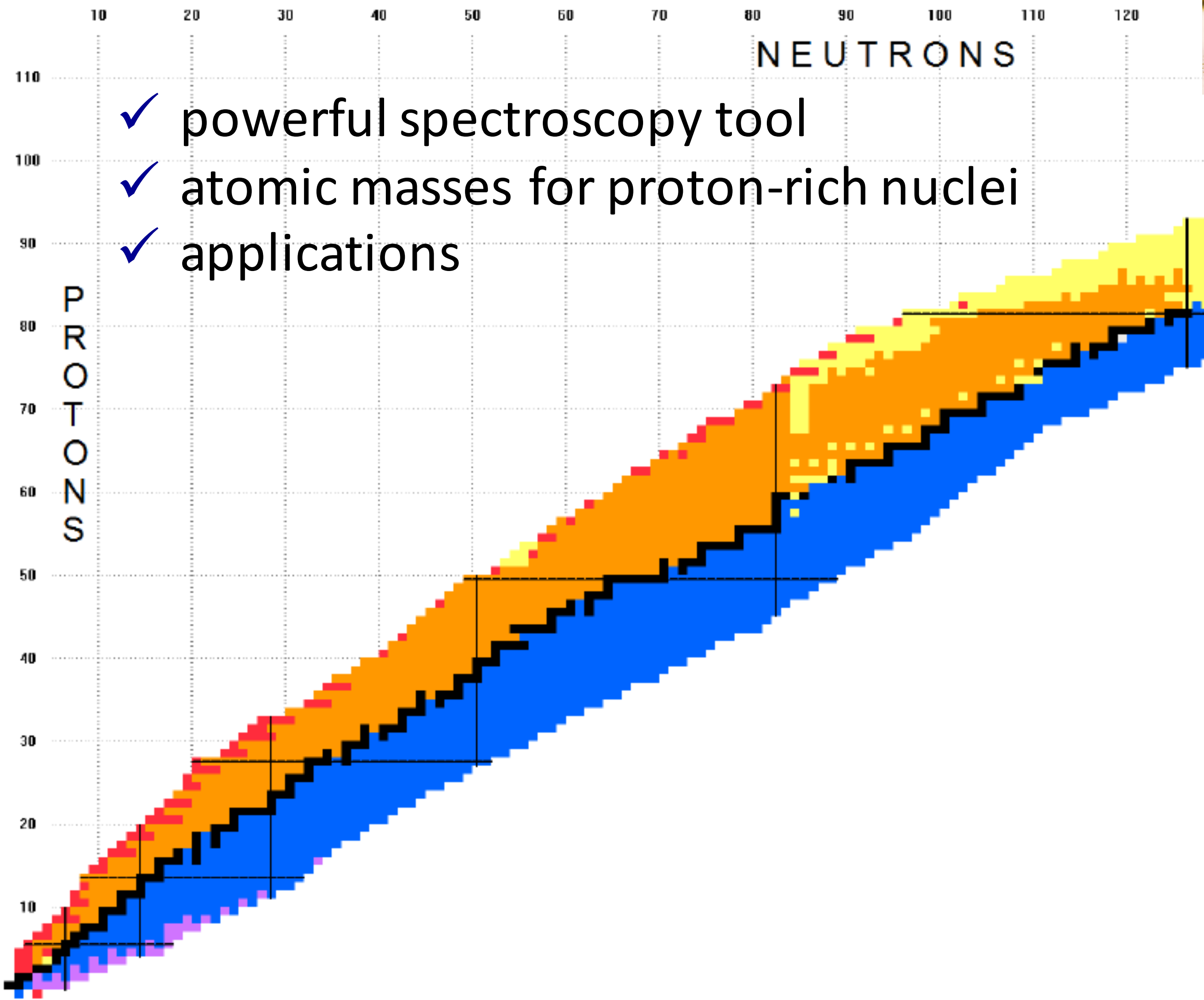
- **excitation energy**
- **quantum numbers and their projections**
- **lifetime**
- **decay modes & branching ratios**

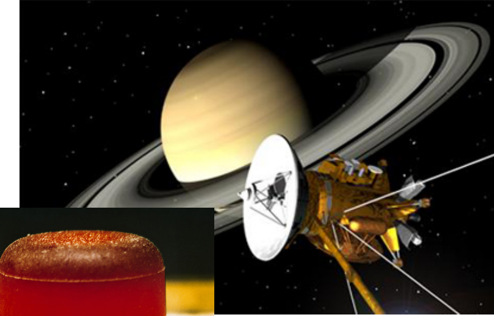
- Q-value – defines the energetics of the decay
  - ✓ controls the lifetime of the parent
  - ✓ the window of daughter states available

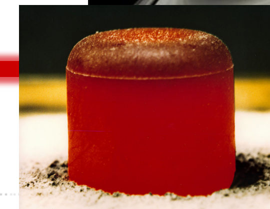
α–decay

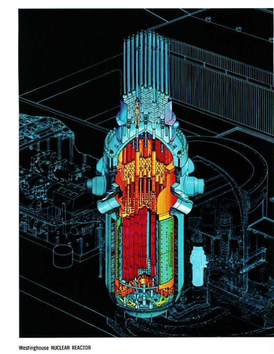


- ✓ powerful spectroscopy tool
- ✓ atomic masses for proton-rich nuclei
- ✓ applications









α–decay – cont.

$$|I_i - I_f| \le l_\alpha \le |I_i + I_f|$$

$$\pi_i \pi_f = (-1)^{l_\alpha}$$

even-even nuclei:

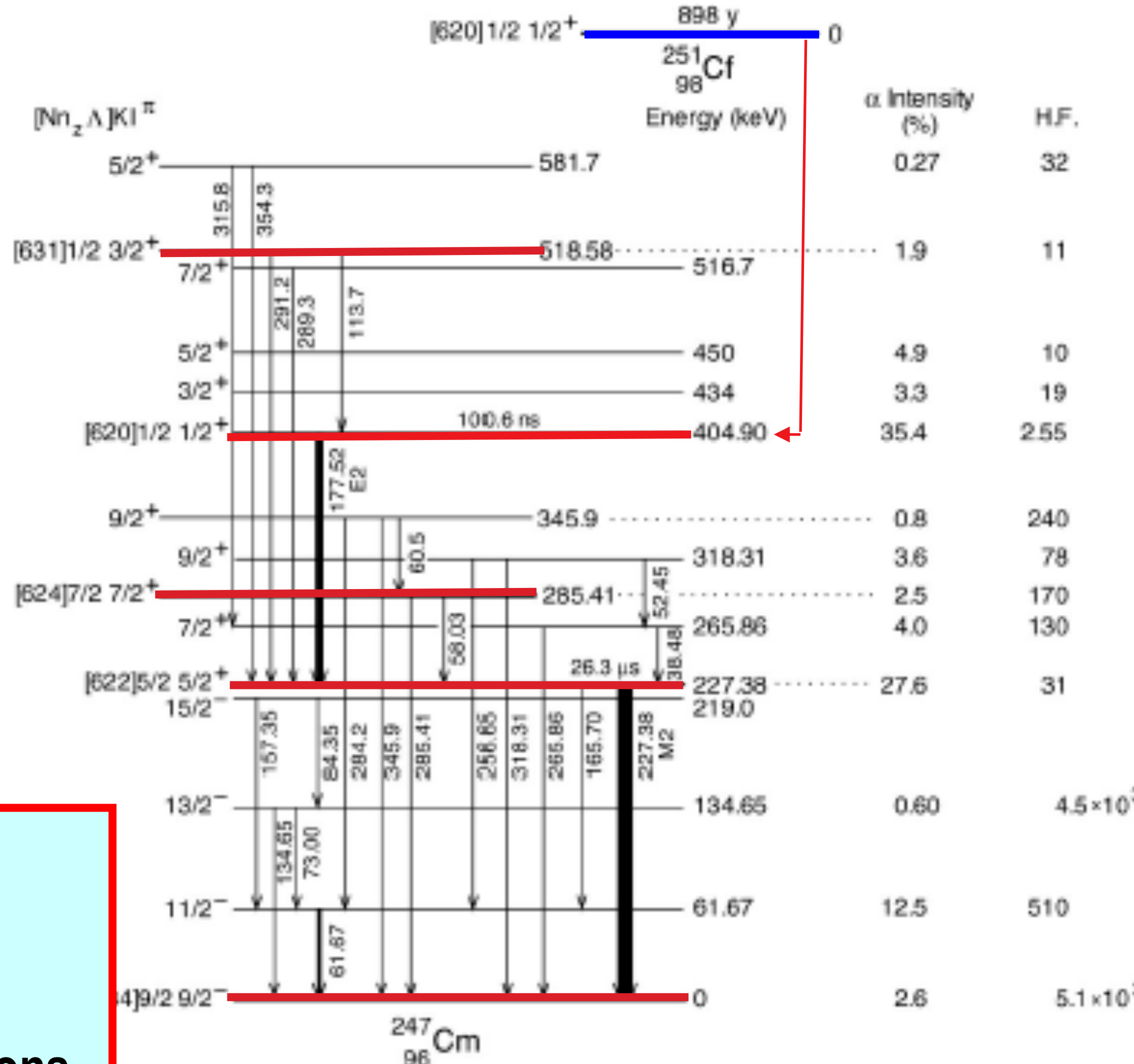
0+ -> 0+; l_α=0

odd-A:

1/2+ -> 1/2+; l_α=**0**,~~1~~

1/2+ -> 3/2+; l_α=~~1~~,**2**

1/2+ -> 9/2-; l_α=4,**5**



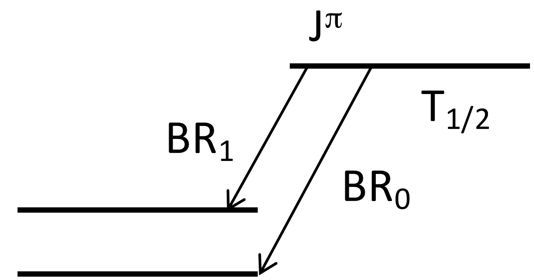
I. Ahmad et al., Phys. Rev. **C68** (2003) 044306

- ❑ Strong dependence on l_α
- ✓ fastest decay for l_α=0
- ❑ Configuration dependence
- ✓ fastest for the same configurations

Hindrance Factor in α–decay

HF < 4 – favorite decay (fast)

$$HF_i = \frac{t_{1/2}^{\alpha_i}(\exp)}{t_{1/2}^{\alpha_i}(th)} = \frac{T_{1/2}(\exp)/BR_i}{t_{1/2}^{\alpha_i}(th)}$$



$t_{1/2}^{\alpha_i}(th)$ M.A. Preston, Phys. Rev. **71** (1947) 865

$$t_{1/2}^{\alpha} = \ln 2 \frac{r_0}{2v} \frac{\mu^2(H_l^2 + K_l^2) + \tan^2\alpha_0(C_l^2 + S_l^2) + 2\mu\tan\alpha_0(C_l K_l - S_l H_l)}{\mu^2 \tan\alpha_0 (H_l C_l + K_l S_l) Q_l} e^{+2\omega_0}$$

✓ depends on r_0 and $Q(\alpha)$ - nuclear radius: $R = r_0 \times A^{1/3}$ $\quad v = \sqrt{2E\alpha / m\alpha}$

$$Q\alpha_i = Q\alpha_0 - E_i = [m(A,Z) - m(A-4,Z-2) - m\alpha] - E_i$$

from AME12

$$Q\alpha_0 = E\alpha_0 \times \frac{m(A,Z)}{m(A-4,Z-2)} = E\alpha_0 \times \left(1 + \frac{4}{(A-4)}\right)$$

$E\alpha_0$, $Q\alpha_0$ in keV

$$Q\alpha_0 = \frac{2 \times m(A,Z) \times E\alpha_0}{m(A-4,Z-2) + \sqrt{m(A-4,Z-2)^2 - 2 \times m(A,Z) \times E\alpha_0}} \approx E\alpha_0 \times \left(1 + \frac{4.0015}{(A-4)}\right) + 0.15$$

relativistic formula

α decay - Experiments

- magnetic spectrometers
- ionization chambers
- semiconductor detectors – mostly Si
  - ✓ Si(Au), PIPS, DSSD, …

- using radioactive sources (off-line)
  - ✓ when lifetimes are sufficiently long

- using nuclear reactions (on-line)
  - ✓ implanting on a catcher foil
  - ✓ implanting directly on the DSSD

absolute determinations of α energies **using the BIPM magnetic spectrometer with a semi-circle focusing of alpha-particles**. These measurements were performed in the 70's - 80's for the **most intense alpha-transitions**

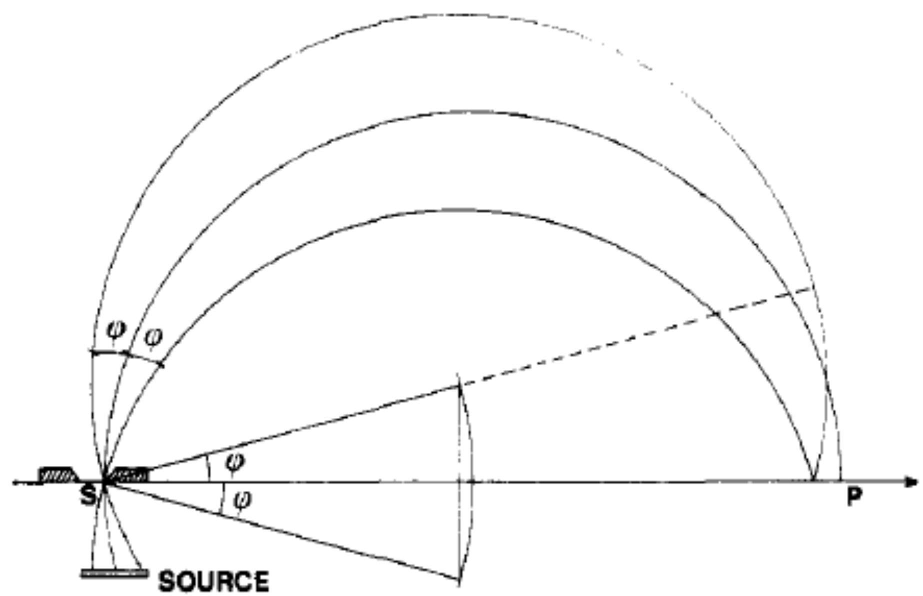
- ✓ **^{228}Th, ^{224,226}Ra, ^{220,222,219}Rn, ^{216,212,218,214,215}Po, ^{212}Bi, ^{227}Th, ^{223}Ra, ^{211}Bi, ^{253}Es, ^{242,244}Cm, ^{241}Am, ^{238}Pu – B. Grennberg, A. Rytz,** Metrologia 7, 65 (1971)
- ✓ **^{232}U, ^{240}Pu – D.J. Gorman, A. Rytz, H.V. Michel,** C. R. Acad. Sci., Ser. B 275, 291 (1972)
- ✓ **^{210}Po - D.J. Gorman, A. Rytz,** C. R. Acad. Sci., Ser. B 277, 29 (1973)
- ✓ **^{239}Pu - A. Rytz,** Proc. Intern. Conf. Atomic Masses and Fundamental Constants, 6th, East Lansing (1979)
- ✓ **^{236}Pu - A. Rytz, R.A.P. Wiltshire,** Nucl. Instrum. Methods 223, 325 (1984)
- ✓ **^{252}Cf, ^{227}Ac - A. Rytz, R.A.P. Wiltshire, M. King,** Nucl. Instrum. Methods Phys. Res. A253, 47 (1986).

Two parameters - the radius of curvature ρ and the mean magnetic induction **B.**

$$E(\alpha) = a\,(B\rho)^2 + b\,(B\rho)^4 + d\,(B\rho)^6$$

The factors **a, b, d** are derived from the latest adjustment of fundamental constants (**m_e, e and N_A**).

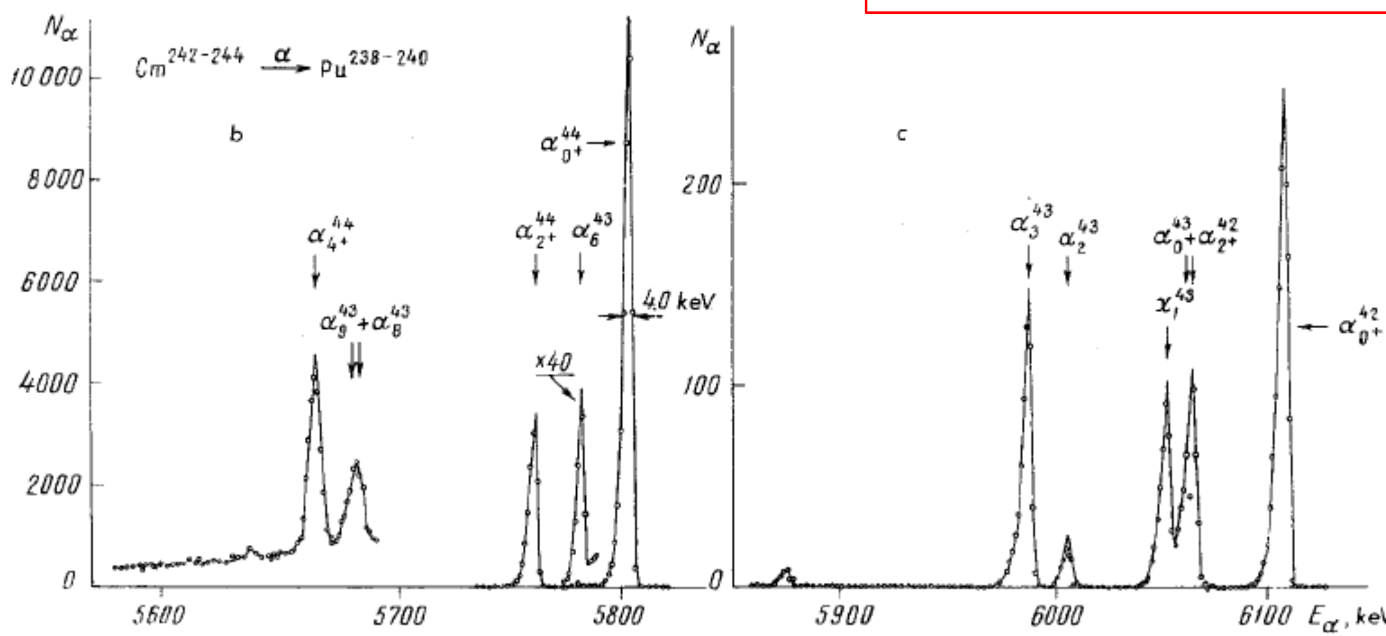
The components of systematic uncertainty are due to length measurements ($4.6 \cdot 10^{-5}$ E(α)), measurement of mean magnetic induction ($1.3 \cdot 10^{-5}$ E(α)) and combined effect of uncertainties of fundamental constants ($0.3 \cdot 10^{-5}$ E(α)), i.e. the total systematic uncertainty is ~$5 \cdot 10^{-5}$ E(α) or ~0.3 keV (^{239}**Pu**).



Magnetic $\pi\sqrt{2}$ α-spectrometers with high luminosity

In 1960's three such big magnetic α spectrometers were built in the Soviet Union – in Moscow (Baranov et al.), St. Petersburg (Dzhelepov et al.) and Dubna (Golovkov et al.).

1.5 keV energy resolution



In respect of alpha-particle energies the measurements with $\pi\sqrt{2}$ magnetic spectrometers are relative – one needs to use alpha-energy "standards".

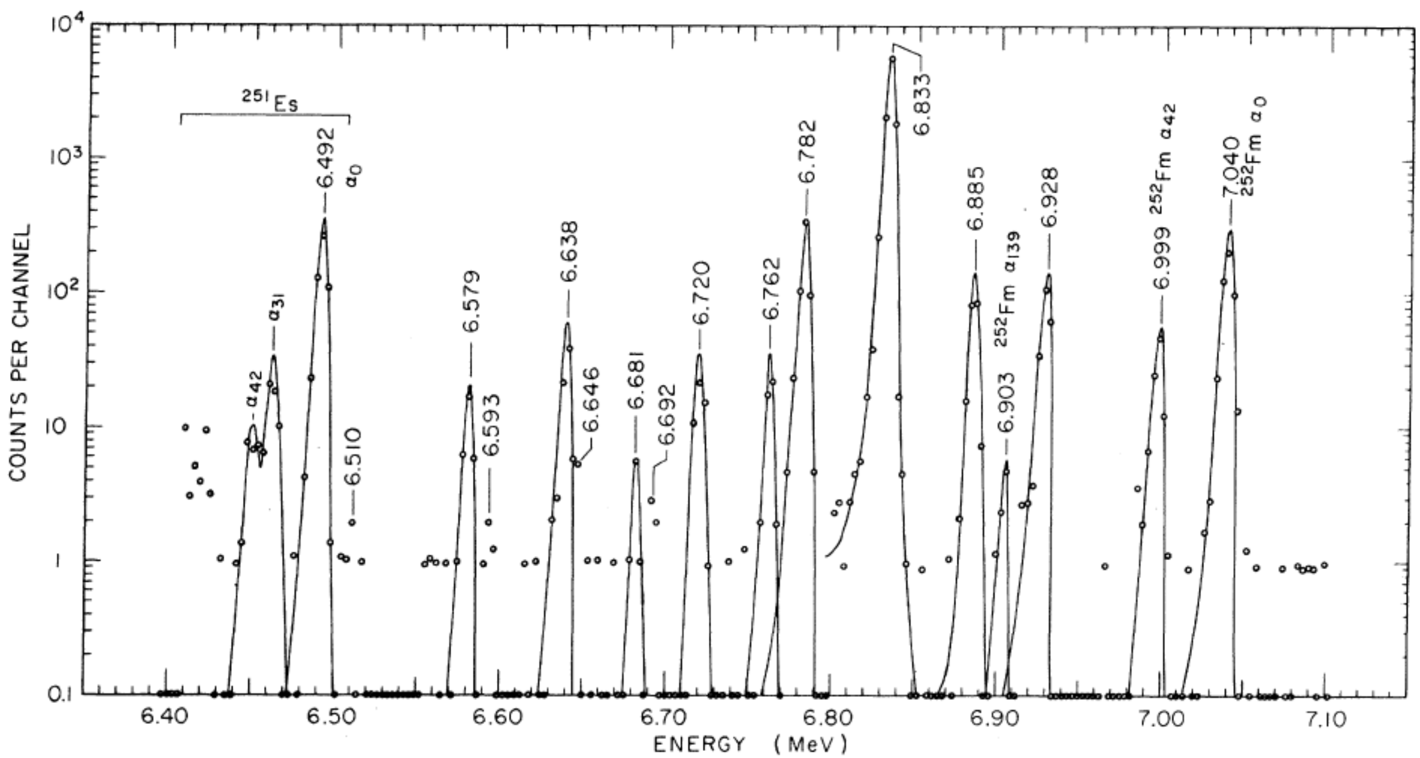
Argonne double-focusing magnetic spectrometer

- ✓ energy resolution (FWHM) of **5 keV**
- ✓ transmission efficiency of Ω=0.1 % for 6 MeV α–particles

HYSICAL REVIEW C VOLUME 8, NUMBER 2 AUGUST 1973

Alpha Decay of ^{251}Fm†

I. Ahmad, J. Milsted, R. K. Sjoblom, J. Lerner, and P. R. Fields



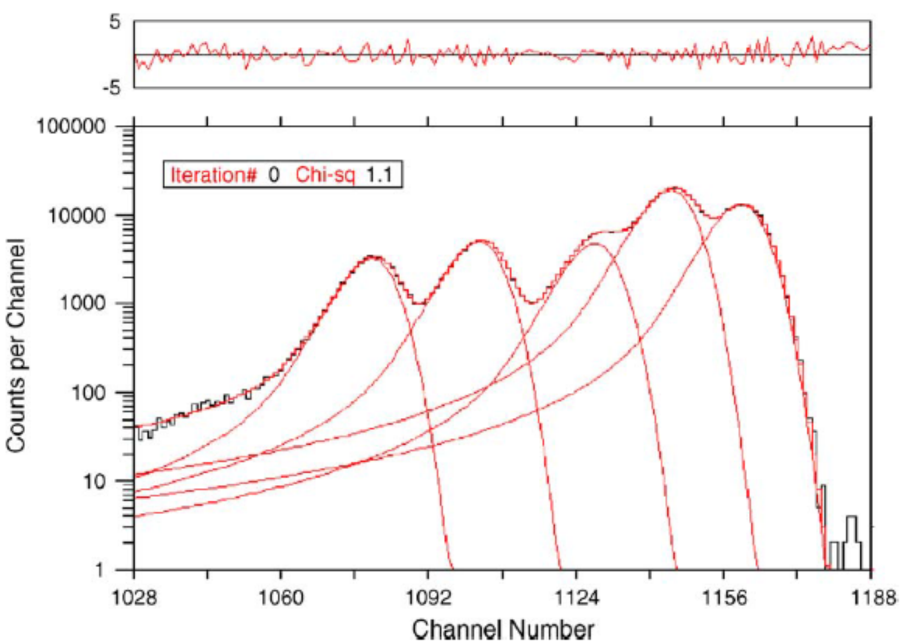
Semiconductor detectors

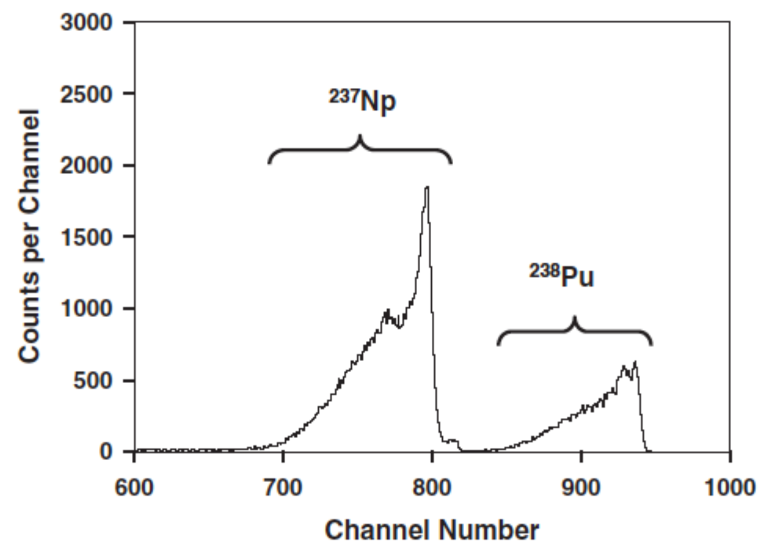
❑ **semiconductor detectors:** Passivated Implanted Planar Silicon (PIPS)

✓ energy resolution (FWHM) of ~**10 keV**

✓small geometrical efficiency of Ω=0.225% in order to minimize α–e- coincidence summing effects

✓ thin and isotopically pure sources
✓ sophisticated data analysis





Harada et al. J. Nucl. Sci. and Techn. 43 (2006) 1289

ATOMIC DATA AND NUCLEAR DATA TABLES **47**, 205–239 (1991)

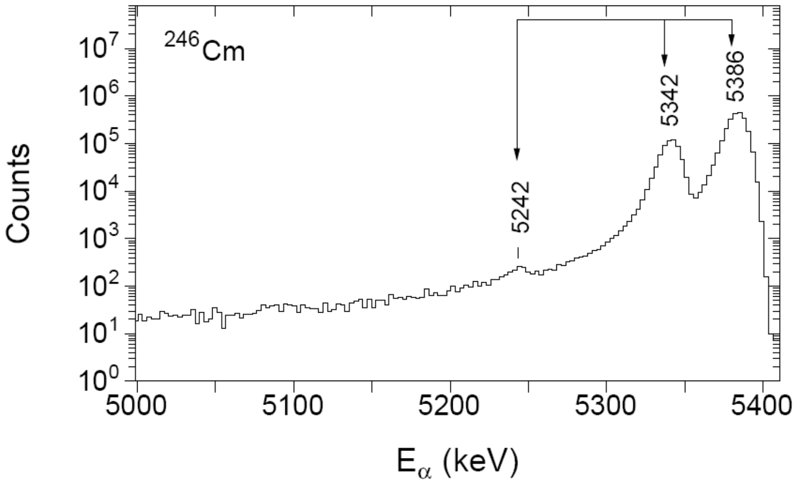
RECOMMENDED ENERGY AND INTENSITY VALUES OF ALPHA PARTICLES FROM RADIOACTIVE DECAY

A. RYTZ*

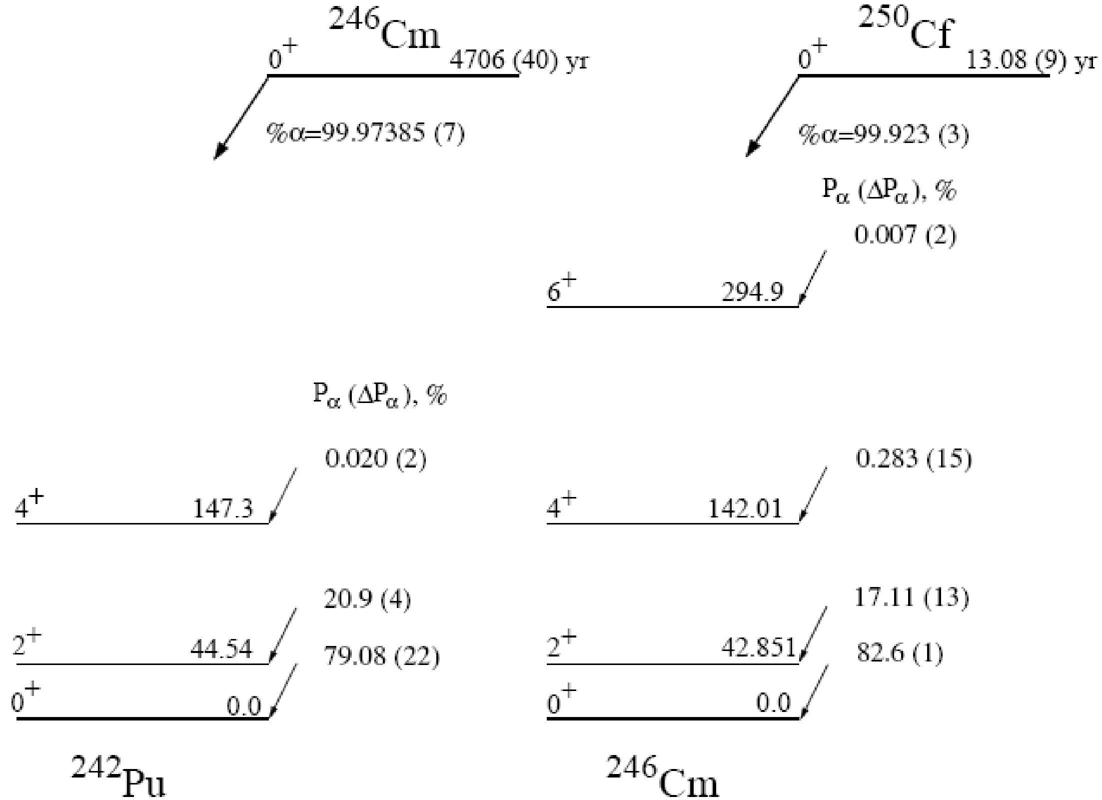
Bureau International des Poids et Mesures
F-92312 Sèvres Cedex, France

recommended values for $E\alpha$ and $I\alpha$

Emission Probabilities



t_m= 23.0 *h* (0.06% geometry)



