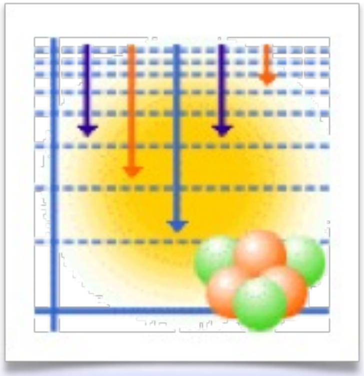
Decay Data in ENSDF

F.G. Kondev
Physics Division, Argonne National Laboratory
kondev@anl.gov



Joint ICTP-IAEA Workshop on Nuclear Structure and Decay Data:
Theory, Experiment and Evaluation, Trieste IT 2022

Introduction

- ❑ decay data are very rich source of nuclear structure information & are of importance to many other areas of science & applications
  - ✓ 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

Introduction – cont.

☐ Experimental Decay Data

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

☐ Evaluated Decay Data

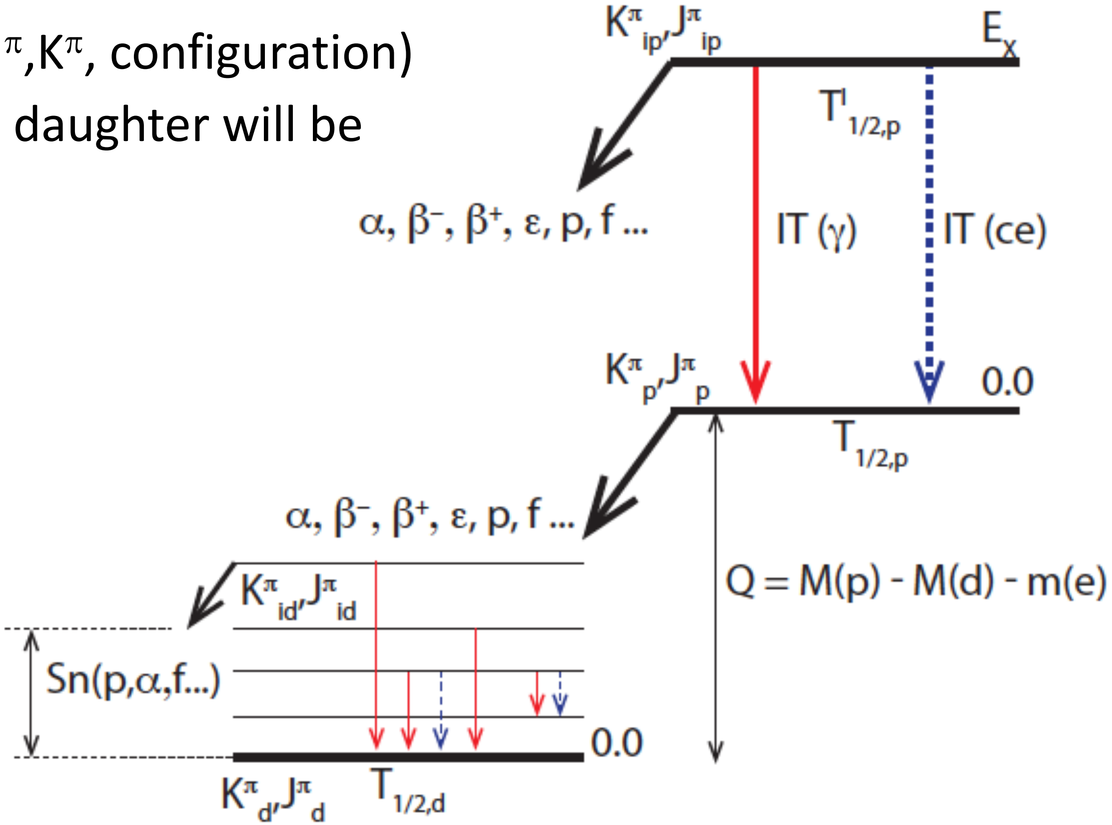
- ✓ Recommended (best) values for nuclear levels and decay radiation properties, deduced by the evaluator using all available experimental data & theoretical calculations (e.g. conv. coefficients)

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 (expt), …

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**

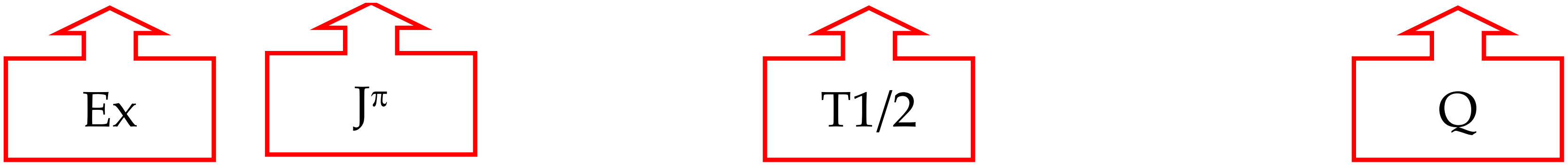


- Q-value – defines the energetics of the decay
  - ✓ controls the lifetime of the parent
  - ✓ the window of daughter states available

Introduction – cont.

- every decay dataset MUST have a Parent record – P in column 8

```
206TL    206HG B- DECAY                1970AS05,1968WO08         08NDS   200805
206TL  H TYP=FUL$AUT=F.G. KONDEV$CIT=NDS 109, 1527 (2008)$CUT=31-Jan-2008$

206TL c  1968Wo08: {+206}Hg produced by {+208}Pb(p,3p) reaction and isotope
206TL2c  separation. |b{+-} measured in proportional counter, ce in Si(Li)
206TL2c  detectors, |g singles and |g|g coincidences in NaI and Ge detector,
206TL3c  and |g|b{+-} coincidences with NaI and Si(Li) detectors.

206TL c  1970As05: {+206}Hg produced by {+208}Pb(p,3p) reaction with E(p)=600
206TL2c  MeV. |g singles measured with Ge detector, lifetime measured with
206TL3c  plastic scintillators.
206TL c  Other: 1969Ha03: survey measurement of level lifetimes using 600 MeV
206TL2c  proton beam on Pb target with isotope separation. Measured limit for
206TL3c  T{-1/2}(305|g).

206HG  P  0          0+                 8.32 M     7             1308     20
```



Ex

col. 10-19

Jπ

col. 22-39

T1/2

col. 40-50

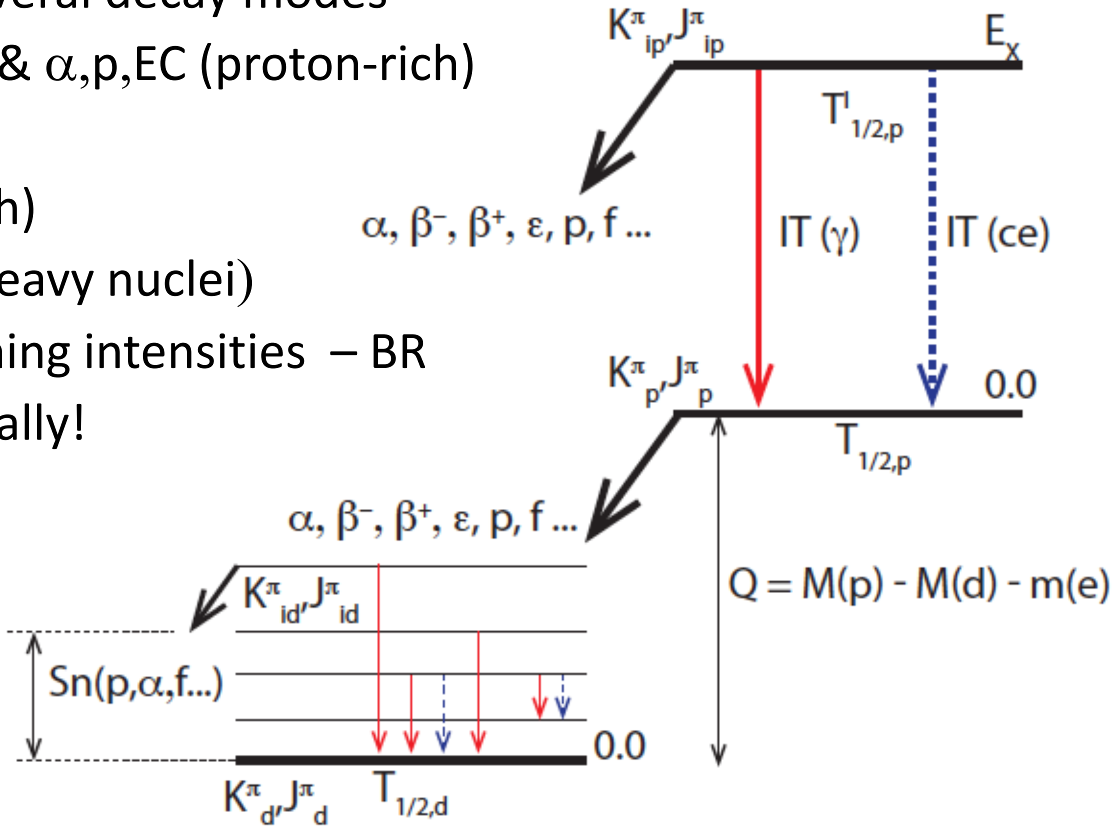
Q

col. 65-75

```
206HG CP T$From 1111AAyy ...
```

Introduction – cont.

- ❑ nuclear state can decay via several decay modes
  - ✓ IT & β^- (neutron-rich) or IT & α,p,EC (proton-rich)
  - ✓ β^- & EC (near the stability)
  - ✓ α & p or α & EC (proton-rich)
  - ✓ α & SF or α & β^- (^{255}Es) (heavy nuclei)
- ❑ one needs to know the branching intensities – BR
  - ✓ not a trivial job experimentally!



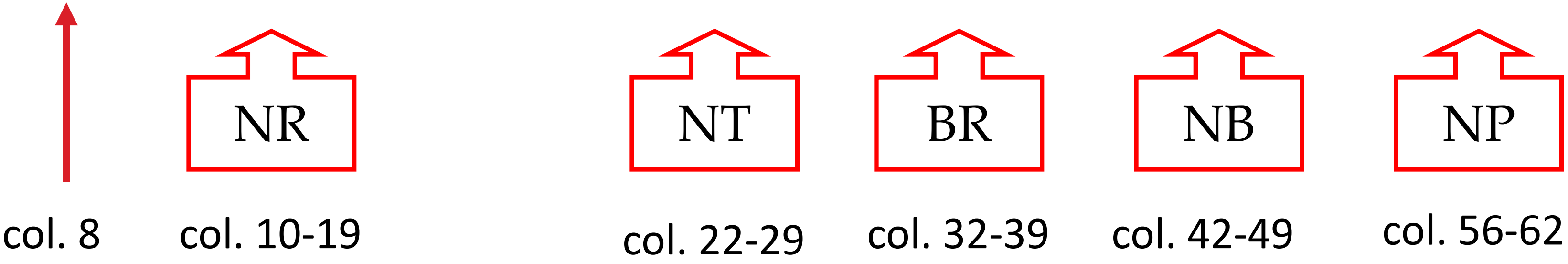
%I = Intensity/100 parent decays

- ❑ usually the experiments provide relative emission probabilities – absolute measurements are difficult & rare
  - ✓ **convert relative to absolute emission probabilities using the properties of the decay scheme – NORMALIZATION**

Introduction – cont.

❑ **every decay dataset MUST have a Normalization record**

```
177HF    177LU B- DECAY (6.647 D)      2001Sc23                  03NDS     200305
177HF  N 0.1036     7            1.0         1.0
```



col. 8

NR col. 10-19

NT col. 22-29

BR col. 32-39

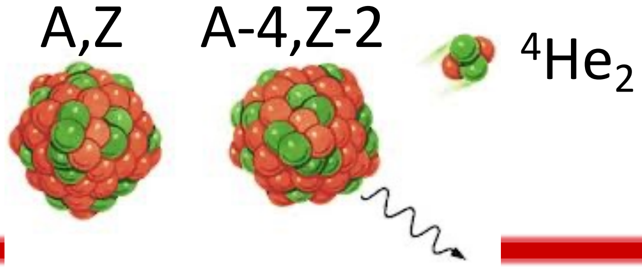
NB col. 42-49

NP col. 56-62

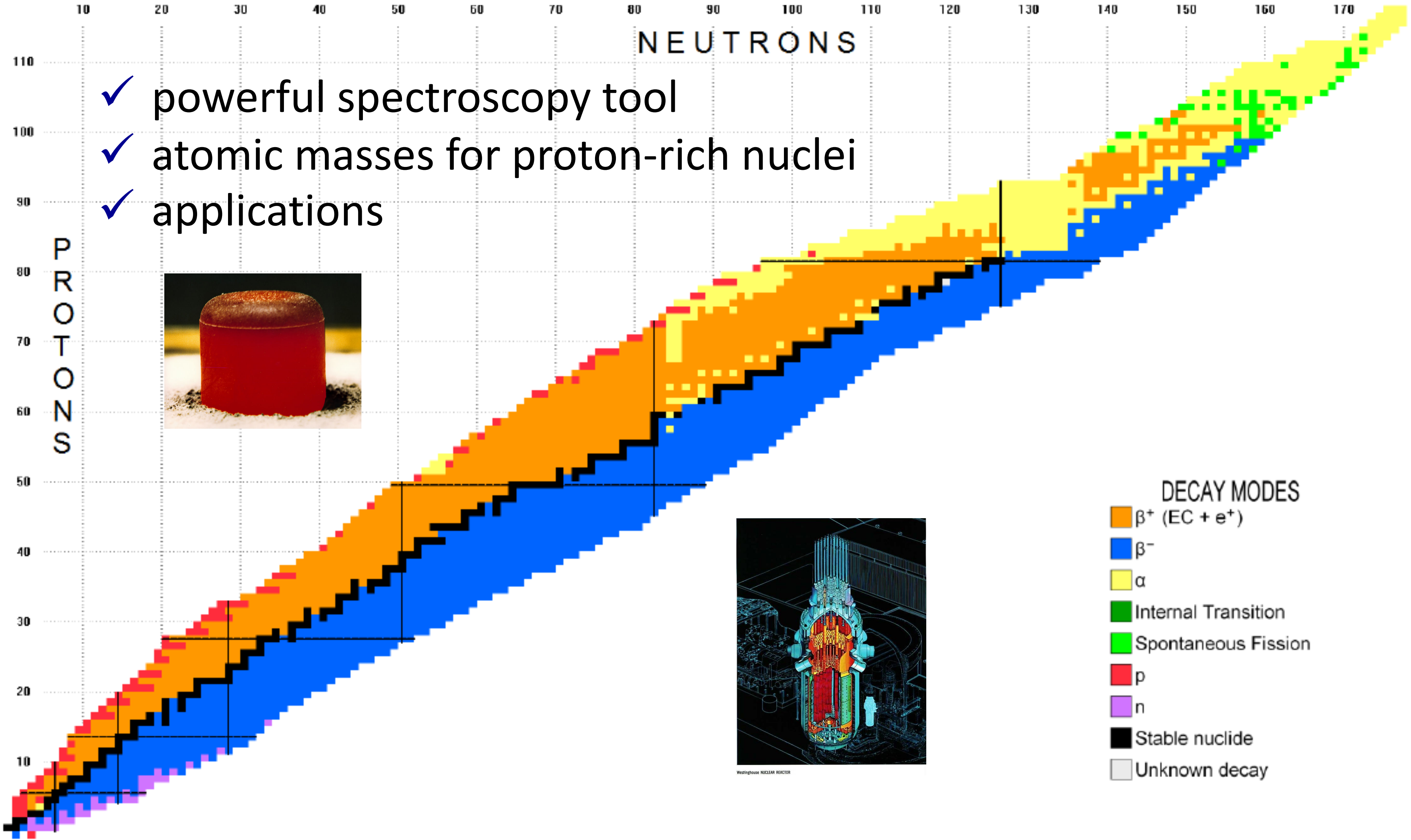
Relative Intensity	Normalization factor	Absolute Intensity
Iγ x	NR x BR	= %Iγ
Iγ (tot) x	NT x BR	= %Iγ (tot)
Iβ (or α or ε) x	NB x BR	= %Iβ (or α or ε)
Iβn (or εp …) x	NP x BR	= %Iβn (or εp …)

```
177HF cN NR$Using absolute |g ray intensity for the 208.3662|g of 10.36% {I7}
177HF2cN from 2001Sc23
```

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:

