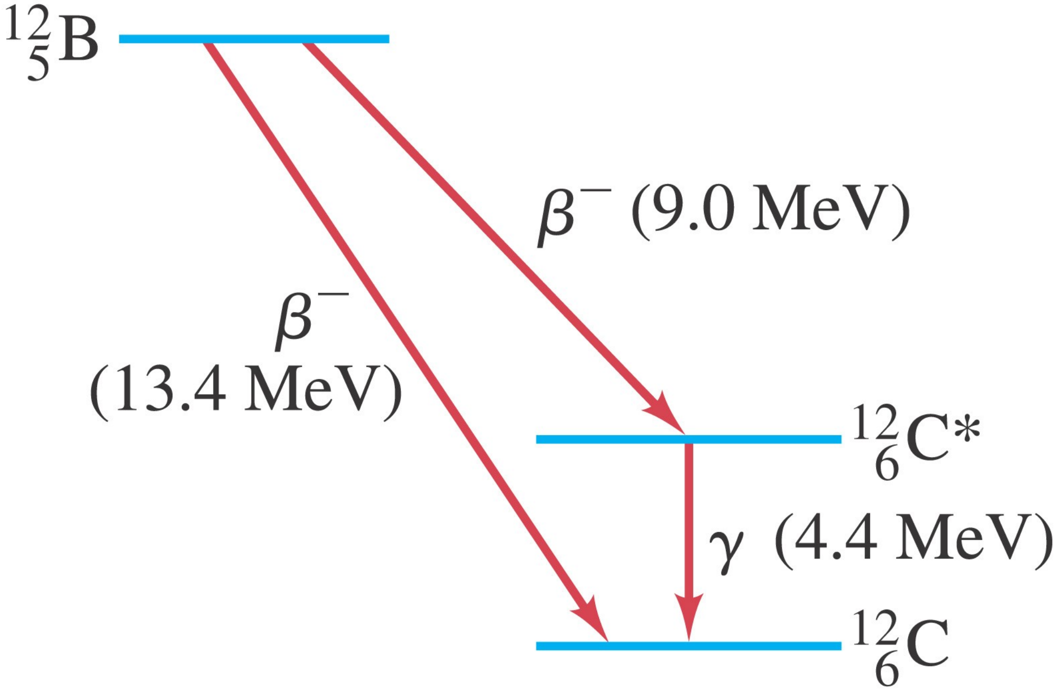
Chapter 30

Nuclear Physics and Radioactivity



Units of Chapter 30

- Structure and Properties of the Nucleus
- Binding Energy and Nuclear Forces
- Radioactivity
- Alpha Decay
- Beta Decay
- Gamma Decay
- Conservation of Nucleon Number and Other Conservation Laws

Units of Chapter 30

- Half-Life and Rate of Decay
- Calculations Involving Decay Rates and Half-Life
- Decay Series
- Radioactive Dating
- Stability and Tunneling
- Detection of Radiation

Structure and Properties of the Nucleus

Any nucleus is made up of **protons** and **neutrons**

A proton has a positive charge of e:

$$m_p = 1.67262 \times 10^{-27}\ \mathrm{kg}$$

A neutron is electrically neutral:

$$m_n = 1.67493 \times 10^{-27}\ \mathrm{kg}$$

A given Nucleus has the following particles -
Total number of '**nucleons**': atomic mass number, A
Proton number: atomic number, Z
Neutron number: $N = A - Z$

Structure and Properties of the Nucleus

Notation: a specific nucleus or ‘**nuclide**’ can be specified as

$${}^{A}_{Z}\mathrm{X}$$

$\mathbf{X}$ is the chemical symbol for the element, Z may not be included – the element symbol dictates Z

Nuclei with the same Z – so they are the same element – but different A (and N) are ‘**isotopes**’.

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

Structure and Properties of the Nucleus

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

$$r \approx \left(1.2 \times 10^{-15}\,\mathrm{m}\right)\left(A^{\frac{1}{3}}\right)$$

Atomic Masses are measured with reference to the carbon-12 atom, which is assigned a mass of exactly 12u. ‘u’ is an atomic mass unit.

$$1\,\mathrm{u} = 1.6605 \times 10^{-27}\,\mathrm{kg} = 931.5\,\mathrm{MeV}/c^2.$$

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Structure and Properties of the Nucleus

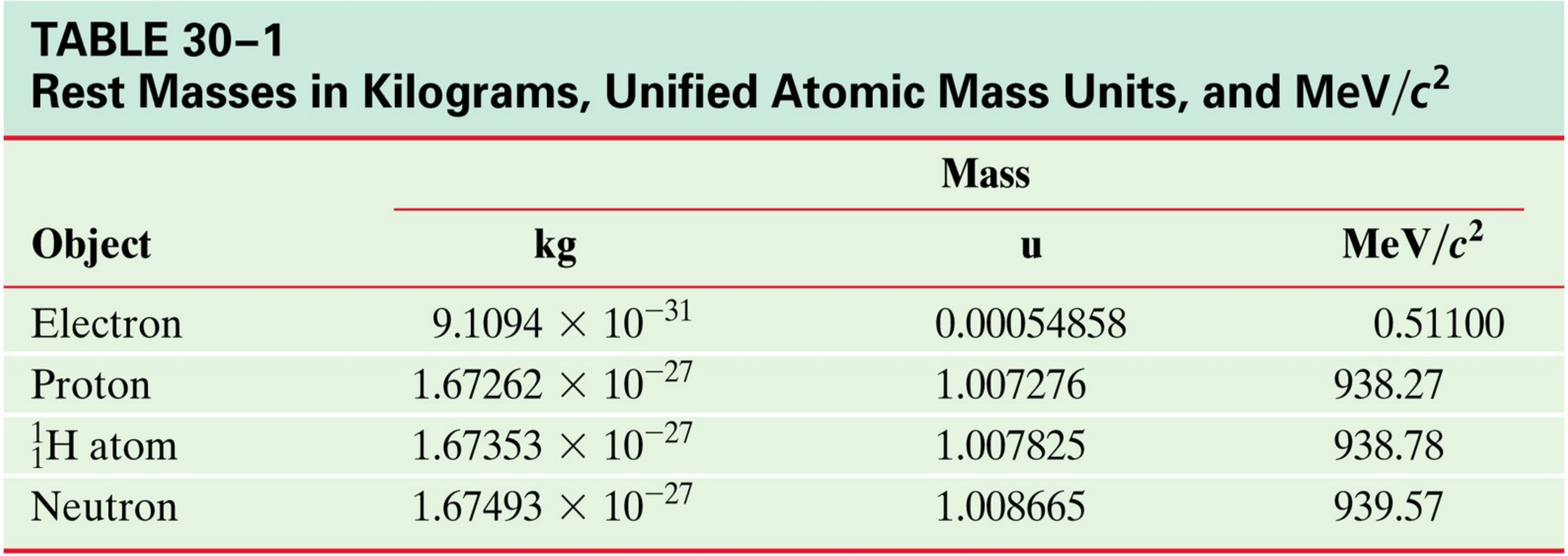


TABLE 30–1
Rest Masses in Kilograms, Unified Atomic Mass Units, and MeV/c^2

Object	Mass		
	kg	u	MeV/c^2
Electron	9.1094×10^{-31}	0.00054858	0.51100
Proton	1.67262×10^{-27}	1.007276	938.27
$^1_1$H atom	1.67353×10^{-27}	1.007825	938.78
Neutron	1.67493×10^{-27}	1.008665	939.57

Note that the mass of an electron is much less than that of a nucleon.

