Physics 161
Lecture 24
Radioactivity (Chapter 29)

November 29, 2018
Final exam

The final exam will take place on
**Wednesday 19th December at 12:00 in LSH-AUD**

The exam will last 3 hours and there will be 30 questions.

There will be 15 questions on the final third of the course (lecture 19 onwards). The rest of the questions may be drawn from any part of the course.
Lecture 24: learning objectives

Review of lecture 23
Resistors in series and parallel
Electric circuits and the Kirchhoff Rules.

This lecture 24, [Chapter 29]
We will define simple structural properties of nuclei.

We will describe radioactivity using the decay rate, decay constant and half-life and identify the three types of radioactive processes.

We will describe the medical consequences of radiation exposure and some applications of radioactivity.
Atoms

An atom is a set of negative electrons bound electromagnetically to a positively charged nucleus. The number, $Z$, of electrons (in the neutral atom) determines the chemical element.
Nucleus of an Atom

The size of the nucleus compared to the size of the atom (or electron cloud) is about the size of this lecture hall to the size of the earth ($10^{-5}$ - 1).

Size of nucleus $\sim 10^{-15}$ m

Size of an atom $\sim 10^{-10}$ m
Atomic nucleus

Atomic nucleus = protons + neutrons.

Proton — positive charge
Neutron — neutral (no charge)
Electron — negative charge, (but there are NO electrons in the nucleus).

\[ M_P = M_N \approx 2000 \, M_e \]

\( Z = \) number of protons
\( A = \) total number of nucleons
\( A = Z + \) number of neutrons

\[ \begin{array}{c|c}
Z & X \\
\hline
A & \\
\end{array} \]

\( X = \) atomic symbol for isotopes with the given \( Z \).

Isotopes are nuclei with same \( Z \) but different \( A \).

Same \( Z \) means same chemistry.
Isotopes: stable or unstable?

Example: C(arbon) isotope half-life

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Half-life</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{10}\text{C}$</td>
<td>19.2 s</td>
</tr>
<tr>
<td>$^{11}\text{C}$</td>
<td>20 m</td>
</tr>
<tr>
<td>$^{12}\text{C}$</td>
<td>stable</td>
</tr>
<tr>
<td>$^{13}\text{C}$</td>
<td>stable (1.1 %)</td>
</tr>
<tr>
<td>$^{14}\text{C}$</td>
<td>5730 y</td>
</tr>
<tr>
<td>$^{15}\text{C}$</td>
<td>2.4 s</td>
</tr>
</tbody>
</table>

Unstable nuclei decay into stable nuclei by emitting radiation.
Binding energy of stable nuclei

The region of greatest binding energy per nucleon is shown by the tan band.

Nuclei to the right of $^{208}_{\text{Pb}}$ are unstable.

The curve represents the binding energy for the most stable isotopes.

Not examinable!
3 Types of nuclear decays

Three types of decay products (= radiation) when unstable nuclei decay into stable nuclei and radiation:

1) Alpha ($\alpha$) particles: Helium nuclei

2) Beta ($\beta$) particles: electrons or positrons (anti-electron)

3) Gamma ($\gamma$) rays: high energy photons (“particles” of light with zero mass)
1. Alpha decay

In an alpha decay, the nucleus emits an alpha particle (a helium nucleus).

**Example-1:**

\[
\frac{238}{92} \text{U} \rightarrow \frac{234}{90} \text{Th} + \frac{4}{2} \text{He}
\]

**Example-2:**

\[
\frac{226}{88} \text{Ra} \rightarrow \frac{222}{86} \text{Rn} + \frac{4}{2} \text{He}
\]

In general:

\[\frac{A}{Z} X \rightarrow \frac{A-4}{Z-2} Y + \frac{4}{2} \text{He}\]

\(\alpha\)-particle has high velocity
iClicker question: decays

In the decay of $^{226}\text{Ra}$ at rest into $^{222}\text{Rn}$ and $^4\text{He}$, the resulting $^4\text{He}$ has a much higher velocity than $^{222}\text{Rn}$. Why?

a) $\text{Rn}$ and $^4\text{He}$ have equal and opposite momentum.
b) $\text{Rn}$ has a much larger mass than $^4\text{He}$.
c) All of the above.
2. Beta decay

In a beta decay, the nucleus emits an electron and an antineutrino or a positron (an anti-electron) and a neutrino.