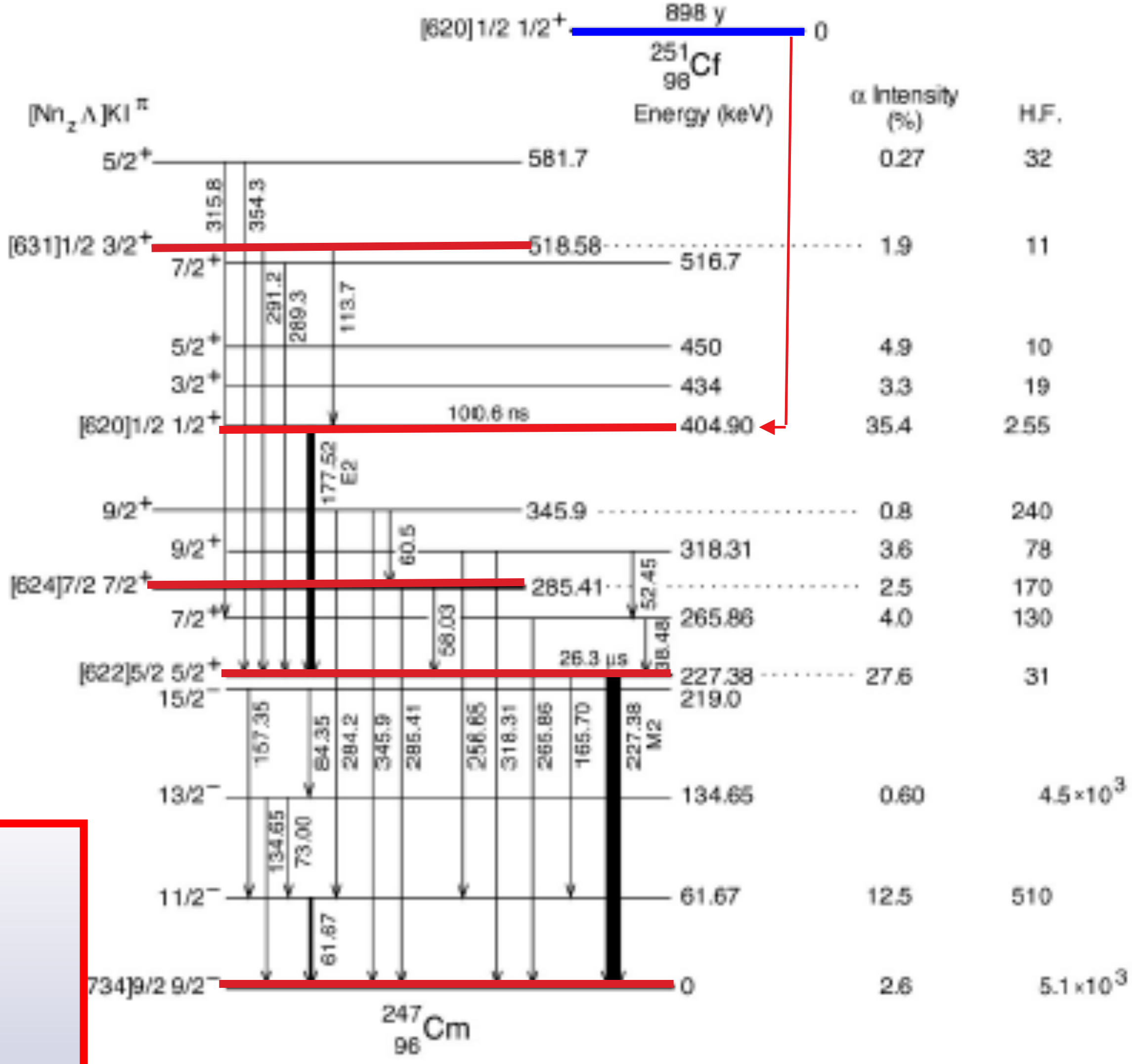
0+ -> 0+; l_α=0

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**

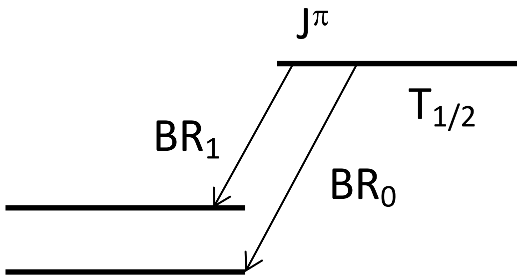
☐ **Configuration dependence**

✓ **fastest for the same configurations**

Hindrance Factor in α–decay

HF < 4 – favored 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(α) - nuclear radius: $R = r_0 \times A^{1/3}$

$$v = \sqrt{2E\alpha / m\alpha}$$

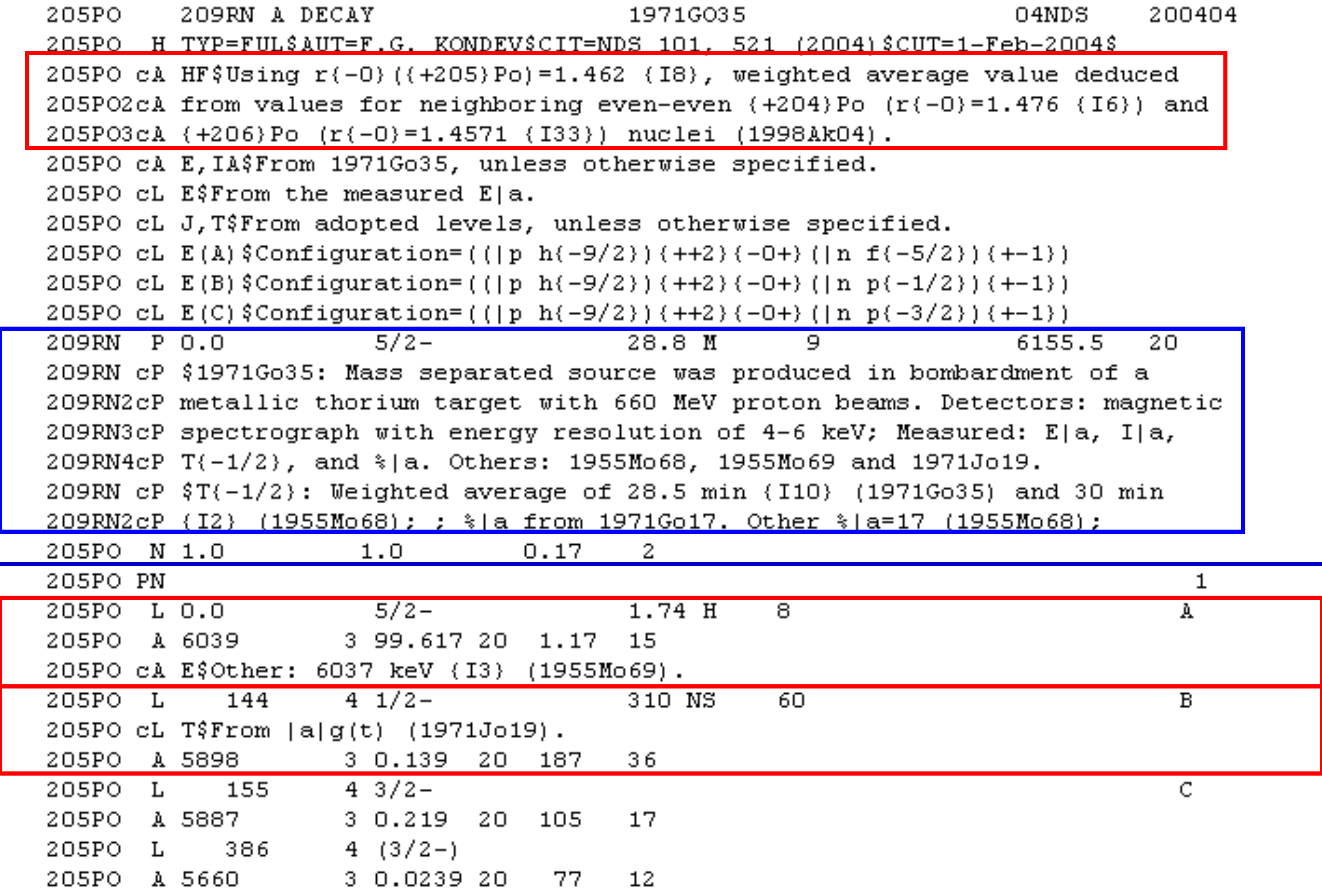
$$Q\alpha = (m(A,Z) - m\alpha) - \sqrt{(m(A,Z) - m\alpha)^2 - 2\times m(A,Z)\times E\alpha} + B_{e,\alpha}$$

$B_{e,\alpha}$=78.6 [eV]

relativistic formula

since AME16

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



```
205PO    209RN A DECAY                 1971GO35                  04NDS    200404
205PO  H TYP=FUL$AUT=F.G. KONDEV$CIT=NDS 101, 521 (2004)$CUT=1-Feb-2004$
205PO cA HF$Using r{-0}({+205}Po)=1.462 {I8}, weighted average value deduced
205PO2cA from values for neighboring even-even {+204}Po (r{-0}=1.476 {I6}) and
205PO3cA {+206}Po (r{-0}=1.4571 {I33}) nuclei (1998Ak04).
205PO cA E,IA$From 1971Go35, unless otherwise specified.
205PO cL E$From the measured E|a.
205PO cL J,T$From adopted levels, unless otherwise specified.
205PO cL E(A)$Configuration=((|p h{-9/2}){++2}{-0+}(|n f{-5/2}){+-1})
205PO cL E(B)$Configuration=((|p h{-9/2}){++2}{-0+}(|n p{-1/2}){+-1})
205PO cL E(C)$Configuration=((|p h{-9/2}){++2}{-0+}(|n p{-3/2}){+-1})
209RN  P 0.0          5/2-             28.8 M      9             6155.5   20
209RN cP $1971Go35: Mass separated source was produced in bombardment of a
209RN2cP metallic thorium target with 660 MeV proton beams. Detectors: magnetic
209RN3cP spectrograph with energy resolution of 4-6 keV; Measured: E|a, I|a,
209RN4cP T{-1/2}, and %|a. Others: 1955Mo68, 1955Mo69 and 1971Jo19.
209RN cP $T{-1/2}: Weighted average of 28.5 min {I10} (1971Go35) and 30 min
209RN2cP {I2} (1955Mo68); ; %|a from 1971Go17. Other %|a=17 (1955Mo68);
205PO  N 1.0         1.0        0.17    2
205PO PN                                                                     1
205PO  L 0.0          5/2-             1.74 H    8                          A
205PO  A 6039       3 99.617 20  1.17  15
205PO cA E$Other: 6037 keV {I3} (1955Mo69).
205PO  L    144     4 1/2-             310 NS    60                         B
205PO cL T$From |a|g(t) (1971Jo19).
205PO  A 5898       3 0.139  20  187   36
205PO  L    155     4 3/2-                                                  C
205PO  A 5887       3 0.219  20  105   17
205PO  L    386     4 (3/2-)
205PO  A 5660       3 0.0239 20   77   12
```

program alphad

^{209}Rn α Decay 1971Go35

Parent ^{209}Rn: E=0.0; Jπ=5/2−; $T_{1/2}$=28.8 min *9*; Q(g.s.)=6155.5 *20*; %α decay=17 *2*.

^{209}Rn: 1971Go35: Mass separated source was produced in bombardment of a metallic thorium target with 660 MeV proton beams. Detectors: magnetic spectrograph with energy resolution of 4–6 keV; Measured: Eα, Iα, $T_{1/2}$, and %α. Others: 1955Mo68, 1955Mo69 and 1971Jo19.

^{209}Rn: $T_{1/2}$: Weighted average of 28.5 min *10* (1971Go35) and 30 min *2* (1955Mo68); ; %α from 1971Go17. Other %α=17 (1955Mo68).

^{205}Po Levels

E(level)[†]	Jπ[‡]	$T_{1/2}$[‡]	
0.0[§]	5/2−	1.74 h *8*	
144[#] *4*	1/2−	310 ns *60*	$T_{1/2}$: From αγ(t)
155[@] *4*	3/2−		
386 *4*	(3/2−)		

[†] From the measured Eα.

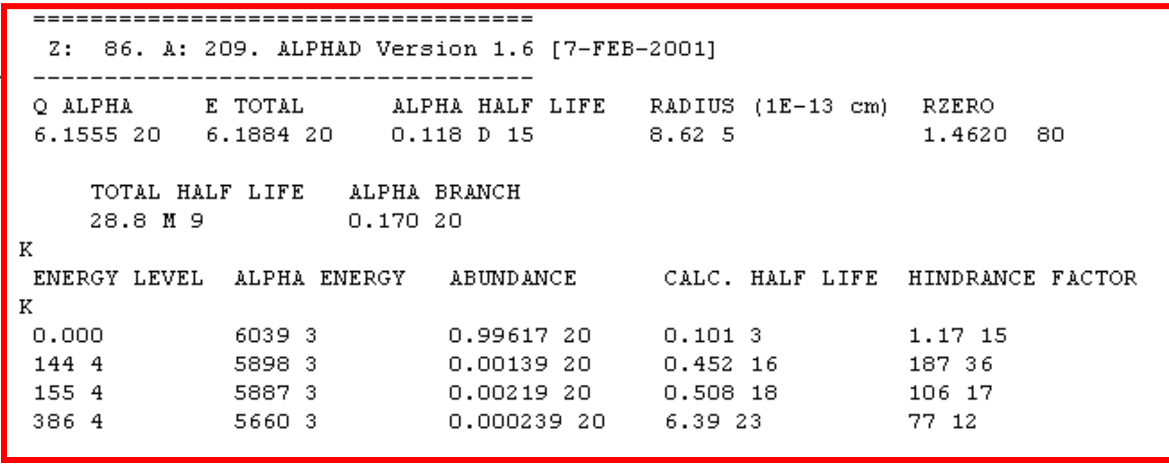
[‡] From adopted levels, unless otherwise specified.

[§] Configuration=$((\pi h_{9/2})^{+2}_{0+}(\nu f_{5/2})^{-1})$.

[#] Configuration=$((\pi h_{9/2})^{+2}_{0+}(\nu p_{1/2})^{-1})$.

[@] Configuration=$((\pi h_{9/2})^{+2}_{0+}(\nu p_{3/2})^{-1})$.

alphad.rpt



```
 ====================================
  Z:  86. A: 209. ALPHAD Version 1.6 [7-FEB-2001]
 ------------------------------------
 Q ALPHA      E TOTAL      ALPHA HALF LIFE    RADIUS (1E-13 cm)  RZERO
 6.1555 20    6.1884 20    0.118 D 15         8.62 5             1.4620  80

     TOTAL HALF LIFE    ALPHA BRANCH
     28.8 M 9           0.170 20
K
 ENERGY LEVEL  ALPHA ENERGY   ABUNDANCE      CALC. HALF LIFE  HINDRANCE FACTOR
K
 0.000         6039 3         0.99617 20     0.101 3          1.17 15
 144 4         5898 3         0.00139 20     0.452 16         187 36
 155 4         5887 3         0.00219 20     0.508 18         106 17
 386 4         5660 3         0.000239 20    6.39 23          77 12
```

α radiations

Eα[‡]	E(level)	Iα[‡][§]	HF[†]	Comments
5660 *3*	386	0.0239 *20*	77 *12*	
5887 *3*	155	0.219 *20*	105 *17*	
5898 *3*	144	0.139 *20*	187 *36*	
6039 *3*	0.0	99.617 *20*	1.17 *15*	Eα: Other: 6037 keV *3* (1955Mo69).

same Jπ and configuration

[†] Using $r_0(^{205}Po)$=1.462 *8*, weighted average value deduced from values for neighboring even-even ^{204}Po (r_0=1.476 *6*) and ^{206}Po (r_0=1.4571 *33*) nuclei (1998Ak04).

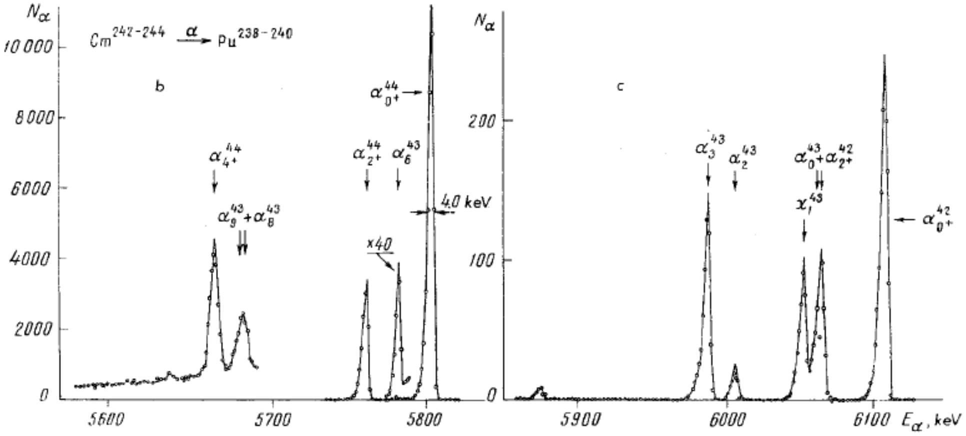
[‡] From 1971Go35, unless otherwise specified.

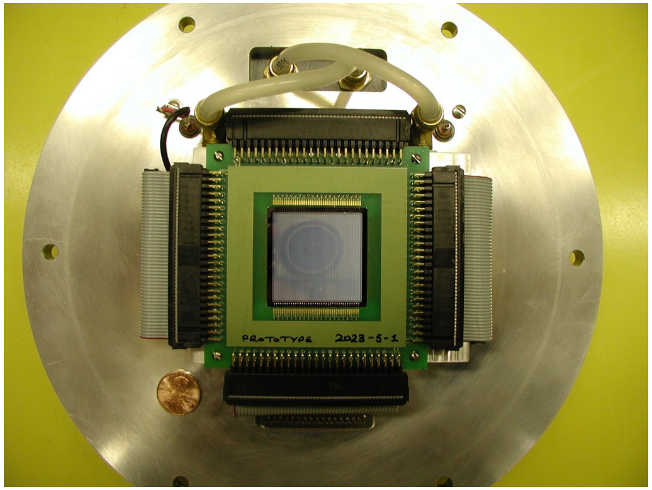
[§] For α intensity per 100 decays, multiply by 0.17 *2*.