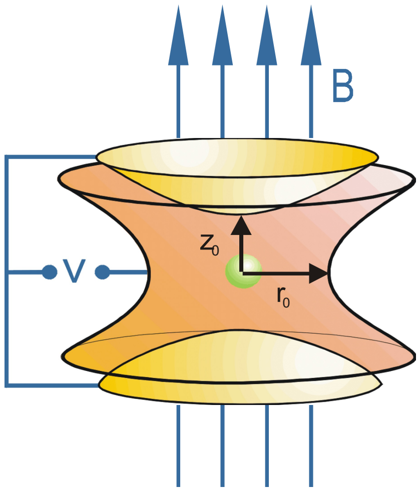
	$\alpha_{0.0}$		$\alpha_{44.5}$		$\alpha_{147.3}$	
Author	E_α, *keV*	P_α, %	E_α, *keV*	P_α, %	E_α, *keV*	P_α, %
Belov et al. (1963)	5387	78	5345	22	–	–
Dzhelepov et al. (1963)	5387 (4)	78 (5)	5345 (5)	22 (5)	–	–
Baranov et al. (1966)	5385	79	5342	21	–	–
Shatinskii (1984)	5386.5 (10)	82.2 (12)	5343.5 (10)	17.8 (12)	–	–
Present work	5386 (3)	79.08 (22)	5342 (3)	20.9 (4)	5242 (3)	0.020 (2)

PHYSICAL REVIEW C **89**, 064318 (2014)

Direct high-precision mass measurements on ^{241,243}Am, ^{244}Pu, and ^{249}Cf

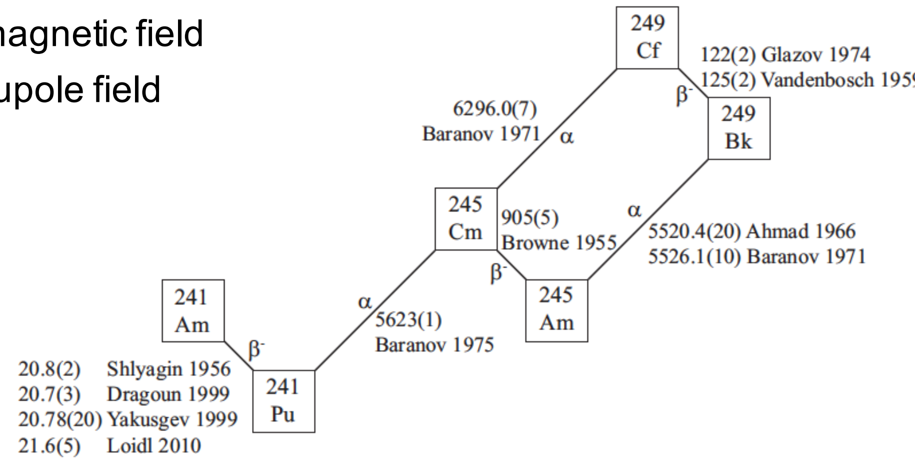
M. Eibach,[1,2,*] T. Beyer,[1] K. Blaum,[1] M. Block,[3] Ch. E. Düllmann,[3,4,5] K. Eberhardt,[2,5] J. Grund,[4] Sz. Nagy,[1] H. Nitsche,[6,7] W. Nörtershäuser,[2,3,8] D. Renisch,[2] K. P. Rykaczewski,[9] F. Schneider,[2,10] C. Smorra,[1,†] J. Vieten,[11] M. Wang,[1,12,13] and K. Wendt[10]

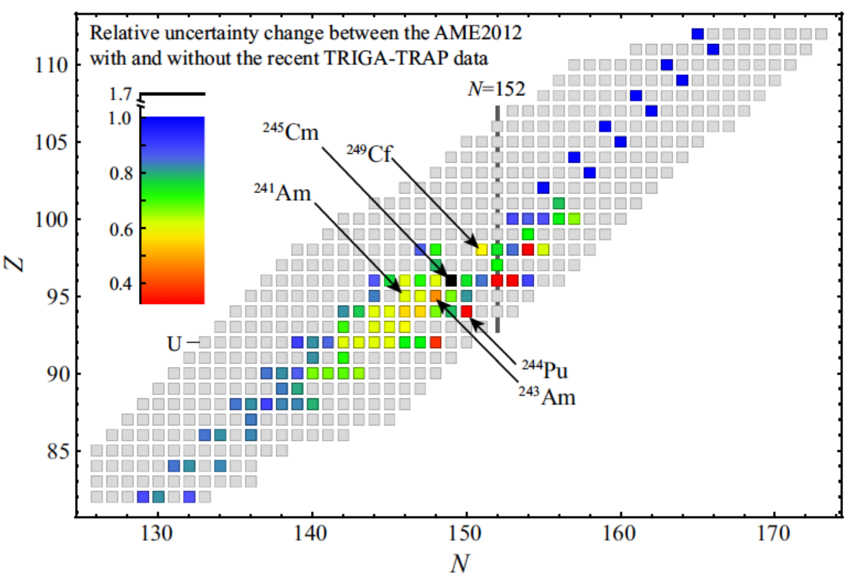
PENNING trap

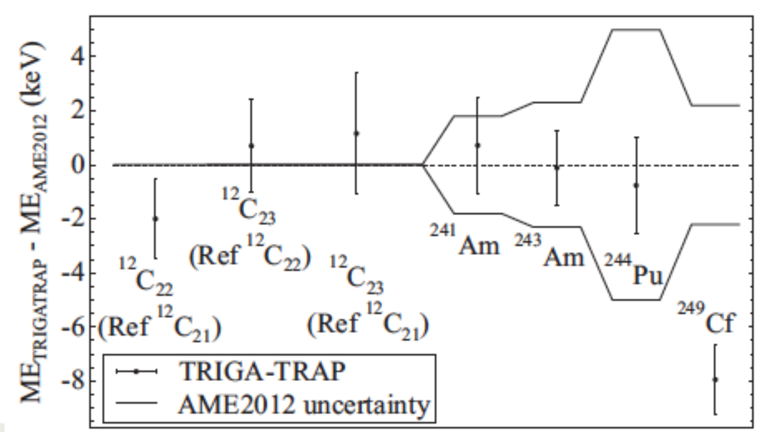


- strong homogeneous magnetic field
- weak electric 3D quadrupole field

$$f_c = \frac{1}{2\pi} \cdot \frac{q}{m} \cdot B$$



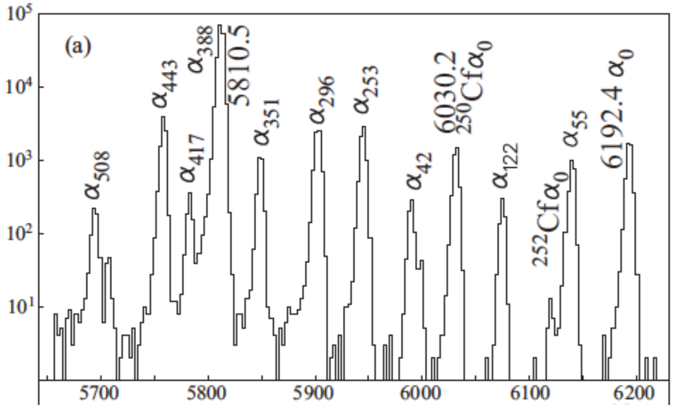




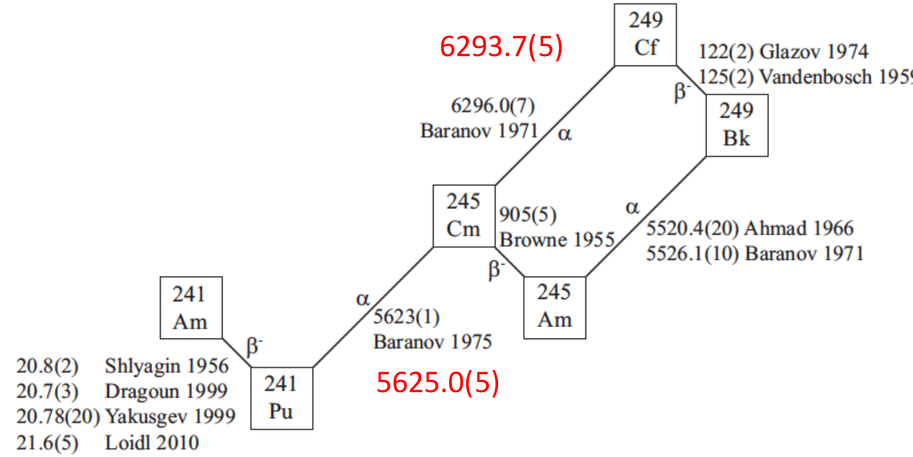
PHYSICAL REVIEW C **91**, 044310 (2015)

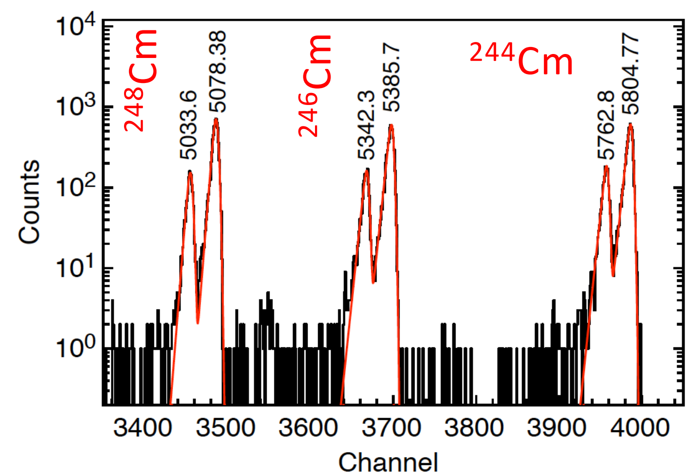
High-resolution α and electron spectroscopy of $^{249}_{98}$Cf

I. Ahmad, J. P. Greene, F. G. Kondev, and S. Zhu
Argonne National Laboratory, Argonne, Illinois 60439, USA

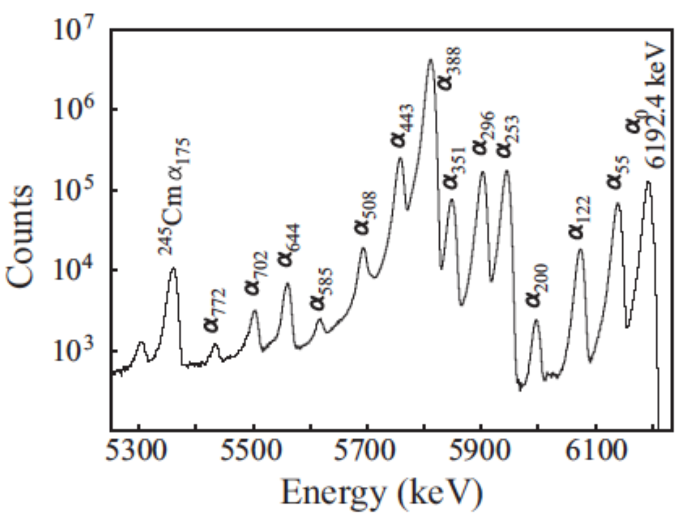


magnetic spectrograph





PIPS

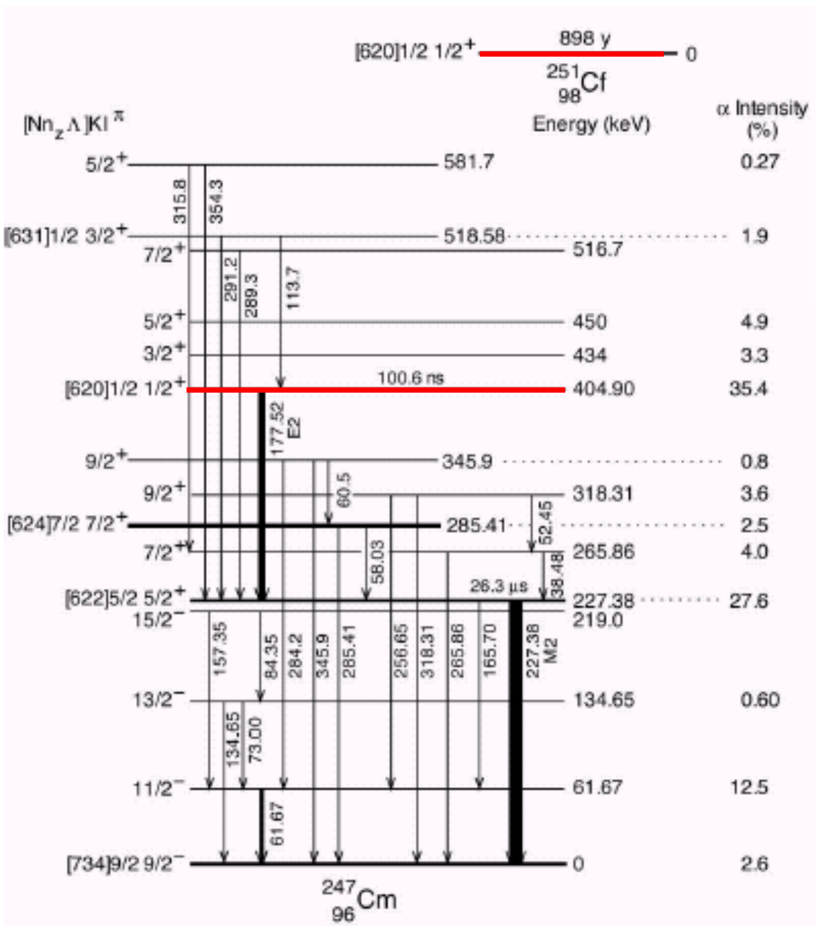


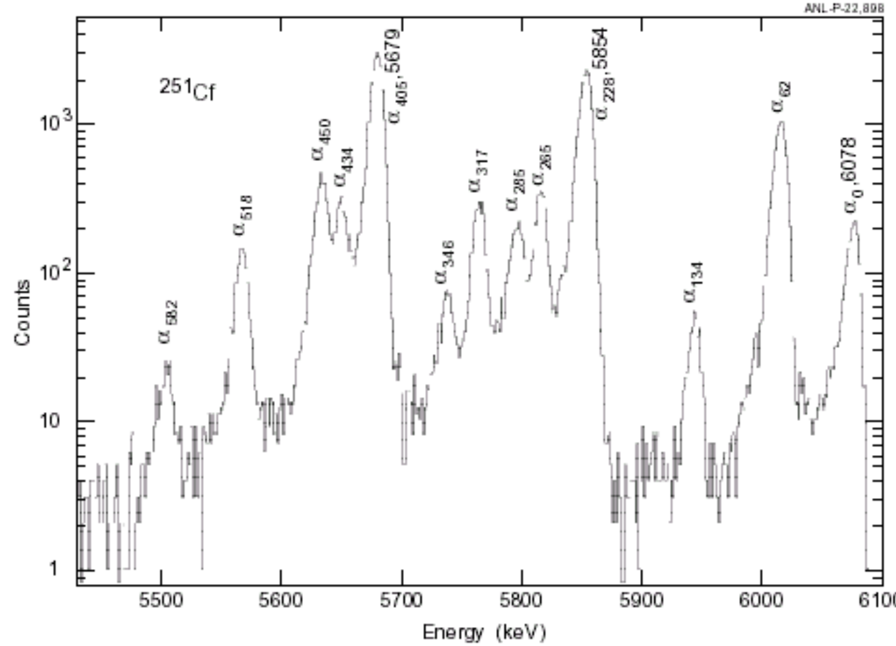
still **8.1 keV** difference!!!

^{251}Cf α–decay

PHYSICAL REVIEW C **68**, 044306 (2003)

Energy levels of ^{247}Cm populated in the α decay of $^{251}_{98}$C

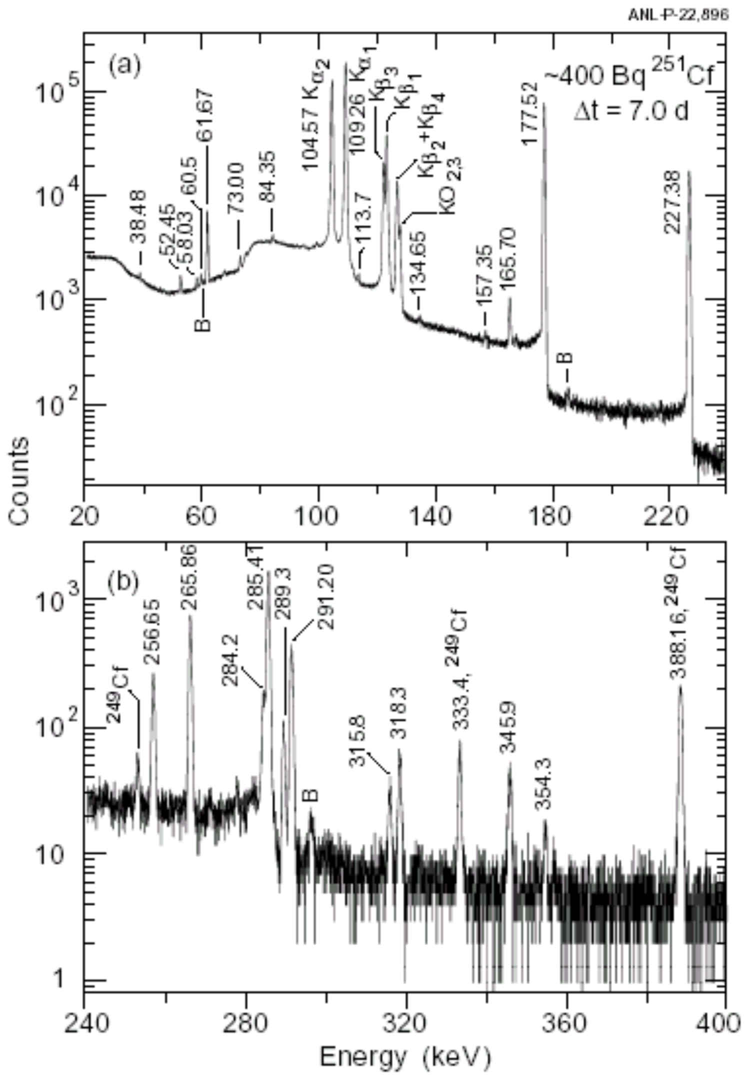




Energy (MeV)	Excited state energy (keV)	Intensity (%)	Hindrance factor[a]
6.078±0.002	0	2.6±0.1	5.1×10^3
6.017±0.002	62	12.5±0.3	5.1×10^2
5.946±0.002	134	0.60±0.06	4.5×10^3
5.854±0.002	228	27.6±0.5	31
5.817±0.002	265	4.0±0.2	1.3×10^2
5.798±0.002	285	2.5±0.2	1.7×10^2
5.766±0.002	317	3.6±0.2	78
5.738±0.002	346	0.8±0.1	2.4×10^2
5.679±0.002	405	35.4±0.5	2.55
5.651±0.002	434	3.3±0.2	19
5.635±0.002	450	4.9±0.2	10
5.568±0.002	518	1.9±0.1	11
5.505±0.002	582	0.27±0.05	32

I. Ahmad et al., Phys. Rev. **C68** (2003) 044306

^{251}Cf α–decay – cont.

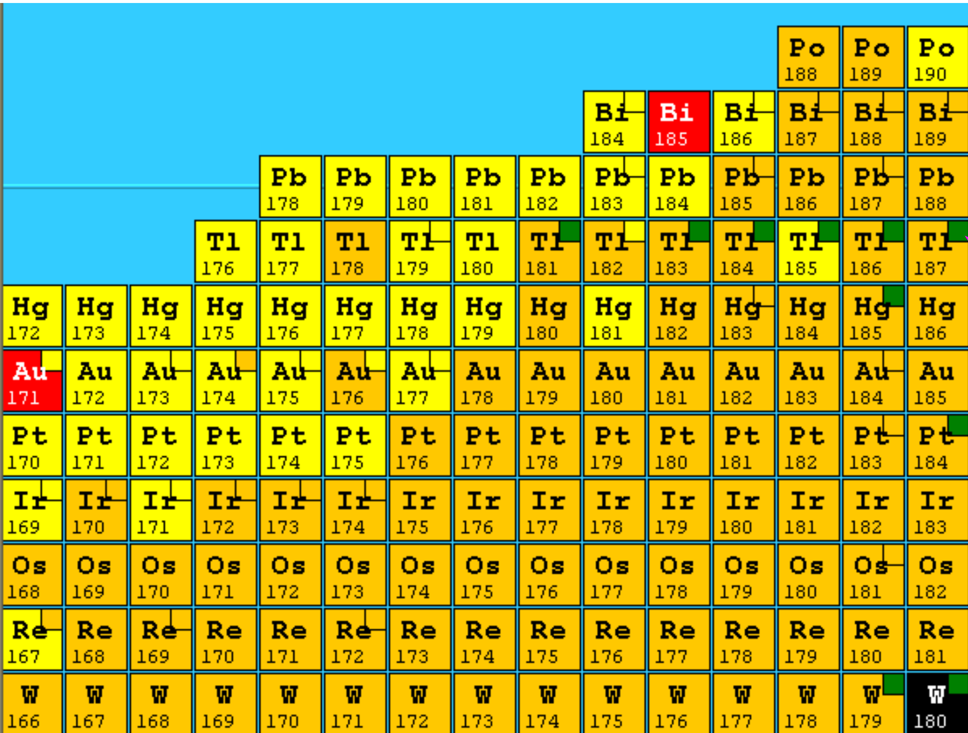


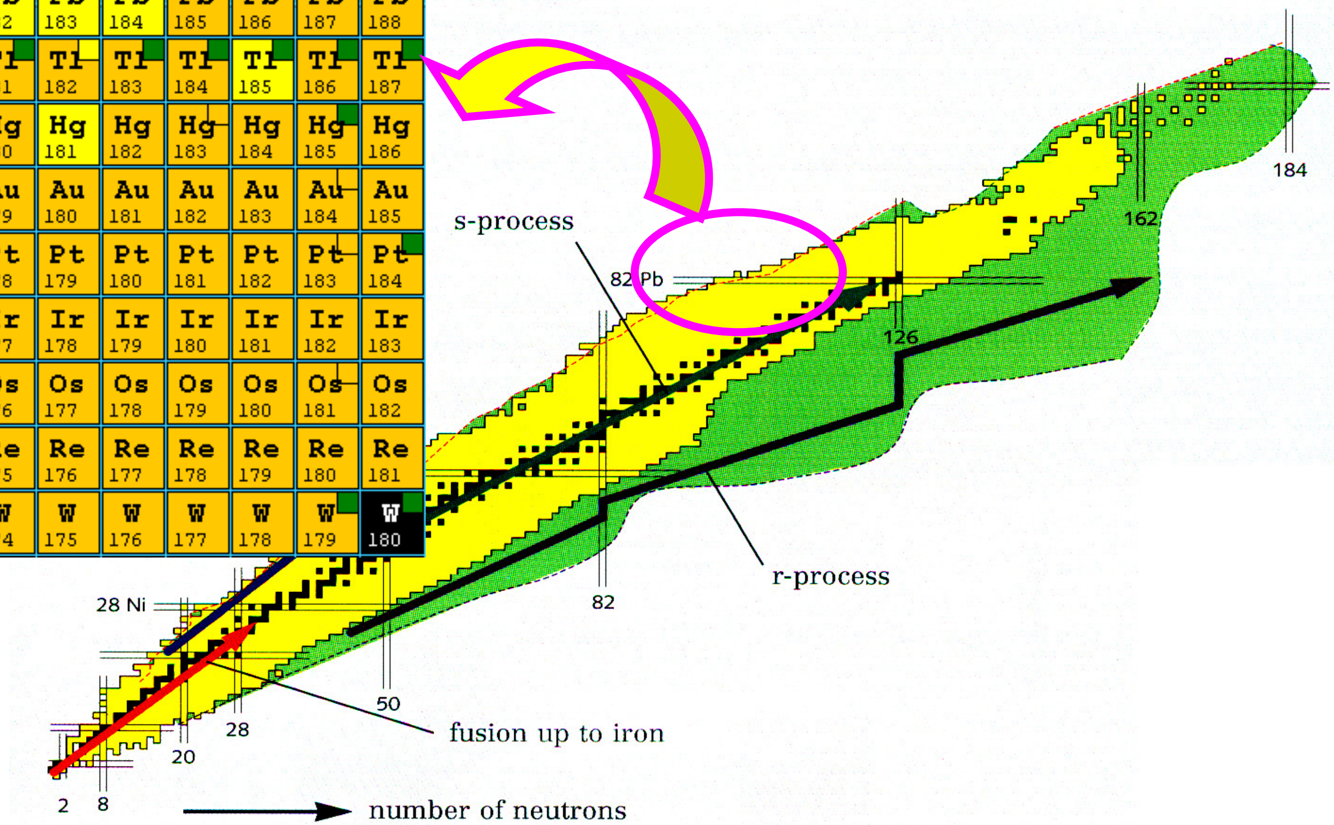
Energy (keV)	Intensity (%)	Transitions Initial→Final
38.48±0.05	0.038±0.006	265.86→227.38
52.45±0.05	0.048±0.005	318.31→265.86
58.03±0.05	0.024±0.005	285.41→227.38
60.5±0.1	0.010±0.003	345.9→285.41
61.67±0.05	0.40±0.03	61.67→0
73.00±0.08	0.040±0.005	134.65→61.67
84.35±0.08	0.040±0.005	219.0→134.65
104.57±0.02	12.6±0.7	Cm $K\alpha_2$
109.26±0.02	19.8±1.0	Cm $K\alpha_1$
113.7±0.1	0.024±0.005	518.58→404.90
122.31±0.02+		Cm $K\beta_3$
123.40±0.02	7.7±0.5	Cm $K\beta_1$
127.01±0.04+		Cm $K\beta_2+K\beta_4$
128.00±0.05	2.6±0.2	Cm $KO_{2,3}$
134.65±0.08	0.014±0.003	134.65→0
157.35±0.08	0.020±0.004	219.0→61.67
165.70±0.05	0.12±0.01	227.38→61.67
177.52±0.02	17.3±0.9	404.90→227.38
227.38±0.02	6.8±0.3	227.38→0
256.65±0.08	0.13±0.01	318.31→61.67
265.86±0.08	0.43±0.03	265.86→0
284.2±0.1	0.12±0.01	345.9→61.67
285.41±0.08	1.13±0.09	285.41→0
289.3±0.1	0.070±0.007	516.7→227.38
291.20±0.08	0.30±0.03	518.58→227.38
315.8±0.1	0.024±0.003	581.7→265.86
318.3±0.1	0.050±0.005	318.31→0
345.9±0.1	0.043±0.004	345.9→0
354.3±0.1	0.013±0.002	581.7→227.38

I. Ahmad et al., Phys. Rev. **C68** (2003) 044306

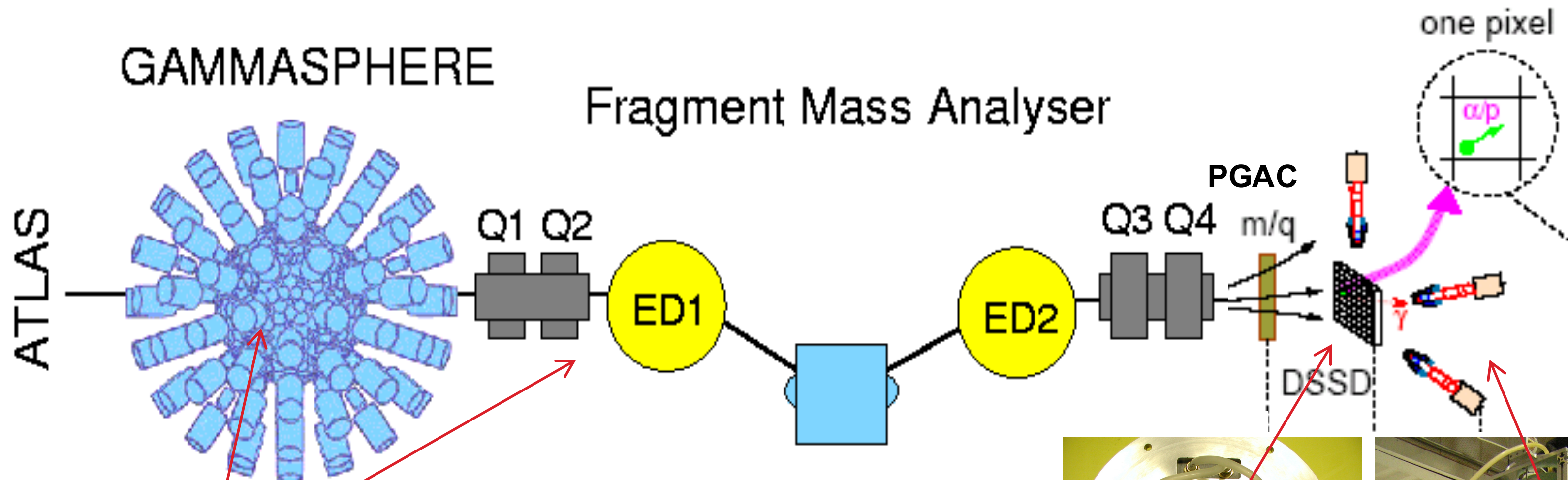
Spectroscopy near the proton drip line

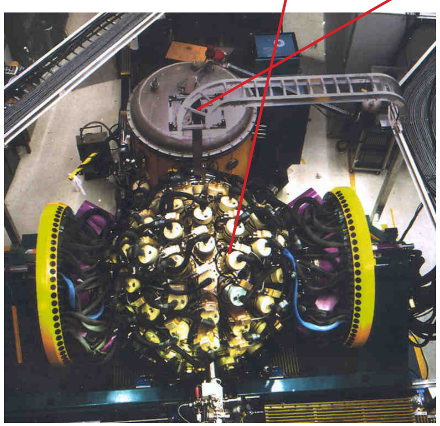
- ❑ many α–decaying isotopes, but often unique competition between α, β+ and even p!
- ❑ relatively short-lived ($T_{1/2}$<10s)!