For example:

\[ ^{14}_6 \text{C} \rightarrow ^{14}_7 \text{N} + e^- + \bar{\nu} \]

In general:

\[ ^A_Z X \rightarrow ^A_{Z+1} Y + e^- + \bar{\nu} \]

\[ ^A_Z X \rightarrow ^A_{Z-1} Y + e^+ + \nu \]

A neutron in the mother nucleus, \( X \), is replaced by a proton in the daughter nucleus, \( Y \). An electron flies away:

\[ _0^1 \text{n} \rightarrow _1^1 \text{p} + e^- + \bar{\nu} \]
3. Gamma decay

In a gamma decay, an excited nucleus emits a gamma ray (a high energy photon or “particle of light”).

For example:

STEP 1

$$\frac{12}{5}B \rightarrow \frac{12}{6}C^* + e^- + \bar{\nu}$$

STEP 2

$$\frac{12}{6}C^* \rightarrow \frac{12}{6}C + \gamma$$

here STEP 2 is the $\gamma$ decay
How to contain Radiation

Alpha particle are easily stopped. Alpha particles outside of your body are no danger. They are stopped by your outer, dead layer of skin. (Breathing in or digesting an alpha particle source is very dangerous).

Electrons and positrons are stopped by your skin.

Gamma rays can travel through your body. X-rays are gamma rays.
iClicker Question: radiation detective

What type of radiation is emitted by the watch and the plate?

a) Alpha.
b) Beta.
c) Gamma.
## Decay chain of uranium 238

<table>
<thead>
<tr>
<th>Type of Radiation</th>
<th>Nuclide</th>
<th>Half-life</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\alpha)</td>
<td>Uranium-238</td>
<td>(4.5 \times 10^9) years</td>
</tr>
<tr>
<td>(\beta)</td>
<td>Thorium-234</td>
<td>24.5 days</td>
</tr>
<tr>
<td>(\beta)</td>
<td>Protactinium-234</td>
<td>1.14 minutes</td>
</tr>
<tr>
<td>(\alpha)</td>
<td>Uranium-234</td>
<td>(4.233 \times 10^5) years</td>
</tr>
<tr>
<td>(\alpha)</td>
<td>Thorium-230</td>
<td>(8.3 \times 10^4) years</td>
</tr>
<tr>
<td>(\alpha)</td>
<td>Radium-226</td>
<td>1590 years</td>
</tr>
<tr>
<td>(\alpha)</td>
<td>Radon-222</td>
<td>3.825 days</td>
</tr>
<tr>
<td>(\alpha)</td>
<td>Polonium-218</td>
<td>3.05 minutes</td>
</tr>
<tr>
<td>(\beta)</td>
<td>Lead-214</td>
<td>26.8 minutes</td>
</tr>
<tr>
<td>(\beta)</td>
<td>Bismuth-214</td>
<td>19.7 minutes</td>
</tr>
<tr>
<td>(\beta)</td>
<td>Polonium-214</td>
<td>(1.5 \times 10^{-4}) seconds</td>
</tr>
<tr>
<td>(\beta)</td>
<td>Lead-210</td>
<td>22 years</td>
</tr>
<tr>
<td>(\beta)</td>
<td>Bismuth-210</td>
<td>5 days</td>
</tr>
<tr>
<td>(\beta)</td>
<td>Polonium-210</td>
<td>140 days</td>
</tr>
<tr>
<td>(\alpha)</td>
<td>Lead-206</td>
<td>stable</td>
</tr>
</tbody>
</table>

**Not examinable!**

**gas**

**stable**
Decay rate, decay constant, half life

Decay rate, $R$:
Number of decays per second in a sample.