Experimental techniques

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

1.5 keV energy resolution



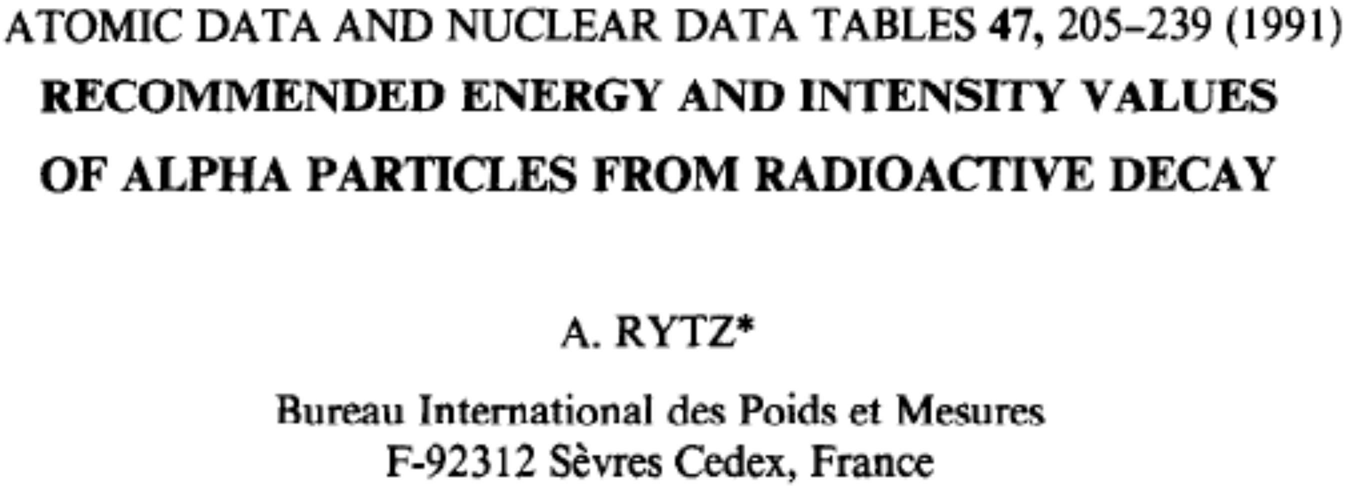


- ❑ using radioactive sources (off-line)
  - ✓ when lifetimes are sufficiently long

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

Energy Calibration

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**



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

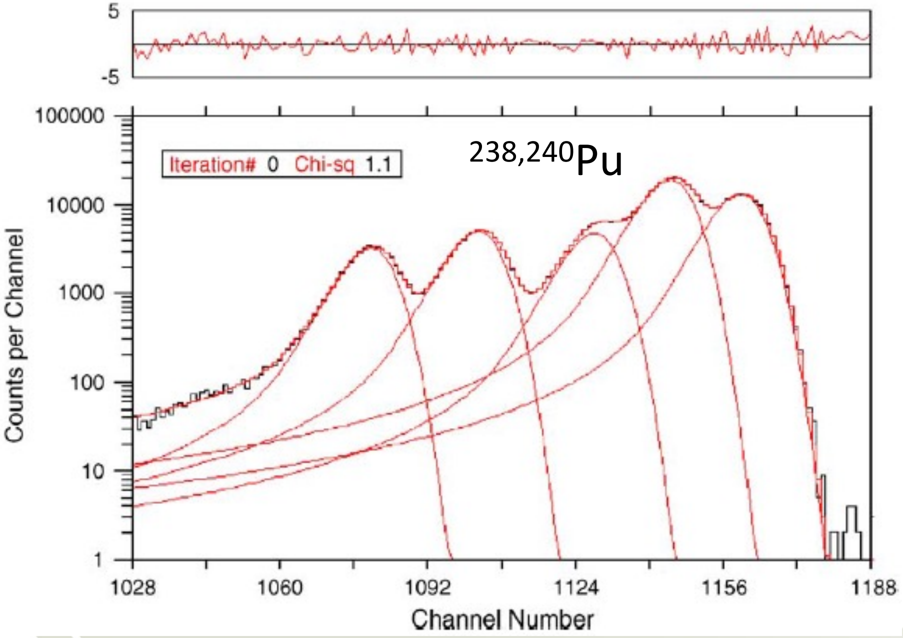
Long-lived radioactive sources

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

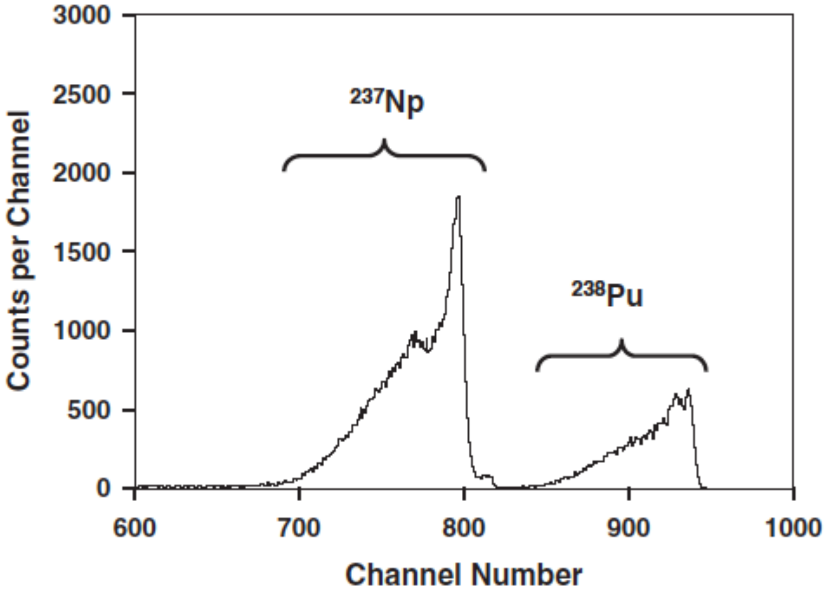
✓ energy resolution (FWHM) of 9-12 keV

✓ small geometrical efficiency (Ω) in order to minimize α–e- coincidence summing effects

✓ sophisticated data analysis



✓ thin and isotopically pure sources

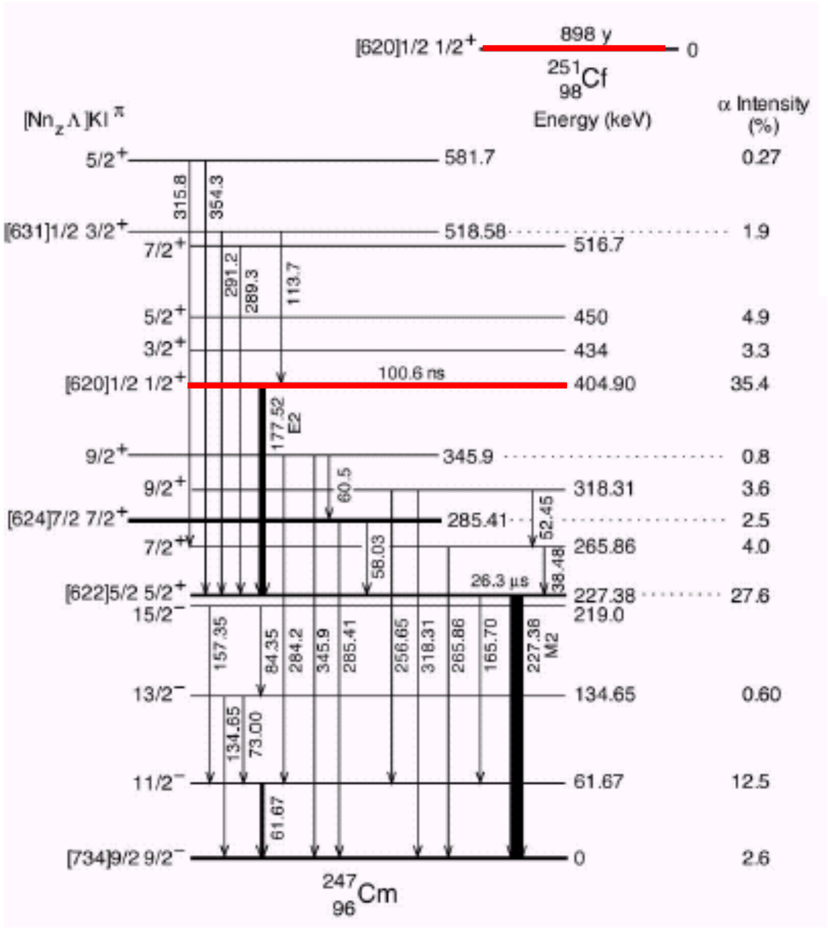


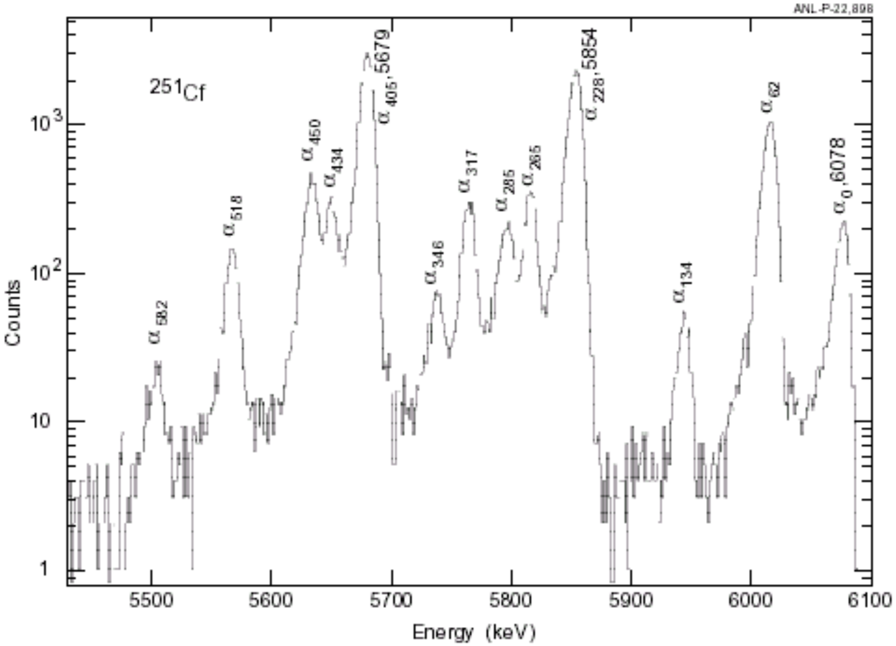
Harada et al. J. Nucl. Sci. and Techn. 43 (2006) 1289

^{251}Cf α–decay

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

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

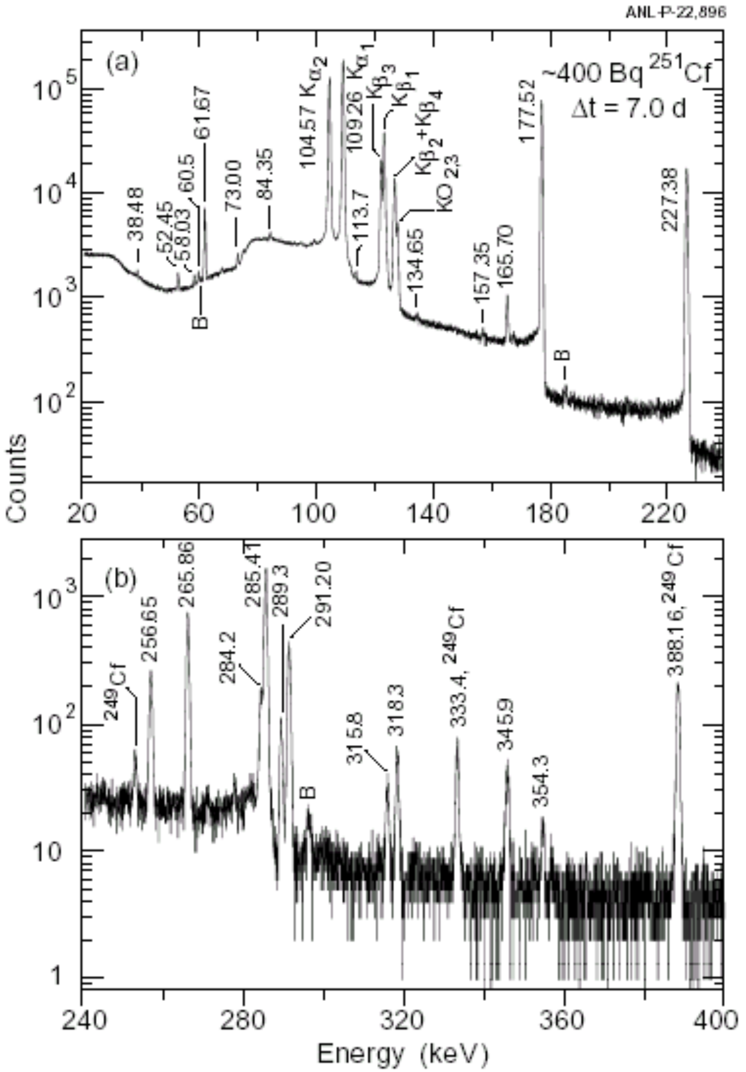


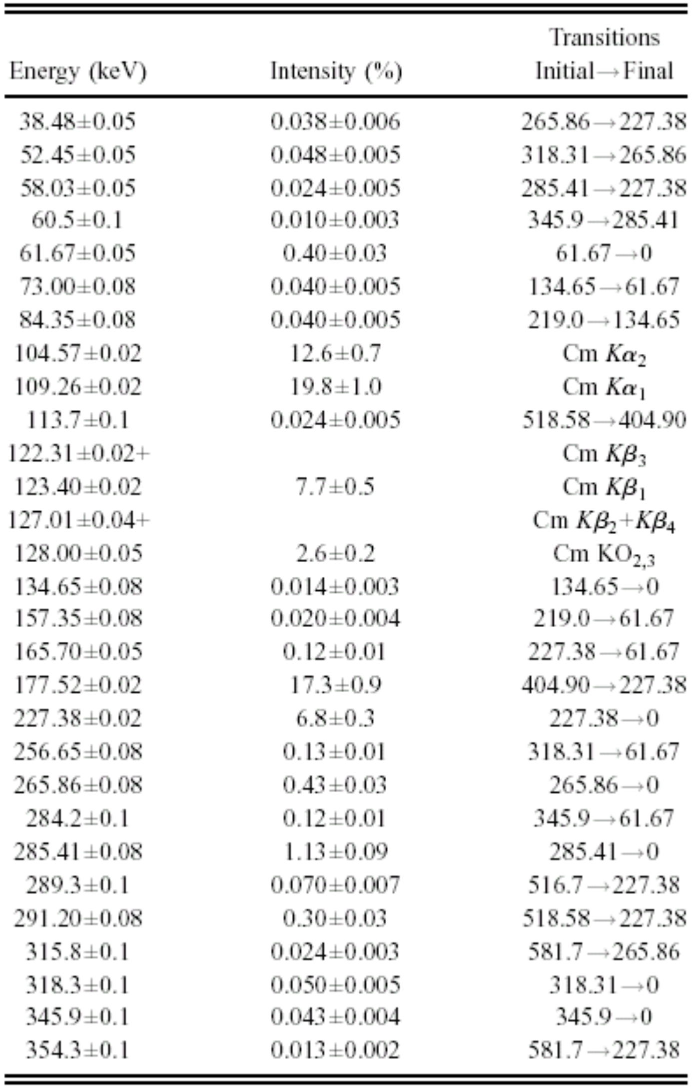


Energy (MeV)	Excited state energy (keV)	Intensity (%)	Hindrance factor[a]
6.078±0.002	0	2.6±0.1	5.1×10^3
6.017±0.002	62	12.5±0.3	5.1×10^2
5.946±0.002	134	0.60±0.06	4.5×10^3
5.854±0.002	228	27.6±0.5	31
5.817±0.002	265	4.0±0.2	1.3×10^2
5.798±0.002	285	2.5±0.2	1.7×10^2
5.766±0.002	317	3.6±0.2	78
5.738±0.002	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.

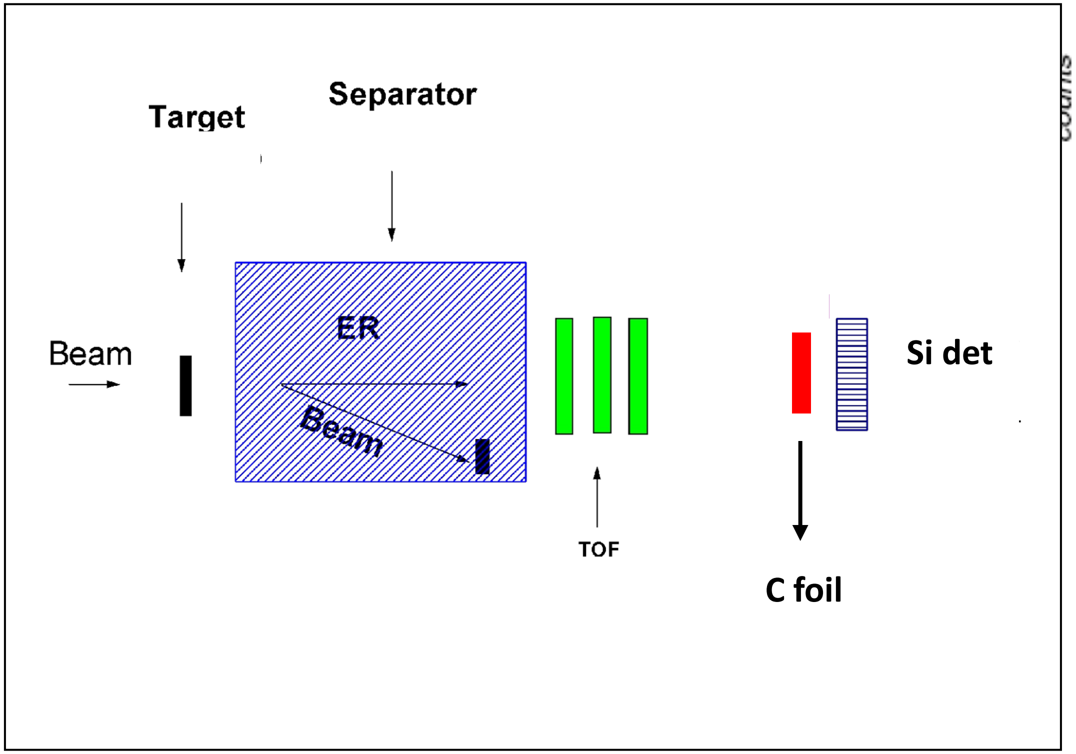


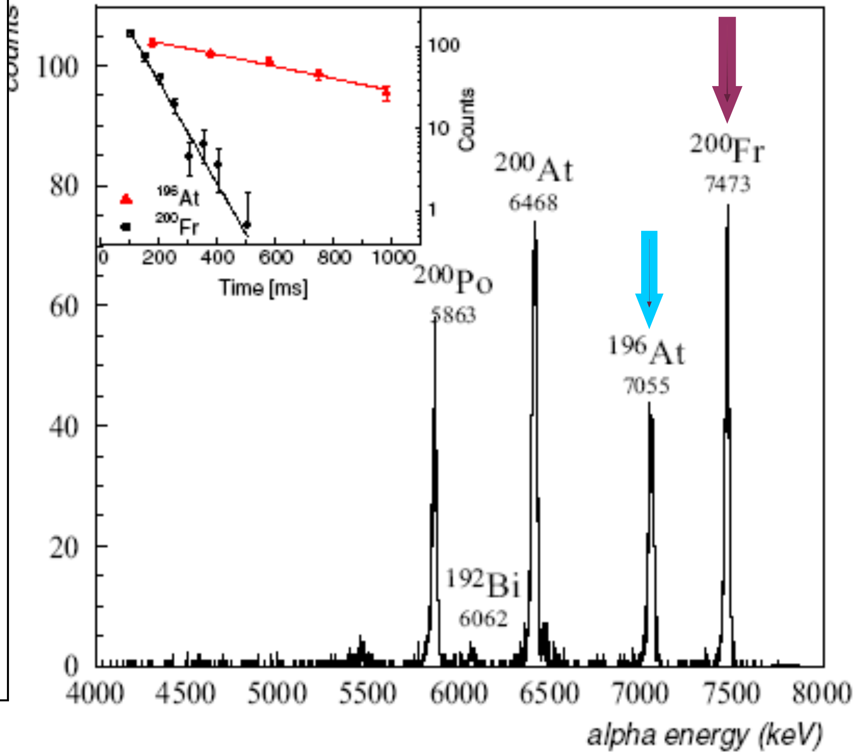


		Transitions
Energy (keV)	Intensity (%)	Initial→Final
38.48±0.05	0.038±0.006	265.86→227.38
52.45±0.05	0.048±0.005	318.31→265.86
58.03±0.05	0.024±0.005	285.41→227.38
60.5±0.1	0.010±0.003	345.9→285.41
61.67±0.05	0.40±0.03	61.67→0
73.00±0.08	0.040±0.005	134.65→61.67
84.35±0.08	0.040±0.005	219.0→134.65
104.57±0.02	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

