Sources of Ionizing Radiation and Radiation Interactions

Reading Material:
Chapter 1, Radiation Detection and Measurements,
Forth Edition, by G. F. Knoll
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photons = principle photon energies in kilo-electron volts, keV, (abundance/decay)
$\beta$ = beta maximum energy in mega-electron volts, MeV, (abundance/decay)
$\beta^+$ = $\beta^+$ decay; $\beta^-$ = $\beta^-$ decay; IT = isomeric transition; ec = electron capture
* X-rays from progeny, mercury, Hg
Beta Decay

Things to consider from imaging viewpoint

Decay products: fast electrons, gamma-ray, X-ray, Auger electrons, and their corresponding

- half-life,
- energy, and
- relative intensity.
Beta Emission

• Beta particle is an ordinary electron. Many atomic and nuclear processes result in the emission of beta particles.

• One of the most common source of beta particles is the beta decay of nuclides, in which

\[
\begin{align*}
\text{Beta decay} & \\
\frac{A}{Z} X & \rightarrow \frac{A}{Z+1} Y + 0_{-1} \beta + \bar{\nu} \\
\text{Beta-plus decay} & \\
\frac{A}{Z} X & \rightarrow \frac{A}{Z-1} Y + 0_{+1} \beta + \nu \\
\text{Electron capture} & \\
\frac{A}{Z} X + e^- & \rightarrow \frac{A}{Z-1} Y + \nu
\end{align*}
\]
“Regular” Beta Decay

\[ \beta^- \]

\[ n \rightarrow p + e^- + \bar{\nu}_e \]
Energy Release of Beta Decay

The energy release in a beta decay is given as

\[ Q = M_p - (M_d + M_e) \]

- The energy release is once again given by the conversion of a fraction of the mass into energy. Note that atomic electron bonding energy is neglected.
- For a beta decay to be possible, the energy release has to be positive.
Typical Energy Spectrum of Beta Particles

- The energy release is shared by all three daughter products. Due to the relatively large mass of the daughter nucleus, it attains only a small fraction of the energy. Therefore, the kinetic energy of the beta particle is

\[ E_{\beta}^{-} \approx Q - E_{\bar{\nu}} \]
An Example of Cancer Therapy with Radiopharmaceuticals

**DIAGNOSIS**
68 Gallium-**Octreotate** PET/CT

**THERAPY**
177 Lutetium-**Octreotate** SPECT-CT

\[ ^{177}\text{Lu} \quad T_{1/2}=6.716\text{ days} \]

\[ \beta^- \]

\( Q_\beta = 0.4971\text{ MeV} \)

\( 78\% \)

\( 12\% \)

\( 0.05\% \)

\( 0.32132 \)

\( 0.11295 \)

\( 0.24967 \)

\( 0 \)

\( ^{177}\text{Hf} \)
Positron Decay
Positron Decay

The energy release $Q$ associated with the positron emission process is given by

$$Q \approx M_p - M_d - M_e - M_{e^+} = M_p - (M_d + 2M_e)$$

where the atomic electron binding energy is ignored.
Orbital Electron Capture and Positron Decay

- Electron capture and positron decay are normally competing processes through which a neutron deficient nucleus may attain an increased stability.

- Both the emission of a positron and the capture of an electron, a neutrino is always emitted in order to conserve energy.

- In positron decay, the neutrino carries the difference between the energy release and the energy of the resultant positron. In electron capture, however, the neutrino must be mono-energetic.
Positron Emission Tomography

Beta-plus decay or positron decay:

\[ ^{A}_{z}X \rightarrow ^{A-1}_{z-1}Y + 0 \beta + \nu \]

Example of positron annihilation

Radiolabeling

What about
- positron range?
- Acollinearity? and ...
Clinical Applications of PET – Functional Brain Imaging

Functional Brain Imaging with Fluorodeoxyglucose (FDG)

http://www.osti.gov/accomplishments/pet.html
Negative and positive [C-11]PiB PET images. [C-11]PiB PET images taken in the axial plane at levels indicated in the sagittal MRI image at the far left. The scans in the top row illustrate the 79-year-old [C-11]PiB(−) DLB subject that is the focus of the current study. There is no evidence of [C-11]PiB retention except for nonspecific retention in the white matter. The scans in the bottom row illustrate a 65-year-old [C-11]PiB(+) AD subject showing high [C-11]PiB retention throughout the neocortex and the striatum.
Positron range in PET imaging: non-conventional isotopes

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² CEA, LIST, F-91191 Gif-sur-Yvette, France
³ Centre d’Études Nucléaires de Bordeaux Gradignan, CNRS/IN2P3, Bordeaux, Gradignan, France

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<th>Isotope</th>
<th>Allowed decay</th>
<th>$T_v$</th>
<th>$E_{\text{mean}}$ (keV)</th>
<th>$E_{\text{max}}$ (keV)</th>
<th>$R_{\text{mean}}$ (mm)³</th>
<th>$R_{\text{max}}$ (mm)³</th>
<th>Example of application</th>
</tr>
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<tr>
<td>$^{64}$Cu</td>
<td>Yes, $\beta^-$ and $\beta^+$</td>
<td>12.7 h</td>
<td>278.2²</td>
<td>653.1</td>
<td>0.56</td>
<td>2.9</td>
<td>Detection of small colorectal tumors (Philpott et al 1995)</td>
</tr>
<tr>
<td>$^{22}$Na</td>
<td>Yes³</td>
<td>2.6 year</td>
<td>220.3</td>
<td>673.5</td>
<td>0.5³</td>
<td>2.8⁵</td>
<td>Scanner calibration (Topping et al 2013)</td>
</tr>
<tr>
<td>$^{52}$Mn</td>
<td>Yes</td>
<td>5.6 d</td>
<td>244.6</td>
<td>575.8</td>
<td>0.63</td>
<td>2.5</td>
<td>Candidate for bone scanning (Link et al 2006)</td>
</tr>
<tr>
<td>$^{89}$Zr</td>
<td>Yes</td>
<td>78.4 h</td>
<td>402.7</td>
<td>902</td>
<td>1.27</td>
<td>4.2</td>
<td>Quantifying the deposition of monoclonal antibodies in the tissues of tumors (Link et al 2006)</td>
</tr>
<tr>
<td>$^{47}$Ti</td>
<td>Yes</td>
<td>3.08 h</td>
<td>442.3</td>
<td>1040.4</td>
<td>1.47</td>
<td>5.2</td>
<td>Uptake measurements to provide insight into the mechanism of the action of titanium chloride (Vaver and Welch 2005)</td>
</tr>
<tr>
<td>$^{51}$Mn</td>
<td>Yes</td>
<td>46.2 min</td>
<td>970.2</td>
<td>2185.8</td>
<td>4.3</td>
<td>12.1</td>
<td>Diagnosis and treatment of blood diseases (Sastris et al 1981)</td>
</tr>
<tr>
<td>$^{99m}$Tc</td>
<td>Yes</td>
<td>52.0 min</td>
<td>1076.6</td>
<td>2362.9</td>
<td>4.7</td>
<td>12.8</td>
<td>PET substitute for $^{99m}$Tc (Liu and Laforet 2007)</td>
</tr>
<tr>
<td>$^{52}$Mn</td>
<td>Yes</td>
<td>21.1 min</td>
<td>1179</td>
<td>2630</td>
<td>5.3</td>
<td>14.5</td>
<td>Myocardial imaging (Hui et al 1979, Daube and Nickles 1985, Tolmachov et al 1994)</td>
</tr>
<tr>
<td>$^{38}$K</td>
<td>Yes</td>
<td>7.64 min</td>
<td>1218.8</td>
<td>2728</td>
<td>5.7</td>
<td>15.3</td>
<td>PET perfusion imaging (Bol et al 1993)</td>
</tr>
<tr>
<td>$^{85}$Y</td>
<td>No</td>
<td>14.7 h</td>
<td>640</td>
<td>2010.4</td>
<td>2.5</td>
<td>11.1</td>
<td>Uptake measurements prior to therapy using $^{85}$Y (Ritsch et al 1996)</td>
</tr>
<tr>
<td>$^{131}$I</td>
<td>No</td>
<td>81 min</td>
<td>1747</td>
<td>4600</td>
<td>8.3</td>
<td>27</td>
<td>Shorter lifetime and higher positron yield than $^{124}$I (Zweif et al 1996)</td>
</tr>
</tbody>
</table>

