# From Level Scheme To Diagnosis

## *Nuclear Data And The Development Of Standards For Quantitative Medical Imaging*


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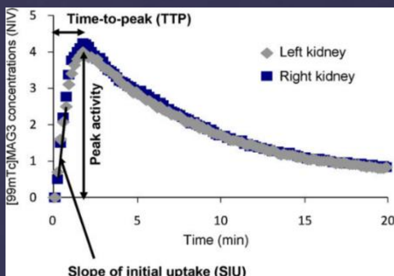
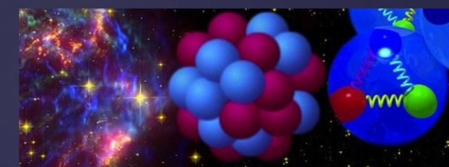
# Accurate decay data are important for a wide range of applications




Internal (and external) dosimetry

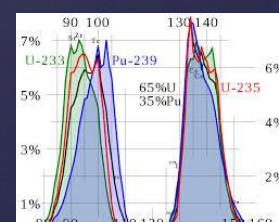
Neutrino experiments



Nuclear astrophysics

Radioactivity metrology

Waste remediation, environmental monitoring




Nuclear forensics

Nuclear power

And many more…

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# Decay data sources

- Data produced in experiments conducted by university groups, national labs, consortia using different methods
- Varying levels of quality of data, especially with regards to uncertainties
- Techniques, detectors improve over time, fall out of favor
- Need for authoritative (neutral) sources to provide critically reviewed data with consistent uncertainties
- Two main groups currently involved with data evaluation

# IAEA NDS/NNDC (and its derivatives)

National Nuclear Data Center (ENSDF)

International Atomic Energy Agency
Nuclear Data Services
Provided by the Nuclear Data Section

- Seeks to be comprehensive source for ALL nuclear structure data
- Geared towards nuclear structure – includes high spin levels, cascades not populated in decay
- Large international group of evaluators
- Does not include atomic data (evaluated, published separately)
- MIRD, Lund, LBNL, etc. are all based on (outdated) ENSDF data
- Rely on advisory groups to prioritize new data and evaluations

# Data from AR_C2440EF3A4A5E5A61346D07DB8FA3FA2_1.ens

**Download:** AR_C2440EF3A4A5E5A61346D07DB8FA3FA2_1.ens **View:** Levels: PostScript level schemes in the Nuclear Data Sheets style

$^{124}$Te

**$^{124}$I Electron Capture Decay 1998Wa18,1969Ra31,1992Wo03**

Published: 2008 Nuclear Data Sheets.

**$^{124}$I Parent:** $E_x$=0.0; $J^\pi$=2-; $T_{1/2}$=4.1760 d *3*; $Q_{g.s.\to g.s.}$=3159.6 *19*; %ε=100

**History**

| Type | Author | Citation | Cutoff Date |
|---|---|---|---|
| Full evaluation | J. Katakura, Z.D. WU | Nuclear Data Sheets 109, 1655 (2008) | 1-Apr-2008 |

1998Wa18: $^{123}$Sb(α,2n), E(α)=32 MeV; four Compton-shielded Ge detectors; measured Eγ, Iγ, γγ-coin; deduced log ft values.

1969Ra31: $^{123}$Sb($^4$He,3n) chemical separation; γ, γγ coin; decay scheme.

1992Wo03: $^{124}$Te(d,2n)$^{124}$I, isotope separator sources; activity standardization by 4π βγ coincidence; measured absolute branchings; measured positron spectra and analyzed main components, measured γ in 400-1726 keV range.

1969Be70: La,C(p,X); Eγ, Iγ, Ice, Eβ+; deduced level scheme.

1969La32: Te(p,xn); Eγ, Iγ, γγ coin; deduced E/β$^+$ branching, level scheme.

2001ElZZ: $^{124}$Te(p,n), E(p)=14 MeV; enriched target 99.8 %; chemical separation; measured γ, X-ray; deduced %Iβ$^+$.

2007Qa02: $^{124}$Te(p,), E(p)=14 MeV; chemical separation; measured β, γ, X-ray, γγ coin; deduced %Iβ$^+$.

The decay scheme is based on that proposed by 1998Wa18. The 2039 keV level has doublet structure according to 2000Do11.

**$^{124}$Te levels**

| $E_{level}$# | $J^\pi$@ | $E_{level}$# | $J^\pi$@ | $E_{level}$# | $J^\pi$@ | $E_{level}$# | $J^\pi$@ |
|---|---|---|---|---|---|---|---|
| 0.0 | 0+ | 2039.34 *6* | 2+ and 3+& | 2454.06 *6* | 2+ | 2746.96 *7* | 1(-) |
| 602.74 *5* | 2+ | 2091.67 *8* | 2+ | 2483.32 *7* | 4+ | 2834.88 *6* | 3- |
| 1248.60 *6* | 4+ | 2224.96 *7* | 4+ | 2521.33 *10* | 2+ | 2886.00 *6* | 3- |
| 1325.51 *6* | 2+ | 2293.68 *6* | 3- | 2641.20 *8* | 2+ | 2987.86 *7* | 1,2+ |
| 1657.28 *10* | 0+ | 2308.39 *18* | 0+ | 2681.45 *9* | 2+ | 3001.12 *7* | 2+,3 |
| 1882.65 *22* | 0+ | 2322.97 *10* | 2+ | 2693.73 *7* | 3- | | |
| 1957.93 *7* | 4+ | 2335.05 *12* | | | | | |

# From a least-squares fit to Eγ's.
@From adopted levels.
&Doublet

**β$^+$,ε Data**

%Iβ$^+_{exp}$=23.0 5 (2001ElZZ), 22.0 5 (2007Qa02).

| $E_\varepsilon$ | $E_{level}$ | $I_{\beta^+}$# | $I_\varepsilon$# | Log *ft* | $I_{\varepsilon+\beta^+}$#@ | |
|---|---|---|---|---|---|---|
| (158.5 ) | 3001.12 | | 0.340 *8* | 6.79 *4* | 0.340 *8* | εK=0.8051 *9*; εL=0.1527 *7*; cm+=0.04224 *21* |
| (171.7 ) | 2987.86 | | 0.021 *4* | 8.08 *9* | 0.021 *4* | εK=0.8104 *7*; εL=0.1486 *6*; cm+=0.04096 *17* |
| (273.6 ) | 2886.00 | | 1.05 *3* | 6.85 *4* | 1.05 *3* | εK=0.8316 *3*; εL=0.13250 *18*; cm+=0.03588 *6* |
| (324.7 ) | 2834.88 | | 4.27 *6* | 6.40 *4* | 4.27 *6* | εK=0.8366 *2*; εL=0.1287 *2*; cm+=0.03469 *4* |
| (412.6 ) | 2746.96 | | 0.584 *20* | 7.49 *4* | 0.584 *20* | εK=0.84206 *9*; εL=0.12454 *7*; cm+=0.03340 *3* |
| (458.1 ) | 2701.53 | | 2.02 *3* | 7.05 *4* | 2.02 *3* | εK=0.8440; εL=0.12308 *6*; cm+=0.03294 *2* |
| (465.9 ) | 2693.73 | | 0.941 *14* | 7.40 *4* | 0.941 *14* | εK=0.8443; εL=0.12286 *6*; cm+=0.03287 *2* |
| (478.1 ) | 2681.45 | | 0.391 *14* | 7.80 *4* | 0.391 *14* | εK=0.8447; εL=0.12253 *5*; cm+=0.03277 *2* |
| | | | | | | 12156 *5*; cm+=0.03247 *2* |

**γ($^{124}$Te)**

α(K)exp values were calculated by using Iγ of 1998Wa18 (below 2400 keV) and 1969Ra31 (above 2400 keV) and each Ice of 1967Ru04, 1969Be70, or 1971Zh01, respectively, normalizing so that α(K)exp(602.72γ)=0.00420 (E2 theory).