No direct detector implantation





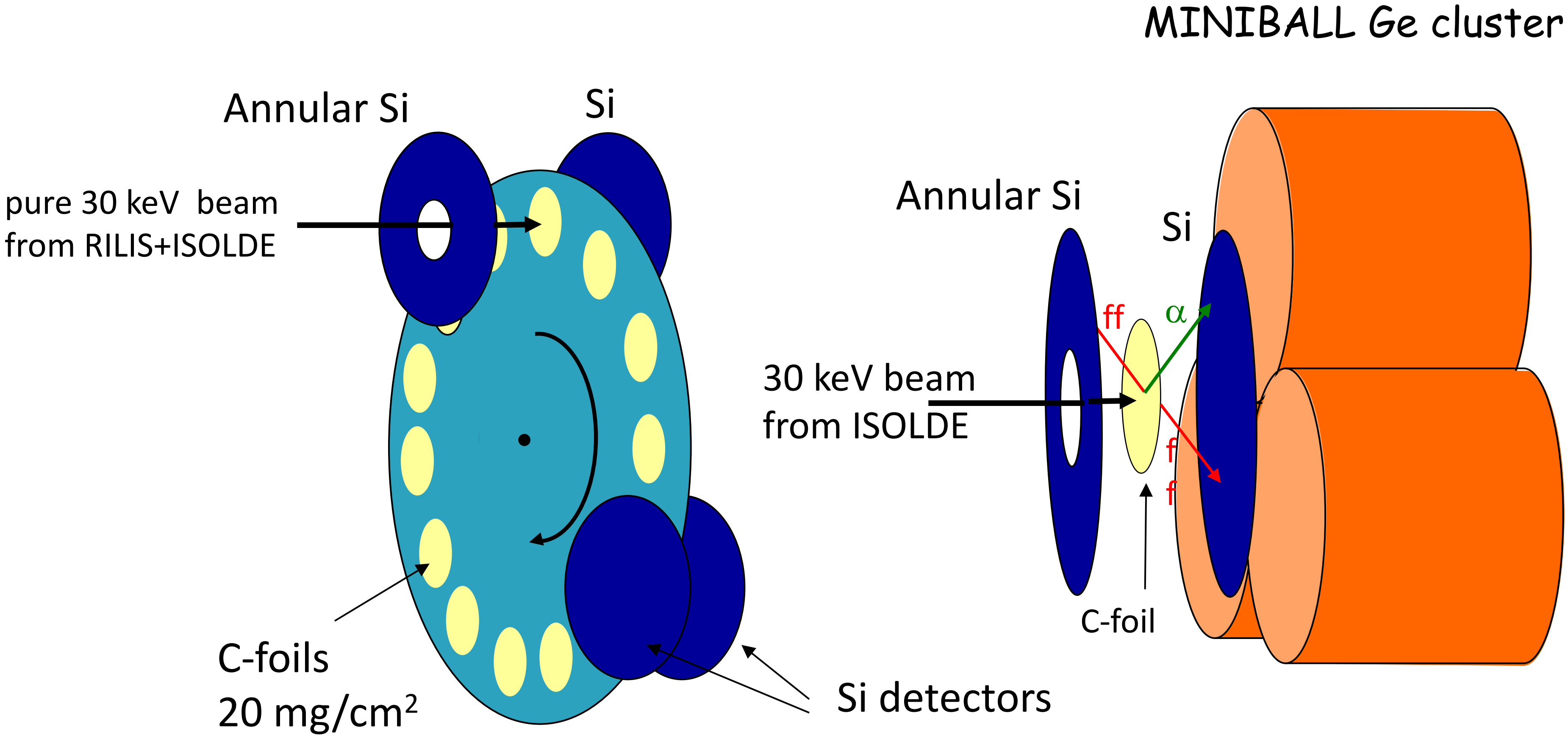
1 GeV pulsed proton beam on 51 g/cm2 ThCx target

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]

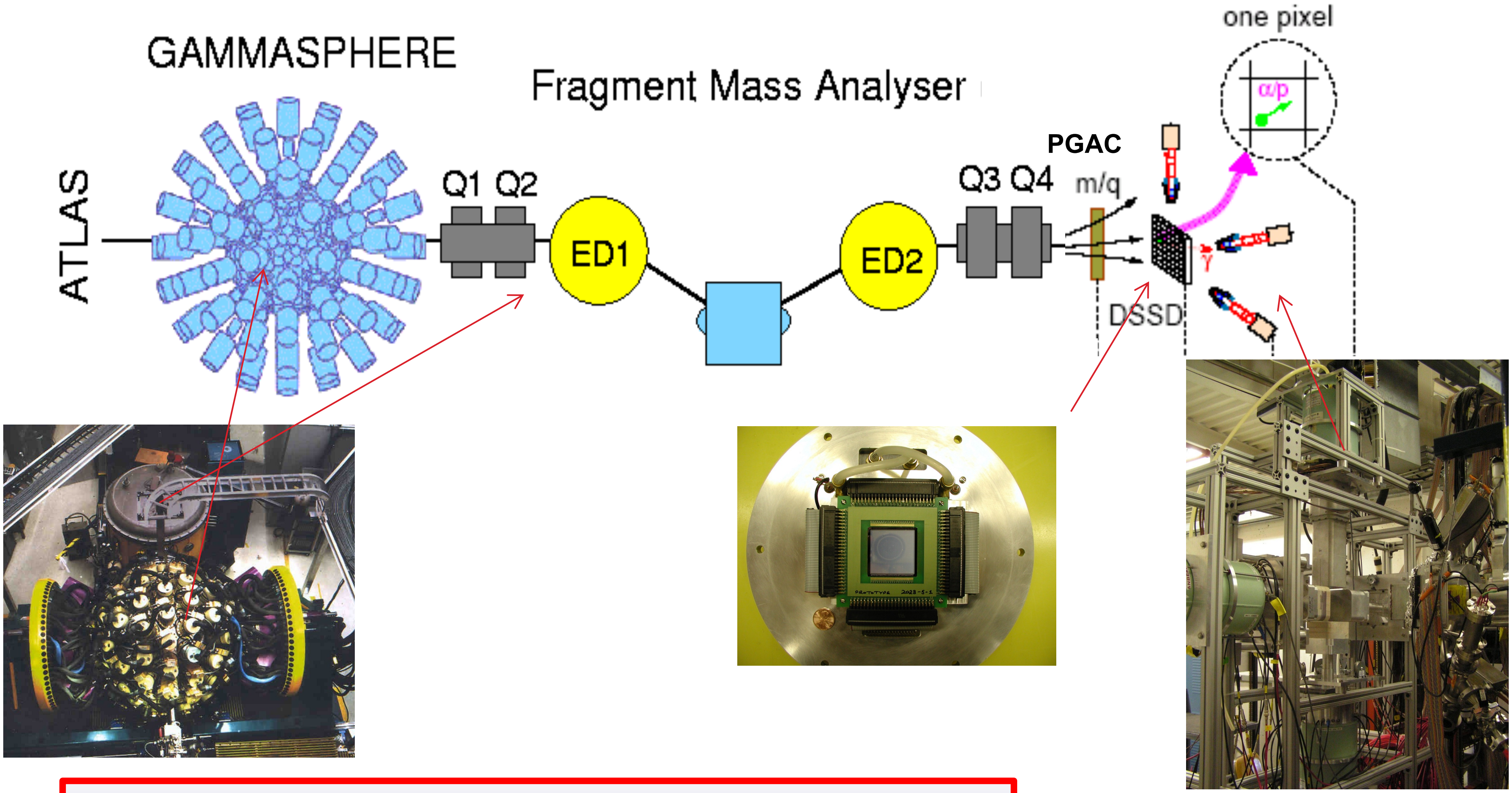
H. De Witte et al., EPJ A23 (2005) 243

Windmill System (WM) at ISOLDE



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

Direct implantation on the detector

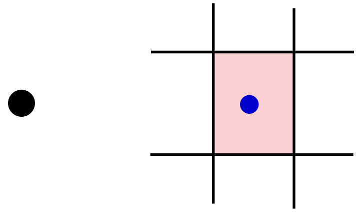


- ✓ spectroscopy of proton-rich nuclei far from stability
- ✓ studies of heavy and super-heavy nuclei

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

Direct implantation on the detector

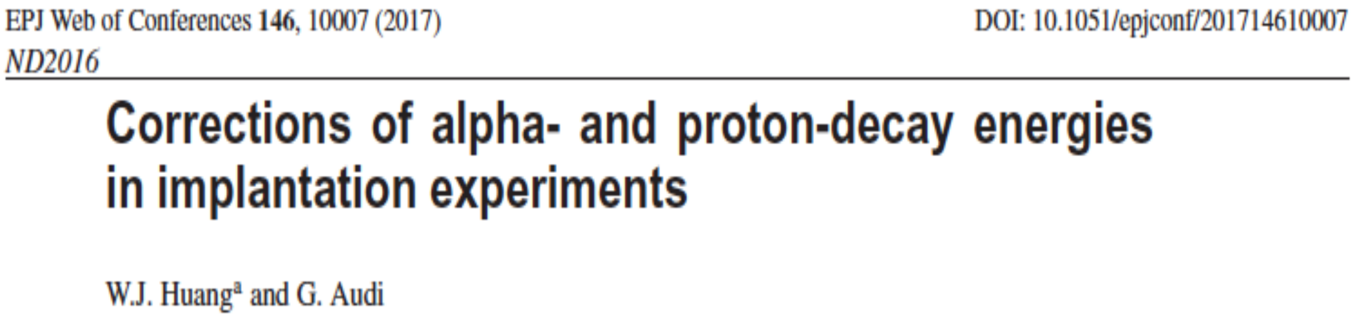
Implantation - Decay within a single pixel



$$Q\alpha = E\alpha \times \left(1 + \frac{4}{A-4}\right) = E\alpha + E\alpha\frac{4}{A-4}$$

Important: how calibration was made?

- ✓ external source, e.g. ^{252}Cf – needs correction
- ✓ internally, but when A(cal) is very different need to be corrected



EPJ Web of Conferences **146**, 10007 (2017) DOI: 10.1051/epjconf/201714610007

ND2016

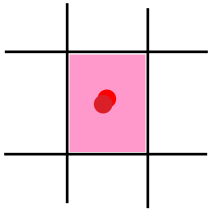
Corrections of alpha- and proton-decay energies in implantation experiments

