Decay Data for Alpha-emitters for medical applications

Seán Collins

Workshop on Standards and Measurements for Alpha Emitting Nuclides in Therapeutic Nuclear Medicine, 22-23 February 2024
Radioactive decay

Radioactive decay is the stochastic process by which an unstable atomic nucleus undergoes spontaneous transformation into one or more daughter nuclei.

Excess binding energy is removed via the emission of alpha- or beta-particles, and/or electromagnetic waves (gamma rays, X-rays) or by nuclear fission.

This excess energy depends on the difference in mass of the parent atom and the daughter atom plus the particle emission (Q-value).
Radioactive Decay

- Each radionuclide undergoes its own unique process to lose this excess binding energy.
- This process could be achieved through multiple pathways.
- Though the decay of a single atom will only go through one.
- This process is illustrated by its “Decay scheme.”
Radioactive Decay

• Some radionuclides can decay by more than one type of decay process

• Which can have different decay branch probabilities
Nuclear Decay Data

- Decay Data is a broad term that covers the values and arrangement associated with the decay processes of a radionuclide.

- It covers multiple parameters, such as:
  - Decay scheme
  - Energy of excited states
  - Spin states (angular momentum)
  - Emission probabilities
  - Half-lives

- These have to be determined experimentally.
Atomic Decay Data

- The term “Decay Data” can also get used to cover atomic data.

- This atomic data is associated from radiations occurring from rearrangements of the atomic electrons.

- Such as X-ray emissions, Auger electron emissions, internal conversion electrons.

- These all have associated energies and emission probabilities.
Radioactive Decay Constants

• Critical to be able to compare measurements of the same solution at any time and space

• It is impossible to predict when a single atom will decay

• However, for significant numbers of identical atoms the decay rate can be expressed as a decay constant ($\lambda$) or half-life ($T_{1/2}$)

• Half-lives of radionuclides have a huge range from near instant to longer than the universe

$$T_{1/2} = \frac{ln(2)}{\lambda}$$
Emission probabilities/intensities

• Along with the half-life, these are probably the most important values for everyday use

• These are the probabilities of the any given emission arising from a single atom decaying

• But it’s like flipping a coin….
Emission probabilities/intensities

- Along with the half-life, these are probably the most important values for everyday use.

- These are the probabilities of the any given emission arising from a single atom decaying.

- But it’s like flipping a coin….

- Who measures just one atom decaying?

- We measure lots of decays!
Decay chains of alpha emitters

\[ N_1(t) = N_1(0)e^{-\lambda_1 t} \quad (j = 1; 227\text{Th}) \]

\[ N_j(t) \approx N_1(0) \left( \prod_{i=1}^{j-1} b_{i+1} \lambda_i \right) \sum_{k=1}^{j} \left( \frac{e^{-\lambda_k t}}{\prod_{i=1}^{j} (\lambda_i - \lambda_k)} \right) \]

\[ A_j(t) = \lambda_j N_j(t) \]

- \( N_j(t) \) = number of atoms of nuclide \( j \) at time \( t \)
- \( \lambda_j \) = decay constant for nuclide \( j \) (s\(^{-1}\))
- \( A_j(t) \) = Activity of nuclide \( j \) at time \( t \)
Reaction cross-section data

- Radionuclides can be produced from stable or unstable isotopes by firing protons, neutrons, or photons at a target.
- There are different reactions to create the same radionuclide:
  - $^{226}\text{Ra}(p,2n)^{225}\text{Ac}$
  - $^{226}\text{Ra}(d,3n)^{225}\text{Ac}$
  - $^{226}\text{Ra}(\gamma,n)^{225}\text{Ra} \rightarrow ^{225}\text{Ac}$
  - $^{232}\text{Th}(p,x)^{225}\text{Ra} \rightarrow ^{225}\text{Ac}$
- Nuclear cross-section of a nucleus is the probability that a nuclear reaction will occur.
- These can be different at different particle energies.
Importance in Nuclear Medicine

