Physics 736

Experimental Methods in Nuclear-, Particle-, and Astrophysics

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Course Goals

• **What are your fields of interest?**
  
  – high-energy?
  – astro/cosmology?
  – neutrino?

  – experiment?
  – theory?
Course Goals

• What do you hope to get out of the course? What are your expectations for Phys 736?
Course Goals

• What do you hope to get out of the course? What are your expectations for Phys 736?
  – take 2 min to write down some personal goals on piece of paper
  – what would you like to learn?
  – can be general or specific
Course Goals

• **My course goals:**

  – provide overview of experimental techniques used in nuclear, particle, and astrophysics
  – develop understanding of detectors and experimental techniques
  – provide the tools and basic to start research: hardware, statistics, analysis etc
  – convey basic statistical techniques and error analysis
  – make you appreciate what goes into a detector design

  – you will learn as much as you put into this course
Course Goals & Feedback

• Feedback and suggestions often and early. Don’t wait until the end of the semester. This would be a waste of everyone’s time.

• Suggestions welcome:
  – topics you are interested in, would like to see covered
  – your input will help shape this class

• For undergraduate classes I usually have an anonymous comment box in classroom. Hope that this is not necessary.
Reading

- Reading will be assigned in preparation for lectures and to provide more details and depth than I can cover.

- It is a chance for you to “explore” a topic.

- We will discuss reading material in class.

- I may ask someone to summarize a paper or topic that was assigned for reading, or lead a discussion. It will be a discussion.
Homework, Projects, Exams

• homework and course reading will be assigned on a roughly biweekly basis

• no final exam, but final project

• you will get time to work on final project

• we will get together as a course for a couple of afternoons during last week of semester to hear presentations
Computational Tools

• Some homework problems and the final project may require some computational work.

• Tools I can recommend and am familiar with
  – ROOT
  – Mathematica
  – C/C++

• You can choose the tool you want or that is used in your research area of interest.
Grades

• We need to give grades but you shouldn’t worry about them. They should not be a concern at this point. This is graduate school and you are getting ready for research.

• Grades will be based on:
  – participation in class (~30%)
  – homework (~30%)
  – final project (~40%)
Course Schedule

- Approximate schedule of topics

<table>
<thead>
<tr>
<th>Date</th>
<th>Day</th>
<th>Week</th>
<th>HW</th>
<th>reading</th>
<th>lecture</th>
<th>Topic</th>
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<tr>
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<td>Wed</td>
<td>1</td>
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<td>01-Mar-10</td>
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<td>03-Mar-10</td>
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<td>due</td>
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<td>08-Mar-10</td>
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<td>simulation, numerical techniques, Monte Carlo</td>
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<td>15-Mar-10</td>
<td>Mon</td>
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<td>16</td>
<td>simulation, numerical techniques, Monte Carlo</td>
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<td>17-Mar-10</td>
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<td>due</td>
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<td>error analysis</td>
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<td>22-Mar-10</td>
<td>Mon</td>
<td>10</td>
<td>18</td>
<td>error analysis</td>
<td></td>
<td></td>
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<tr>
<td>24-Mar-10</td>
<td>Wed</td>
<td>10</td>
<td>assigned</td>
<td>19</td>
<td>error analysis</td>
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</tr>
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<td>29-Mar-10</td>
<td>Mon</td>
<td>11</td>
<td>spring recess</td>
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<td></td>
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<td>31-Mar-10</td>
<td>Wed</td>
<td>11</td>
<td>spring recess</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>05-Apr-10</td>
<td>Mon</td>
<td>12</td>
<td>20</td>
<td>statistical techniques</td>
<td></td>
<td></td>
</tr>
<tr>
<td>07-Apr-10</td>
<td>Wed</td>
<td>12</td>
<td>due</td>
<td>21</td>
<td>statistical techniques</td>
<td></td>
</tr>
<tr>
<td>12-Apr-10</td>
<td>Mon</td>
<td>13</td>
<td>22</td>
<td>statistical techniques</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14-Apr-10</td>
<td>Wed</td>
<td>13</td>
<td>assigned</td>
<td>23</td>
<td>statistical techniques</td>
<td></td>
</tr>
<tr>
<td>19-Apr-10</td>
<td>Mon</td>
<td>14</td>
<td>24</td>
<td>detectors and experiments</td>
<td></td>
<td></td>
</tr>
<tr>
<td>21-Apr-10</td>
<td>Wed</td>
<td>14</td>
<td>due</td>
<td>25</td>
<td>detectors and experiments</td>
<td></td>
</tr>
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<td>26-Apr-10</td>
<td>Mon</td>
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<td>detectors and experiments</td>
<td></td>
<td></td>
</tr>
<tr>
<td>28-Apr-10</td>
<td>Wed</td>
<td>15</td>
<td>27</td>
<td>detectors and experiments</td>
<td></td>
<td></td>
</tr>
<tr>
<td>03-May-10</td>
<td>Mon</td>
<td>16</td>
<td>28</td>
<td>project presentations</td>
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<td></td>
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<tr>
<td>05-May-10</td>
<td>Wed</td>
<td>16</td>
<td>29</td>
<td>project presentations</td>
<td></td>
<td></td>
</tr>
<tr>
<td>07-May-10</td>
<td>Fri</td>
<td>16</td>
<td>last day of class</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

