Phys102 Lecture 34/35

Nuclear Physics and Radioactivity

Key Points

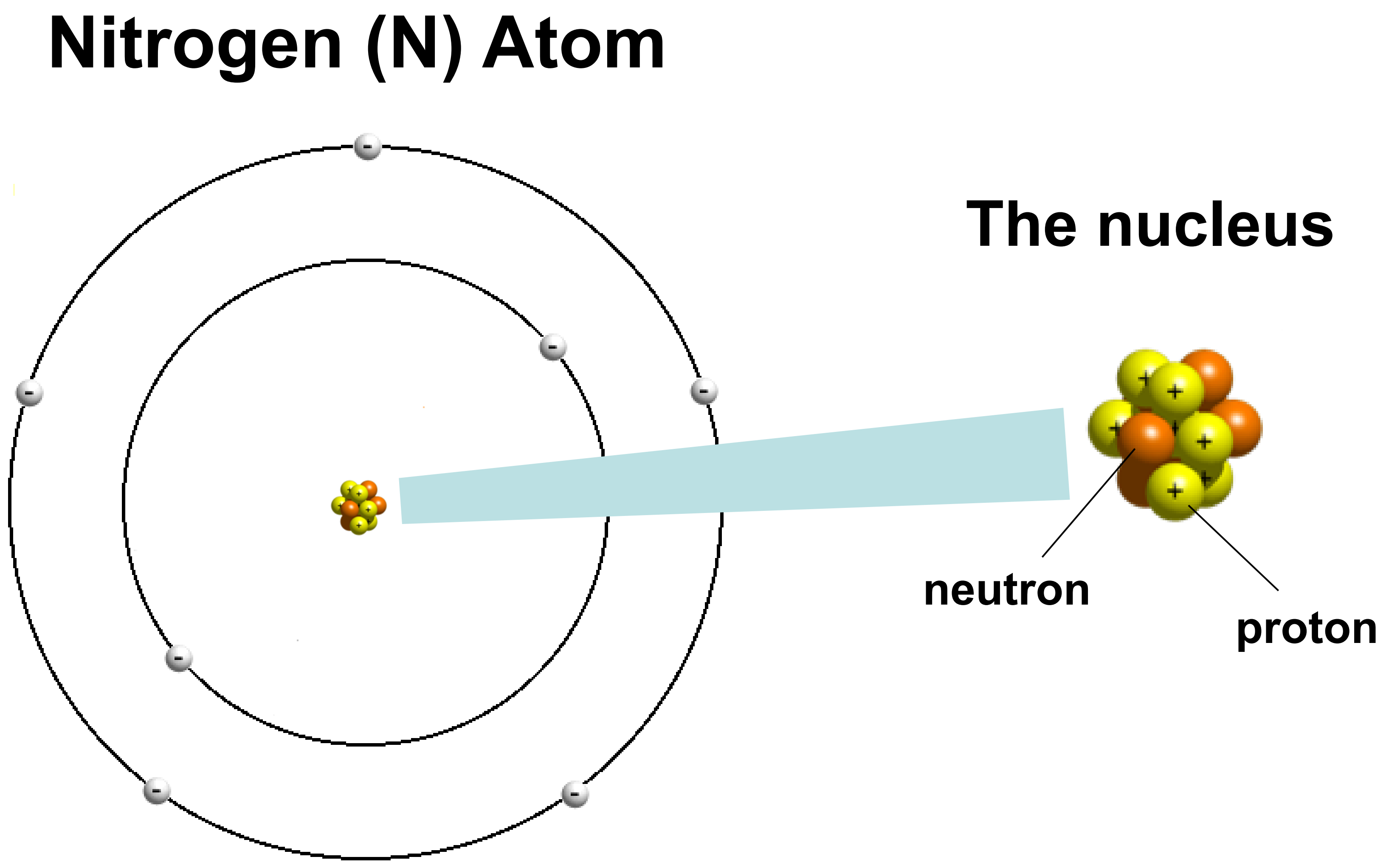
- Structure and Properties of the Nucleus
- Alpha, Beta and Gamma Decays
- Calculations Involving Decay Rates and Half-Life
- Radioactive Dating

References

SFU Ed: 42-1,2,3,4,5,6,7,8,9,10.