Clinical Radiopharmacy Pathway

Production and Supply → Radiopharmacy → Administration → Quantitative Imaging → Dosimetry

Cross-sections → Production
Half-life → Activity
Gamma-ray emission intensities → Quantitative Imaging
Decay branching ratios → Quality control

Dosimetry
How does metrology underpin decay data

- Decay Data parameters are measurable quantities

- Traceability and standards underpin these measurements

- Primary standards provide significant benefits for determining absolute emission intensities

Absolute gamma-ray emission intensities
Examples of ‘recent’ decay data measurements

A Knight’s Tale (2001)
Ra-223 and decay progeny gamma-ray emission intensities
Ra-223 and decay progeny gamma-ray emission intensities

- Total of 148 gamma-rays from the decay series
- No previous absolute gamma-ray emission measurements just normalised values available
- Absolute emission intensities calculated from decay scheme
- Gamma-ray spectrometry showed agreement with the primary techniques...so no problem?
Ra-223 and decay progeny gamma-ray emission intensities

• 18% range in the activities determined from the main gamma-ray emissions

• No confidence in this data
# Ra-223 and decay progeny gamma-ray emission intensities

## Absolute emission intensities

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Ra-223 and decay progeny gamma-ray emission intensities

Relative emission intensities

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Ra-223 and decay progeny gamma-ray emission intensities

<table>
<thead>
<tr>
<th>Energy /keV</th>
<th>$I_\gamma$ /per 100 decay DDEP (Bé et al., 2011)</th>
<th>$I_\gamma$ /per 100 decay ENSDF (Singh et al., 2021)</th>
<th>$I_{DDEP}/I_{ENSDF}$</th>
<th>Precision improvement factor ($u(I_{DDEP})/u(I_{ENSDF})$)</th>
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<td>154.2</td>
<td>5.84(13)</td>
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<td>14.23(32)</td>
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<td>2.85(6)</td>
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<td>1.28(4)</td>
<td>1.2184(86)</td>
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</table>
Th-227 gamma-ray emission intensities

- Calculated absolute gamma-ray emissions lacked precision
  - > 8% uncertainty due to scaling factor
- Previous data published was either in the 1960s or from a private communication in 1992
Th-227 gamma-ray emission intensities

- Order of magnitude improvement in precision
Effect on time zero determination

\[ \frac{A(t)}{A_0(227\text{Th})} \]

\( t - t_0 \) (d)

\( ^{227}\text{Th} \)

\( (^{223}\text{Ra}, ^{219}\text{Rn}, ^{215}\text{Po}, ^{211}\text{Pb}, ^{211}\text{Bi}, ^{207}\text{Tl}) \)

\( (^{215}\text{At}, ^{211}\text{Po}) \)
Ac-225 half-life

• Previously a half-life of 10.0(1) d from a measurement in 1950

Measurement of the $^{225}\text{Ac}$ half-life

S. Pommé $^a$, M. Marouli $^a$, G. Suliman $^a$, H. Dikmen $^b$, R. Van Ammel $^b$, V. Jobbágy $^c$, A. Dirican $^c$, H. Stroh $^c$, J. Paepen $^c$, F. Bruchertseifer $^b$, C. Apostolidis $^b$, A. Morgenstern $^b$

$^a$ European Commission, Joint Research Centre, Institute for Reference Materials and Measurements, Reinaerdeg 111, B-2440 Geel, Belgium
$^b$ European Commission, Joint Research Centre, Institute for Transuranium Elements, P.O. Box 2340, 76126 Karlsruhe, Germany

**HIGHLIGHTS**

- Measured $^{225}\text{Ac}$ half-life by six methods.
- The result is $T_{1/2}(^{225}\text{Ac})=9.920 (3)$ d.
- $^{225}\text{Ac}$ and its daughter $^{225}\text{Rn}$ are important for targeted alpha therapy.