The decay rate $R$ is proportional to the number $N$ of nuclei in the sample.

$$R = \left| \frac{\Delta N}{\Delta t} \right| = \lambda N$$

Decay constant, $\lambda$:
The constant of proportionality $\lambda$ relating the decay rate $R$ and number $N$ of nuclei.

The unit of radioactivity is the Becquerel (Bq), where $1 \text{ Bq} = 1$ decay/s.
iClicker question: decays

In a sample $N(t)$ is the total number of nuclei at time $t$. $R(t)$ is the number of nuclei that decay per second at time $t$.

How are $N(t+1)$, $N(t)$ and $R(t)$ related?

a) $N(t+1) = N(t)$
b) $N(t+1) = R(t)$
c) $N(t+1) = N(t) + R(t)$
d) $N(t+1) = N(t) - R(t)$
Becquerel and Curie

The **unit of radioactivity** is the **Becquerel** (Bq), where

\[ 1 \text{ Bq} = 1 \text{ decay/s}. \]

Another common unit is the **Curie** (Ci), where

\[ 1 \text{ Ci} = 3.7 \times 10^{10} \text{ decays/s} \]

_(the approximate activity of 1 g of Rn)_

Marie Curie is the only scientist to have won Nobel Prizes in two different fields.

She was the first woman to win a Nobel Prize and the only woman to win two.

The Curie family has won five Nobel Prizes between four family members.
Decay constant, half life

The decay rate or activity, \( R(t) \), is proportional to the number of nuclei. \( R(t) = \lambda N(t) \).

Using this, it is possible to show that the number of nuclei, \( N(t) \), remaining after a certain time \( t \) is related to the original number of nuclei \( N_0 \) (at time = 0) by

\[
N(t) = N_0 e^{-\lambda t}
\]

**Half life:** \( T(1/2) \) or \( T_{1/2} \);
Time taken for half of the radioactive nuclei to decay.
\[ e^{-\lambda T(1/2)} = 1/2. \]
iClicker question: decays

Suppose that the half-life $T_{\frac{1}{2}}$ of a isotope is 4 s. A sample contains $N_0$ nuclei of that isotope. What fraction of the original sample is left after 12 s?

a) $N_0/2$.
b) $N_0/4$.
c) $N_0/8$.
d) $N_0/16$.
e) $N_0/32$. 
## Half life examples

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Half-life</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{238}\text{U}$</td>
<td>4.5 billion years</td>
</tr>
<tr>
<td>$^{40}\text{K}$</td>
<td>1.3 billion years</td>
</tr>
<tr>
<td>$^{235}\text{U}$</td>
<td>710 million years</td>
</tr>
<tr>
<td>$^{239}\text{Pu}$</td>
<td>24,000 years</td>
</tr>
<tr>
<td>$^{14}\text{C}$</td>
<td>5,730 years</td>
</tr>
<tr>
<td>$^{90}\text{Sr}$</td>
<td>30 years</td>
</tr>
</tbody>
</table>

These values explain why there is so little $^{235}\text{U}$ left. All nuclei more massive than uranium have half-lives much less than 4.5 billion years.

**Question:** why is uranium the heaviest naturally occurring element?
Carbon dating

Carbon-14 produced in the atmosphere by cosmic rays

\[
\frac{14}{7}N + n \rightarrow \frac{14}{6}C + p
\]

Carbon-14 decays with a half-life of 5730 years

\[
\frac{14}{6}C \rightarrow \frac{14}{7}N + \beta^- + \bar{\nu}
\]

- When alive, plants take up \( CO_2 \) containing a small fraction of \( ^{14}C \) as part of the \( CO_2 \) molecule.

- Once dead, the plants no longer take up \( CO_2 \).

- By measuring the fraction of \( ^{14}C / ^{12}C \), we can tell approximately when the plant died (up to ~ 60,000 years)

Question: How can we date rocks to be several billion years old?
Smoke detector

$^{241}\text{Am}$ decays by emitting 5.5 MeV alpha particle with half-life 420 years. Typically there is about 1 micro Curie ($10^4$ Bq) in a smoke detector.