6^{th} Ed: 30-1,2,3,4,5,6,7,8,9,10,11.

Atomic Structure



Structure and Properties of the Nucleus

A nucleus is made of protons and neutrons.

A proton is positively charged. Its mass is:

$$m_{\mathrm{p}} = 1.67262 \times 10^{-27}\,\mathrm{kg}$$

A neutron is electrically neutral:

$$m_{\mathrm{n}} = 1.67493 \times 10^{-27}\,\mathrm{kg}$$

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: $N = A - Z$. Therefore, A and Z are sufficient to specify a nuclide.

Nuclides are symbolized as : $^{A}_{Z}\mathrm{X}$

X is the chemical symbol for the element; it contains the same information as Z but in a more easily recognizable form.

Structure and Properties of the Nucleus

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.

Structure and Properties of the Nucleus

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

$$r \approx \left(1.2 \times 10^{-15}\,\mathrm{m}\right)\left(A^{\frac{1}{3}}\right) \qquad \textbf{(42-1)}$$

Structure and Properties of the Nucleus

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*.**

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

Structure and Properties of the Nucleus

From the following table, you can see that the electron is considerably less massive than a nucleon.

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

	Mass		
Object	**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

Binding Energy and Nuclear Forces

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?

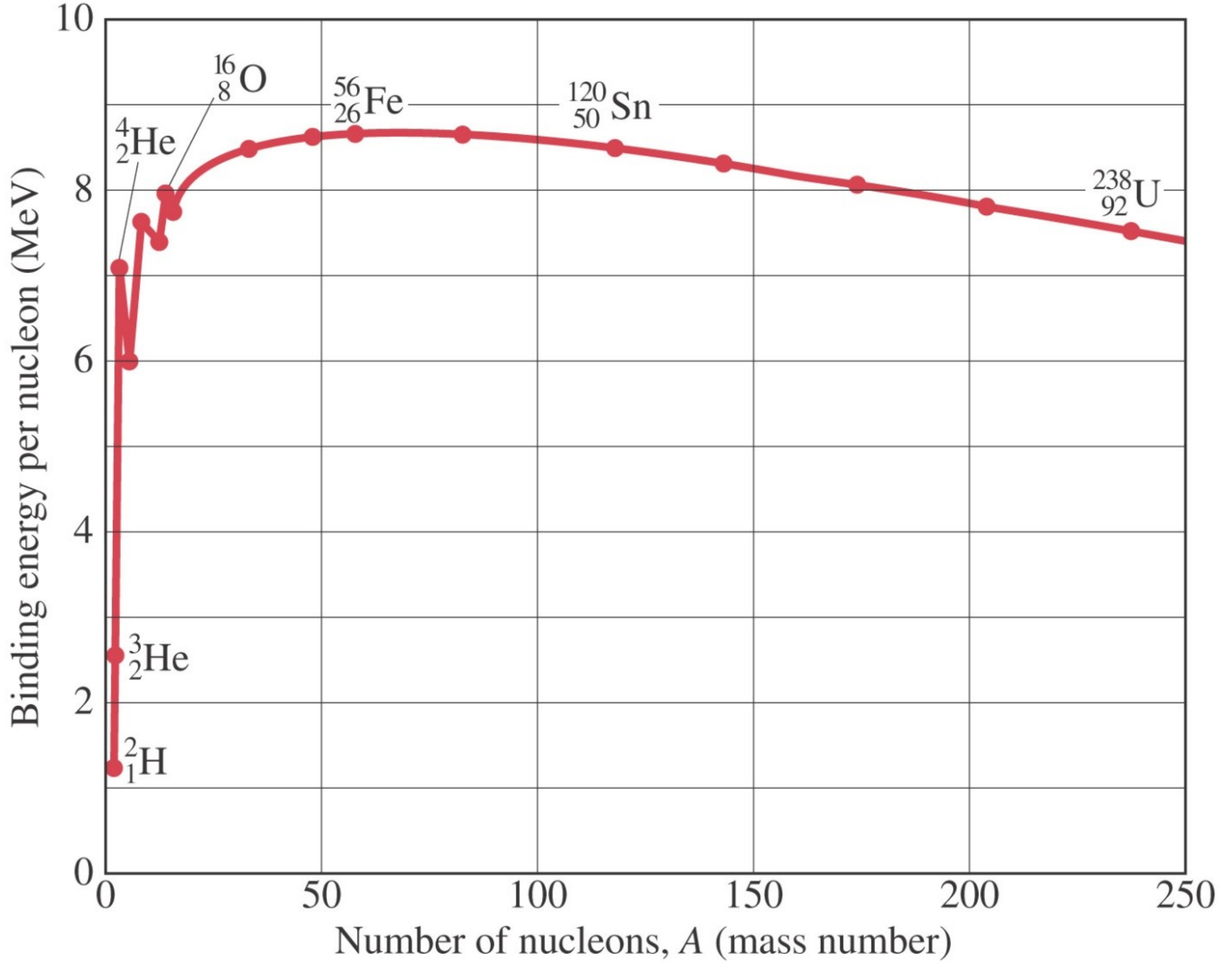
Binding Energy and Nuclear Forces

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.

Binding Energy and Nuclear Forces

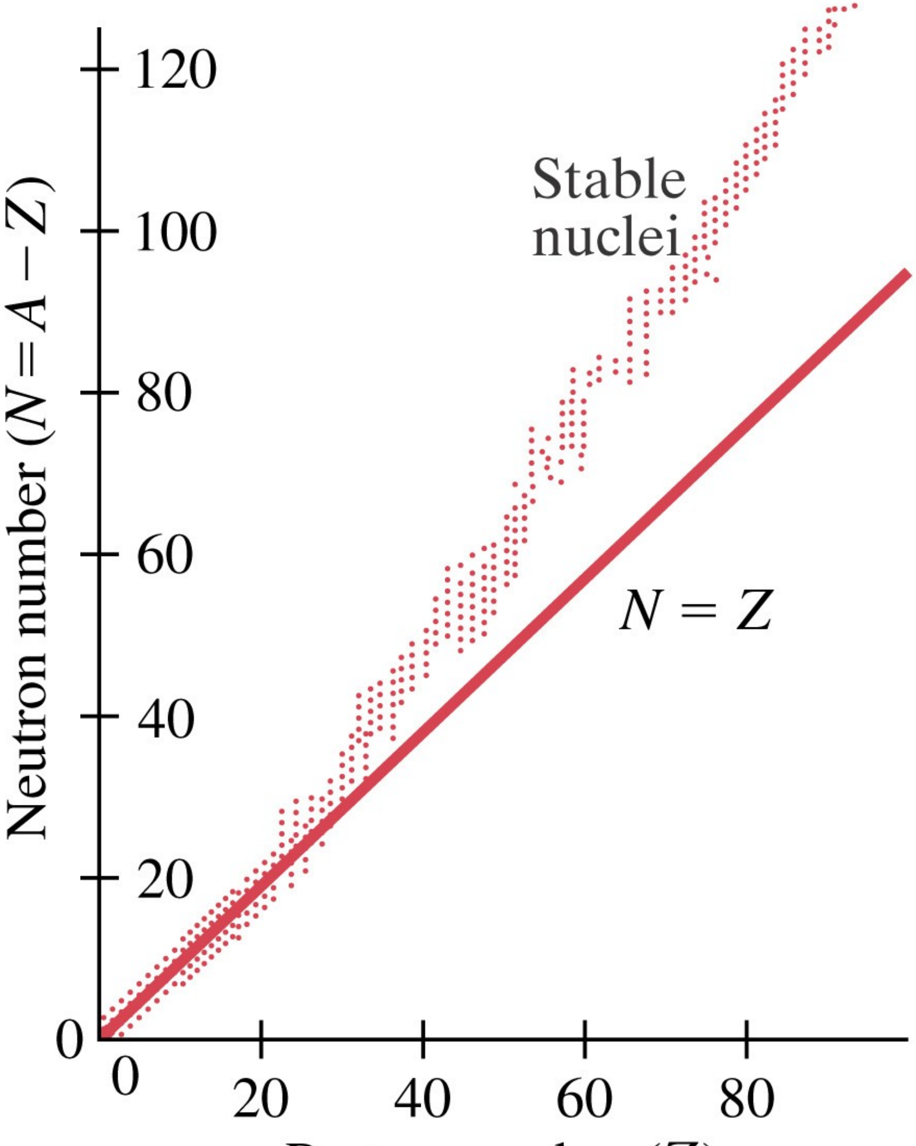
To compare how tightly bound different nuclei are, we divide the binding energy by A to get the binding energy per nucleon.