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* (Le Loirec and Champion 2007b).
* (Le Loirec and Champion 2007c).
* Mean value for positron emission only.
* Decay to the ground state of $^{22}$Na is forbidden ($3^+ \rightarrow 0^+$); instead, nearly 100% of the decays are to an excited state, $^{22}$Na ($3^+ \rightarrow 22$Ne* ($2^+$)) (Lederer et al 1967).
* (Le Loirec 2007).

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Figure 5. Functions $P_{2\nu}(\delta)$ obtained from Monte Carlo calculations (broken lines) compared with the expressions defined by (3) using the values of $A$ and $B$ provided in table 2 (smooth lines).
A Few Details on Positron Decay and Their Implications to PET

<table>
<thead>
<tr>
<th>Isotope</th>
<th>half-life (min)</th>
<th>Maximum positron energy (MeV)</th>
<th>Positron range in water (FWHM in mm)</th>
<th>Production method</th>
</tr>
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<tbody>
<tr>
<td>$^{11}\text{C}$</td>
<td>20.3</td>
<td>0.96</td>
<td>1.1</td>
<td>cyclotron</td>
</tr>
<tr>
<td>$^{13}\text{N}$</td>
<td>9.97</td>
<td>1.19</td>
<td>1.4</td>
<td>cyclotron</td>
</tr>
<tr>
<td>$^{15}\text{O}$</td>
<td>2.03</td>
<td>1.70</td>
<td>1.5</td>
<td>cyclotron</td>
</tr>
<tr>
<td>$^{18}\text{F}$</td>
<td>109.8</td>
<td>0.64</td>
<td>1.0</td>
<td>cyclotron</td>
</tr>
<tr>
<td>$^{68}\text{Ga}$</td>
<td>67.8</td>
<td>1.89</td>
<td>1.7</td>
<td>generator</td>
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<td>$^{82}\text{Rb}$</td>
<td>1.26</td>
<td>3.15</td>
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Table 2. Properties of commonly used positron emitting radio-isotopes

Element of life.
What is $[^{18}\text{F}]$FDG?

GENERAL INFORMATION
Chemical name of $[^{18}\text{F}]$FDG is $[^{18}\text{F}]-2$-Fluoro-2-deoxy-$\beta$-D-glucopyranose, Chemical Abstract Service registry number 63503-12-8. More commonly it is called $[^{18}\text{F}]$Fluorodeoxyglucose or simply FDG.
This compound is a radioactive derivative of 2-deoxy-D-glucose labelled with positron-emitting isotope $^{18}\text{F}$ in the position 2 of the glucose core structure.

Relative molecular mass: 181.15 g/mol

NAMES:
FDG
$[^{18}\text{F}]$FLUORODEOXYGLUCOSE
$[^{18}\text{F}]-2$-Fluoro-2-deoxy-$\beta$-D-glucopyranose

For more details please refer to review article on radiohalogenated sugars.
Functional Imaging with Tremendous Sensitivity Under In Vivo Settings

PET studies of glucose metabolism to map human brain's response in performing different tasks.


**PET-labeled probes for biological imaging:** (from S. Cherry, UC Davis)

- Hemodynamic parameters ($H_2^{15}O$, $^{15}O$-butanol, $^{11}CO$, $^{13}NH_3$....)
- Substrate metabolism ($^{18}F$-FDG, $^{15}O_2$, $^{11}C$-palmitic acid....)
- Protein synthesis ($^{11}C$-leucine, $^{11}C$-methionine, $^{11}C$-tyrosine)
- Enzyme activity ($^{11}C$-deprenyl, $^{18}F$-deoxyuracil....)
- Drugs ($^{11}C$-cocaine, $^{13}N$-cisplatin, $^{18}F$-fluorouracil....)
- Receptor affinity ($^{11}C$-raclopride, $^{11}C$-carfentanil, $^{11}C$-scopalamine)
- Neurotransmitter biochemistry ($^{18}F$-fluorodopa, $^{11}C$-ephedrine....)
- Gene expression ($^{18}F$-penciclovir, $^{18}F$-antisense oligonucleotides) .........

L. J. Meng, University of Illinois Technology Showcase, April 5th, 2021
Electron Capture
Energy Release Through Orbital Electron Capture

For positron decay to be possible, we need

\[ Q = M_p - M_d - M_e - M_{e^+} > 0, \]
so

\[ M_p > M_d + M_e + M_{e^+} = M_d + 2M_e \]

\( M_p \) and \( M_d \) are the atomic masses of the parent and daughter atoms.

For Electron Capture to occur,

\[ Q = M_p - M_d - \phi > 0 \]
so that

\[ M_p > M_d + \phi \]

where \( \phi \) is the binding energy of the orbital electron.
Internal Conversion

- Conversion electrons can originate from several different electron shells within the atom, a single excited state generally leads to several groups of electrons with different energies.
- The only practical laboratory scale source of mono-energetic electron groups in high keV to MeV energy range.
Auger Electrons

- The excitation energy of the atom may be transferred to one of the outer electrons, causing it to be ejected from the atom.
- Auger electrons are roughly the analogue of internal conversion electrons when the excitation energy originates in the atom rather than in the nucleus.

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**Figure 3.7** (A) The usual emission of a K characteristic X-ray, $h\nu$, energy equal to $E_K - E_L$, the difference in binding energy for the two orbital electrons, K and L. (B) $h\nu$ has been absorbed and a monoenergetic Auger electron is emitted, in the example shown, from the M shell, the energy of which is $E_K - E_L - E_M$. (C) In its final state the atom has vacancies in the L and M orbitals.
Special SPECT Imaging Applications: Single Photon Emission Microscopy

Imaging of mouse kidney I-125, Data from Center for Gamma Ray Imaging, University of Arizona

In vivo imaging of (~1500) radiolabeled T cells labeled with I-125 in mouse brain using SPECT (Meng, 2009).
What would be an ideal gamma ray emitter for nuclear imaging?