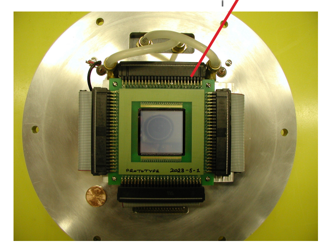




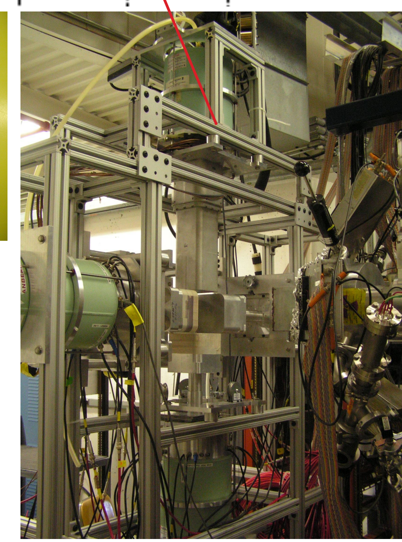
Decay Tagging







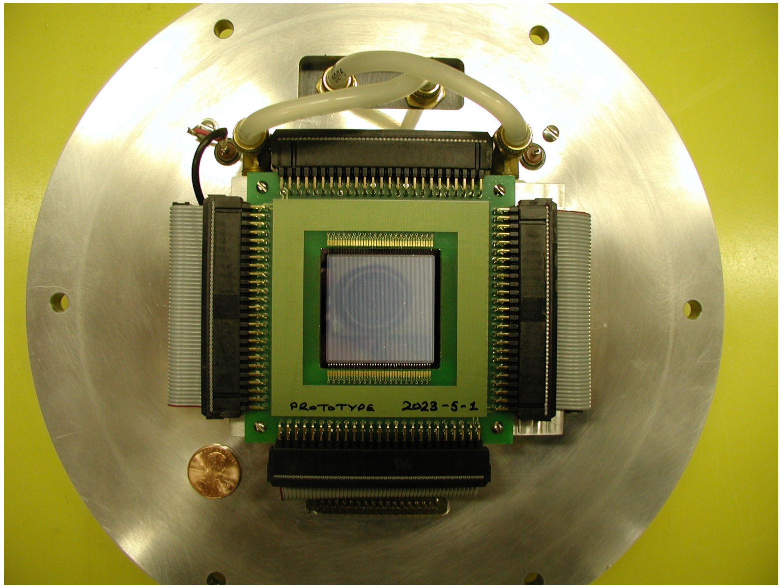
- ✓ ^{90}Zr + ^{90,92}Zr@^{180}Hg
- ✓ ^{90}Zr + ^{82}Mo@^{182}Pb
- ✓ ^{89}Y + ^{90}Zr@^{179}Au
- ✓ ^{84}Sr + ${}^{92\text{-}96}$Mo@${}^{176\text{-}180}$Hg
- ✓ **^{89}Y + ^{92}Mo@^{181}Tl@375 MeV**



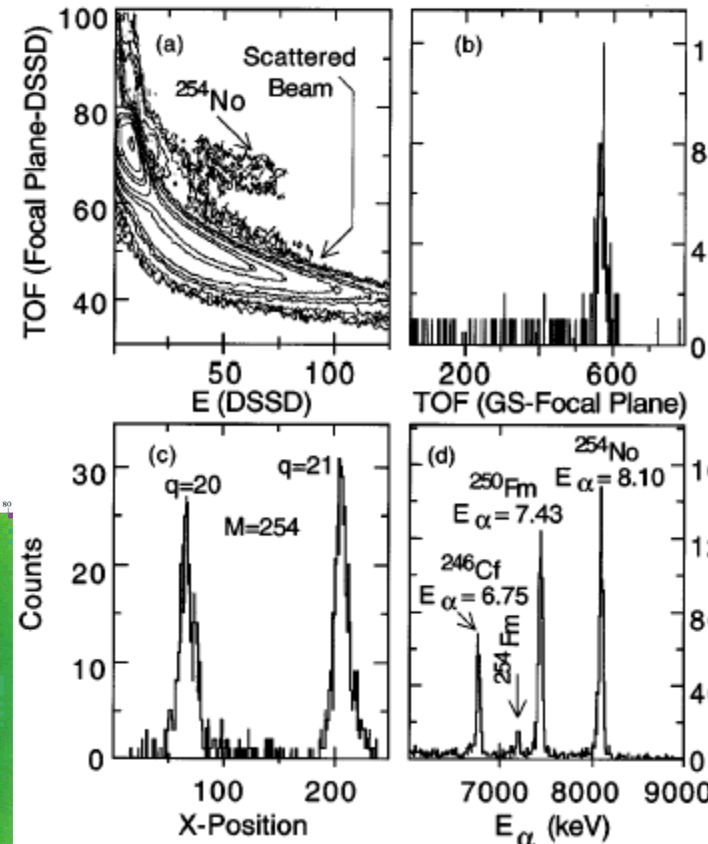
X-array

one “Super-Clover” &
four 70 X 70 mm Clovers

The Heart of RDT: the DSSD

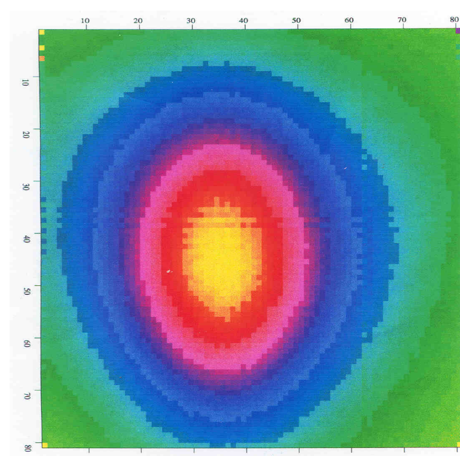


$^{208}Pb(^{48}Ca,2n)^{254}No$



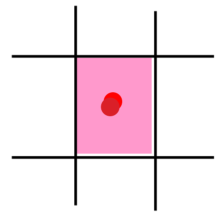
80 x 80 detector 300 μm strips,
Each with high, low, and delay line amplifiers, for implant, decay, and fast-decay recognition.

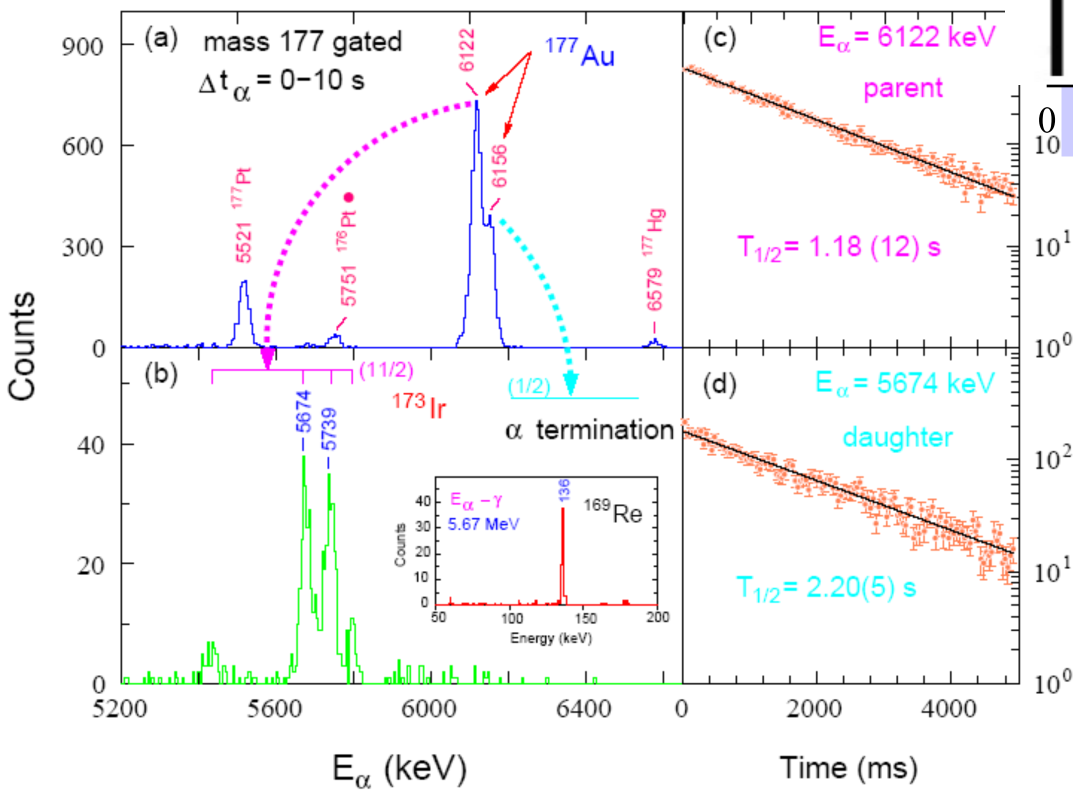
Data from DSSD showing implant pattern 40 cm beyond the focal plane

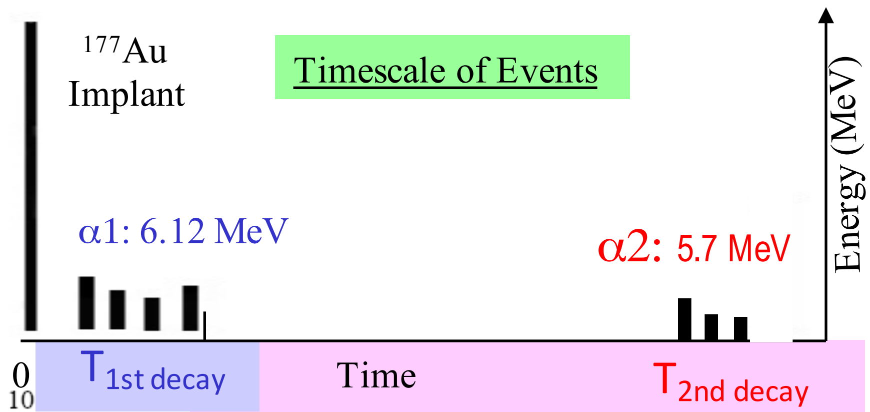


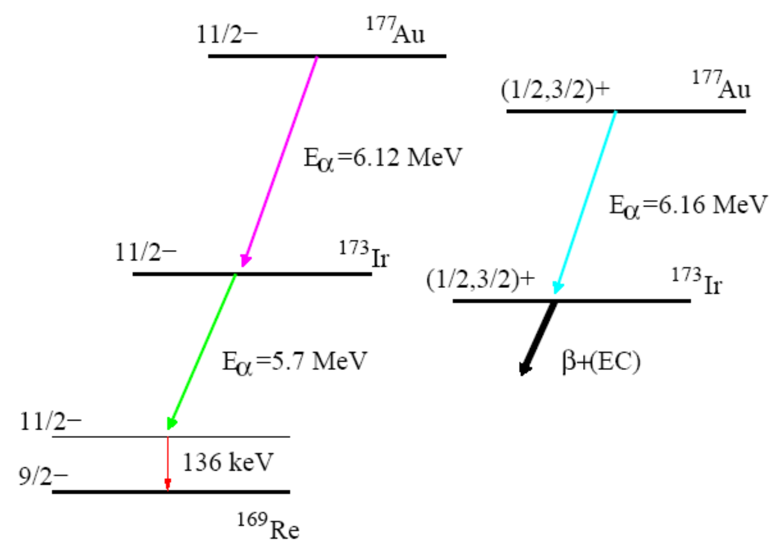
α1–α2 (parent-daughter) correlations

Implantation->Decay 1->Decay 2 within a single pixel



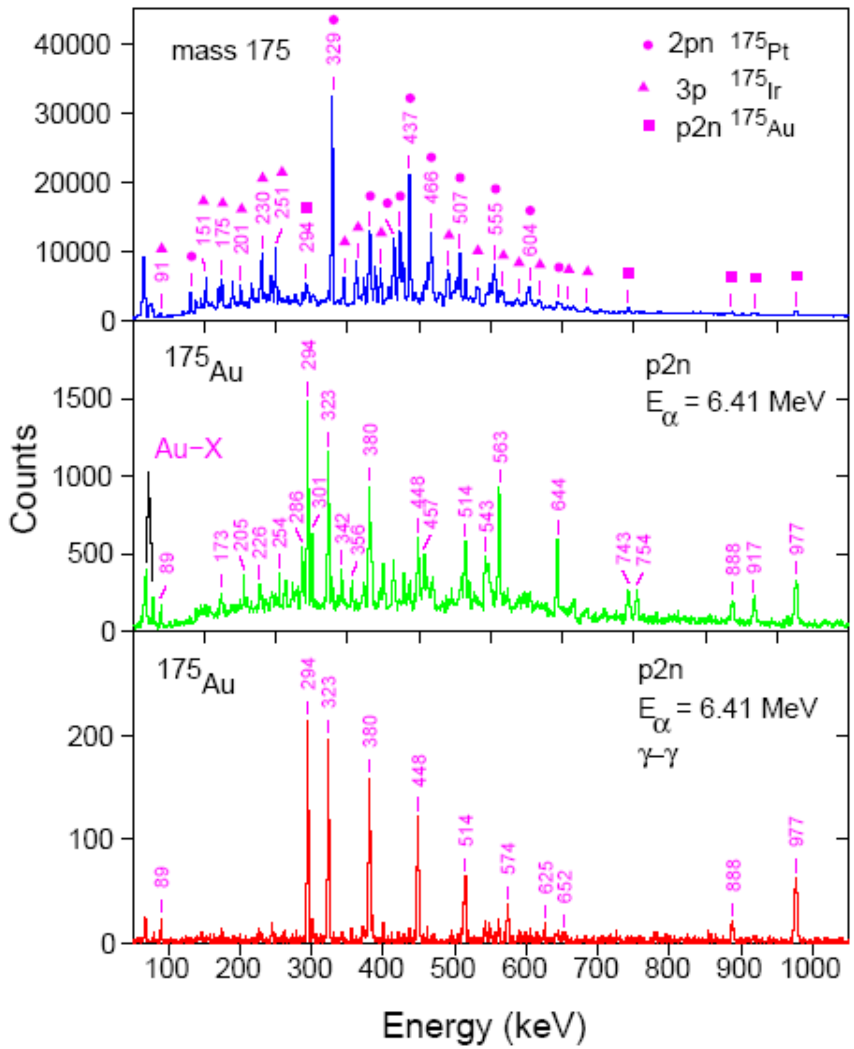






F.G. Kondev et al. Phys. Lett. B528 (2002) 221

Odd-Z Au (Z=79) isotopes–sample spectra



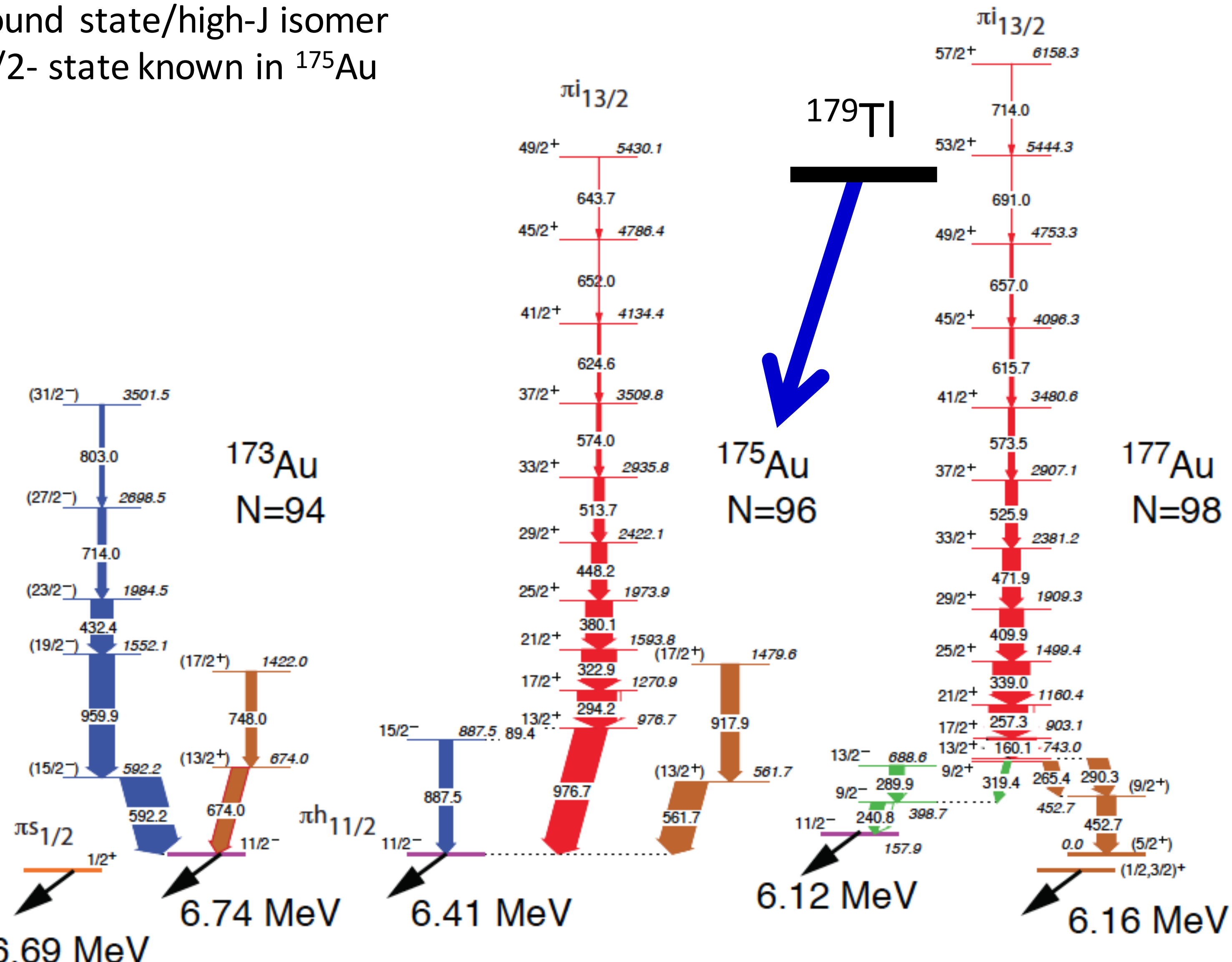
mass gated

channel gated

structure gated

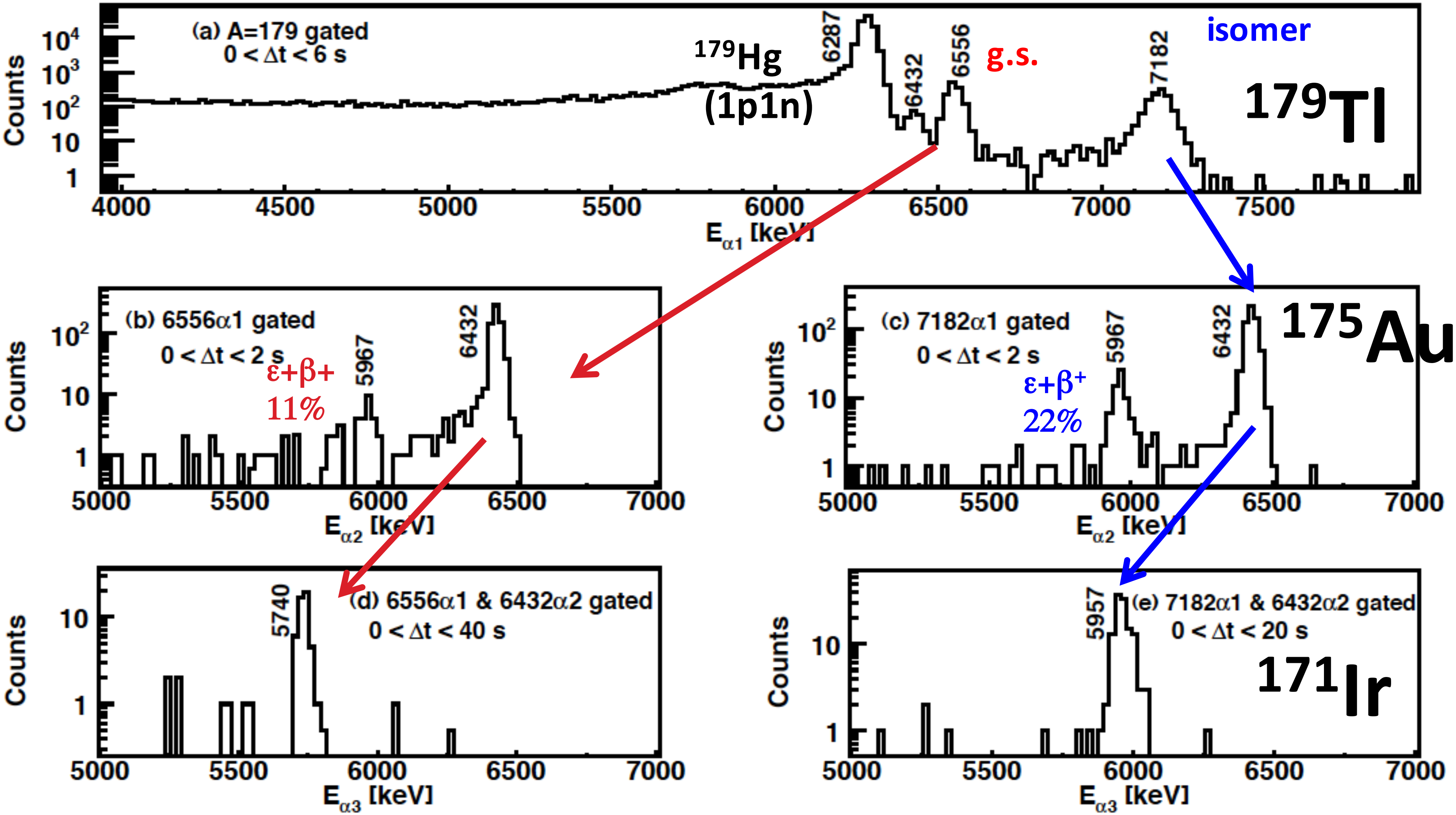
Neutron-deficient Au nuclei (Z=79)

- low-J ground state/high-J isomer
- only 11/2- state known in ^{175}Au



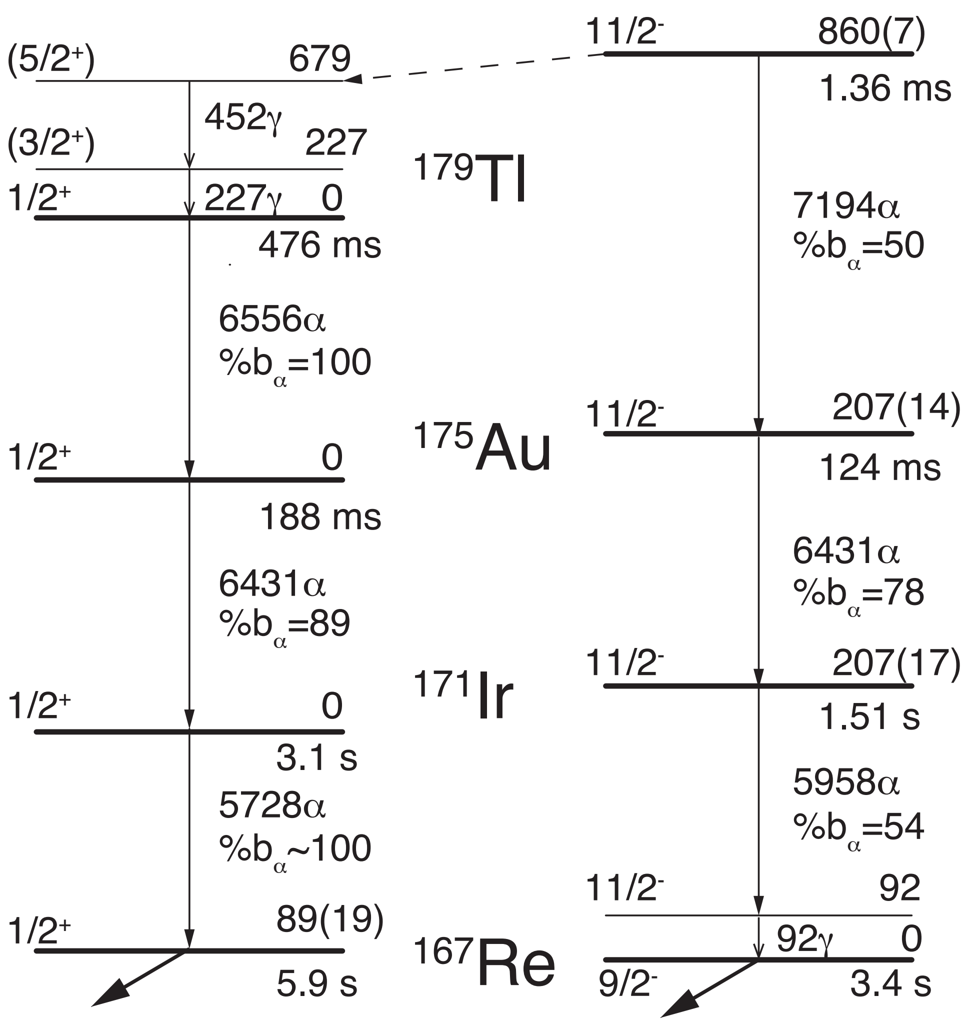
F.G. Kondev et al., PLB 512 (2001)

^{179}Tl: α–decay properties



$$HF_i = \frac{T_{1/2}^{Exp}(\alpha_i)}{T_{1/2}^{Theory}} = \frac{T_{1/2}^{Exp} / BR_i}{T_{1/2}^{Theory}}$$

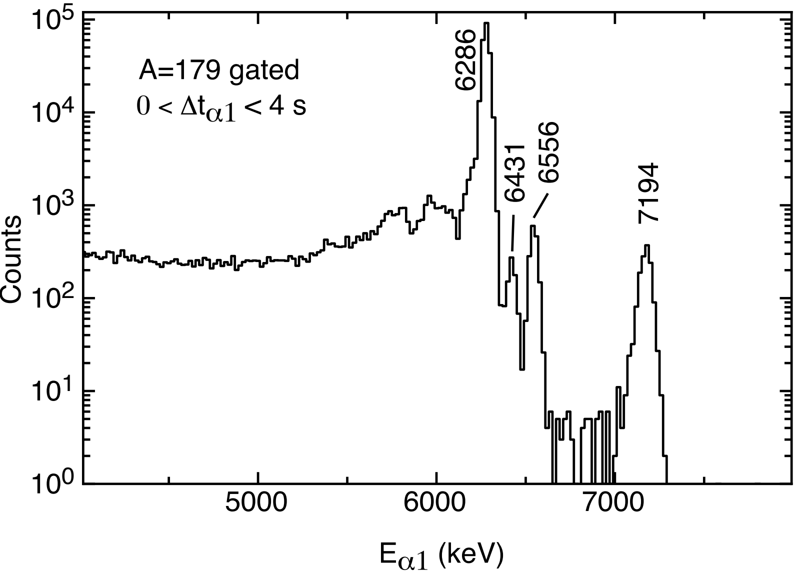
$T_{1/2}^{Theory}$ M.A. Preston, Phys. Rev. **71** (1947) 865



HF < 4 favorite (ΔL=0)decay

1/2+	11/2-
1.12 (6)	$\boxed{0.50\ (3)}$
2.16 (17)	1.63 (19)
$\boxed{0.36\ (6)\ \%b_{\alpha}\text{\textasciitilde}15\%}$	2.2 (4)

^{179}Tl: lifetimes



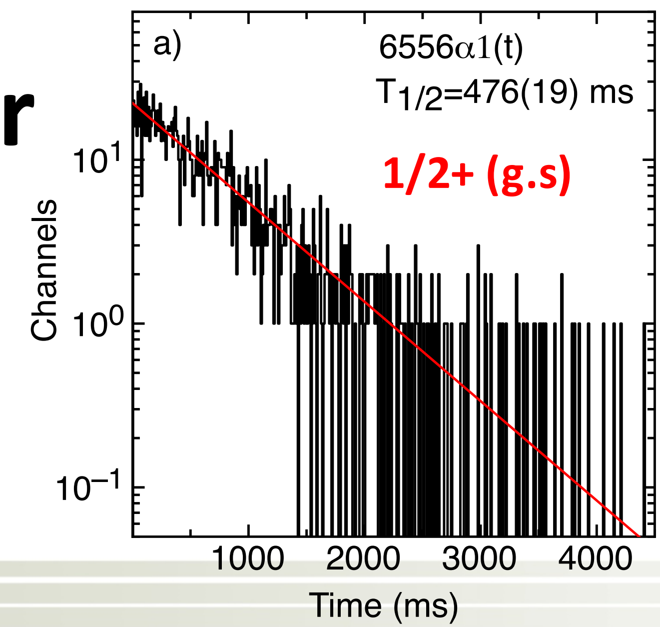
^{179}Tl – g.s.

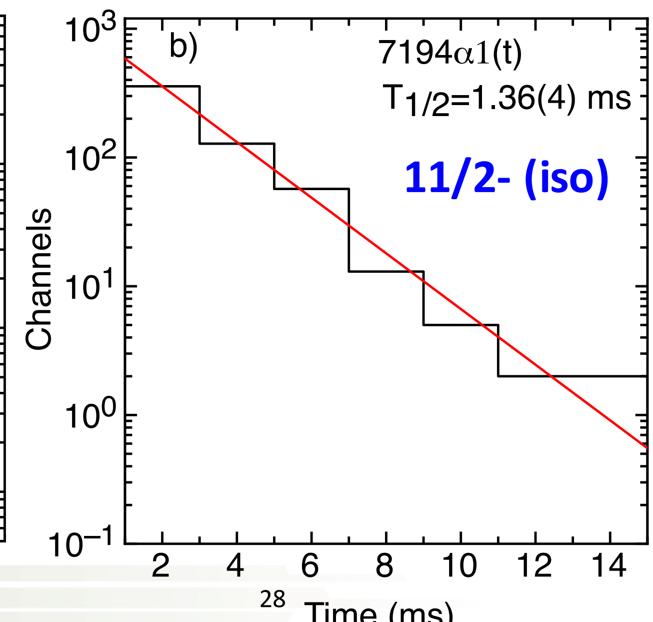
476 (19) ms
present

415 (55) ms – LBNL
230 (40) ms – ANL (1998)
160 (+90-40) ms – GSI (1993)

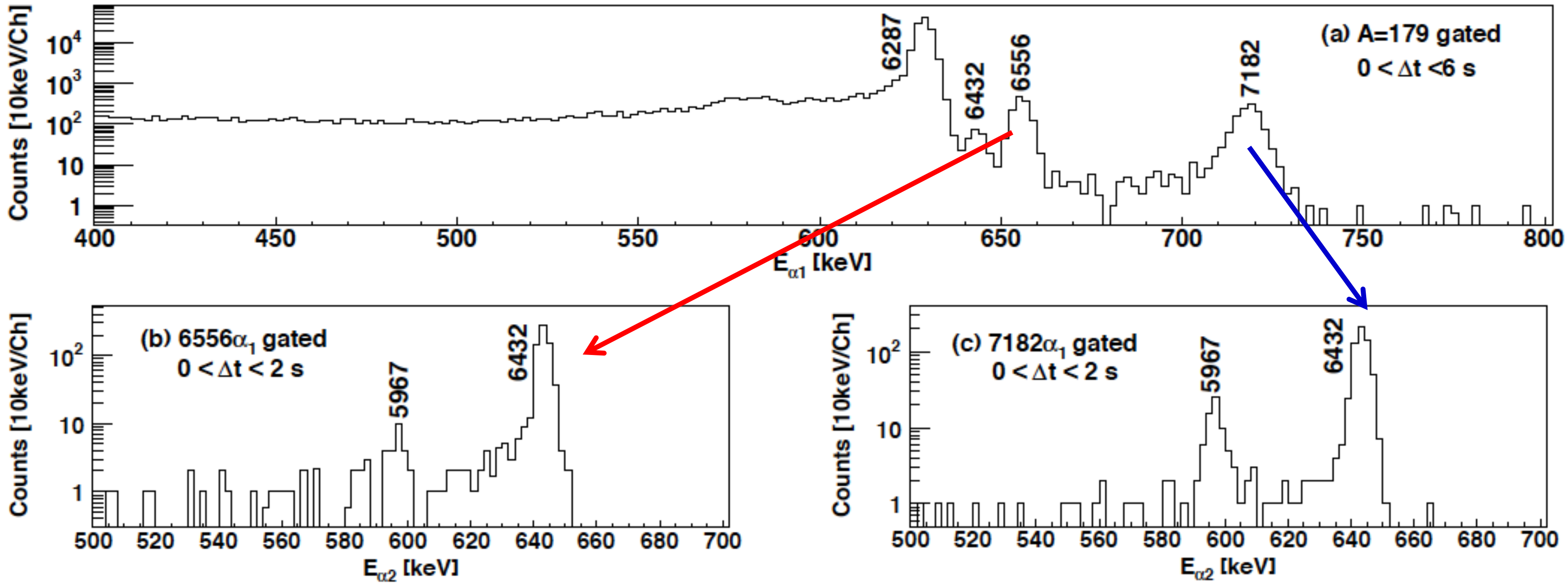
^{179}Tl – isomer

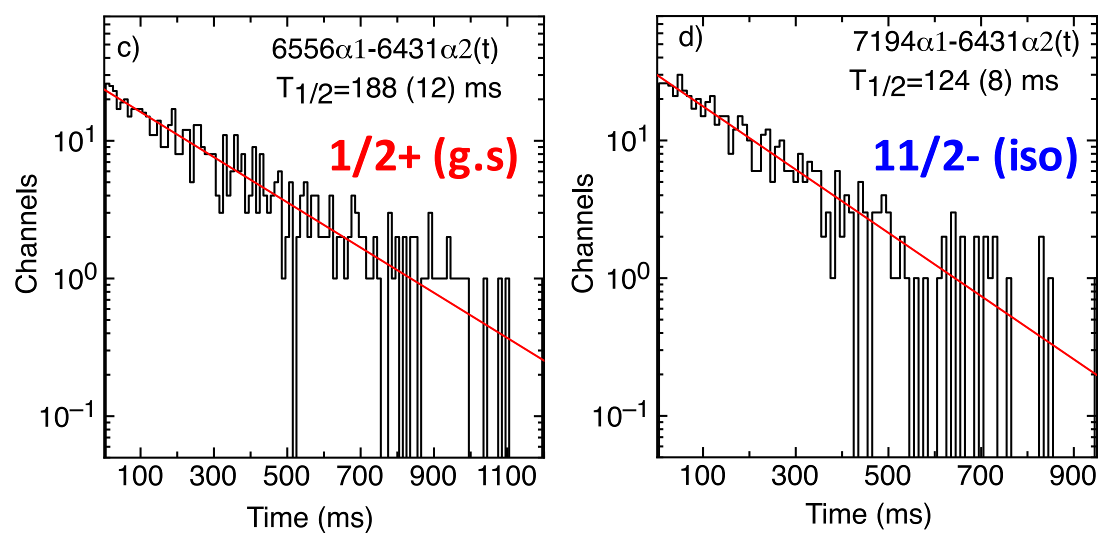
good agreement with previous measurements





^{175}Au: lifetimes





similar, but not identical!