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. 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.

Binding Energy and Nuclear Forces

Nuclei that are unstable decay; many such 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

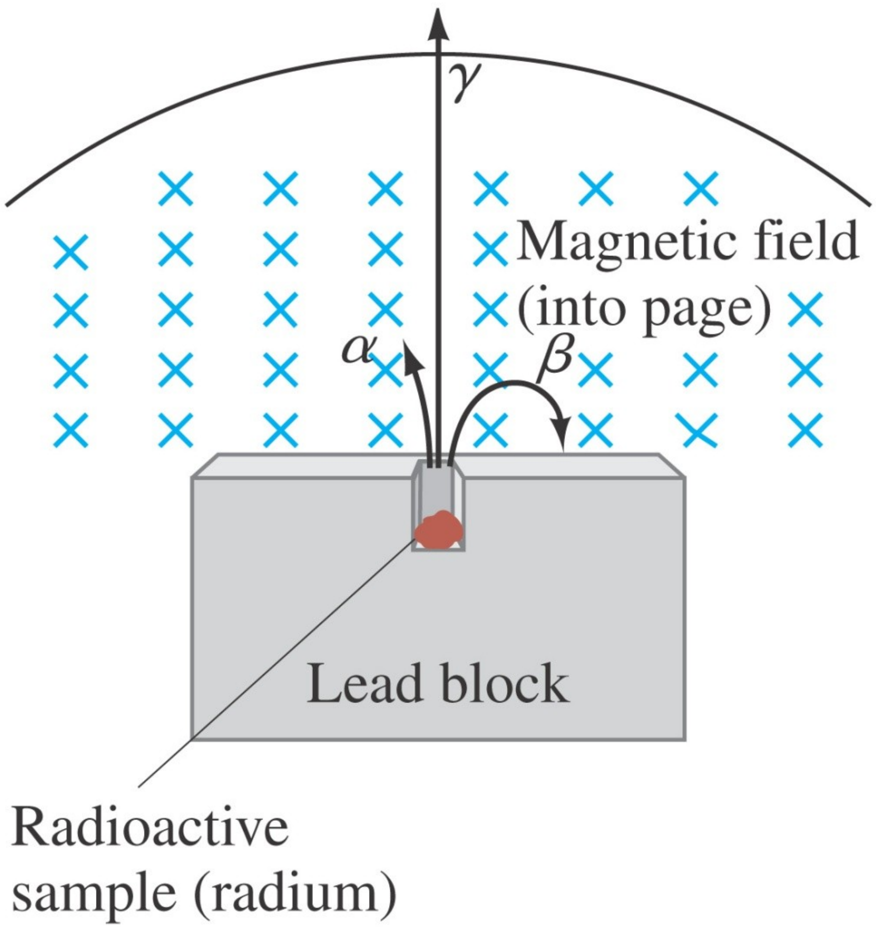
Radioactive rays were observed to be of three types:

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.

Radioactivity

Alpha and beta rays are bent in opposite directions in a magnetic field, while gamma rays are not bent at all.