Binding Energy and Nuclear Forces

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

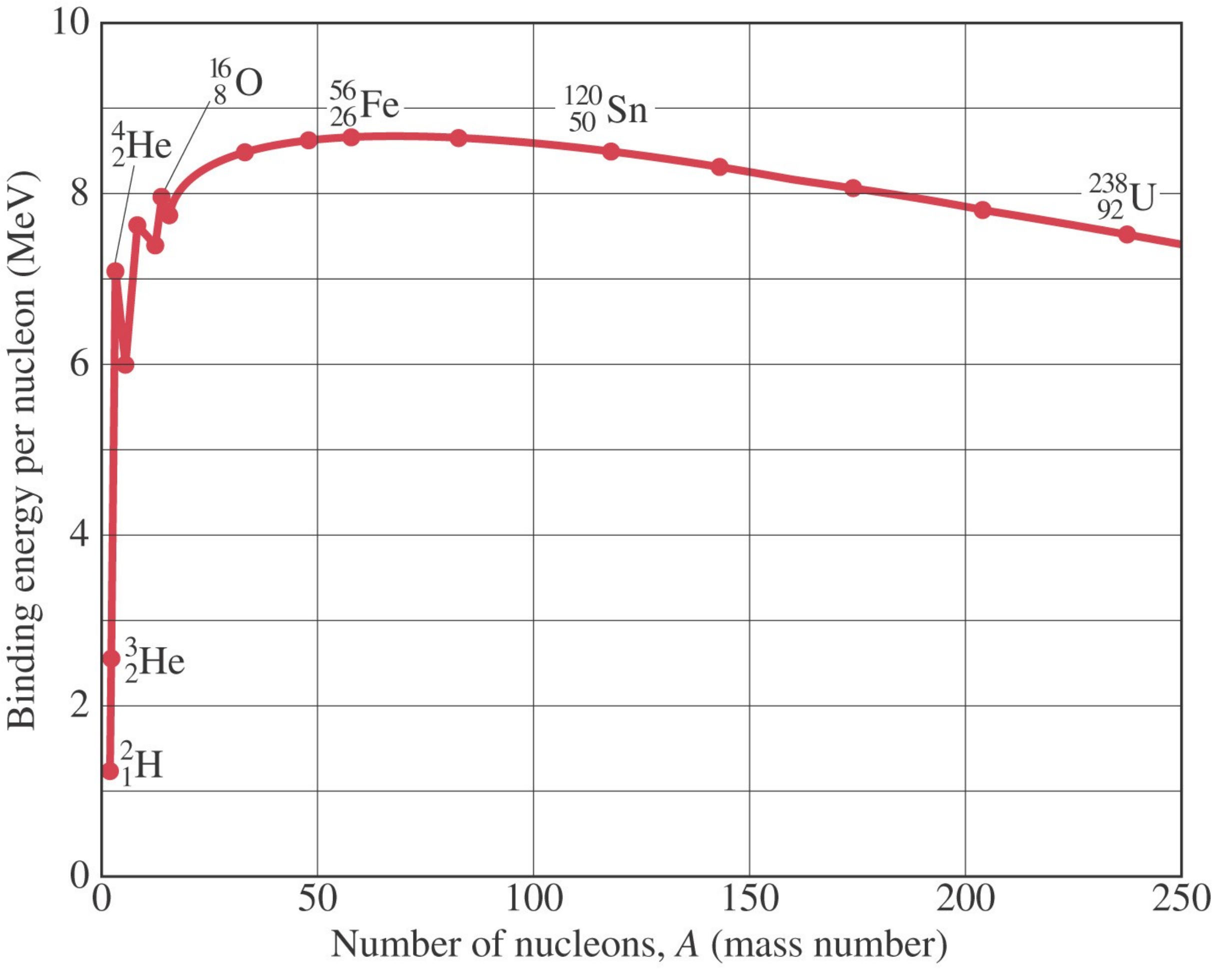
Where has the mass gone?

Energy, as radiation or kinetic energy, is released during formation of a nucleus by ‘fusion’ of smaller nuclei, giving a net mass difference.

This difference between the total mass of separate nucleons and the mass of the final nucleus is then the total binding energy of that nucleus.

