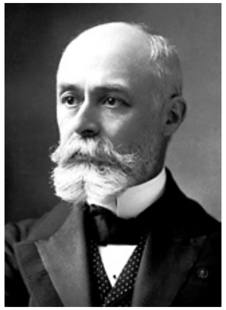
# Radioactivity

**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.**

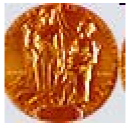
**Marie and Pierre Curie isolated two new elements that were highly radioactive; they are now called polonium and radium.**



Henri Becquerel

Pierre Curie

Marie Curie



The Nobel Prize in Physics 1903
for their work on radioactivity

# Radioactivity

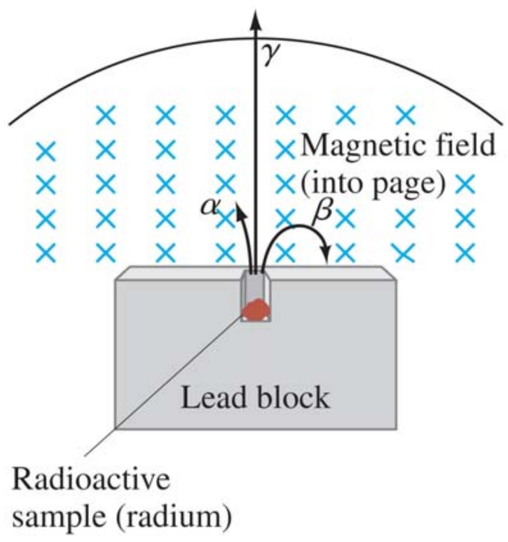
Radioactive rays were observed to be of three types:

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

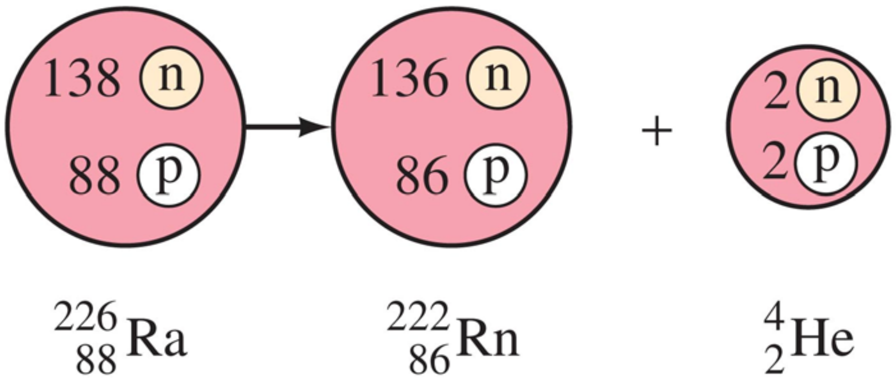
We now know that alpha rays are helium nuclei, beta rays are electrons, and gamma rays are electromagnetic radiation.



# Alpha Decay

**Radium-226 will alpha decay to radon-222:**

$$^{226}_{88}\mathrm{Ra} \rightarrow \, ^{222}_{86}\mathrm{Rn} + \, ^{4}_{2}\mathrm{He}$$




1. **Why do some nuclei decay ?**
2. **Why emit $\alpha$'s, and not protons, or neutrons ?**

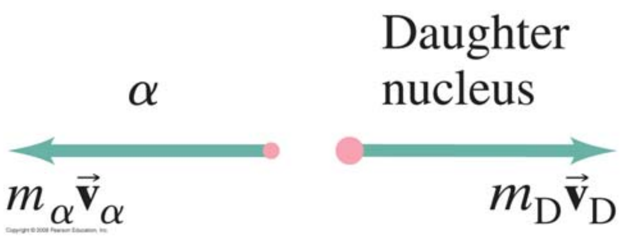
# Alpha Decay

α **decay :**

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

**- 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: $m_\alpha v_\alpha = m_D v_D$

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

Kinetic energy:

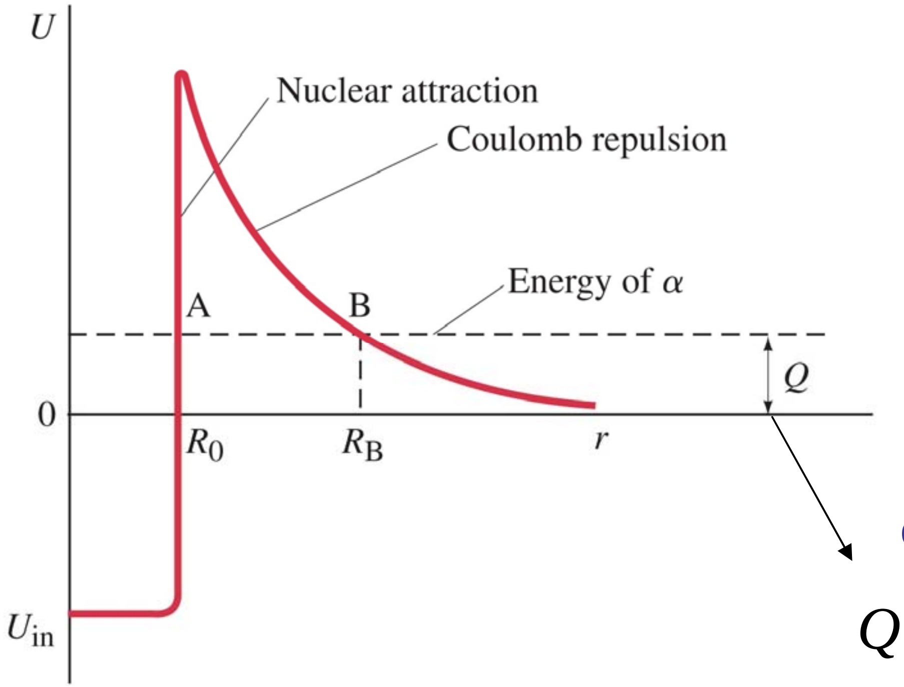
$$K_\alpha = \frac{1}{2} m_\alpha v_\alpha^2 = \frac{1}{2} m_\alpha \left( \frac{m_D v_D}{m_\alpha} \right)^2 = \left( \frac{m_D}{m_\alpha} \right) K_D$$

$$K_{tot} = K_\alpha + K_D$$

# Alpha Decay

**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:**

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

**desintegration energy**

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

# Alpha Decay

**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.**

**quantum tunneling: quantitative**

$$T \approx e^{-2\int_{r'}^{r''}\sqrt{\left(2m/\hbar^2\right)\left[V(r)-E\right]}dr}$$

# Beta Decay

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

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

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.

# Beta Decay

The electron in beta decay is not an orbital electron; it is created in the decay.

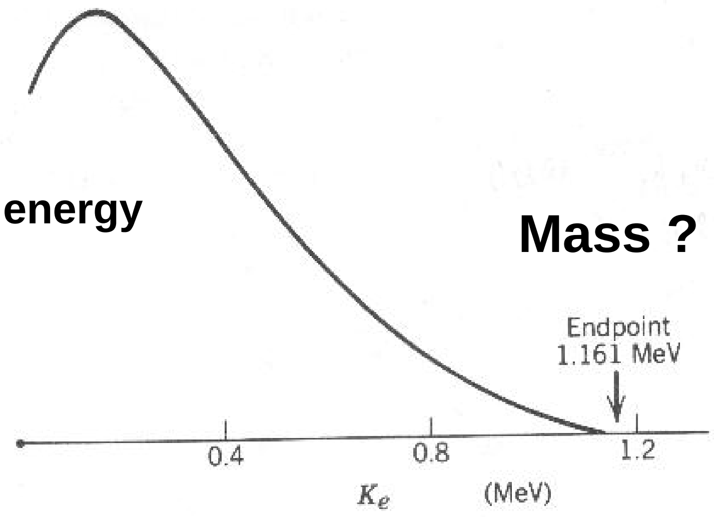
The fundamental process is a neutron decaying to a proton, electron, and neutrino:

$$n \to p + e^- + \text{neutrino}.$$

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.