**$I_\gamma$ Normalization, $I_{(\gamma+ce)}$ Normalization:** Iγ/100 decays=0.0629 6; Iγ per 100 decays are determined from an intensity calibrated source of $^{124}$I by 4π βγ coincidence method (1992Wo03).

| $E_\gamma$@ | $E_{level}$ | $I_\gamma$#@ | Mult.a | δa | α | $I_{\gamma+ce}$# | Comments |
|---|---|---|---|---|---|---|---|
| 166.04 *24* | 3001.12 | 0.13 *5* | | | | | |
| 307.34 *10* | 3001.12 | 0.33 *4* | | | | | |
| 335.67 *13* | 2293.68 | 0.28 *5* | E1 | | 0.00707 | | α(K)=0.00613 *9*; α(L)=0.000754 *11*; α(M)=0.0001496 *21*; α(N+..)=$3.26\times10^{-5}$ *5* α(N)=$2.94\times10^{-5}$ *5*; α(O)=$3.15\times10^{-6}$ *5* |
| 351.47 *13* | 2834.88 | 0.36 *5* | | | | | |
| x381.7 *5* | | 0.28 *2* | | | | | |
| 402.80 *20* | 2886.00 | 0.23 *5* | | | | | |
| 443.88 *8* | 2483.32 | 0.60 *5* | M1+E2 | | 0.0121 *6* | | α(K)=0.0103 *7*; α(L)=0.00138 *3*; α(M)=0.000276 *7*; α(N+..)=$6.01\times10^{-5}$ *11* α(N)=$5.43\times10^{-5}$ *11*; α(O)=$5.75\times10^{-6}$ *14* |
| x478.7 *5* | | 0.43 *4* | | | | | |

# Decay Data Evaluation Project (DDEP)

- Organized in 1994 to meet the needs of radiation standards laboratories (radioactivity, dose)
- Seeks to be authoritative source for DECAY data: emitted photons and (non-continuous) particle spectra
- Most precise values with realistic uncertainties
- Efforts are coordinated by the LNHB Nuclear Data Group and International Committee for Radionuclide Metrology (ICRM) Non-Neutron Data Working Group
- Priorities for new data and evaluations initiated by individual evaluators based on interest

In 2005, the ICRM adopted the use of DDEP data for all its activities; Consultative Committee for Ionizing Radiation, Section (II) followed by mandating DDEP data be used in all international comparisons

$^{133}_{56}\mathrm{Ba}_{77}$

## 1 Decay Scheme

$^{133}$Ba disintegrates by electron capture mainly to two $^{133}$Cs excited levels of 437 keV (85.4%) and of 383 keV (14.5%) with three very minor branches to the 160 keV, 81 keV excited levels and the ground state.

*Le baryum 133 se désintègre par capture électronique principalement vers deux niveaux excités de 437 keV et 383 keV du césium 133.*

## 2 Nuclear Data

$T_{1/2}$($^{133}$Ba ) : 10,539 (6) a
$Q^{+}$($^{133}$Ba ) : 517,3 (10) keV

### 2.1 Electron Capture Transitions

| | Energy (keV) | Probability (%) | Nature | lg $ft$ | $P_K$ | $P_L$ | $P_M$ |
|---|---|---|---|---|---|---|---|
| $\epsilon_{0,4}$ | 80,3 (10) | 85,41 (53) | Allowed | 6,63 | 0,671 (5) | 0,251 (4) | 0,0777 (11) |
| $\epsilon_{0,3}$ | 133,5 (10) | 14,46 (51) | Allowed | 8,03 | 0,7727 (9) | 0,1755 (7) | 0,05174 (23) |
| $\epsilon_{0,2}$ | 356,7 (10) | <0,3 | 2nd Forbidden | >10,6 | 0,83 | 0,13 | 0,037 |
| $\epsilon_{0,1}$ | 436,3 (10) | <0,7 | 2nd Forbidden | >10,9 | 0,84 | 0,13 | 0,037 |
| $\epsilon_{0,0}$ | 517,3 (10) | <0,0005 | Unique 2nd Forbidden | >13,9 | 0,77 | 0,18 | 0,05 |

### 2.2 Gamma Transitions and Internal Conversion Coefficients

| | Energy (keV) | $P_{\gamma+ce}$ (%) | Multipolarity | $\alpha_K$ | $\alpha_L$ | $\alpha_M$ | $\alpha_T$ |
|---|---|---|---|---|---|---|---|
| $\gamma_{4,3}$(Cs) | 53,1622 (18) | 14,25 (46) | M1+E2 | 4,78 (7) | 0,70 (5) | 0,144 (12) | 5,66 (11) |
| $\gamma_{2,1}$(Cs) | 79,6142 (19) | 7,3 (5) | M1+E2 | 1,495 (22) | 0,217 (6) | 0,0447 (13) | 1,77 (3) |
| $\gamma_{1,0}$(Cs) | 80,9979 (11) | 90,05 (6) | M1+E2 | 1,431 (20) | 0,216 (4) | 0,0447 (8) | 1,703 (24) |
| $\gamma_{2,0}$(Cs) | 160,6121 (16) | 0,826 (9) | M1+E2 | 0,234 (4) | 0,0471 (13) | 0,0099 (3) | 0,294 (6) |
| $\gamma_{3,2}$(Cs) | 223,237 (2) | 0,494 (6) | M1+E2 | 0,0836 (12) | 0,01103 (16) | 0,00226 (4) | 0,0975 (14) |
| $\gamma_{4,2}$(Cs) | 276,3992 (21) | 7,53 (6) | E2 | 0,0460 (7) | 0,00842 (12) | 0,001763 (25) | 0,0566 (8) |
| $\gamma_{3,1}$(Cs) | 302,8512 (16) | 19,10 (12) | M1+E2 | 0,0373 (6) | 0,00484 (7) | 0,000988 (14) | 0,0434 (6) |
| $\gamma_{4,1}$(Cs) | 356,0134 (17) | 63,63 (20) | E2 | 0,0211 (3) | 0,00346 (5) | 0,000721 (10) | 0,0254 (4) |
| $\gamma_{3,0}$(Cs) | 383,8491 (12) | 9,12 (6) | E2 | 0,01684 (24) | 0,00270 (4) | 0,000560 (8) | 0,0202 (3) |

## 3 Atomic Data

### 3.1 Cs

$\omega_K$ : 0,894 (4)
$\bar{\omega}_L$ : 0,104 (5)
$n_{KL}$ : 0,895 (4)

#### 3.1.1 X Radiations

| | | Energy (keV) | Relative probability |
|---|---|---|---|
| $X_K$ | | | |
| | $K\alpha_2$ | 30,6254 | 54,13 |
| | $K\alpha_1$ | 30,9731 | 100 |
| | $K\beta_3$ | 34,9197 | 29,21532 |
| | $K\beta_1$ | 34,9873 | |

#### 3.1.2 Auger Electrons

| | Energy (keV) | Relative probability |
|---|---|---|
| Auger K | | |
| KLL | 24,411 - 25,804 | 100 |
| KLX | 28,991 - 30,961 | 47,2 |
| KXY | 33,55 - 35,96 | 5,56 |
| Auger L | 2,5777 - 5,5590 | |

## 4 Electron Emissions

| | | Energy (keV) | Electrons (per 100 disint.) |
|---|---|---|---|
| $e_{AL}$ | (Cs) | 2,5777 - 5,5590 | 136,8 (8) |
| $e_{AK}$ | (Cs) | | |
| | KLL | 24,411 - 25,804 | 14,1 (6) |
| | KLX | 28,991 - 30,961 | |
| | KXY | 33,55 - 35,96 | |
| $ec_{4,3\ T}$ | (Cs) | 17,1776 - 53,1508 | 12,11 (41) |

## 5 Photon Emissions

### 5.1 X-Ray Emissions

| | | Energy (keV) | Photons (per 100 disint.) | | |
|---|---|---|---|---|---|
| XL | (Cs) | 3,7946 - 5,5525 | 15,87 (26) | | |
| $XK\alpha_2$ | (Cs) | 30,6254 | 33,8 (4) | } | $K\alpha$ |
| $XK\alpha_1$ | (Cs) | 30,9731 | 62,4 (7) | | |
| $XK\beta_3$ | (Cs) | 34,9197 | 18,24 (29) | | $K'\beta_1$ |
| $XK\beta_1$ | (Cs) | 34,9873 | | | |
| $XK\beta_5''$ | (Cs) | 35,252 | | | |
| $XK\beta_2$ | (Cs) | 35,822 | 4,45 (12) | | $K'\beta_2$ |
| $XK\beta_4$ | (Cs) | 35,907 | | | |
| $XKO_{2,3}$ | (Cs) | 35,972 | | | |