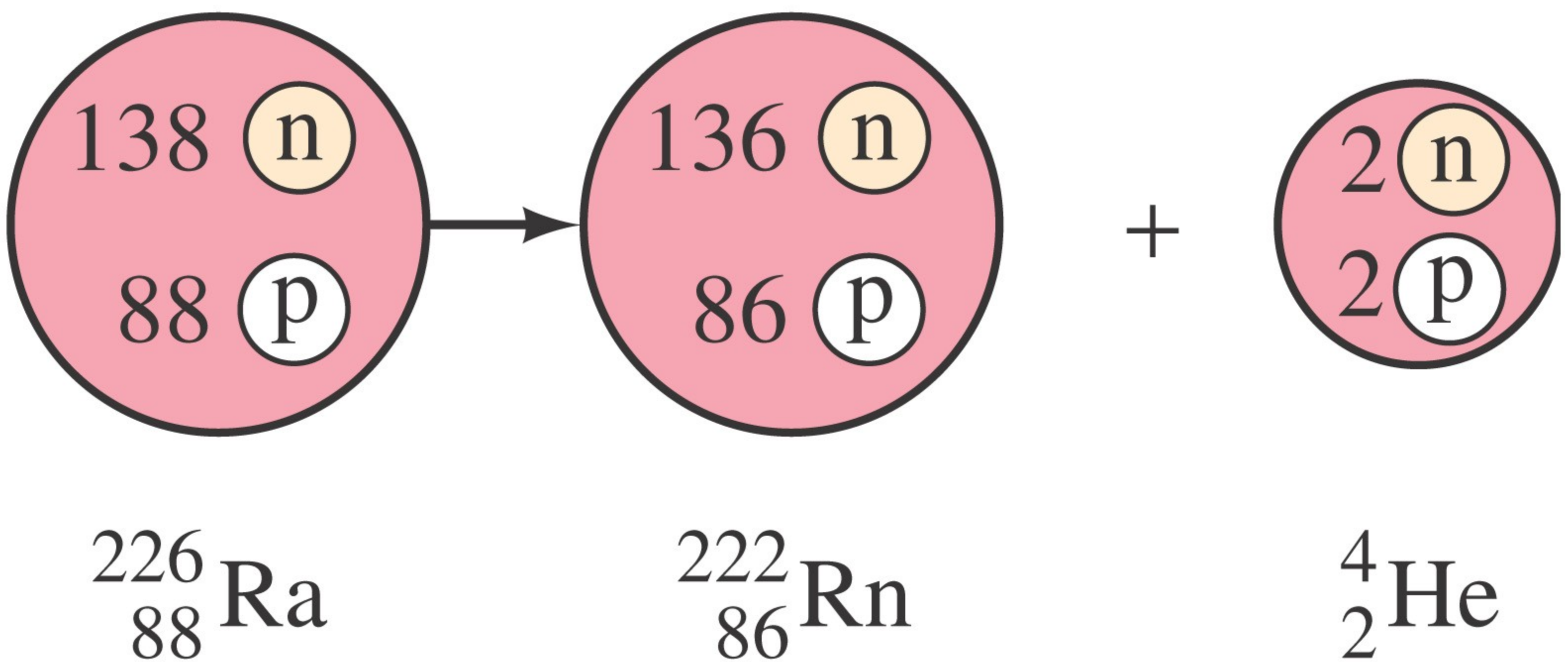


Alpha Decay

Example of alpha decay:

Radium-226 will alpha-decay to radon-22

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



Alpha Decay

In general, alpha decay 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 Decay

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

Alpha Decay

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

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 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:

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

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 years had passed.

The symbol for the neutrino is the Greek letter nu (*v*); using this, we 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:

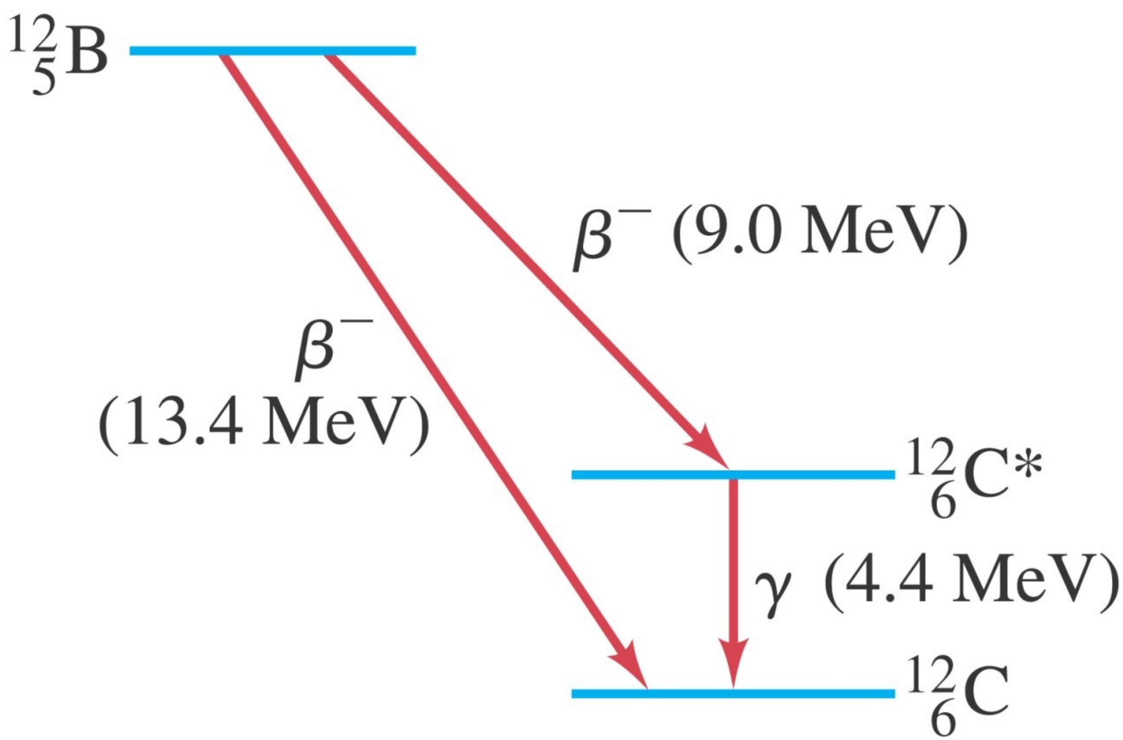
$$^{19}_{10}\mathrm{Ne} \rightarrow\ ^{19}_{9}\mathrm{F} + \mathrm{e}^{+} + \nu$$

And a nucleus can capture one of its inner electrons:

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

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 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:

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

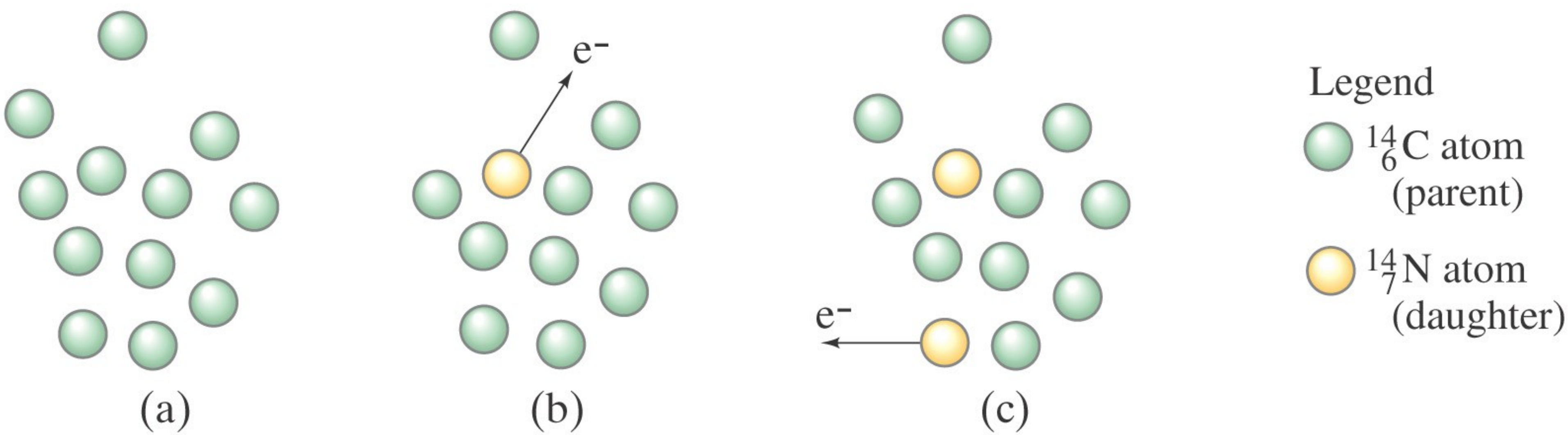
† Electron capture.