**1.**

**Electron kinetic energy**
**In $\beta$-decay of**
**$^{210}$Bi**




**Mass ?**

**2.**

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

# Beta Decay

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

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

**And a nucleus can capture one of its inner electrons:**

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

**How to detect EC ?**

# Beta Decay

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

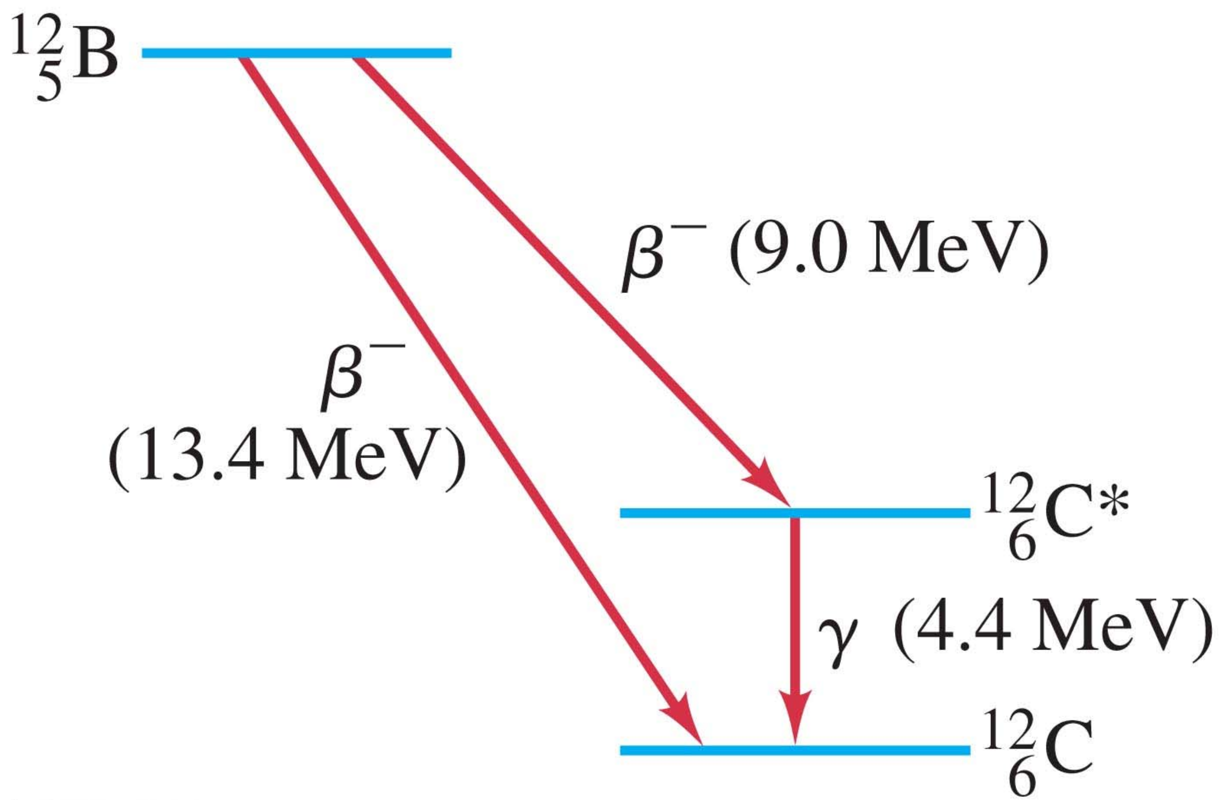
$$
\begin{aligned}
{}^{A}_{Z}\mathrm{N} &\rightarrow {}^{A}_{Z+1}\mathrm{N}' + \mathrm{e}^{-} + \bar{\nu} && [\beta^{-}\ \mathrm{decay}],\\
{}^{A}_{Z}\mathrm{N} &\rightarrow {}^{A}_{Z-1}\mathrm{N}' + \mathrm{e}^{+} + \nu && [\beta^{+}\ \mathrm{decay}].
\end{aligned}
$$

**And similarly for electron capture:**

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

# 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 41–2 The Three Types of Radioactive Decay**

| |
|---|
| *α decay:* |
| $^{A}_{Z}\mathrm{N} \rightarrow\ ^{A-4}_{Z-2}\mathrm{N}' + \,^{4}_{2}\mathrm{He}$ |
| *β decay:* |
| $^{A}_{Z}\mathrm{N} \rightarrow\ ^{A}_{Z+1}\mathrm{N}' + \mathrm{e}^{-} + \bar{\nu}$ |
| $^{A}_{Z}\mathrm{N} \rightarrow\ ^{A}_{Z-1}\mathrm{N}' + \mathrm{e}^{+} + \nu$ |
| $^{A}_{Z}\mathrm{N} + \mathrm{e}^{-} \rightarrow\ ^{A}_{Z-1}\mathrm{N}' + \nu$ [EC]† |
| *γ decay:* |
| $^{A}_{Z}\mathrm{N}^{*} \rightarrow\ ^{A}_{Z}\mathrm{N} + \gamma$ |