### 5.2 Gamma Emissions

| | Energy (keV) | Photons (per 100 disint.) |
|---|---|---|
| $\gamma_{4,3}$(Cs) | 53,1622 (18) | 2,14 (6) |
| $\gamma_{2,1}$(Cs) | 79,6142 (19) | 2,63 (19) |
| $\gamma_{1,0}$(Cs) | 80,9979 (11) | 33,31 (30) |
| $\gamma_{2,0}$(Cs) | 160,6121 (16) | 0,638 (6) |
| $\gamma_{3,2}$(Cs) | 223,2368 (13) | 0,450 (5) |

## 6 Main Production Modes

$\left\{ \begin{array}{l} Ba-132(n,\gamma)Ba-133 \quad \sigma : 6{,}5\ (8)\ \text{barns} \\ \text{Possible impurities: } Ba-131,\ Ba-140 \end{array} \right.$

$Ba-132(n,\gamma)Ba-133m \quad \sigma : 0{,}5\ \text{barns}$

$\left\{ \begin{array}{l} Ca-133(p,n)Ba-133 \\ \text{Possible impurities: } Cs-132 \end{array} \right.$

## 7 References


- E.I. Wyatt, S.A. Reynolds, T.H. Handley, W.S. Lyon, H.A. Parker. Nucl. Sci. Eng. 11 (1961) 74 (Half-life)
- P. Blasi, M. Bocciolini, P.R. Maurenzig, P. Sona, N. Taccetti. Nuovo Cim. 50B (1967) 298 (Gamma-ray emission probabilities)
- J.A. Bearden. Rev. Mod. Phys. 39 (1967) 78 (X-ray energies)
- D.P. Donnelly, J.J. Reidy, M.L. Wiedenbeck. Phys. Rev. 173 (1968) 1192 (Gamma-ray emission probabilities)
- S.A. Reynolds, J.F. Emery, E.I. Wyatt. Nucl. Sci. Eng. 32 (1968) 46 (Half-life)
- P. Alexander, J. P. Lau. Nucl. Phys. A121 (1968) 612 (Gamma-ray emission probabilities, ICC)
- V. Narang, H. Houtermans. In: Proc. Conf. Electron Capture and Higher Order Processes in Nucl. Decays, Debrecen, Hungary, D. Berenyi, Ed. Eotvos Lorand Phys.Soc. Budapest, (1968) 97

# Most important part – written narrative of how evaluation was performed

- Survey of data
- What data were included, excluded and WHY
- Any adjustments made to values
- Explain differences from previous evaluations (also ESNDF)

**Comments on evaluation** $^{133}$**Ba**

**$^{133}$Ba - Comments on evaluation of decay data**
by V.P. Chechev and N.K. Kuzmenko

The first DDEP evaluation of $^{133}$Ba decay data was completed by these authors in January 2004 (2004BeZR). The current updated evaluation was completed in May 2015 with a literature cut-off by the same date. The main changes compared to the initial evaluation are mainly due to new publications: 2012Wa38 (Q-value), 2008Ki07 (theoretical internal conversion coefficients), 2014Manohar (relative gamma and conversion electron probabilities) and 2010Sc08, 2012Fi12, 2014Un01 (half-life measurements and corrections).

**1. DECAY SCHEME**

$^{133}$Ba decays primarily by allowed electron capture (ε) branches to the $1/2^+$ and $3/2^+$ $^{133}$Cs levels at 437 and 383 keV. As to the intensities of the other possible ε branches to the $^{133}$Cs ground state and levels at 81 and 161 keV they can be estimated from log *ft* systematics. From that of 1998Si17, one expects the log *ft* of the unique 2$^{nd}$ forbidden decay to the ground state to be greater than 13.9 which corresponds to a branch of less than 0.0005%. Similarly, the log *ft* of the 2$^{nd}$ forbidden decays to the 81- and 161-keV levels are expected to be grea which corresponds to branches of less than 0.7% and 0.3%, respectively. Our e each of these branches obtained from the intensity balance at the above levels ag

**Table 1.** Experimental values of the $^{133}$Ba half-life (in days)

| N | Author(s) and year | Reference | $T_{1/2}$ (d) | Method and comments |
|---|---|---|---|---|
| 1 | Wyatt *et al.* (1961) | 1961Wy01 | 3908 (73) | γ-ray scintillation spectroscopy and a beta proportional counter; |
| 2 | Lagoutine *et al.* (1968) | 1968La10 | 2849 (37) | Ionization chamber, γ-ray scintillation spectroscopy and 4πβ- proportional counter; *omitted* because of the large deviation from the mean value |
| 3 | Reynolds *et al.* (1968) | 1968Re04 | 3894 (44) | γ-ray scintillation spectroscopy and a beta proportional counter |
| 4 | Walz *et al.* (1970) | 1970Wa19 | 3781 (15) | 4πγ ionization chamber; *omitted* as superseded by 12 |
| 5 | Emery *et al.* (1972) | 1972Em01 | 3981 (37) | γ-ray scintillation spectroscopy and a beta proportional counter; omitted on the Chauvenet's criterion |

**Comments on evaluation** $^{133}$**Ba**

The values before 1961 were omitted due to their large uncertainties (more than 1 year).

The values of 1970Wa19, 1982HoZJ, 1992Un01, 2002Un02 and 2012Fi12 were omitted as they were replaced by later results from the same group.

Also the value of 1968La10 was omitted on statistical considerations because of a great contribution into the $\chi^2$ value (27 σ from adopted value).

The uncertainty of 1997Ma75 was increased to 0.98 days to adjust weights according to the Limitation of Relative Statistical Weight method (LWM). In consequence the LWEIGHT program chose the weighted average of 3849.3 days and external uncertainty of 2.3 days. The internal uncertainty is 0.74 d and the smallest experimental uncertainty is 0.7 d. The ratio of the reduced $\chi^2 / (\chi^2)_{crit}$ is 10.0/2.4.

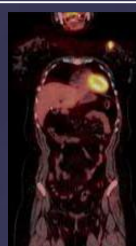
What does nuclear data have to do with quantitative imaging?

# Measurement needs in patient-specific image-based treatment planning for nuclear medicine

Diagnosis, staging, follow-up

Treatment plan

Therapy



Imaging data
(SPECT, PET-CT, PET-MR)

Need to know injected **activity**

Dosimetry models
(e.g., MIRD)

$$D = \sum_{all\ organs} \frac{k\tilde{A}_S \sum n_i E_i \varphi_{T\leftarrow S}}{m_s}$$

Calculate **activity** in each organ

Activity measurement

Accurately administer prescribed **activity**

Dose verification

- **Verify** delivered dose,
- **Validate** dose model
- **Establish** dose-response relationship

**Imaging provides input data**

**Determines required dosage**

Monitor changes in tumor size, metabolism

**Missing: verification of dose model, experimental measurement of delivered dose, both traceable to SI**

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# Need for accurate calibrations and standards

- Ensure that repeated administrations and imaging studies are based on same activity measurements
- Enable comparability of data from multiple centers during clinical trials
- "Ground truth" for model development, validating new imaging techniques
- When tied to traceable dose measurements, allows dose-response relationships to be established

# Development of a primary radioactivity standard

# Primary Standardization

- Method is *self-contained* (i.e., measurements of tracer and traced nuclide made simultaneously) and *does not rely on external standards* for efficiency determination
- Any corrections made must be small and able to be made with high accuracy
- Level scheme data may limit degree of “primary-ness”
- Not primary methods: HPGe and Si(Li) photon, $e^-$, $\alpha$, or $\beta$ spectrometry, ionization chambers

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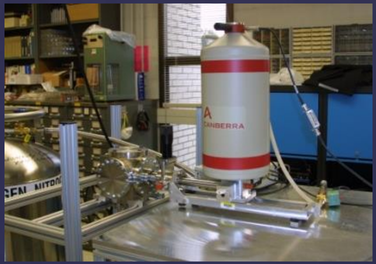
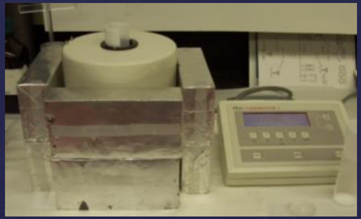
# Different radiations, different techniques

Choice of technique depends on level scheme of radionuclide being measured !!