- Reasonably penetrative...
- Half-life comparable to the biological process we are trying to visualize...
- Easy radiochemistry...
- Biologically safe...
- Clean ...
Metastable Nuclear States and Gamma Ray Emission

The lifetimes of nuclear excited states vary, but $\sim 10^{-10}$ s can be regarded as typical. Thus, gamma rays are usually emitted quickly after radioactive decay to an excited daughter state.

In some cases, however, selection rules prevent photon emission for an extended period of time. The excited state of $^{137}_{56}\text{Ba}$ following the decay of $^{137}_{55}\text{Cs}$ has a half-life of 2.55 min. Such a long-lived nuclear state is termed metastable and is designated by the symbol m: $^{137m}_{56}\text{Ba}$.

Another example of a metastable nuclide is $^{99m}_{43}\text{Tc}$, which results from the beta decay of the molybdenum isotope $^{99}_{42}\text{Mo}$. An isomeric transition (IT) to the ground state is followed by isomeric transition (IT) to the ground state.

Decay Scheme for $^{99}\text{Mo}$
Metastable Nuclear States and Gamma Ray Emission

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Tc-99m Sestamibi Myocardial Perfusion Imaging (MPI)

Exercise stress Tc-99m Sestamibi single day myocardial perfusion SPECT images of the female patient with a significant (80%) distal left main coronary artery disease. Classic features of the high-risk scan are present: severe partially reversible perfusion defect, involvement of the LAD and LCX territory, visual transient ischemic dilation and abnormal TID ratio (1.21). The patient presented with symptoms of stable atypical angina. No significant ECG or hemodynamic changes were noted during the stress portion of the test.

https://www.researchgate.net/figure/Exercise-stress-Tc-99m-Sestamibi-single-day-myocardial-perfusion-SPECT-images-of-the_fig1_283448406
What do MPI images look like?

In a typical nuclear cardiac imaging exam, the physician reviews:

- Static “Summed Perfusion Images”
- Dynamic “Gated Images”

Perfusion Images are viewed in three orientations:
SA – Short Axis
VLA – Vertical Long Axis
HLA - Horizontal Long Axis
Therapeutic Beta Emitters
# Common isotopes used in nuclear medicine

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Photons = principal photon energies in kilo-electron volts, keV, (abundance/decay). 
$\beta$ = beta maximum energy in mega-electron volts, MeV, (abundance/decay). 
$\beta^+$ = $\beta^+$ decay; $\beta^-$ = $\beta^-$ decay; IT = isomeric transition; ec = electron capture. 
* X-rays from progeny, mercury, Hg.
## Therapeutic Beta Emitters

Table 1 - Physical and nuclear characteristics of bone-seeking therapeutic radionuclides

<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>Maximum energy (MeV)</th>
<th>Average energy (MeV)</th>
<th>Average Range (mm)</th>
<th>$T_{\text{half}}$ (days)</th>
<th>$E_{\text{photon}}$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strontium-89</td>
<td>1.46</td>
<td>0.58</td>
<td>2.4</td>
<td>50.5</td>
<td>None</td>
</tr>
<tr>
<td>Phosphorus-32</td>
<td>1.71</td>
<td>0.70</td>
<td>3.0</td>
<td>14.3</td>
<td>None</td>
</tr>
<tr>
<td>Tin-117m</td>
<td>0.13$^2$</td>
<td>---</td>
<td>0.22</td>
<td>14.0</td>
<td>0.159 (86%)</td>
</tr>
<tr>
<td></td>
<td>0.15$^2$</td>
<td>---</td>
<td>0.29</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Erbium-169</td>
<td>0.34</td>
<td>0.11</td>
<td>0.30</td>
<td>9.3</td>
<td>None</td>
</tr>
<tr>
<td>Lutetium-177</td>
<td>0.50</td>
<td>0.14</td>
<td>0.35</td>
<td>6.7</td>
<td>0.208 (11%)</td>
</tr>
<tr>
<td>Rhenium-186</td>
<td>1.08</td>
<td>0.33</td>
<td>1.05</td>
<td>3.7</td>
<td>0.137 (9%)</td>
</tr>
<tr>
<td>Samarium-153</td>
<td>0.81</td>
<td>0.22</td>
<td>0.55</td>
<td>1.9</td>
<td>0.103 (29%)</td>
</tr>
<tr>
<td>Holmium-166</td>
<td>1.84</td>
<td>0.67</td>
<td>3.3</td>
<td>1.1</td>
<td>0.081 (6%)</td>
</tr>
<tr>
<td>Rhenium-188</td>
<td>2.12</td>
<td>0.64</td>
<td>3.8</td>
<td>0.71</td>
<td>0.155 (10%)</td>
</tr>
</tbody>
</table>

1. Arranged in order of decreasing half-life
2. Conversion electrons with discrete energies (and range).
Examples for Beta Decay

- Complicated decay schemes and the emission of other particles such as gamma rays.
- Pure beta emitters: $^3\text{H}$, $^{14}\text{C}$, $^{32}\text{P}$ and $^{90}\text{Sr}$.

**Figure 4.7.** Iodine-131 transformation (decay) scheme.
I-131 Whole Body Imaging

Differentiation between malignancy and benign changes with SPECT/CT in a patient with thyroid cancer who underwent 131I whole-body imaging to assess for residual recurrent disease. Anterior (a) and posterior (b) 131I scans show focal activity in the right suprarenal region.

Coronal (c) and axial (d) SPECT/CT images show that the uptake is located in the renal collecting system (arrow), consistent with physiologic urinary activity, and not recurrence of disease.

www.lancastergeneralhealth.org/LGH/ECommerceSite/
Serial post-I 131 therapy scans (anterior whole body views). (A) Age 10, 3.01 GBq; (B) age 11, 2.95 GBq; (C) age 13, 4.3 GBq; (D) age 14, 5.1 GBq; (E) age 15, 9.9 GBq, 7 months before conception. Neck disease present at age 13 (C) was treated surgically. The final study (E) showed the presence of radioiodine avid bilateral pulmonary metastases (<5 mm maximum diameter on computed tomography) and very small, low-grade lower neck disease. The focal uptake in the left upper abdomen is colonic and is likely physiological in nature.
\textbf{\textsuperscript{225}Ac-PSMA-617 for PSMA-Targeted \textalpha-Radiation Therapy of Metastatic Castration-Resistant Prostate Cancer}

Clemens Kratochwil\textsuperscript{1}, Frank Bruchertseifer\textsuperscript{2}, Frederik L. Giesel\textsuperscript{1}, Mirjam Weis\textsuperscript{2}, Frederik A. Verburg\textsuperscript{3}, Felix Mottaghy\textsuperscript{3}, Klaus Kopka\textsuperscript{4}, Christos Apostolidis\textsuperscript{2}, Uwe Haberkorn\textsuperscript{1}, and Alfred Morgenstern\textsuperscript{2}