† 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**

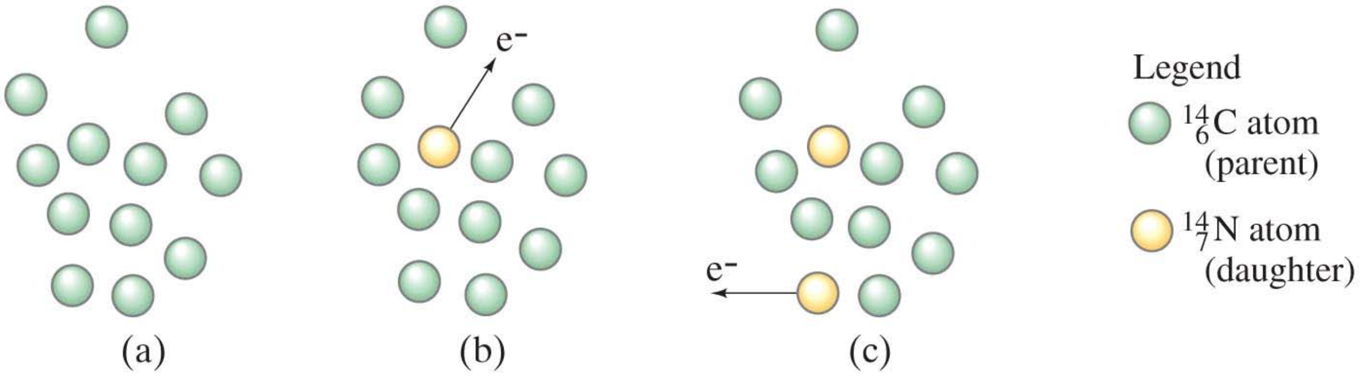
**Strong force → Baryons**

**Weak force → 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.

**Spontaneous process**




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

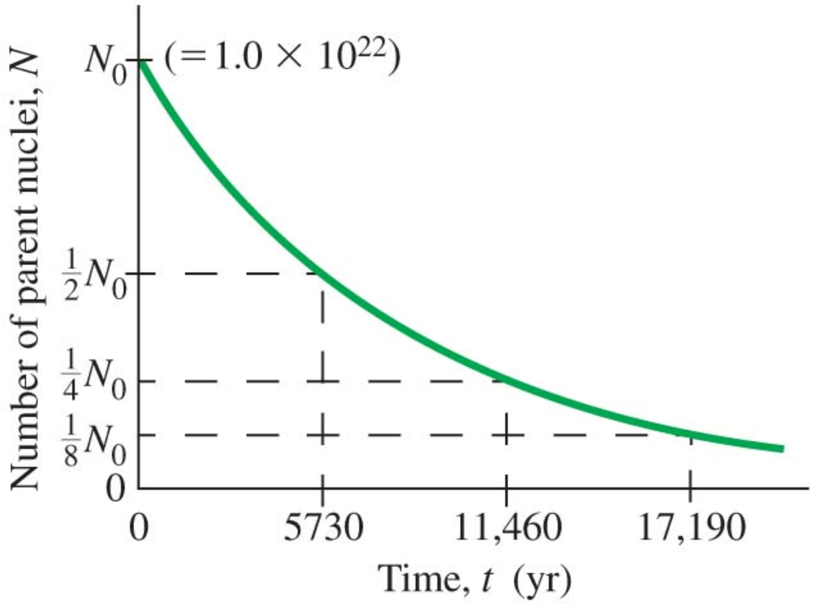
$$dN = -\lambda N \, dt.$$

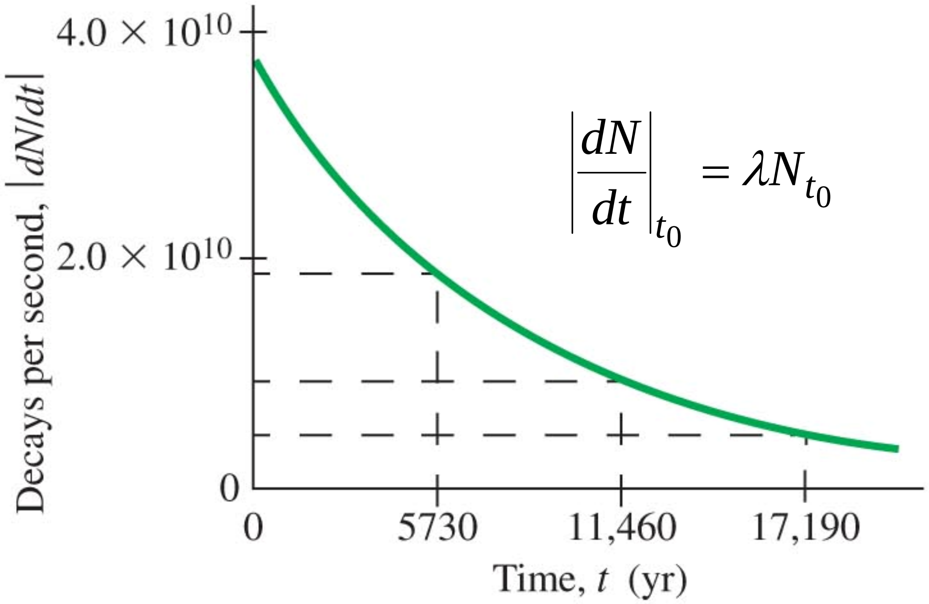
Here, $\lambda$ is a constant characteristic of that particular nuclide, and is called the decay constant.

# Half-Life and Rate of Decay

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

$$N = N_0 e^{-\lambda t}.$$




**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:**

$$T_{\frac{1}{2}} = \frac{\ln 2}{\lambda} = \frac{0.693}{\lambda}.$$

# Radioactive Dating

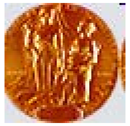
Radioactive dating with carbon-14.