*To give higher degree of confidence, multiple techniques should be used when possible.*







# Developing a primary radionuclide standard

*Philosophy: Make as many measurements with as many techniques as possible, changing as many variables as possible.*

Stock solution: dose vial containing ~126 MBq $GeCl_4$ in 5 mL of 0.5 mol $L^{-1}$ HCL

*Dilute 1 mL of stock solution with 4 mL carrier**

*Dilute 4 mL of stock solution with 1 mL carrier**

**A1**

**A2**

Counting in NIST “4π”γ ionization chamber, radionuclide activity calibrators

Counting in NIST “4π”γ ionization chamber, radionuclide activity calibrators

*Dilute A1 (DF = 3.556) with carrier**

**A1D1**

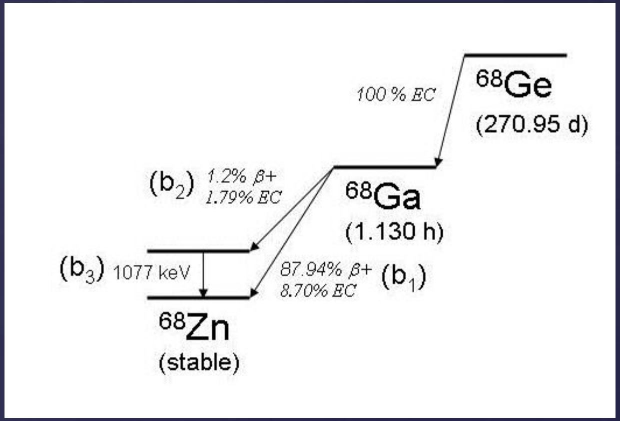
*Dilute A1D1 (DF = 57.620) with carrier**

Counting in NIST “4π”γ ionization chamber

**A1D2**

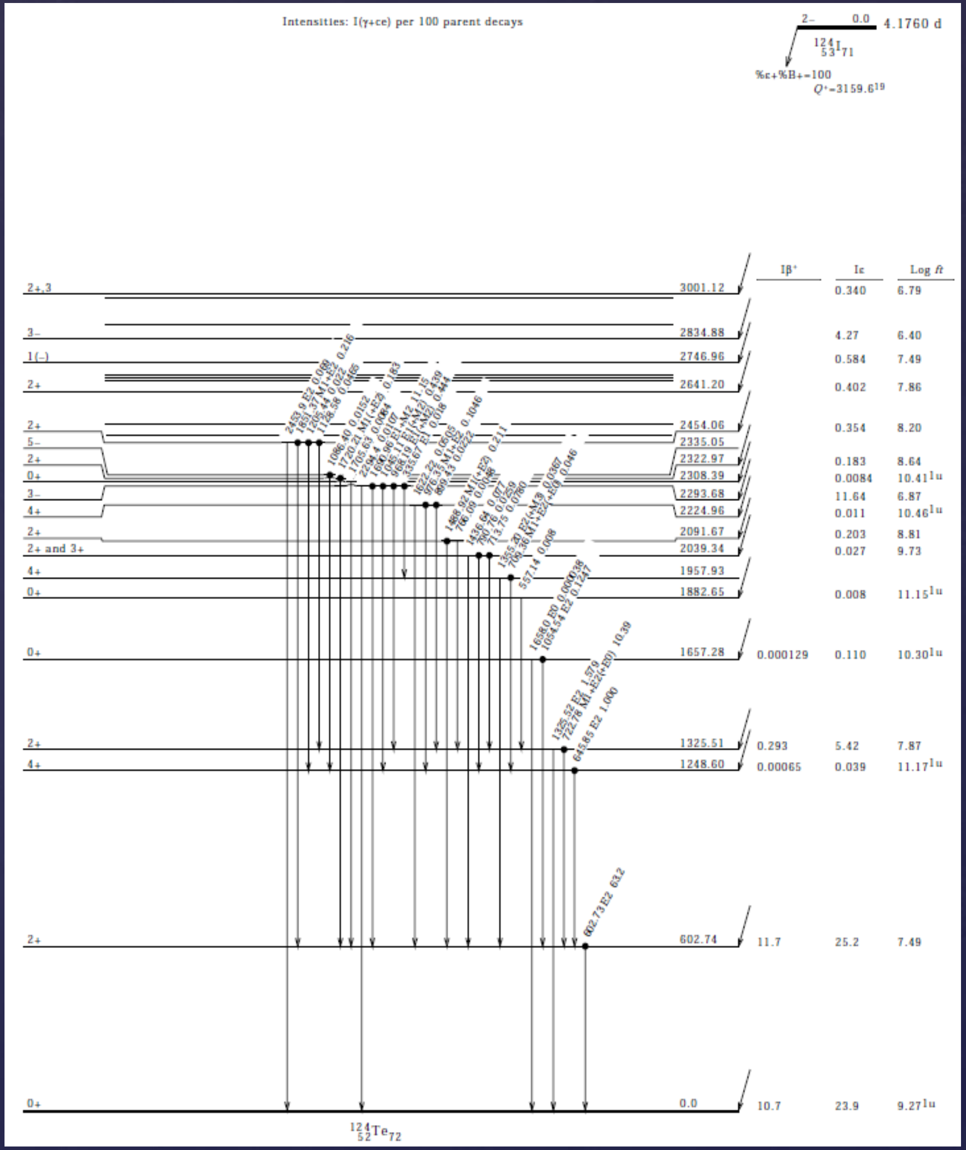
Liquid scintillation counting (LSC) sources measured with TDCR, $^{3}$H-standard efficiency tracing, and 4πβ–γ anticoincidence counting

Point sources: measurement on HPGe systems



# Role of nuclear data in standards for quantitative imaging

- Nearly all methods will require accurate $T_{1/2}$ values
- $\alpha$, $\beta^{\pm}$, EC branching ratios
- $P_{\gamma}$, x ray probabilities for photon emitters
- LSC methods also need Auger, conversion electron probabilities
- Not only for main nuclide, but also for all impurities!



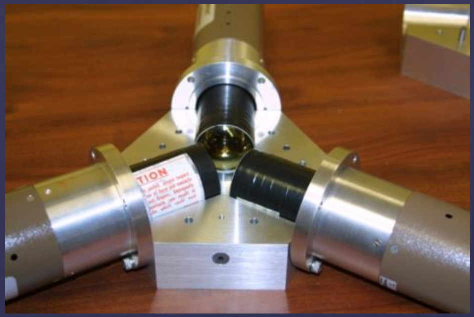

For PET imaging, $T_{1/2}$, $P_{\beta\pm}$, $P_{\gamma}$ of interferences most important

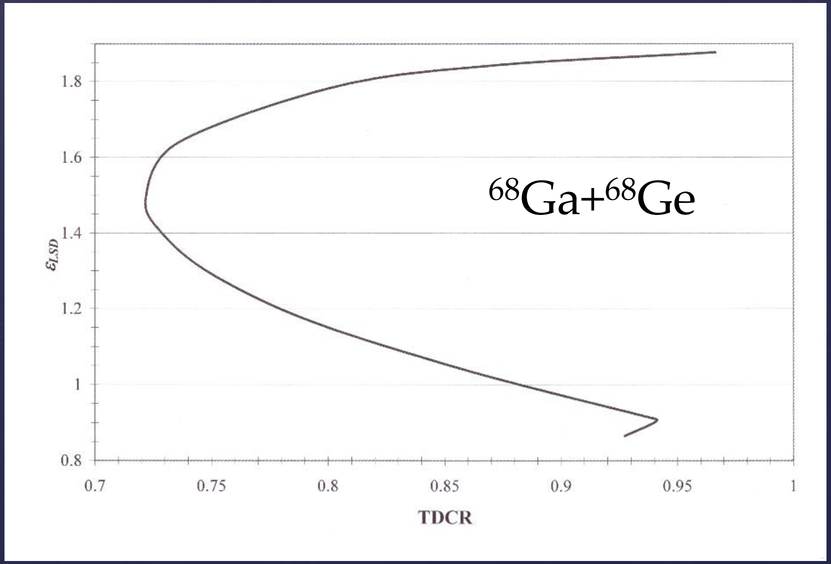
# Example: Triple-to-Double Coincidence Ratio (TDCR) Method

- Uses a specially-designed three photomultiplier tube (PMT) instrument
- Coincidences refer to the photons emitted from the scintillator – NOT the radionuclide!

$$\frac{\phi_T}{\phi_D} = \left[\int_0^{E_{\max}} S(E)(1-e^{EQ(E)/3\lambda})^3 dE\right] \times \left[\int_0^{E_{\max}} S(E)\left[3(1-e^{EQ(E)/3\lambda})^2 - 2(1-e^{EQ(E)/3\lambda})^3\right] dE\right]^{-1}$$

Assumes equal PMT efficiencies





*S*(E): spectrum of all emitted energy

*includes $\beta^{\pm}$, Augers, x rays, IC $e^{-}$, Comptons from photon interactions with scintillator*

Requires complete knowledge of level scheme!