\textsuperscript{1}Department of Nuclear Medicine, University Hospital Heidelberg, Heidelberg, Germany; \textsuperscript{2}European Commission, Joint Research Centre, Institute for Transuranium Elements, Karlsruhe, Germany; \textsuperscript{3}Department of Nuclear Medicine, RWTH University Hospital Aachen, Aachen, Germany; and \textsuperscript{4}Division of Radiopharmaceutical Chemistry, German Cancer Research Center, Heidelberg, Germany

\textbf{FIGURE 1.} \textsuperscript{68}Ga-PSMA-11 PET/CT scans of patient A. Pretherapeutic tumor spread (A), restaging 2 mo after third cycle of \textsuperscript{225}Ac-PSMA-617 (B), and restaging 2 mo after one additional consolidation therapy (C).
Hyperspectral SPECT Imaging of TAT

Estimated crosstalk of Th227/Ra223 imaging.

VOI quantification. Left: Th-227; Right: Ra-223.

H&E staining of VX2 tumor and surrounding liver section (A) and corresponding α-Camera image (C) 3 hours post-injection of $^{225}$Ac-DOTAGA-TDA. (B) Merged image showing segmented high-intensity regions overlayed on H&E stained slide. Segmented regions do not exactly match the tumor boundaries due to differences in tissue processing and because the comparison is made across two different 12-µm-thick sections.

Data presented in this slide is kindly provided by our collaborators, Dr. Eric Frey and Dr. Yong Du at Johns Hopkins Medical School.
Atomic Emissions
Energy Release of Orbital Electron Capture

For Positron Decay to be possible, we need

\[ Q = M_p - M_d - M_e - M_{e^+} > 0, \]

so

\[ M_p > M_d + M_e + M_{e^+} = M_d + 2M_e \]

\( M_p \) and \( M_d \) are the atomic masses of the parent and daughter atoms.

For Electron Capture to occur,

\[ Q = M_p - M_d - \phi > 0 \]

so that

\[ M_p > M_d + \phi \]

where \( \phi \) is the binding energy of the orbital electron.
Internal Conversion

Begins with an excited nuclear state

De-excite through the emission of a gamma ray

\[ E_{\beta^-} = E_{ex} - E_b \]

The excitation energy is transferred directly to an orbital electron, causing it to be ejected from the atom

Conversion electron with an energy

IC Coefficient (or Branching Ratio) = \( \frac{N_\gamma}{N_e} \)
Auger Electrons and Characteristic X-rays

- The excitation energy of the atom may be transferred to one of the outer electrons, causing it to be ejected from the atom.
- Auger electrons are roughly the analogue of internal conversion electrons when the excitation energy originates in the atom rather than in the nucleus.

\[ E_{a.e.} = (E_K - E_{L_1}) - E_{L_23} \]

Figure 3.7 (A) The usual emission of a K characteristic X-ray, \( h\nu \), energy equal to \( E_K - E_L \), the difference in binding energy for the two orbital electrons, K and L. (B) \( h\nu \) has been absorbed and a monoenergetic Auger electron is emitted, in the example shown, from the M shell, the energy of which is \( E_K - E_L - E_M \). (C) In its final state the atom has vacancies in the L and M orbitals.
Examples of Radioactivity from Medical Radioisotopes

1 Decay Scheme

1-123 disintegrate by electron capture mainly via the 159 keV level of Te-123 (97%).
L'isotope 1-123 se désintègre par capture électronique principalement vers le niveau excité de 159 keV du tellure 1-123, avec une probabilité de 97%.

2 Nuclear Data

\[ T_{1/2}^{(123I)} : 12.2334 \text{ (37) h} \]

\[ T_{1/2}^{(123Te)} : 12 \text{ (1012 a) } \]

\[ Q^{(123I)} : 1234 \text{ (3) keV} \]

2.1 Electron Capture Transitions

<table>
<thead>
<tr>
<th>Energy (keV)</th>
<th>Probability × 100</th>
<th>Nature</th>
<th>lg ft</th>
<th>( P_E )</th>
<th>( P_T )</th>
<th>( P_M )</th>
</tr>
</thead>
<tbody>
<tr>
<td>165.8 (30)</td>
<td>0.0070 (4)</td>
<td>Allowed</td>
<td>7.50</td>
<td>0.8892 (21)</td>
<td>0.1543 (15)</td>
<td>0.0339 (7)</td>
</tr>
<tr>
<td>197.4 (30)</td>
<td>0.0020 (9)</td>
<td>Allowed</td>
<td>8.27</td>
<td>0.8192 (19)</td>
<td>0.1427 (13)</td>
<td>0.0318 (6)</td>
</tr>
<tr>
<td>237.9 (30)</td>
<td>0.0003 (5)</td>
<td>1st Forbidden</td>
<td>8.31</td>
<td>0.8296 (16)</td>
<td>0.1363 (12)</td>
<td>0.0309 (6)</td>
</tr>
<tr>
<td>283.3 (30)</td>
<td>0.0044 (12)</td>
<td>Allowed</td>
<td>7.32</td>
<td>0.8377 (15)</td>
<td>0.1258 (11)</td>
<td>0.0279 (5)</td>
</tr>
<tr>
<td>350.4 (30)</td>
<td>0.1461 (30)</td>
<td>Allowed</td>
<td>7.29</td>
<td>0.8436 (14)</td>
<td>0.1237 (10)</td>
<td>0.0267 (5)</td>
</tr>
<tr>
<td>464.7 (30)</td>
<td>0.0073 (6)</td>
<td>Allowed</td>
<td>8.02</td>
<td>0.8441 (14)</td>
<td>0.1231 (10)</td>
<td>0.0269 (5)</td>
</tr>
<tr>
<td>536.5 (30)</td>
<td>0.1109 (33)</td>
<td>Allowed</td>
<td>6.08</td>
<td>0.8661 (14)</td>
<td>0.1216 (10)</td>
<td>0.0252 (5)</td>
</tr>
<tr>
<td>546 (3)</td>
<td>1.10 (12)</td>
<td>Allowed</td>
<td>6.69</td>
<td>0.8661 (10)</td>
<td>0.1214 (10)</td>
<td>0.0261 (5)</td>
</tr>
<tr>
<td>726.9 (30)</td>
<td>0.340 (42)</td>
<td>Allowed</td>
<td>7.35</td>
<td>0.8561 (14)</td>
<td>0.1187 (10)</td>
<td>0.0254 (5)</td>
</tr>
<tr>
<td>743.3 (30)</td>
<td>0.0025 (36)</td>
<td>Allowed</td>
<td>9.52</td>
<td>0.8583 (16)</td>
<td>0.1186 (10)</td>
<td>0.0254 (5)</td>
</tr>
<tr>
<td>794 (3)</td>
<td>0.419 (5)</td>
<td>Allowed</td>
<td>7.95</td>
<td>0.8583 (14)</td>
<td>0.1181 (10)</td>
<td>0.0255 (5)</td>
</tr>
<tr>
<td>1075 (3)</td>
<td>0.178 (32)</td>
<td>Allowed</td>
<td>5.26</td>
<td>0.8553 (14)</td>
<td>0.1163 (10)</td>
<td>0.0248 (5)</td>
</tr>
</tbody>
</table>