Production of C-14 (steady portion in atmosphere ~1.3 x $10^{-12}$):

$$^{14}_{7}N + n \rightarrow {}^{14}_{6}C + p$$

**Evaluate Example 41-12**

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



**Willard Libby**

**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"

# Radioactive Dating

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.

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

# Half-Life and Rate of Decay

**Sample activity.**

**The isotope $^{14}_{6}C$ has a half-life of 5730 yr. If a sample contains 1.00 x $10^{22}$ carbon-14 nuclei, what is the activity of the sample?**

**Safety: activity versus half-life.**

**One might think that a short half-life material is safer than a long half-life material because it will not last as long. Is this an accurate representation of the situation?**

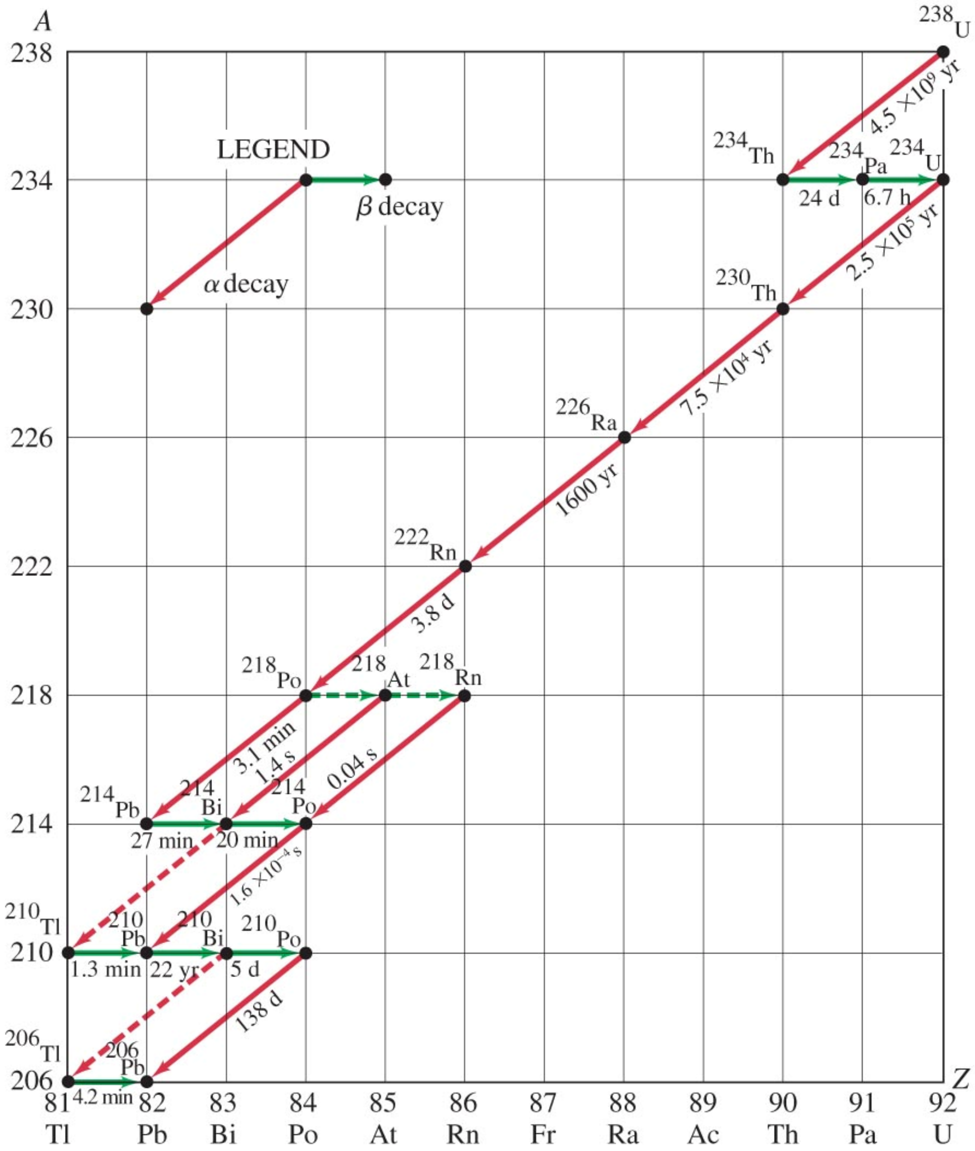
**Discuss:**

- **Radio active waist**

- **Medical isotopes**

- **Radiological damage**

# Decay Series



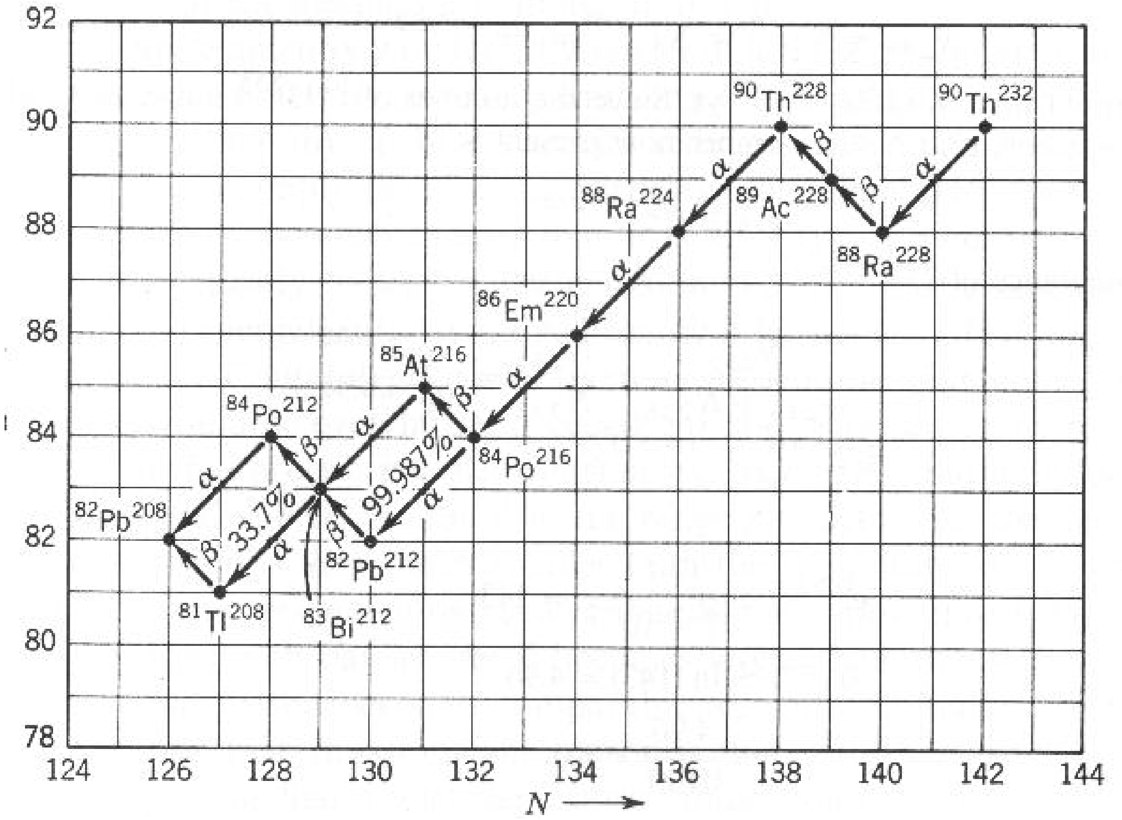

**A decay series occurs when one radioactive isotope decays to another radioactive isotope, which decays to another, and so on. This allows the creation of nuclei that otherwise would not exist in nature.**

## Pb-series

4n+2 series

Which element radiates most ?