# Example: $P_{\beta+}/P_{EC}$ in $^{124}$I

Total level feedings determined from in/out intensity imbalances

- Need good $P_\gamma$ for all transitions – relies on activity!
- Need $\alpha_{Tot}$ to compute total intensities (usually calc from theory)
- $P_{\beta+}/P_{EC}$ calculated (from theory) using total intensity differences

| Level # | E | Sum in | s | Sum out | s | D | s | Recommended | s | ENSDF | Δ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 65.4037 | 0.6000 | 0.0000 | 0.0000 | 65.4037 | 0.6000 | 34.40 | 0.6 | 34.6 | 0.58% |
| 1 | 602.74 | 26.2261 | 0.2738 | 63.2334 | 0.6000 | -37.0073 | 0.6595 | 37.01 | 0.7 | 36.9 | 0.29% |
| 2 | 1248.6 | 0.9692 | 0.0356 | 0.9913 | 0.0903 | -0.0221 | 0.0971 | 0.022 | 0.01 | 0.04 | 44.75% |
| 3 | 1325.51 | 6.2175 | 0.0775 | 11.9247 | 0.1767 | -5.7072 | 0.1929 | 5.71 | 0.19 | 5.71 | 0.05% |
| 4 | 1657.28 | 0.0183 | 0.0038 | 0.1244 | 0.0067 | -0.1061 | 0.0077 | 0.106 | 0.08 | 0.11 | 3.52% |
| 5 | 1882.65 | 0.0000 | 0.0030 | 0.0252 | 0.0163 | -0.0252 | 0.0165 | 0.025 | 0.016 | 0.008 | 214.56% |
| 6 | 1957.93 | 0.0850 | 0.0092 | 0.0813 | 0.0070 | 0.0037 | 0.0116 | - | - | - | - |
| 7 | 2039.34 | 0.1549 | 0.0110 | 0.1812 | 0.0119 | -0.0263 | 0.0162 | 0.026 | 0.008 | 0.027 | 2.57% |
| 8 | 2091.67 | 0.0153 | 0.0052 | 0.2073 | 0.0056 | -0.1920 | 0.0076 | 0.192 | 0.008 | 0.203 | 5.43% |
| 9 | 2224.96 | 0.1803 | 0.0198 | 0.1711 | 0.0054 | 0.0092 | 0.0205 | 0.009 | 0.005 | 0.011 | 16.39% |
| 10 | 2293.68 | 0.4118 | 0.1817 | 11.9490 | 0.1808 | -11.5371 | 0.2564 | 11.54 | 0.25 | 11.64 | 0.88% |
| 11 | 2308.39 | 0.0000 | 0.0010 | 0.0092 | 0.0021 | -0.0092 | 0.0023 | 0.009 | 0.002 | 0.0084 | 9.60% |
| 12 | 2322.97 | 0.0063 | 0.0102 | 0.2200 | 0.0056 | -0.2136 | 0.0116 | 0.214 | 0.012 | 0.183 | 16.75% |
| 13 | 2335.05 | 0.0070 | 0.0051 | 0.0270 | 0.0301 | -0.0200 | 0.0305 | 0.02 | 0.01 | - | - |
| 14 | 2454.06 | 0.0286 | 0.0203 | 0.3576 | 0.0202 | -0.3290 | 0.0286 | 0.329 | 0.029 | 0.354 | 7.07% |
| 15 | 2483.32 | 0.0529 | 0.0104 | 0.0676 | 0.0055 | -0.0147 | 0.0117 | 0.015 | 0.007 | 0.01 | 46.96% |
| 16 | 2521.33 | 0.0000 | 0.0040 | 0.1726 | 0.0052 | -0.1726 | 0.0065 | 0.173 | 0.006 | 0.181 | 4.63% |
| 17 | 2641.2 | 0.0000 | 0.0080 | 0.4031 | 0.0135 | -0.4031 | 0.0157 | 0.403 | 0.016 | 0.402 | 0.28% |
| 18 | 2681.45 | 0.0000 | 0.0140 | 0.3907 | 0.0149 | -0.3907 | 0.0204 | 0.391 | 0.020 | 0.391 | 0.07% |
| 19 | 2693.73 | 0.0169 | 0.0285 | 0.9574 | 0.0153 | -0.9405 | 0.0323 | 0.941 | 0.032 | 0.941 | 0.05% |
| 20 | 2701.53 | 0.0000 | 0.0149 | 1.9772 | 0.0290 | -1.9772 | 0.0326 | 1.98 | 0.03 | 2.02 | 2.12% |
| 21 | 2746.96 | 0.0000 | 0.0000 | 0.5818 | 0.0204 | -0.5818 | 0.0204 | 0.006 | 0.001 | - | - |
| 22 | 2817.4 | 0.0000 | 0.0000 | 0.0057 | 0.0006 | -0.0057 | 0.0006 | 0.582 | 0.020 | 0.584 | 0.34% |
| 23 | 2834.88 | 0.0083 | 0.0145 | 4.2273 | 0.0699 | -4.2191 | 0.0714 | 4.22 | 0.07 | 4.27 | 1.19% |
| 24 | 2859.1 | 0.0000 | 0.0000 | 0.0031 | 0.0013 | -0.0031 | 0.0013 | 0.003 | 0.001 | - | - |
| 25 | 2886 | 0.0000 | 0.0000 | 1.1209 | 0.0620 | -1.1209 | 0.0620 | 1.12 | 0.062 | 1.05 | 6.75% |
| 26 | 2945.6 | 0.0000 | 0.0000 | 0.0286 | 0.0032 | -0.0286 | 0.0032 | 0.029 | 0.003 | - | - |
| 27 | 2987.86 | 0.0000 | 0.0000 | 0.0260 | 0.0046 | -0.0260 | 0.0046 | 0.026 | 0.005 | 0.021 | 23.87% |
| 28 | 3001.12 | 0.0000 | 0.0000 | 0.3374 | 0.0141 | -0.3374 | 0.0141 | 0.337 | 0.014 | 0.34 | 0.77% |

Evaluated $P_{\beta+}$ = 22.64(22) per 100 decays

Qaim, et al. 2007: 22.1(5) per 100 decays (-2.4 %)

Woods, et al 1992: 21.62(41) per 100 decays (-4.7 %)