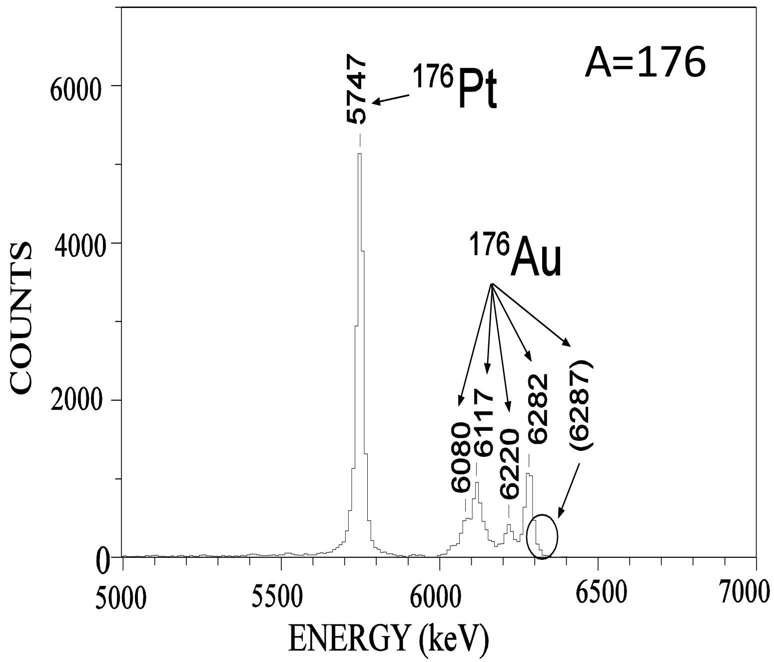
188 (12) ms – 124 (8) ms

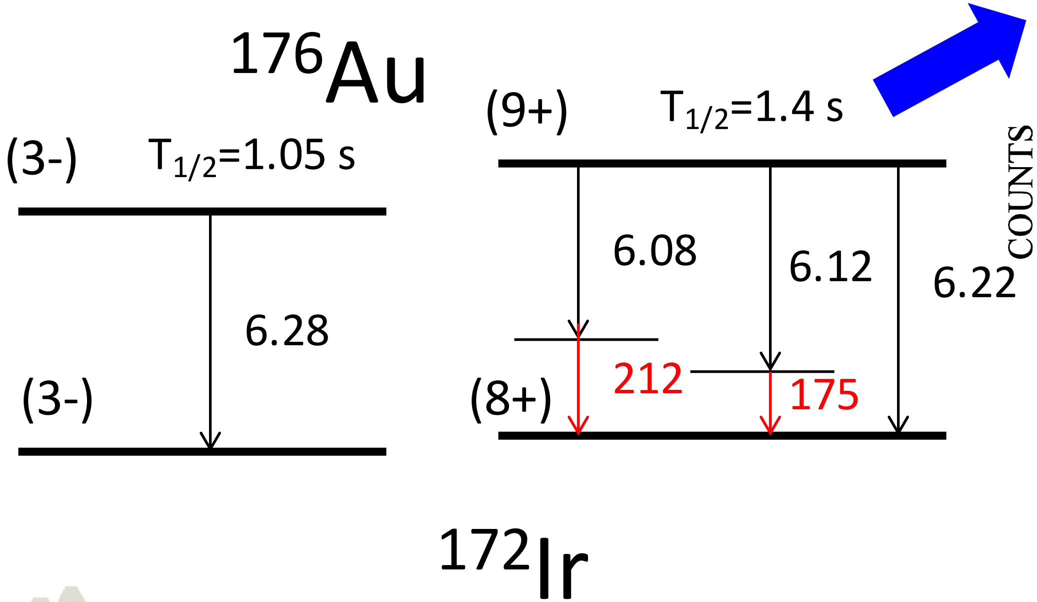
158 (3) ms using 6432α(t)

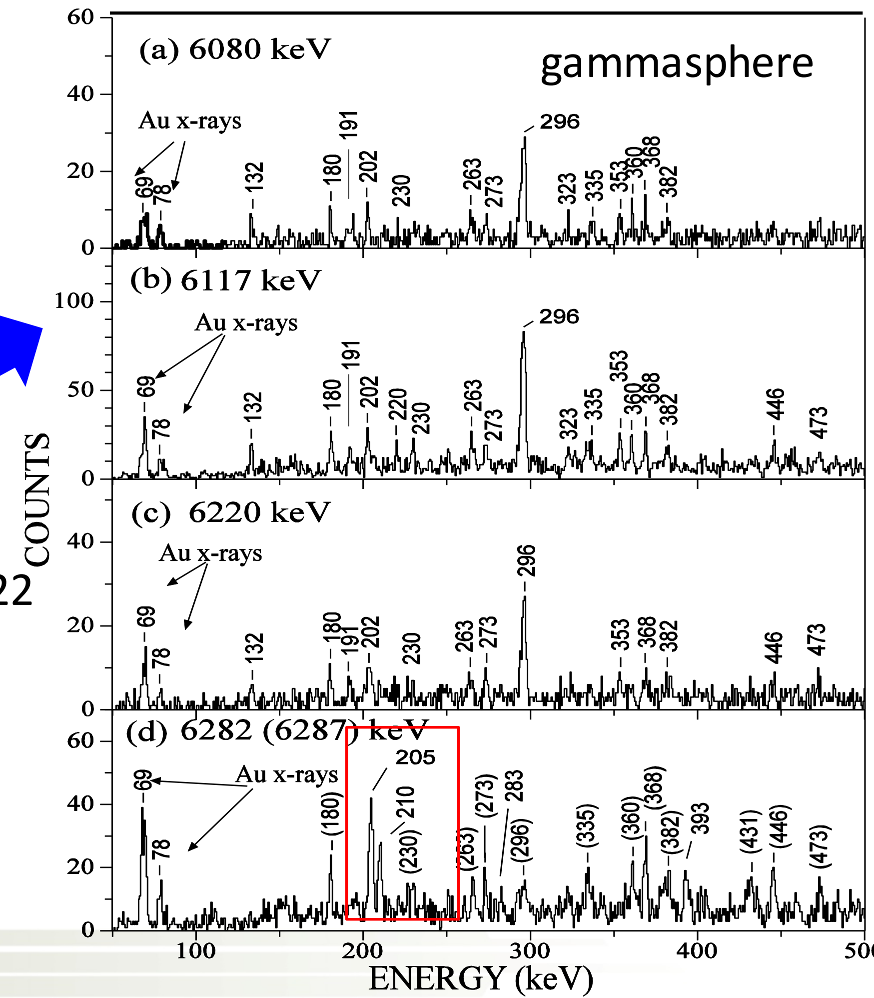
F.G. Kondev et al., PLB 512 (2001)

$^{84}Sr + ^{94}Mo@^{178}Hg\ (pn)^{176}Au$
Gammasphere & FMA

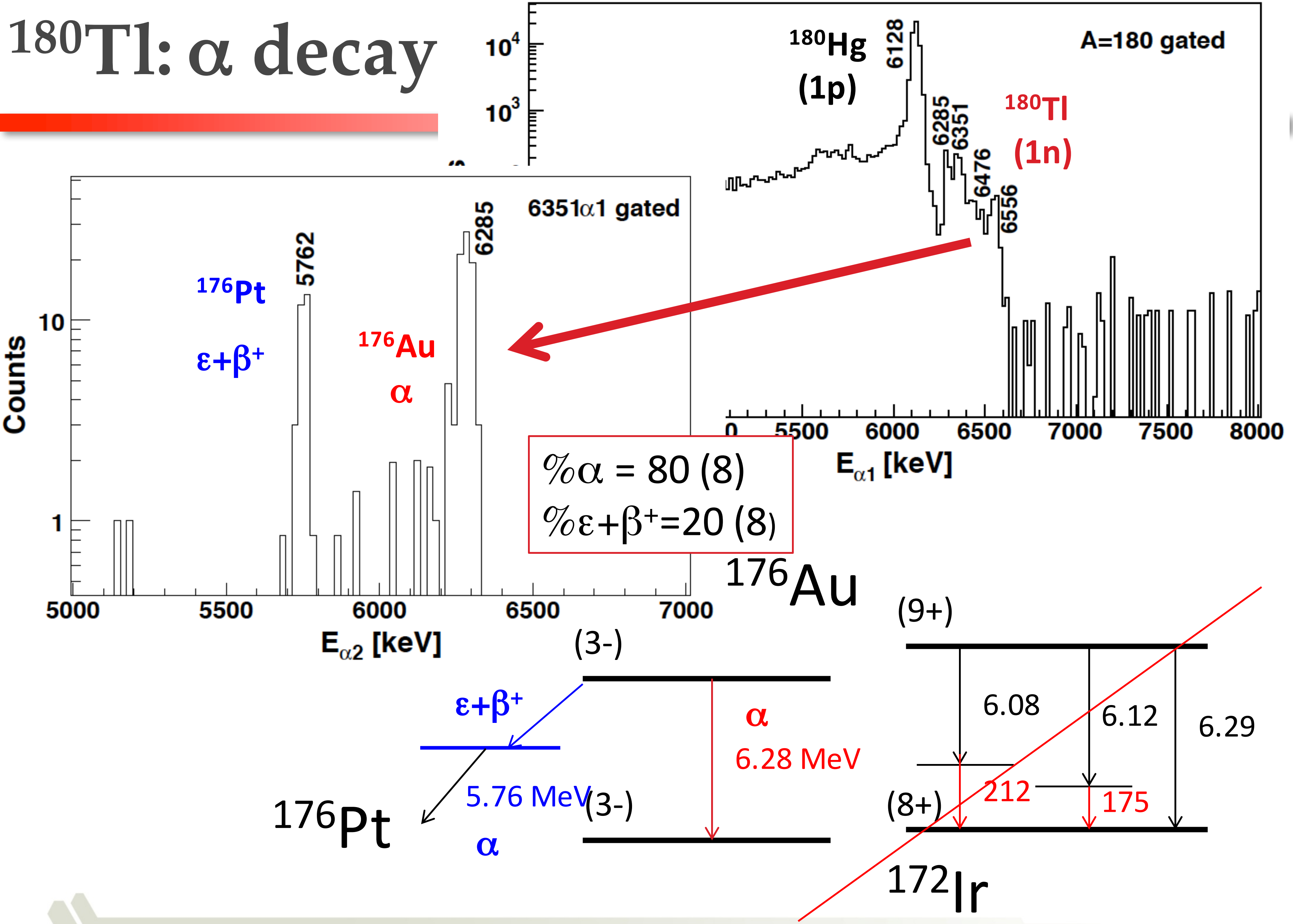
J.T.M. Goon, PhD thesis, UT







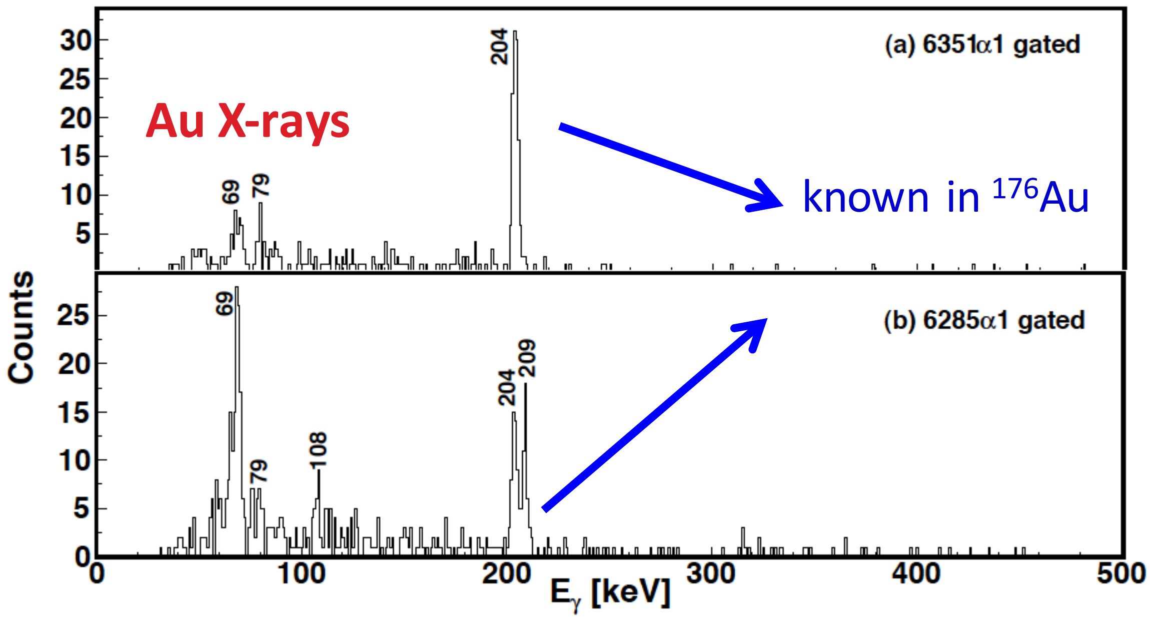
^{180}Tl: α decay

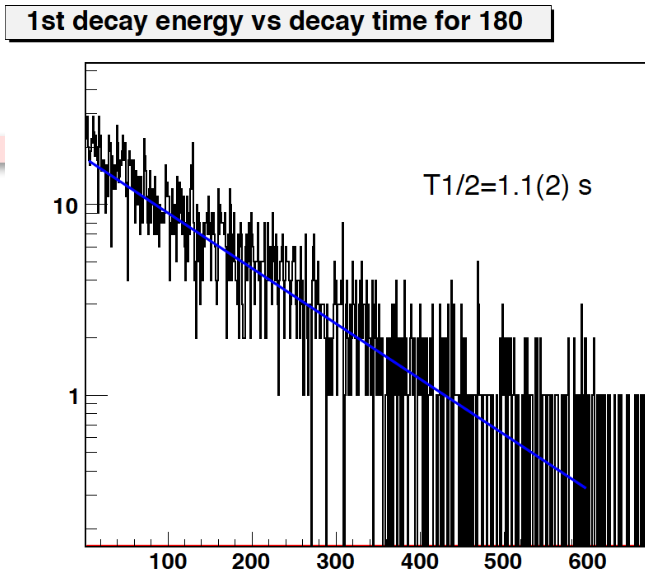


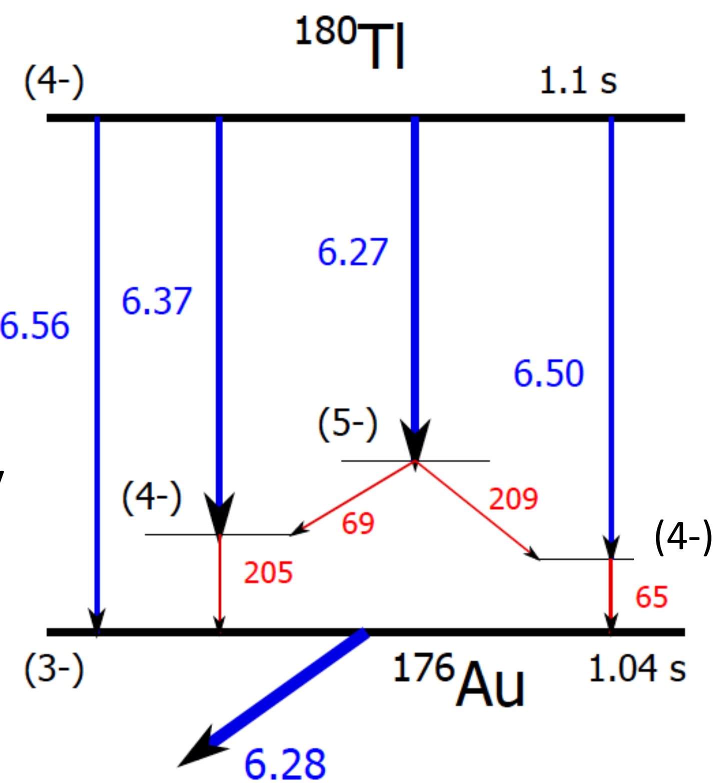
$\%\alpha = 80\ (8)$

$\%\varepsilon+\beta^{+} = 20\ (8)$

^{180}Tl: α–γ coincidences







✓ decay of a single state in ^{180}Tl

^{180}Tl:

I$^{\pi}$=**4-** and **5-**: $\pi 1/2^{+}$ ($s_{1/2}$) x $\nu 9/2^{-}$ ($h_{9/2}$) - favored α-decay

^{176}Au:

I$^{\pi}$=3- and 4-: $\pi 1/2^{+}$ ($s_{1/2}$) x $\nu 7/2^{-}$ ($f_{f/2}$)

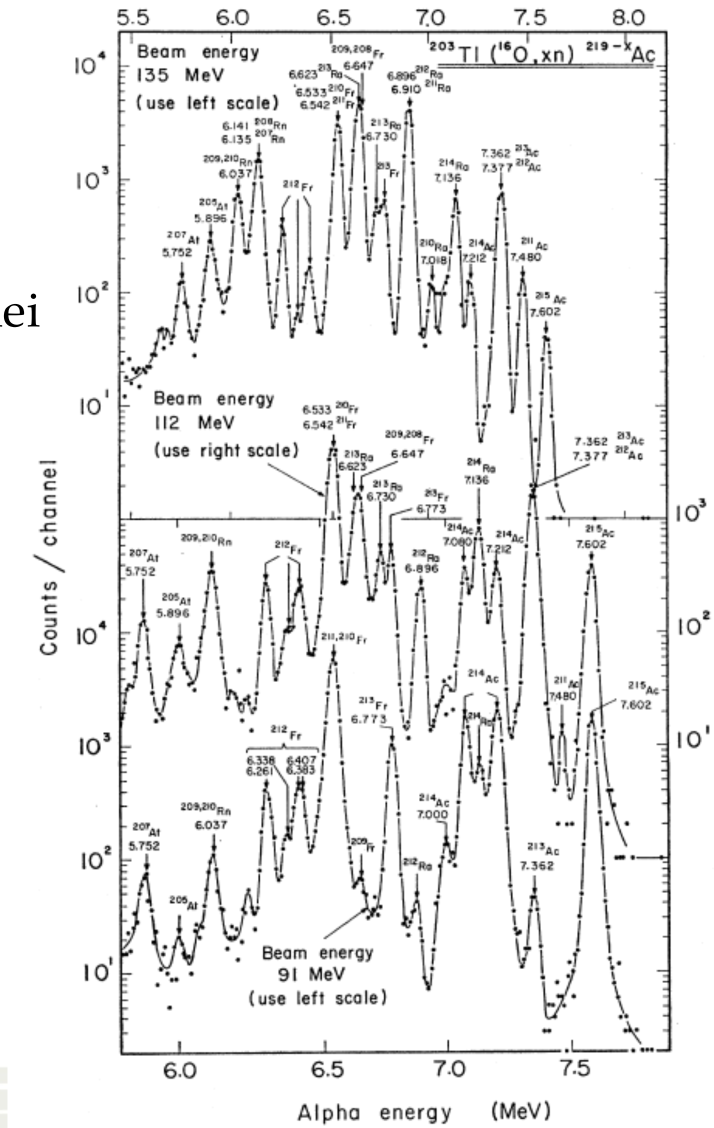
PHYSICAL REVIEW VOLUME 167, NUMBER 4 20 MARCH 1968

On-Line Alpha Spectroscopy of Neutron-Deficient Actinium Isotopes*

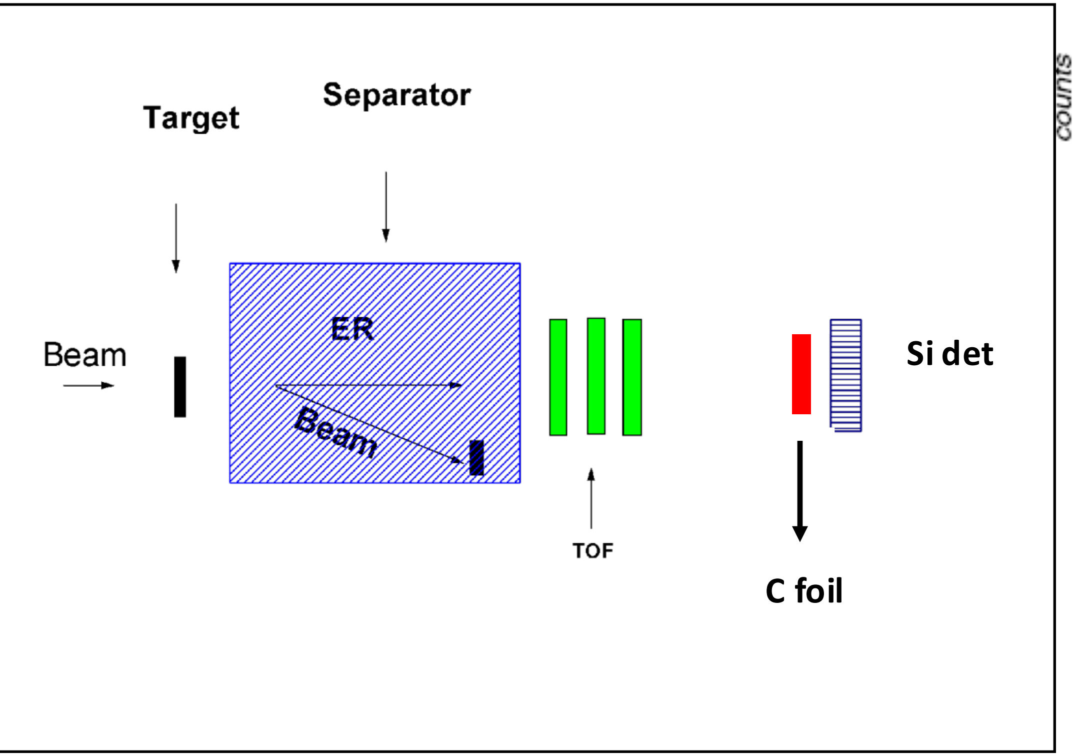
KALEVI VALLI, WILLIAM J. TREYTL,† AND EARL K. HYDE
Lawrence Radiation Laboratory, University of California, Berkeley, California

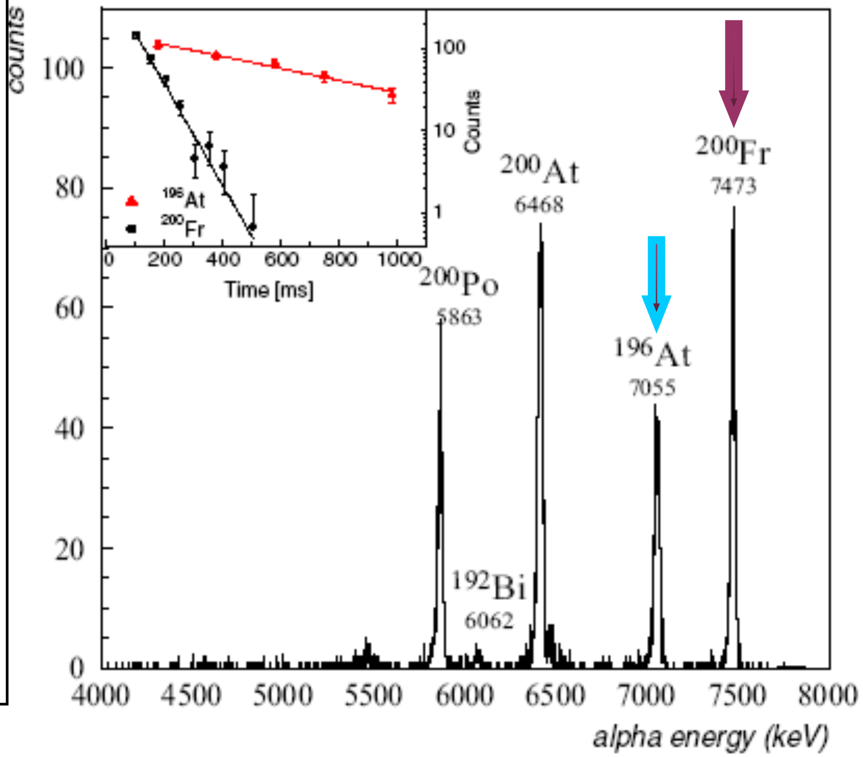
- ✓ using HI fusion reactions to produce various nuclei
- ✓ collect recoils on a catcher foil
- ✓ Si(Au) surface-barrier detector or PIPS

✓ using excitation function measurements for isotopic identification



No direct detector implantation





1 GeV pulsed proton beam on 51 g/cm2 ThCx target

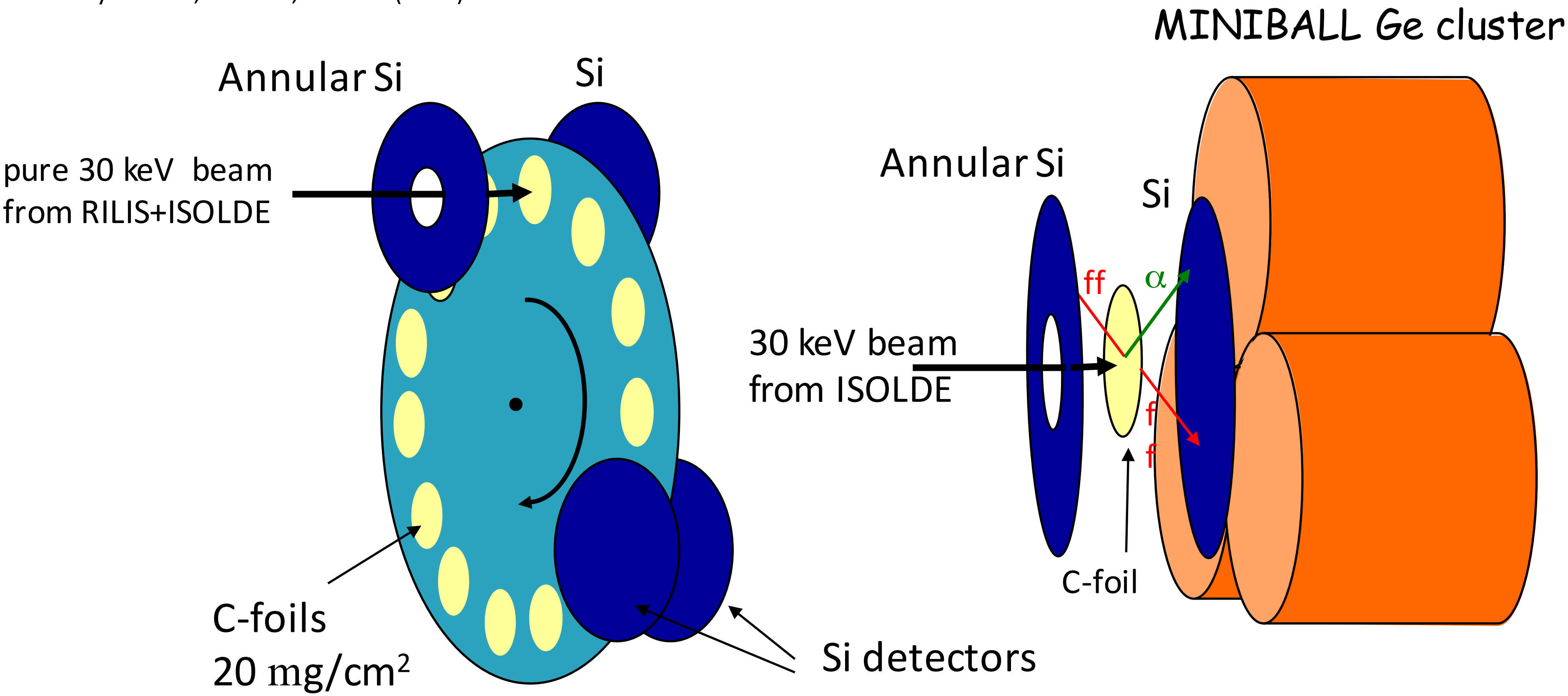
on-line mass separation (ISOLDE)/CERN

Isotope	Energy (keV)	$T_{1/2}$	Reference
^{200}Fr	7473(12)	49(4) ms	this work
	7500(30)	570^{+270}_{-140} ms	[4]
	7468(9)	19^{+13}_{-6} ms	[5]

H. De Witte et al., EPJ A23 (2005) 243

Windmill System (WM) at ISOLDE

A. Andreyev et al., PRL 105, 252502 (2010)



Setup: Si detectors from both sides of the C-foil

- Simple setup & DAQ: 4 PIPS (1 of them – annular)
- Large geometrical efficiency (up to 80%)
- 2 fold fission fragment coincidences
- ff-gamma coincidences
- Digital electronics

Beta decay : Introduction

<u>Beta Decay:</u> **universal term for all weak-interaction transitions between two neighboring isobars**

Takes place is 3 different forms

$\beta-$, $\beta+$ & EC (capture of an atomic electron)

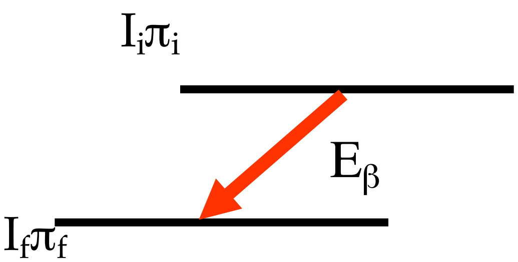
$\beta+$: $p \rightarrow n + e^+ + \nu$

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

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

a nucleon inside the nucleus is transformed into another

Classification of β decay transition



$$I_i = I_f + L_\beta + S_\beta$$

$$\pi_i \pi_f = (-1)^{L_\beta}$$

$$L_\beta = l_{\beta-(\beta+)} + l_{\tilde{\nu}(\nu)}$$

$$S_\beta = s_{\beta-(\beta+)} + s_{\tilde{\nu}(\nu)} = \begin{cases} 0 & \uparrow\downarrow \\ 1 & \downarrow\downarrow \textit{ or } \uparrow\uparrow \end{cases}$$

$L_\beta = n$ defines the degree of forbiddenness (n)

allowed

when $L_\beta = n = 0$ and $\pi_i\pi_f = +1$

$$\Delta I = \left| I_i - I_f \right| \equiv 0,1$$

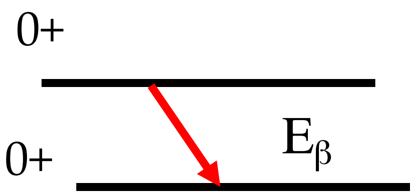
forbidden

when the angular momentum conservation requires that $L_\beta = n > 0$ and/or $\pi_i\pi_f = -1$

Classification of the allowed decay

$$(\pi_i \pi_f = +1)$$

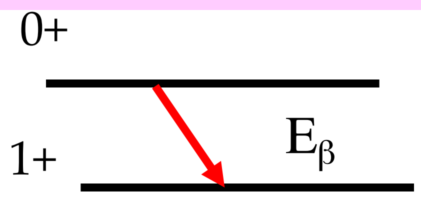
Fermi



$$\Delta I = |I_i - I_f| \equiv 0$$

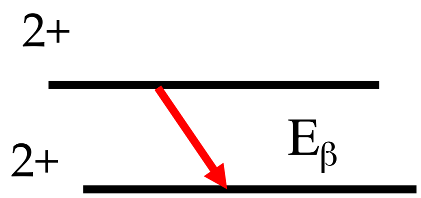
$$L_\beta = 0 \qquad S_\beta = 0 \downarrow\uparrow$$

Gamow-Teller



$$\Delta I = |I_i - I_f| \equiv 1$$

$$L_\beta = 0 \quad S_\beta = 1 \uparrow\uparrow or \downarrow\downarrow$$



mixed Fermi & Gamow-Teller

$$\Delta I = |I_i - I_f| \equiv 0 \qquad I_i \neq 0$$

Classification of β decay transitions

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
	.	.	.