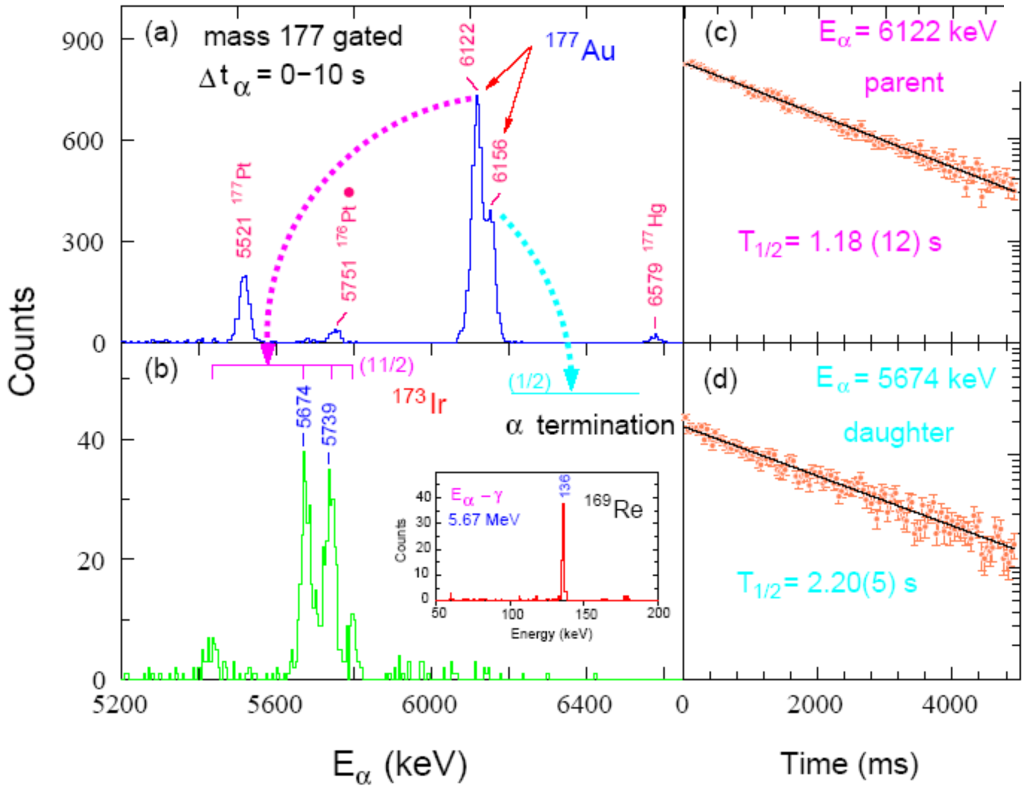
W.J. Huang[a] and G. Audi

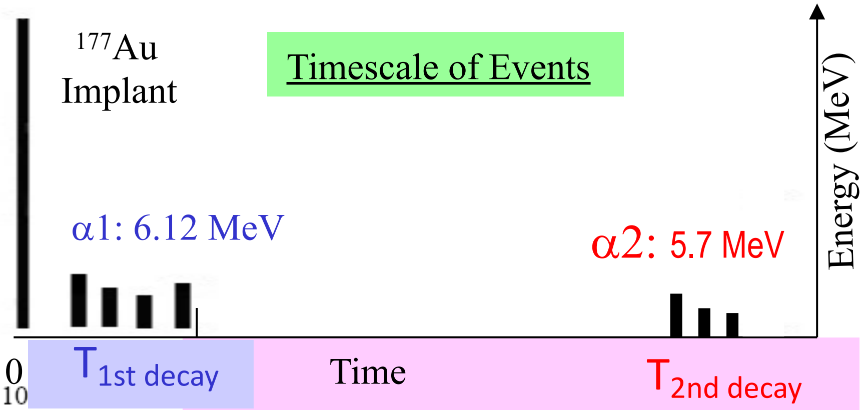
α1–α2 (parent-daughter) correlations

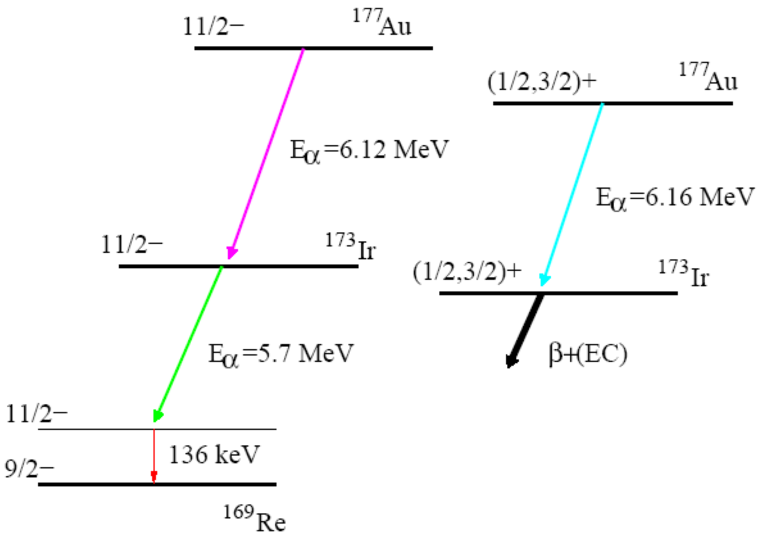
^{84}Sr + $^{92-96}$Mo@$^{176-180}$Hg

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



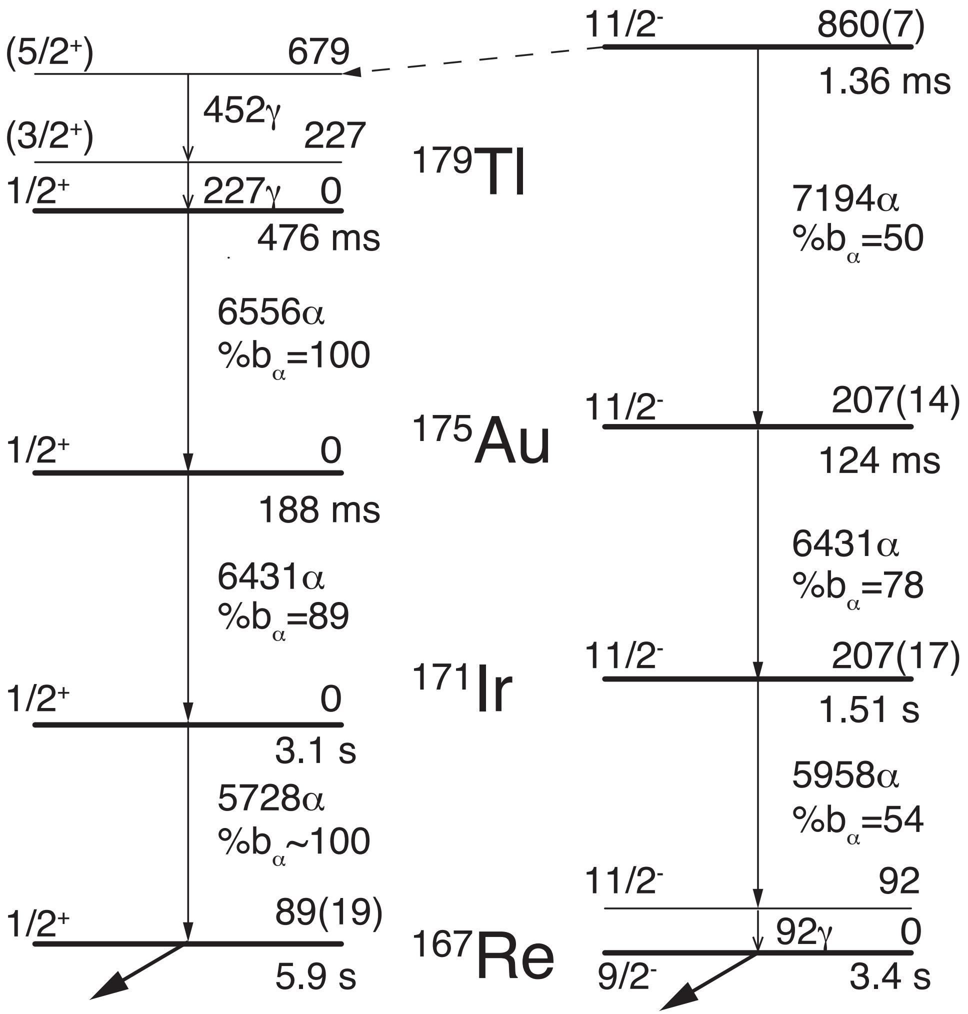






F.G. Kondev et al. Phys. Lett. B528 (2002) 221

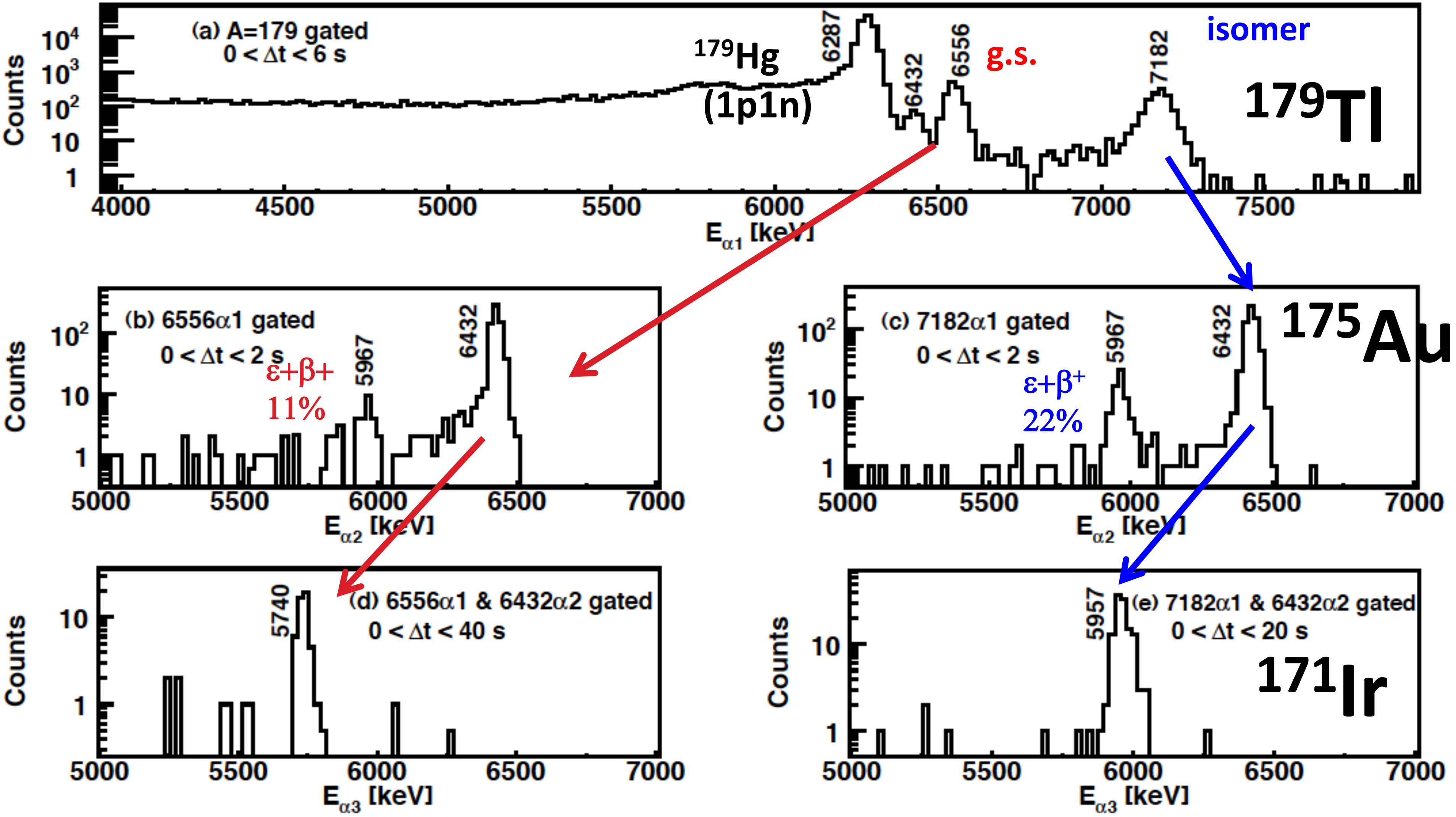
$$HF_i = \frac{T_{1/2}^{Exp}(\alpha_i)}{T_{1/2}^{Theory}} = \frac{T_{1/2}^{Exp}\ /\ BR_i}{T_{1/2}^{Theory}}$$



HF < 4 favored (ΔL=0)decay

1/2+	11/2-
1.12 (6)	0.50 (3)
2.16 (17)	1.63 (19)
0.36 (6) %b_α~15%	2.2 (4)

^{179}Tl: α–decay properties ^{89}Y + ^{92}Mo@^{181}Tl@375 MeV



Guidelines for evaluators

- ❑ **Start with a collection of all references – NSR is very useful!**
- ❑ **Complete the ID record – provide information about the key references**
  - ✓ how the parent nuclide was produced, which techniques and equipment were used; what was the energy resolution of the spectrometer and what was actually measured
  - ✓ mention other relevant references only by the NSR key number (for the benefit of the reader)
- ❑ **Complete the Parent record**
  - ✓ Ex, J^{π} and T1/2 from "Adopted Levels" of the parent nuclide, BUT check for new data and reevaluate, if needed
  - ✓ $Q\alpha$ from AME20 (2021Wa16)
- ❑ **Deduce r0 (if not an even-even nuclide) and include it in the HF record – the new alphad program also provides it**

Guidelines for evaluators – cont.

NO GAMMA RAYS WERE MEASURED

- ☐ **Include measured Eα and Iα with the corresponding level**
  - ✓ if there is more than one reference you may use averages, BUT be careful – need to compare oranges with oranges, e.g. magnetic spectrometer (ΔE ~4 keV) vs Si (ΔE ~20 keV)
  - ✓ most measurements are relative to Eα from a standard radionuclide. If available, include this information in a comment.
  - ✓ use Ritz's (At. Data and Nucl. Data Tables 47, 205 (1991)) - evaluated Eα and Iα - when no new values are available.
  - ✓ renormalize Iα, so that SUM $I\alpha_i$ = 100 % - have a simple spreadsheet handy
  - ✓ provide comments on Eα and Iα , where appropriate
- ☐ **Complete the Normalization record – BR**
  - ✓ BR from Adopted levels of the parent, BUT check for new data are reevaluate, if needed

Guidelines for evaluators – cont.

GAMMA RAYS WERE MEASURED

- ☐ Include measured Eα and Iα (as in the earlier slide)
- ☐ Include measured Eγ and Iγ
  - ✓ if there is more than one reference you may use averages, BUT be careful – need to compare oranges with oranges
  - ✓ include Mult. & MR – use "Adopted gammas" or J^{π} differences if not available
  - ✓ include measured ICC and/or sub-shell ratios to support Mult. assignment or to deduce MR as a comment record to a corresponding G record
  - ✓ include T1/2 available for a particular level – usually αγ(t) coincidence data
- ☐ Run BrICC to deduce conversion electron coefficients
- ☐ Run GTOL – determine level energies and intensity balances
- ☐ Complete the Normalization record – NR and BR
  - ✓ NR - need to convert to %Iγ
  - ✓ BR from Adopted levels of the parent, BUT check for new data are reevaluate, if needed

Guideline for evaluators-cont.

- **Run FMTCHK – check that everything is OK**
- **Run ALPHAD - calculate HF**
- **Run RADLIST - check the decay scheme for consistency**

$$Qeff = \sum_{i=1}^{allBF} Q_i BF_i; Qcalc = \sum_{j=1}^{all\gamma} E_{\gamma j} P_{\gamma j} + \sum_{k=1}^{all\beta} E_{\beta k} P_{\beta k} + \sum_{l=1}^{all\alpha} E_{\alpha l} P_{\alpha l} + etc. \quad Consistency = \left[\frac{Qeff - Qcalc}{Qeff} \right] \times 100\%$$

Beta decay - Introduction

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

Takes place is 3 different forms

β^-, β^+ & **EC** (capture of an atomic electron)

β^+: $p \rightarrow n + e^+ + \nu$

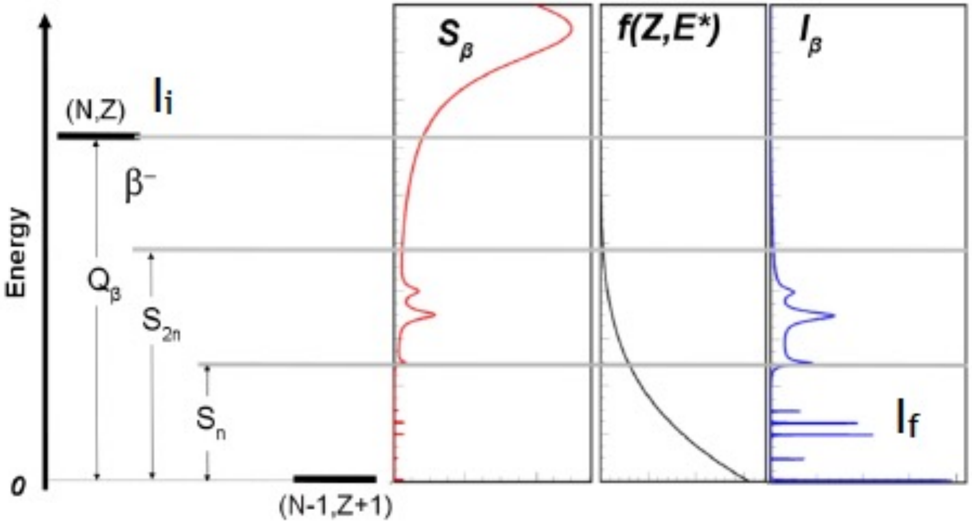
EC: $p + e^- \rightarrow n + \nu$

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

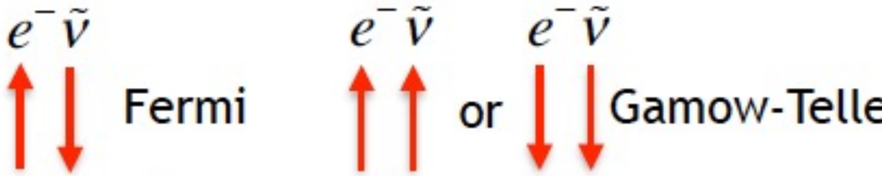
a nucleon inside the nucleus is transformed into another

Beta decay - Introduction: cont.

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



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



$$s_\beta = 0$$

$$0^+ \rightarrow 0^+$$

$$s_\beta = 1$$

$$1^+ \rightarrow 0^+$$

transition probability

S$_{if}$ - strength function

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

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
	.	.	.

β decay Hindrance Factor

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

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

statistical rate function (phase-space factor): the energy & nuclear structure dependences of the decay transition

η^2 contains the nuclear matrix elements

Log *ft* values

$$\log ft = \log f + \log t$$

coming from calculations

coming from experiment

Decay Mode	Type	$\Delta I\ (\pi_i\pi_f)$	$\log f$
β– **EC + β+**	allowed	0, +1 (+)	$\log f_0^-$ $\log(f_0^{EC} + f_0^+)$
β– **EC + β+**	1st-forb unique	∓2 (-)	$\log f_0^- + \log(f_1^- / f_0^-)$ $\log[(f_1^{EC} + f_1^+)/(f_0^{EC} + f_0^+)]$

N.B. Gove and M. Martin, Nuclear Data Tables **10** (1971) 205

improved values from the BETASHAPE code – see X. Mougeot presentation

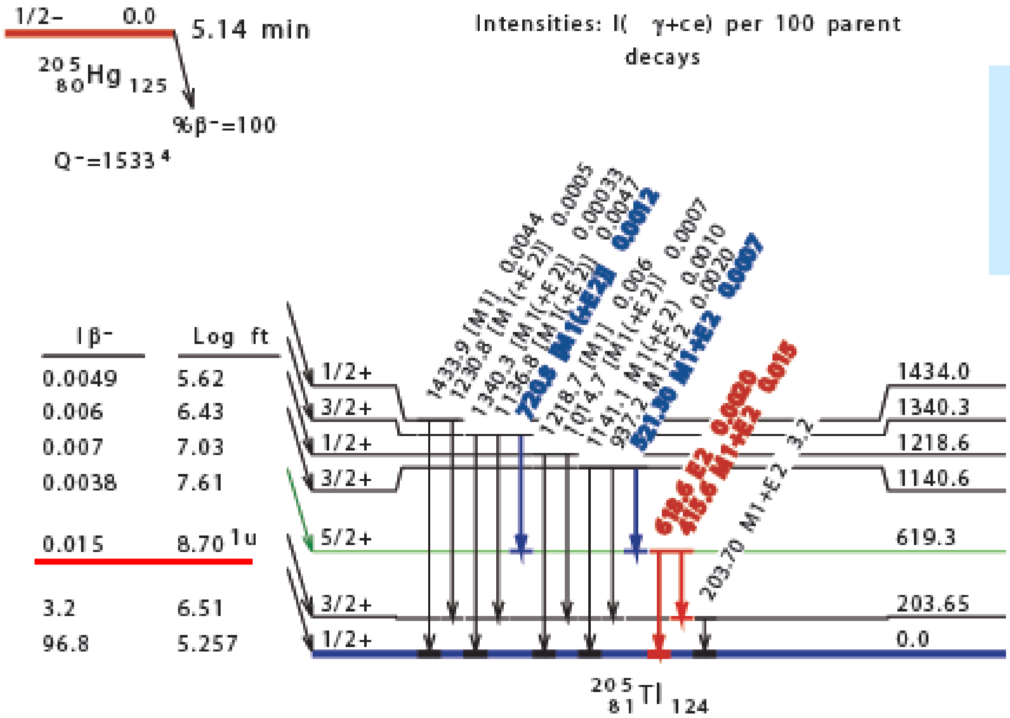
Log *t*

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

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

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

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



- ❑ 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

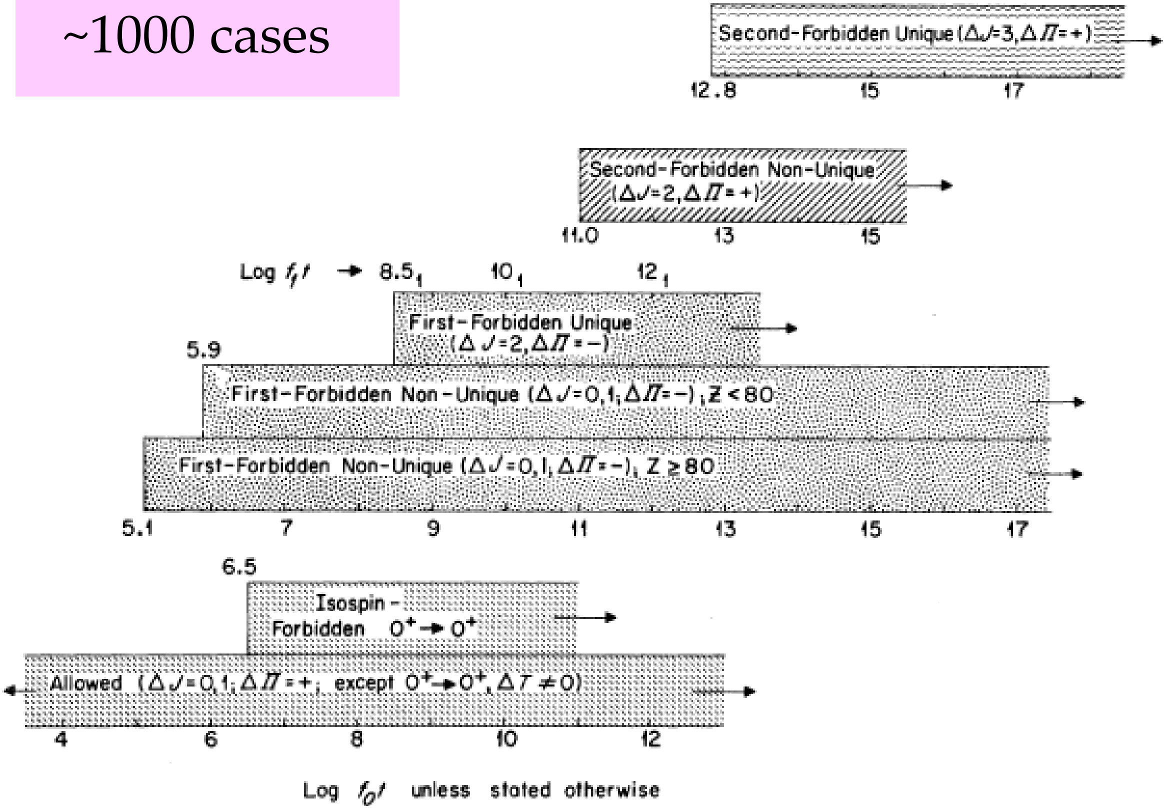
Rules for Spin and Parity Assignments Based on Log*ft* Values*