**This has a direct effect on both activity determinations and image quantification!**

# MICELLE2 input files for 1 of 9 decay branches considered for $^{124}$I

```
'Atomic number                :'       52
'WK,WL1,WL2,WL3               :'      .877,  .041,  .074,  .074
'F12,F13,F23                  :'      .180,  .280,  .155

'PKL1L1,L2,L3,M1,M2,M3,M4,M5:'      .0785, .0936, .1167, .0277, .0176, .0222, .0015, ...
'PKL1N1,N2,N3,O1,O2,O3       :'      .0059, .0035, .0044, .0008, .0004, .0002
'PKL2L2,L3,M1,M2,M3,M4,M5    :'      .0121, .2548, .0137, .0041, .0292, .0007, .0061
'PKL2N1,N2,N3,N5,O1,O3       :'      .0028, .0008, .0076, .0010, .0004, .0004
'PKL3L3,M1,M2,M3,M4,M5       :'      .1296, .0170, .0397, .0421, .0066, .0068
'PKL3N1,N2,N3,N4,N5,O1,O2,O3:'      .0034, .0076, .0080, .0011, .0011, .0005, .0008,...
'PKM1M1,M2,M3,N1,N2,N3       :'      .0024, .0026, .0032, .0010, .0005, .0006
'PKM2M3,N1,N2                :'      .0064, .0005, .0012
'PKM3M3,M4,M5,N1,N2,N3       :'      .0034, .0009, .0009, .0007, .0012, .0013

'PL1L2M1,M2,M3,M4,M5         :'      .0000, .0000, .0000, .0000, .0000
'PL1L2N1..N7,O1..O6,P1..P3  :'      .2882, .2013, .2572, .0690, .1146, .0000, .0000,...
'PL1L3M1,M2,M3,M4,M5         :'      .0000, .0000, .0000, .0000, .0000
'PL1L3N1..N7,O1..O7,P1..P3  :'      .2325, .1024, .1950, .1826, .2373, .0000, .0000, ...

'PL1M1M1,M2,M3,M4,M5         :'      .0315, .0628, .1165, .0916, .1317
'PL1M1N1..N7,O1..O5,P3      :'      .0113, .0121, .0222, .0133, .0191, .0000, .0000
'PL1M2M3..M5,N1..N7,O1,O5   :'      .0026, .0026, .0342, .0091, .0004, .0033, .0000, ...
'PL1M3M3,M4,M5,N1,N2,N4,O1  :'      .0026, .0244, .0169, .0168, .0008, .0021, .0022
'PL1M4M4,M5,N1..N7,O1,O5    :'      .0051, .1883, .0128, .0006, .0046, .0015, .0203,...
'PL1M5M5,N1..N7,O1..O5      :'      .0531, .0182, .0059, .0033, .0195, .0120, .0000,...
'PL1N1N1,N2,N4,N2N4,O1,N4N4 :'      .0010, .0018, .0032, .0018, .0026, .0002, .0006,...
...
```

etc.

```
 'I124_EC5'

''                   BASIC DATA

'Decay scheme (1-14)        :'        11
'Atomic data                :'        'TE_ATOM.DAT'


''                   EC DECAY

'PK,PL1,PL2,PM              :'         0.8366,.12869,.0,.03469


''                   BETA DECAY

'Endpoint energy                 ='            0.
'Mass number                     ='            0.
'Daughter nucl. atomic number    ='            0.
'Forbiddenness                   ='            0
'Shape factor coefficients       ='            0.,0.,0.


''                   GAMMA TRANSITIONS

'PGAM,EGAM (1)              :'         0.032,1509.36
'PIK,PIL1,PIL2,PIL3,PIM (3) :'         0.000268,0.0000303,0.,0.,0
'PGAM,EGAM (2)              :'         0.1104,1690.96
'PIK,PIL1,PIL2,PIL3,PIM (1) :'         0.000213,0.000024,0.0,0.0,0.0
'PGAM,EGAM (3)              :'         0.629,602.73
'PIK,PIL1,PIL2,PIL3,PIM (1) :'         0.0045,0.00052,0.000059,0.000412,0.000124


----
DECAY SCHEME
      1     PURE EC
      3     EC-IC/GAMMA
      5     IC/GAMMA
      6     EC-IC/GAMMA-IC/GAMMA
      7     IC/GAMMA-IC/GAMMA
      8     BETA-IC/GAMMA
      9     BETA-IC/GAMMA-IC/GAMMA
     10     PURE BETA
     11     EC-IC/GAMMA-IC/GAMMA-IC/GAMMA
     12     IC/GAMMA-IC/GAMMA-IC/GAMMA
     13     PURE BETA+
     14     BETA+-IC/GAMMA
```

Experimental $P_{\gamma}$ depends on:

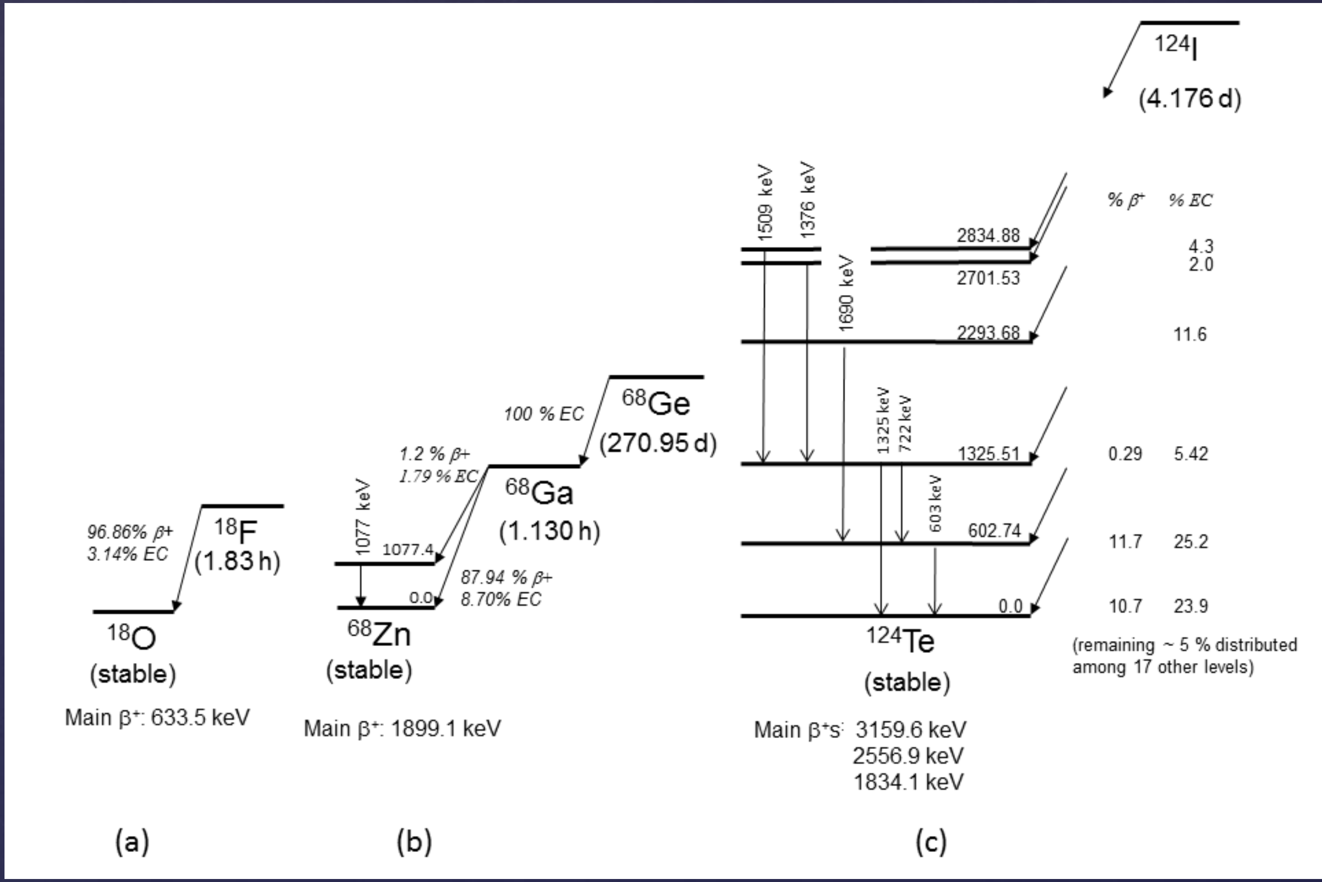
- Absolute activity value
- Ability to accurately count photons at a given energy

Experimental measurement of $\alpha_{Tot}$ also important!

**Nuclear data measurements require the best available activity measurements, but most standardization methods require at least some nuclear data!**

?

# Quantitation and nuclides with complex decay schemes




How will differences in decay schemes influence responses in activity calibrator and scanner?