What we want to know accurately?

Key observable

β– feeding intensity

Nuclear Structure

$$S_\beta(E) = \frac{I_\beta(E)}{f_n(Q_\beta - E, Z)T_{1/2}} = \frac{1}{f_n t}$$

$$S_\beta(E) \propto \left|M_{fi}\right|^2$$

statistical rate function (phase-space factor)

level half-life

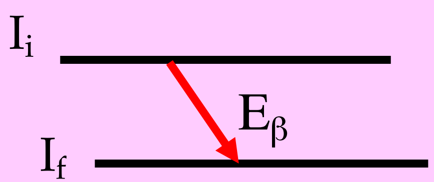
$$f_n = \int_1^W p_e W_e (W_0 - W_e)^2 F(Z, W_e)(C_n / \eta^2)\, dW_e$$

$$HF_\beta^n = \frac{T_{1/2}^{\beta_i}}{T_{1/2}^n} = \left(\frac{g^2 \eta^2}{2\pi^3 \ln 2}\right) f_n t$$

Some useful empirical rules

The fifth power beta decay rule of tumb:

the speed of a β transition increases approximately in proportion to the fifth power of the total transition energy (if other things are being equal, of course)



$$\frac{1}{\tau} \propto \left[\left(M(Z) - M(Z \pm 1)\right)c^2\right]^5$$

- **depends on spin and parity changes between the initial and final state**
- **additional hindrance due to nuclear structure effects – isospin, "l-forbidden", "K-forbidden", etc.**

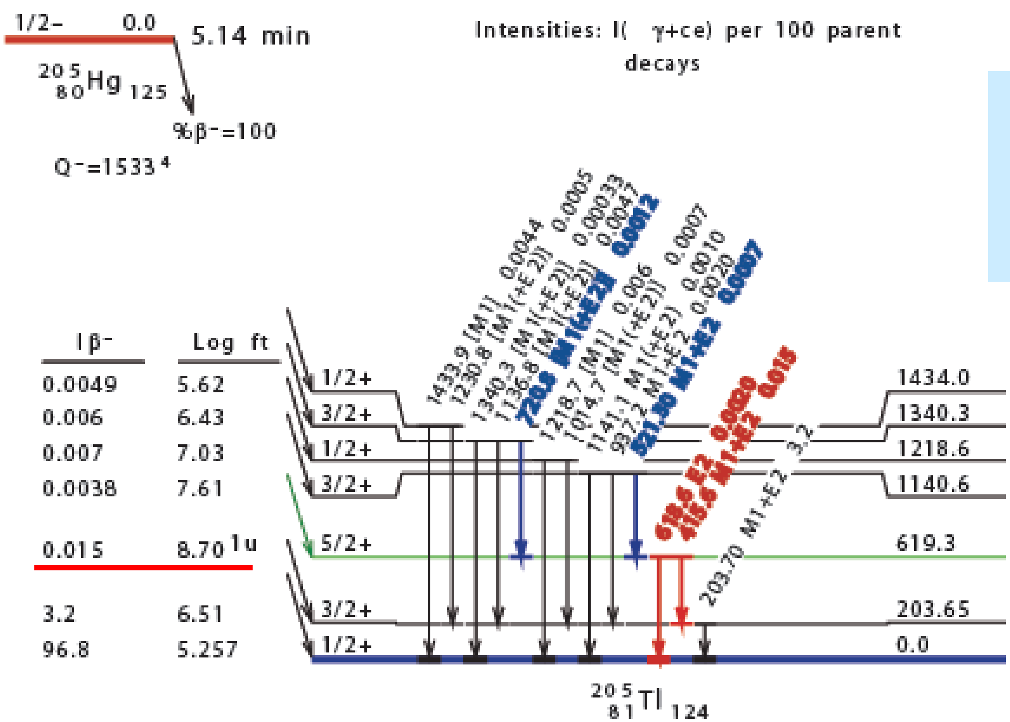
Log *ft* values

$$t \equiv T_{1/2}^{\beta_i} = \frac{T_{1/2}^{\exp}}{P_{\beta_i}}$$

$$P_{\beta_i} = \eta[I^{tot}(out) - I^{tot}(in)]$$

$$I^{tot}(out/in) = \sum_i I_{\gamma_i}(1+\alpha_{Ti})$$

$$\alpha_T(M1+E2) = \frac{\alpha_T(M1) + \delta^2 \alpha_T(E2)}{1+\delta^2}$$



- What we want to know accurately
  - ✓ $T_{1/2}$, I_γ, α_T & δ

In

$$\frac{I^{tot}(521+721) = 0.086(16)}{I^{tot}(416+619) = 0.78(10)} = 0.69(10)$$

(net)

Out

$$\eta = 0.0022 \rightarrow t = 2.056\times10^6[s] \rightarrow \log t = 6.31 \rightarrow \log f = 2.386 \rightarrow \log ft = 8.7$$

Rules for Spin/Parity Assignments

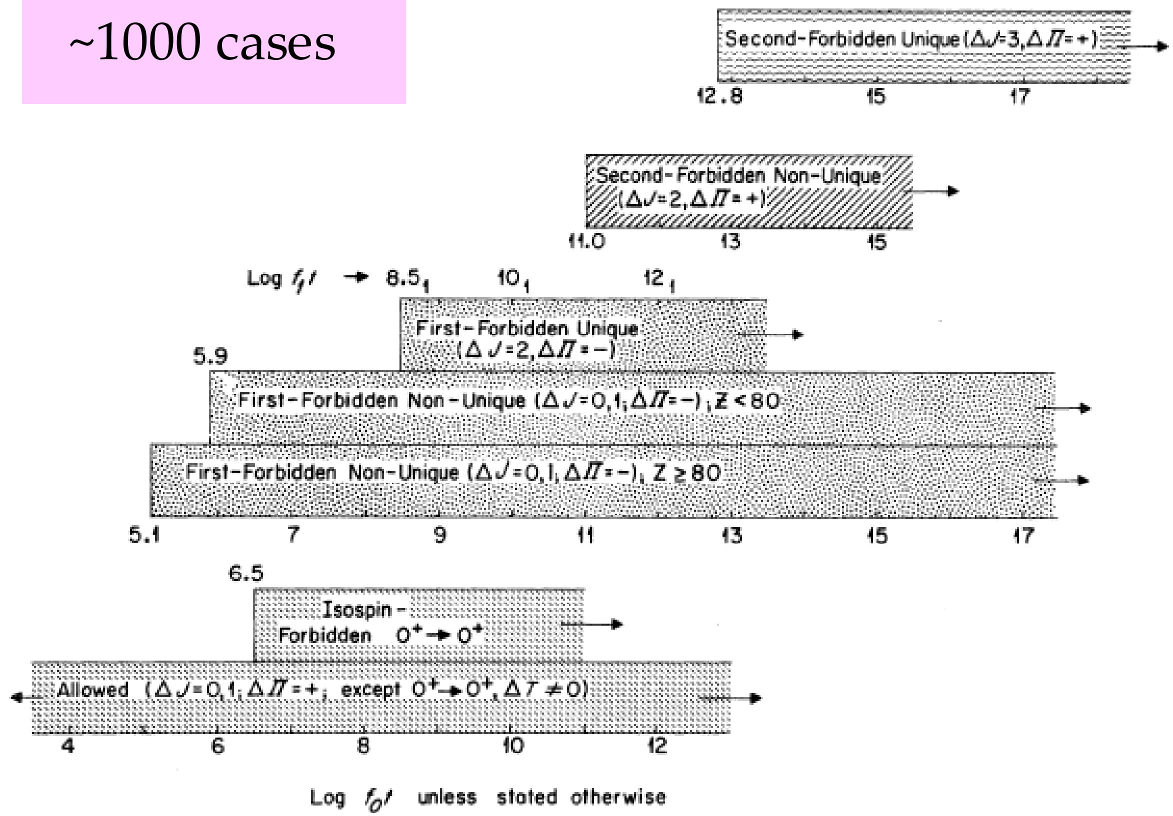
PHYSICAL REVIEW C VOLUME 7, NUMBER 5 MAY 1973

Rules for Spin and Parity Assignments Based on Log*ft* Values*

S. Raman and N. B. Gove
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830
(Received 25 October 1972)

- There are only a few cases where unambiguous assignment can be made
- "pandemonium effect" – neutron rich nuclei – log *ft* is a just lower limit!
- needs to know the decay scheme and its properties accurately!

~1000 cases



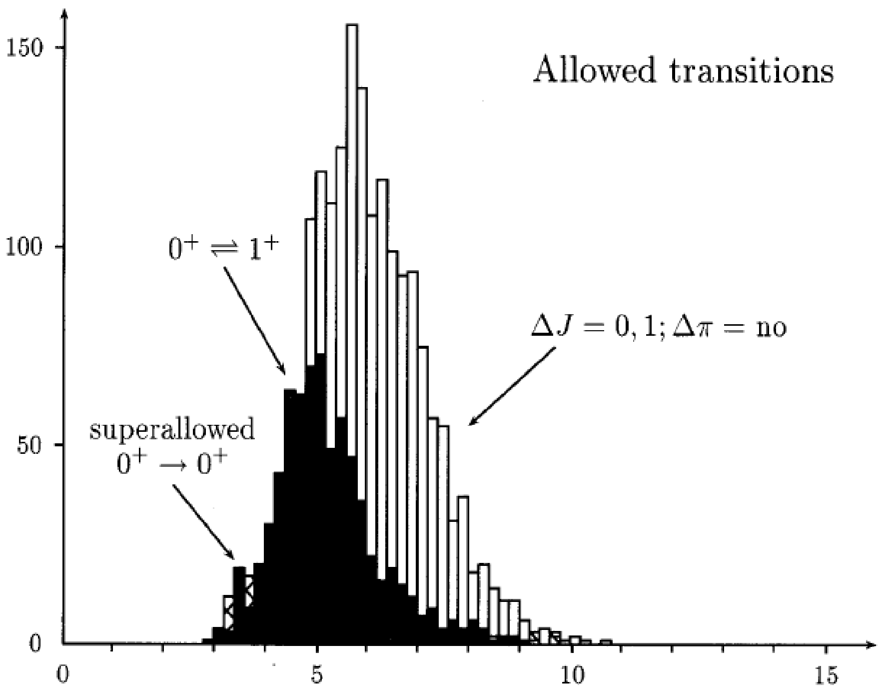
Log *ft* values – latest review

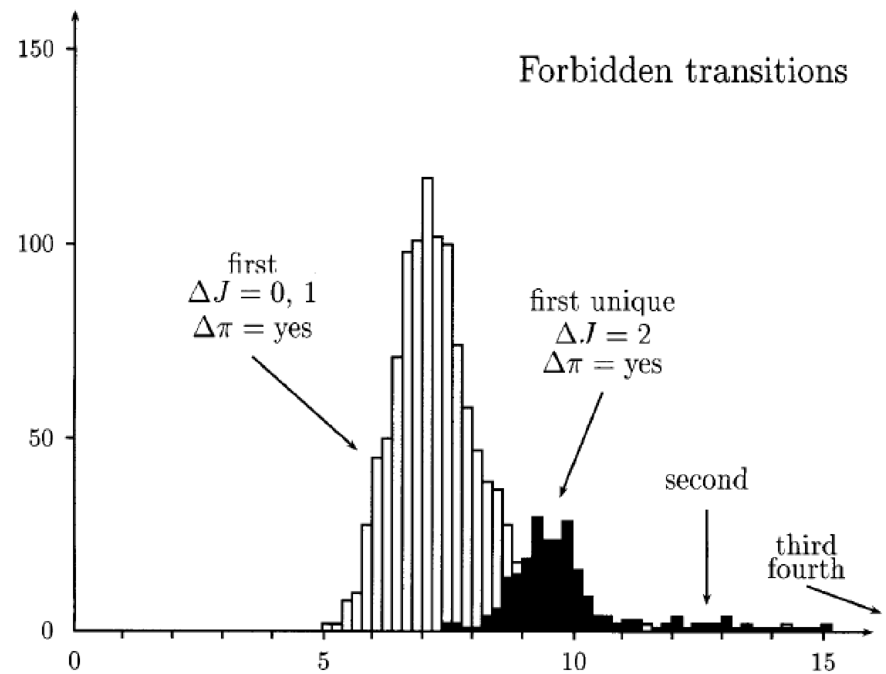
Nuclear Data Sheets 84, 487 (1998)
Article No. DS980015

~3900 cases -> gives centroids and widths

Review Of Log*ft* Values In β Decay*

B. Singh, J.L. Rodriguez, S.S.M. Wong & J.K. Tuli

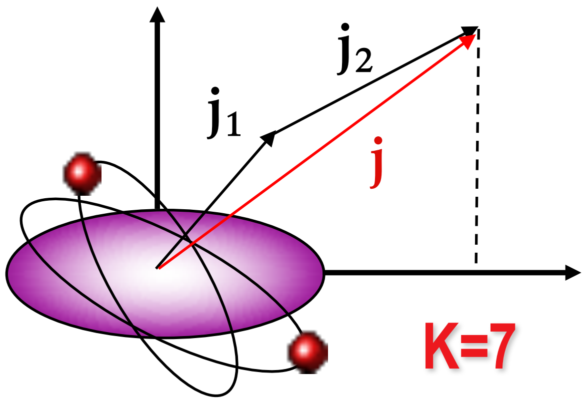




Log *ft*

Beta decay of odd-odd nuclei

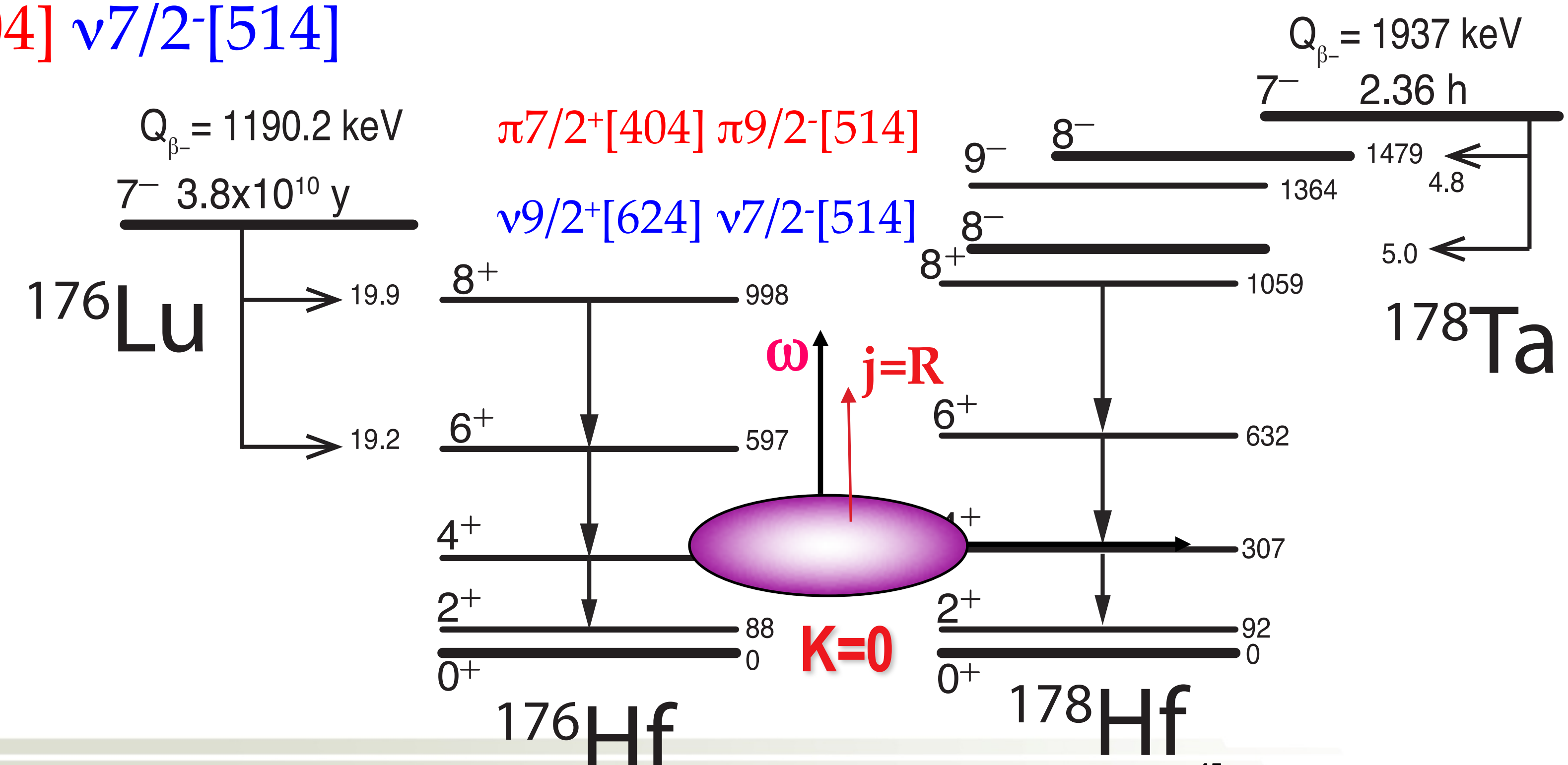
$$\boxed{\mathit{log}\ \mathrm{ft} = (\mathit{log}\ \mathrm{ft})_{sp} \times P^2 \times HF}$$



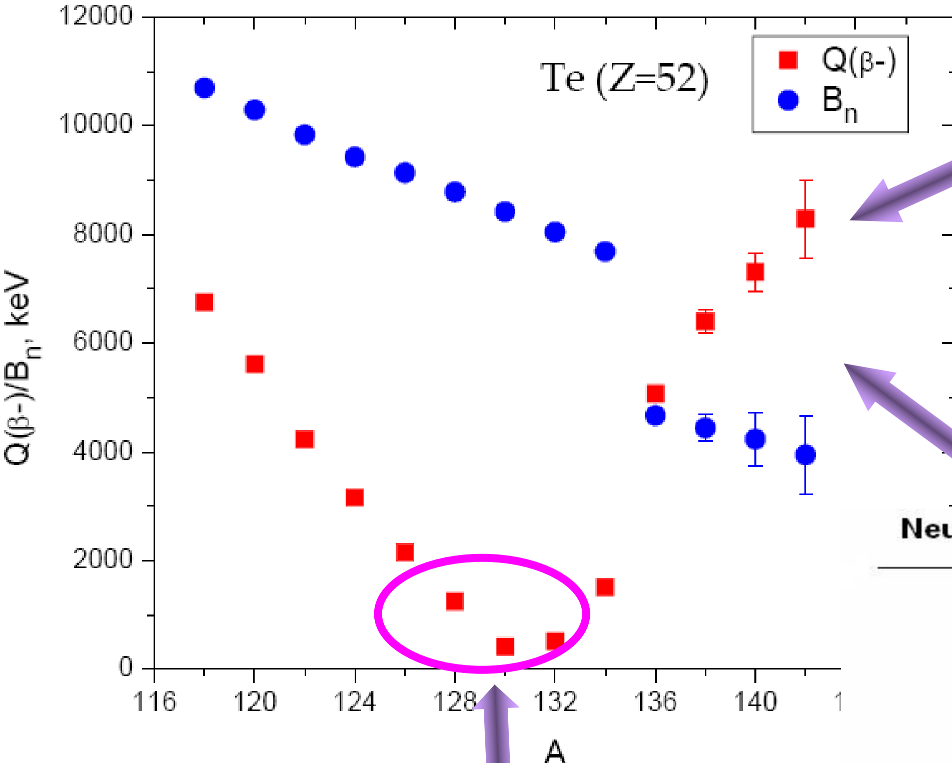
$\pi 7/2^+[404]\ \nu 7/2^-[514]$

$\pi 9/2^-[514]$ <- $\nu 7/2^-[514]$: ***log* ft =4.4 (spin-flip)**

$\pi 7/2^+[404]$ -> $\nu 9/2^+[624]$: ***log* ft =6.7**

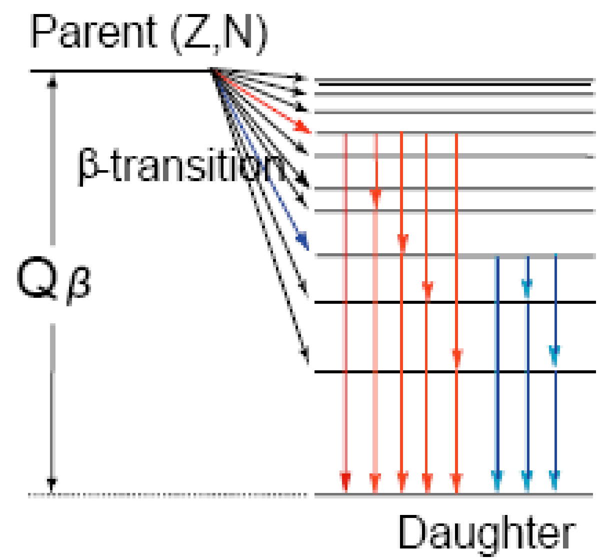


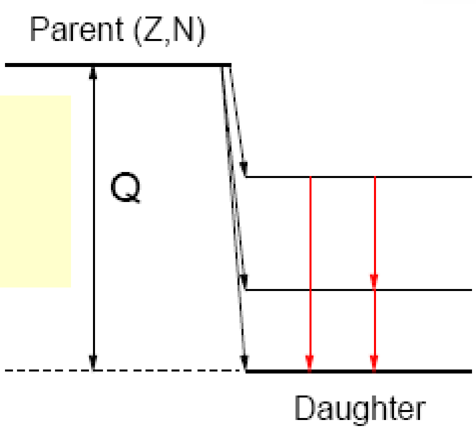
β– decay of N-rich nuclei

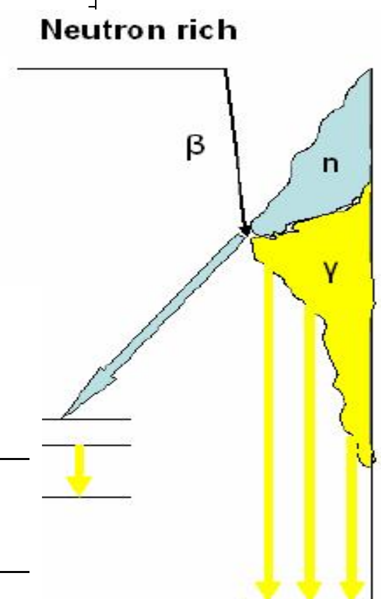


G. Audi et al., NP A729 (2003)

“large” $Q_{\beta-}$ – large density of levels and more complicated decay schemes – usually low γ–ray multiplicities, but isomers!



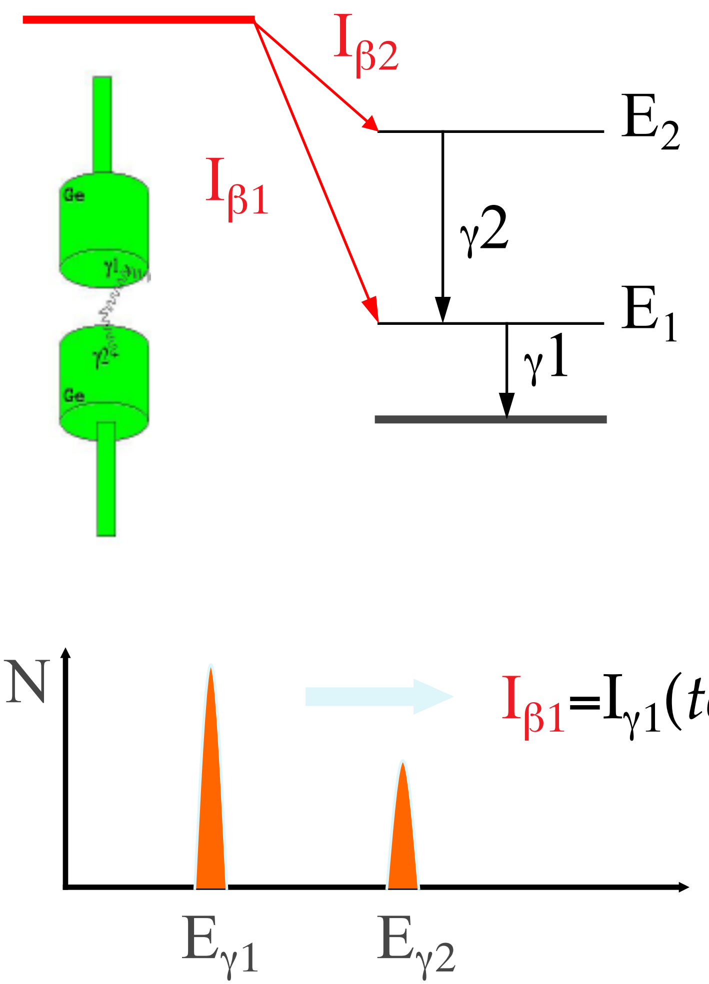




“small” $Q_{\beta-}$ - the level schemes are well understood

$Q_{\beta-} > B_n$

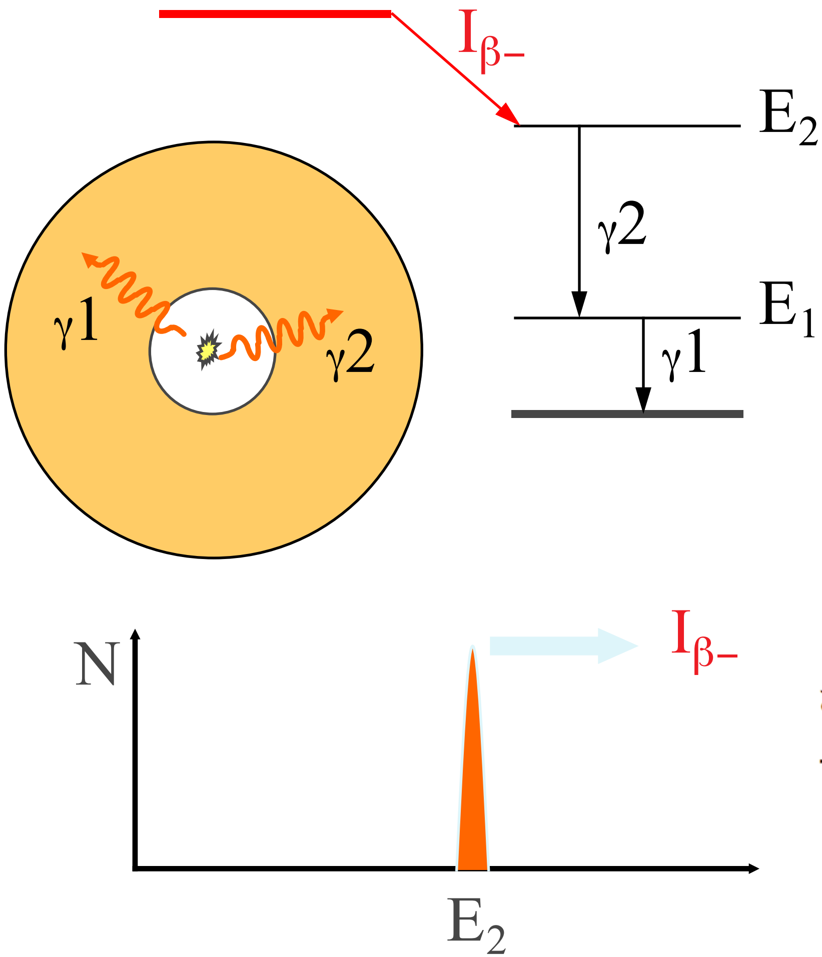
High-resolution gamma-ray spectroscopy



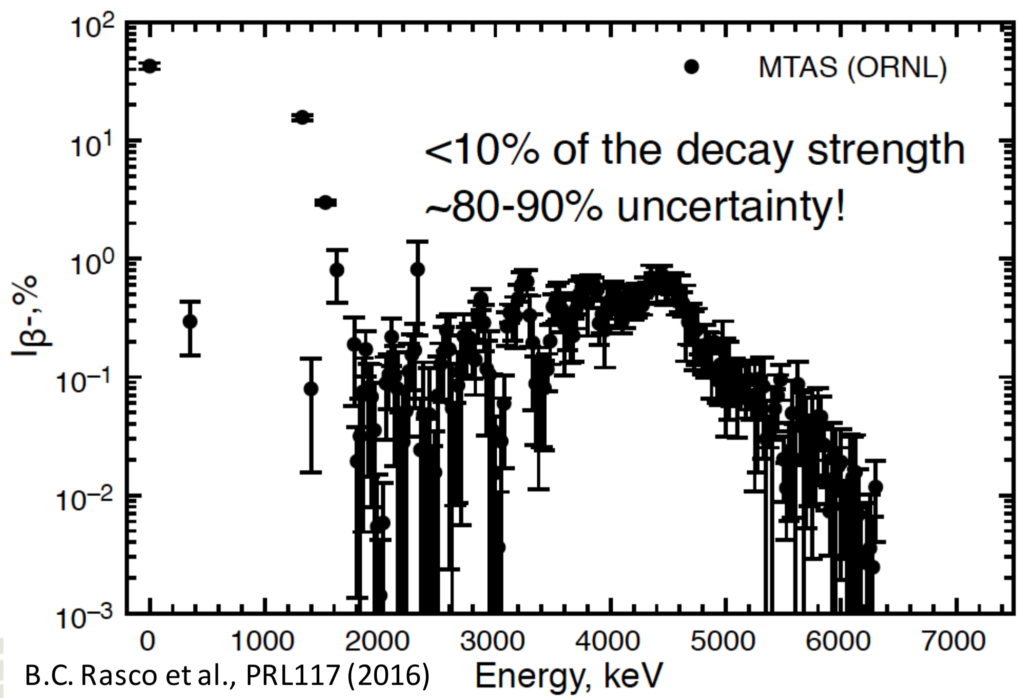
$$I_{\beta 1} = I_{\gamma 1}(tot) - I_{\gamma 2}(tot)$$

- depends on the accurate knowledge of the decay scheme – level energies, J^{π}, mult., ICC
- not studied with state-of-the art equipments – low sensitivity & effect of the "Pandemonium"

Total Absorption Gamma-ray Spectroscopy (TAGS)



- Compromised when isomeric states are presented
- Compromised when $\beta^{-}n$ are emitted
- Compromised by isotope/isobar contaminations
- The analysis is cumbersome

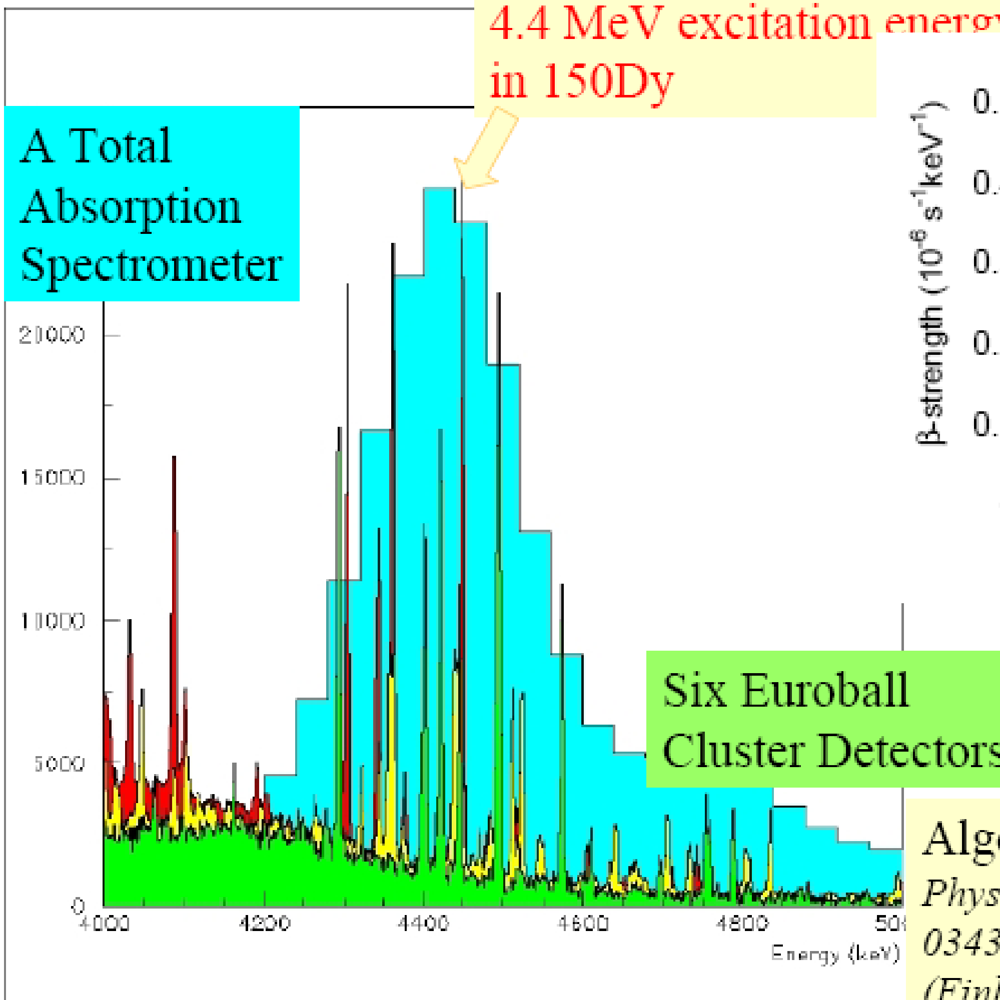


B.C. Rasco et al., PRL117 (2016)

We need both - HRGS and TAGS!

