Final Exam
- Mon, Dec 15, at 10:05am-12:05 pm, 2103 Chamberlin
- 3 equation sheets allowed
- About 30% on new material
- Rest on topics of exam1, exam2, exam3.

Study Tips:
Download blank exams and take them.
Download blank quizzes and take them.
Look through group problems.
Look through lab question sheets.

Physics 208 Exit survey
- Please take web exit survey
- Link on course web site
- Also will receive an email.
- Helps us to understand what was effective (and ineffective!) in the course.

Radioactive nuclei
- Equal # neutrons and protons

Radioactive decay
- Unstable nuclei decay by emitting particle
- Can be photon (light particle), or matter particle.
- Emitted particle carries away energy
  - Can strip electrons from atoms (ionizing radiation)
  - Break apart chemical bonds in living cells (radiation damage)

Biological effects of radiation
- Radiation damage depends on
  - Energy deposited / tissue mass (1 Gy (gray) = 1 J/kg)
  - Damaging effect of particle (RBE, relative biological effectiveness)

<table>
<thead>
<tr>
<th>Radiation type</th>
<th>RBE</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-rays</td>
<td>1</td>
</tr>
<tr>
<td>Gamma rays</td>
<td>1</td>
</tr>
<tr>
<td>Beta particles</td>
<td>1-2</td>
</tr>
<tr>
<td>Alpha particles</td>
<td>10-20</td>
</tr>
</tbody>
</table>

- Dose equivalent = (Energy deposited / tissue mass) x RBE
  - Units of Sv (sieverts) [older unit = rem, 1 rem = 0.01 Sv]
  - Common units mSv (10^{-3} Sv), mrem (10^{-3} rem)
  - Common "safe" limit = 500 mrem/yr = 5 mSv/yr

Radioactive tracers
- Worked on radioactivity as student with Ernest Rutherford.
- Lodged in nearby boarding home.
- Suspected his landlady was serving meals later in week "recycled" from the Sunday meat pie.
- His landlady denied this!
- deHevesy described his first foray into nuclear medicine:

  "The coming Sunday in an unguarded moment I added some radioactive deposit [lead-212] to the freshly prepared pie and on the following Wednesday, with the aid of an electroscope, I demonstrated to the landlady the presence of the active deposit in the soufflé."
A random process

- Radioactive decay is a random process
  - It has some probability of occurring.
- For one nucleus,
  - \( \text{Prob}(\text{decay in } \Delta t) = r \Delta t \)
  - \( r = \text{decay rate} \)
- For \( N \) nuclei,
  - \# decays \( \Delta N = N \times \text{Prob}(\text{decay}) = rN \Delta t \)
  - \# decays / s = \( \frac{\Delta N}{\Delta t} = rN \)
  \[ N = N_0 e^{-rt} \]

Radioactive half-life

- Example of random decay.
- Start with 8,000 identical radioactive nuclei
- After one half-life, half the nuclei have decayed.

Radioactive decay question

A piece of radioactive material is initially observed to have 10,000 radioactive nuclei.
3 hours later, you measure 1,250 radioactive nuclei.
The half-life is

A. ½ hour  
B. 1 hour  
C. 3 hours  
D. 8 hours  

Quantifying radioactivity

- Decay rate \( r \) (\text{Units of s}^{-1})
- \( \text{Prob}(\text{nucleus decays in time } \Delta t) = r \Delta t \)
- Activity \( R \) (\text{Units of becquerel (1 Bq=1 s}^{-1}) \) or curie (1 Ci=3.7x10^{10} \text{ s}^{-1})
  - Mean \# decays / s = \( rN \), \( N=\# \text{nuclei in sample} \)
- Half-life \( t_{\frac{1}{2}} \) (\text{Units of s})
  - time for half of nuclei to decay = \( t_{\frac{1}{2}} = \frac{\ln 2}{r} \approx 0.693 \)
  \[ N = N_0 e^{-rt} \]

Different types of radioactivity

- Three different types of decay observed:
  - Alpha decay
  - Beta decay
  - Gamma decay
  (First three letters of Greek alphabet).