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



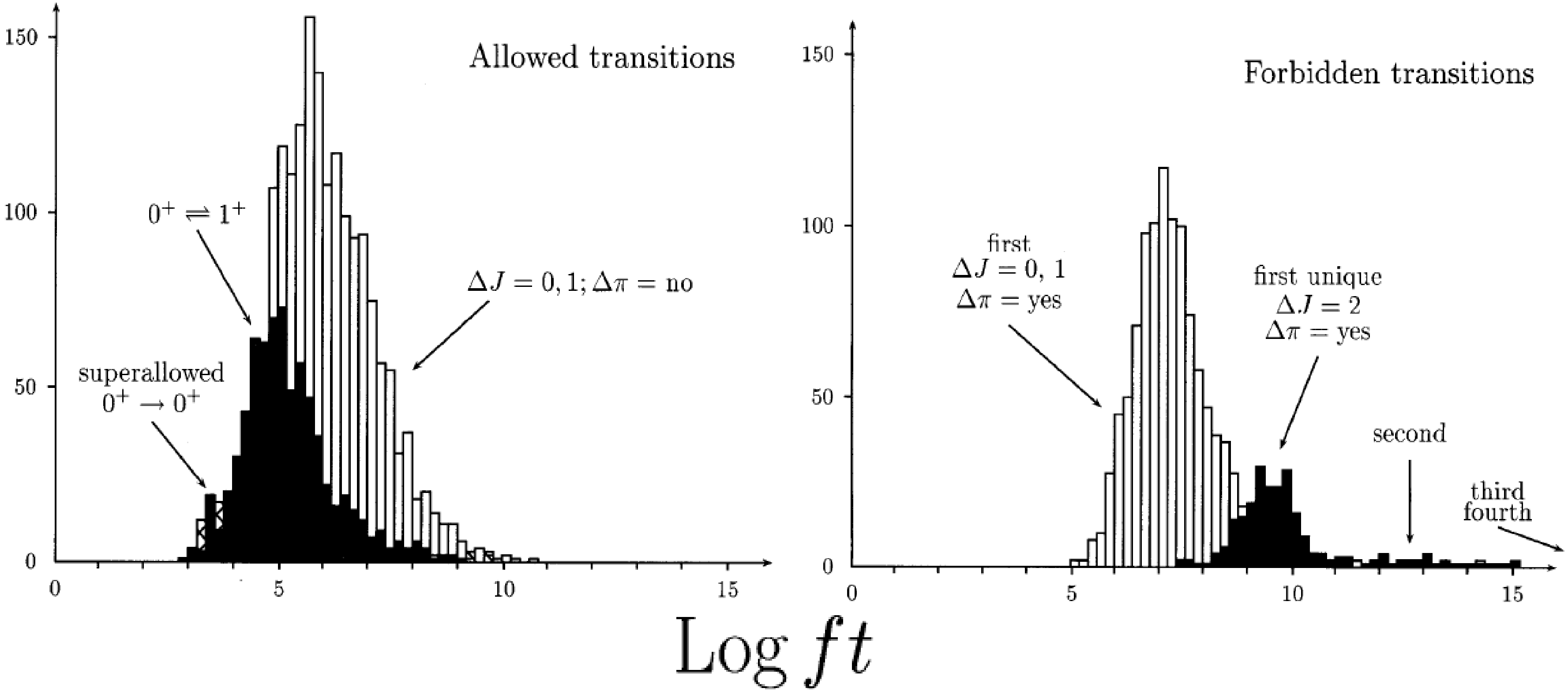
Log *ft* values – latest review

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

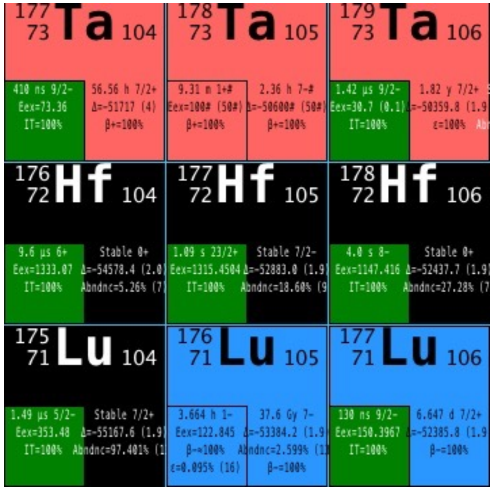
~3900 cases -> gives centroids and widths

Review Of Log*ft* Values In β Decay*

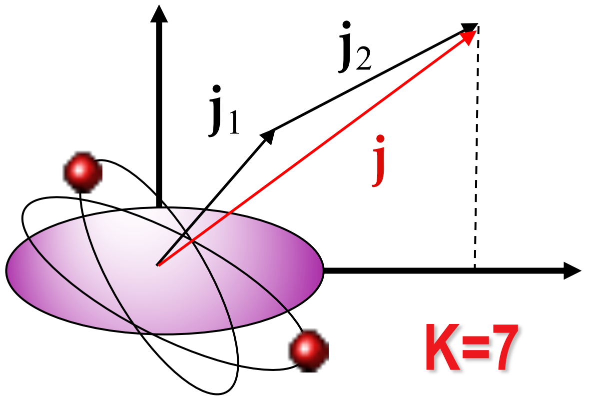
B. Singh, J.L. Rodriguez, S.S.M. Wong & J.K. Tuli



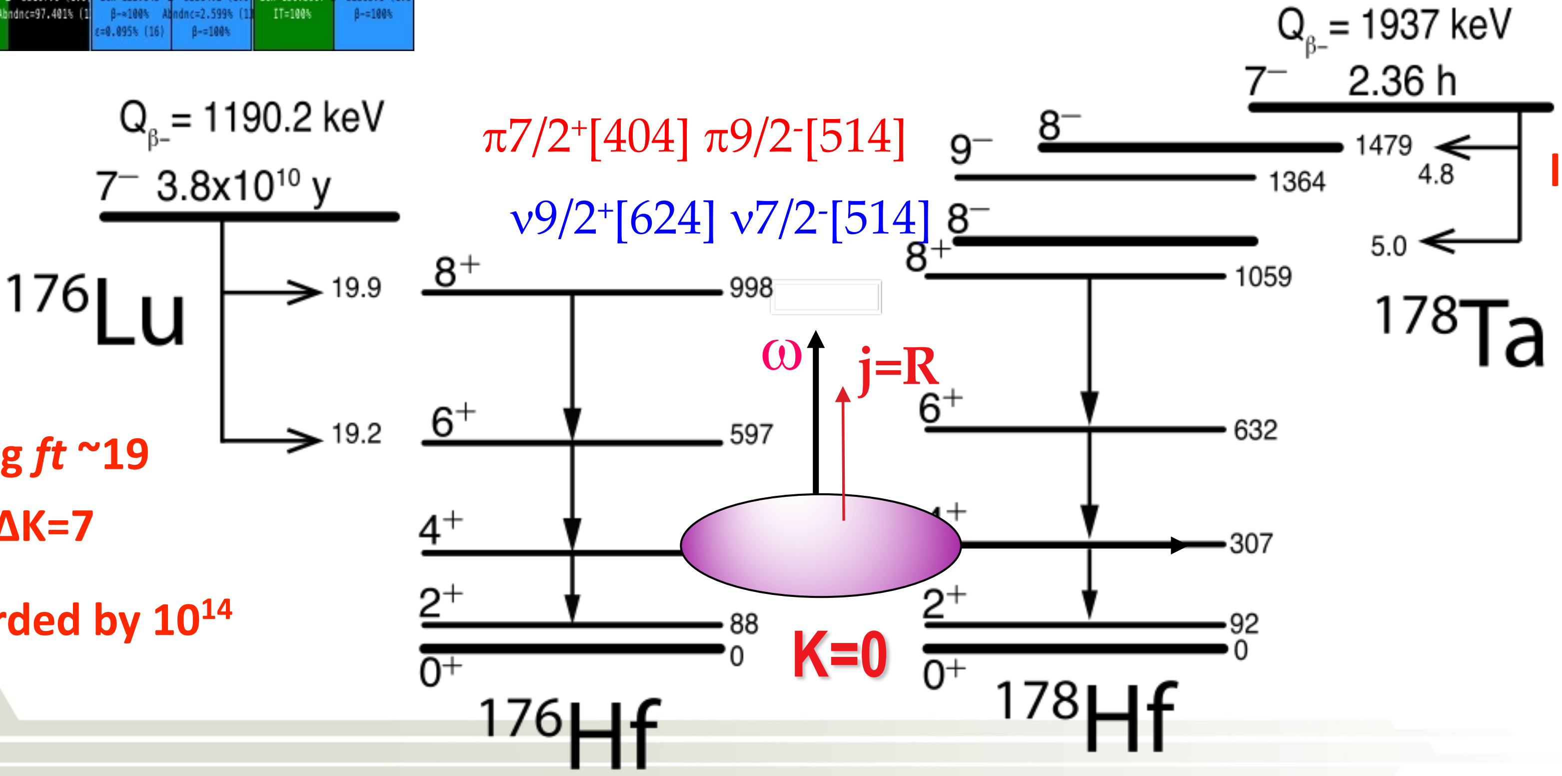
Beta decay of odd-odd nuclei



$^{177}_{73}$Ta 104 410 ns 9/2- Eex=73.36 IT=100% 56.56 h 7/2+ Δ=-51717 (4) β+=100%	$^{178}_{73}$Ta 105 9.31 m 1+# Eex=100# (50#) β+=100% 2.36 h 7-# Δ=-50600# (50#) β+=100%	$^{179}_{73}$Ta 106 1.42 μs 9/2- Eex=30.7 (0.1) IT=100% 1.82 y 7/2+ Δ=-50359.8 (1.9 ε=100%
$^{176}_{72}$Hf 104 9.6 μs 6+ Eex=1333.07 IT=100% Stable 0+ Δ=-54578.4 (2.0) Abndnc=5.26% (7)	$^{177}_{72}$Hf 105 1.09 s 23/2+ Eex=1315.4504 IT=100% Stable 7/2- Δ=-52883.0 (1.9) Abndnc=18.60% (9	$^{178}_{72}$Hf 106 4.0 s 8- Eex=1147.416 IT=100% Stable 0+ Δ=-52437.7 (1.9) Abndnc=27.28% (7
$^{175}_{71}$Lu 104 1.49 μs 5/2- Eex=353.48 IT=100% Stable 7/2+ Δ=-55167.6 (1.9) Abndnc=97.401% (1	$^{176}_{71}$Lu 105 3.664 h 1- Eex=122.845 β-≈100% ε=0.095% (16) 37.6 Gy 7- Δ=-53384.2 (1.9 Abndnc=2.599% (1 β-=100%	$^{177}_{71}$Lu 106 130 ns 9/2- Eex=150.3967 IT=100% 6.647 d 7/2+ Δ=-52385.8 (1.9 β-=100%



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



$\pi 7/2^+[404]$ $\pi 9/2^-[514]$

$\nu 9/2^+[624]$ $\nu 7/2^-[514]$

log *ft* ~19

ΔK=7

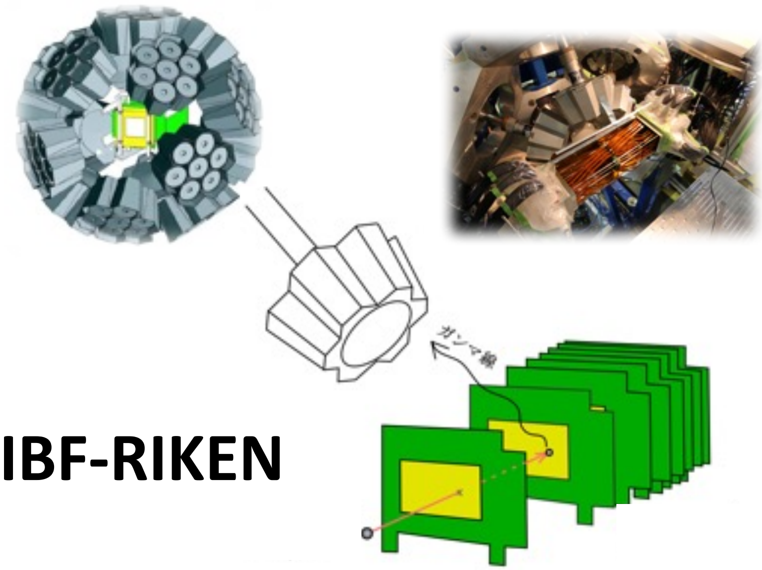
retarded by 10^{14}

log *ft* ~5

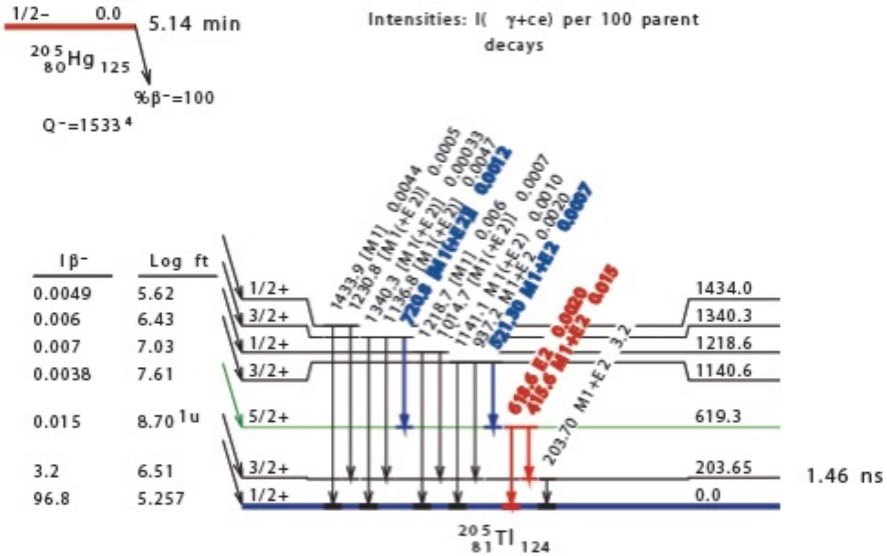
ΔK=1

Experimental Approaches

Discrete β-γ-γ Coincidence Spectroscopy



RIBF-RIKEN



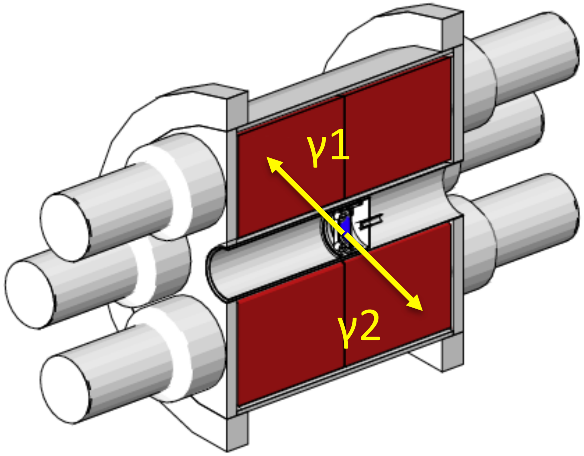
$$I_{\beta_i} = \sum I^{tot}_{\gamma_i}(out) - \sum I^{tot}_{\gamma_i}(in)$$

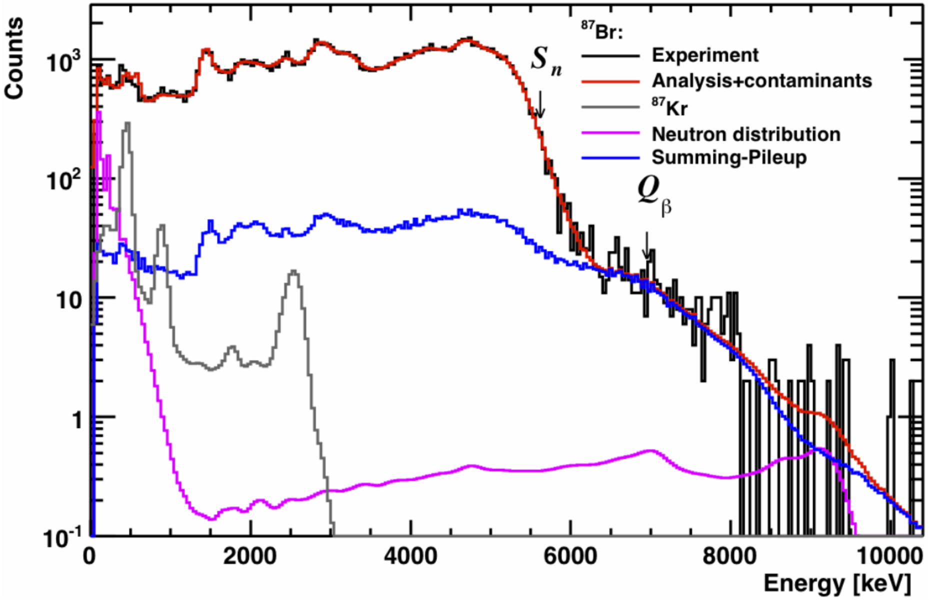
- need a complete knowledge of the decay scheme & detailed nuclear structure information -> intensity balances to determine I_β
- complications when far from stability & when g.s to g.s decay information is needed
- state-of-the-art detector equipment

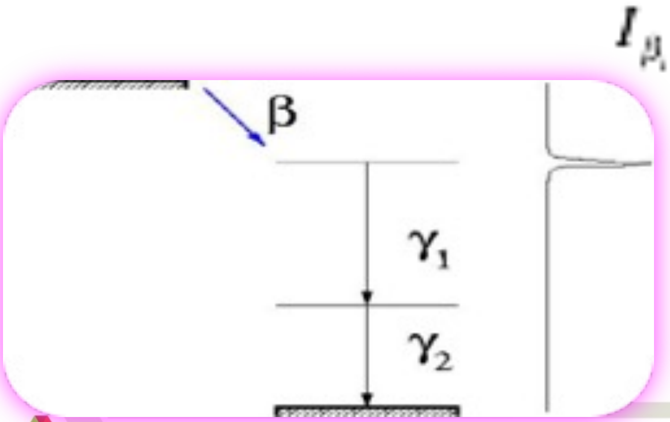
- most studies in the past involved a single HpGe detector - lack of γ-γ coincidences - incomplete decay schemes - **www.nndc.bnl.gov/ENSDF**

Experimental Approaches - cont.

Total Gamma-ray Absorption Spectroscopy







- large γ-ray efficiency (GOOD!), but low energy resolution & resolving power
- must know the details of the decay scheme - often not the case and relies on simulations complications when isomers are presented
- complicated unfolding procedure - often non-unique solutions - unreliable uncertainties

Beta Decay (β^-, β^+ and EC)

- **Energy (keV)**
  - Give E_β(max) *only* if experimental value is so accurate that it could be used as input to mass adjustment
  - Do not give E_β(avg.), program LOGFT calculates its value
- **Absolute intensity** (%I_β, per 100 decays of the parent nucleus)
  - Give experimental value, if used for normalizing the decay scheme
  - Give absolute value deduced from g-ray transition intensity balance (Program GTOL)
- **Log *ft***
  - Usually authors assign spins and parities. Nevertheless, verify that the relevant log *ft* values are consistent with their assignments
  - Give (I_{ec}+$I_{\beta+}$) feedings deduced from γ-ray transition intensity balances. Program LOGFT calculates (from theory) ec and β^+ probabilities as well sub-shell (P_K, P_L, P_M, …) probabilities
- Give (in comments) x-ray intensities. These are useful for normalizing or testing the decay scheme

Guidelines for evaluators

- ☐ **Start with a collection of all references – NSR is very useful!**
- ☐ **Complete the ID record – provide information about the key references**
  - ✓ **how the parent nuclide was produced, which techniques and equipment were used; what was the energy resolution of the spectrometer and what was actually measured**
  - ✓ **mention other relevant references only by the NSR key number (for the benefit of the reader)**
- ☐ **Complete the Parent record**
  - ✓ **Ex, J^{π} and T1/2 from "Adopted Levels" of the parent nuclide, BUT check for new data and reevaluate, if needed**
  - ✓ **Qβ from AME20 mass evaluation (2021Wa16)**

```
205TL    205HG B- DECAY                1971HI01                  93NDS    200310
205TL  H TYP=FUL$AUT=F. G. KONDEV$CIT=NDS 69,679 (1993)$CUT=1-Nov-2002$
205BI c  1971HI01: Mass-separated source; Detectors: NaI(Tl), two Ge(Li), 2 mm
205BI2c  thick Si(Li) with energy resolution of about 4 keV, a double focusing
205BI3c  magnetic spectrometer; Measured: |g, |g|g coin, NaI |g(t), ce.
205BI c  Others: 1971Sh35.
205TL CG E,RI$From 1971Hi01, unless otherwise specified.
205TL CG M,MR$From adopted gammas, unless otherwise specified.
205TL CL E$From a least-squares fit to EG.
205TL CL J$From adopted levels.
205HG  P 0.0          1/2-             5.14 M    9               1533     4
```

Guidelines for evaluators – cont.

