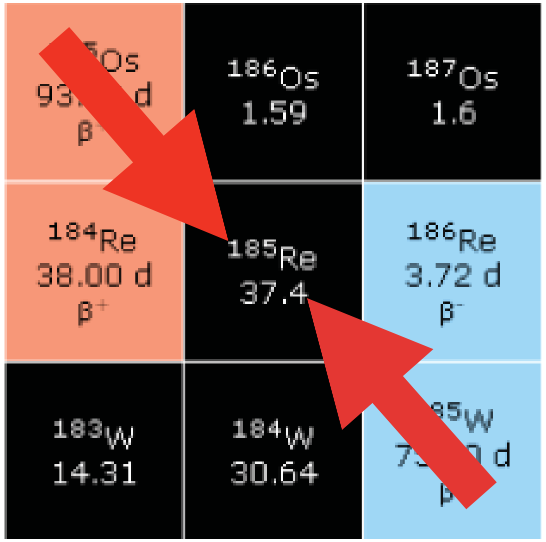
Beta decay : Introduction

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)

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

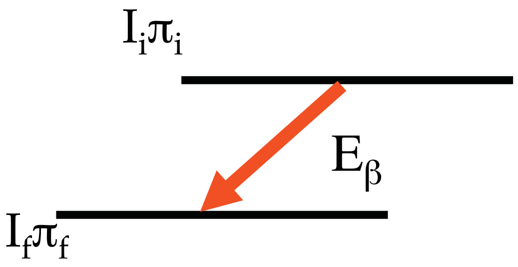
$EC: p + e- \rightarrow n + \nu$



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

a nucleon inside the nucleus is transformed into another

Classification of β decay transition



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

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

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

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

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

allowed

forbidden

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

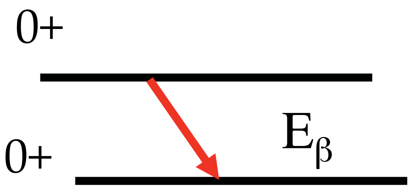
$$\Delta I = \left| I_i - I_f \right| \equiv 0{,}1$$

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

Classification of allowed decay

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

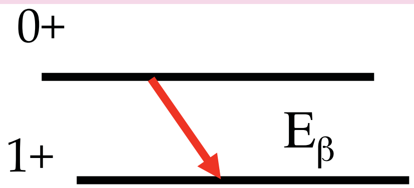
Fermi



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

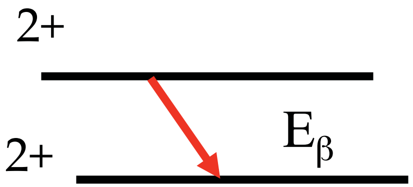
$$L_\beta = 0 \quad S_\beta = 0 \downarrow\uparrow$$

Gamow-Teller



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

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



mixed Fermi & Gamow-Teller

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

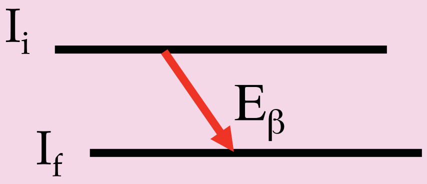
Classification of β decay transitions

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
	.	.	.

Some useful empirical rules

The fifth power beta decay rule:

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)



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

- 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.

β decay lifetime

$t \equiv T_{1/2}^{\beta_i} = \frac{T_{1/2}^{\exp}}{P_{\beta_i}}$ partial half-life of a given β⁻ (β⁺,EC) decay branch (*i*)

$$\frac{\ln 2}{T_{1/2}^{n}} = \frac{g^2}{2\pi^3}\int_1^W p_e W_e (W_0 - W_e)^2 F(Z, W_e) C_n dW_e$$

g – week interaction coupling constant

p_e – momentum of the β particle

W_e – total energy of the β particle

W_0 – maximum energy of the β particle

$F(Z,W_e)$ – Fermi function – distortion of the β particle wave function by the nuclear charge

C_n – shape factor

Z – atomic number

β decay Hindrance Factor

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

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

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	ΔI ($\pi_i \pi_f$)	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

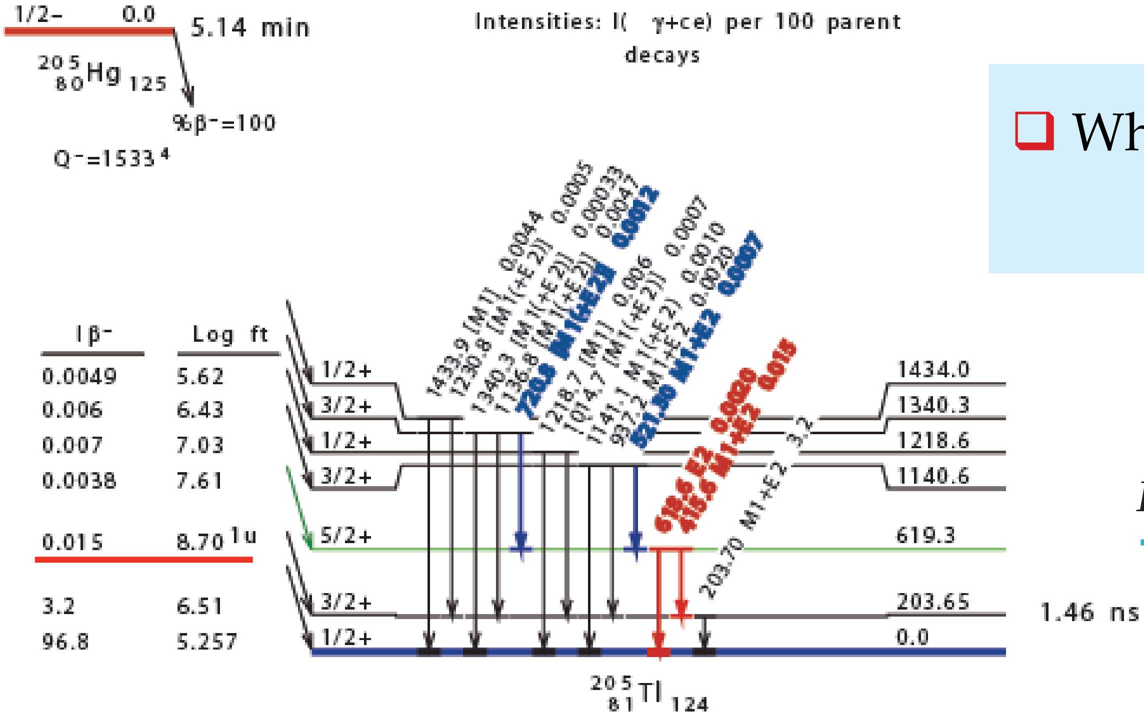
Log *t*

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

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

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

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



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

In

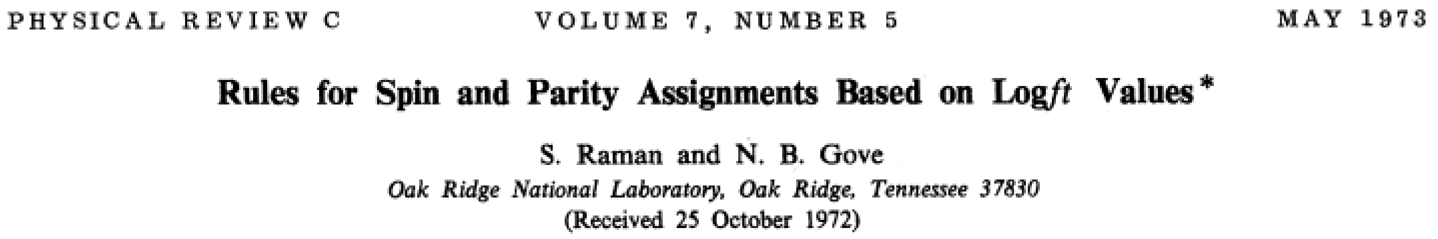
$$\frac{I^{tot}(521+721) = 0.086(16)}{I^{tot}(416+619) = 0.78(10)} = 0.69(10)$$

(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

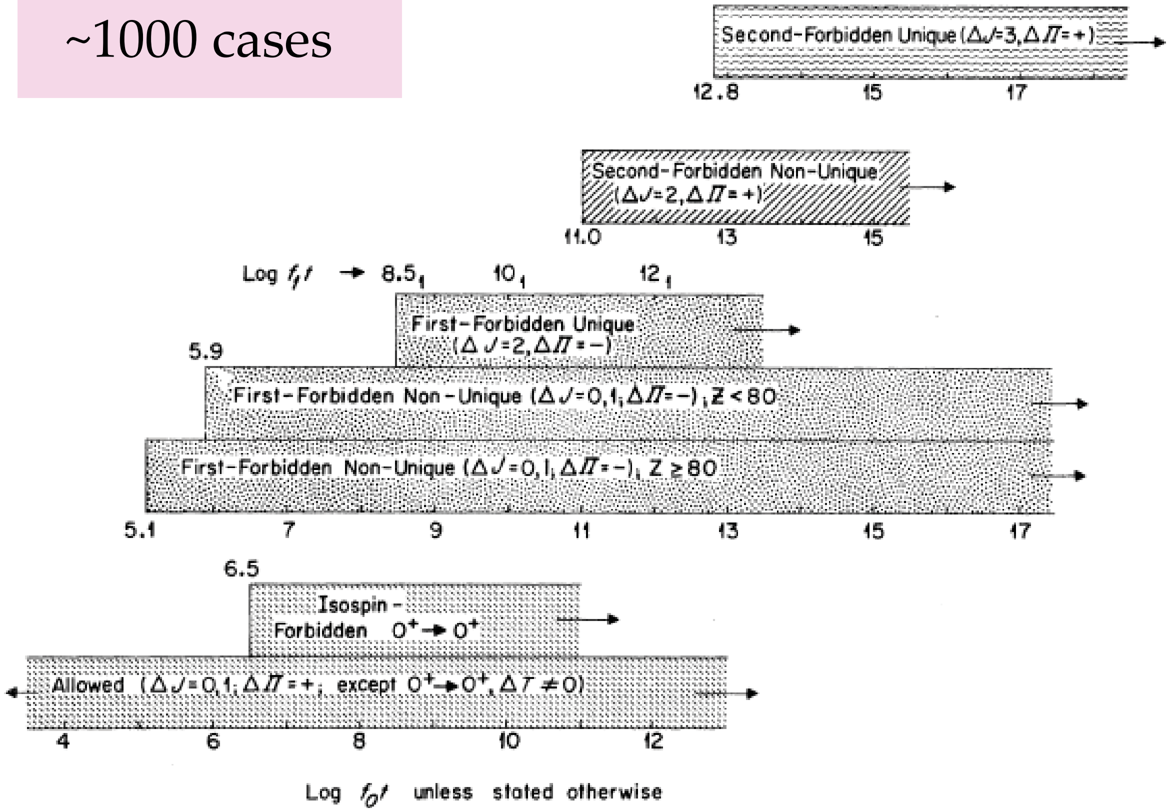
Rules for Spin and Parity Assignments Based on Log*ft* Values*