Binding Energy and Nuclear Forces

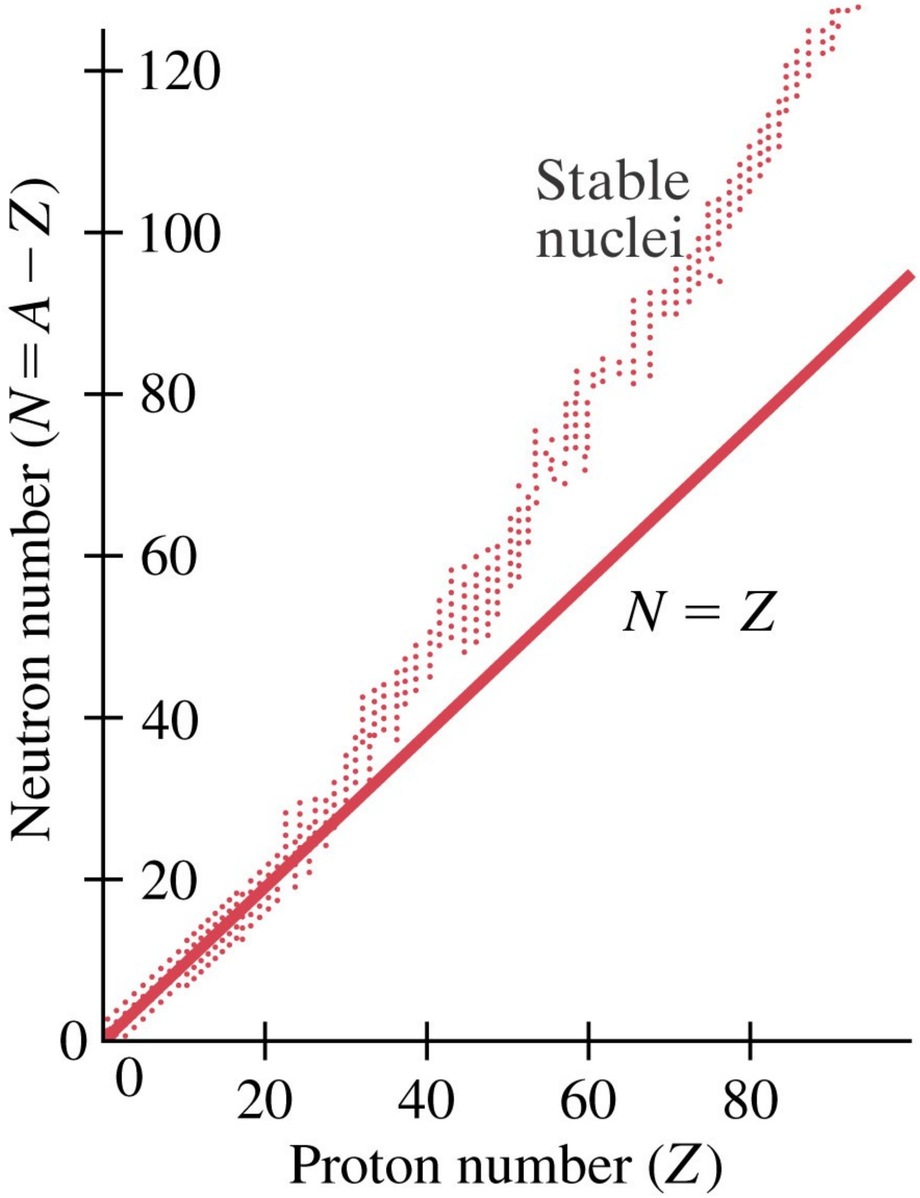
To compare how tightly bound different nuclei are, we divide the binding energy by A to get the binding energy per nucleon.



Binding Energy and Nuclear Forces

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.



Binding Energy and Nuclear Forces

The force that binds the nucleons together is called the **strong nuclear force.**

This is a very strong, but very short-range, force. It is essentially zero if the nucleons are more than about 10^{-15} m apart, which roughly corresponds to the size of a nucleus. The Coulomb force is long-range; this is why extra neutrons are needed for stability of high-Z nuclei.

Unstable nuclei decay; some decays are governed by another force, called the **weak nuclear force.**

Radioactivity

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

Three types of ‘Radioactive Rays’ were found

- **Alpha rays,** which barely penetrate a sheet of paper
- **Beta rays,** which can penetrate 3 mm of aluminum
- **Gamma rays,** which penetrate several cm of lead

We now know that

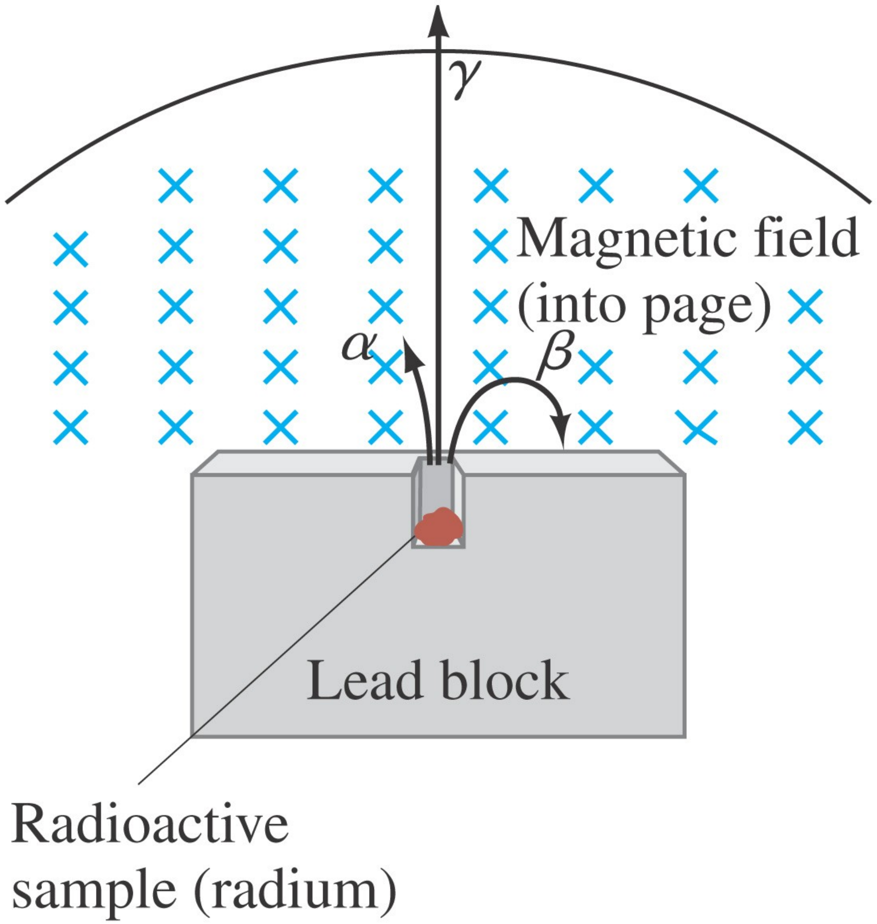
alpha rays are helium nuclei,

beta rays are electrons, and

gamma rays are electromagnetic radiation.

Radioactivity

Regular **Alpha** and **Beta rays** are bent in opposite directions in a magnetic field, thus have opposite charge; while **gamma rays** are not bent at all.

