Physics 736

Experimental Methods in Nuclear-, Particle-, and Astrophysics

- Interaction of Radiation with Matter -

Karsten Heeger
heeger@wisc.edu
# Class Schedule & Course Website

**Course website**


<table>
<thead>
<tr>
<th>Week#</th>
<th>Day</th>
<th>Date</th>
<th>Topics</th>
<th>References for this Class</th>
<th>Homework &amp; Required Reading for Next Class</th>
<th>Slides</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>Wed Jan 23, 2013</td>
<td><strong>Course Introduction</strong> - organization, syllabus, textbooks</td>
<td>PDG, common radioactive sources</td>
<td>PDG, detectors for non-accelerator physics</td>
<td>lect1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>Radiation and Matter:</strong> - nuclear processes, radiation sources and radioactivity</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>Mon Jan 28, 2013</td>
<td><strong>Radiation and Matter:</strong> - nuclear processes, radiation sources and radioactivity</td>
<td>Leo, chapter 1&amp;2</td>
<td>PDG, interaction with matter</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>PDG, interaction with matter</td>
<td>PDG, radioactivity</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Wed Jan 30, 2013</td>
<td><strong>Interaction of Radiation with Matter:</strong> - neutrons, photons</td>
<td>Leo, chapter 1&amp;2</td>
<td>HW#1 due Feb 6</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>PDG, interaction with matter</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>PDG, radioactivity</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Reading

• Particle Detectors for Non-Accelerator Physics

  • particle interaction/detection
    – what is the most interesting method you saw?

  • detectors?
    – biggest detector?
    – most interesting detector medium?

• radioactivity and nuclear decay
  – why do we care?
Lecture Goals

• basic nuclear processes

• radiation sources
  – how to calculate activities
  – activation

• passage of radiation through matter
  – neutrons
  – photons
  – (charged particles)
Nuclear Processes and Radiation Sources

• **basic nuclear processes**
  – alpha decay
  – beta decay
  – electron capture
  – annihilation radiation
  – internal conversion
  – γ emission of nucleus, X-rays
  – Auger electrons
  – neutron sources
    • fission
    • nuclear reactions

• **radiation sources**
  – source encapsulation (thick vs thin)
  – energy of source radiation (continuous, monoenergetic, degradation)
  – backgrounds from radiation sources (e.g. gamma)
Review of Last Lecture

Internal Conversion?
Auger Electron?
X-Ray?
Review of Last Lecture

A

Auger

B

Internal conversion

C

X-ray
What process is shown in this energy spectrum?
Beta-Spectrum and Internal Conversion

$^{203}$Hg, which decays to $^{203}$Tl by beta emission, leaving the $^{203}$Tl in an electromagnetically excited state.

- can proceed to the ground state by emitting a 279.190 keV gamma ray, or by internal conversion. In this case the internal conversion is more probable.

- internal conversion process can interact with any of the orbital electrons, the result is a spectrum of internal conversion electrons which will be seen as superimposed upon the electron energy spectrum of the beta emission.

- Energy yield of this electromagnetic transition: 279.190 keV => ejected electrons will have that energy minus their binding energy in the $^{203}$Tl daughter atom.

Electron emissions from the Hg-203 to Tl-203 decay, measured by A. H. Wapstra, et al., Physica 20, 169 (1954)
<table>
<thead>
<tr>
<th>name</th>
<th>reaction</th>
<th>energy spectrum</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta^-$</td>
<td>$(A, Z) \rightarrow (A, Z + 1)e^- \bar{\nu}_e$</td>
<td>continuous</td>
</tr>
<tr>
<td>$\beta^+$</td>
<td>$(A, Z) \rightarrow (A, Z - 1)e^+ \nu_e$</td>
<td>continuous</td>
</tr>
<tr>
<td>$\epsilon^-$-capture</td>
<td>$e^- (A, Z) \rightarrow (A, Z - 1)\nu_e$ + atomic X-rays/Auger e$^-$/s</td>
<td>discrete</td>
</tr>
<tr>
<td>$2\beta$</td>
<td>$(A, Z) \rightarrow (A, Z \pm 2)2e^\pm 2\bar{\nu}_e(2\nu_e)$</td>
<td>continuous</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>$(A, Z) \rightarrow (A - 4, Z - 2)^4\text{He}$</td>
<td>discrete</td>
</tr>
<tr>
<td>fission</td>
<td>$(A, Z) \rightarrow (A_1, Z_1)(A_2, Z_2)$ (+neutrons)</td>
<td>continuous</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>$(A, Z)^* \rightarrow (A, Z)\gamma$</td>
<td>discrete</td>
</tr>
<tr>
<td>Internal conversion</td>
<td>$e^- (A, Z)^* \rightarrow (A, Z)e^-$ + atomic X-rays/Auger e$^-$/s</td>
<td>discrete</td>
</tr>
</tbody>
</table>
Review of Last Lecture