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



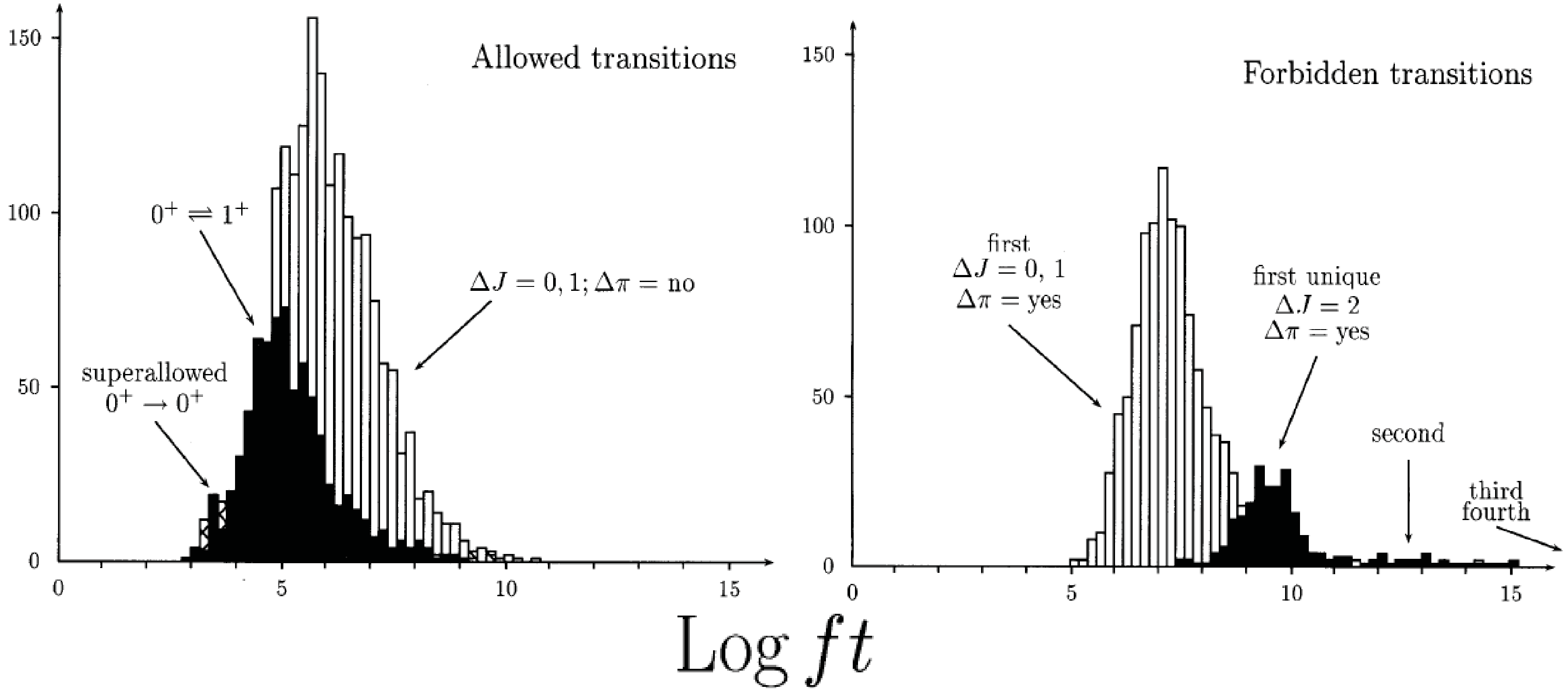
Log *ft* values – latest review

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

~3900 cases -> gives centroids and widths

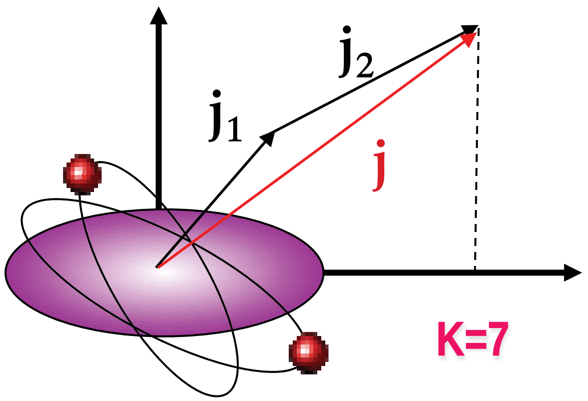
Review Of Log*ft* Values In β Decay*

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



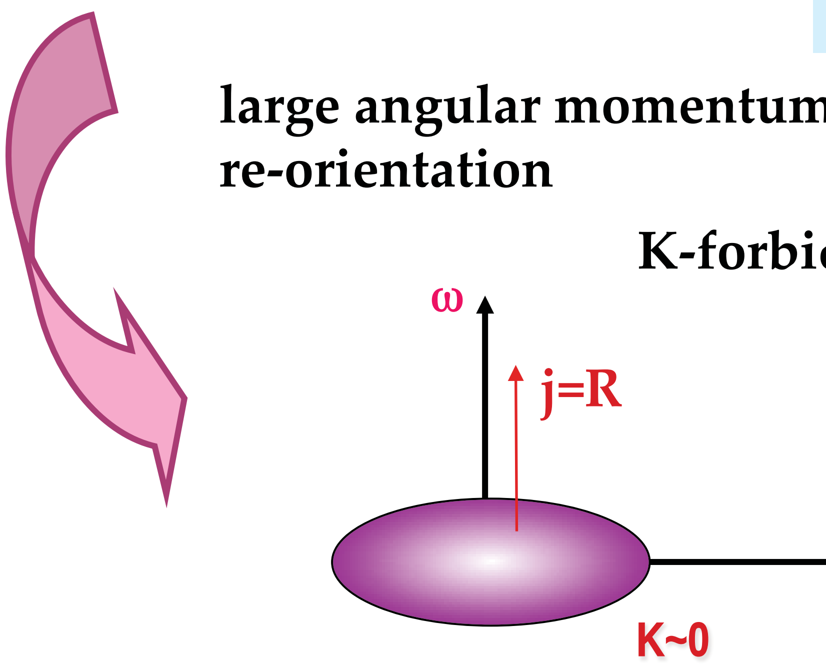
…but be careful, nuclear structure is important

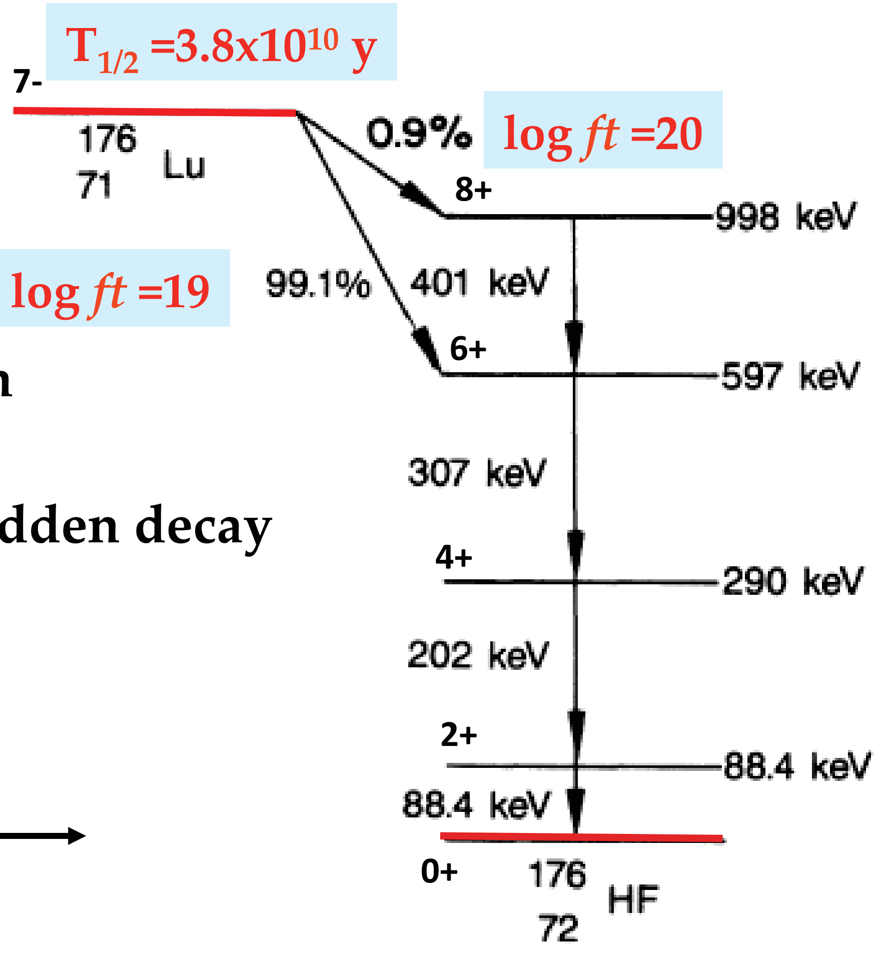
First forbidden → 5 < log *ft* <10



large angular momentum re-orientation

K-forbidden decay





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 AME12 mass evaluation (2012Wa08)

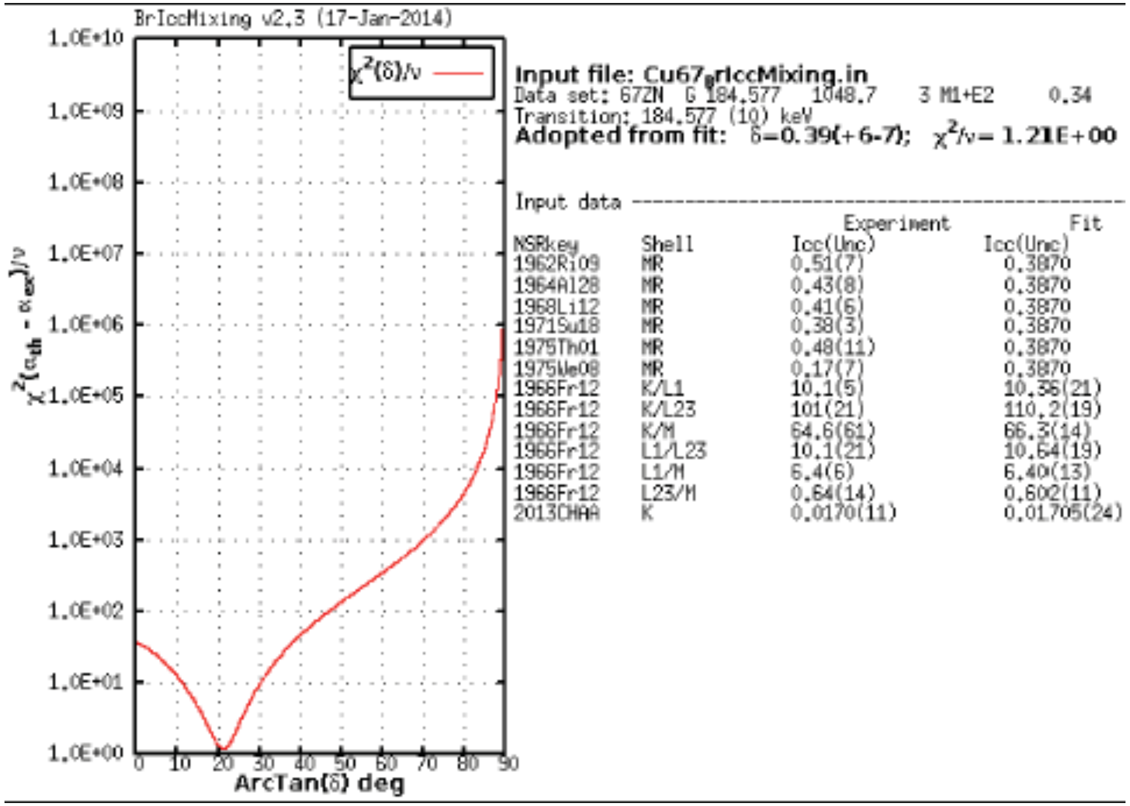
```
205TL    205HG B- DECAY                1971HI01                  93NDS    200310
205TL  H TYP=FUL$AUT=F. G. KONDEV$CIT=NDS 69,679 (1993)$CUT=1-Nov-2002$
205BI c  1971HI01: Mass-separated source; Detectors: NaI(Tl), two Ge(Li), 2 mm
205BI2c  thick Si(Li) with energy resolution of about 4 keV, a double 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.

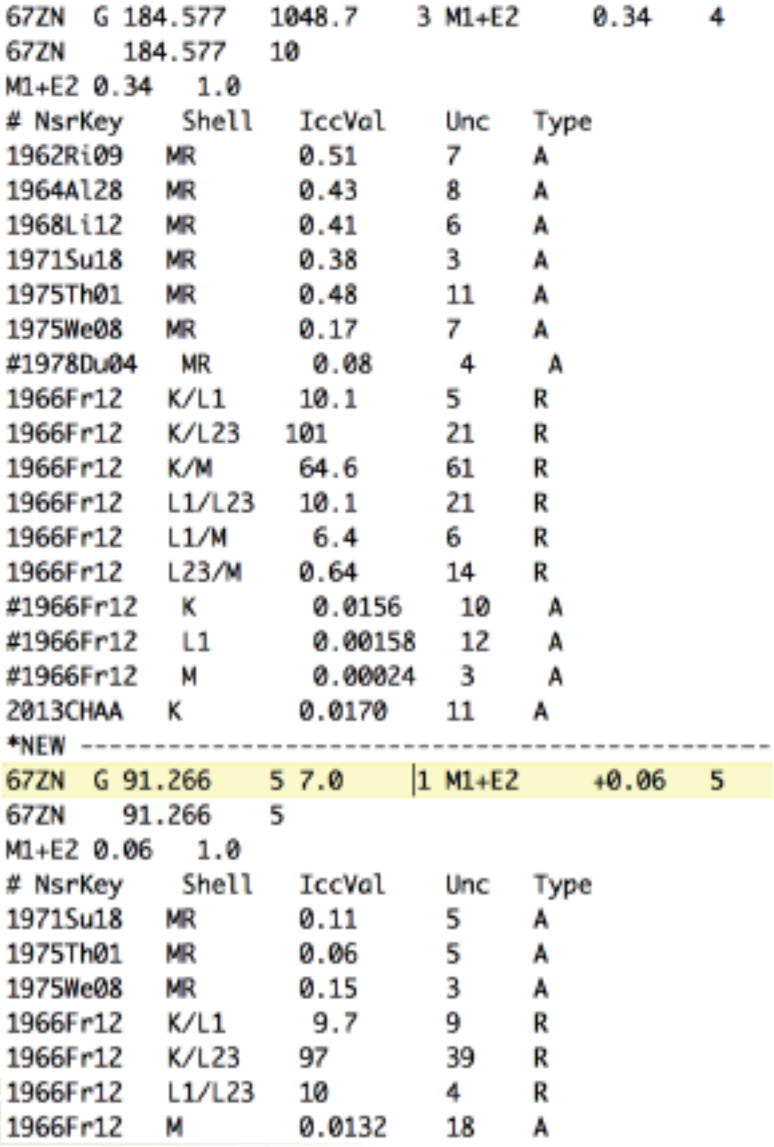
- ☐ **Include measured Eγ and Iγ**
  - ✓**if there is more than one reference you may use averages (avetools program), BUT be careful – need to compare oranges with oranges**
  - ✓ **include Mult. & MR – use "Adopted gammas" – if Mult. is not known, but initial and final J$^{\pi}$ are – use [ ], e.g. [E2], so ICC can be calculate**
  - ✓ **include measured ICC and/or sub-shell ratios to support Mult. assignment or to deduce MR**
  - ✓ **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**

Evaluation of multiple mixing ratios

Program: **Briccmixing**
T.Kibedi (ANU)



```
Input file: Cu67_rIccMixing.in
Data set: 67ZN  G 184.577   1048.7    3 M1+E2      0.34
Transition: 184.577 (10) keV
Adopted from fit:   δ=0.39(+6-7);   χ2/ν= 1.21E+00