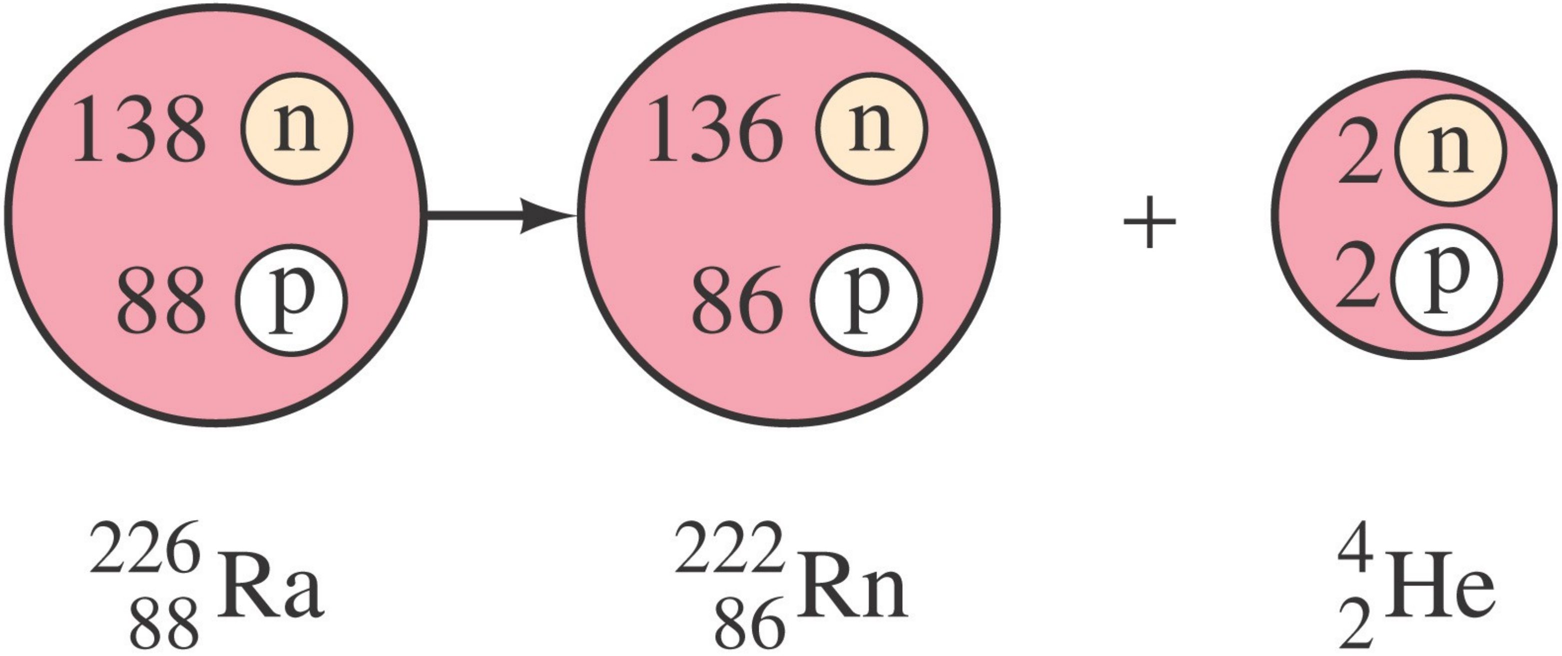


Alpha Decay

Example of alpha decay:

Radium-226 will alpha-decay to **Radon-222**

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



Alpha Decay

In general, an alpha decay process can be written:

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

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.

Alpha particles themselves are very stable.

Beta Decay

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

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

The final 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 atomic orbital electron; it is created in the decay.

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

$$\mathrm{n} \rightarrow \mathrm{p} + \mathrm{e}^{-} + \text{a neutrino.}$$

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.

Beta 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 yrs had passed after they were ‘predicted’.

The symbol for the neutrino is the Greek letter nu, ν We can write the beta decay of carbon-14 as:

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

Beta Decay

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

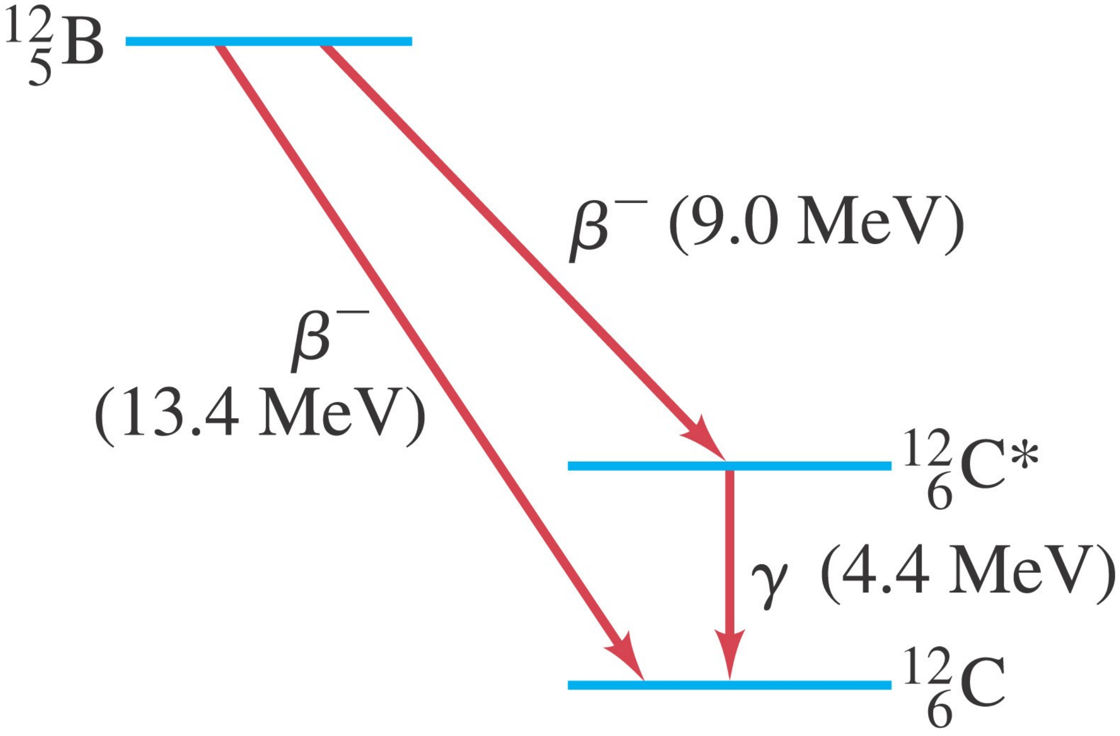
$$^{19}_{10}\mathrm{Ne} \rightarrow\ ^{19}_{9}\mathrm{F} + \mathrm{e}^{+} + \nu$$

A nucleus can also capture one of its inner electrons.