2.2 Gamma Transitions and Internal Conversion Coefficients

<table>
<thead>
<tr>
<th>Energy (keV)</th>
<th>( P_{\gamma \rightarrow 0} \times 100 )</th>
<th>Multipolarity</th>
<th>( \alpha_K )</th>
<th>( \alpha_L )</th>
<th>( \alpha_T )</th>
</tr>
</thead>
<tbody>
<tr>
<td>158.0 (5)</td>
<td>99.22 (30)</td>
<td>M1 + 1.225E2</td>
<td>0.1648 (16)</td>
<td>0.02160 (22)</td>
<td>0.1918 (19)</td>
</tr>
<tr>
<td>174.3 (3)</td>
<td>0.0099 (30)</td>
<td>M1 + 0.60 E2</td>
<td>0.159 (32)</td>
<td>0.020 (12)</td>
<td>0.195 (47)</td>
</tr>
<tr>
<td>192.1 (8)</td>
<td>0.021 (6)</td>
<td>M1 + 0.60 E2</td>
<td>0.138 (24)</td>
<td>0.024 (10)</td>
<td>0.168 (39)</td>
</tr>
<tr>
<td>192.1 (9)</td>
<td>0.0227 (10)</td>
<td>M1 + 0.60 E2</td>
<td>0.118 (20)</td>
<td>0.026 (8)</td>
<td>0.143 (30)</td>
</tr>
<tr>
<td>197.22 (11)</td>
<td>0.0083 (70)</td>
<td>M1 + 0.60 E2</td>
<td>0.139 (18)</td>
<td>0.018 (7)</td>
<td>0.132 (26)</td>
</tr>
<tr>
<td>198.25 (12)</td>
<td>0.040 (8)</td>
<td>M1 + 0.60 E2</td>
<td>0.107 (17)</td>
<td>0.018 (7)</td>
<td>0.130 (26)</td>
</tr>
<tr>
<td>206.79 (10)</td>
<td>0.0367 (9)</td>
<td>M1 + 0.60 E2</td>
<td>0.094 (14)</td>
<td>0.016 (5)</td>
<td>0.114 (21)</td>
</tr>
<tr>
<td>207.82 (13)</td>
<td>0.0125 (30)</td>
<td>M1 + 0.60 E2</td>
<td>0.093 (14)</td>
<td>0.015 (5)</td>
<td>0.119 (20)</td>
</tr>
<tr>
<td>247.96 (8)</td>
<td>0.0743 (25)</td>
<td>M1 + 0.60 E2</td>
<td>0.054 (5)</td>
<td>0.0084 (21)</td>
<td>0.065 (8)</td>
</tr>
<tr>
<td>257.52 (9)</td>
<td>0.0017 (2)</td>
<td>E2</td>
<td>0.0026 (16)</td>
<td>0.00017 (27)</td>
<td>0.0046 (19)</td>
</tr>
<tr>
<td>278.28 (8)</td>
<td>0.0021 (4)</td>
<td>M1 + 0.60 E2</td>
<td>0.0057 (22)</td>
<td>0.0056 (11)</td>
<td>0.0059 (30)</td>
</tr>
<tr>
<td>281.03 (7)</td>
<td>0.0022 (10)</td>
<td>M1 + 0.60 E2</td>
<td>0.0042 (20)</td>
<td>0.0048 (11)</td>
<td>0.0042 (33)</td>
</tr>
<tr>
<td>295.17 (21)</td>
<td>0.0058 (2)</td>
<td>E2</td>
<td>0.0023 (7)</td>
<td>0.00376 (11)</td>
<td>0.0028 (4)</td>
</tr>
<tr>
<td>320.39 (18)</td>
<td>0.0026 (6)</td>
<td>E2</td>
<td>0.0071 (34)</td>
<td>0.00376 (11)</td>
<td>0.0028 (4)</td>
</tr>
<tr>
<td>390.1 (11)</td>
<td>0.0119 (34)</td>
<td>E2</td>
<td>0.0023 (7)</td>
<td>0.00376 (11)</td>
<td>0.0028 (4)</td>
</tr>
<tr>
<td>464.7 (15)</td>
<td>0.0041 (22)</td>
<td>E2</td>
<td>0.00017 (27)</td>
<td>0.00016 (3)</td>
<td>0.00017 (27)</td>
</tr>
<tr>
<td>539.6 (8)</td>
<td>0.003 (33)</td>
<td>E2 + 50% M3</td>
<td>0.002 (26)</td>
<td>0.0001 (4)</td>
<td>0.0001 (4)</td>
</tr>
<tr>
<td>556.16 (16)</td>
<td>0.0029 (3)</td>
<td>E2</td>
<td>0.0011 (37)</td>
<td>0.0041 (8)</td>
<td>0.0041 (8)</td>
</tr>
<tr>
<td>632.84 (12)</td>
<td>0.0011 (3)</td>
<td>E2</td>
<td>0.00017 (27)</td>
<td>0.00016 (3)</td>
<td>0.00017 (27)</td>
</tr>
<tr>
<td>733.88 (20)</td>
<td>0.0012 (8)</td>
<td>E2</td>
<td>0.00017 (27)</td>
<td>0.00016 (3)</td>
<td>0.00017 (27)</td>
</tr>
<tr>
<td>818.06 (16)</td>
<td>0.0029 (17)</td>
<td>E2</td>
<td>0.0011 (37)</td>
<td>0.0041 (8)</td>
<td>0.0041 (8)</td>
</tr>
<tr>
<td>983.91 (23)</td>
<td>0.0011 (8)</td>
<td>E2</td>
<td>0.00017 (27)</td>
<td>0.00016 (3)</td>
<td>0.00017 (27)</td>
</tr>
<tr>
<td>1058.15 (18)</td>
<td>0.0012 (7)</td>
<td>E2</td>
<td>0.00017 (27)</td>
<td>0.00016 (3)</td>
<td>0.00017 (27)</td>
</tr>
</tbody>
</table>

3 Atomic Data

3.1 Te

\[ \omega_K : 0.375 \text{ (4)} \]
\[ \omega_L : 0.0862 \text{ (35)} \]
\[ \omega_{KL} : 0.017 \text{ (4)} \]
3.1.1 X Radiations