Input data ---------------------------------------------------
                                  Experiment               Fit
NSRkey      Shell        Icc(Unc)              Icc(Unc)
1962Ri09    MR           0.51(7)                 0.3870
1964Al28    MR           0.43(8)                 0.3870
1968Li12    MR           0.41(6)                 0.3870
1971Su18    MR           0.38(3)                 0.3870
1975Th01    MR           0.48(11)                0.3870
1975We08    MR           0.17(7)                 0.3870
1966Fr12    K/L1         10.1(5)                 10.36(21)
1966Fr12    K/L23        101(21)                 110.2(19)
1966Fr12    K/M          64.6(61)                66.3(14)
1966Fr12    L1/L23       10.1(21)                10.64(19)
1966Fr12    L1/M         6.4(6)                  6.40(13)
1966Fr12    L23/M        0.64(14)                0.602(11)
2013CHAA    K            0.0170(11)              0.01705(24)
```



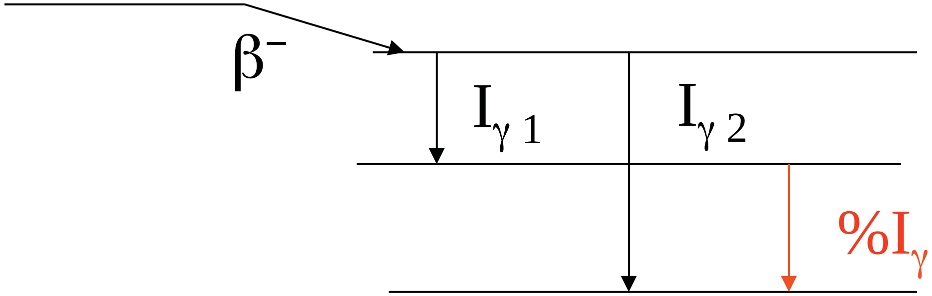
```
67ZN   G 184.577   1048.7    3 M1+E2      0.34     4
67ZN     184.577   10
M1+E2 0.34    1.0
# NsrKey      Shell     IccVal      Unc    Type
1962Ri09     MR        0.51        7      A
1964Al28     MR        0.43        8      A
1968Li12     MR        0.41        6      A
1971Su18     MR        0.38        3      A
1975Th01     MR        0.48        11     A
1975We08     MR        0.17        7      A
#1978Du04     MR        0.08        4      A
1966Fr12     K/L1      10.1        5      R
1966Fr12     K/L23    101          21     R
1966Fr12     K/M       64.6        61     R
1966Fr12     L1/L23    10.1        21     R
1966Fr12     L1/M       6.4        6      R
1966Fr12     L23/M     0.64        14     R
#1966Fr12     K          0.0156     10     A
#1966Fr12     L1         0.00158    12     A
#1966Fr12     M          0.00024    3      A
2013CHAA     K         0.0170      11     A
*NEW ---------------------------------------------
67ZN   G 91.266      5 7.0      1 M1+E2      +0.06    5
67ZN     91.266      5
M1+E2 0.06    1.0
# NsrKey      Shell     IccVal      Unc    Type
1971Su18     MR        0.11        5      A
1975Th01     MR        0.06        5      A
1975We08     MR        0.15        3      A
1966Fr12     K/L1        9.7       9      R
1966Fr12     K/L23     97          39     R
1966Fr12     L1/L23    10          4      R
1966Fr12     M         0.0132      18     A
```

```
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.

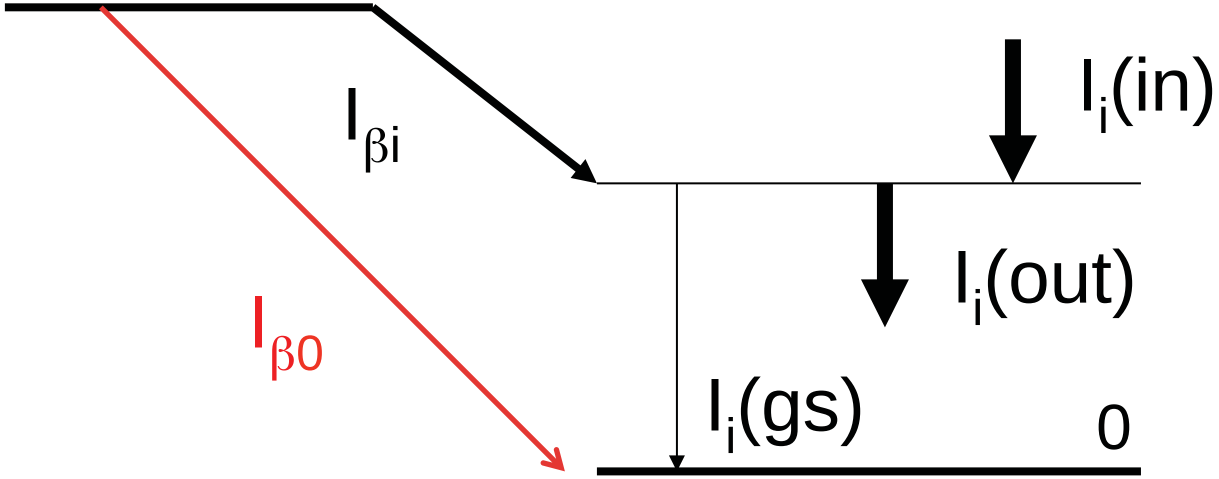
- ☐ **Complete the Normalization record – NR and BR**
  - ✓ **NR - need to convert to %Iγ**
  - ✓ **BR from Adopted levels of the parent, BUT check for new data are reevaluate, if needed**
- ☐ **Run GTOL – determine level energies and intensity balances**

Absolute intensity of one gamma ray is known (%I_γ)



- ✓ Relative intensity $I_\gamma \pm \Delta I_\gamma$
- ✓ Absolute intensity $\%I_\gamma \pm \Delta\%I_\gamma$
- ✓ Normalization factor $N = \%I_\gamma / I_\gamma$
- ✓ Uncertainty $\Delta N =[(\Delta\%I_\gamma / \%I_\gamma)^2+(\Delta I_\gamma / I_\gamma)^2]^{1/2} \times N$
- ✓ Then $\%I_{\gamma\,1} = N \times I_{\gamma\,1}$
- ✓ $\Delta\%I_{\gamma\,1} = [(\Delta N/N)^2 + (\Delta I_{\gamma\,1}/ I_{\gamma\,1})^2]^{1/2} \times I_{\gamma\,1}$

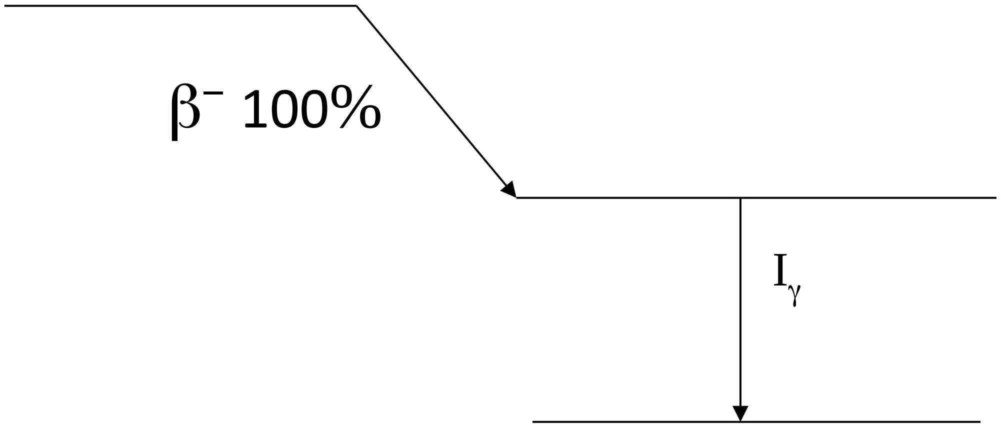
Normalization from the decay scheme



The corresponding normalization factor is:

N = (100-$I_{\beta 0}$) / Σ[I_i(out) + I_i(gs) – I_i(in)] =
(100-$I_{\beta 0}$) / Σ[I_i(out) – I_i(in)] + Σ I_i(gs), but
Σ[I_i(out) – I_i(in)] = 0, therefore
N = (100-$I_{\beta 0}$) / Σ I_i(gs)

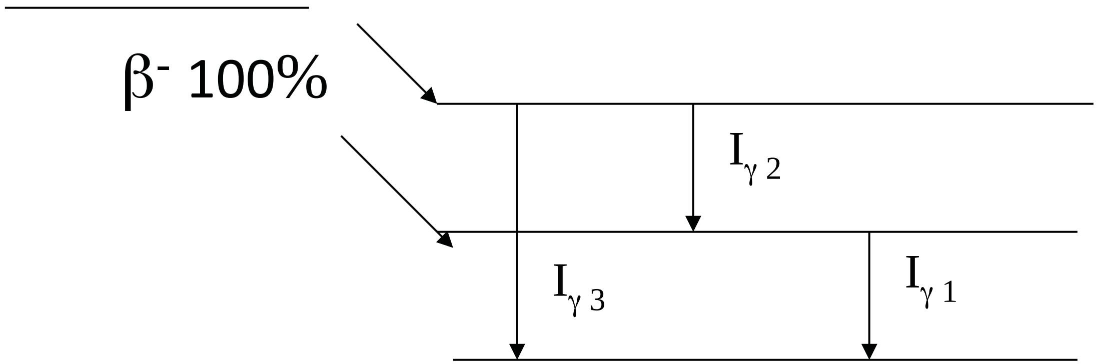
Normalization from the decay scheme – cont.



- ✓ Iγ: relative γ-ray intensity; α: total conversion coefficient

$$N \times I_\gamma \times (1 + \alpha) = 100\%$$

- ✓ Normalization factor $N = 100/ I_\gamma \times (1 + \alpha)$
- ✓ Absolute γ-ray intensity $\% I_\gamma = N \times I_\gamma = 100/ (1 + \alpha)$
- ✓ Uncertainty $\Delta\% I_\gamma = 100 \times \Delta\alpha/(1 + \alpha)^2$

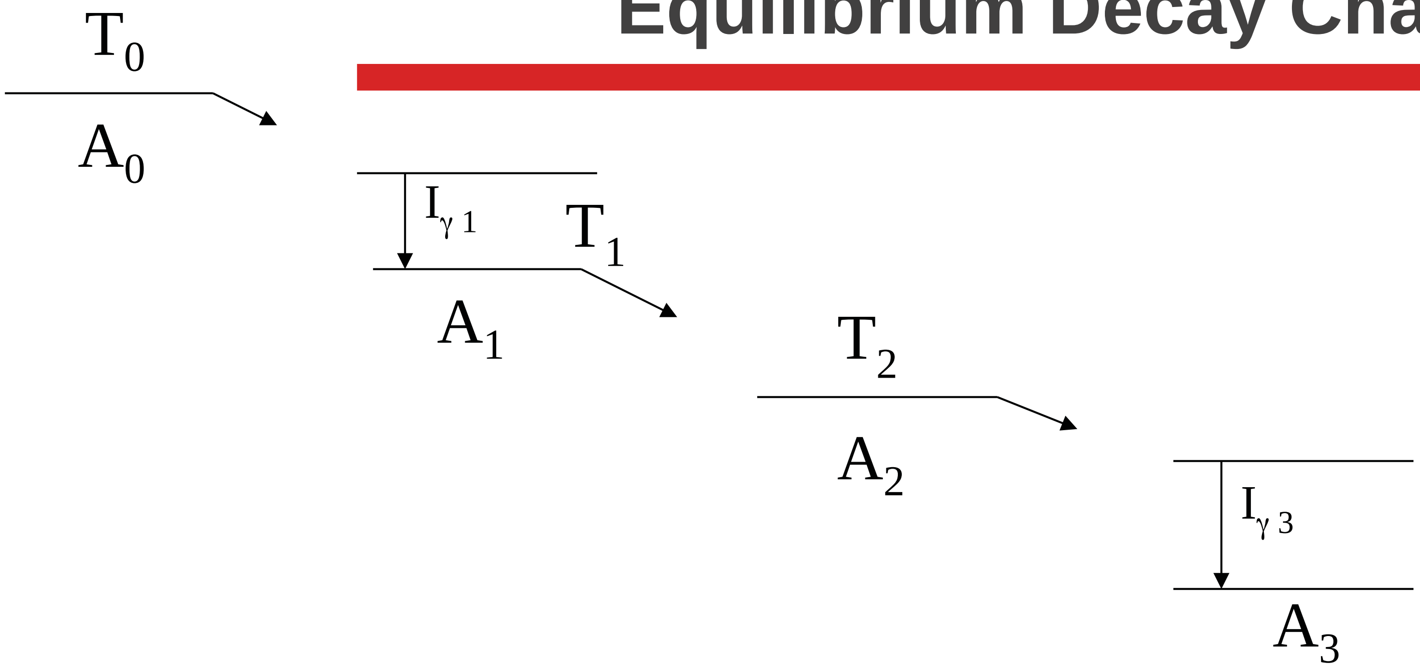


- Normalization factor $N = 100 / I_{\gamma 1}(1 + \alpha_1) + I_{\gamma 3}(1 + \alpha_3)$
- $\% I_{\gamma 1} = N \times I_{\gamma 1} = 100 \times I_{\gamma 1} / I_{\gamma 1}(1 + \alpha_1) + I_{\gamma 3}(1 + \alpha_3)$
- $\% I_{\gamma 3} = N \times I_{\gamma 3} = 100 \times I_{\gamma 3} / I_{\gamma 1}(1 + \alpha_1) + I_{\gamma 3}(1 + \alpha_3)$
- $\% I_{\gamma 2} = N \times I_{\gamma 2} = 100 \times I_{\gamma 2} / I_{\gamma 1}(1 + \alpha_1) + I_{\gamma 3}(1 + \alpha_3)$
- Calculate uncertainties in $\%I_{\gamma 1}$, $\% I_{\gamma 2}$, and $\% I_{\gamma 3}$. Use 1.4% fractional uncertainty in α_1 and α_3.