# Decay Series

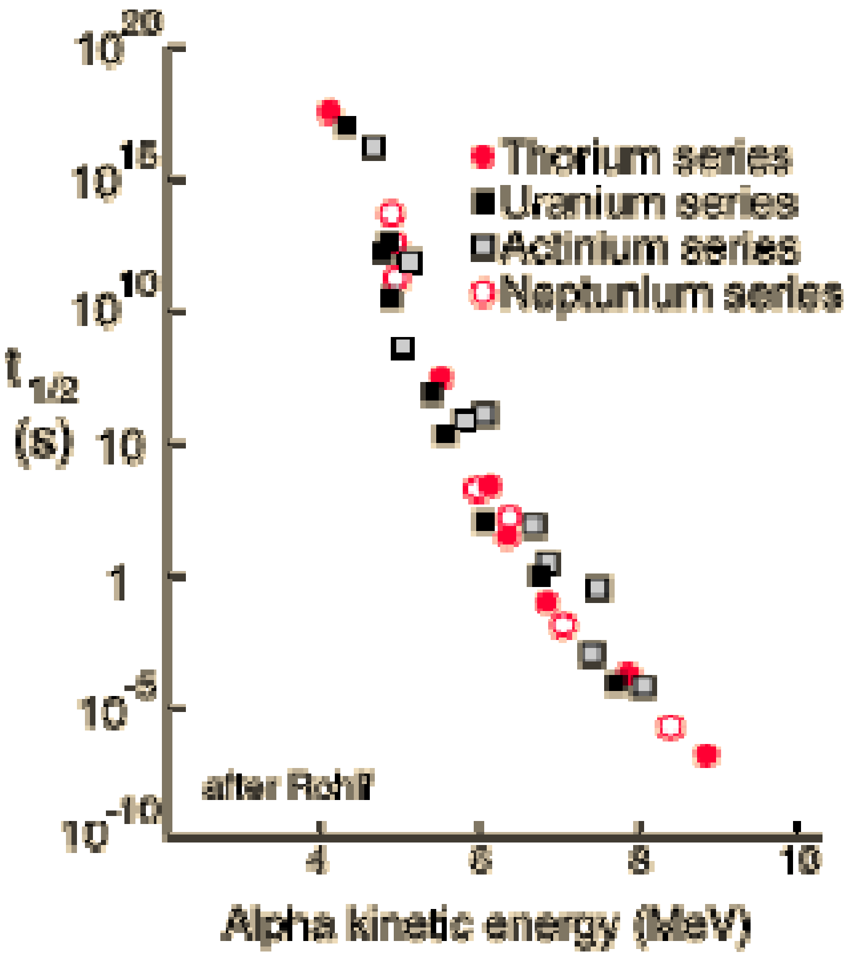



4n series

4n+1 series: $^{237}$Np

4n+3 series: $^{235}$U

# Half lives and kinetic energies of $\alpha$'s




There is an extremely wide variety of half-livesin $\alpha$-decay;
and a connection to kinetic energy.

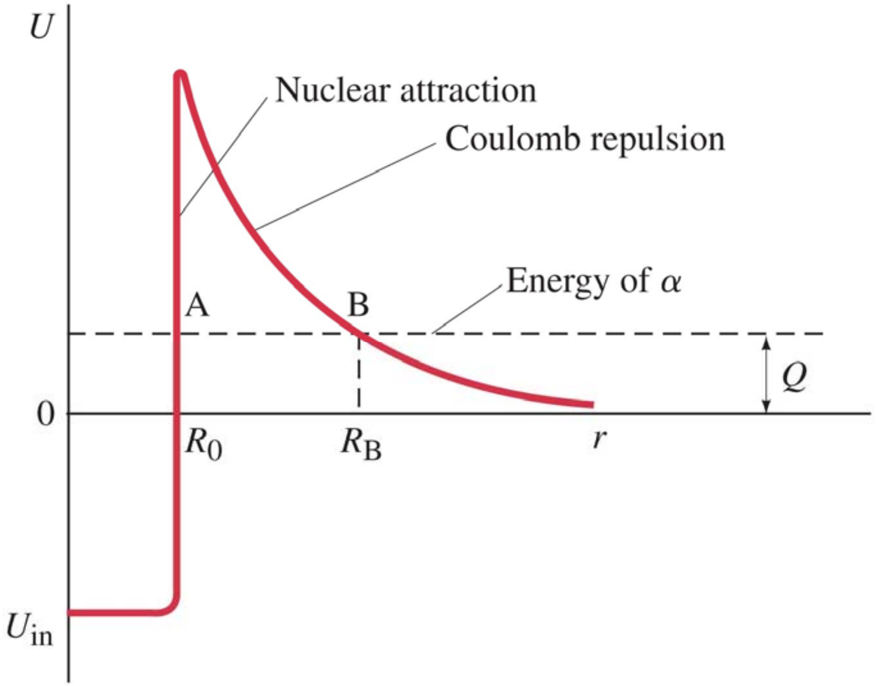
Why is that ?

Note: $\alpha$'s have a characteristic energy for each decay

Why ?