Ernest Rutherford (1899): "These experiments show that the uranium radiation is complex and that there are present at least two distinct types of radiation - one that is very readily absorbed, which will be termed for convenience the alpha-radiation, and the other of more penetrative character which will be termed the beta-radiation."
Heavy nucleus spontaneously emits alpha particle

- nucleus loses 2 neutrons and 2 protons.
- It becomes a different element (Z is changed).
- Example:

\[ ^{238}\text{U} \rightarrow ^{234}\text{Th} + ^{4}\text{He} \]

92 protons
2 neutrons
90 protons
2 neutrons

Example of α decay

Radon

- Radon is in the 238U decay series
- Radon is an α emitter that presents an environmental hazard
- Inhalation of radon and its daughters can ionize lung cells increasing risk of lung cancer

http://www.radonwisconsin.com/

Activity of Radon

- 222Rn has a half-life of 3.83 days.
- Suppose your basement has \( 4.0 \times 10^8 \) such nuclei in the air. What is the activity?

We are trying to find number of decays/sec.

So we have to know decay constant to get \( R = rN \)

\[
R = \frac{\ln 2}{\tau} \cdot \frac{1}{3.83 \text{days} \times 86,400 \text{s/day}} = 2.09 \times 10^{-7} \text{s}^{-1}
\]

\[
R = \frac{\delta N}{\delta t} = rN = 2.09 \times 10^{-7} \text{s} \times 4.0 \times 10^8 \text{nuclei} = 836 \text{decays/s}
\]

\[
R = 836 \text{ decays/s} \times \frac{1 \text{Ci}}{2.7 \times 10^{10} \text{ decays/s}} = 0.023 \mu\text{Ci}
\]

Beta decay

- Number of neutrons decreases by one
- Number of protons increases by one
- Electron (beta particle) emitted

But nucleus has only neutrons & protons.
**Beta decay**

- Nucleus emits an electron (negative charge)
- Must be balanced by a positive charge appearing in the nucleus.

This occurs as a neutron changing into a proton

**Changing particles**

Neutron made up of quarks.
One of the down quarks changed to an up quark.
New combination of quarks is a proton.

**beta decay example**

\[
\begin{align*}
14^6\text{C} & \rightarrow 14^7\text{N} + e^- \\
\{8\text{ neutrons} \} & \rightarrow \{7\text{ neutrons} \} \\
\{6\text{ protons} \} & \rightarrow \{7\text{ protons} \} \\
14\text{ nucleons} & \rightarrow 14\text{ nucleons} + 1\text{ electron} \\
6\text{ positive} & \rightarrow 7\text{ positive} \\
\text{charges} & \rightarrow \text{charges} + 1\text{ negative charge}
\end{align*}
\]

Used in radioactive carbon dating.
Half-life 5,730 years.

**Radiocarbon dating**

- $^{14}$C has a half-life of ~6,000 years, continually decaying back into $^{14}$N.
- Steady-state achieved in atmosphere, with $^{14}$C:$^{12}$C ratio ~ 1:1 trillion (1 part in $10^{12}$)

As long as biological material alive, atmospheric carbon mix ingested (as CO$_2$), ratio stays fixed.

After death, no exchange with atmosphere. Ratio starts to change as $^{14}$C decays

**Carbon-dating question**

The $^{14}$C:$^{12}$C ratio in a fossil bone is found to be 1/8 that of the ratio in the bone of a living animal. The half-life of $^{14}$C is 5,730 years. What is the approximate age of the fossil?

A. 7,640 years
B. 17,200 years
C. 22,900 years
D. 45,800 years

Since the ratio has been reduced by a factor of 8, three half-lives have passed. 3 x 5,730 years = 17,190 years

**Other carbon decays**

- Lightest isotopes of carbon emit positron – antiparticle of electron, has positive charge!

This is antimatter
Gamma decay

Alpha decay (alpha particle emitted),
Beta decay (electron or positron emitted),
can leave nucleus in excited state
- Nucleus has excited states just like hydrogen atom
- Emits photon as it drops to lower state.

Nucleus also emits photon as it drops to ground state
This is gamma radiation
Extremely high energy photons.

Decay summary

- Alpha decay
  - Nucleus emits He nucleus (2 protons, 2 neutrons)
  - Nucleus loses 2 protons, 2 neutrons
- Beta decay
  - Nucleus emits electron
  - Neutron changes to proton in nucleus
- Beta\(^+\) decay
  - Nucleus emits positron
  - Proton changes to neutron in nucleus
- Gamma decay
  - Nucleus emits photon
  - As it drops from excited state