• Name a common neutron source!
Review of Last Lecture

• Name a common neutron source!
  – AmBe

• Name a common positron source!
Review of Last Lecture

• Name a common neutron source!
  – AmBe

• Name a common positron source!
  – Na-22
Source Activity Units

• source activity = \# of decay processes

• activity ≠ dose
Radioactivity

- **natural**
  - fossil
  - cosmogenic

- **artificial/man-made**
  - nuclear laboratories/accelerators
  - in reactors (fusion, fission)
### Nuclei with $10^8$ yr $< T_{1/2} < 10^{12}$ yr

<table>
<thead>
<tr>
<th>Decay</th>
<th>Half-life (years)</th>
<th>Isotopic abundance (percent)</th>
<th>Activity (Bq kg$^{-1}$) (element)</th>
<th>Activity (Bq kg$^{-1}$) (crust)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{40}$K $\rightarrow$ $^{40}$Ca $e^- \bar{\nu}_e$ $\pm 89%$  $^{40}$Ar $\nu_e$  $\pm 11%$</td>
<td>$1.28 \times 10^9$</td>
<td>0.0117</td>
<td>$3.0 \times 10^4$</td>
<td>$6.3 \times 10^2$</td>
</tr>
<tr>
<td>$^{87}$Rb $\rightarrow$ $^{87}$Sr $e^- \bar{\nu}_e$</td>
<td>$4.75 \times 10^{10}$</td>
<td>27.83</td>
<td>$8.8 \times 10^5$</td>
<td>$8.0 \times 10^1$</td>
</tr>
<tr>
<td>$^{146}$Sm $\rightarrow$ $^{142}$Nd $\alpha$</td>
<td>$1.03 \times 10^8$</td>
<td>$&lt; 10^{-7}$</td>
<td>$&lt; 1$</td>
<td>$&lt; 10^{-4}$</td>
</tr>
<tr>
<td>$^{147}$Sm $\rightarrow$ $^{143}$Nd $\alpha$</td>
<td>$1.06 \times 10^{11}$</td>
<td>15.1</td>
<td>$1.3 \times 10^5$</td>
<td>$9 \times 10^{-1}$</td>
</tr>
<tr>
<td>$^{176}$Lu $\rightarrow$ $^{176}$Hf $e^-$</td>
<td>$3.78 \times 10^{10}$</td>
<td>2.61</td>
<td>$5.5 \times 10^4$</td>
<td>$4 \times 10^{-2}$</td>
</tr>
<tr>
<td>$^{187}$Re $\rightarrow$ $^{187}$Os $e^- \bar{\nu}_e$</td>
<td>$4.15 \times 10^{10}$</td>
<td>62.6</td>
<td>$1.1 \times 10^6$</td>
<td>$8 \times 10^{-4}$</td>
</tr>
<tr>
<td>$^{232}$Th $\rightarrow$ $^{228}$Ra $\alpha$</td>
<td>$1.405 \times 10^{10}$</td>
<td>100</td>
<td>$4.05 \times 10^6$</td>
<td>$3.5 \times 10^2$</td>
</tr>
<tr>
<td>$^{235}$U $\rightarrow$ $^{231}$Th $\alpha$</td>
<td>$7.038 \times 10^8$</td>
<td>0.72</td>
<td>$5.7 \times 10^5$</td>
<td>$1.7 \times 10^1$</td>
</tr>
<tr>
<td>$^{238}$U $\rightarrow$ $^{234}$Th $\alpha$</td>
<td>$4.468 \times 10^9$</td>
<td>99.275</td>
<td>$1.2 \times 10^7$</td>
<td>$4.7 \times 10^2$</td>
</tr>
</tbody>
</table>