E. Browne, Nucl. Instr. and Meth. **A249**, 461 (1986).

or use computer program GABS

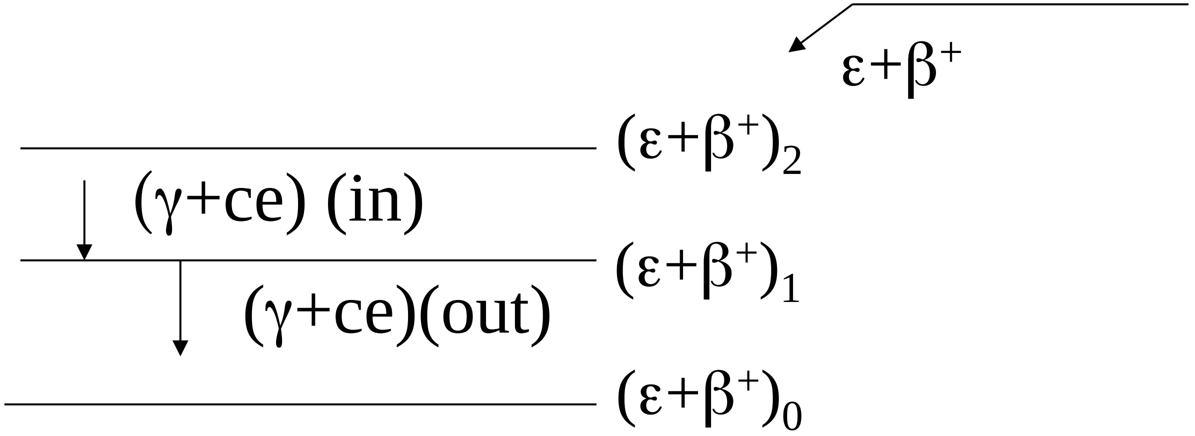
Equilibrium Decay Chain



- $T_0 > T_1, T_2$ are the radionuclide half-lives,
- For t = 0 only radionuclide A_0 exists,
- $\% I_{\gamma 3}$, $I_{\gamma 3}$, and $I_{\gamma 1}$ are known.
- Then, at equilibrium
- $\% I_{\gamma 1} = (\% I_{\gamma 3}/I_{\gamma 3}) \times I_{\gamma 1} \times (T_0/(T_0 - T_1)) \times (T_0/(T_0 - T_2))$

Normalization factor $N = \% I_{\gamma 3}/ I_{\gamma 3}$

Annihilation radiation intensity is known



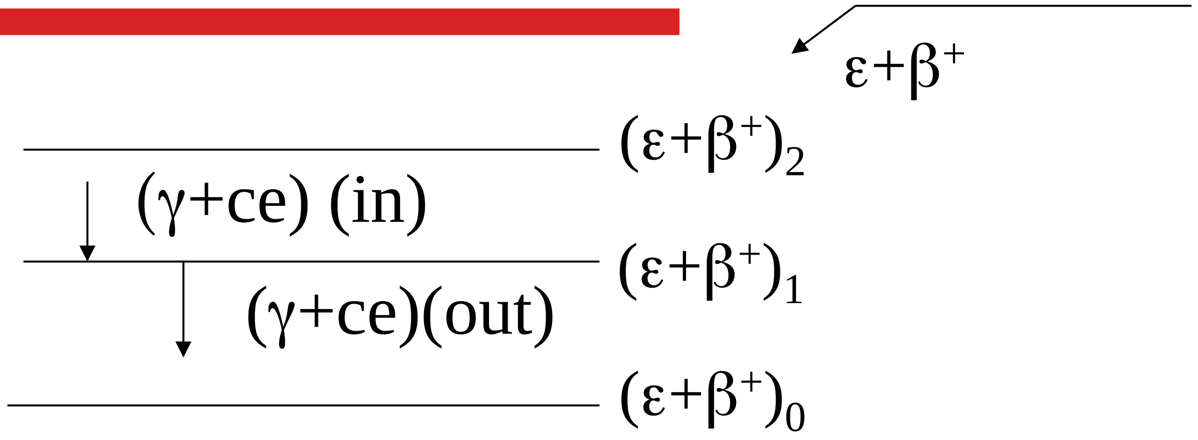
- $I(\gamma\underline{+})$ = Relative annihilation radiation intensity
- X_i = Intensity imbalance at the ith level = $(\gamma+ce)$ (out) – $(\gamma+ce)$ (in)
- $r_i = \varepsilon_i / \beta^+_i$ theoretical ratio to ith level
- $X_i = \varepsilon_i + \beta^+_i = \beta^+_i\ (1 + r_i)$, therefore $\beta^+_i = X_i / 1 + r_i$

$$2\ [X_0 / (1 + r_0) + \Sigma\, X_i / (1 + r_i)] = I(\gamma\underline{+}) \text{ .... } (1)$$

$$[X_0 + \Sigma\, I_{\gamma i}\ (\gamma + ce) \text{ to gs }]\ N \quad = 100 \text{ .... } (2)$$

- Solve equation (1) for X_0 (rel. gs feeding).
- Solve equation (2) for N (normalization factor).

X-ray intensity is known



$\varepsilon+\beta^+$

$(\varepsilon+\beta^+)_2$

$(\gamma$+ce) (in)

$(\varepsilon+\beta^+)_1$

$(\gamma$+ce)(out)

$(\varepsilon+\beta^+)_0$

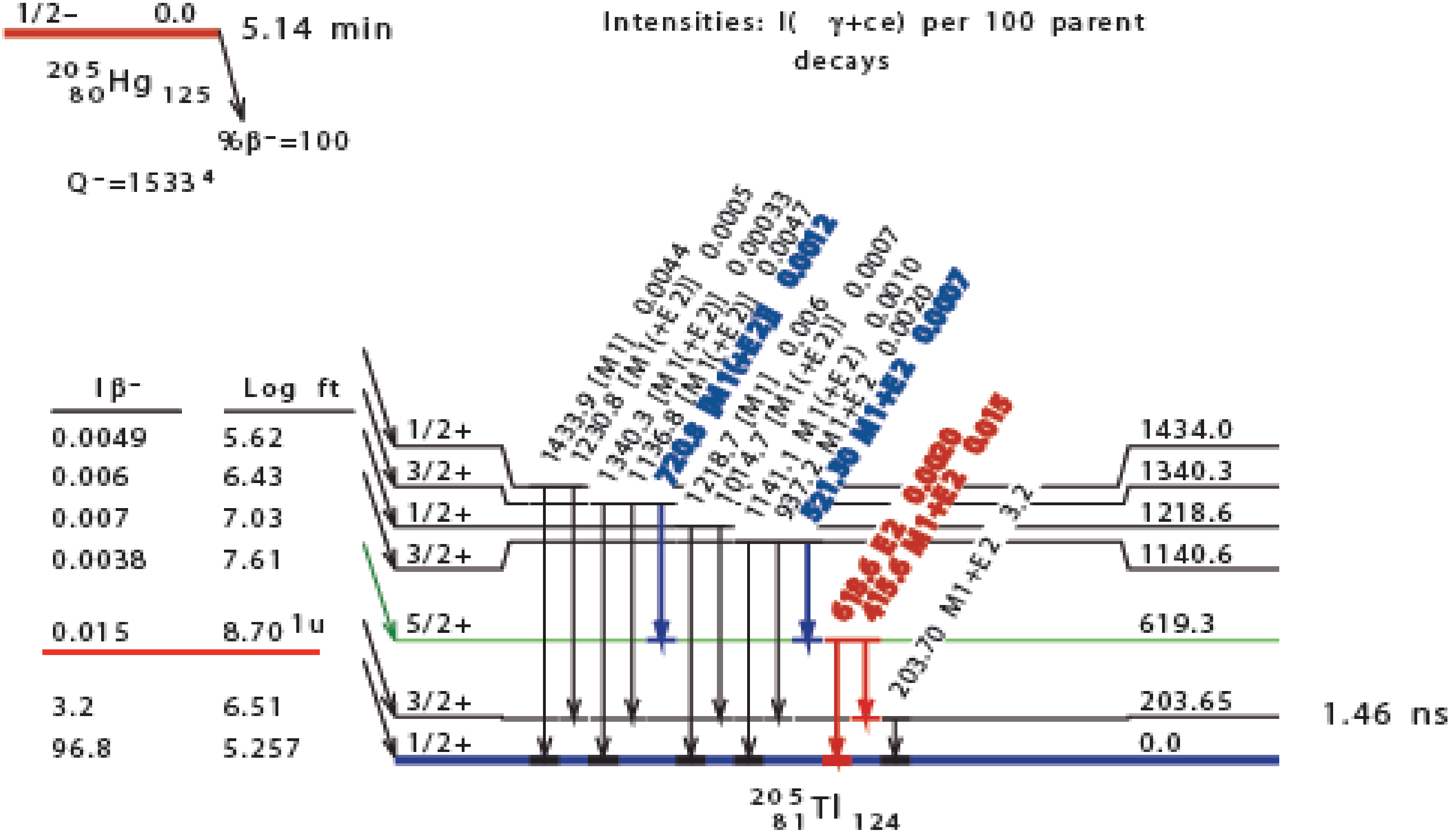
- I_K = Relative Kx-ray intensity
- X_i = Intensity imbalance at the ith level = $(\gamma$+ce) (out) – $(\gamma$+ce) (in)
- $r_i = \varepsilon_i / \beta^+_i$ theoretical ratio to ith level
- $X_i = \varepsilon_i + \beta^+_i$, so $\varepsilon_i = X_i r_i / 1 + r_i$ (atomic vacancies); ω_K=K-fluorsc.yield
- P_{Ki} = Fraction of the electron-capture decay from the K shell
- $I_K = \omega_K [\varepsilon_0 \times P_{K0} + \Sigma \varepsilon_i \times P_{Ki}]$

$$I_K = \omega_K [P_{K0}\times X_0 r_0 / (1 + r_0) + \Sigma P_{Ki}\times X_i r_i / 1 + r_i]...(1)$$

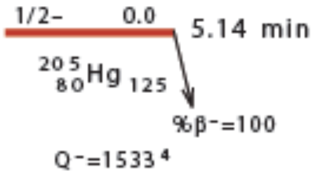
$$[X_0 + \Sigma I_i(\gamma + ce) \text{ to gs}]\ N = 100\ ....\ (2)$$

- Solve equation (1) for X_0, equation (2) for N.

^{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
```

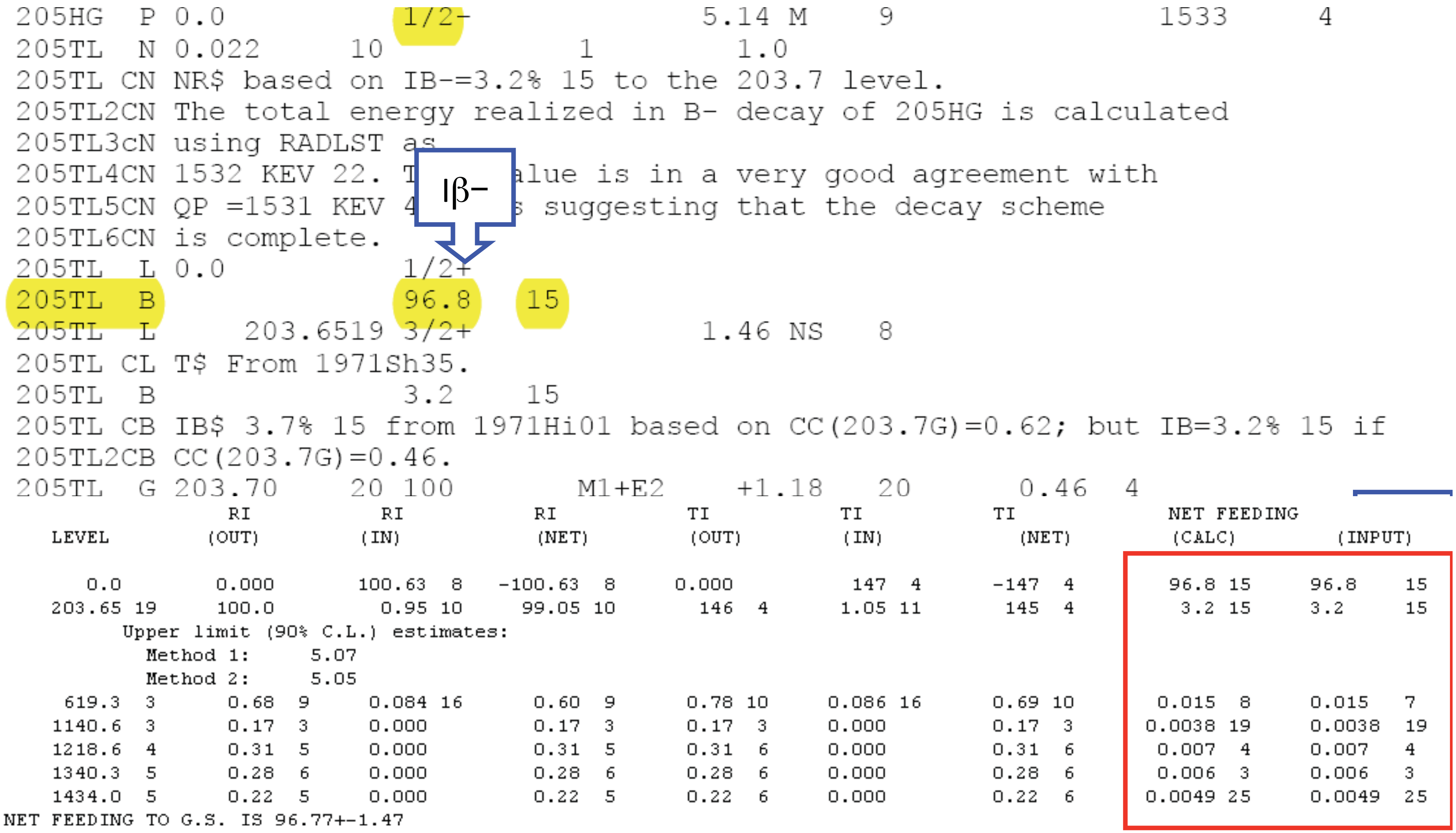


Intensities: I(γ+ce) per 100 parent decays

program GTOL

