Chapter 30
Nuclear Physics and Radioactivity
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http://www.particleadventure.org/
Atoms

- Atoms are categorized into groups that shared similar chemical properties (as in the Periodic Table of the Elements).
- This indicated that atoms were made up of simpler building blocks, and that it was these simpler building blocks in different combinations that determined which atoms had which chemical properties.
- Experiments which "looked" into an atom using particle probes indicated that atoms had structure. These experiments helped scientists determine that atoms have a tiny but dense, positive nucleus and a cloud of negative electrons (e⁻).
Scale of the atom

• While an atom is tiny, the nucleus is ten thousand times smaller than the atom and the quarks and electrons are at least ten thousand times smaller than that.

• We don't know exactly how small quarks and electrons are; they are definitely smaller than $10^{-18}$ meters, and they might literally be points, but we do not know.

• It is also possible that quarks and electrons are not fundamental after all, and will turn out to be made up of other, more fundamental particles.
Nucleus is made of protons and neutrons

Proton has positive charge; here is its mass:

\[ m_p = 1.67262 \times 10^{-27} \text{ kg} \]

Neutron is electrically neutral, and slightly more massive than the proton:

\[ m_n = 1.67493 \times 10^{-27} \text{ kg} \]
30-1 Structure and Properties of the Nucleus

Neutrons and protons are collectively called nucleons.
The different nuclei are referred to as nuclides.
Number of protons: atomic number, $Z$
Number of nucleons: atomic mass number, $A$
Neutron number: $N = A - Z$

$A$ and $Z$ are sufficient to specify a nuclide. Nuclides are symbolized as follows:

$$\frac{A}{Z}X,$$

$X$ is the chemical symbol for the element; it contains the same information as $Z$ but in a more easily recognizable form.
Nuclei with the same $Z$—so they are the same element—but different $N$ are called isotopes.

For many elements, several different isotopes exist in nature.

Natural abundance is the percentage of a particular element that consists of a particular isotope in nature.

Because of wave-particle duality, the size of the nucleus is somewhat fuzzy. Measurements of high-energy electron scattering yield:

$$ r \approx (1.2 \times 10^{-15} \text{ m})(A^{1/3}) \quad (30-1) $$
Masses of atoms are measured with reference to the carbon-12 atom, which is assigned a mass of exactly 12u. A u is a unified atomic mass unit.

\[ 1 \text{ u} = 1.6605 \times 10^{-27} \text{ kg} = 931.5 \text{ MeV}/c^2 \]
From the following table, you can see that the electron is considerably less massive than a nucleon.

<table>
<thead>
<tr>
<th>Object</th>
<th>Mass (kg)</th>
<th>Mass (u)</th>
<th>Mass (MeV/c²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron</td>
<td>$9.1094 \times 10^{-31}$</td>
<td>0.00054858</td>
<td>0.51100</td>
</tr>
<tr>
<td>Proton</td>
<td>$1.67262 \times 10^{-27}$</td>
<td>1.007276</td>
<td>938.27</td>
</tr>
<tr>
<td>$^1$H atom</td>
<td>$1.67353 \times 10^{-27}$</td>
<td>1.007825</td>
<td>938.78</td>
</tr>
<tr>
<td>Neutron</td>
<td>$1.67493 \times 10^{-27}$</td>
<td>1.008665</td>
<td>939.57</td>
</tr>
</tbody>
</table>

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The total mass of a stable nucleus is always less than the sum of the masses of its separate protons and neutrons.

Where has the mass gone?

It has become energy, such as radiation or kinetic energy, released during the formation of the nucleus.

This difference between the total mass of the constituents and the mass of the nucleus is called the total binding energy of the nucleus.
To compare how tightly bound different nuclei are, we divide the binding energy by $A$ to get the binding energy per nucleon.
The higher the binding energy per nucleon, the more stable the nucleus.

More massive nuclei require extra neutrons to overcome the Coulomb repulsion of the protons in order to be stable.