Isotopic abundance is terrestrial mix.
$^{40}$K

- EC (10.5%)
  - $Q_{ec} = 0.95$ MeV

- $E_\gamma = 1.46$ MeV

- EC (0.2%)
  - $Q_{ec} = 1.505$

- $\beta^-$ (89.3%)
  - $Q = 1.31$ MeV

- $0^+$
  - $^{40}$Ca

- $2^+$
  - $^{40}$Ar
# Natural Radioactivity Chains

3 chains of natural radioactivity

<table>
<thead>
<tr>
<th>Uranium Series</th>
<th>Actinium Series</th>
<th>Thorium Series</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{238}U_{92}$ 4.468 Gyr</td>
<td>$^{235}U_{92}$ 0.7038 Gyr</td>
<td>$^{232}Th_{90}$ 14.05 Gyr</td>
</tr>
<tr>
<td>$^{234}Th_{90}$ 24.10 d</td>
<td>$^{231}Th_{90}$ 25.52 h</td>
<td>$^{228}Ra_{88}$ 5.75 y</td>
</tr>
<tr>
<td>$^{234}Pa_{91}$ 1.17 m</td>
<td>$^{231}Pa_{91}$ 32760 y</td>
<td>$^{228}Ac_{89}$ 6.15 h</td>
</tr>
<tr>
<td>$^{234}U_{92}$ 245.5 kyr</td>
<td>$^{227}Ac_{89}$ 21.773 y</td>
<td>$^{228}Th_{90}$ 1.9116 y</td>
</tr>
<tr>
<td>$^{230}Th_{90}$ 75.38 kyr</td>
<td>$^{227}Th_{90}$ 18.72 d</td>
<td>$^{224}Ra_{88}$ 3.66 d</td>
</tr>
<tr>
<td>$^{226}Ra_{88}$ 1600 y</td>
<td>$^{219}Ra_{88}$ 11.435 d</td>
<td>$^{220}Rn_{86}$ 55.6 s</td>
</tr>
<tr>
<td>$^{222}Rn_{86}$ 3.8235 d</td>
<td>$^{215}Rn_{86}$ 3.96 s</td>
<td>$^{216}Po_{84}$ 0.145 s</td>
</tr>
<tr>
<td>$^{218}Po_{84}$ 3.10 m</td>
<td>$^{211}Po_{84}$ 1.781 ms</td>
<td>$^{212}Pb_{82}$ 10.64 h</td>
</tr>
<tr>
<td>$^{214}Pb_{82}$ 26.8 m</td>
<td>$^{211}Pb_{82}$ 36.1 m</td>
<td>$^{212}Bi_{83}$ 60.55 m</td>
</tr>
<tr>
<td>$^{214}Bi_{83}$ 19.9 m</td>
<td>$^{211}Bi_{83}$ 2.14 m</td>
<td>$^{207}Tl_{81}$ 4.77 m</td>
</tr>
<tr>
<td>$^{210}Pb_{82}$ 22.3 y</td>
<td>$^{207}Pb_{82}$ &gt; 10$^{20}$ yr</td>
<td>64% $^{212}Po_{84}$ 0.299 μs</td>
</tr>
<tr>
<td>$^{210}Bi_{83}$ 5.013 d</td>
<td>$^{207}Pb_{82}$ &gt; 10$^{20}$ yr</td>
<td>36% $^{208}Tl_{81}$ 3.053 m</td>
</tr>
<tr>
<td>$^{210}Po_{84}$ 138.376 d</td>
<td>$^{208}Pb_{82}$ &gt; 10$^{20}$ yr</td>
<td></td>
</tr>
</tbody>
</table>
Flux of Cosmic Radiation

peaked at ~ 300 MeV

falling like $E^{-3}$

outside Earth's atmosphere
Cosmic-Ray Induced Showers

Fluxes as a function of depth

Earth surface

Fluxes (vertical flux in m^2 s^-1 sr^-1 vs. atmospheric depth in g cm^-2)

- p, n
- $\nu_\mu, \bar{\nu}_\mu$
- $\mu^\pm$
- $e^\pm$
- $\pi^\pm$
Production of Artificial Radioactivity

ISOL
- primary beam
- thick target
- ion source
- mass, charge separator
- ion trap/source
- post accelerator
- secondary target

In-Flight
- primary beam
- thin target
- nuclei emerging from target can be mass selected
- storage—cooler ring
Radioactive Decay
Poisson Distribution

Poisson Distribution PDF

Random Variable

Probability

λ=1
λ=10
λ=50
Poisson Distribution

\[ \mu = 0.5 \]

\[ \mu = 1 \]

\[ \mu = 4 \]

\[ \mu = 10 \]
Radioactive Decay Chains

- a) transient equilibrium
- b) secular equilibrium

Fig: Leo
Radioactive Decays

- Question
  - which half-live dominates?
  - what would you measure?

\[ ^{90}\text{Sr} \xrightarrow{\beta^-} ^{90}\text{Y} \xrightarrow{\beta^-} ^{90}\text{Zr} \]

- Dominance of half-life 28 yrs (Sr) and 64.8 hrs (Y) leads to measurement of long-lived Sr content.
Table of Isotopes

![Table of the Isotopes](http://ie.lbl.gov/)

---

**Primary Decay Modes**
- Stable
- Electron Capture
- Neutron Decay
- Beta Decay
- Alpha Decay
- Proton Decay
- Isomer Transfer
- Other

---

Karsten Heeger, Univ. of Wisconsin

Physics 736, Spring 2013
- Passage of Particles & Radiation Through Matter -
Interaction of Particles & Radiation with Matter

- neutrons
  - ....

- photons
  - ....

- charged particles
  - ......
Interaction of Particles & Radiation with Matter

- neutrons
  - elastic scattering $A(n,n)A$
  - inelastic scattering $A(n,n')A^*, A(n,2n')B$
  - radiative n capture
  - n captures
  - fissions $(n,f)$
  - hadron shower production at high E

- photons
  - ......

- charged particles
  - ......
Interaction of Particles\&Radiation with Matter

• neutrons
  – ..... 

• photons
  – photoelectric effect 
  – Compton scattering 
  – pair production 
  – nuclear photo dissociation ($\gamma,n$) 

• charged particles
  – .....
Interaction of Particles & Radiation with Matter

- neutrons
  - .......
- photons
  - .......
- charged particles
  - inelastic collisions w/ atomic e-
  - elastic scattering
  - Cherenkov radiation
  - nuclear reactions
  - Brehmsstrahlung
Interaction of Particles & Radiation with Matter

- What is more penetrating?
  - X-rays, γ-rays or
  - charged particles?

  - and what about neutrons?