Smoke detectors are completely safe as long as encapsulated. The alpha particles only go a few centimeters in air. They can be stopped by a sheet of paper or by your outer layer of skin. Do not inhale the Americium.
Radiation effect on living tissue

Radiation can ionize (remove electrons from) atoms, breaking molecular bonds. The DNA molecules that contain our genetic code are particularly susceptible to radiation damage.

Cancer
DNA mutations can lead to the growth of cancer cells.

Radiation sickness / death
Significant radiation exposure can cause cell death.
Unit of radiation exposure

The unit of biological damage to cells is a rem or sievert. Note that you don’t need to know what these stand for for the exam. Nor do you need to know how to convert between them. In this course, we will stick to rem.

2 billion (2 x 10^9) gamma rays going through 1 square centimeter of your body would deliver a dose of 1 rem. If this were delivered to your whole body, meaning that every square centimeter of you body was exposed to 2 billion gamma rays, you would have a 1 rem whole body dose.
Cancer dose

The whole body dose needed for near certainty of inducing cancer is **2500 rem**.

Even small doses have some probability of inducing cancer and it is likely cumulative over your lifetime. **25 rem** exposure would mean a 1% risk of cancer.

On average, **1 in 10,000** chance per year of getting cancer. To put that in perspective, even with no exposure we have a **20%** risk of cancer over our lifetime.

- **Below 100 rem**
  - **No short term illness**
- **100-200 rem**
  - **Short term illness**
- **300 rem**
  - **50% chance of death**
- **More than 1000 rem**
  - **Survival unlikely**
Cosmic rays

The Earth is continually bombarded by radiation from outer space. Particles hit the Earth’s atmosphere and then shower. About 1 particle per second through an outstretched hand or 30 mrem per year. This is about 1 in a 1000 chance of inducing cancer over a person’s lifetime. Airline flight crews receive the greatest radiation exposure of any profession. About 200 mrem per year.
Background radiation
You are radioactive

0.01% of the potassium in your body is radioactive $^{40}\text{K}$. There are about $10^{20}$ radioactive $^{40}\text{K}$ atoms in your body. About 4 mg. About 1000 decay every second so your body emits about 1000 gamma rays every second. This corresponds to about 20 mrem over a lifetime. So there is about 1 in 100,000 chance that you will give yourself cancer.
Natural radioactivity

<table>
<thead>
<tr>
<th>Source</th>
<th>Sea Level</th>
<th>Denver</th>
</tr>
</thead>
<tbody>
<tr>
<td>cosmic rays</td>
<td>28</td>
<td>55</td>
</tr>
<tr>
<td>terrestrial (rock)</td>
<td>46</td>
<td>90</td>
</tr>
<tr>
<td>food and water</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>air (mostly radon)</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td>air travel</td>
<td>1 per 1,000 miles traveled</td>
<td></td>
</tr>
<tr>
<td>house</td>
<td>7 if made of stone/brick/concrete</td>
<td></td>
</tr>
<tr>
<td>medical X-ray</td>
<td>40 each (airport X-ray negligible)</td>
<td></td>
</tr>
<tr>
<td>nuclear med. treatment</td>
<td>14 each</td>
<td></td>
</tr>
<tr>
<td>within 50 miles of nuclear plant</td>
<td>0.009</td>
<td></td>
</tr>
<tr>
<td>within 50 miles of coal plant</td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td>total for no travel/medical</td>
<td>316</td>
<td>387</td>
</tr>
</tbody>
</table>

Average dose is 300 to 400 mrem (0.3 to 0.4 rem). One in 10 thousand chance per year of getting cancer. Over a 100 year lifetime 1% chance of getting cancer from radiation.
Radioactive substance A has a decay constant that is three times that of substance B. Substance B has a half-life of 6 h, what is the half-life of Substance A?

a) 18 h.
b) 6 h.
c) 3 h.
d) 2 h.
d) 12 h.