Radioactivity

Toward 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 involves transmutation of the elements; the alchemists dream.









The Nobel Prize in Physics 1903 for their work on radioactivity

Henri Becquerel

Pierre Curie

Marie Curie

Radioactivity

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.



Radium-226 will alpha decay to radon-222:



- 1. Why do some nuclei decay ?
- 2. Why emit α 's, and not protons, or neutrons ?

 α decay :

$$^{A}_{Z}N \rightarrow ^{A-4}_{Z-2}N' + ^{4}_{2}He$$

strong nuclear force cannot hold a large nucleus together
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.

Who takes the kinetic energy?



Momentum conservation: $m_{\alpha}v_{\alpha} = m_Dv_D$

So:
$$v_{\alpha} = m_D v_D / m_{\alpha}$$

Kinetic energy:

$$K_{\alpha} = \frac{1}{2}m_{\alpha}v_{\alpha}^{2} = \frac{1}{2}m_{\alpha}\left(\frac{m_{D}v_{D}}{m_{\alpha}}\right)^{2} = \left(\frac{m_{D}}{m_{\alpha}}\right)K_{D}$$
$$K_{tot} = K_{\alpha} + K_{D} = \left(1 + \frac{m_{\alpha}}{m_{D}}\right)K_{\alpha}$$

When a nucleus decays through alpha emission, energy is released. Why is it that these nuclei do not decay immediately?

Although energy is released in the decay, there is still an energy barrier:



Quantum tunneling through a barrier

Heisenberg uncertainty : energy conservation can be violated as long as the violation does not last too long:

$$(\Delta E)(\Delta t) \approx rac{h}{2\pi}$$

Compare to the stochastic process of spontaneous emission

desintegration energy

$$Q = M_{\text{parent}}c^2 - (M_D + m_\alpha)c^2$$

Heisenberg
$$(\Delta E)(\Delta t) \approx \frac{h}{2\pi}$$

The higher the barrier, the less time the alpha particle has to get through it, and the less likely that is to happen.

T

quantum tunneling: quantitative

$$= 2 \int_{r'}^{r''} \sqrt{\left(\frac{2m}{\hbar^2}\right)} [V(r) - E] dr$$

$$\approx e^{r'}$$

Half lives and kinetic energies of α 's



There is an extremely wide variety of half-lives in α -decay; and a connection to kinetic energy.

Why is that ?

Note: α's have a characteristic energy for each decay

Why?

Half lives and kinetic energies of α 's

$$Q = M_{\text{parent}} c^2 - (M_D + m_\alpha)c^2$$



- 1. Higher kinetic energy means traversing a smaller barrier
- 2. Uni-partcile decay gives a specific energy (momentum conservation)

Beta decay occurs when a nucleus emits an electron. An example is the decay of carbon-14:

$${}^{14}_{6}C \rightarrow {}^{14}_{7}N + e^- + neutrino$$

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 Nobel Prize in Physics 1938

Enrico Fermi

Mass balance:

$${}^{14}_{6}C \rightarrow {}^{14}_{7}N + e^{-} + neutrino$$

 \downarrow
Charged particle (nucleus + 6 electrons)

Left: mass ${}^{14}C = 14.003242$ Right: mass ${}^{14}N$ -nucleus + 6 electrons + 1 electron = mass(${}^{14}N$)= 14.003074

 Δ (mc²)= 156 keV

Is this 156 keV the kinetic energy of electron ?

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:

$$n \rightarrow p + e^- + neutrino$$
.

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.



2.

Law of Physics; Angular momentum Conservation Particles have spin 1/2

Beta decay can also occur where the nucleus emits a positron rather than an electron:

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

And a nucleus can capture one of its inner electrons:

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

How to detect EC ?

In general, we can write beta decay in the following form:

$${}^{A}_{Z}N \rightarrow {}^{A}_{Z+1}N' + e^{-} + \overline{\nu} \qquad [\beta^{-} \operatorname{decay}],$$

$${}^{A}_{Z}N \rightarrow {}^{A}_{Z-1}N' + e^{+} + \nu \qquad [\beta^{+} \operatorname{decay}].$$

And similarly for electron capture:

$${}^{A}_{Z}N + e^{-} \rightarrow {}^{A}_{Z-1}N' + \nu$$

Gamma Decay

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.



Conservation of Nucleon Number and Other Conservation Laws

TABLE 41–2The ThreeTypes of Radioactive Decay

 α decay:

$${}^{A}_{Z}N \rightarrow {}^{A-4}_{Z-2}N' + {}^{4}_{2}He$$

 β decay:

γ decay:

$${}^{A}_{Z}N^{*} \rightarrow {}^{A}_{Z}N + \gamma$$

[†] Electron capture.*Indicates the excited state of a nucleus.

A new law is evident by studying radioactive decay: the total number of nucleons cannot change.

Conservation of Baryon number

Strong force \rightarrow Baryons Weak force \rightarrow Leptons

Half-Life and Rate of Decay

Nuclear decay is a random process; the decay of any nucleus is not influenced by the decay of any other.



Number of decays in a short time interval is proportional to the number of nuclei present and to the time:

$$dN = -\lambda N dt.$$

Here, λ is a constant characteristic of that particular nuclide, and is called the decay constant.

Exponential decay

This equation can be solved for *N* as a function of time:

 $N = N_0 e^{-\lambda t}$ Radio active decay law



Decay constant is given on an exponential scale: $\tau = 1/\lambda$

Half Life



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:

Rate of Decay



So the activity decreases exponentially in time at the same rate !



Radioactive Dating

Radioactive dating with carbon-14.

Production of C-14 (steady portion in atmosphere ~1.3 x 10⁻¹²):

$$^{14}_7N + n \rightarrow ^{14}_6C + p$$

Balance: continual production of C-14 against its radioactive decay

Objects older than about 60,000 years cannot be dated this way – there is too little carbon-14 left.

Evaluate Example 41-12





The Nobel Prize in Chemistry 1960

"for his method to use carbon-14 for age determination in archaeology, geology, geophysics, and other branches of science" τ =1/ λ =5730 year

Willard Libby

Radioactive Dating

Other isotopes are useful for geologic time scale dating.

Uranium-238 has a half-life of 4.5 x 10⁹ years, and has been used to date the oldest rocks on Earth.

Other radio-active isotopes are used for dating as well.

Decay Series



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.

Pb-series

4n+2 series

Which element radiates most?

Decay Series





4n+1 series: ²³⁷Np

4n+3 series: ²³⁵U

Detection of Radiation



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.

Detection of Radiation



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.

Detection of Radiation

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.



Positron Emission Tomography (PET)

For positron emission tomography, the patient is given material containing radioactive (positron-emitting) isotopes. The patient is then positioned inside a ring of detectors, which measure how the material is absorbed in different parts of the body.



Positron Emission Tomography (PET)



- 1) Production of PET isotopes in cyclotron
- 2) Inclusion of isotopes in "edible substance" (FDG)
- 3) Motion of active molecule into tumor locations (1 h)
- 4) Positron emission in the body

$$^{18}_{9}F \rightarrow e^+ + ^{18}_{8}O + v$$

 $T_{1/2} = 110 \text{ min}$
 $^{11}_{6}C \rightarrow e^+ + ^{11}_{5}B + v$
 $T_{1/2} = 20 \text{ min}$

- 5) Relaxation of the positron in the body
- 6) Electron positron annihilation $e^+ + e^- \rightarrow 2\gamma$
- 7) Detection and imaging of gamma's (511 keV) with computed tomography