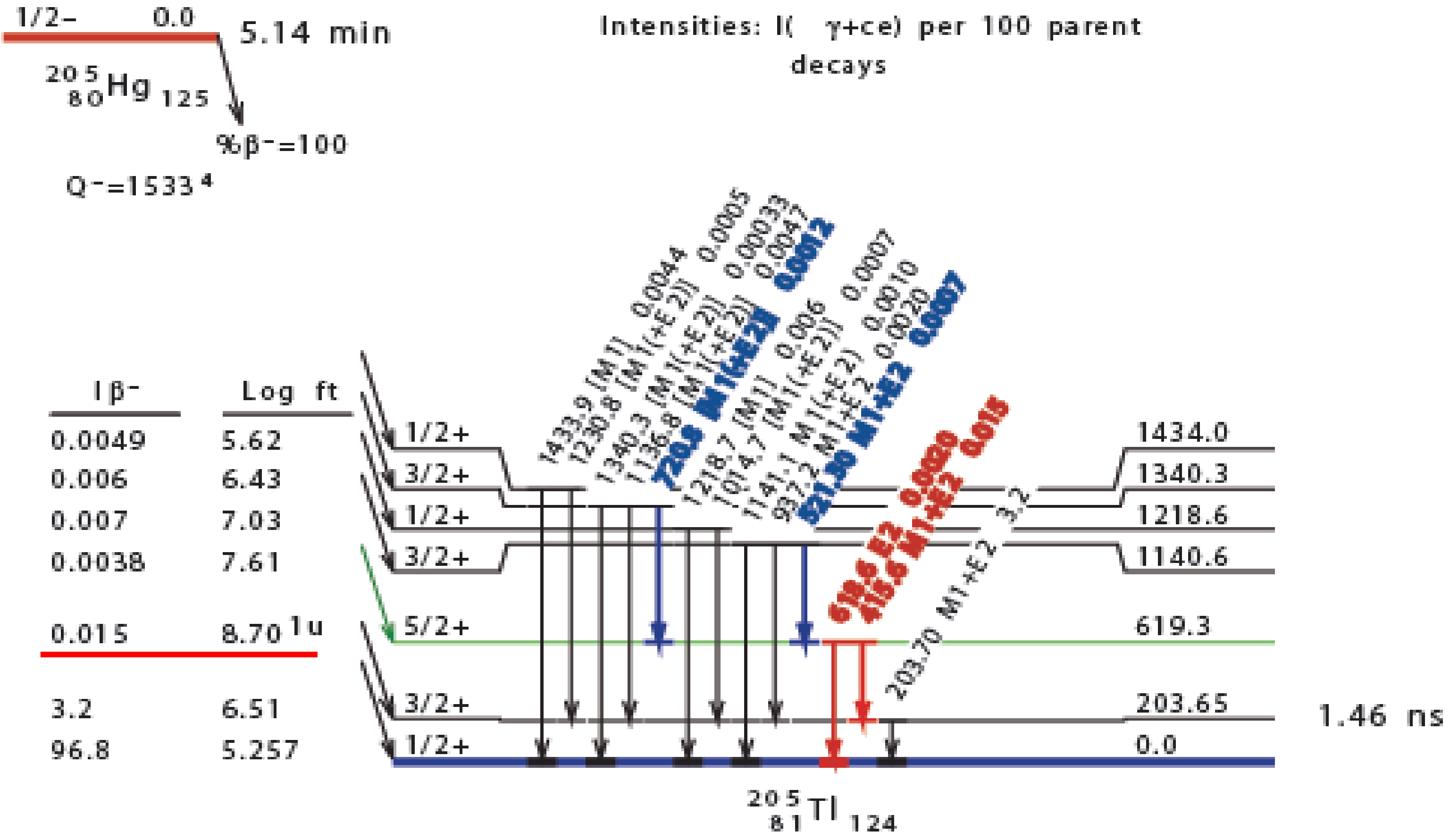
- ☐ **Include measured Eγ and Iγ**
  - ✓if there is more than one reference you may use averages (avetools program), BUT be careful – need to compare oranges with oranges
  - ✓ include Mult. & MR – use "Adopted gammas" – if Mult. is not known, but initial and final J^{π} are – use [ ], e.g. [E2], so ICC can be calculated
  - ✓ include measured ICC and/or sub-shell ratios to support Mult. assignment or to deduce MR – use BrIccMixing program
  - ✓ include T1/2 available for a particular level – usually βγ(t) coincidence data
- ☐ **Run BrICC to deduce conversion electron coefficients**
  - ✓ be careful when dealing with transitions containing E0 admixtures (mostly J to J) or those with anomalous ICC (penetration) – use experimental ICC

```
205TL  L 0.0          1/2+
205TL  B              96.8   15
205TL  L     203.6519 3/2+             1.46 NS   8
205TL CL T$ From 1971Sh35.
205TL  G 203.70    20  100      M1+E2    +1.18   20      0.46  4
205TL CG CC$ From adopted gammas.
205TL3 G EKC=0.29 4 $ ELC=0.132 6 $ EMC+=0.040 3
205TLS G KC=0.50 8$LC=0.167$MC=0.0415 5$NC+=0.0133 2
205TL  L      619.3 3 5/2+
205TL  G 415.6     3  0.59   8  M1+E2     -0.069 10      0.168
205TLS G KC=0.138$LC=0.0232$MC=0.00541$NC+=0.00174
205TL  G 618.6     7  0.090  20 E2                      0.0173
205TLS G KC=0.0130 4$LC=0.00328 10
205TL  L     1140.6 3 3/2+
205TL  G 521.30    5  0.033  3  M1+E2     2.2    GE     0.031  6
205TL CG RI$ From adopted gammas.
205TLS G KC=0.023 5$LC=0.0060 7
205TL  G 937.2     6  0.093  20 M1+E2     4      GE
205TLS G CC=0.0077 4$KC=0.0061 4$LC=0.00118 5
205TL  G 1141.1    15 0.045  20 M1(+E2)  -0.25   25     0.012011
205TLS G KC=0.0098 9$LC=0.00160 14
```

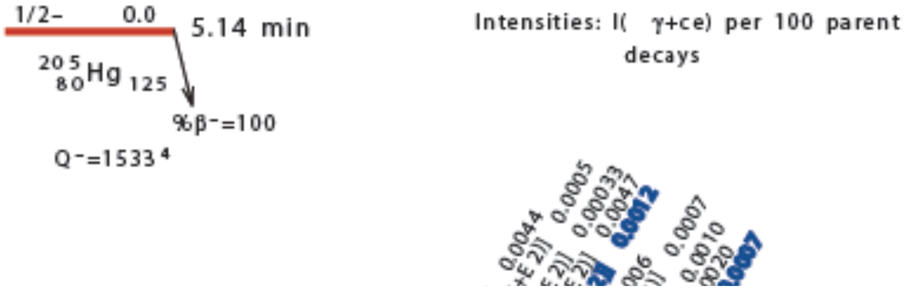
Guidelines for evaluators – cont.

- ☐ **Complete the Normalization record – NR and BR**
  - ✓ **NR - need to convert to %Iγ**
  - ✓ **BR from Adopted levels of the parent, BUT check for new data are reevaluate, if needed**
- ☐ **Run GTOL – determine level energies and intensity balances**

^{205}Hg β– decay as an example



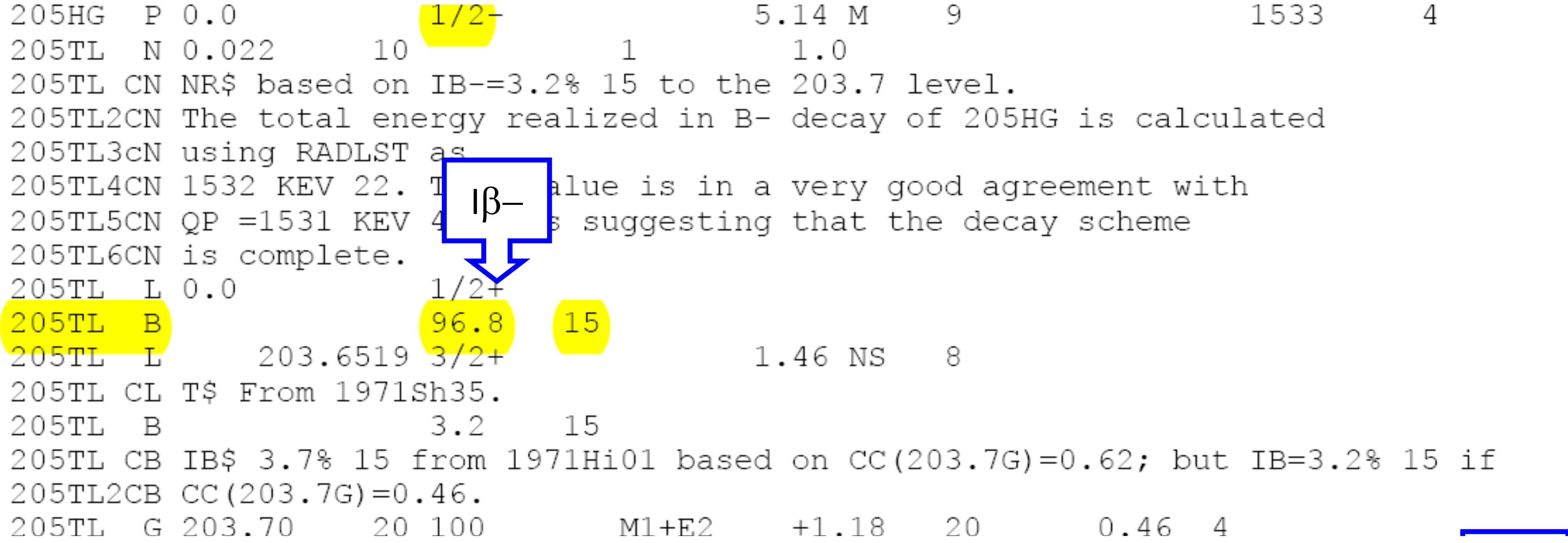
```
205HG  P 0.0          1/2-             5.14 M    9              1533     4
205TL  N 0.022      10          1        1.0
205TL CN NR$ based on IB-=3.2% 15 to the 203.7 level.
205TL2CN The total energy realized in B- decay of 205HG is calculated
205TL3cN using RADLST as
205TL4CN 1532 KEV 22. This value is in a very good agreement with
205TL5CN QP =1531 KEV 4, thus suggesting that the decay scheme
205TL6CN is complete.
205TL  L 0.0          1/2+
205TL  B              96.8   15
205TL  L     203.6519 3/2+             1.46 NS   8
205TL CL T$ From 1971Sh35.
205TL  G 203.70     20 100       M1+E2    +1.18  20      0.46  4
```



program GTOL

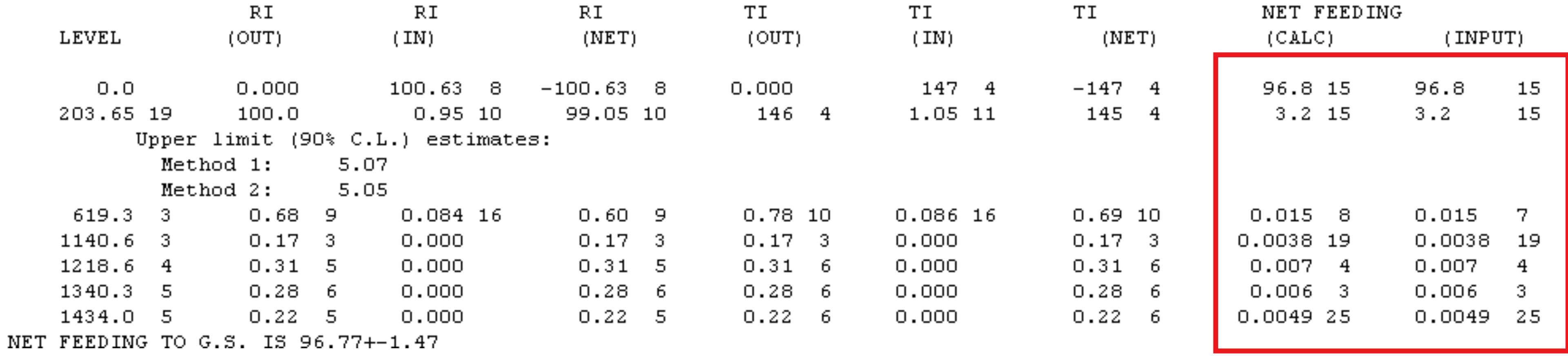
```
                 RI          RI           RI          TI          TI          TI               NET FEEDING
   LEVEL        (OUT)       (IN)         (NET)       (OUT)       (IN)        (NET)          (CALC)        (INPUT)

    0.0         0.000      100.63   8   -100.63   8    0.000        147   4    -147   4      96.8 15      96.8     15
  203.65 19     100.0        0.95 10     99.05 10     146   4     1.05 11     145   4       3.2 15      3.2      15
       Upper limit (90% C.L.) estimates:
         Method 1:      5.07
         Method 2:      5.05
   619.3   3     0.68  9    0.084 16      0.60   9    0.78 10    0.086 16     0.69 10     0.015   8     0.015    7
  1140.6   3     0.17  3    0.000         0.17   3    0.17  3    0.000        0.17  3     0.0038 19     0.0038  19
  1218.6   4     0.31  5    0.000         0.31   5    0.31  6    0.000        0.31  6     0.007   4     0.007    4
  1340.3   5     0.28  6    0.000         0.28   6    0.28  6    0.000        0.28  6     0.006   3     0.006    3
  1434.0   5     0.22  5    0.000         0.22   5    0.22  6    0.000        0.22  6     0.0049 25     0.0049  25
NET FEEDING TO G.S. IS 96.77+-1.47
```

Before running the LOGFT program



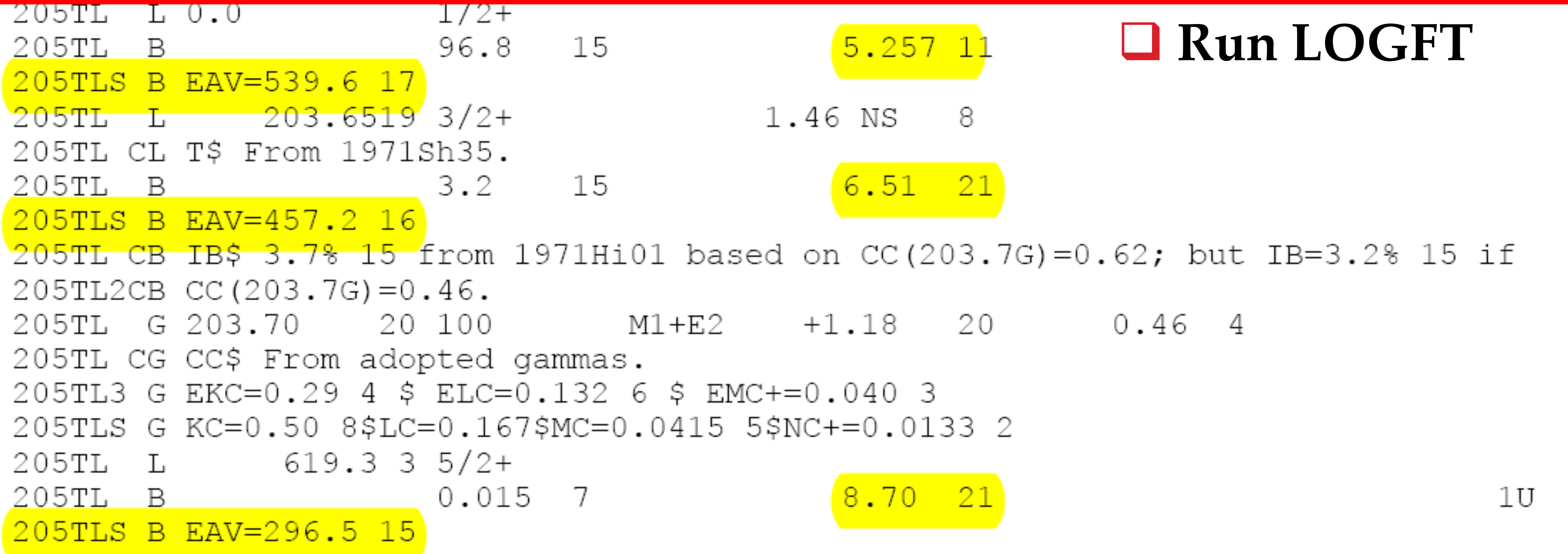
```
205HG  P 0.0             1/2-             5.14 M   9                 1533     4
205TL  N 0.022      10             1        1.0
205TL CN NR$ based on IB-=3.2% 15 to the 203.7 level.
205TL2CN The total energy realized in B- decay of 205HG is calculated
205TL3cN using RADLST as
205TL4CN 1532 KEV 22. T       alue is in a very good agreement with
205TL5CN QP =1531 KEV 4       s suggesting that the decay scheme
205TL6CN is complete.
205TL  L 0.0             1/2+
205TL  B                 96.8    15
205TL  L      203.6519 3/2+             1.46 NS   8
205TL CL T$ From 1971Sh35.
205TL  B                 3.2     15
205TL CB IB$ 3.7% 15 from 1971Hi01 based on CC(203.7G)=0.62; but IB=3.2% 15 if
205TL2CB CC(203.7G)=0.46.
205TL  G 203.70     20 100        M1+E2    +1.18   20        0.46  4
```