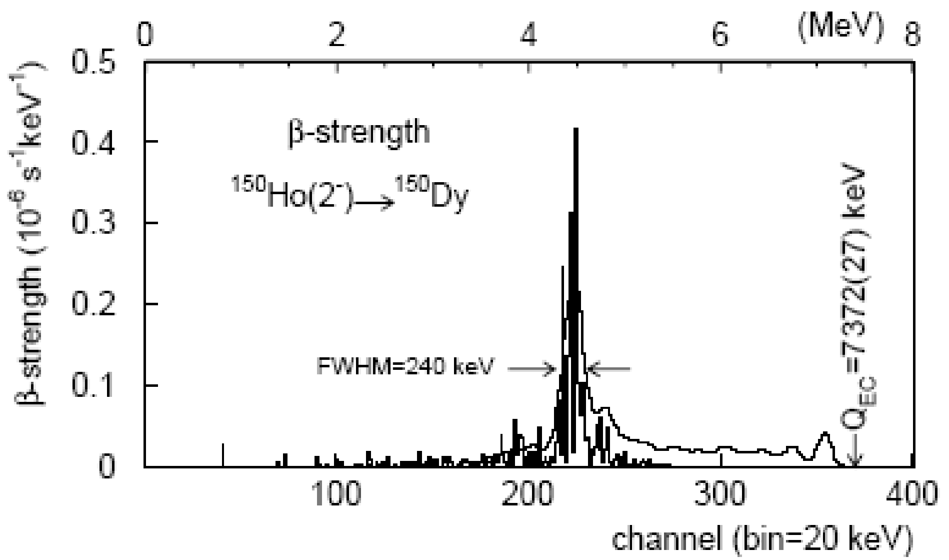
4.4 MeV excitation energy in 150Dy

A Total Absorption Spectrometer

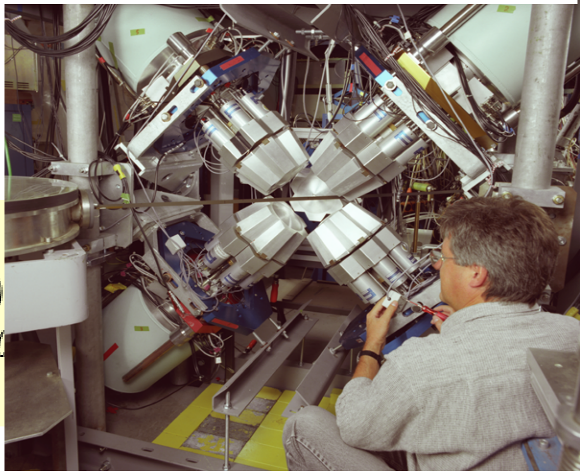


Six Euroball Cluster Detectors

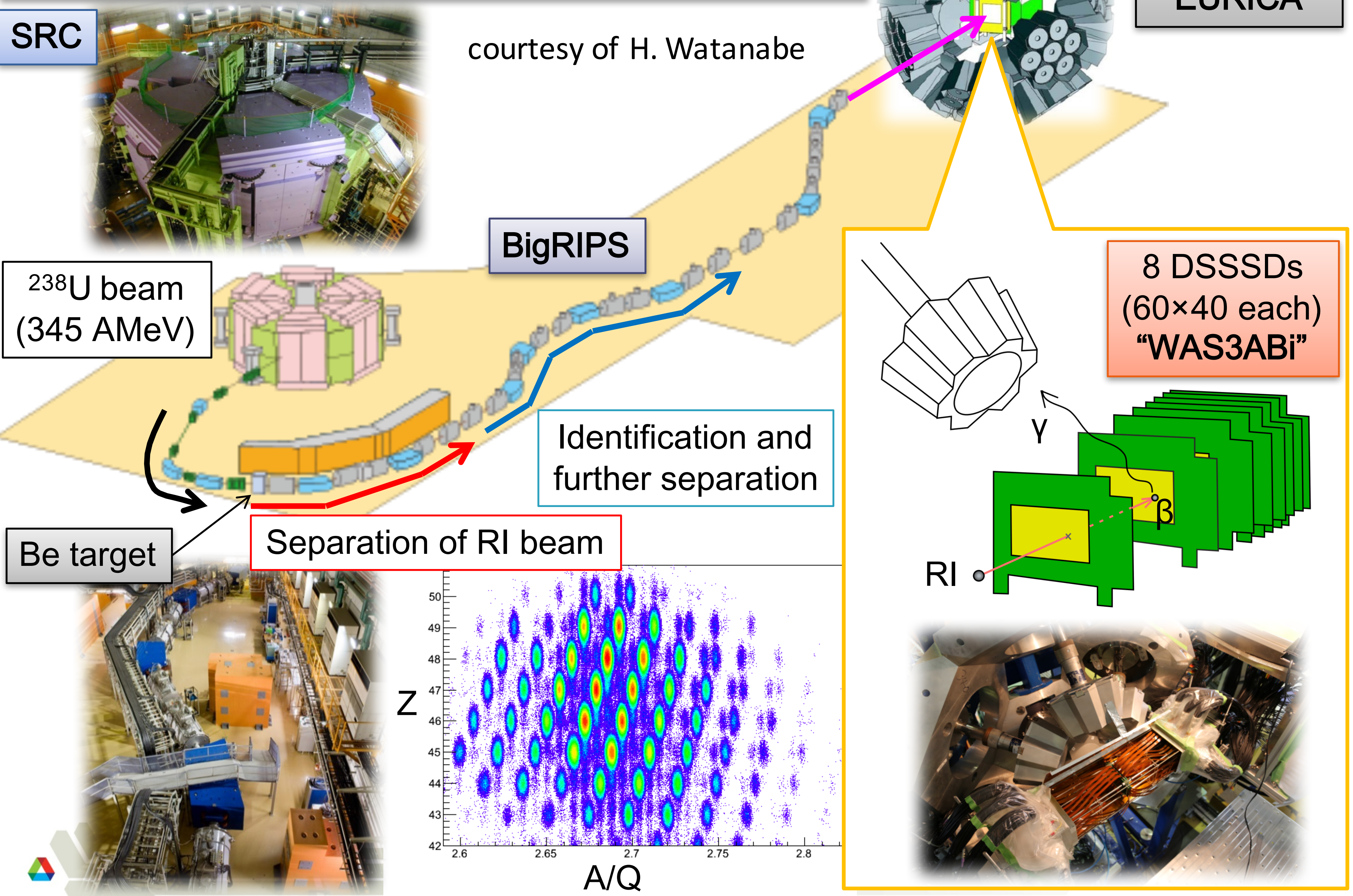
Q(EC) = 7.4 MeV



Algora et al
Phys. Rev C 68 (2003) 034301 and ENAM 20… (Finland)



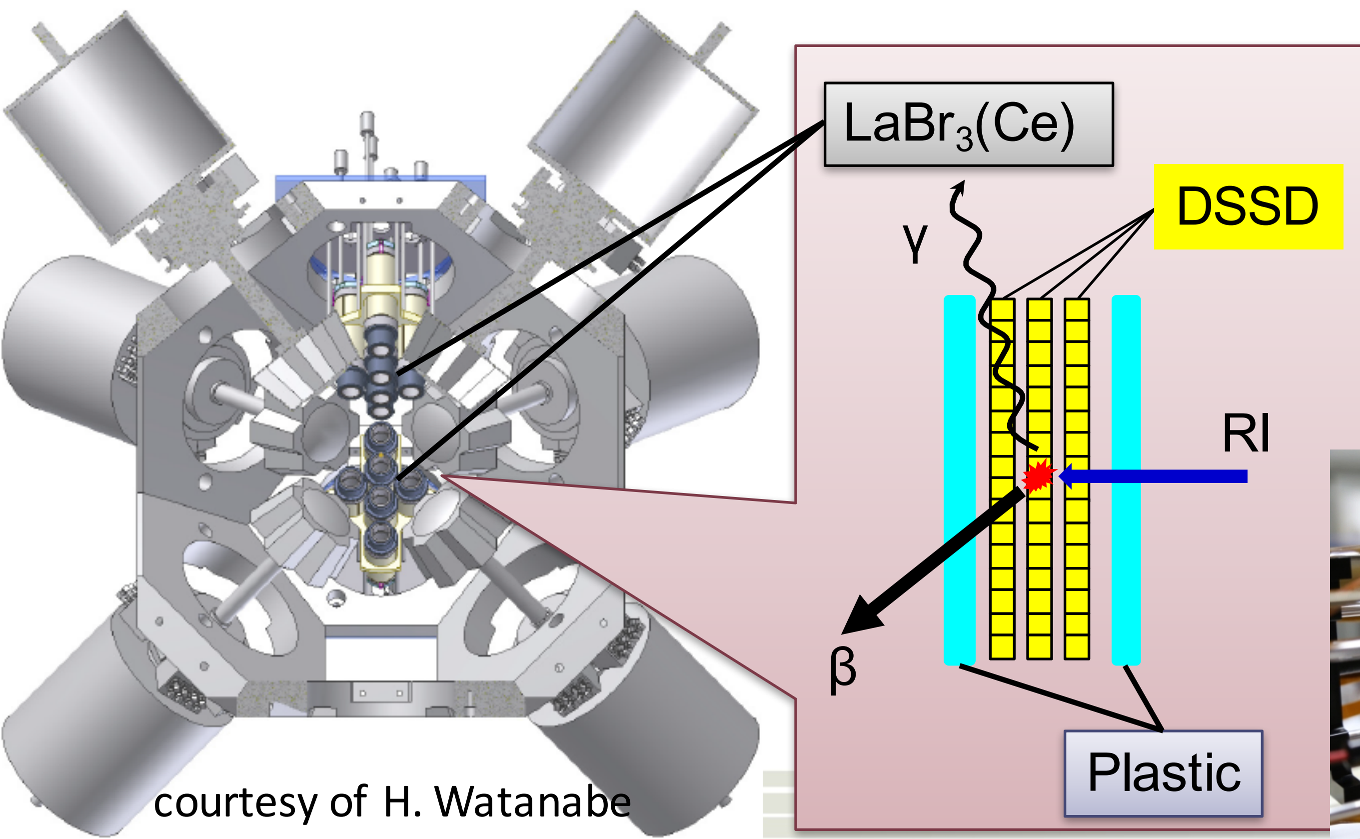
Radioactive Isotope-Beam Factory (RIBF) at RIKEN



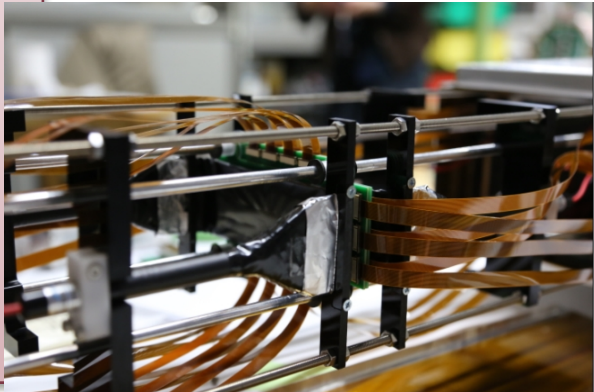
Fast timing demonstration with EURICA

- **18 $LaBr_3$(Ce) scintillators (Φ1.5”×2”)** on three vacant slots for γ rays
  ※Contributed from U. of Surrey and Brighton
- **BC-418 plastic counters (2-mm thick)** beside the DSSDs for β rays

Fast-timing measurement



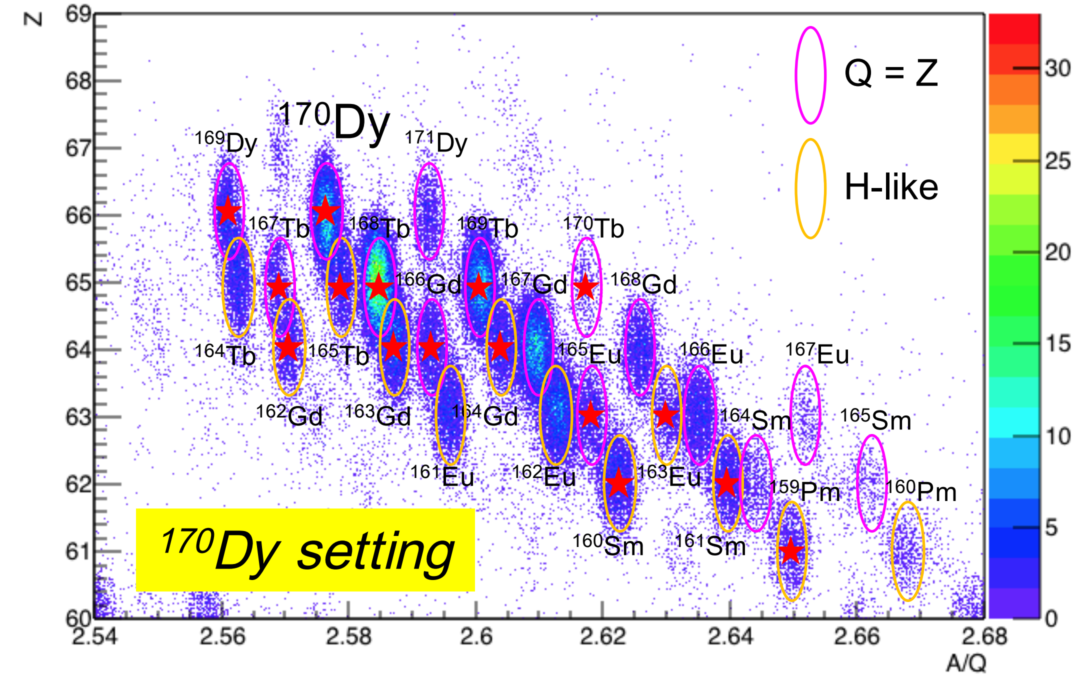
courtesy of H. Watanabe

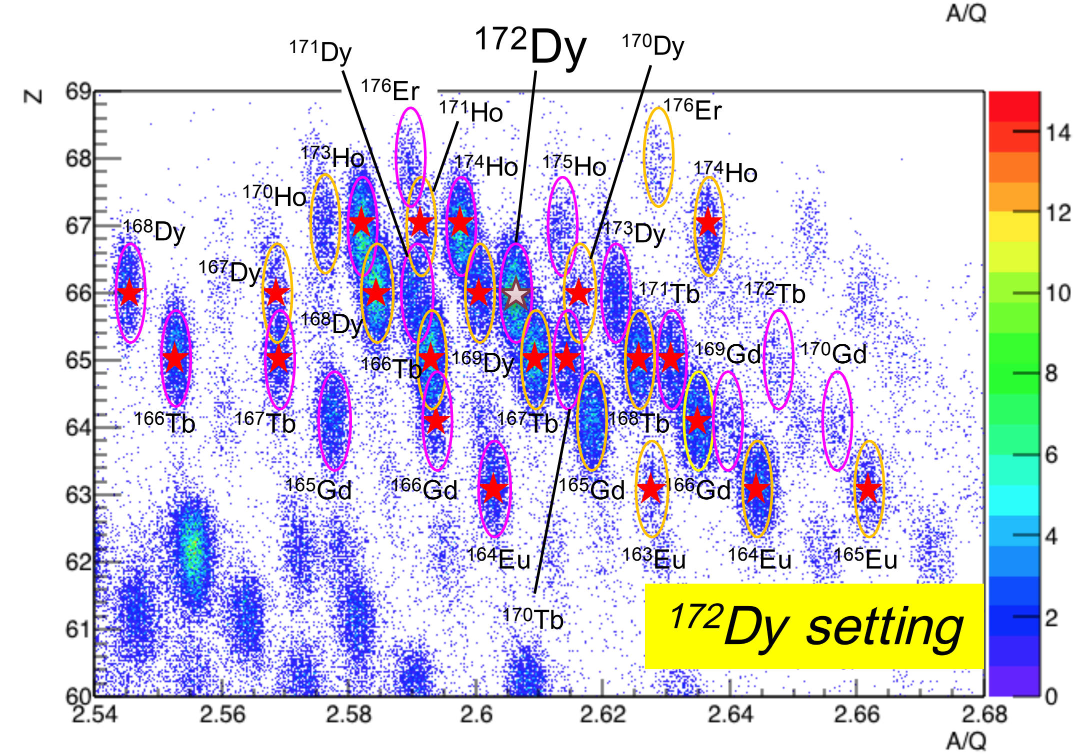


In-flight fission of ^{238}U + Isotope separation

Nov. 2014 (3 days)

- High intensity (10~15 pnA)
- Slits optimized for ^{170,172}Dy
- $\Delta A/Q$ ~ 0.05 %
  - ⇒ Separate charge state





Ion	BigRIPS
$^{170}Dy^{66+}$	12932
$^{172}Dy^{66+}$	8272

courtesy of H. Watanabe

★ Isomer in μs

☆ Isomer in ms

$^{172}_{66}\mathrm{Dy}_{106}$

Low-energy electron & Shorter time range

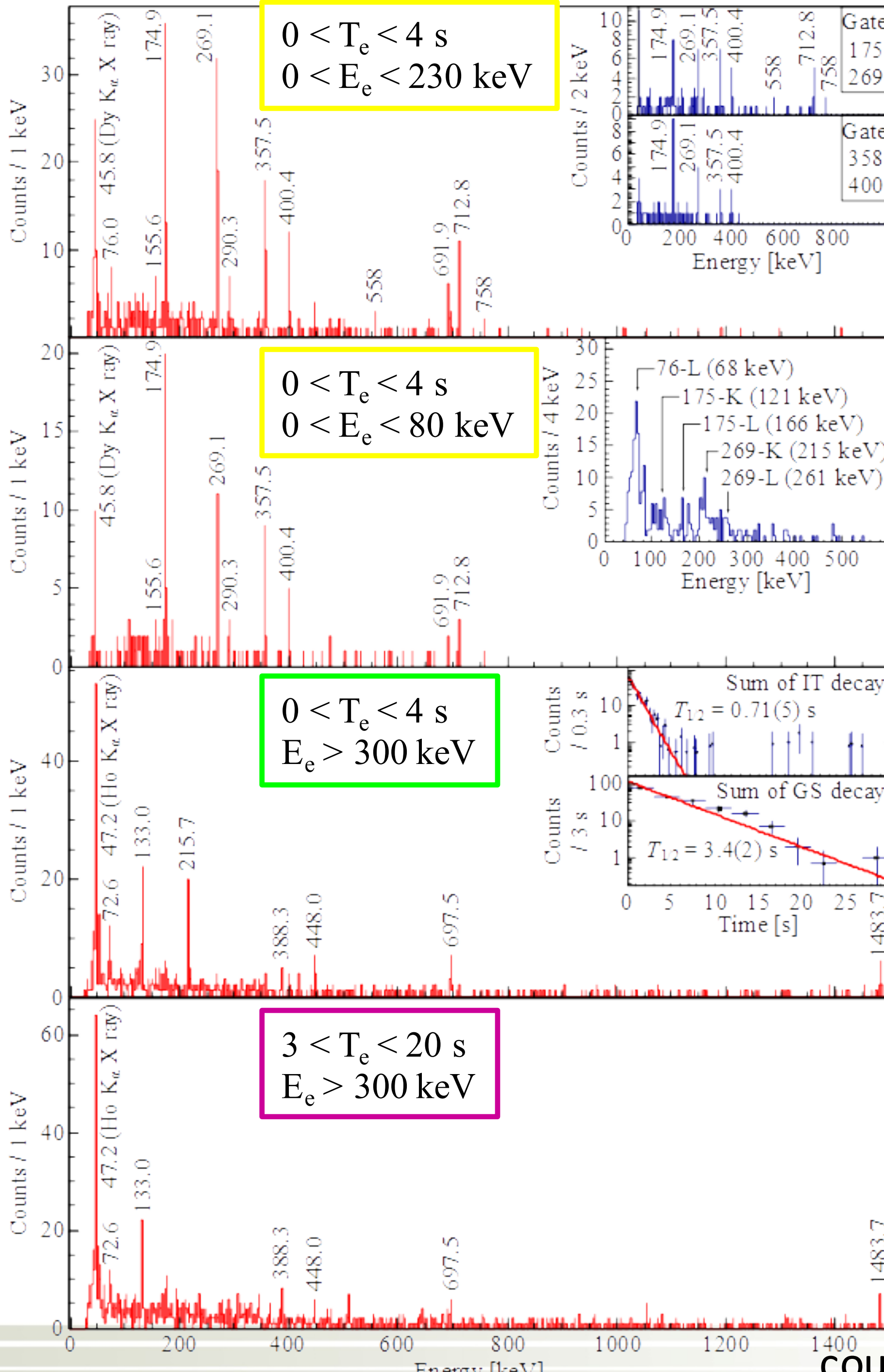
⇒ **Internal decay from isomer**

High-energy electron & Shorter time range

⇒ **β decay from isomer**

High-energy electron & Longer time range

⇒ **β decay from ground state**



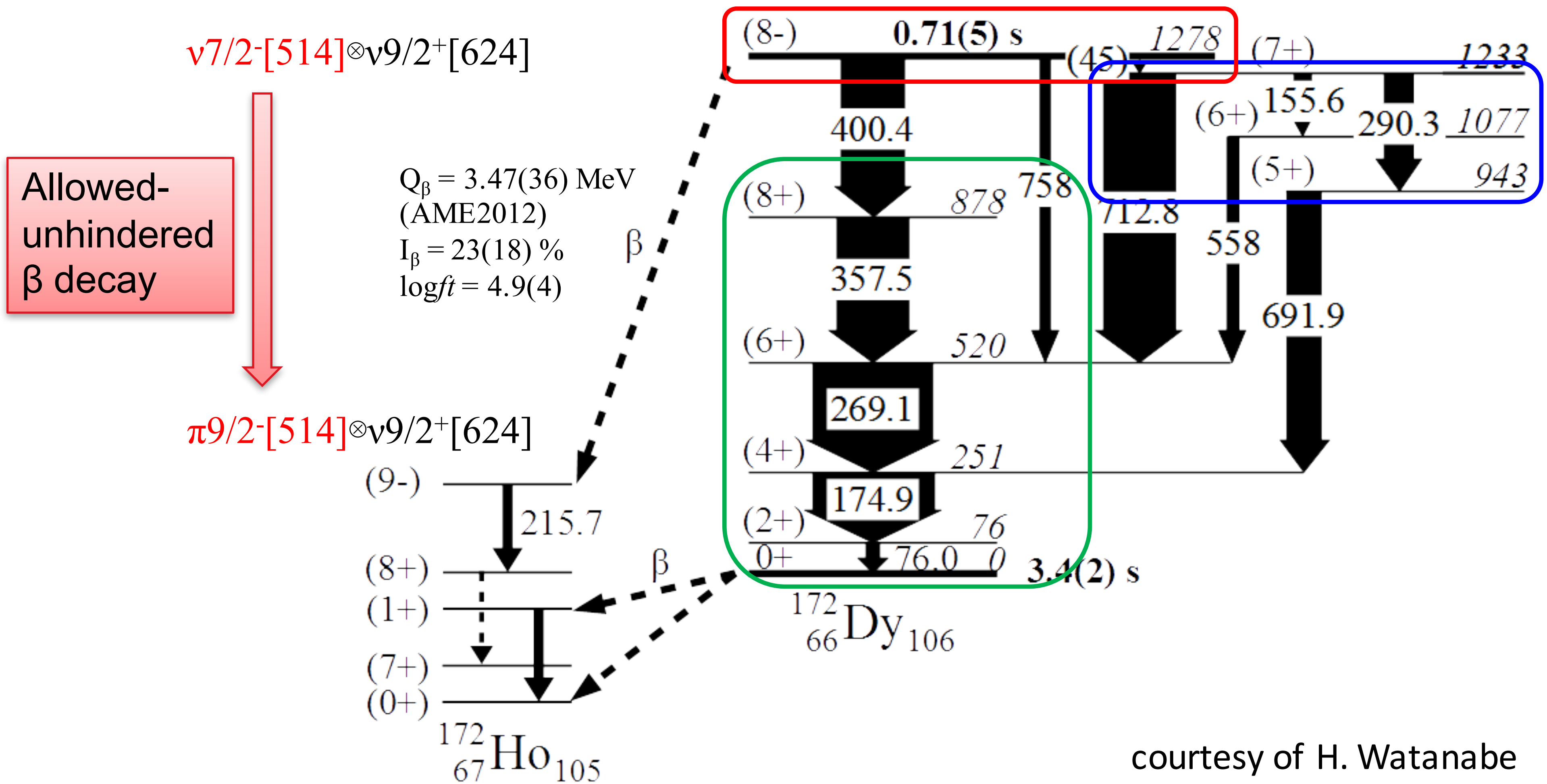
γ-γ coincidence

γ-ray gated electron spectrum

$T_{1/2}$ = 0.71(5)s

$T_{1/2}$ = 3.4(2)s

courtesy of H. Watanabe



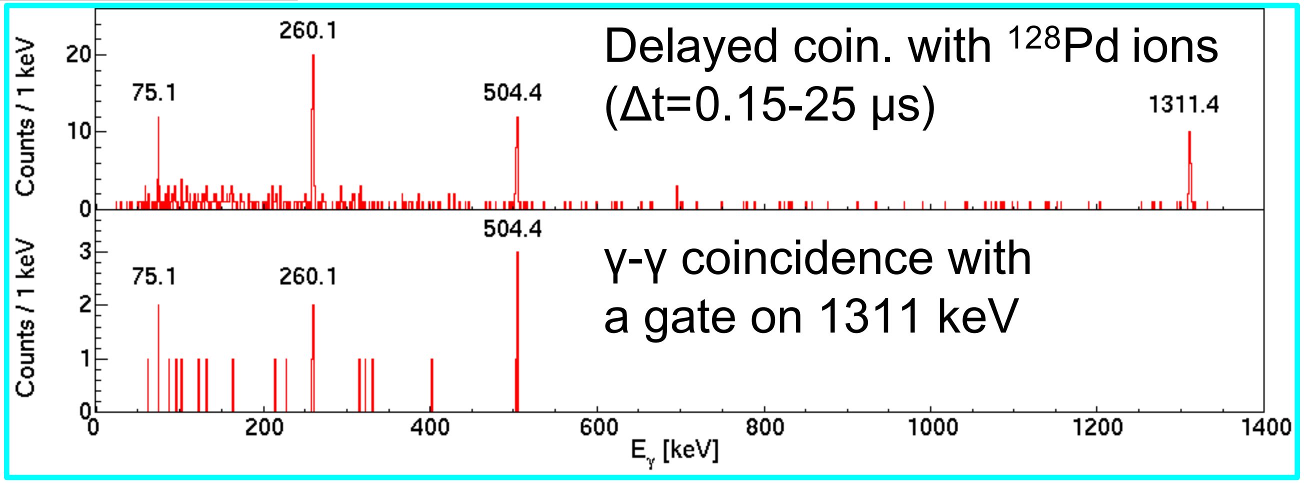
Long-lived isomer ($T_{1/2}$ = 0.71 s) ⇨ **K^{π} = 8-: ν7/2$^-$[514]⊗ν9/2$^+$[624]**