will be updated throughout the semester
Textbooks

• There is no one, single good textbook for this course. We will use chapters from a variety of books.

• Scanned PDFs of chapters will be available to registered course participants.

• Supplemental course material will be posted on website.

• All textbooks are available in the library.
Textbooks

• **Detectors:**
  – **Knoll:** good reference book for experimentalist, a little word, good coverage of most topic, not quite in enough depth, focus on hardware and measurements
  – **Leo:** similar to Knoll, shorter, not quite the same coverage, not quite as advanced
  – **Green:** theory, hardware, and design of particle physics detectors, relatively recent, published in 2000
  – **Longair:** high energy astrophysics, theory and detectors
  – **Pobell, Enss:** Low temperature detectors and physics

• **Statistics/Error Analysis**
  – **Bevington:** the standard in error analysis
  – **Barlow:** good intro into statistics
  – **James:** more on statistical techniques

• **Reference**
  – **Particle Data Group:** good review articles, concise and dense
Course Website

- All materials will be posted on website, except for handwritten lecture notes.

- There will be three websites:
  - Resource page on my website with syllabus, schedule, lecture PDFs, reading material, links, etc.
  - Password protected library reserve page for use of copyright protected material in course. Only access with NetID.
  - Jump page on department website.
Physics 736

Interaction of Radiation and Particles with Matter

- Basic nuclear processes and radiation sources -
• What are we interested in measuring?
Particles & Radiation

• What are we interested in measuring?

  – Charged particle radiation
    • fast electrons
    • heavy charged particles

  – Uncharged particles and radiation
    • electromagnetic radiation
    • neutrons
    • neutrinos
    • WIMPS?
## Radioactivity

<table>
<thead>
<tr>
<th>Name</th>
<th>Reaction</th>
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</thead>
<tbody>
<tr>
<td>$\beta^-$</td>
<td>$(A, Z) \rightarrow (A, Z + 1)e^- \bar{\nu}_e$</td>
</tr>
<tr>
<td>$\beta^+$</td>
<td>$(A, Z) \rightarrow (A, Z - 1)e^+ \nu_e$</td>
</tr>
<tr>
<td>$e^-$-capture</td>
<td>$e^- (A, Z) \rightarrow (A, Z - 1)\nu_e$</td>
</tr>
<tr>
<td></td>
<td>$+$ atomic X-rays/Auger $e^-$'s</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>
</tr>
<tr>
<td>$\alpha$</td>
<td>$(A, Z) \rightarrow (A - 4, Z - 2)^4\text{He}$</td>
</tr>
<tr>
<td>Fission</td>
<td>$(A, Z) \rightarrow (A_1, Z_1) (A_2, Z_2) (+\text{neutrons})$</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>$(A, Z)^* \rightarrow (A, Z)\gamma$</td>
</tr>
<tr>
<td>Internal conversion</td>
<td>$e^- (A, Z)^* \rightarrow (A, Z)e^-$</td>
</tr>
<tr>
<td></td>
<td>$+$ atomic X-rays/Auger $e^-$'s</td>
</tr>
</tbody>
</table>
## Radioactivity

<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>$e^-$-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>
Alpha Decay

\[ ^{240}_{94}\text{Pu} \rightarrow ^{236}_{92}\text{U} + \alpha \text{- particle = } ^{4}_{2}\text{He} \]

\[ ^{212}_{82}\text{Bi} \]

\[ ^{209}_{82}\text{Tl} \]