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

Gamma Decay (or Emission)

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

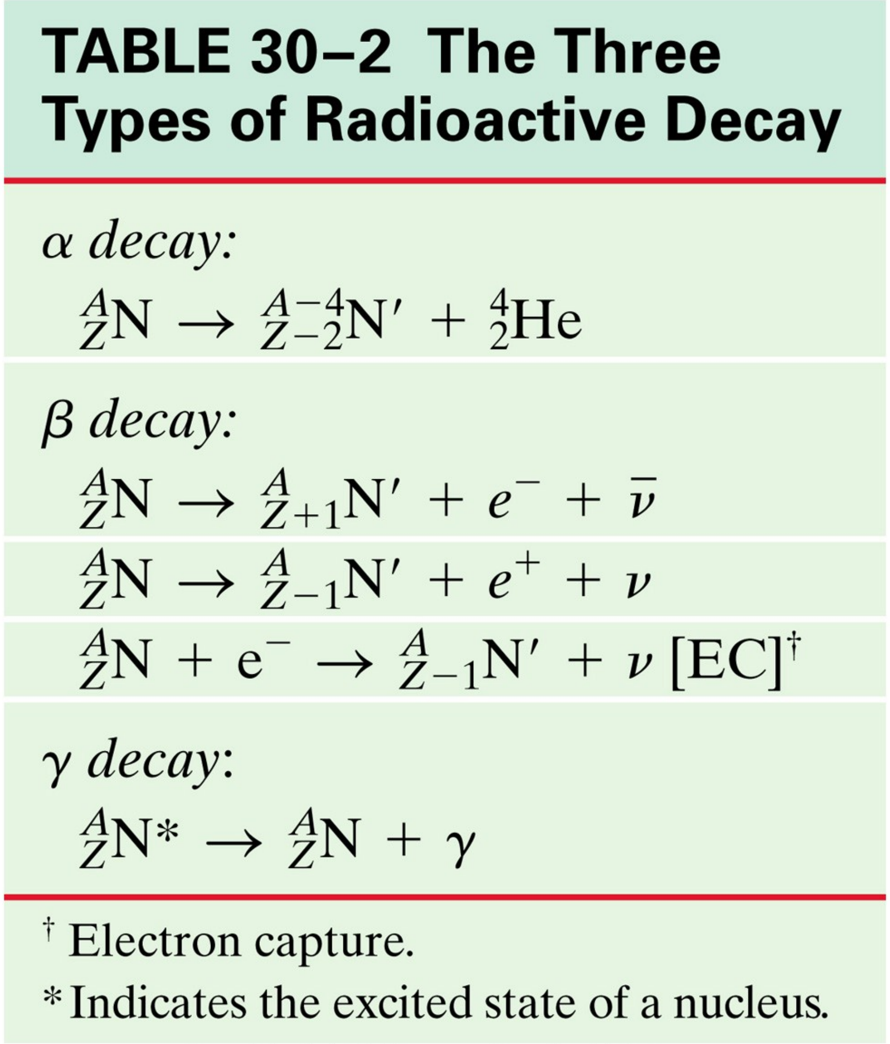


TABLE 30–2 The Three Types of Radioactive Decay

α decay:

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

β decay:

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

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

$${}^{A}_{Z}\mathrm{N} + \mathrm{e}^{-} \rightarrow {}^{A}_{Z-1}\mathrm{N}' + \nu \ [\mathrm{EC}]^{\dagger}$$

γ decay:

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

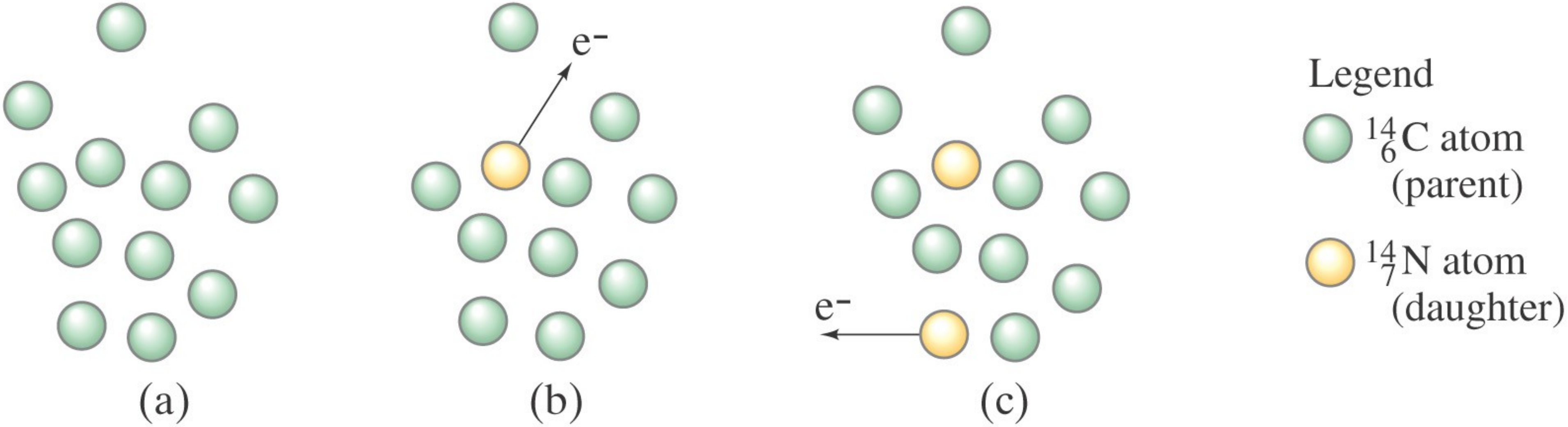
† Electron capture.

* Indicates the excited state of a nucleus.

A new conservation law becomes evident by studying details of radioactive decay: **the total number of nucleons cannot change.**