```
  LEVEL         RI          RI          RI         TI          TI          TI            NET FEEDING
               (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
```

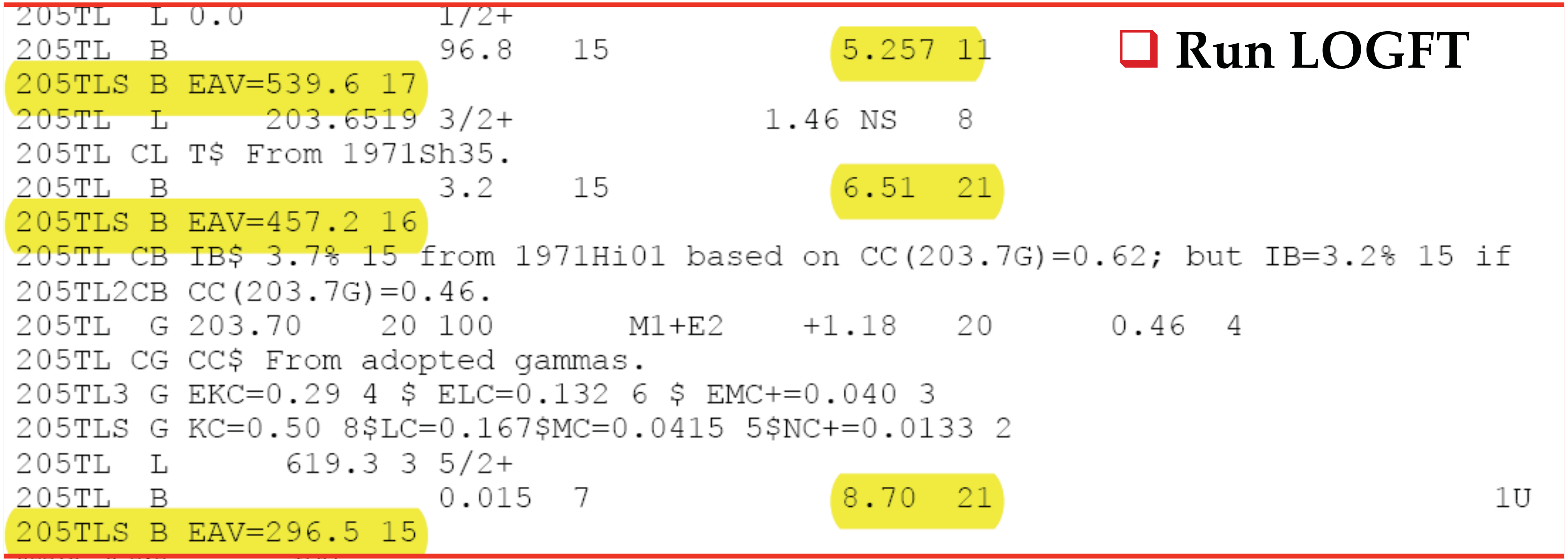
Before running the LOGFT program



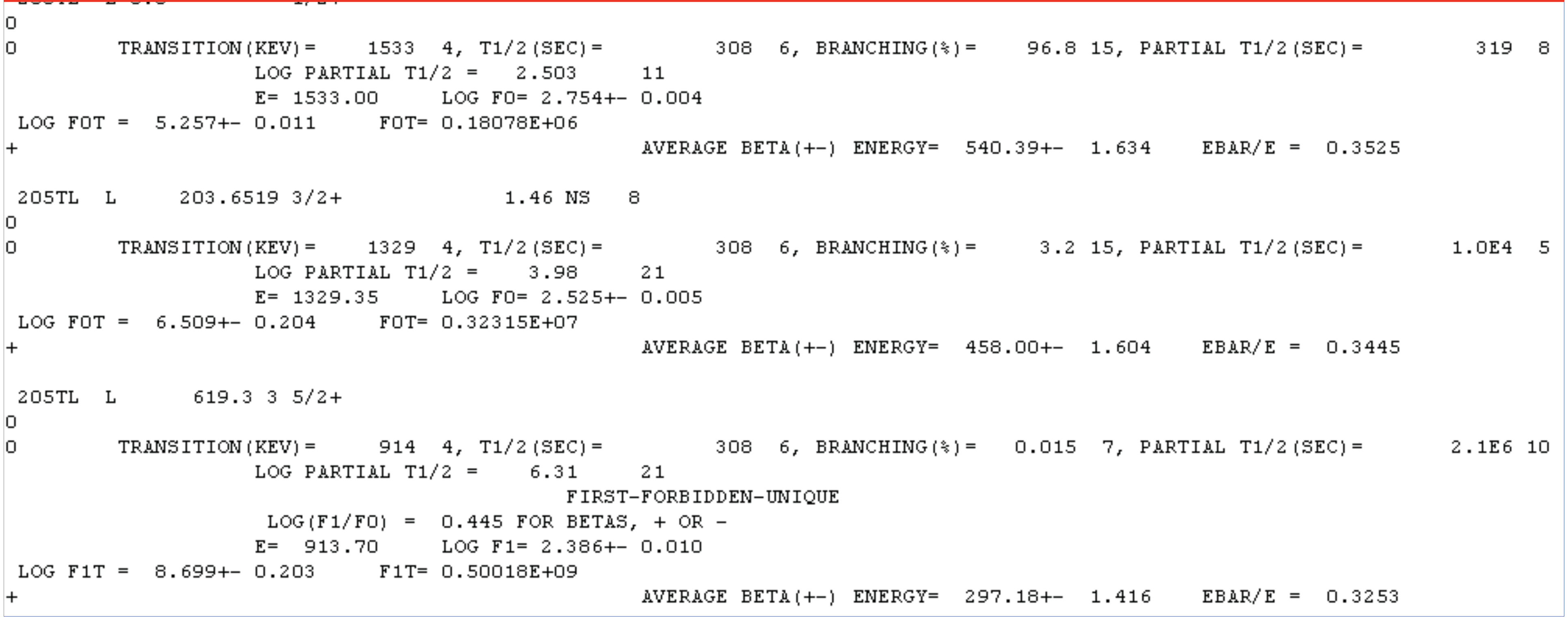
```
205HG  P 0.0           1/2-                5.14 M    9               1533     4
205TL  N 0.022    10            1         1.0
205TL CN NR$ based on IB-=3.2% 15 to the 203.7 level.
205TL2CN The total energy realized in B- decay of 205HG is calculated
205TL3cN using RADLST as
205TL4CN 1532 KEV 22. 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
```

```
                   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
```

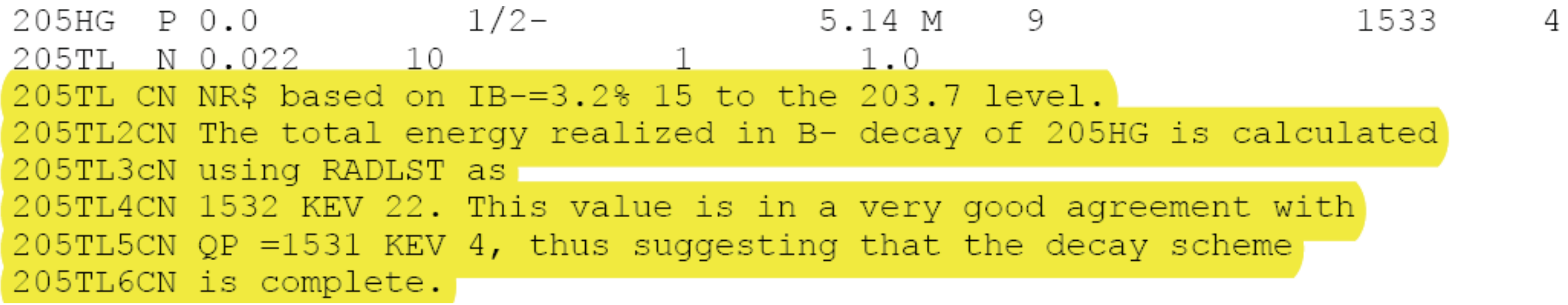


```
0
0        TRANSITION(KEV)=    1533   4, T1/2(SEC)=         308   6, BRANCHING(%)=    96.8 15, PARTIAL T1/2(SEC)=         319   8
                    LOG PARTIAL T1/2 =    2.503      11
                    E= 1533.00      LOG FO= 2.754+- 0.004
 LOG FOT =  5.257+- 0.011     FOT= 0.18078E+06
+    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

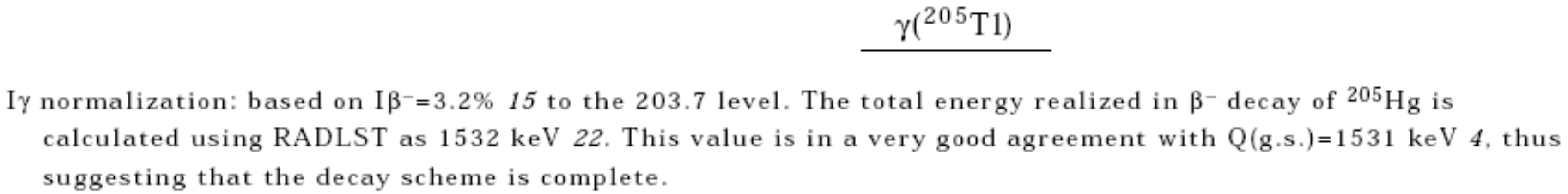
Guideline for evaluators-cont.