There are no completely stable nuclei above $Z=82$.

What happens to unstable nucleus?
30-2 Binding Energy and Nuclear Forces

The force that binds the nucleons together is called the strong nuclear force. It is a very strong, but short-range, force. It is essentially zero if the nucleons are more than about $10^{-15}$ m apart. The Coulomb force is long-range; this is why extra neutrons are needed for stability in high-$Z$ nuclei. Strong force acts between quarks, that compose protons and neutrons. Quarks from different protons and neutrons are attracted to each other, holding the whole nucleus together. This interaction is stronger than the Coulomb force.

Nuclei that are unstable decay; many such decays are governed by another force called the weak nuclear force.
Towards the end of the 19th century, minerals were found that would darken a photographic plate even in the absence of light.

This phenomenon is now called radioactivity.

Marie and Pierre Curie isolated two new elements that were highly radioactive; they are now called polonium and radium.

Radioactivity is the result of the disintegration or decay of an unstable nucleus.
Radioactive rays were observed to be of three types:

1. Alpha rays, which could barely penetrate a piece of paper
2. Beta rays, which could penetrate 3 mm of aluminum
3. Gamma rays, which could penetrate several centimeters of lead

We now know that alpha rays are helium nuclei, beta rays are electrons, and gamma rays are electromagnetic radiation.
Alpha and beta rays are bent in opposite directions in a magnetic field, while gamma rays are not bent at all.
Example of alpha decay:
Radium-226 will alpha-decay to radon-22

\[
^{226}_{88}\text{Ra} \rightarrow ^{222}_{86}\text{Rn} + ^{4}_{2}\text{He}
\]
In general, alpha decay can be written:

\[ \frac{A}{Z}N \rightarrow \frac{A-4}{Z-2}N' + \frac{4}{2}\text{He} \]

Alpha decay occurs when the strong nuclear force cannot hold a large nucleus together. The mass of the parent nucleus is greater than the sum of the masses of the daughter nucleus and the alpha particle; this difference is called the disintegration energy.
30-4 Alpha Decay

Alpha decay is so much more likely than other forms of nuclear disintegration because the alpha particle itself is quite stable.

One type of smoke detector uses alpha radiation—the presence of smoke is enough to absorb the alpha rays and keep them from striking the collector plate.
Beta decay occurs when a nucleus emits an electron. An example is the decay of carbon-14:

\[ ^{14}_{6}\text{C} \rightarrow ^{14}_{7}\text{N} + e^- + \text{neutrino}, \]

The nucleus still has 14 nucleons, but it has one more proton and one fewer neutron.

This decay is an example of an interaction that proceeds via the weak nuclear force.
The electron in beta decay is not an orbital electron; it is created in the decay.

The fundamental process is a neutron decaying to a proton, electron, and neutrino:

\[ n \rightarrow p + e^- + \text{neutrino}. \]

The need for a particle such as the neutrino was discovered through analysis of energy and momentum conservation in beta decay—it could not be a two-particle decay.
Neutrinos are notoriously difficult to detect, as they interact only weakly, and direct evidence for their existence was not available until more than 20 years had passed.

The symbol for the neutrino is the Greek letter nu (ν); using this, we write the beta decay of carbon-14 as (the bar over the neutrino means that it is an antineutrino):

\[
\frac{14}{6}\text{C} \rightarrow \frac{14}{7}\text{N} + e^- + \bar{\nu}.
\]
Beta decay can also occur where the nucleus emits a positron rather than an electron:

$$^{19}_{10}\text{Ne} \rightarrow ^{19}_{9}\text{F} + e^+ + \nu,$$

And a nucleus can capture one of its inner electrons:

$$^{7}_{4}\text{Be} + e^- \rightarrow ^{7}_{3}\text{Li} + \nu,$$

Beta-decays transmute one chemical element into another. Beta decay does not change the number $A$ of nucleons in the nucleus but changes only its charge $Z$. 