Half-Life and Rate of Decay

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



Half-Life and Rate of Decay

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

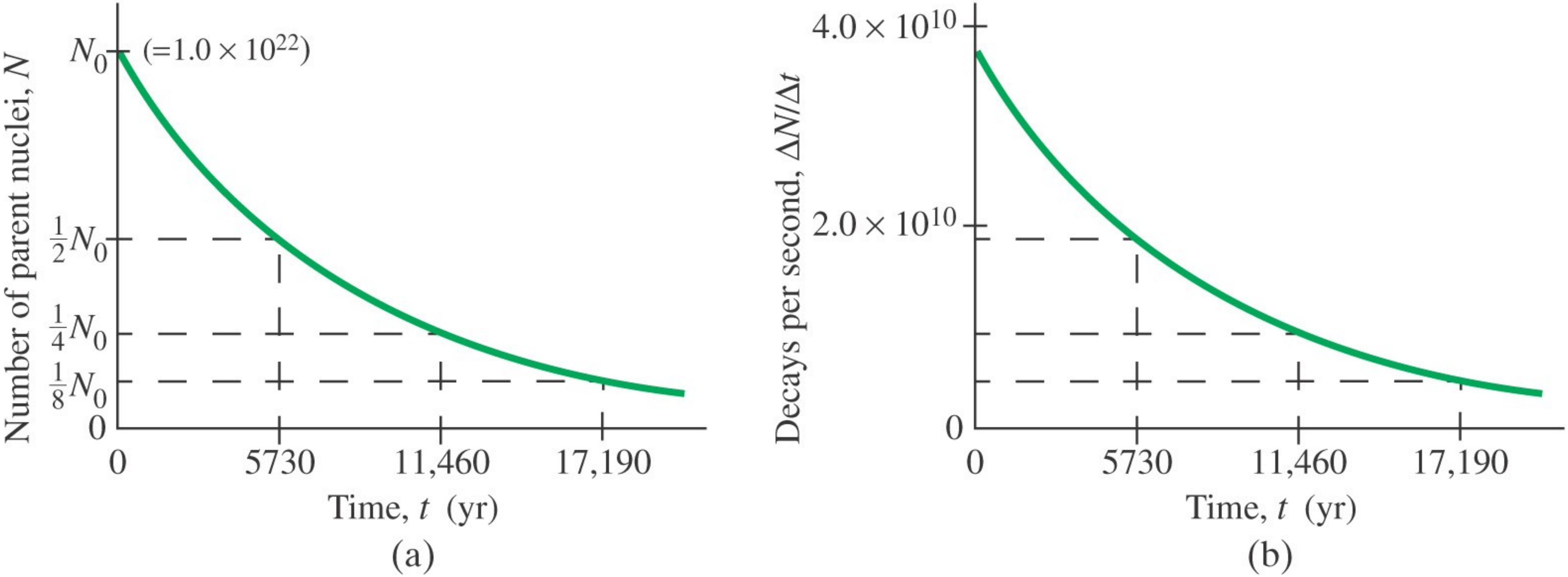
$$\Delta N = -\lambda N \,\Delta t$$

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

Half-Life and Rate of Decay

This rate equation can be solved using calculus, the result for N as a function of time is

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



Half-Life and Rate of Decay

The **half-life** of a particular nuclide is the time it takes for half the nuclei in a given sample to decay. This is related to the decay constant by

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

It is often more useful in calculations to think in terms of an exponential lifetime, $\tau = 1 / \lambda$

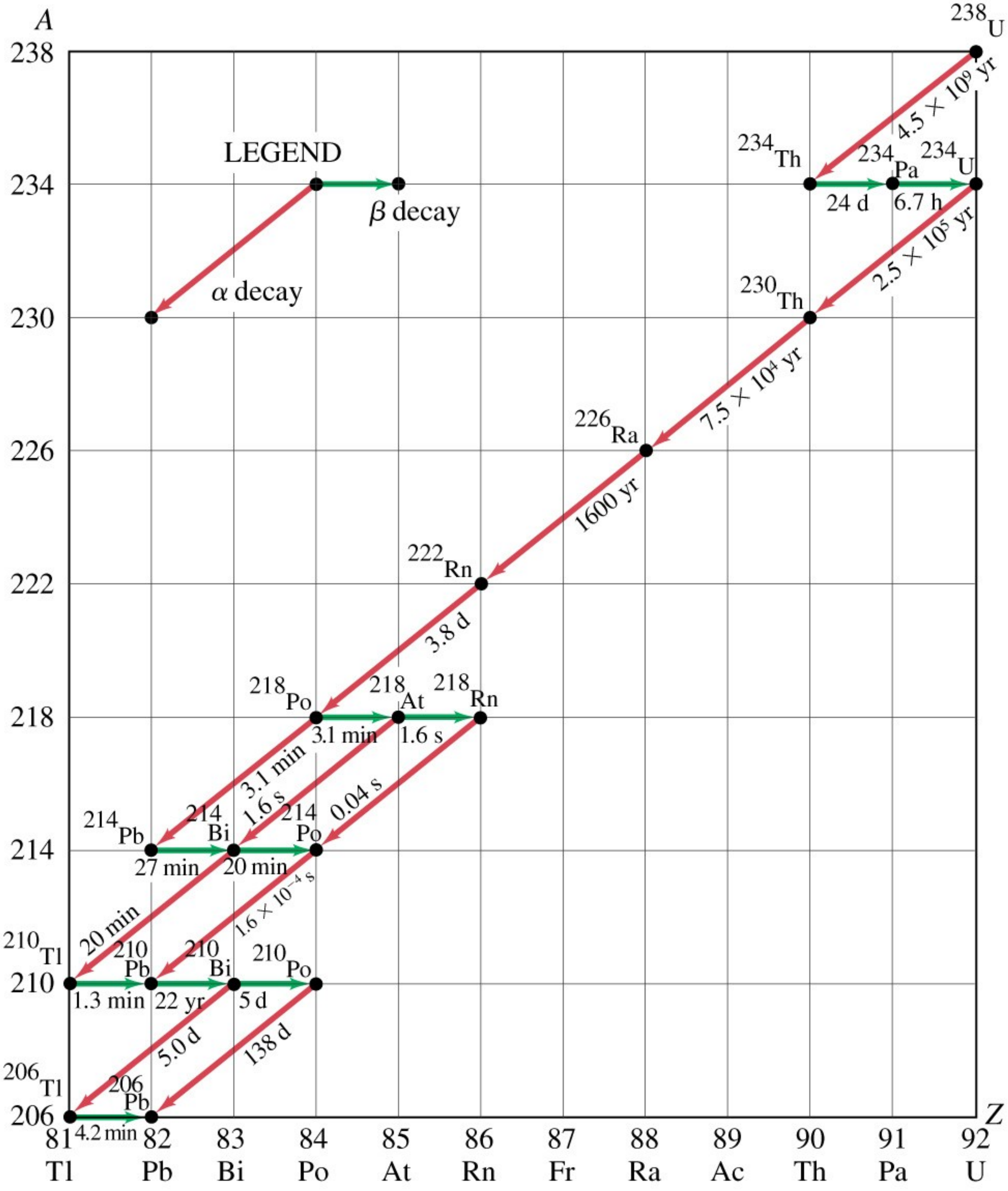
One also then has $T_{1/2} = 0.693\ \tau$

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.

The Nuclear Decay Series

starting from ^{238}U



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Radioactive Dating

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.

Radioactive Dating

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 tissue age deduced.

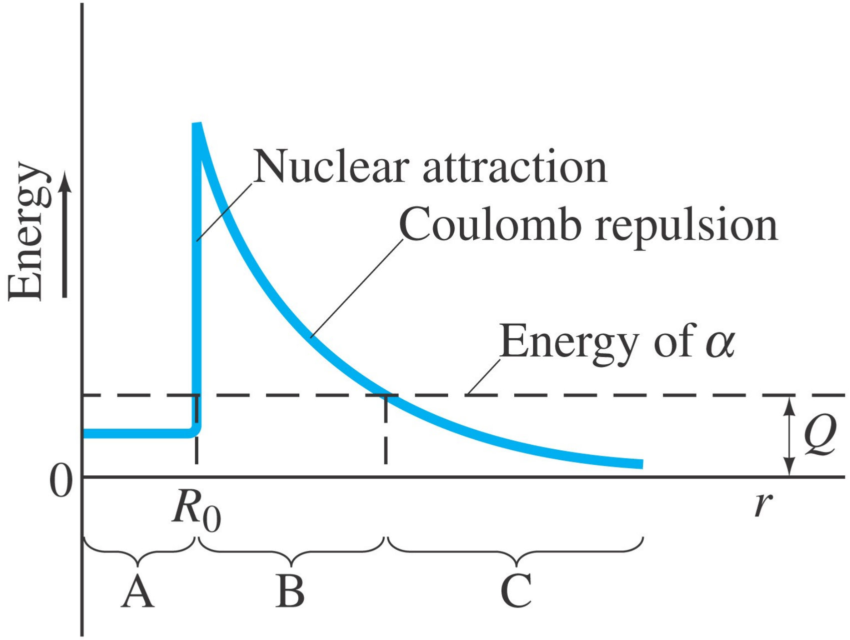
Objects older than about 60,000 years cannot be dated this way – there is too little carbon-14 left.