❑ **Check the decay scheme for consistency (using RADLST)**

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

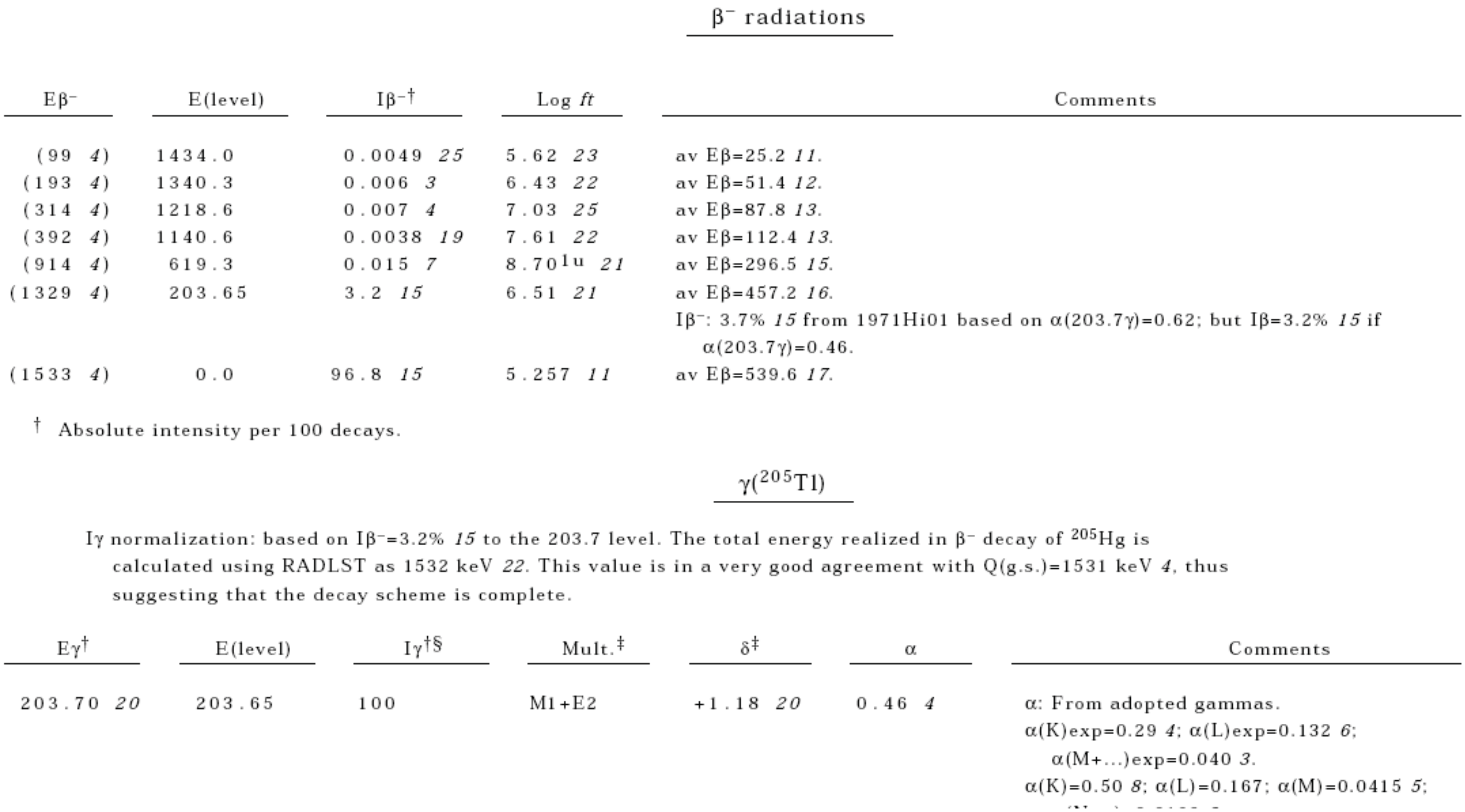


```
205HG  P 0.0          1/2-             5.14 M    9               1533     4
205TL  N 0.022     10           1        1.0
205TL CN NR$ based on IB-=3.2% 15 to the 203.7 level.
205TL2CN The total energy realized in B- decay of 205HG is calculated
205TL3cN using RADLST as
205TL4CN 1532 KEV 22. This 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 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.



β^- radiations

$E\beta^-$	E(level)	$I\beta^{-\dagger}$	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*. $I\beta^-$: 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.

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

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.

$E\gamma^\dagger$	E(level)	$I\gamma^{\dagger\S}$	Mult.‡	$\delta^\ddagger$	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 -** AME2012 – new tables were published – 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 (Δδ)
  - ✓ 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 (Δδ) – 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.?

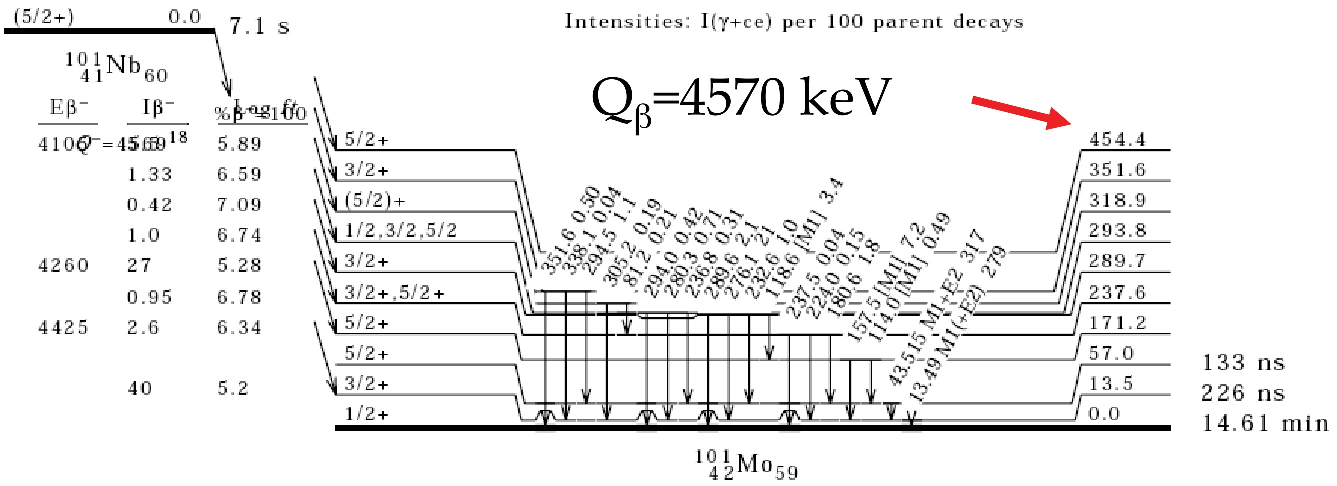
- ☐ **Beta Radiation Properties:** E_β (ΔE_β), I_β (ΔI_β)
  - ✓ E_β (ΔE_β) – it is not discrete, usually maximum and mean energies are deduced from the known decay scheme and decay Q value
  - ✓ I_β (ΔI_β) – deduced from intensity balances - > need to look carefully if $I_{\beta+}$ has been measured, 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

Dealing with incomplete data

“Pandemonium” effect

J. Hardy et al, PLB 71 (1977) 307



Q_β=4570 keV

Intensity balances are compromised!

One may expect %Iβ_i to be inaccurate

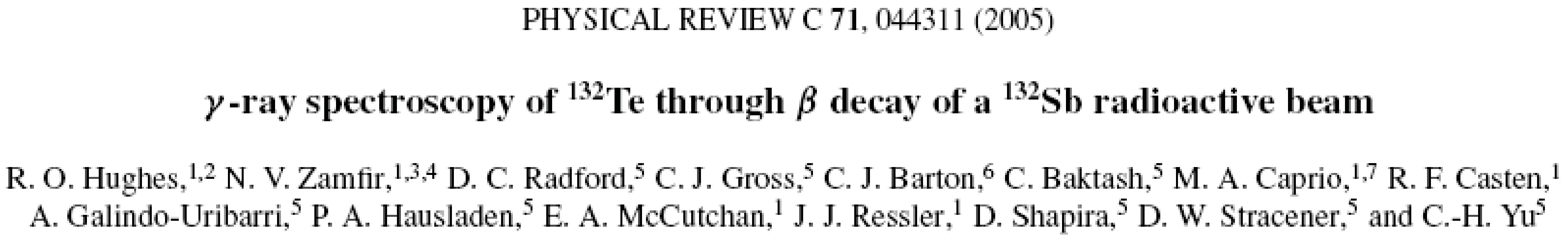
- ✓ missing many gamma rays
- ✓ unknown Mult., MR, ICC

log *ft* values are just lower limits …

- ✓ cannot be used for J$^\pi$ assignment

MUST include appropriate comments

Large gamma-ray arrays & RB facilities

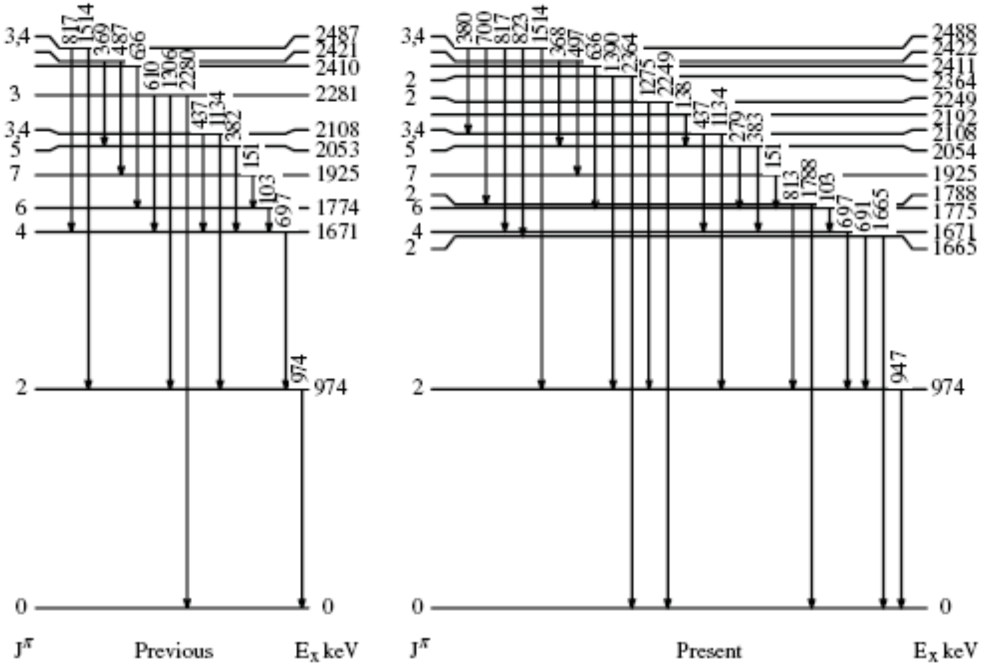


PHYSICAL REVIEW C 71, 044311 (2005)

γ-ray spectroscopy of ^{132}Te through β decay of a ^{132}Sb radioactive beam

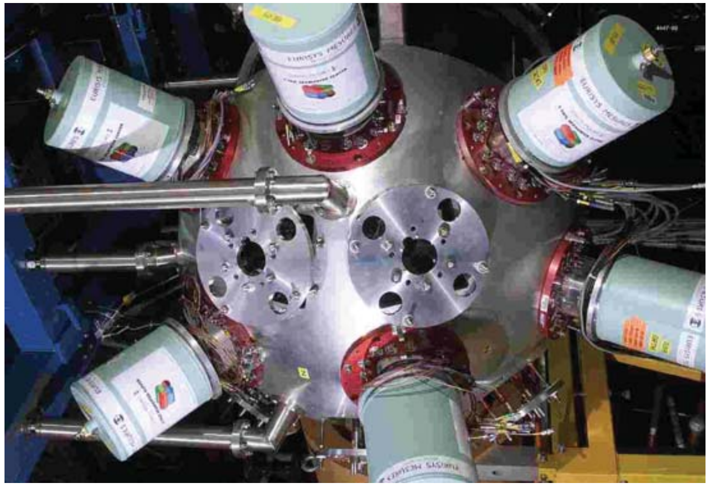
R. O. Hughes,[1,2] N. V. Zamfir,[1,3,4] D. C. Radford,[5] C. J. Gross,[5] C. J. Barton,[6] C. Baktash,[5] M. A. Caprio,[1,7] R. F. Casten,[1] A. Galindo-Uribarri,[5] P. A. Hausladen,[5] E. A. McCutchan,[1] J. J. Ressler,[1] D. Shapira,[5] D. W. Stracener,[5] and C.-H. Yu[5]

- ✓ using ^{132}Sb beam (10^7 pps) at 396 MeV produced from proton-induced fission