<table>
<thead>
<tr>
<th>Energy</th>
<th>Relative probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>keV</td>
<td></td>
</tr>
<tr>
<td>$X_K$</td>
<td></td>
</tr>
<tr>
<td>K$_{\alpha 2}$</td>
<td>27.202</td>
</tr>
<tr>
<td>K$_{\alpha 1}$</td>
<td>27.4725</td>
</tr>
<tr>
<td>K$_{\beta 3}$</td>
<td>30.9446</td>
</tr>
<tr>
<td>K$_{\beta 1}$</td>
<td>30.996</td>
</tr>
<tr>
<td>K$_{\beta 2}$</td>
<td>31.236</td>
</tr>
<tr>
<td>K$_{\beta 1}$</td>
<td>31.241</td>
</tr>
<tr>
<td>K$_{\beta 2}$</td>
<td>31.708</td>
</tr>
<tr>
<td>K$_{\beta 1}$</td>
<td>31.774</td>
</tr>
<tr>
<td>KO$_{2,3}$</td>
<td>31.812</td>
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</table>

<table>
<thead>
<tr>
<th>Energy</th>
<th>Relative probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>keV</td>
<td></td>
</tr>
<tr>
<td>$X_L$</td>
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</tr>
<tr>
<td>L$_f$</td>
<td>3.336</td>
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<tr>
<td>L$_0$</td>
<td>3.76 – 3.77</td>
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<tr>
<td>L$_\gamma$</td>
<td>3.996</td>
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<tr>
<td>L$_\beta$</td>
<td>4.62 – 4.37</td>
</tr>
<tr>
<td>L$_\gamma$</td>
<td>4.44 – 4.82</td>
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</table>

3.1.2 Auger Electrons

<table>
<thead>
<tr>
<th>Energy</th>
<th>Relative probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>keV</td>
<td></td>
</tr>
<tr>
<td>Auger K</td>
<td></td>
</tr>
<tr>
<td>KLL</td>
<td>21.804 – 22.989</td>
</tr>
<tr>
<td>KLL</td>
<td>25.814 - 27.470</td>
</tr>
<tr>
<td>KXY</td>
<td>29.80 - 31.81</td>
</tr>
<tr>
<td>Auger L</td>
<td>2.3 – 4.8</td>
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</table>

4 Electron Emissions

<table>
<thead>
<tr>
<th>Energy</th>
<th>Electrons per 100 disint.</th>
</tr>
</thead>
<tbody>
<tr>
<td>keV</td>
<td></td>
</tr>
<tr>
<td>$\epsilon_{AL}$ (Te)</td>
<td>2.3 – 4.8</td>
</tr>
<tr>
<td>$\epsilon_{AK}$ (Te)</td>
<td>21.894 – 22.989</td>
</tr>
<tr>
<td>$\epsilon_{KL}$ (Te)</td>
<td>25.814 – 27.470</td>
</tr>
<tr>
<td>$\epsilon_{KXY}$ (Te)</td>
<td>29.80 – 31.81</td>
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</tbody>
</table>

5 Photon Emissions

5.1 X-Ray Emissions

<table>
<thead>
<tr>
<th>Energy</th>
<th>Photons per 100 disint.</th>
</tr>
</thead>
<tbody>
<tr>
<td>keV</td>
<td></td>
</tr>
<tr>
<td>$XL$ (Te)</td>
<td>3.336 – 4.82</td>
</tr>
<tr>
<td>$XK_{\alpha 2}$ (Te)</td>
<td>27.292</td>
</tr>
<tr>
<td>$XK_{\alpha 1}$ (Te)</td>
<td>27.4725</td>
</tr>
<tr>
<td>$XK_{\beta 3}$ (Te)</td>
<td>30.9446</td>
</tr>
<tr>
<td>$XK_{\beta 1}$ (Te)</td>
<td>30.996</td>
</tr>
<tr>
<td>$XK_{\beta 2}$ (Te)</td>
<td>31.236</td>
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<tr>
<td>$XK_{\beta 1}$ (Te)</td>
<td>31.241</td>
</tr>
<tr>
<td>$XK_{\beta 2}$ (Te)</td>
<td>31.708</td>
</tr>
<tr>
<td>$XK_{\beta 4}$ (Te)</td>
<td>31.774</td>
</tr>
<tr>
<td>$XKO_{2,3}$ (Te)</td>
<td>31.812</td>
</tr>
</tbody>
</table>

5.2 Gamma Emissions

<table>
<thead>
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<th>Photons per 100 disint.</th>
</tr>
</thead>
<tbody>
<tr>
<td>keV</td>
<td></td>
</tr>
<tr>
<td>$\gamma_{1,2}(Te)$</td>
<td>158.97 (5)</td>
</tr>
<tr>
<td>$\gamma_{1,3,10}(Te)$</td>
<td>174.2 (3)</td>
</tr>
</tbody>
</table>
Alpha Decay
Alpha Emission

- An alpha particle is a highly energetic helium nucleus consisting of two neutrons and 2 protons.
- It is normally emitted from isotopes when the neutron-to-proton ratio is too low – through the so-called alpha decay.
- Atomic number and atomic mass number are conserved in alpha decays.
Alpha Emission

- In heavy elements, a potential barrier of ~25MeV has to be overcome for an alpha particle to escape from the potential well.
- It would require a minimum kinetic energy of ~3.8MeV for the alpha particle to “tunneling through” the potential well is

![Diagram](image)

**Fig. 4.1.** Potential inside and in the vicinity of a nucleus.
Energy Spectra of Alpha Particles

Alpha decays are sometimes accompanied by the excited daughter products which complicates the resultant alpha particle spectra.

The kinetic energy of alpha particles generated is given by

$$E_{\alpha} = Q \cdot (A - 4) / A$$

Measured energy spectrum of alpha particles emitted from the decay of $^{238}\text{Pu}$. 

FIGURE 3.4. Nuclear decay scheme of $^{226}\text{Ra}$. 

226  
\[ ^{226} \text{Ra} \]  
4.785

4.785
94.4%

4.602
5.5%

0.186
3.3%

226  
\[ ^{226} \text{Ra} \]  
4.785

4.602
5.5%

0.186
3.3%

222  
\[ ^{222} \text{Rn} \]  
0
Energy Release in Alpha Emission

- The required kinetic energy has to come from the decrease in mass following the decay process.
- The relationship between mass and energy associated with an alpha emission is given as

\[ M_p = M_d + M_\alpha + 2M_e + Q, \]  

(4.1)

where \( M_p \), \( M_d \), \( M_\alpha \), and \( M_e \) are respectively equal to the masses of the parent, the daughter, the emitted alpha particle, and the two orbital electrons that are lost during the transition to the lower atomic numbered daughter, while \( Q \) is the total energy release associated with the radioactive transformation.
Energy Loss Mechanisms

**FIGURE 5.1.** (Top) Alpha-particle autoradiograph of rat bone after inhalation of $^{241}$Am. Biological preparation by R. Masse and N. Parmentier. (Bottom) Beta-particle autoradiograph of isolated rat-brain nucleus. The $^{14}$C-thymidine incorporated in the nucleolus is located at the track origin of the electron emitted by the tracer element. Biological preparation by M. Wintzerith and P. Mandel. (Courtesy R. Rechenmann and E. Wittendorp-Rechenmann, Laboratoire de Biophysique des Rayonnements et de Methodologie INSERM U.220, Strasbourg, France.)
Targeted Therapy – Basic Principles