Other isotopes are useful for geologic time scale dating.Uranium-238 has a half-life of 4.5×10^9 years, and has been used to date the oldest rocks on Earth as about 4 billion years old.

Stability and Tunneling

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:



Stability and Tunneling

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:

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

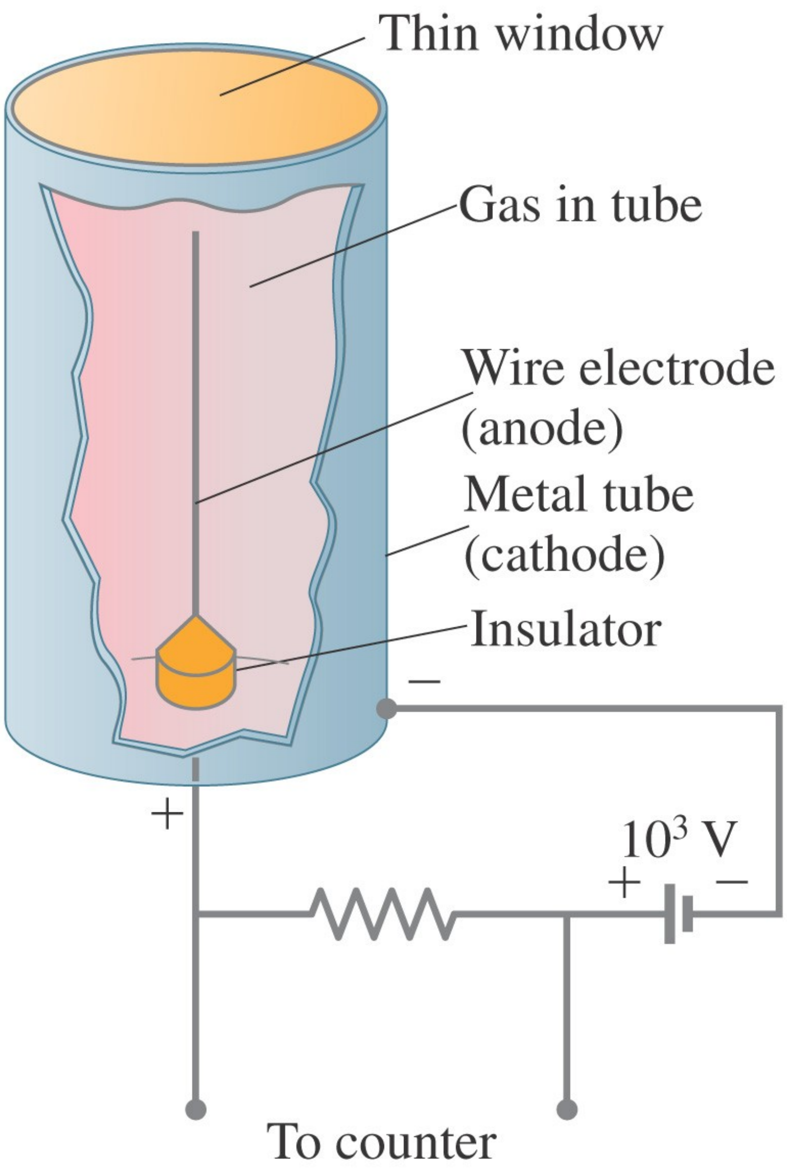
Stability and Tunneling

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.

Detection of Radiation

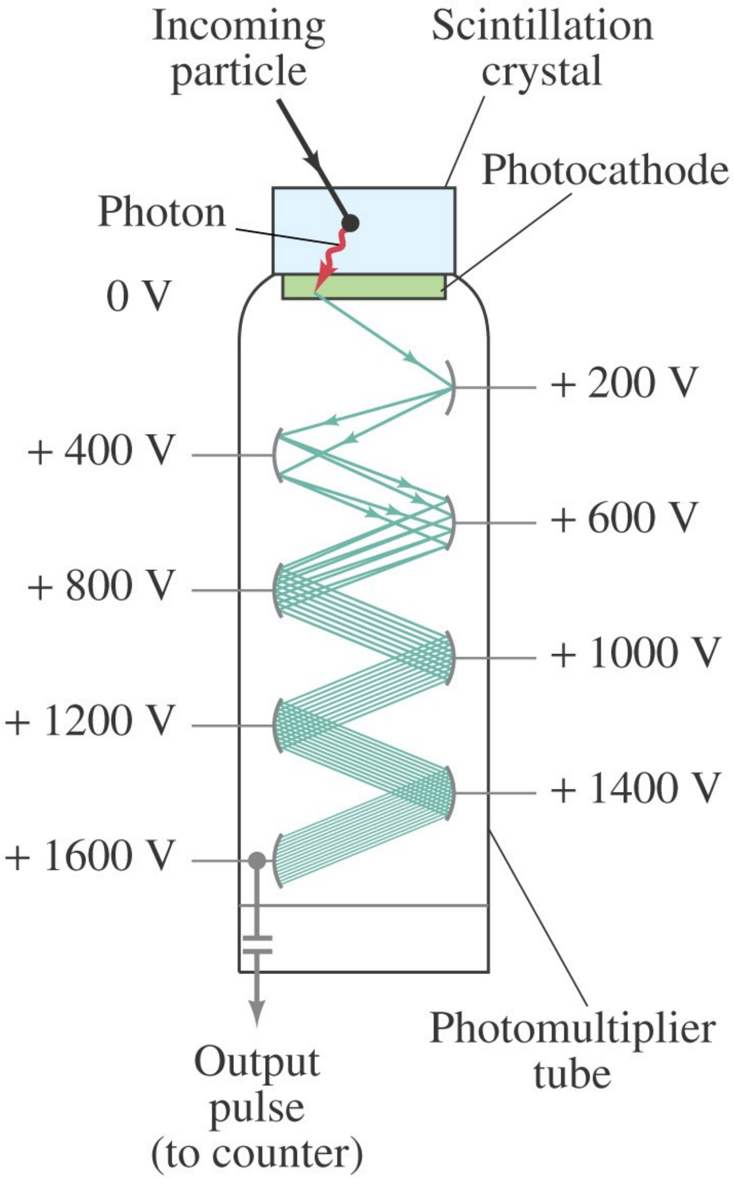
Individual particles such as electrons, neutrons, and protons cannot be seen directly, so their existence must be inferred through measurements. Many different devices, of varying levels of sophistication, have been developed to do this.