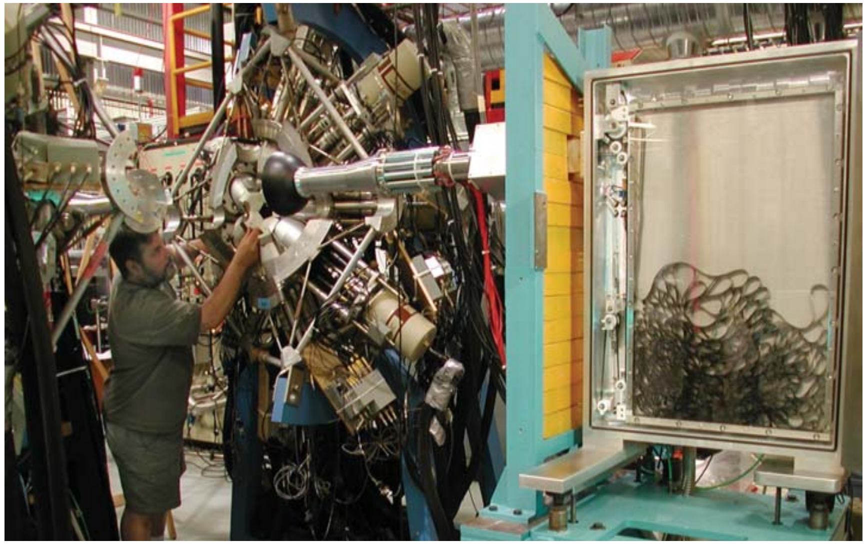
- ✓ significantly revised level scheme
- ✓ more than 195 new transitions

CLARION – 11 Clovers, ORNL



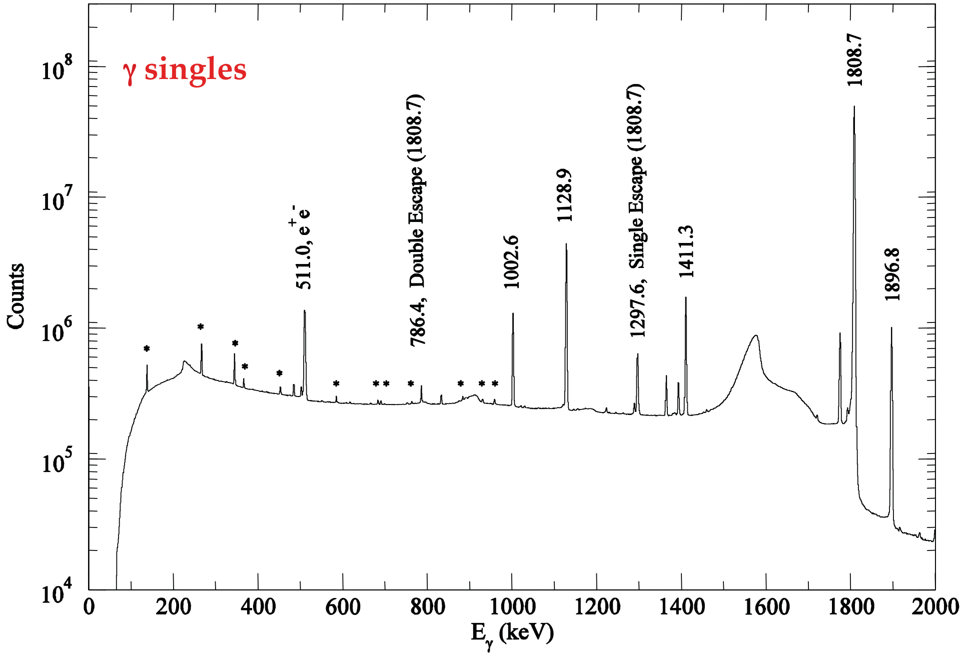
TRIUMF, CANADA

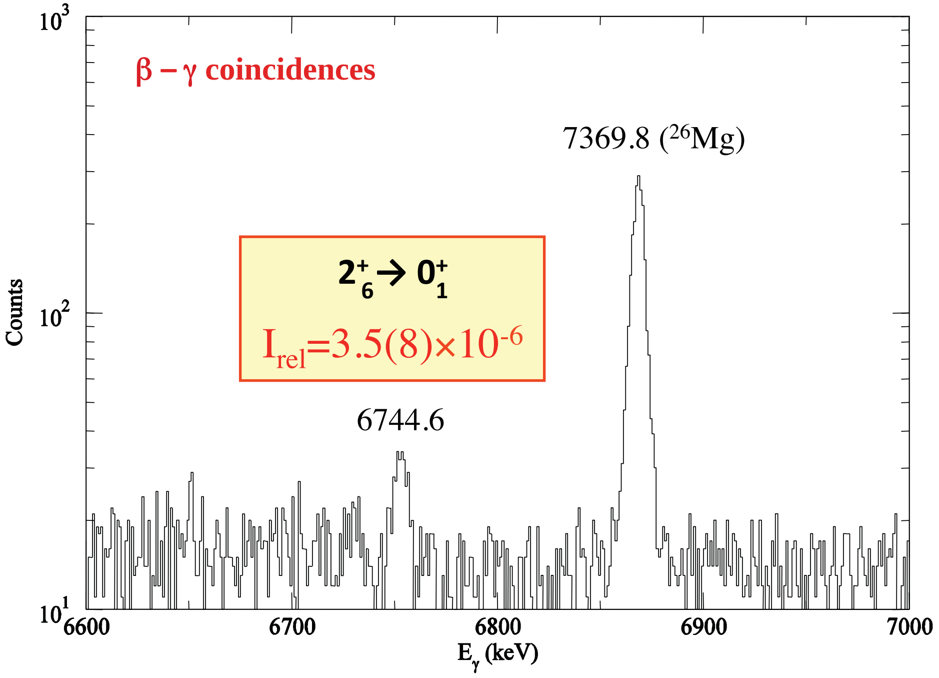
8p & SCEPTAR



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

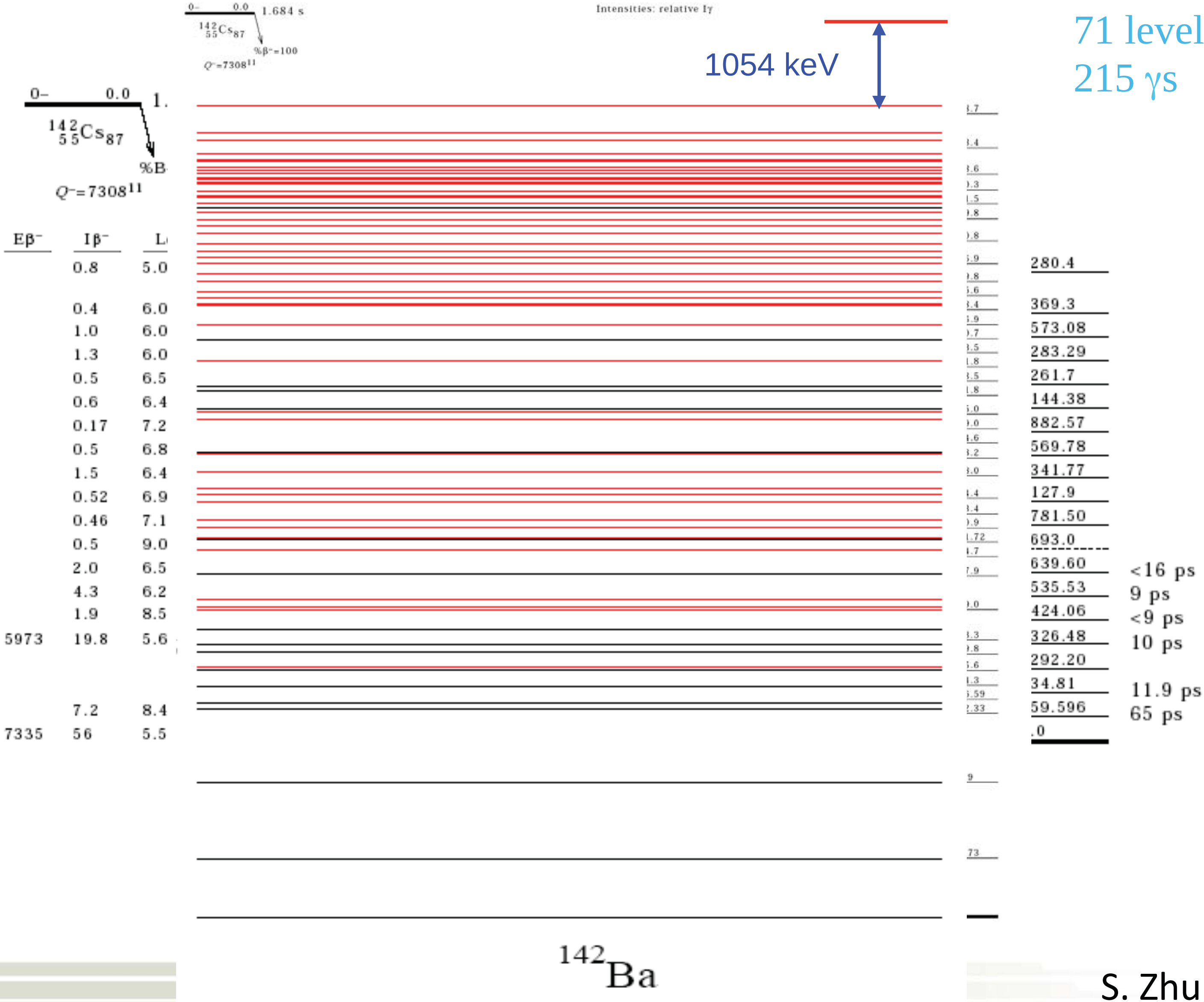
^{26}Na beam: 10^6 s^{-1} for 12 hours, trigger rate 24 kHz





Expanded β-decay level scheme of ^{142}Ba

CARIBU & Gammasphere at ANL



Sn=6183(8) keV

1054 keV

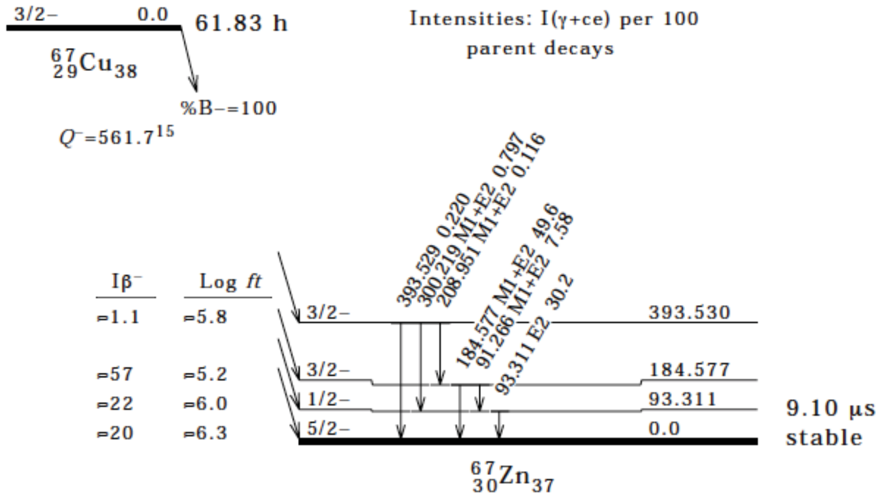
71 levels

215 γs

S. Zhu, ANL

Huo Junde, Huang Xiaolong, J.K. Tuli Nuclear Data Sheets 106, 159 (2005)

ENSDF & TOI99



^{67}Zn levels

E$_{level}$#	J$^{\pi}$@	T$_{½}$	Comments
0.0	5/2-	stable	
93.311 *5*	1/2-	9.10 *μs* *7*	**T$_{½}$:** from 1973Le18.
184.577 *6*	3/2-		
393.530 *7*	3/2-		

β⁻ Radiations

E$_{β^-}$	E$_{level}$	I$_{β^-}$#	Log *ft*	Comments
(168.2)	393.530	≈1.1	≈5.8	av Eβ=51.0 *25*
(377.1)	184.577	≈57	≈5.2	av Eβ=121 *3*
(468.4)	93.311	≈22	≈6.0	av Eβ=154 *3*
(561.7)	0.0	≈20	≈6.3	av Eβ=189 *3* **I$_{β^-}$:** from 1953Ea11.

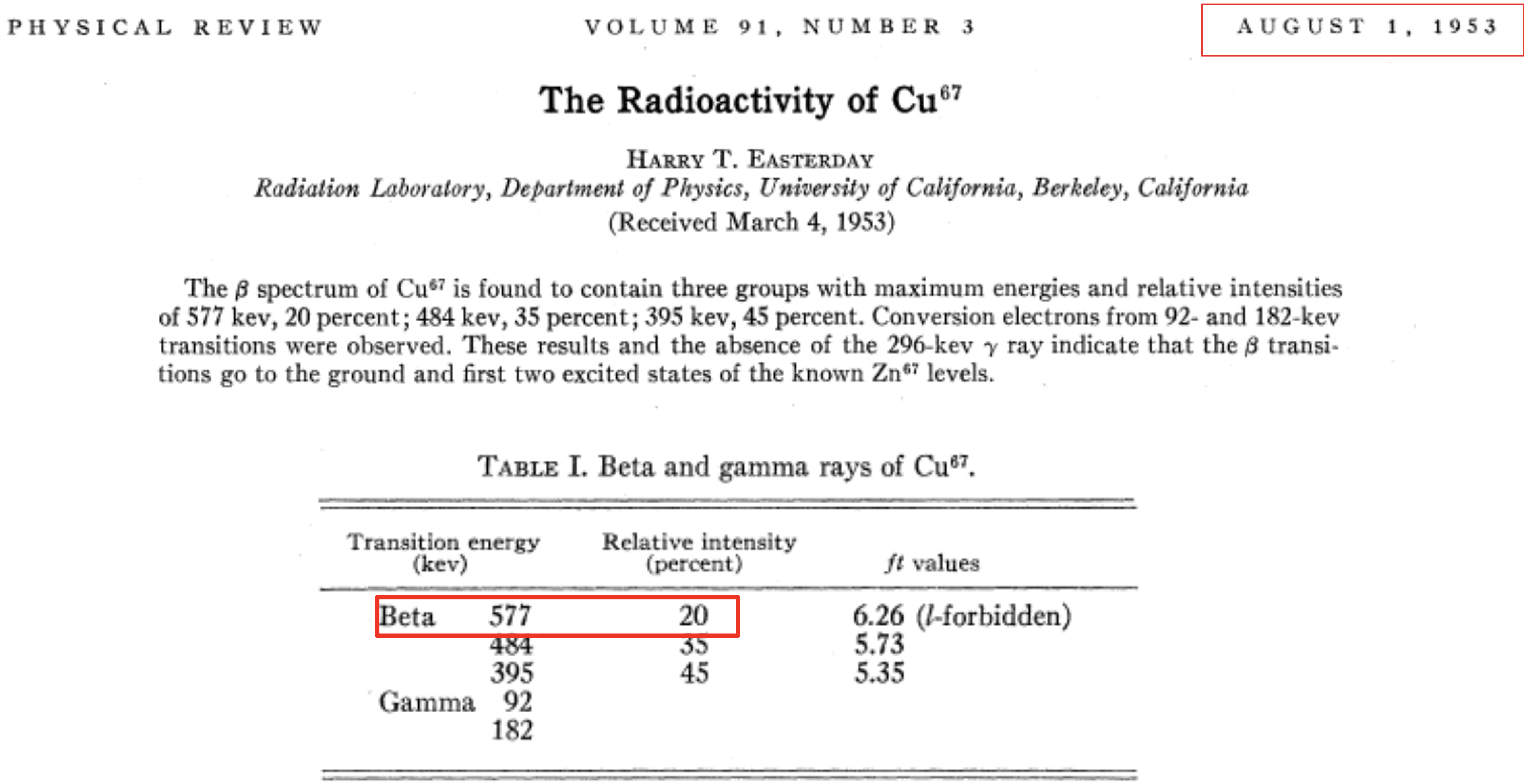
I$_{γ}$ Normalization: Based on a g.s. β⁻ branching of ≈20% (1953Ea11) and 10% E2 for the 184γ corresponding to the δ=0.34 4 derived from the ce data of 1966Fr12.

very precise ... , BUT

E$_{γ}$@	E$_{level}$	I$_{γ}$#@	Mult.&	δ&	α	Comments
91.266 *5*	184.577	7.0 *1*	M1+E2	+0.06 *5*	0.083 *8*	α(K)exp=0.066 10(1969Li04) α(K)=0.073 *7*; α(L)=0.0076 *8*
93.311 *5*	93.311	16.1 *2*	E2		0.873	α(K)exp=0.77 8(1966Fr12) α(K)=0.751; α(L)=0.0920
184.577 *10*	184.577	48.7 *3*	M1+E2	0.34 *4*	0.0180 *13*	α(K)exp=0.0156 10(1966Fr12) α(K)=0.0158 *11*; α(L)=0.00165 *12* **δ:** from α(K)exp+α(L1)exp=1.72×10-2 10(1966Fr12).
208.951 *10*	393.530	0.115 *5*	M1+E2	-0.034 *21*	0.00913 *6*	α(K)=0.00804 *6*; α(L)=0.00082
300.219 *10*	393.530	0.797 *11*	M1+E2	+0.20 *8*		
393.529 *10*	393.530	0.220 *8*				**δ:** -0.17 8 or -2.4 3 for M1+E2.

For absolute intensity per 100 decays, multiply by 1.00.

@From 1978Me10.



PHYSICAL REVIEW VOLUME 91, NUMBER 3 AUGUST 1, 1953

The Radioactivity of Cu^{67}

HARRY T. EASTERDAY
Radiation Laboratory, Department of Physics, University of California, Berkeley, California

(Received March 4, 1953)

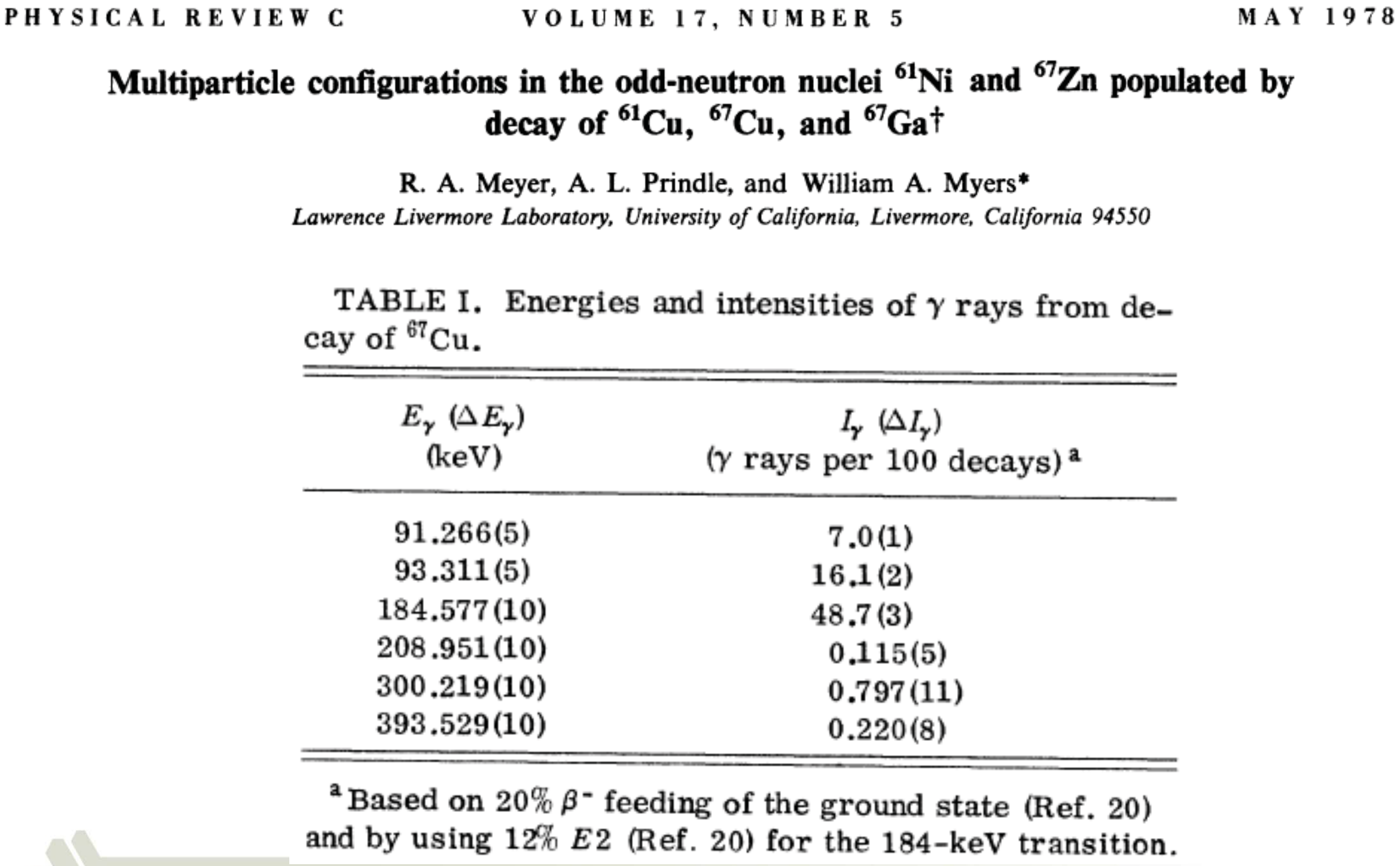
The β spectrum of Cu^{67} is found to contain three groups with maximum energies and relative intensities of 577 kev, 20 percent; 484 kev, 35 percent; 395 kev, 45 percent. Conversion electrons from 92- and 182-kev transitions were observed. These results and the absence of the 296-kev γ ray indicate that the β transitions go to the ground and first two excited states of the known Zn^{67} levels.