# Example: $^{90}Y$ imaging and dose calculations using traceable phantom on calibrated scanner

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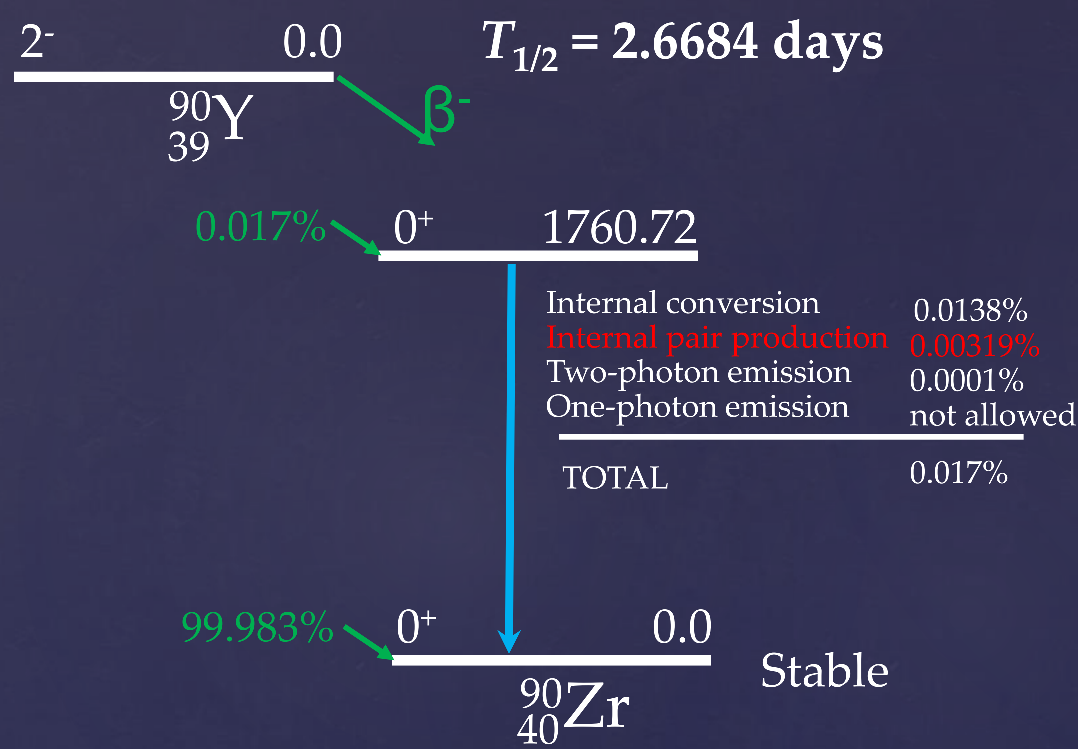
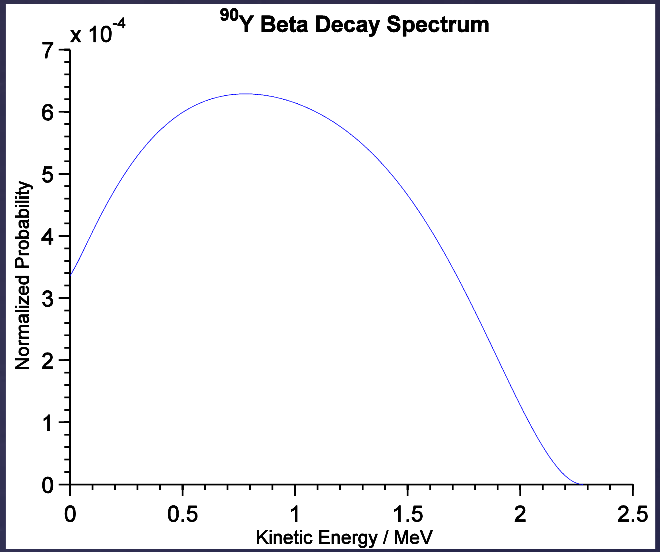
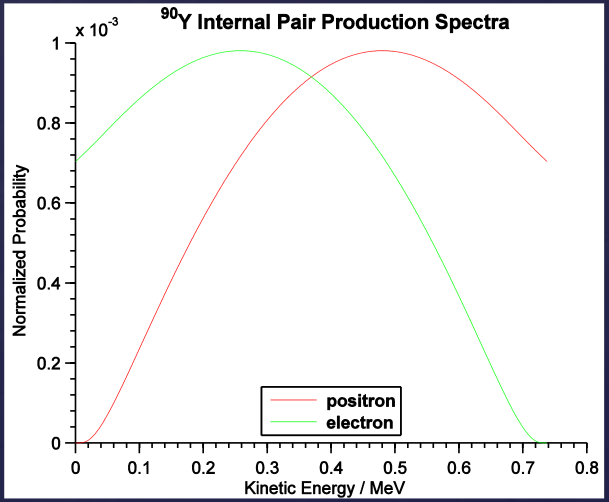
# Y-90 Internal Pair Production




$$Q = 2279.8 \text{ keV}$$




| | CSDA Range Water (mm) | |
|---|---|---|
| | Mean | Max |
| $\beta^-$ (ground state) | 4.11 | 11.29 |
| $\beta^+$ (internal pair) | 1.53 | 2.98 |

Radial Dose Extent

Component of PET Image Resolution

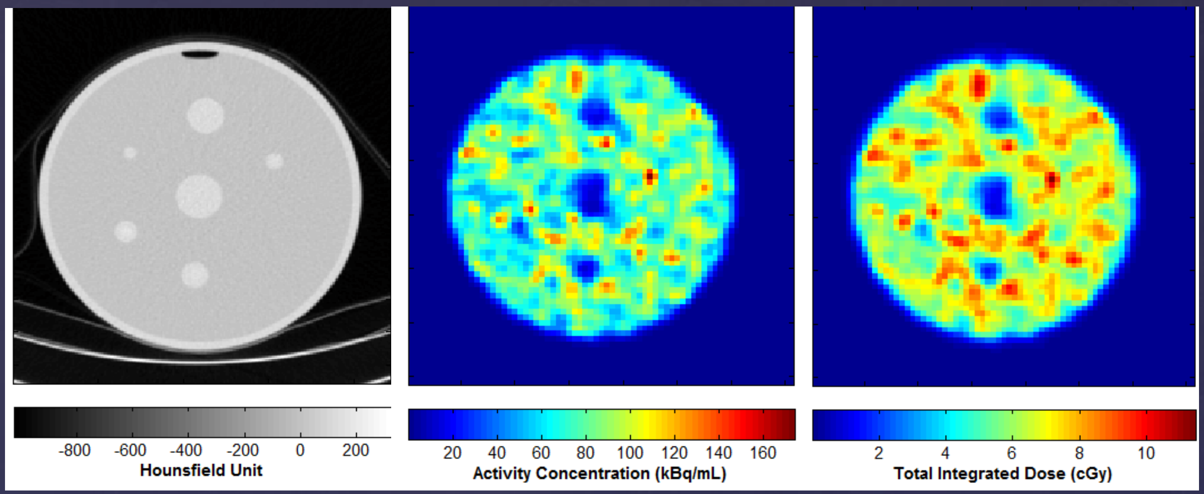
# $^{90}$Y PET Phantom study

- Scanner calibrated 5 days before scanner ($^{18}$F recovery test: -5 %)
- 500 MBq of $^{90}YCl_3$ +0.5 mol/L HCl
- 6 cold spheres representing tumors with diameters ranging from 9.5 mm to 31.8 mm
- $C_A$ calibrated with 2 primary LS techniques

| | Measured Activity Concentration (kBq/g) (Decay Corrected to Start of PET Scan) | Combined Standard Uncertainty (%) |
|---|---|---|
| **TDCR** | 87.6 | 0.35 |
| **CIEMAT-NIST** | 88.3 | 0.43 |

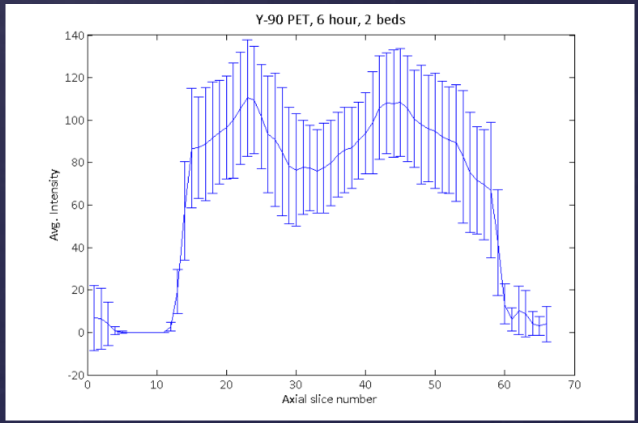
**PET quantification relies on multiplying observed "counts" by pair production branching ratio!!**