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.

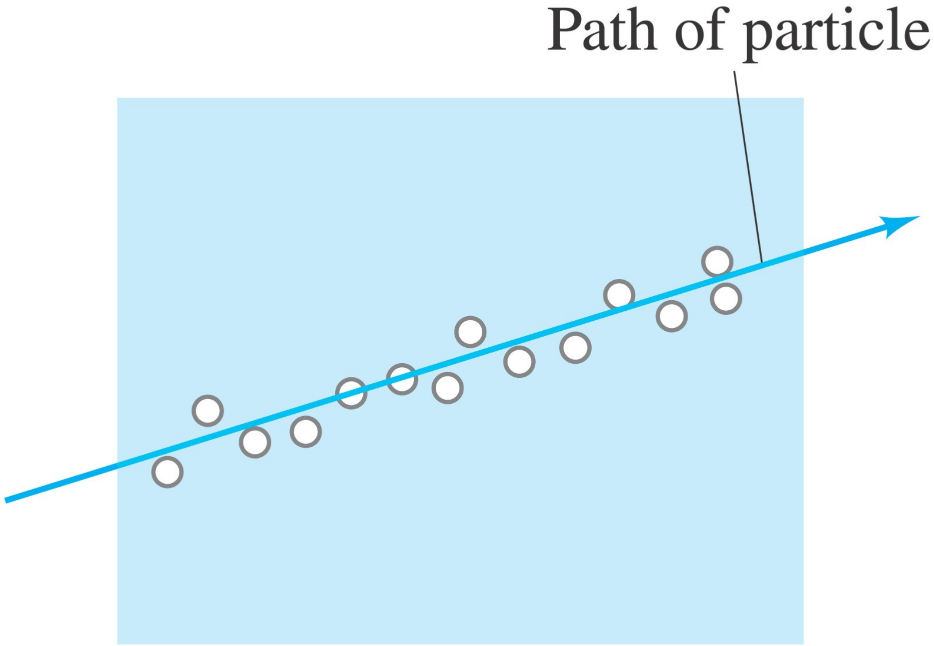
Detection of Radiation



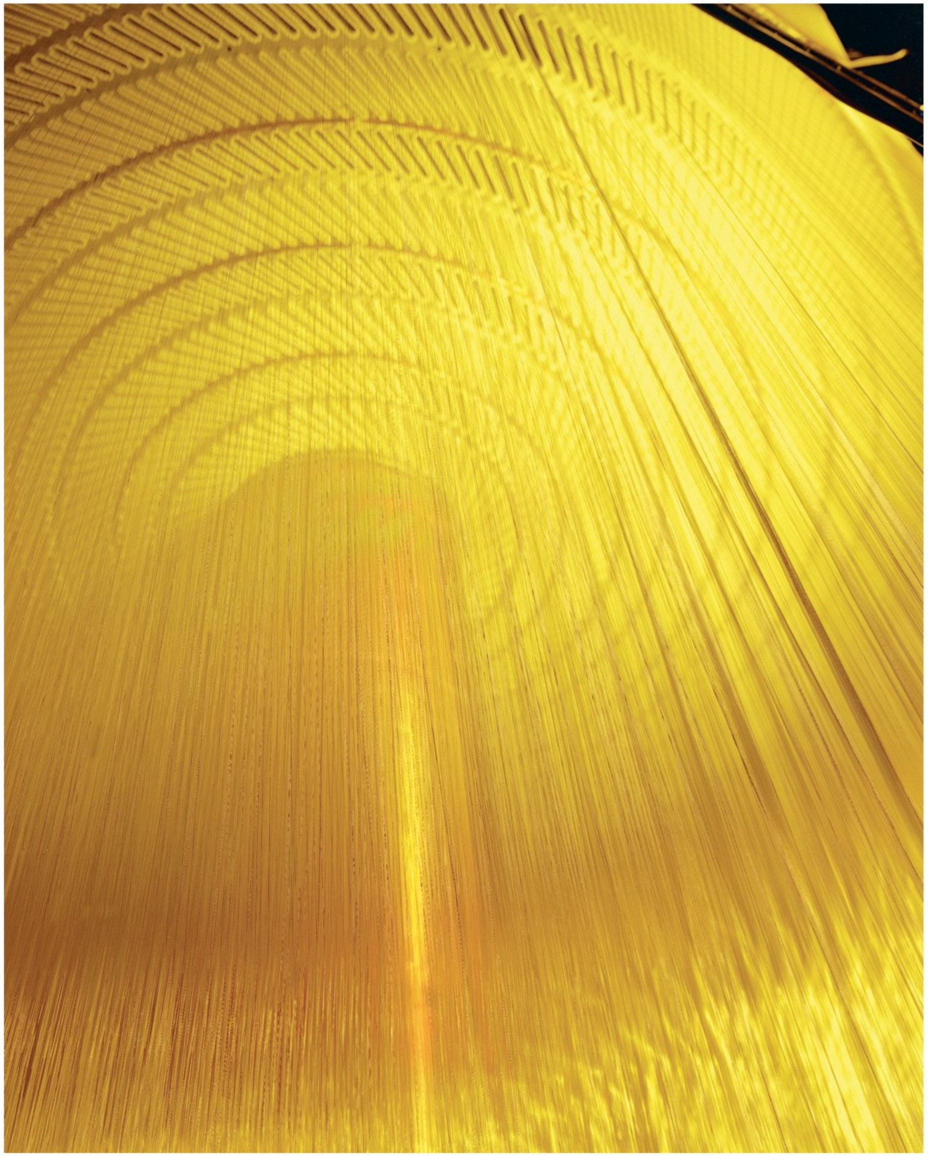
A scintillation counter uses a scintillator – a material that emits light when a charged particle goes through it. The scintillator is made light-tight, and the light flashes are viewed with a photomultiplier tube, which has a photocathode that emits an electron when struck by a photon and then a series 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.



Detection of Radiation



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: $^{A}_{Z}\mathrm{X}$
- Nuclear masses are measured in u; carbon-12 is defined as having a mass of 12 u

$$1\ \mathrm{u} = 931.5\ \mathrm{MeV}/c^2 = 1.66 \times 10^{-27}\ \mathrm{kg}$$

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

Summary of Chapter 30

- 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 $T_{1/2} = 0.693 / \lambda$