β-Particle
Range: 800-5000 μm
LET: 0.8 keV/μm

α-Particle
Range: 40-90 μm
LET: 100 keV/μm

Fig. 5.3 Single-collision energy-loss spectra for 50-eV and 150-eV electrons and 1-MeV protons in liquid water. (Courtesy Oak Ridge National Laboratory, operated by Martin Marietta Energy Systems, Inc., for the Department of Energy.)
Alpha emitting isotopes for therapeutic applications in nuclear medicine

<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>Half-Life</th>
<th>Max. Particle Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>At-211</td>
<td>7.2 hrs</td>
<td>6.0 MeV</td>
</tr>
<tr>
<td>Bi-213</td>
<td>46 min</td>
<td>6.0 MeV</td>
</tr>
<tr>
<td>Ra-223</td>
<td>11.4 days</td>
<td>5.8 MeV</td>
</tr>
<tr>
<td>Ac-225</td>
<td>10.0 days</td>
<td>5.9 MeV</td>
</tr>
</tbody>
</table>

## Decay of Ra-223

<table>
<thead>
<tr>
<th>Decay Chain</th>
<th>Branching Ratio</th>
<th>Half-life</th>
<th>Alpha and Recoil Nuclei (MeV)</th>
<th>Beta and Auger Electrons (MeV)</th>
<th>Gamma and X-Rays (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ra-223</td>
<td></td>
<td>11.43 days</td>
<td>5.77</td>
<td>0.078</td>
<td>0.141</td>
</tr>
<tr>
<td>Rn-219</td>
<td>100%</td>
<td>3.96 s</td>
<td>6.88</td>
<td>0.007</td>
<td>0.059</td>
</tr>
<tr>
<td>Po-215</td>
<td>100%</td>
<td>1.78 ms</td>
<td>7.49</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>Pb-211</td>
<td>100%</td>
<td>36.10 min</td>
<td>-</td>
<td>0.454</td>
<td>0.064</td>
</tr>
<tr>
<td>Bi-211</td>
<td>100%</td>
<td>2.14 min</td>
<td>6.66</td>
<td>0.010</td>
<td>0.047</td>
</tr>
<tr>
<td>Tl-207</td>
<td>99.7%</td>
<td>4.77 min</td>
<td>-</td>
<td>0.494</td>
<td>0.002</td>
</tr>
<tr>
<td>Po-211</td>
<td>0.3%</td>
<td>0.52 s</td>
<td>7.61</td>
<td>0.000</td>
<td>0.008</td>
</tr>
</tbody>
</table>

Biodistribution of Ra-223

Original article
Quantitative imaging of $^{223}$Ra-chloride (Alpharadin) for targeted alpha-emitting radionuclide therapy of bone metastases
Cecilia Hindorf, Sarah Chittenden, Anne-Kirsti Aksnes, Chris Parker, and Glenn D. Flux

Graph showing counts vs. energy (keV) with time points at 4h, 48h, and 144h.

Images showing anterior and posterior views at each time point.
Dosimetry of bone metastases in targeted radionuclide therapy with alpha-emitting $^{223}$Ra-dichloride
Therapeutic Radiometals Beyond $^{177}$Lu and $^{90}$Y: Production and Application of Promising $\alpha$-Particle, $\beta^-$-Particle, and Auger Electron Emitters

Cristina Müller$^{1,2}$, Nicholas P. van der Meulen$^{1,3}$, Martina Benešová$^{1,2}$, and Roger Schibbi$^{1,2}$

$^1$Center for Radiopharmaceutical Sciences ETH-PSI-USZ, Paul Scherrer Institut, Villigen-PSA, Switzerland; $^2$Department of Chemistry and Applied Biosciences, ETH Zurich, Zurich, Switzerland; and $^3$Laboratory of Radiochemistry, Paul Scherrer Institut, Villigen-PSA, Switzerland

**TERBIUM-149**

$^{149}$Tb was first proposed for targeted $\alpha$-therapy by Allen and Blagojevic (41). Unlike most $\alpha$-emitters, it decays predominantly by the emission of a single low-energy $\alpha$-particle, positrons, and $\gamma$-radiation (Fig. 1A) (42). Beyer et al. chose the Nd(12C,5n)$^{149}$Dy $\rightarrow$ $^{149}$Tb production route at the European Organization for Nuclear Research (42). Later, $^{149}$Tb was produced by proton-induced spallation of a tantalum target followed by an online isotope separation process (37,42,43). In this scenario, $^{149}$Tb had to be separated from isobars and pseudoisobars with a mass of 149 using cation-exchange chromatography (37,42,43).

The first preclinical therapy study with $^{149}$Tb was performed in a mouse model of leukemia with $^{49}$Tb-labeled cyclohexane-DTPA–functionalized rituximab (43). This therapy resulted in the long-term survival of mice without evidence of recurrence 120 d after

---

**FIGURE 1.** (A) Decay of $^{149}$Tb to stable $^{149}$Sm, $^{145}$Nd, and $^{141}$Pr. EC = electron capture. (B) Maximum-intensity projection (MIP) of PET/CT image of AR42J tumor–bearing mouse 2 h after injection of $^{149}$Tb-DOTANOC (7 MBq). Bl = urinary bladder; Ki = kidney; Tu = tumor. (Adapted with permission of (45).)
Therapeutic Radiometals Beyond $^{177}$Lu and $^{90}$Y: Production and Application of Promising $\alpha$-Particle, $\beta^-$-Particle, and Auger Electron Emitters

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FIGURE 4. (A) $^{68}$Ga-PSMA-11 PET/CT scan of patient with pretherapeutic tumor spread. PSA = prostate-specific antigen. (B) Restaging 2 mo after third cycle of $^{225}$Ac-PSMA-617 (9–10 MBq). (C) Restaging 2 mo after single additional consolidation therapy (6 MBq). $^{177}$Lu-PSMA-617 was contraindicated because of diffuse red marrow infiltration. (Reproduced from (68)).

FIGURE 3. Decay of $^{225}$Ac to $^{213}$Bi and stable $^{209}$Bi.
X-Rays Sources
What Can We Learn from X-rays?

“The radiograph of Bera Rontgen’s hand”, taken 22 Dec. 1895

Wilhelm Conrad Röntgen,
The Nobel Prize in Physics 1901.

A brain image from the first prototype clinical CT imager, 1972.

Godfrey N. Hounsfield, The Nobel Prize in Physiology or Medicine 1979
X-ray Imaging Examples

Double mandibular fracture with strong displacement to the left.