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**Alpha Decay**

![Diagram of alpha decay](image1)

\[ V(r) = \frac{2(Z-2)e^2}{4\pi\varepsilon_0 r} \]

**Gamow 1928**

- Instability

**Table 1.2. Characteristics of some alpha emitters**

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Half-life</th>
<th>Energies [MeV]</th>
<th>Branching</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{241}\text{Am})</td>
<td>433 yrs.</td>
<td>5.486, 5.443</td>
<td>85%, 12.8%</td>
</tr>
<tr>
<td>(^{210}\text{Po})</td>
<td>138 days</td>
<td>5.305</td>
<td>100%</td>
</tr>
<tr>
<td>(^{242}\text{Cm})</td>
<td>163 days</td>
<td>6.113, 6.070</td>
<td>74%, 26%</td>
</tr>
</tbody>
</table>

**Text**

Because of its double charge, +2e, alpha particles have a very high rate of energy loss in matter. The range of an alpha particle in air is only a few centimeters, for example. For this reason, it is necessary to make the source as thin as possible in order to minimize energy loss and particle absorption. Most sources are made, in fact, by depositing the isotope on the surface of a suitable backing material and protecting it with an extremely thin layer of metal foil.
Beta-decay

Positron energy spectrum from beta decay of $^{64}$Cu

Q of the reaction $= 0.653$ MeV

Table 1.3. List of pure $\beta^-$ emitters

<table>
<thead>
<tr>
<th>Source</th>
<th>Half-life</th>
<th>$E_{\text{max}}$ [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{34}$H</td>
<td>12.26 yr</td>
<td>0.0186</td>
</tr>
<tr>
<td>$^{35}$Cl</td>
<td>5730 yr</td>
<td>0.156</td>
</tr>
<tr>
<td>$^{35}$P</td>
<td>14.28 d</td>
<td>1.710</td>
</tr>
<tr>
<td>$^{35}$P</td>
<td>24.4 d</td>
<td>0.248</td>
</tr>
<tr>
<td>$^{35}$S</td>
<td>87.9 d</td>
<td>0.167</td>
</tr>
<tr>
<td>$^{36}$Cl</td>
<td>$3.08 \times 10^5$ yr</td>
<td>0.714</td>
</tr>
<tr>
<td>$^{43}$Ca</td>
<td>165 d</td>
<td>0.252</td>
</tr>
<tr>
<td>$^{57}$Ni</td>
<td>92 yr</td>
<td>0.067</td>
</tr>
<tr>
<td>$^{90}$Sr/$^{90}$Y</td>
<td>$27.7$ yr/$64$ h</td>
<td>0.546/2.27</td>
</tr>
<tr>
<td>$^{99}$Tc</td>
<td>$2.12 \times 10^5$ yr</td>
<td>0.292</td>
</tr>
<tr>
<td>$^{147}$Pm</td>
<td>2.62 yr</td>
<td>0.224</td>
</tr>
<tr>
<td>$^{208}$Tl</td>
<td>3.81 yr</td>
<td>0.766</td>
</tr>
</tbody>
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Electron Capture

Auger electron
Annihilation Radiation

![Graph of annihilation radiation spectrum](image)

- **22Na**
- **ANNIHILATION PEAK**
  - 0.511 MeV
  - 1.27 MeV

**Pulse height** vs **intensity** graph showing the annihilation peak at 0.511 MeV and another peak at 1.27 MeV.
Internal Conversion

looks like 2-step process classically

-> single quantum process, amplitude can be calculated with perturbation theory
Internal Conversion Process:

- information from the internal conversion electrons about the binding energies of the electrons in the daughter atom

- relative intensities of these internal conversion electron peaks can give information about the electric multipole character of the nucleus.
Beta-Spectrum and Internal Conversion

- $^{203}\text{Hg}$, which decays to $^{203}\text{Tl}$ by beta emission, leaving the $^{203}\text{Tl}$ 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 $^{203}\text{Tl}$ daughter atom.

Electron emissions from the Hg-203 to Tl-203 decay, measured by A. H. Wapstra, et al., Physica 20, 169 (1954)
Auger Electrons

- proton
- K-shell electron
- L-shell electron
- M- or outer-shell electron

2.5MeV protons

"Auger electron"

Auger Process

X-Ray Process

Fermi level
L_{2,3}
L_1
K
Core Hole
Core Hole
Neutron Sources

- spontaneous fission
- nuclear reactions