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Gamma rays are very high-energy photons. They are emitted when a nucleus decays from an excited state to a lower state, just as photons are emitted by electrons returning to a lower state.

In gamma decay, A and Z remain the same, so after it we will have the same chemical element.
A new conservation law that is evident by studying radioactive decay is that the total number of nucleons cannot change.

Total charge is also conserved in all decays.

### TABLE 30–2  The Three Types of Radioactive Decay

<table>
<thead>
<tr>
<th>Type</th>
<th>Reaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>α decay</td>
<td>$\frac{A}{Z}N \rightarrow \frac{A-4}{Z-2}N' + \frac{4}{2}He$</td>
</tr>
<tr>
<td>β decay</td>
<td>$\frac{A}{Z}N \rightarrow \frac{A}{Z+1}N' + e^- + \bar{v}$</td>
</tr>
<tr>
<td></td>
<td>$\frac{A}{Z}N \rightarrow \frac{A}{Z-1}N' + e^+ + v$</td>
</tr>
<tr>
<td></td>
<td>$\frac{A}{2}N + e^- \rightarrow \frac{A}{Z-1}N' + v$ [EC]$^\dagger$</td>
</tr>
<tr>
<td>γ decay</td>
<td>$\frac{A}{2}N^* \rightarrow \frac{A}{Z}N + \gamma$</td>
</tr>
</tbody>
</table>

$^\dagger$Electron capture.

*Indicates the excited state of a nucleus.
Example 1

Calculate the total binding energy and the binding energy per nucleon for $^7_3\text{Li}$

Solution: We find the binding energy from the masses, using hydrogen atoms in place of protons so that we account for the mass of the electrons.

$$BE = \left[ 3m(\text{}^1\text{H}) + 4m(n) - m(\text{}^7\text{Li}) \right]c^2 =$$

$$= \left[ 3 \cdot 1.007825u + 4 \cdot 1.008665u - 7.016003u \right]c^2\left(\frac{931.5\text{MeV} / c^2}{u}\right) =$$

$$= 39.25 \text{ MeV}$$

$$\frac{BE}{N} = \frac{39.25}{7} = 5.607 \text{ MeV} / \text{nucleon}$$
Example 2

$^{24}_{11}Na$ is radioactive. Is it a $\beta^-$ or $\beta^+$ emitter? Write down the decay reaction and estimate the maximum kinetic energy of the emitted $\beta$.

Solution: From Appendix B, this is a $\beta^-$ emitter.

\[
^{24}_{11}Na \rightarrow ^{24}_{12}Mg + \beta^- + \bar{\nu}
\]

\[
KE = \left[ m\left(^{24}_{11}Na\right) - m\left(^{24}_{12}Mg\right) \right]c^2 =
\]

\[
= [23.990963u - 23.985042u]c^2 \left( \frac{931.5\, MeV}{c^2} \right)u =
\]

\[
= 5.515\, MeV
\]
Nuclear decay is a random process; the decay of any nucleus is not influenced by the decay of any other.
Therefore, the number of decays in a short time interval is proportional to the number of nuclei present and to the time:

$$\Delta N = -\lambda N \Delta t \quad (30-3a)$$

Here, $\lambda$ is a constant characteristic of that particular nuclide, called the decay constant.
This equation can be solved, using calculus, for $N$ as a function of time:

$$N = N_0 e^{-\lambda t}, \quad (30-4)$$
The half-life is the time it takes for half the nuclei in a given sample to decay. It is related to the decay constant:

$$T_{1/2} = \frac{\ln 2}{\lambda} = \frac{0.693}{\lambda}. \quad (30-6)$$
Example 3

• The activity of radioactive source decreases by 5.5% in 31 hours. What is the half-life of this source?
• Solution: The original activity is $\lambda N_0$, so the activity 31.0 hours later is $0.945 \lambda N_0$.

\[
0.945 \lambda N_0 = \lambda N_0 e^{-\lambda t} \quad \Rightarrow \quad \ln 0.945 = -\lambda t = -\frac{\ln 2}{T_{1/2}}t
\]

\[
T_{1/2} = -\frac{\ln 2}{\ln 0.945} \cdot 31 = 379.84 \text{ h} \quad \text{or} \quad 15.8 \text{ days}
\]
A decay series occurs when one radioactive isotope decays to another radioactive isotope, which decays to another, and so on. This allows the creation of nuclei that otherwise would not exist in nature.
Radioactive dating can be done by analyzing the fraction of carbon in organic material that is carbon-14.