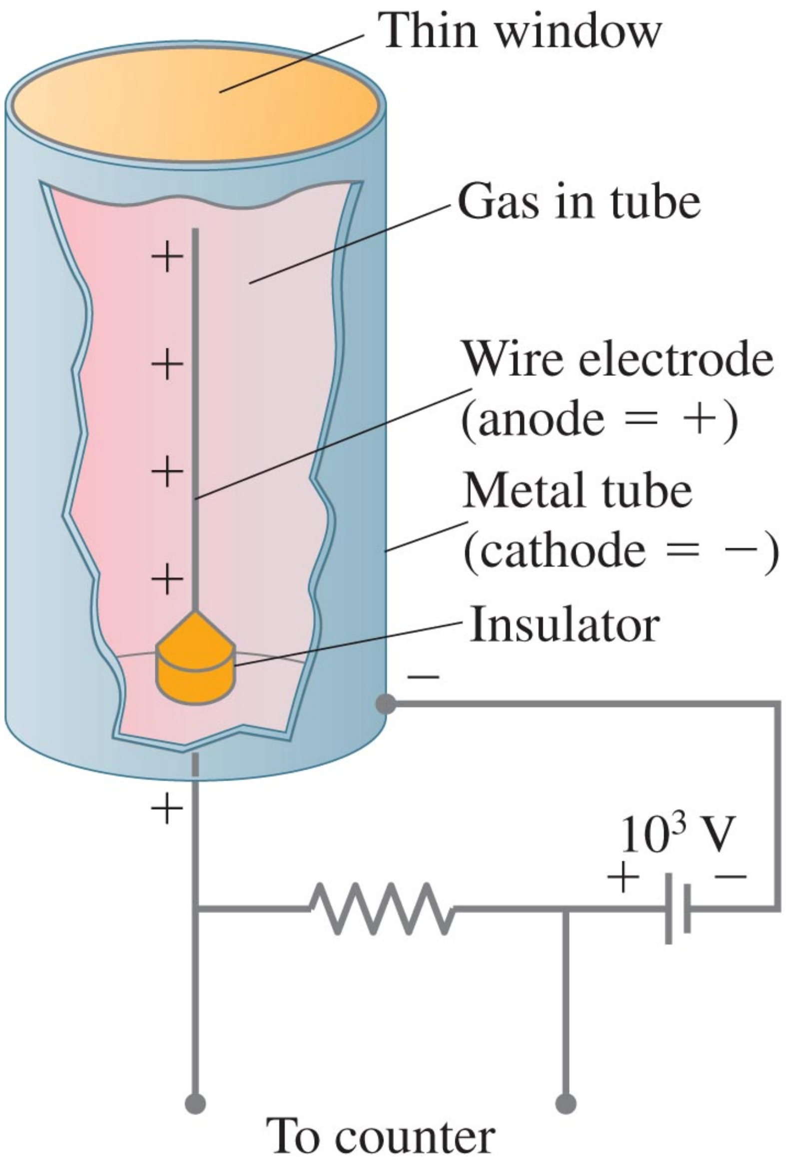
# Half lives and kinetic energies of α's

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



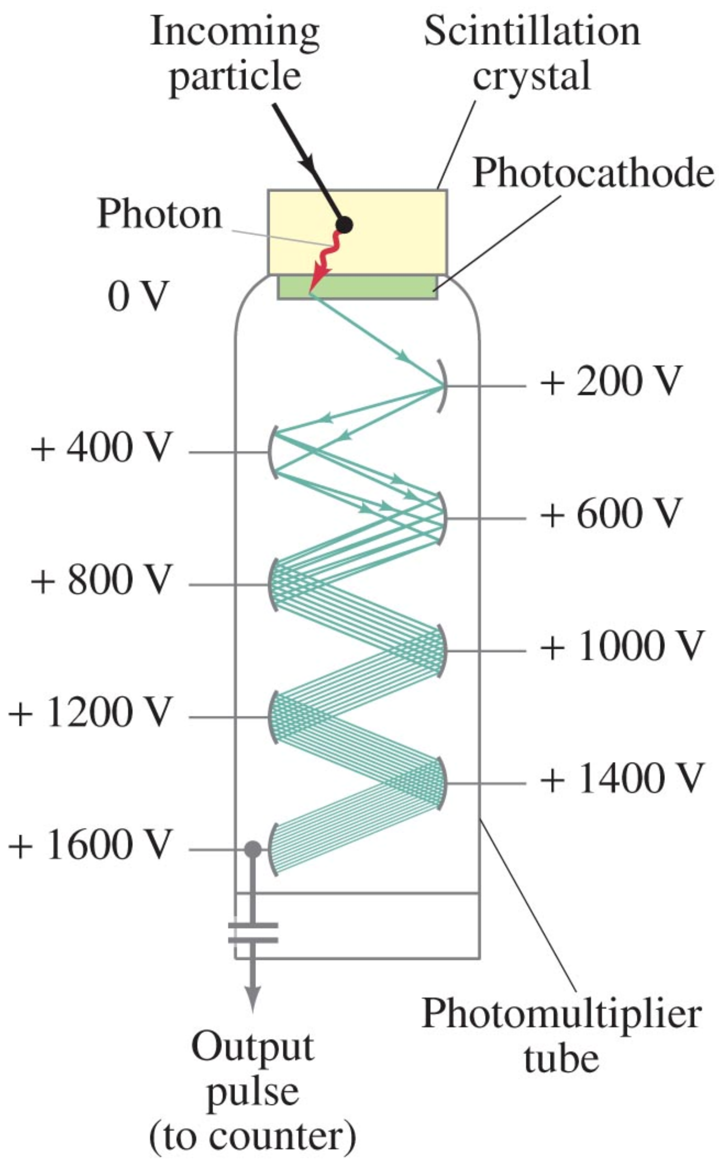

1. Higher kinetic energy means tarversing a smaller barrier
2. Uni-partcile decay gives a specific energy (momentum conservation)

# 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.