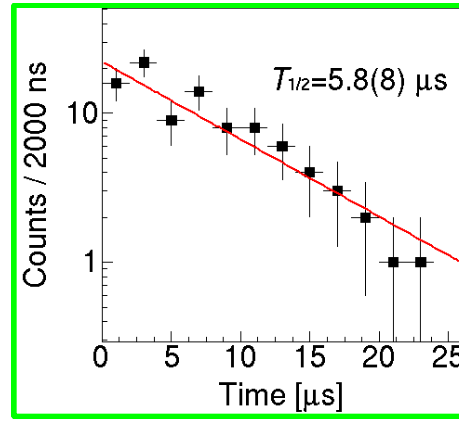
- Internal decay to
  - K^{π} = 0+ ground-state band via 400 keV [E1] and 758 keV [M2]
  - K^{π} = 2+ γ-vibrational band via 45 keV [E1] (unobserved)
- β decay to ^{172}Ho ⇒ **log*ft* = 4.9(4)** ※Feeding only to the 216-keV transition is assumed

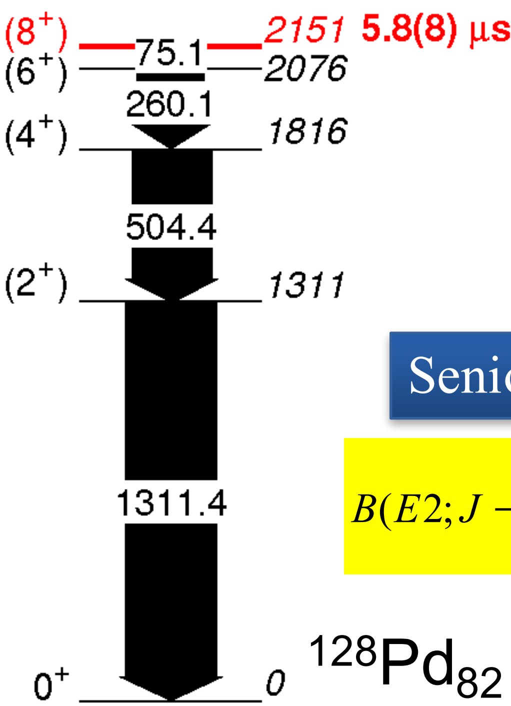
Allowed-unhindered β decay

$^{128}_{46}Pd_{82}$ Seniority isomer

H. Watanabe et. al., Phys. Rev. Lett. 111, 152501 (2013)

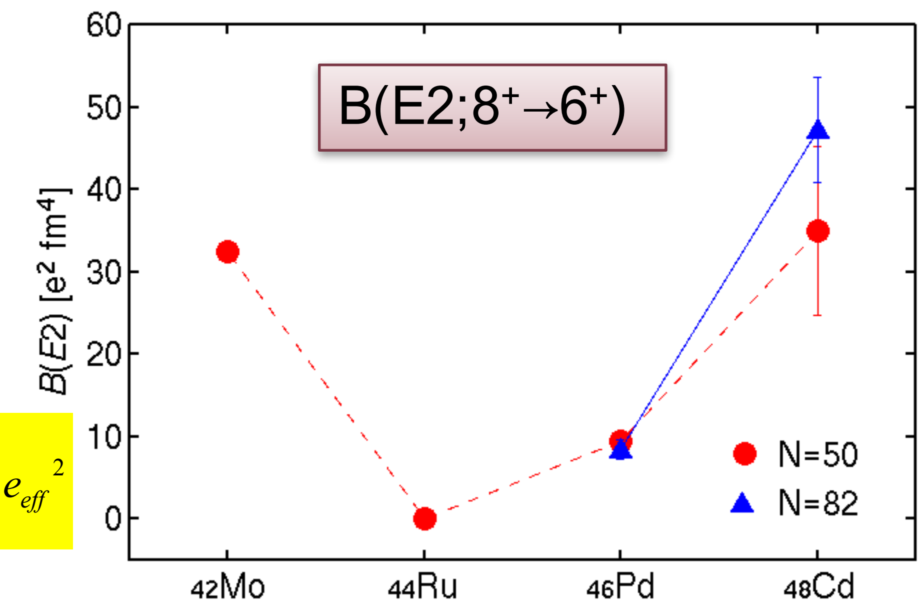






Seniority (ν) scheme

$$B(E2;J \rightarrow J-2) \propto \left(\frac{2j+1-2n}{2j+1-2\nu}\right)^2 \times e_{eff}^{\ 2}$$

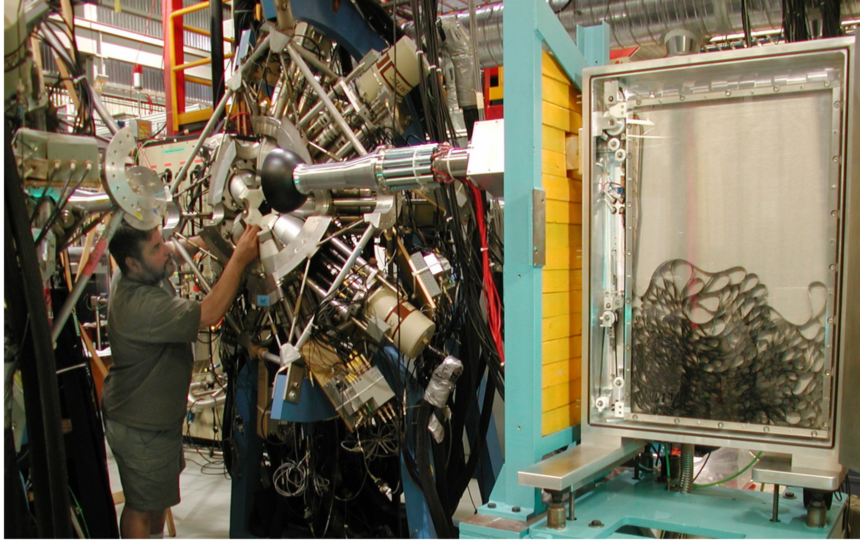


courtesy of H. Watanabe

Good ν=2 in the well isolated $\pi g_{9/2}$ subshell ⇒ Robust shell closure at N=82

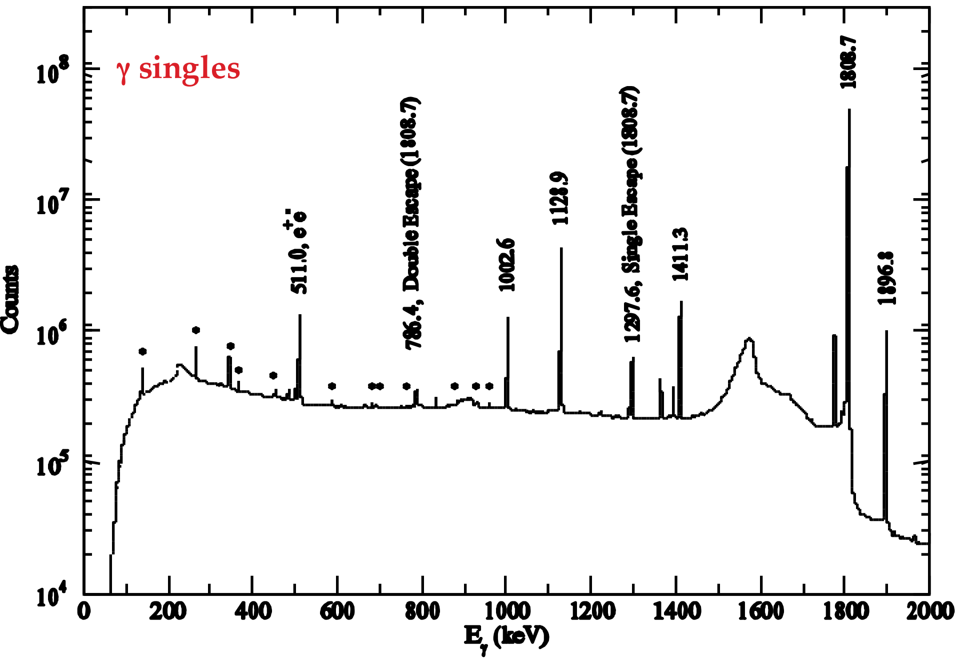
TRIUMF, CANADA

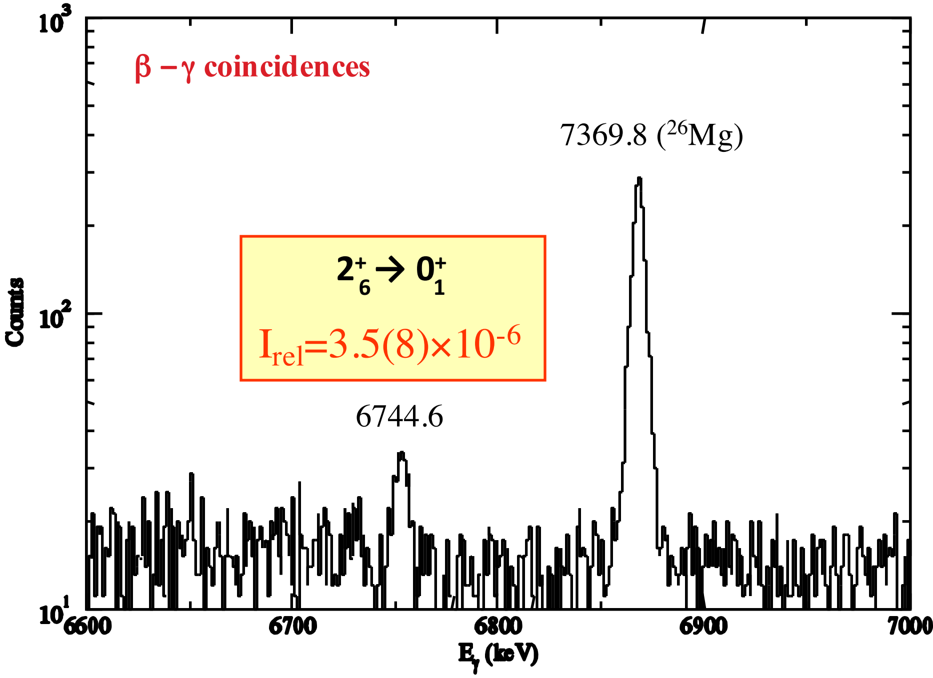
8π & SCEPTAR



G.F. Grinyer et al., Phys. Rev. C **71**, 044309 (2005)

^{26}**Na beam: 10^6 s^{-1} for 12 hours, trigger rate 24 kHz**



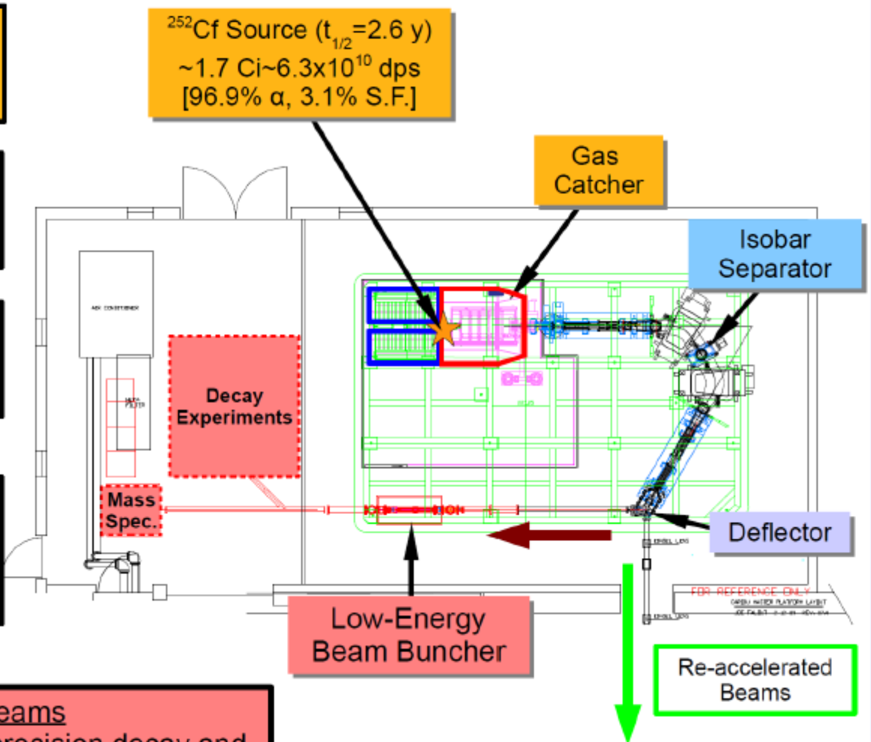


CARIBU-ANL

^{252}Cf fission fragments are slowed and focused in a helium-gas catcher

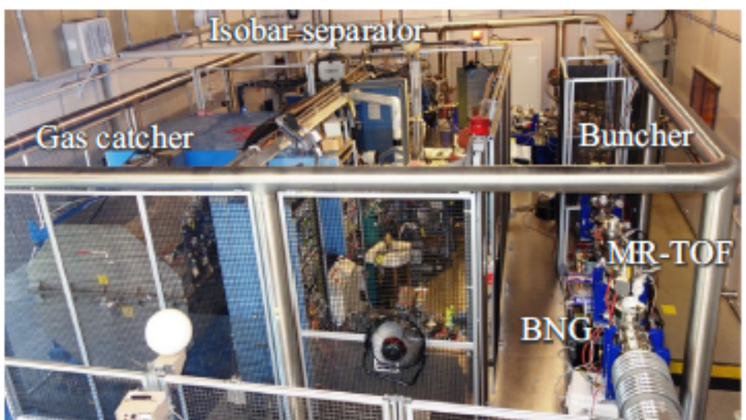
Beams of a desired mass are selected by a 120º magnetic isobar separator

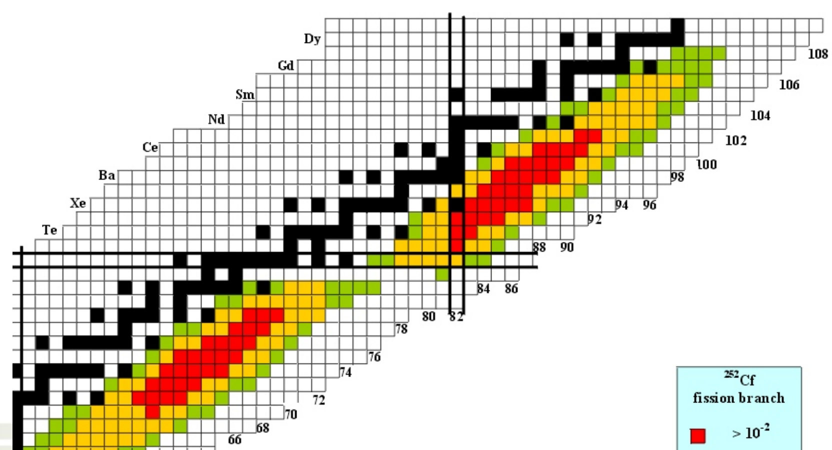
The neutron-rich beams can be deflected to low-energy or re-accelerated beam lines



<u>Re-accelerated beams</u>
Charge bred and injected into ATLAS resulting in energies up to ~15 MeV/A

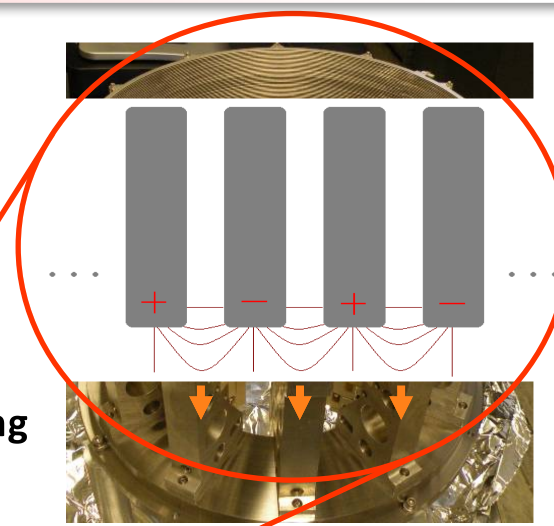
<u>Low Energy Beams</u>
Beams bunched for use in precision decay and mass spectrometry experiments

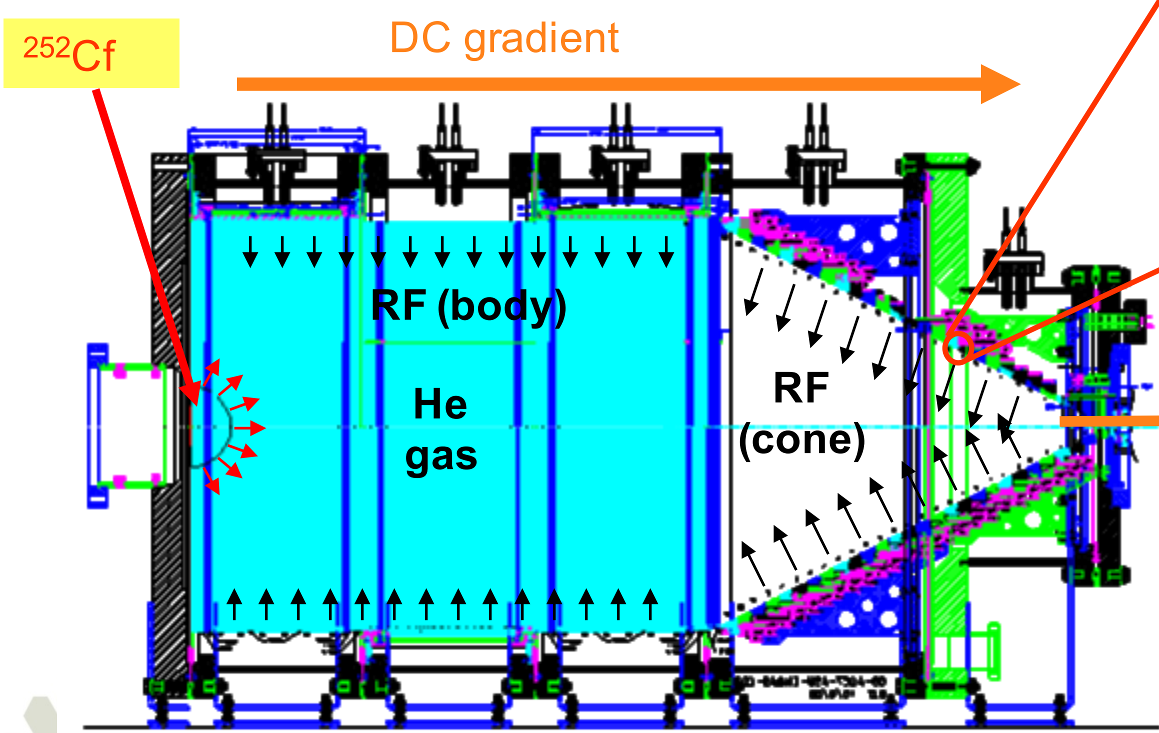


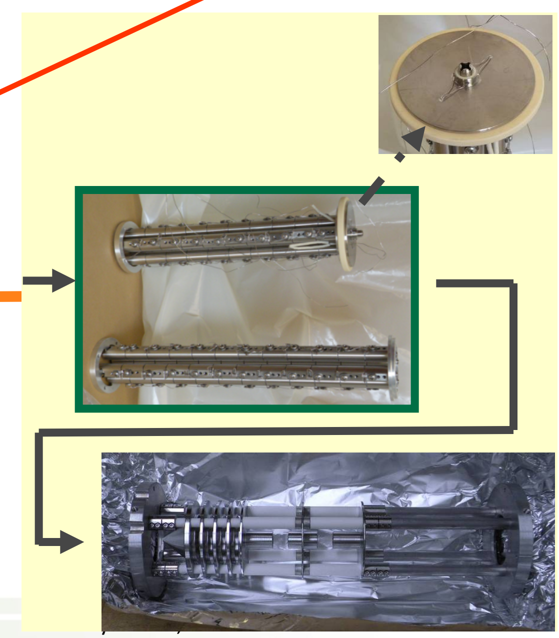


CARIBU gas catcher: transforms fission recoils into a beam with good optical properties

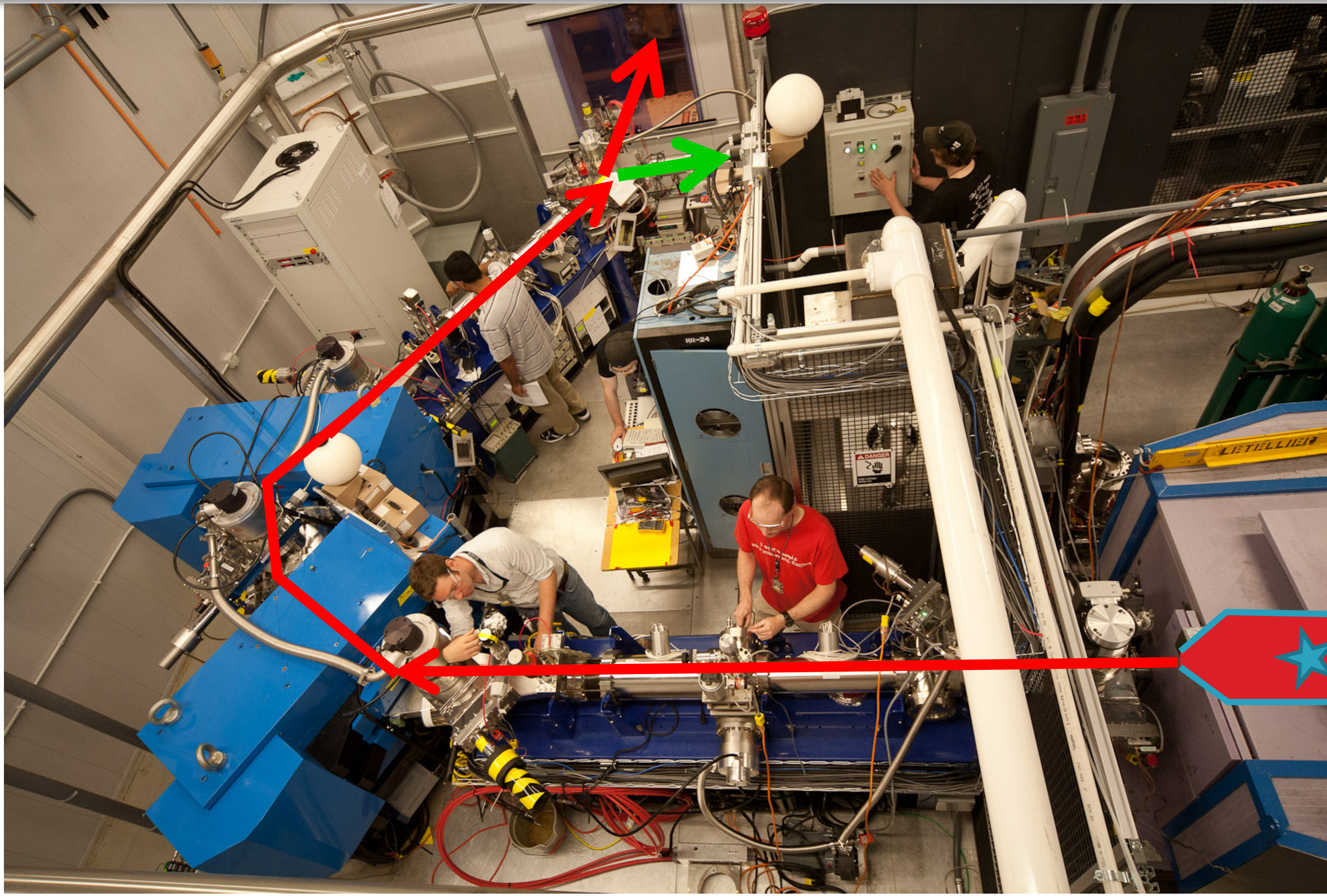
- **Based on smaller devices developed at ANL**
  - **Radioactive recoils stop in sub-ppb level impurity Helium gas**
  - **Radioactive ion transport by RF field + DC field + gas flow**
  - **Stainless steel and ceramics construction (1.2 m length, 50 cm inner diameter)**
  - **Fast and essentially universally applicable**
  - **Extraction in 2 RFQ sections with µRFQs for differential pumping**





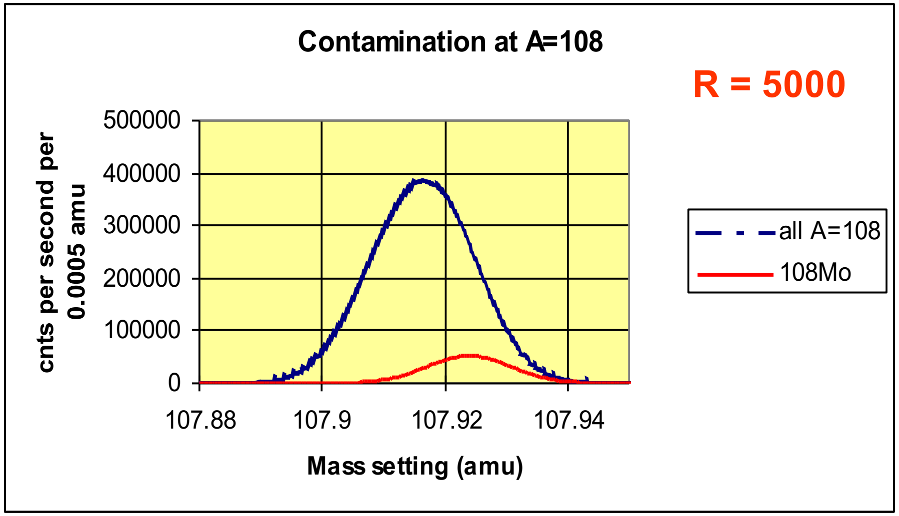


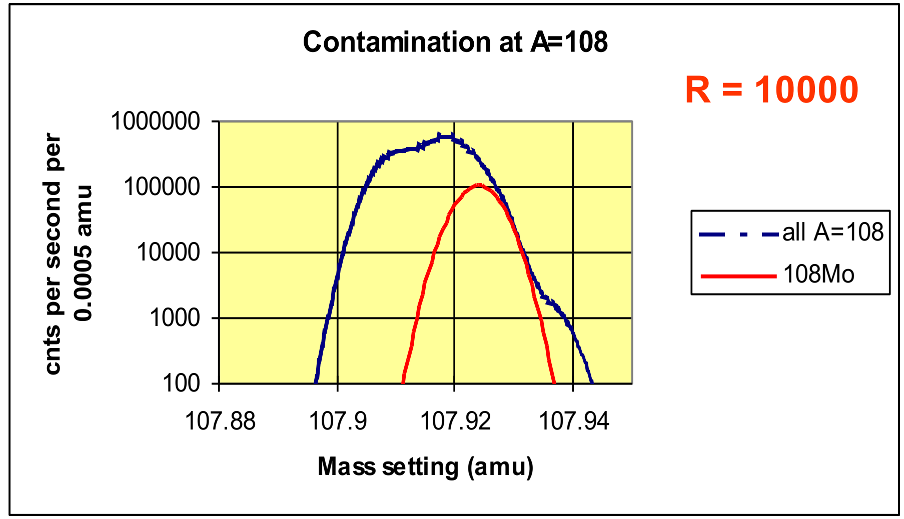
Selection by compact CARIBU isobar separator

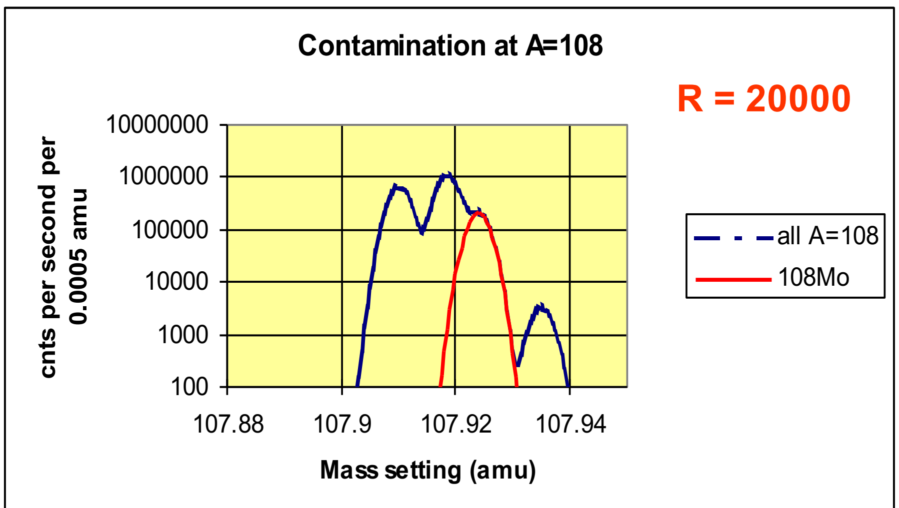


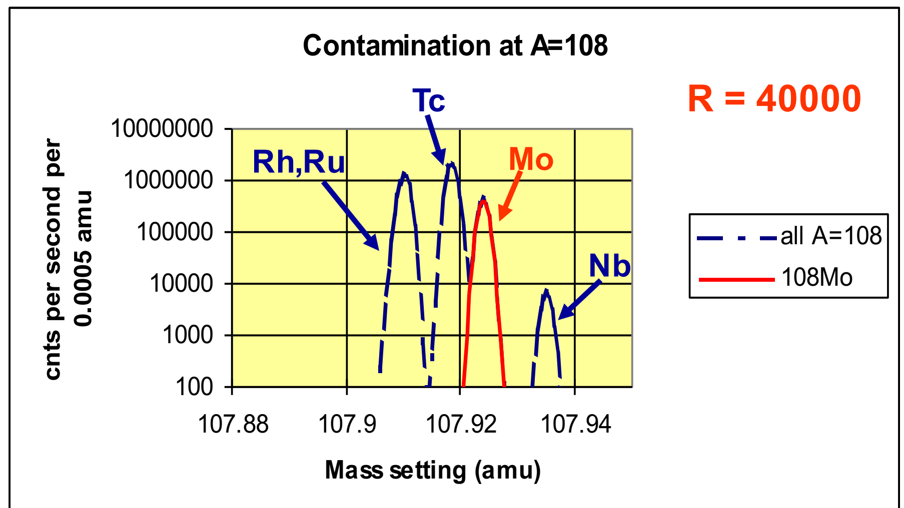
M/ΔM = 14000-20000 @ >70% transmission … still being improved