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<thead>
<tr>
<th>References</th>
<th>$T_{1/2}$ (d)</th>
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<td>2012PO14</td>
<td>9.9200 (36)</td>
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<td>2013BO</td>
<td>9.9120 (63)</td>
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<td>2020KO06</td>
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**Recommended** $9.9172 (21)$ Weighted mean, internal uncertainty
Status and needs of radionuclides being investigated for targeted alpha-particle therapy

DE GRYTER

Radiochim. Acta 2022, 110(6–9), 609–644

Contribution to “Diamond Jubilee of RCA”

Alan L. Nichols*

Status of the decay data for medical radionuclides: existing and potential diagnostic $\gamma$ emitters, diagnostic $\beta^+$ emitters and therapeutic radioisotopes

https://doi.org/10.3155/ract-2022-0004
Received January 6, 2022; accepted April 10, 2022; published online May 18, 2022

Abstract: Recommended half-lives and specific well-defined emission energies and absolute emission probabilities are important input parameters that should be well-defined to assist in ensuring the diagnostic and therapeutic treatment of tumours, and the various nuclear

adequate quantification of the required decay data (i.e., dose calculations include half-lives, energies and emission probabilities of $\alpha$, $\beta^+$, various electron particles, $\gamma$ and $X$-rays, along with other related parameters). Specific radionuclides possess decay characteristics that have been found to be appropriate or potentially suitable in the diagnosis or radio-therapeutic treatment of tumours, and the various nuclear


https://zenodo.org/records/8247129
Status and needs of radionuclides being investigated for targeted alpha-particle therapy

- **Tb-149**
  - Precision measurements of the half-lives of Tb-149 and its decay progenies (Eu-145 and Gd-149) are needed.
  - New studies are required to improve the precision of the alpha decay branching ratio.
  - There is a requirement for new studies of the gamma-ray emission intensities to confirm the accuracy of the single study and to improve the precision.
  - There is also a requirement to improve the gamma-ray emission intensities of the decay progenies.

- **At-211**
  - New half-life determinations with complete uncertainty evaluation are required.

- **Ac-225**
  - Extensive gamma-ray emission intensity studies and γ-γ coincidence studies are recommended.

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\[ _{227}^{\text{Th}}: \text{Extensive and significant } \alpha \text{ decay directly to the ground (24.2\% } \alpha), \text{ third (23.5\% } \alpha), \text{ thirteen (20.4\% } \alpha) \text{ and sixteenth (8.3\% } \alpha) \text{ excited states of } _{223}^{\text{Ra}}, \text{ as well as depopulation by 235.96-, 256.23- and 329.85-keV } \gamma \text{ rays and 220 lower-intensity } \gamma \text{ transitions from 6.5 to 1025 keV – extensive and complex decay scheme that includes as many as 223 } \gamma \text{ rays of which the placement of thirty-six are in doubt, while at least a further forty-nine } \gamma \text{ rays remain unplaced; more extensive } \gamma \text{ singles and } \gamma-\gamma \text{ coincidence studies merited} \]
Importance of Decay Data Evaluations

- Evaluated datasets provide the decay data that most use on a routine basis
- There are several databases of evaluated decay data
  - NNDC
  - Decay Data Evaluation Project (DDEP)
- However, there can be a significant lag between publication of new data and its inclusion in new evaluated datasets
- There are not enough evaluators and too many radionuclides

https://www.nndc.bnl.gov/

Current Challenges for Decay Data

- Recognition
- Technical
- Skilled People
- Robustness & Validity of Data
Future outlook

• There are new programs that have built in metrology to measure decay data for medical radionuclides

• NuPECC Long Range plan (in progress) has identified decay data, metrology, and needs for societal applications
Conclusion

- Decay data is a broad term covering a large field
- They are measurable quantities
- A lot of the data is old and does not benefit from traceability or metrology
- It has an impact across the radiopharmaceutical pathway
- There is still plenty to do but significant improvements have been made in the last 10 years
  - State-of-the-art techniques
  - Metrology and traceability
  - Robust uncertainties
- Decay data is seeing an increase in interest and the need for better confidence in the data
- There are new programmes underway that identify the need for metrology in decay data