The ratio of carbon-14 to carbon-12 in the atmosphere has been roughly constant over thousands of years. A living plant or tree will be constantly exchanging carbon with the atmosphere, and will have the same carbon ratio in its tissues.
When the plant dies, this exchange stops. Carbon-14 has a half-life of about 5730 years; it gradually decays away and becomes a smaller and smaller fraction of the total carbon in the plant tissue.

This fraction can be measured, and the age of the tissue deduced.

Objects older than about 60,000 years cannot be dated this way—there is too little carbon-14 left.
Other isotopes are useful for geologic time scale dating.

Uranium-238 has a half-life of $4.5 \times 10^9$ years, and has been used to date the oldest rocks on Earth as about 4 billion years old.
When a nucleus decays through alpha emission, energy is released. Why is it that these nuclei do not decay immediately?

The answer is that, although energy is released in the decay, there is still an energy barrier:
The alpha particle can escape through a quantum mechanical phenomenon called tunneling.

As stated in the Heisenberg uncertainty principle, energy conservation can be violated as long as the violation does not last too long:

\[ Q = M_P c^2 - (M_D + m_\alpha)c^2. \]  \hspace{1cm} (30-2)
The higher the energy barrier, the less time the alpha particle has to get through it, and the less likely that is to happen. This accounts for the extremely wide variation in half-lives for alpha decay.
Individual particles such as electrons, neutrons, and protons cannot be seen directly, so their existence must be inferred through measurements. Many different devices, of varying levels of sophistication, have been developed to do this.
The Geiger counter is a gas-filled tube with a wire in the center. The wire is at high voltage; the case is grounded. When a charged particle passes through, it ionizes the gas. The ions cascade onto the wire, producing a pulse.
A scintillation counter uses a scintillator—a material that emits light when a charged particle goes through it. The scintillator is made light-tight, and the light flashes are viewed with a photomultiplier tube, which has a photocathode that emits an electron when struck by a photon and then a series of amplifiers.
A cloud chamber contains a supercooled gas; when a charged particle goes through, droplets form along its track. Similarly, a bubble chamber contains a superheated liquid, and it is bubbles that form. In either case, the tracks can be photographed and measured.
A wire drift chamber is somewhat similar to, but vastly more sophisticated than, a Geiger counter. Many wires are present, some at high voltage and some grounded; in addition to the presence of a signal, the time it takes the pulse to arrive at the wire is measured, allowing very precise measurement of position.
Summary of Chapter 30

- Nuclei contain protons and neutrons—nucleons
- Total number of nucleons, $A$, is atomic mass number
- Number of protons, $Z$, is atomic number
- Isotope notation: $^{A}_{Z}X$
- Nuclear masses are measured in u; carbon-12 is defined as having a mass of 12 u

$$1 \text{ u} = 1.6605 \times 10^{-27} \text{ kg} = 931.5 \text{ MeV/c}^2$$
Summary of Chapter 30

• Difference between mass of nucleus and mass of its constituents is binding energy

• Unstable nuclei decay through alpha, beta, or gamma emission

• An alpha particle is a helium nucleus; a beta particle is an electron or positron; a gamma ray is a highly energetic photon

• Nuclei are held together by the strong nuclear force; the weak nuclear force is responsible for beta decay
Electric charge, linear and angular momentum, mass-energy, and nucleon number are all conserved.

Radioactive decay is a statistical process.

The number of decays per unit time is proportional to the number of nuclei present:

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

The half-life is the time it takes for half the nuclei to decay.