Contamination at A=108 versus separator resolution









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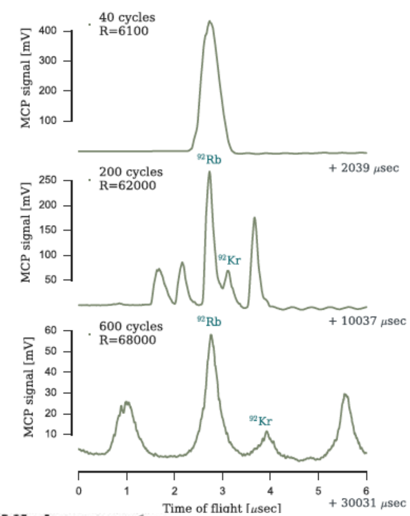
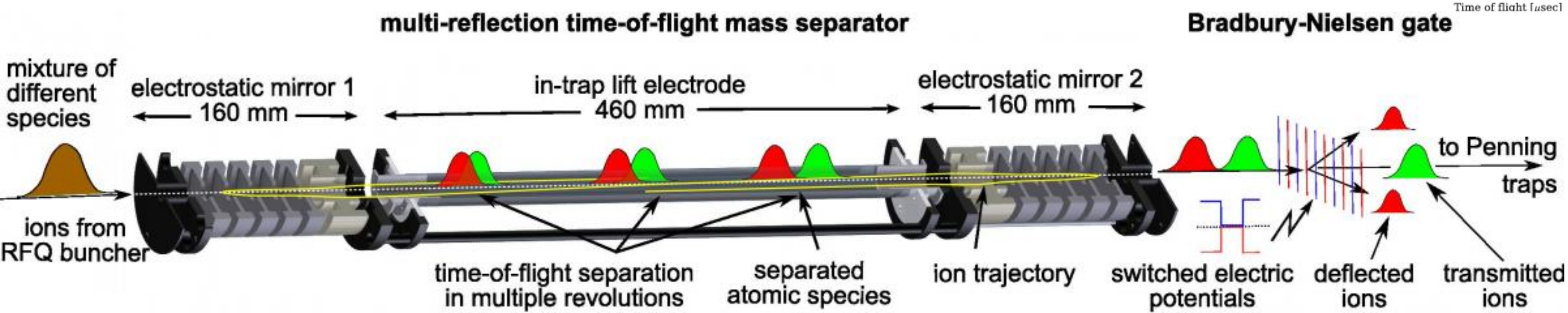
First operation and mass separation with the CARIBU MR-TOF

Tsviki Y. Hirsh[a,b,*], Nancy Paul[b,c], Mary Burkey[b,d], Ani Aprahamian[c], Fritz Buchinger[e], Shane Caldwell[b,d], Jason A. Clark[b], Anthony F. Levand[b], Lin Ling Ying[b], Scott T. Marley[c], Graeme E. Morgan[a,b], Andrew Nystrom[b,c], Rodney Orford[b,e], Adrian Pérez Galván[b,a], John Rohrer[b], Guy Savard[b,d], Kumar S. Sharma[a], Kevin Siegl[b,c]

- **‘Fast’ isobar separator:**
  - ✓ **Based on ISOLTRAP/ISOLDE design:**
  - ✓ **~ 1.3 m long MR-TOF**
  - ✓ **Currently mass resolving power, R ~ 50,000 with ~ 50% transmission in ~ 15 ms**



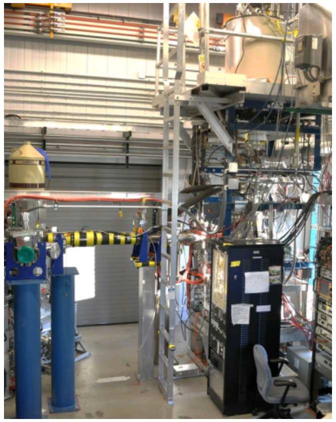


The CARIBU low-energy experimental area

- Delivers 1.5 kV to 10 kV beam to experimental stations
- Pulsed beams with rates from ~ 50 ms to seconds
- Low emittance
- Experimental stations:

CPT

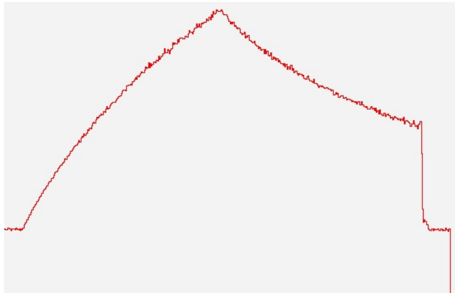
(installed)



TAPE STATION

(installed)

Tape cycle



X-ARRAY

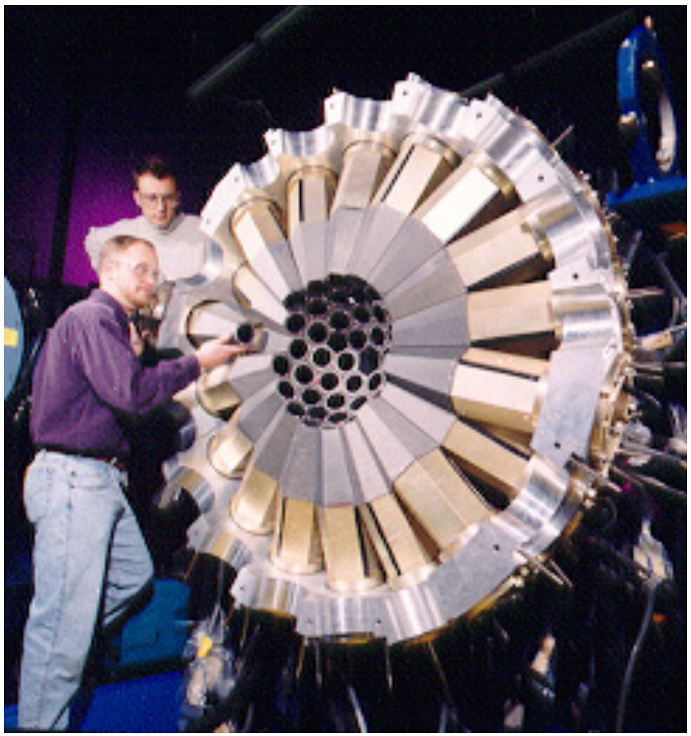
(installed)

LASER SPECTROSCOPY: After CPT move (end of 2016)

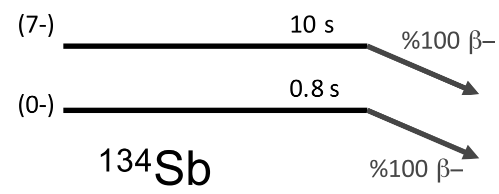
- Limited amount of space … removal of Tandem will provide new experimental area

β^- decay studies with Gammasphere

110 Ge detectors (Compton-suppressed), covering 4π



- ✓ high resolution & sensitivity
- ✓ powerful β–γ–γ coin – resolving weak cascades & isomers!

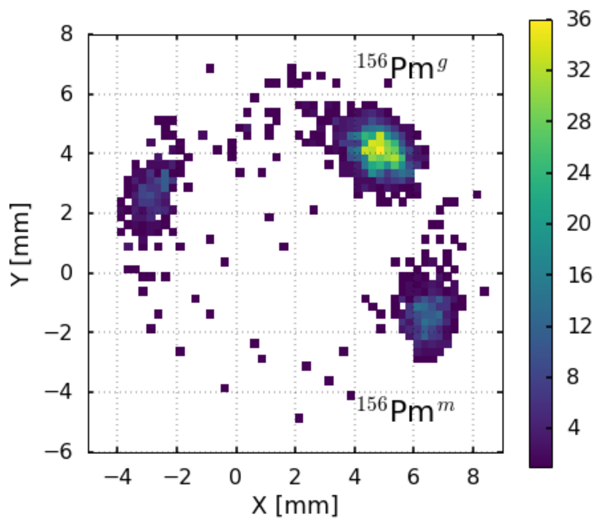


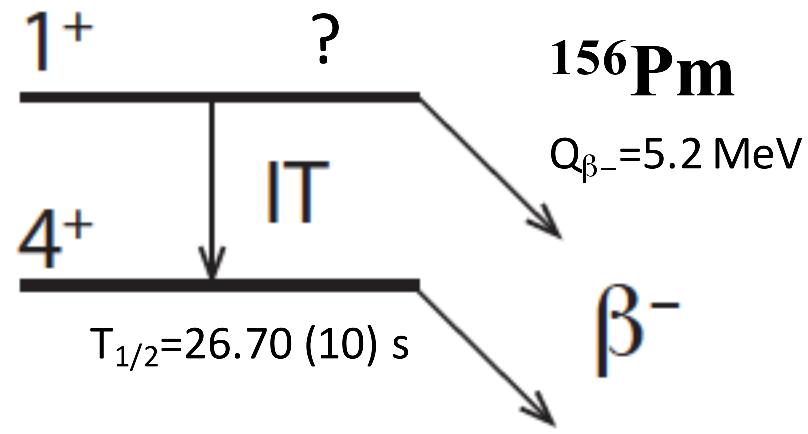
<u>GS as a calorimeter</u>

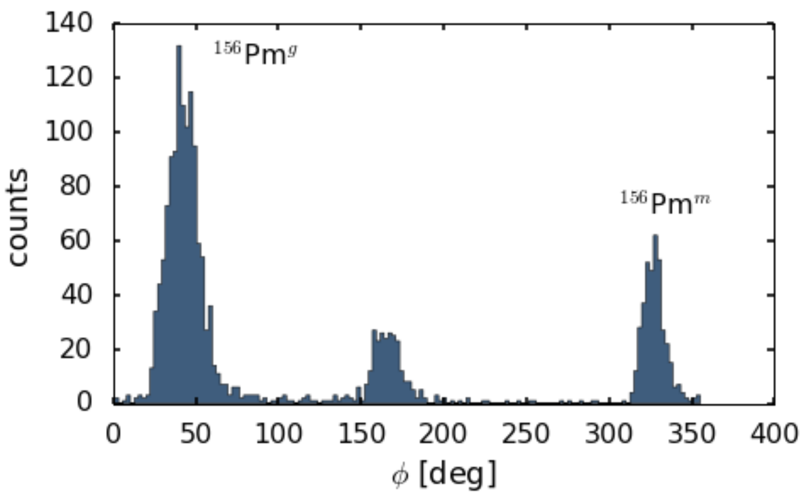
- ✓ P. Reiter et al. Phys.Rev.Lett. 84, 3542 (2000)
- ✓ with a modest upgrade – suitable for β^- decay studies

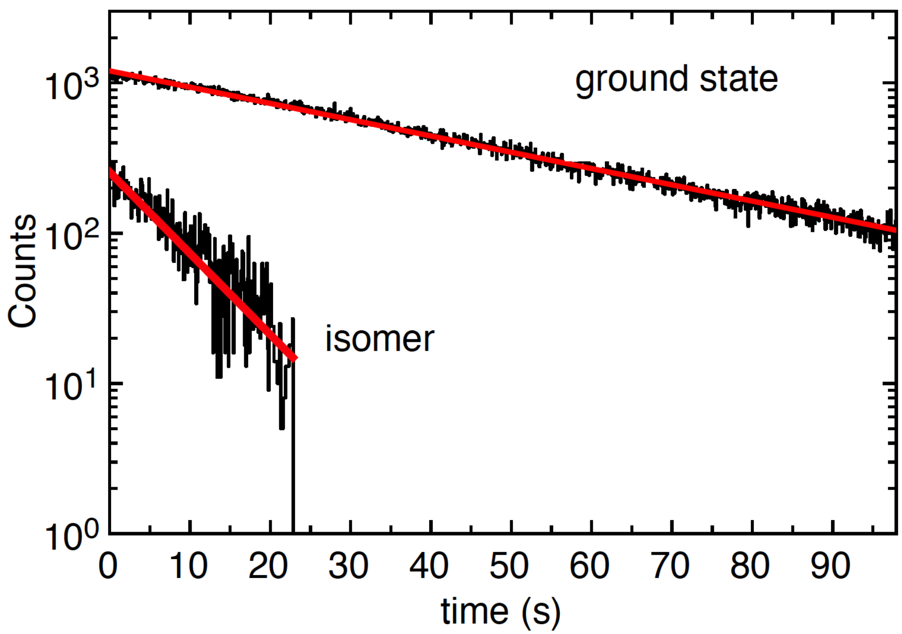
❑ combining direct spectroscopy with callorimetry

isomer studies: ^{156}Pm decay

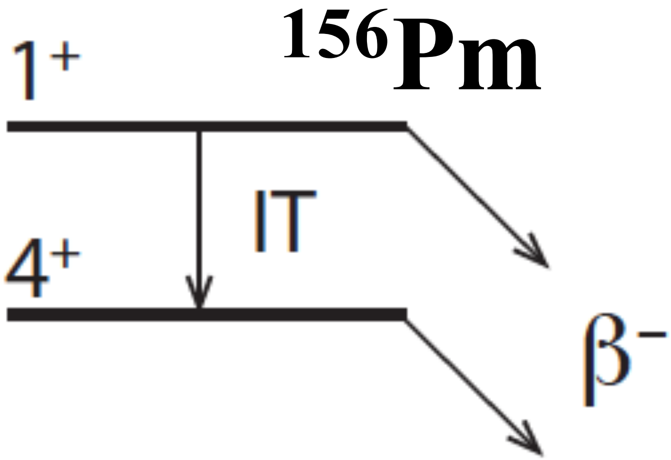


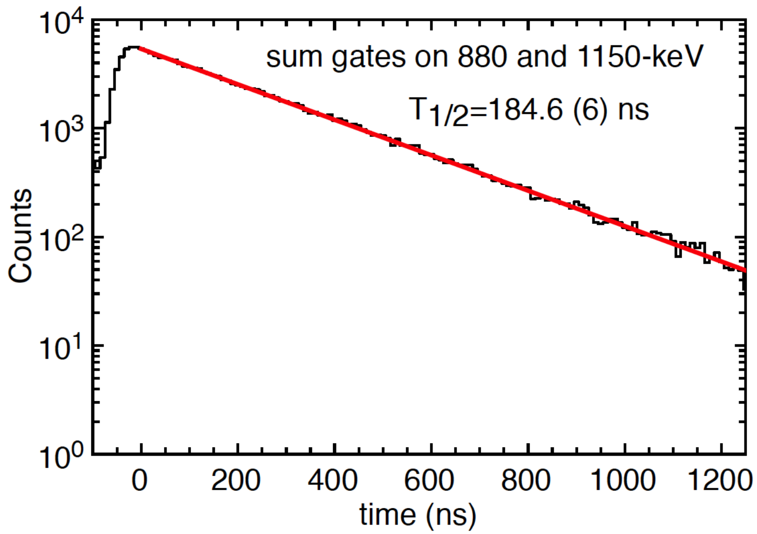




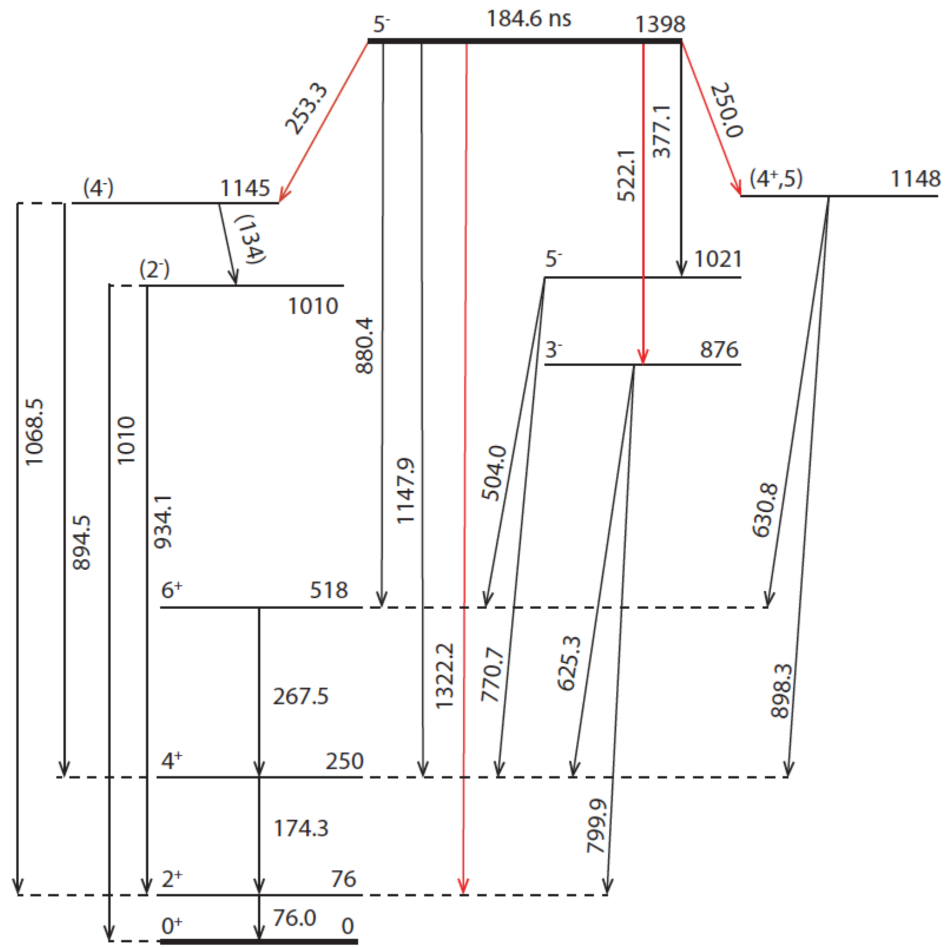


detailed β–γ–γ spectroscopy





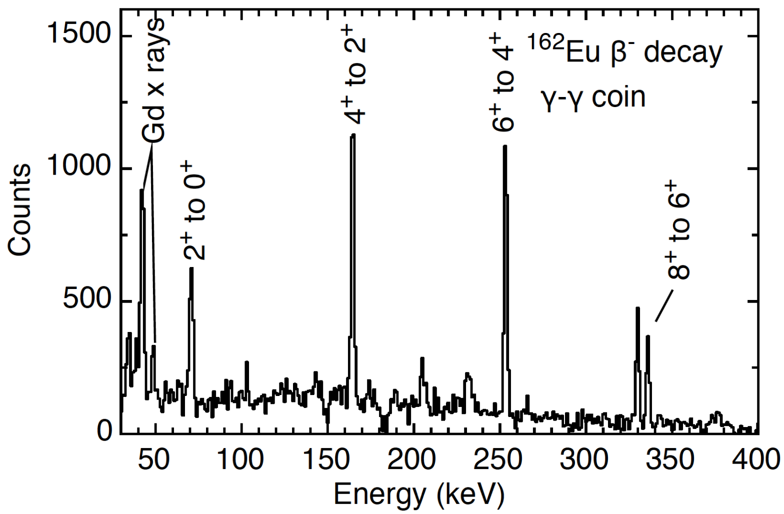
Kπ=5- isomer

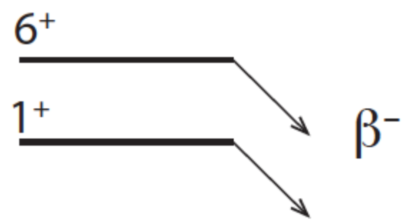


156Sm

… significant differences with the TAS data of Greenwood …

isomer studies: ^{162}Eu decay

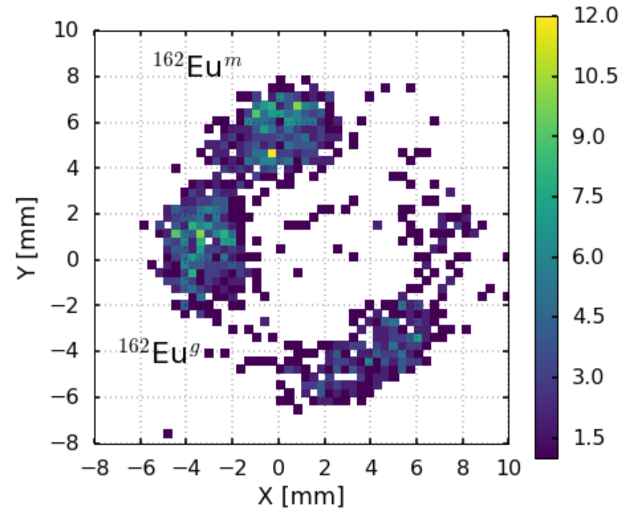


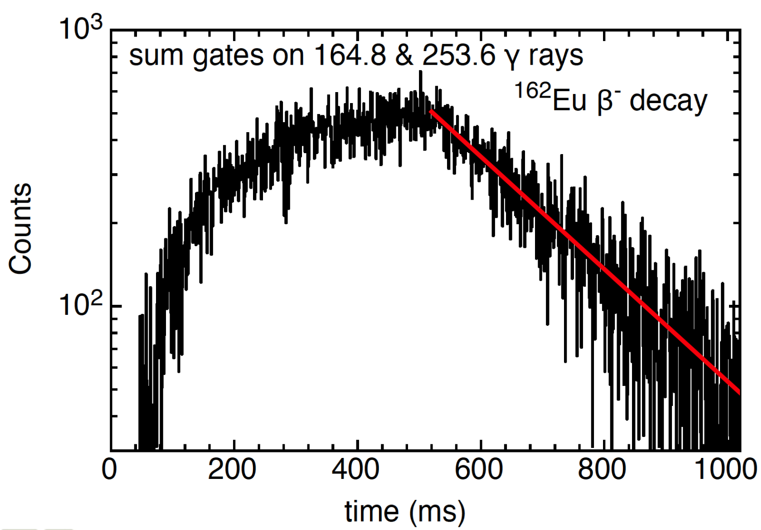


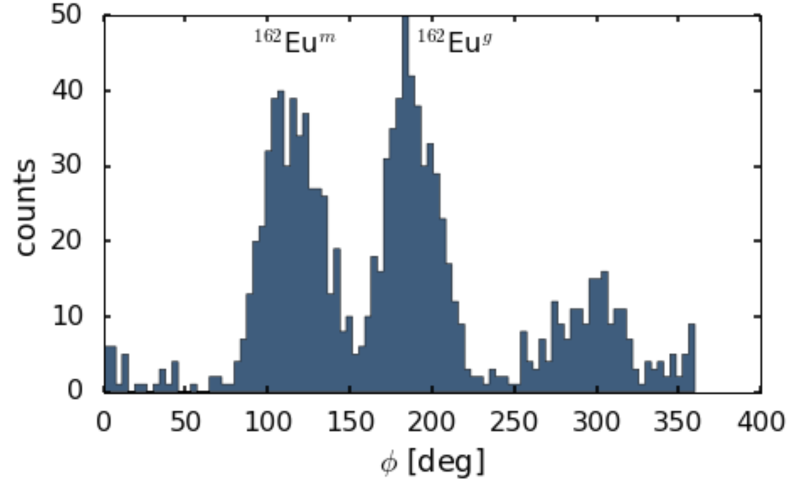
10.6 (1) s from Gd X-rays

Greenwood et al. PRC 35 (1987) 1065

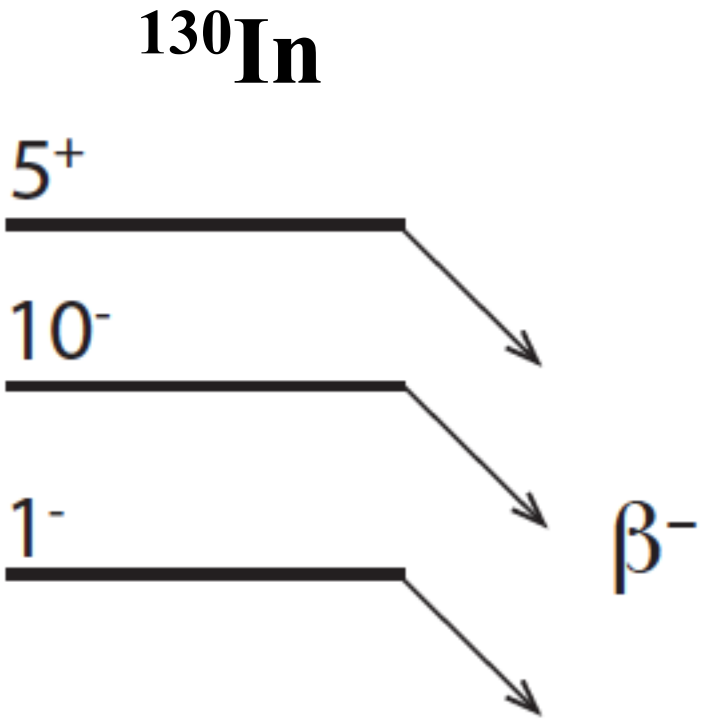
^{162}Eu

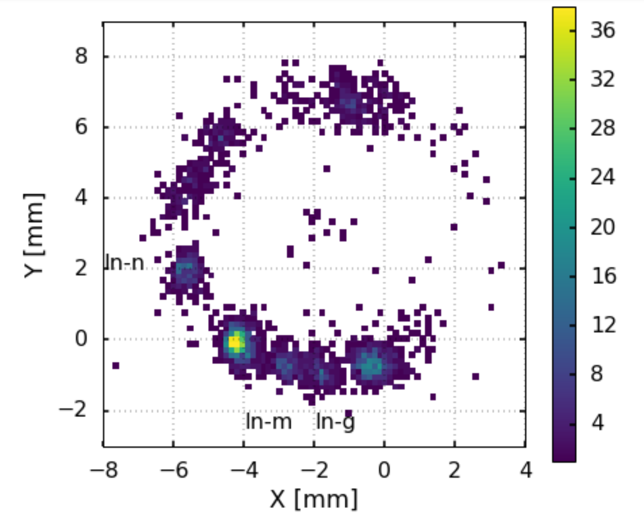


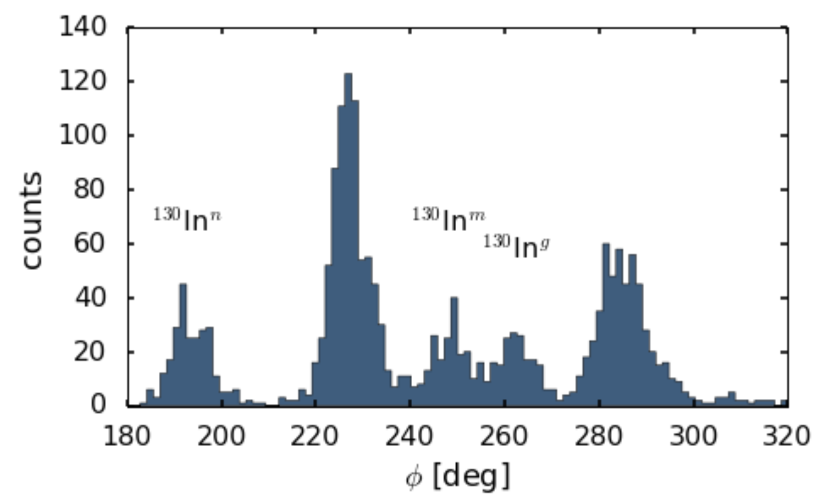




isomer studies: ^{130}In



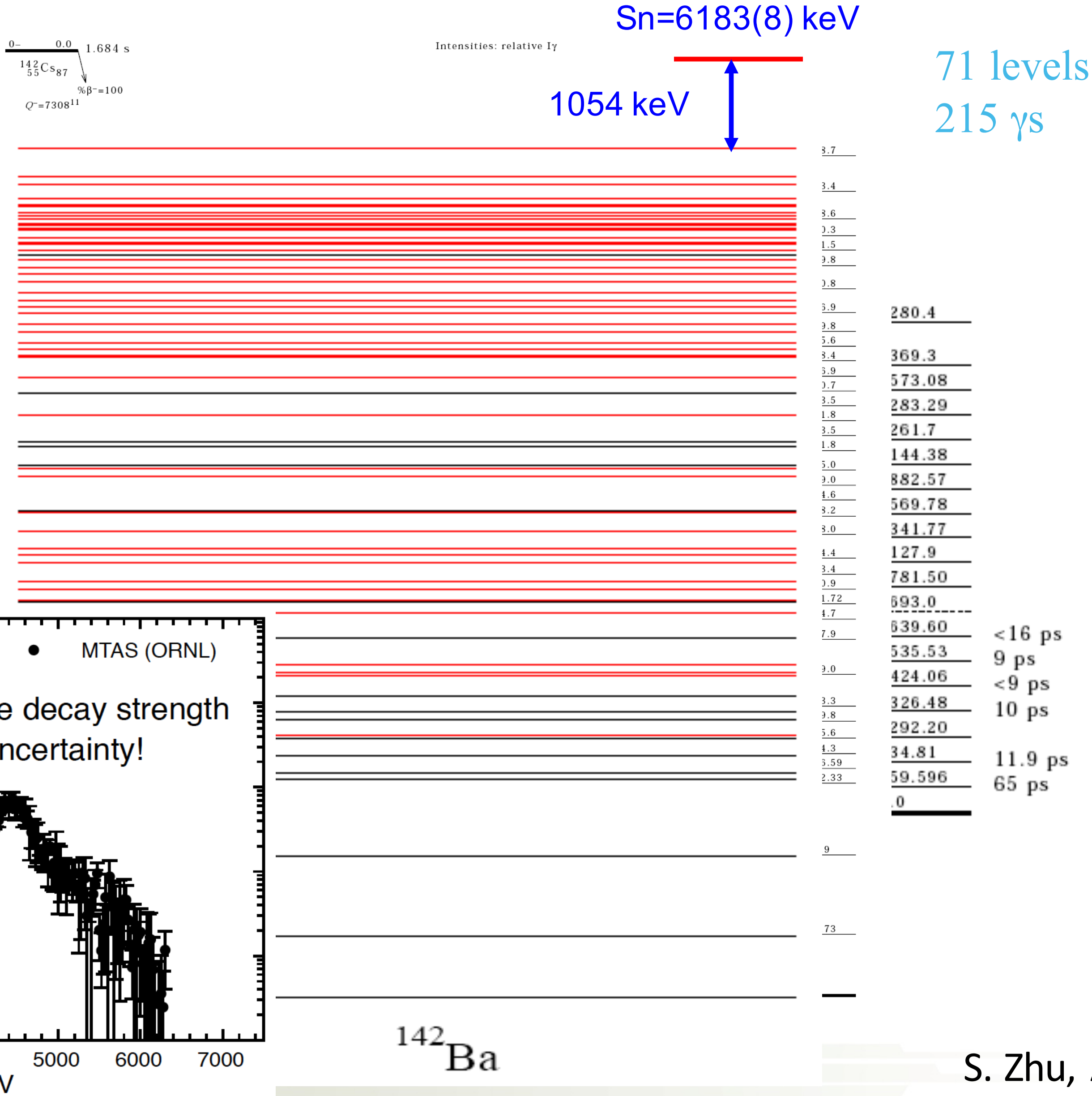




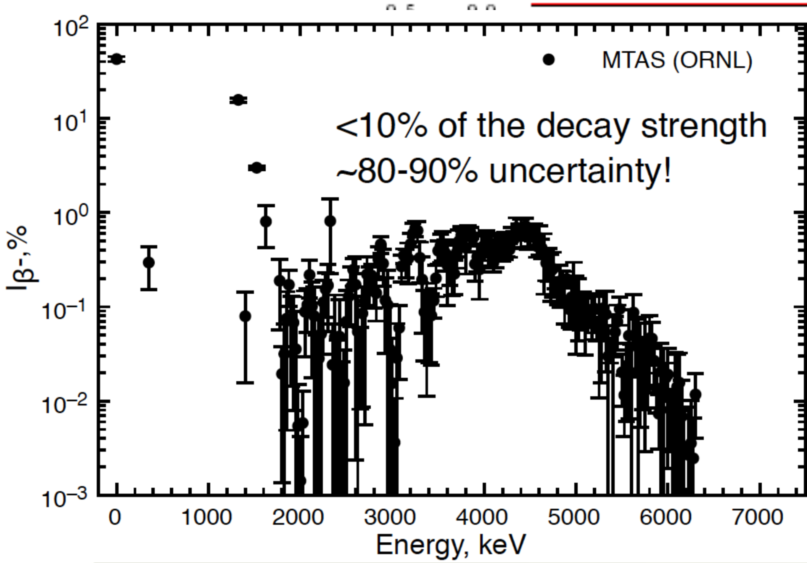
courtesy of G. Savard & J. Clark

Expanded ^{142}Cs β-decay level scheme

CARIBU & Gammasphere at ANL



B.C. Rasco et al., PRL117 (2016)



S. Zhu, ANL