Solitary humeral bone cyst known as "fallen leaf sign"
Sources of Electromagnetic Radiation – X-ray Emission Through Bremsstrahlung

- When fast electrons decelerated in the Coulomb field of a nucleus, part of its energy is converted into electromagnetic radiation in the form of Bremsstrahlung (a German word for “braking radiation”).
X-ray Generation – Bremmstrahlung

- Target nucleus positive charge \((Z\cdot p^+)\) attracts incident \(e^-\)
- Deceleration of an incident \(e^-\) occurs in the proximity of the target atom nucleus
- \(E\) lost by \(e^-\) is gained by the EM photon (x-ray) generated
  - The impact parameter distance, the closest approach to the nucleus by the \(e^-\) determines the amount of \(E\) loss
  - The Coulomb force of attraction varies strongly with distance \((\propto 1/r^2)\); ↓ distance → ↑ deceleration and \(E\) loss → ↑ photon \(E\)
  - Direct impact on the nucleus determines the maximum x-ray \(E\) \((E_{\text{max}})\)
Interestingly, this process creates a relatively uniform spectrum.

**Bremsstrahlung X-ray Energy Spectrum**

\[ \text{Intensity} = n \hbar \nu \]

Photon energy spectrum $\varepsilon_0$
The Unfiltered Bremsstrahlung Spectrum
Thick Target X-ray Formation

We can model target as a series of thin targets. Electrons successively loses energy as they moves deeper into the target.

Each layer produces a flat energy spectrum with decreasing peak energy level.
X-ray Generation – Characteristic X-rays

Hydrogen  $Z = 1$

Tungsten  $Z = 74$

Electron binding energy
X-ray Generation – Characteristic X-rays

• e\(^-\) of the target atom have a binding energy (BE) that depends on atomic Z (rem: \(BE_K \propto Z^2\)) and the shell (\(BE_K > BE_L > BE_M > \ldots\))

• When e\(^-(KE)\) incident on the target exceeds the target atom e\(^-(BE)\), it’s energetically possible for a collisional interaction to eject the bound electron and ionize the atom.

• What would happen then?
X-ray Generation – Characteristic X-rays

- Within each shell (other than K) there are discrete $E$ orbitals ($\ell = 0, 1, \ldots, n-1$) → characteristic x-ray fine $E$ splitting
- Characteristic x-rays other than those generated through K-shell transitions are unimportant

**TABLE 5-2. K-SHELL CHARACTERISTIC X-RAY ENERGIES (keV) OF COMMON X-RAY TUBE TARGET MATERIALS\(^a\)**

<table>
<thead>
<tr>
<th>Shell Transition</th>
<th>Tungsten</th>
<th>Molybdenum</th>
<th>Rhodium</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{\alpha 1}$</td>
<td>59.32</td>
<td>17.48</td>
<td>20.22</td>
</tr>
<tr>
<td>$K_{\alpha 2}$</td>
<td>57.98</td>
<td>17.37</td>
<td>20.07</td>
</tr>
<tr>
<td>$K_{\beta 1}$</td>
<td>67.24</td>
<td>19.61</td>
<td>22.72</td>
</tr>
</tbody>
</table>

\(^a\)Note: Only prominent transitions are listed.
### Physical Designs Considerations

**Typical micro-focus X-ray source**

**Rotating anode X-ray source**

(Left) Liquid metal jet anode
http://www.excillum.com/technology/metal-jet-technology.html
X-ray Generation – X-ray Tube

**Figure 5.3**
An x-ray tube.

**Figure 5.4**
Schematic diagram of an x-ray tube.

- Anode assembly
- Cathode assembly
- Filament circuit
- High voltage
- Stator
- Motor, Why?
- Rotating target
- Electron beam? How are electrons generated?
- X-rays
- Ground
- Filament

X-ray Generation – Characteristic X-rays

**Figure 5.5**
Relative intensity of x-ray photons. (Adapted from Webster, 1998. This material is used by permission of John Wiley & Sons, Inc.)

- **Bremstrahlung** (x-rays within anode)
- **Characteristic radiation**
- **Leaving tube**
- **Leaving anode**
- **After filter**
- **Leaving body**

*Beam hardening*

*Superimposed multiple flat spectrum with decreasing cutoff energy*

*Low energy X-rays suffer attenuation inside the anode*

*Further attenuation by the source package.*

*External filtering to reduce low E photons \(\rightarrow\) lower dose*
X-ray Computed Tomography (CT)

0.2 % attenuation change detectable in CT Images !!

**FIGURE 13-27.** The mathematical problem posed by computed tomographic (CT) reconstruction is to calculate image data (the pixel values—A, B, C, and D) from the projection values (arrows). For the simple image of four pixels shown here, algebra can be used to solve for the pixel values. With the six equations shown, using substitution of equations, the solution can be determined as illustrated. For the larger images of clinical CT, algebraic solutions become unfeasible, and filtered backprojection methods are used.
Example of Potential Problems Caused by the Imperfection of X-ray Sources – Beam Hardening
Beam hardening artifact occurs because the algorithm that reconstructs the image fails when faced with an interface between a high-density structure such as a metallic prosthesis or thick bone and surrounding soft tissue. The 'spray' or 'streak' artifact results. It can be seen in the posterior fossa in most CT brains.
Sources of Electromagnetic Radiation – Bremsstrahlung

• The bremsstrahlung spectrum can be altered by filtration.
• This is the underlying process for standard X-ray tubes.
Synchrotron Radiation
Sources of Electromagnetic Radiation
– Synchrotron Radiation

• Emitted when charged particles are accelerated (or decelerated) in a curved path or orbit.
• From visible light (a few eV) to X-ray energies (~10^4 eV).
• Very intense !!!
Synchrotron Radiation

Bending magnet  Undulator magnet


Covered in lecture
X-ray Generation – Bremmstrahlung

- Target nucleus positive charge \((Z \cdot p^+)\) attracts incident \(e^-\)
- Deceleration of an incident \(e^-\) occurs in the proximity of the target atom nucleus
- \(E\) lost by \(e^-\) is gained by the EM photon (x-ray) generated
  - The impact parameter distance, the closest approach to the nucleus by the \(e^-\) determines the amount of \(E\) loss
  - The Coulomb force of attraction varies strongly with distance \((\propto 1/r^2); \downarrow\) distance \(\rightarrow \uparrow\) deceleration and \(E\) loss \(\rightarrow \uparrow\) photon \(E\)
  - Direct impact on the nucleus determines the maximum x-ray \(E\) \((E_{\text{max}})\)

Covered in lecture
Sources of Electromagnetic Radiation – Selection of X-rays of a Single Energy

A typical monochromator setup

Covered in lecture
Sources of Electromagnetic Radiation
– Synchrotron Radiation

European Synchrotron Radiation Facility

Circumference
844 m

"booster"
synchrotron
6 GeV

linear accelerator
200 MeV

storage ring

ID 18

Advanced Photon Source (APS)

From http://www-hasylab.desy.de/science/groups/schneider_group/misc/RR-Lecture-1.pdf

NPRE 435, Radiological Imaging, Fall 2021
Radiation Sources and Interactions
• Stunning imaging resolution at the order down to a few tens of nm
• Reveal interesting physical properties of the object, X-ray fluorescence, diffraction–enhanced imaging

Covered in lecture