# Accuracy & Uniformity of Activity, Dose




**X-ray CT** **PET** **Dose Map**

Dose map calculated by 3D convolution of imaging data with $^{90}$Y dose kernel from MCNP6




| | Rel. Stdev. of Voxels | Mean Voxel Value | Reference Value | Mean Activity Recovered % |
|---|---|---|---|---|
| **PET Image** | 25.5% | 81.6 kBq/g | 87.6 kBq/g | 93.1% |
| **Dose Map** | 19.8% | 6.7 cGy | 7.2 cGy | 93.1% |

- 12-h count
- 15 cm ROI in center of phantom
- Within-ROI variability = 23.1 %
- Between-slice variability = 1.3 %

Success of that experiment depended on good data for

- $E_{\beta,\mathrm{max}}$
- $\beta^-$ spectrum shape
- Pair production branching ratio
- $T_{1/2}$

# Barriers to improving or increasing the volume of data

- Nuclear physics community has expertise and facilities, but research driven in different direction
- Metrology community focused on activity measurement, but input data are big source of uncertainty
- Consistent, correct measurement uncertainty assessment is needed from data providers
- Many "Primary" standardization methods still require data that are derived from the same measurement!
- Number of techniques used in NMIs getting smaller
- Number of people in metrology and nuclear spectroscopy fields is declining

# Opportunities

- $T_{1/2}$, $P_\gamma$ measurements can be added as routine part of standardizations
- $P_{\beta-}$ measurements can be made with many existing β–γ coincidence systems currently in use
- Combination of measurement (plastic scintillators, Si(Li)) and Monte Carlo for $P_{\beta\pm}$ and spectrum shapes
- Revive *e*- and $\beta^\pm$ spectrometers for shape factor, ICC measurements
- New generation of cryogenic spectrometers can enable $P\alpha$ (and eventually $P\gamma$ measurements) once calibration can be worked out
- Need to bring nuclear physics and metrology communities together

# Needs for standards and data measurements for quantitative imaging/nuclear medicine

- Standards (and comparisons!) for short-lived radionuclides: $^{11}C$, $^{18}F$, $^{82}Rb$, $^{99m}Tc$
- Standards for emerging radionuclides
  - Imaging: $^{64}Cu$, $^{67}Cu$, $^{76}Br$, $^{86}Y$, $^{89}Zr$, $^{124}I$, $^{203}Pb$
  - Therapy: $^{223}Ra$, $^{225}Ac$, $^{227}Th$
- Comparisons between NMIs for solid phantoms
- Nuclear data
  - Beta shape factors and branching ratios (esp. for positrons) – $^{90}Y$ pair production branch
  - $\alpha$ branching ratios: see $\alpha$-emitters listed above
  - $T_{1/2}$ with low (but realistic) uncertainties

# Conclusions

- Availability of standards and calibrated phantoms is helping enhance accuracy and uncertainty in quantitative PET and SPECT
- Development of primary standards is key to providing the necessary standards
- Many standardization techniques rely on evaluated decay data
- Opportunities exist for the nuclear physics and radionuclide metrology communities to work together to provide the needed data
- More primary standards needed to serve the needs of the imaging community!

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# http://www.nucleide.org/DDEP_WG/DDEPdata.htm

Accueil LNHB | Remonter | Sommaire LNHB | Dosimétrie | Radioactivité


This introduction presents a brief description of the radioactivity physical processes, the enumeration of the evaluation rules leading to the recommended values, and a summary of the symbols and terms used in all the publications.

Explanation on recommended data and their evaluation (in various languages):

**Tables of evaluated data and comments on evaluation**
Pages updated by the Laboratoire National Henri Becquerel
All questions about the data must be sent to the authors. See chapter Addresses.

updated: **24th March 2016**
newly added: **Er-169**
recently updated: **Ba-133, Ba-140**
ASCII files updated on: **19/11/2015**
(**219** nuclides in table, sorted by **alphabetical order** / atomic number / mass number / edition date)

(History of older evaluations, sorted by **alphabetical order**)

**Please cite our evaluations using the following references:**

| In | Publication | Year | ISBN | NSR | BibTeX |
|---|---|---|---|---|---|
| 99 | CEA Report - Table de Radionucléides | 1999 | 2-7272-0200-8 | 1999BeZQ | TabRad_v0.bib |
| 1 | Monographie BIPM-5 - Table of Radionuclides, vol. 1 | 2004 | 92-822-2206-3 | 2004BeZQ | TabRad_v1.bib |
| 2 | Monographie BIPM-5 - Table of Radionuclides, vol. 2 | 2004 | 92-822-2207-1 | 2004BeZR | TabRad_v2.bib |
| 3 | Monographie BIPM-5 - Table of Radionuclides, vol. 3 | 2006 | 92-822-2218-7 | 2006BeZL | TabRad_v3.bib |
| 4 | Monographie BIPM-5 - Table of Radionuclides, vol. 4 | 2008 | 92-822-2231-4 | 2008BeZV | TabRad_v4.bib |
| 5 | Monographie BIPM-5 - Table of Radionuclides, vol. 5 | 2010 | 13 978-92-822-2234-8 | 2010BeZQ | TabRad_v5.bib |
| 6 | Monographie BIPM-5 - Table of Radionuclides, vol. 6 | 2011 | 13 978-92-822-2242-3 | 2011BeZW | TabRad_v6.bib |
| 7 | Monographie BIPM-5 - Table of Radionuclides, vol. 7 | 2013 | 13 978-92-822-2248-5 | 2013BeZP | TabRad_v7.bib |
| 8 | Monographie BIPM-5 - Table of Radionuclides, vol. 8 | 2016? | to be published | 2016Be?? | - |

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(Type of updates: **N** - new evaluation; **1** - update in comments only; **2** - minor update in table; **3** - major update in table)

| Nuclide | | Tables | Comments | ASCII files | | | In | UpDate | Type |
|---|---|---|---|---|---|---|---|---|---|
| | | | | ENSDF | PenNuc | Lara | | | |
| Ac-225 | $^{225}Ac$ | table | comments | ensdf | pennuc | txt | 5 | 26/08/2009 | 3 |
| Ac-227 | $^{227}Ac$ | table | comments | ensdf | pennuc | txt | 4 | 16/02/2009 | 2 |
| Ac-228 | $^{228}Ac$ | table | comments | ensdf | pennuc | txt | 6 | 22/01/2010 | 3 |
| Ag-108 | $^{108}Ag$ | table | comments | ensdf | pennuc | txt | 3 | 4/09/2006 | 2 |
| Ag-108m | $^{108m}Ag$ | table | comments | ensdf | pennuc | txt | 3 | 17/01/2012 | 2 |
| Ag-110 | $^{110}Ag$ | table | comments | ensdf | pennuc | txt | 1 | 12/03/2004 | 1 |
| Ag-110m | $^{110m}Ag$ | table | comments | ensdf | pennuc | txt | 1 | 24/03/2004 | 1 |

| Nuclide | | Tables | Comments | ASCII files | | | In | UpDate | Type |
|---|---|---|---|---|---|---|---|---|---|
| | | | | ENSDF | PenNuc | Lara | | | |
| O-15 | $^{15}O$ | table | comments | ensdf | pennuc | txt | 1 | 1/06/2004 | 1 |
| P-32 | $^{32}P$ | table | comments | ensdf | pennuc | txt | 1 | 8/04/2004 | 1 |
| P-33 | $^{33}P$ | table | comments | ensdf | pennuc | txt | 1 | 8/04/2004 | 1 |
| Pa-231 | $^{231}Pa$ | table | comments | ensdf | pennuc | txt | 6 | 23/02/2011 | 3 |
| Pa-233 | $^{233}Pa$ | table | comments | ensdf | pennuc | txt | 5 | 11/01/2010 | 2 |
| Pa-234 | $^{234}Pa$ | table | comments | ensdf | pennuc | txt | 6 | 31/01/2011 | 3 |
| Pa-234m | $^{234m}Pa$ | table | comments | ensdf | pennuc | txt | 6 | 31/01/2011 | 3 |

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NIST