TABLE I. Beta and gamma rays of Cu^{67}.

	Transition energy (kev)	Relative intensity (percent)	*ft* values
Beta	577	20	6.26 (*l*-forbidden)
	484	35	5.73
	395	45	5.35
Gamma	92		
	182		

no uncertainty – the quoted value is approximate!

Relative γ–ray emission probabilities



PHYSICAL REVIEW C VOLUME 17, NUMBER 5 MAY 1978

Multiparticle configurations in the odd-neutron nuclei ^{61}Ni and ^{67}Zn populated by decay of ^{61}Cu, ^{67}Cu, and ^{67}Ga†

R. A. Meyer, A. L. Prindle, and William A. Myers*

Lawrence Livermore Laboratory, University of California, Livermore, California 94550

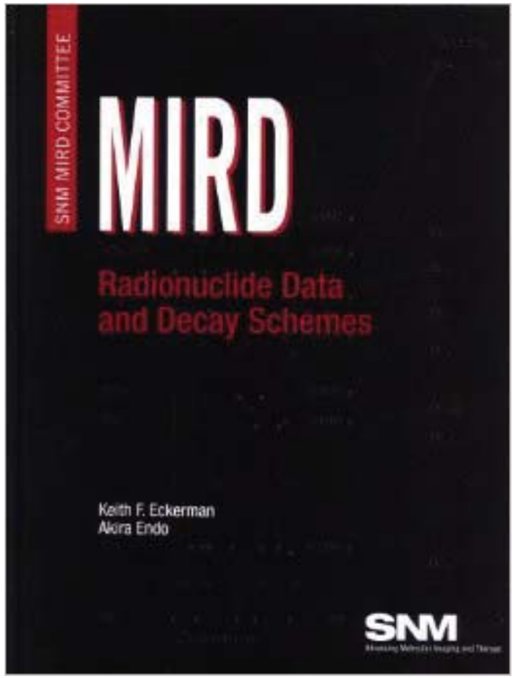
TABLE I. Energies and intensities of γ rays from decay of ^{67}Cu.

E_γ (ΔE_γ) (keV)	I_γ (ΔI_γ) (γ rays per 100 decays)[a]
91.266(5)	7.0(1)
93.311(5)	16.1(2)
184.577(10)	48.7(3)
208.951(10)	0.115(5)
300.219(10)	0.797(11)
393.529(10)	0.220(8)

[a] Based on 20% β^- feeding of the ground state (Ref. 20) and by using 12% $E2$ (Ref. 20) for the 184-keV transition.

Ground-state to Ground-state $\beta-$ branch

ENSDF	**~20%**
MIRD (NNDC)	20%
MIRD (med)	20%
NUDAT	20 **(2)**%
JEFF3.1	20 **(2)**%
ENDF/B-VII.1	20 **(2)**%

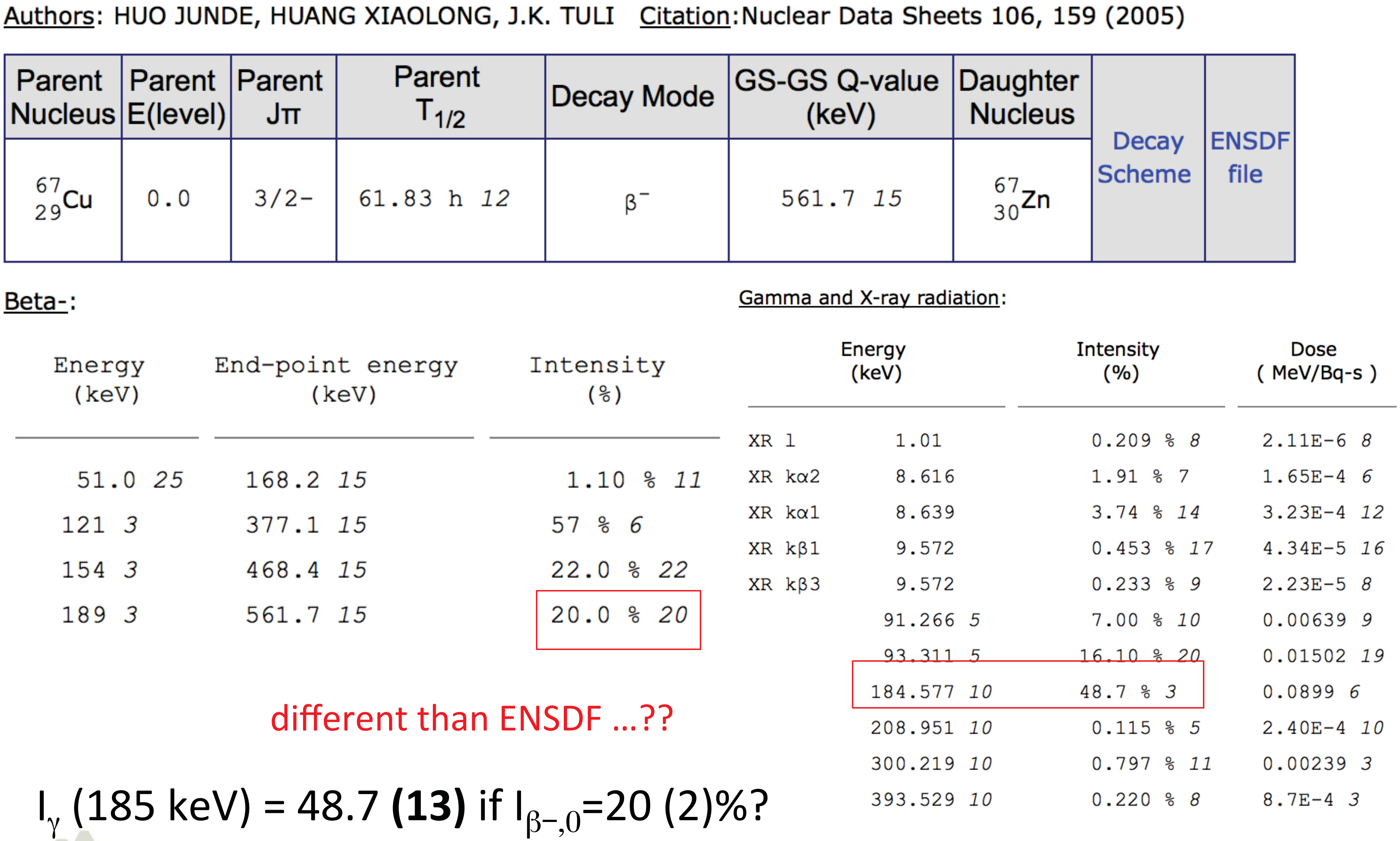


I_γ (185 keV) = 48.7 **(3)**% - used in all????, but …
one should get 48.7 **(13)*** if $I_{\beta-,0}$=20 (2)%?

* - using the same ICCs as in the ensdf evaluation

BUT it is deduced with some (important) assumptions!!!!

NUDAT (nndc.bnl.gov)



Authors: HUO JUNDE, HUANG XIAOLONG, J.K. TULI Citation:Nuclear Data Sheets 106, 159 (2005)

Parent Nucleus	Parent E(level)	Parent Jπ	Parent $T_{1/2}$	Decay Mode	GS-GS Q-value (keV)	Daughter Nucleus	Decay Scheme	ENSDF file
$^{67}_{29}$Cu	0.0	3/2-	61.83 h *12*	β^-	561.7 *15*	$^{67}_{30}$Zn		

Beta-:

Energy (keV)	End-point energy (keV)	Intensity (%)
51.0 *25*	168.2 *15*	1.10 % *11*
121 *3*	377.1 *15*	57 % *6*
154 *3*	468.4 *15*	22.0 % *22*
189 *3*	561.7 *15*	20.0 % *20*

Gamma and X-ray radiation:

	Energy (keV)	Intensity (%)	Dose (MeV/Bq-s)
XR l	1.01	0.209 % *8*	2.11E-6 *8*
XR kα2	8.616	1.91 % *7*	1.65E-4 *6*
XR kα1	8.639	3.74 % *14*	3.23E-4 *12*
XR kβ1	9.572	0.453 % *17*	4.34E-5 *16*
XR kβ3	9.572	0.233 % *9*	2.23E-5 *8*
	91.266 *5*	7.00 % *10*	0.00639 *9*
	93.311 *5*	16.10 % *20*	0.01502 *19*
	184.577 *10*	48.7 % *3*	0.0899 *6*
	208.951 *10*	0.115 % *5*	2.40E-4 *10*
	300.219 *10*	0.797 % *11*	0.00239 *3*
	393.529 *10*	0.220 % *8*	8.7E-4 *3*

different than ENSDF …??

I_γ (185 keV) = 48.7 **(13)** if $I_{\beta-,0}$=20 (2)%?

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!