Iβ−

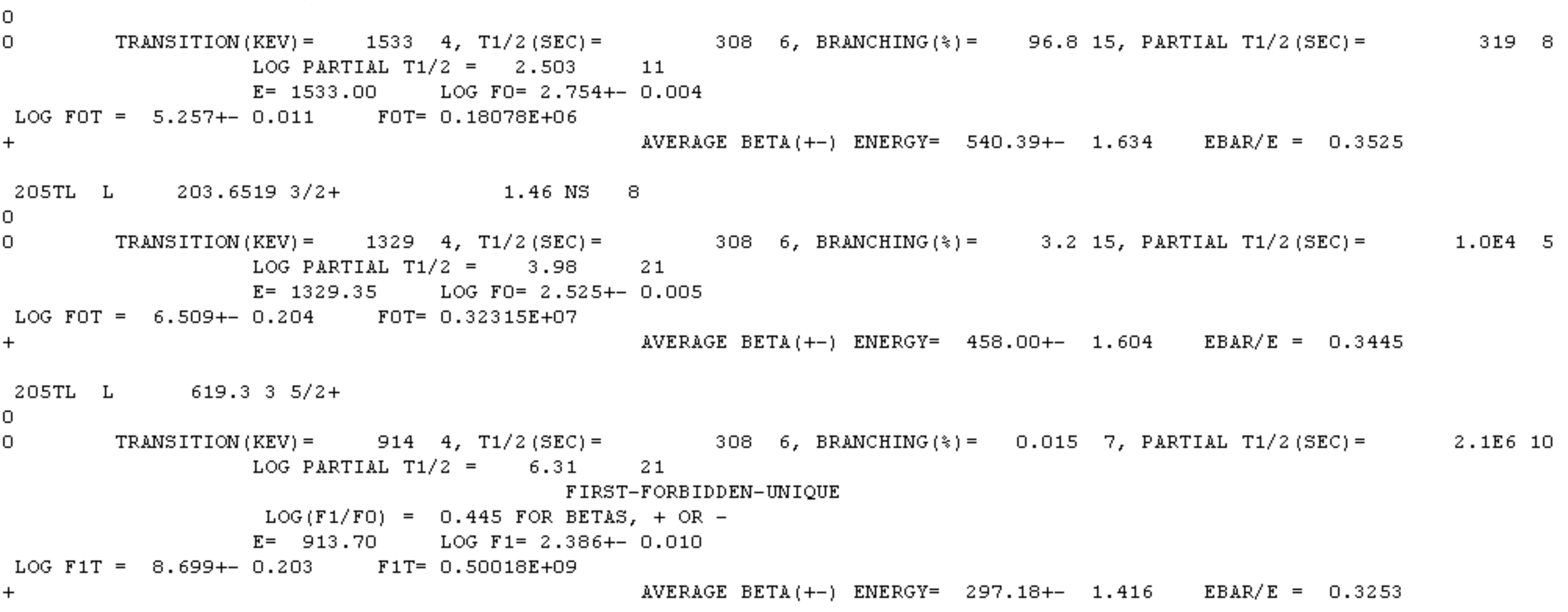


```
                  RI           RI           RI           TI           TI           TI            NET FEEDING
   LEVEL        (OUT)         (IN)        (NET)        (OUT)         (IN)         (NET)         (CALC)       (INPUT)

    0.0        0.000       100.63  8   -100.63  8    0.000         147   4     -147   4      96.8 15      96.8     15
   203.65 19   100.0         0.95 10     99.05 10     146   4     1.05 11       145   4       3.2 15      3.2      15
        Upper limit (90% C.L.) estimates:
          Method 1:      5.07
          Method 2:      5.05
    619.3  3     0.68  9     0.084 16      0.60  9     0.78 10     0.086 16      0.69 10     0.015  8     0.015    7
   1140.6  3     0.17  3     0.000         0.17  3     0.17  3     0.000         0.17  3    0.0038 19     0.0038  19
   1218.6  4     0.31  5     0.000         0.31  5     0.31  6     0.000         0.31  6     0.007  4     0.007    4
   1340.3  5     0.28  6     0.000         0.28  6     0.28  6     0.000         0.28  6     0.006  3     0.006    3
   1434.0  5     0.22  5     0.000         0.22  5     0.22  6     0.000         0.22  6    0.0049 25     0.0049  25
NET FEEDING TO G.S. IS 96.77+-1.47
```

❑ Run LOGFT



```
205TL  L 0.0         1/2+
205TL  B             96.8   15              5.257 11
205TLS B EAV=539.6 17
205TL  L     203.6519 3/2+                1.46 NS   8
205TL CL T$ From 1971Sh35.
205TL  B             3.2    15              6.51  21
205TLS B EAV=457.2 16
205TL CB IB$ 3.7% 15 from 1971Hi01 based on CC(203.7G)=0.62; but IB=3.2% 15 if
205TL2CB CC(203.7G)=0.46.
205TL  G 203.70    20 100       M1+E2    +1.18   20      0.46  4
205TL CG CC$ From adopted gammas.
205TL3 G EKC=0.29 4 $ ELC=0.132 6 $ EMC+=0.040 3
205TLS G KC=0.50 8$LC=0.167$MC=0.0415 5$NC+=0.0133 2
205TL  L      619.3 3 5/2+
205TL  B             0.015  7               8.70  21                            1U
205TLS B EAV=296.5 15
```

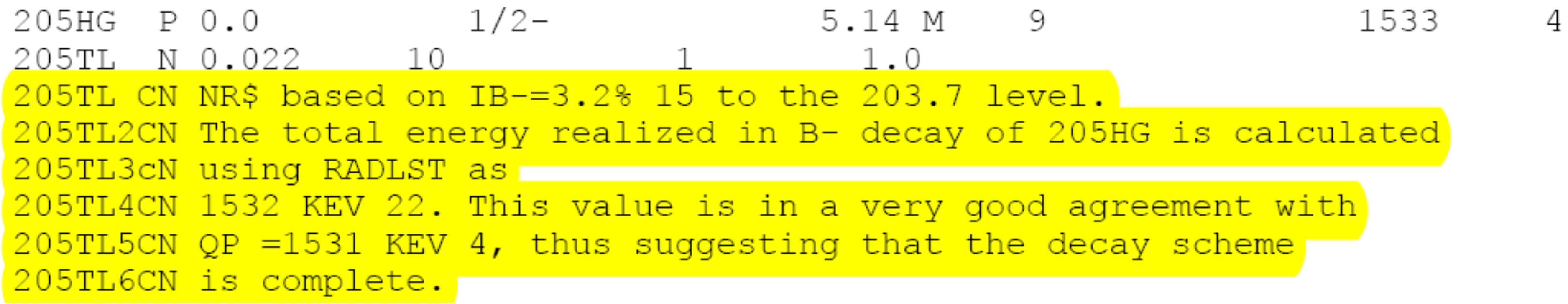


```
0
0        TRANSITION(KEV)=    1533   4, T1/2(SEC)=         308   6, BRANCHING(%)=    96.8 15, PARTIAL T1/2(SEC)=        319   8
                    LOG PARTIAL T1/2 =    2.503      11
                    E= 1533.00    LOG F0= 2.754+- 0.004
 LOG FOT =  5.257+- 0.011     FOT= 0.18078E+06
+                                                   AVERAGE BETA(+-) ENERGY=  540.39+-  1.634    EBAR/E =  0.3525

 205TL   L     203.6519 3/2+            1.46 NS   8
0
0        TRANSITION(KEV)=    1329   4, T1/2(SEC)=         308   6, BRANCHING(%)=     3.2 15, PARTIAL T1/2(SEC)=      1.0E4   5
                    LOG PARTIAL T1/2 =     3.98      21
                    E= 1329.35    LOG F0= 2.525+- 0.005
 LOG FOT =  6.509+- 0.204     FOT= 0.32315E+07
+                                                   AVERAGE BETA(+-) ENERGY=  458.00+-  1.604    EBAR/E =  0.3445

 205TL   L      619.3  3 5/2+
0
0        TRANSITION(KEV)=     914   4, T1/2(SEC)=         308   6, BRANCHING(%)=   0.015   7, PARTIAL T1/2(SEC)=      2.1E6 10
                    LOG PARTIAL T1/2 =     6.31      21
                                             FIRST-FORBIDDEN-UNIQUE
                     LOG(F1/F0)  =  0.445 FOR BETAS, + OR -
                    E=   913.70    LOG F1= 2.386+- 0.010
 LOG F1T =  8.699+- 0.203     F1T= 0.50018E+09
+                                                   AVERAGE BETA(+-) ENERGY=  297.18+-  1.416    EBAR/E =  0.3253
```

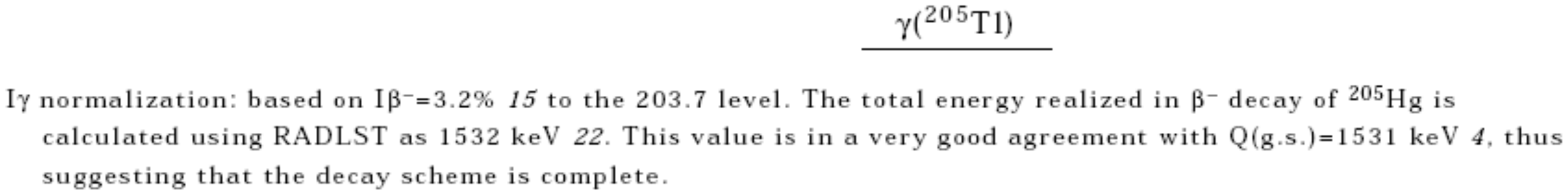
Guideline for evaluators-cont.

- ☐ **Check the decay scheme for consistency (using RADLST)**

$$Qeff=\sum_{i=1}^{allBF}Q_iBF_i;\quad Qcalc=\sum_{j=1}^{all\gamma}E_{\gamma j}P_{\gamma j}+\sum_{k=1}^{all\beta}E_{\beta k}P_{\beta k}+\sum_{l=1}^{all\alpha}E_{\alpha l}P_{\alpha l}+etc.\quad Consistency=\left[\frac{Qeff-Qcalc}{Qeff}\right]\times 100\%$$

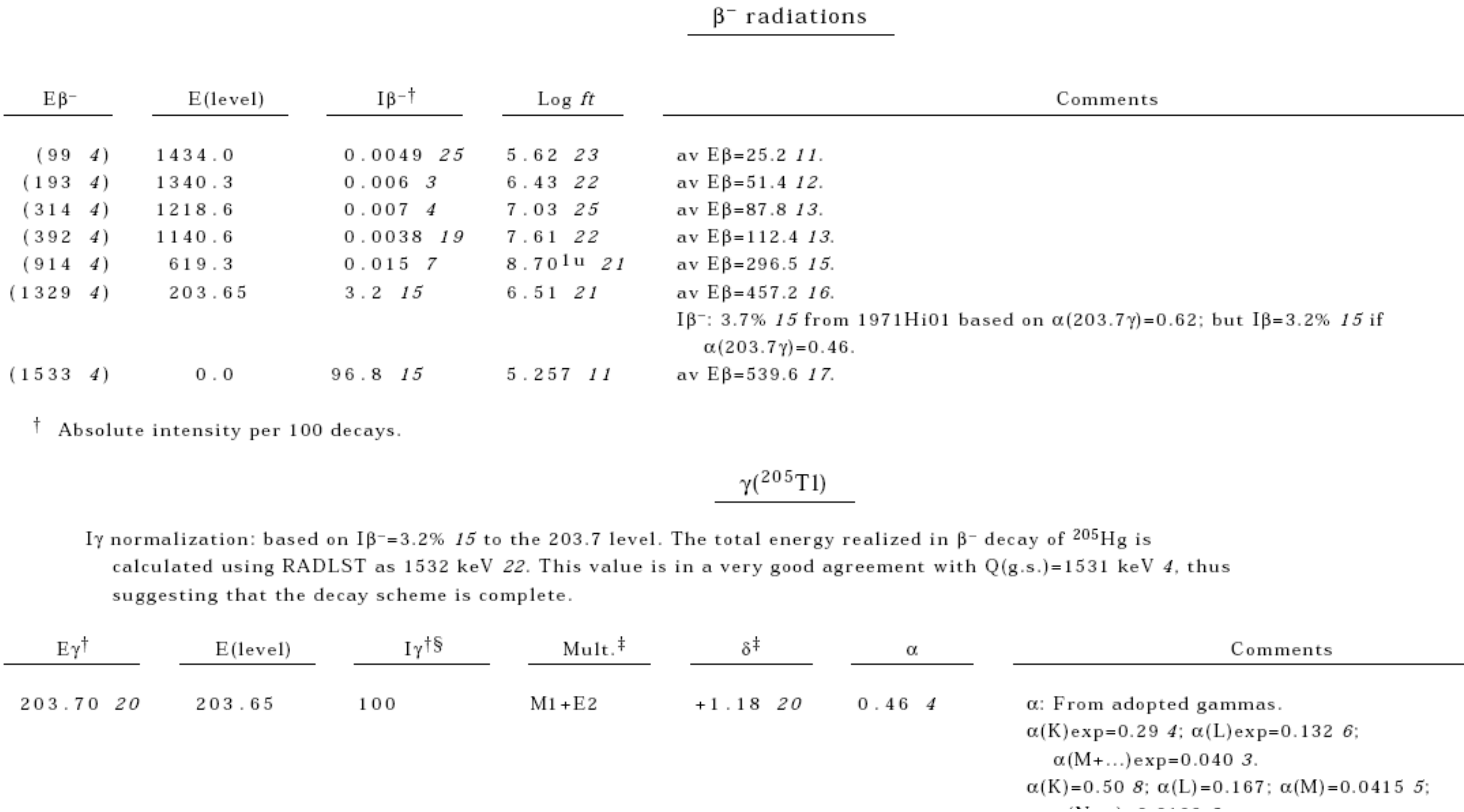


```
205HG  P 0.0          1/2-             5.14 M    9               1533     4
205TL  N 0.022     10           1        1.0
205TL CN NR$ based on IB-=3.2% 15 to the 203.7 level.
205TL2CN The total energy realized in B- decay of 205HG is calculated
205TL3cN using RADLST as
205TL4CN 1532 KEV 22. This value is in a very good agreement with
205TL5CN QP =1531 KEV 4, thus suggesting that the decay scheme
205TL6CN is complete.
```



$\gamma(^{205}\mathrm{Tl})$

Iγ normalization: based on $I\beta^-$=3.2% *15* to the 203.7 level. The total energy realized in β^- decay of ^{205}Hg is calculated using RADLST as 1532 keV *22*. This value is in a very good agreement with Q(g.s.)=1531 keV *4*, thus suggesting that the decay scheme is complete.



β⁻ radiations

Eβ⁻	E(level)	Iβ⁻†	Log *ft*	Comments
(99 *4*)	1434.0	0.0049 *25*	5.62 *23*	av Eβ=25.2 *11*.
(193 *4*)	1340.3	0.006 *3*	6.43 *22*	av Eβ=51.4 *12*.
(314 *4*)	1218.6	0.007 *4*	7.03 *25*	av Eβ=87.8 *13*.
(392 *4*)	1140.6	0.0038 *19*	7.61 *22*	av Eβ=112.4 *13*.
(914 *4*)	619.3	0.015 *7*	8.70^{1u} *21*	av Eβ=296.5 *15*.
(1329 *4*)	203.65	3.2 *15*	6.51 *21*	av Eβ=457.2 *16*. Iβ⁻: 3.7% *15* from 1971Hi01 based on α(203.7γ)=0.62; but Iβ=3.2% *15* if α(203.7γ)=0.46.
(1533 *4*)	0.0	96.8 *15*	5.257 *11*	av Eβ=539.6 *17*.

† Absolute intensity per 100 decays.

γ(^{205}Tl)

Iγ normalization: based on Iβ⁻=3.2% *15* to the 203.7 level. The total energy realized in β⁻ decay of ^{205}Hg is calculated using RADLST as 1532 keV *22*. This value is in a very good agreement with Q(g.s.)=1531 keV *4*, thus suggesting that the decay scheme is complete.

Eγ†	E(level)	Iγ†§	Mult.‡	δ‡	α	Comments
203.70 *20*	203.65	100	M1+E2	+1.18 *20*	0.46 *4*	α: From adopted gammas. α(K)exp=0.29 *4*; α(L)exp=0.132 *6*; α(M+...)exp=0.040 *3*. α(K)=0.50 *8*; α(L)=0.167; α(M)=0.0415 *5*;

Decay Data – What is evaluated?

- ☐ **Q values -** AME2020 – surprises driven by new measurements – don't use end-point energies!

- ☐ **Level Properties:** E (ΔE), J^{π}, $T_{1/2}$ ($\Delta T_{1/2}$), BR(Decay mode(s))
  - ✓ E (ΔE) – least-squares fit procedure to ALL available data (not only decay – high-precision reaction data) -> should be used to determine signature radiations, e.g. E_{γ}, E_{β}, E_{α}, …
  - ✓ J^{π} – important when dealing with large decay data schemes -> defines transition multipolarities and ICC
  - ✓ $T_{1/2}$ ($\Delta T_{1/2}$)
  - ✓ BR – in many cases only one mode measured, but the second inferred from 100-%BR1; lack of separating EC from β+: %EC+%B=100 -> what is measured and what is deduced?

Decay Data – What is evaluated-cont.?

- **Gamma Radiation Properties:** E_γ (ΔE_γ), I_γ (ΔI_γ), Mult., δ ($\Delta\delta$)
  - ✓ E_γ (ΔE_γ) – need to be evaluated in a relation to a particular nuclear level (not only decay – high-precision reaction data, e.g. bent-curve spectrometers); the recommended ones determined from lsq-fit level energies
  - ✓ I_γ (ΔI_γ) – MUST be evaluated. One must consider BR from reactions for weakly populated levels in β/α decay
  - ✓ Mult. – sometime inferred from the decay scheme and from reactions data – important to deduce ICC
  - ✓ δ ($\Delta\delta$) – Must be evaluated. Frequently reactions data must be consulted
  - ✓ careful when dealing with E0 or mixed E0+M1+E2 transitions: simplified approaches use experimental ICC and Iγ(tot); or penetration effect for ICC (mostly for heavy nuclei)

Decay Data – What is evaluated-cont.?

- ☐ **Beta Radiation Properties:** E_β (ΔE_β), I_β (ΔI_β)
  - ✓ E_β (ΔE_β) – it is not discrete, usually maximum and mean energies are deduced from the known decay scheme and decay Q value
  - ✓ I_β (ΔI_β) – deduced from intensity balances - > need to look carefully if $I_{\beta+}$ has been measured, usually deduced from the (calculated) $I_{\beta+}$/EC ratio
- ☐ **Alpha Radiation Properties:** E_α (ΔE_α), I_α (ΔI_α)
  - ✓ E_α (ΔE_α) – from level energy differences & Qα values; directly measured ones are usually with low uncertainties
  - ✓ I_α (ΔI_α) – both directly and indirectly (from Iγ)
- ☐ **Atomic Radiation:**
  - ✓ CE, X-rays, Auger and Coster-Kronig are derived quantities, except ICC for mixed E0+M1+E2 transitions and those affected by penetration

Some personal notes …

☐ Be critical to the experimental data you are dealing with!

- ✓ as all nuclei are different, so are the experiments

☐ A good evaluation is not just simply averaging numbers!

- ✓ sometime the most accurate value quoted in the literature is not the best one!

☐ Enjoy what you are doing!