* Indicates the excited state of a nucleus.

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

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.



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:

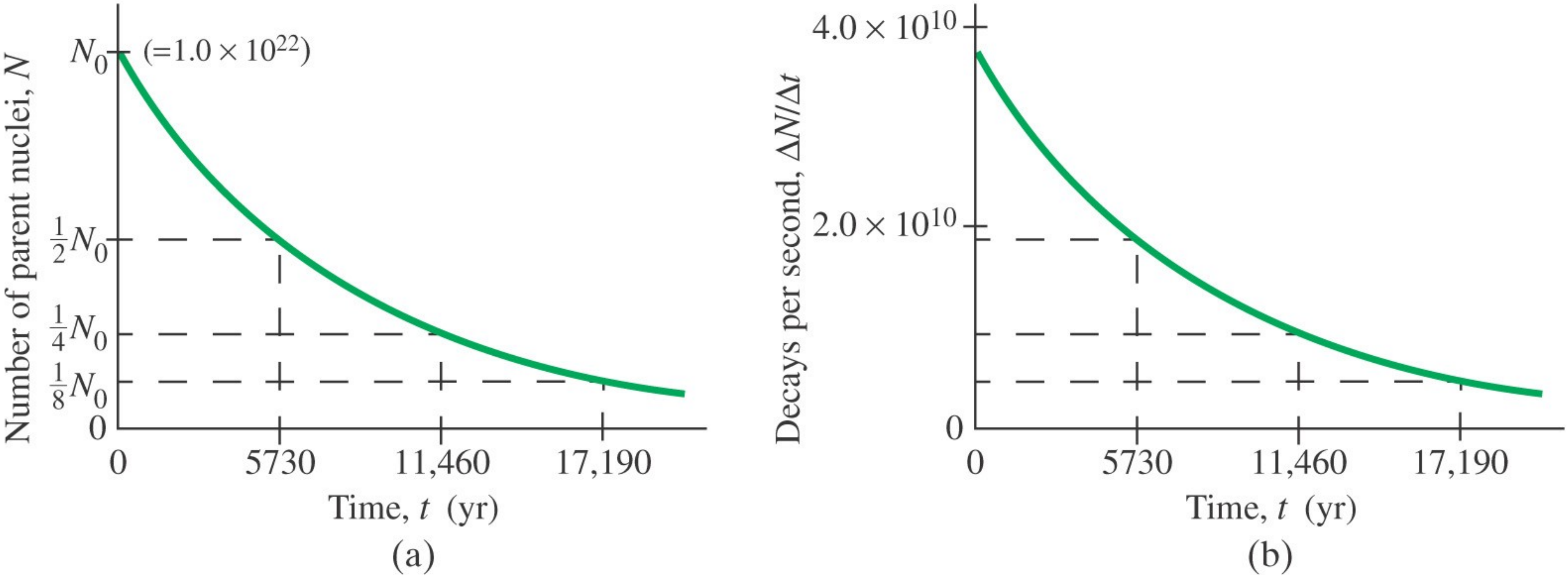
$$\Delta N = -\lambda N \, \Delta t \qquad \text{(30-3a)}$$

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

Half-Life and Rate of Decay

This equation can be solved, using calculus, for N as a function of time:

$$N = N_0 e^{-\lambda t} \qquad \textbf{(30-4)}$$



Half-Life and Rate of Decay

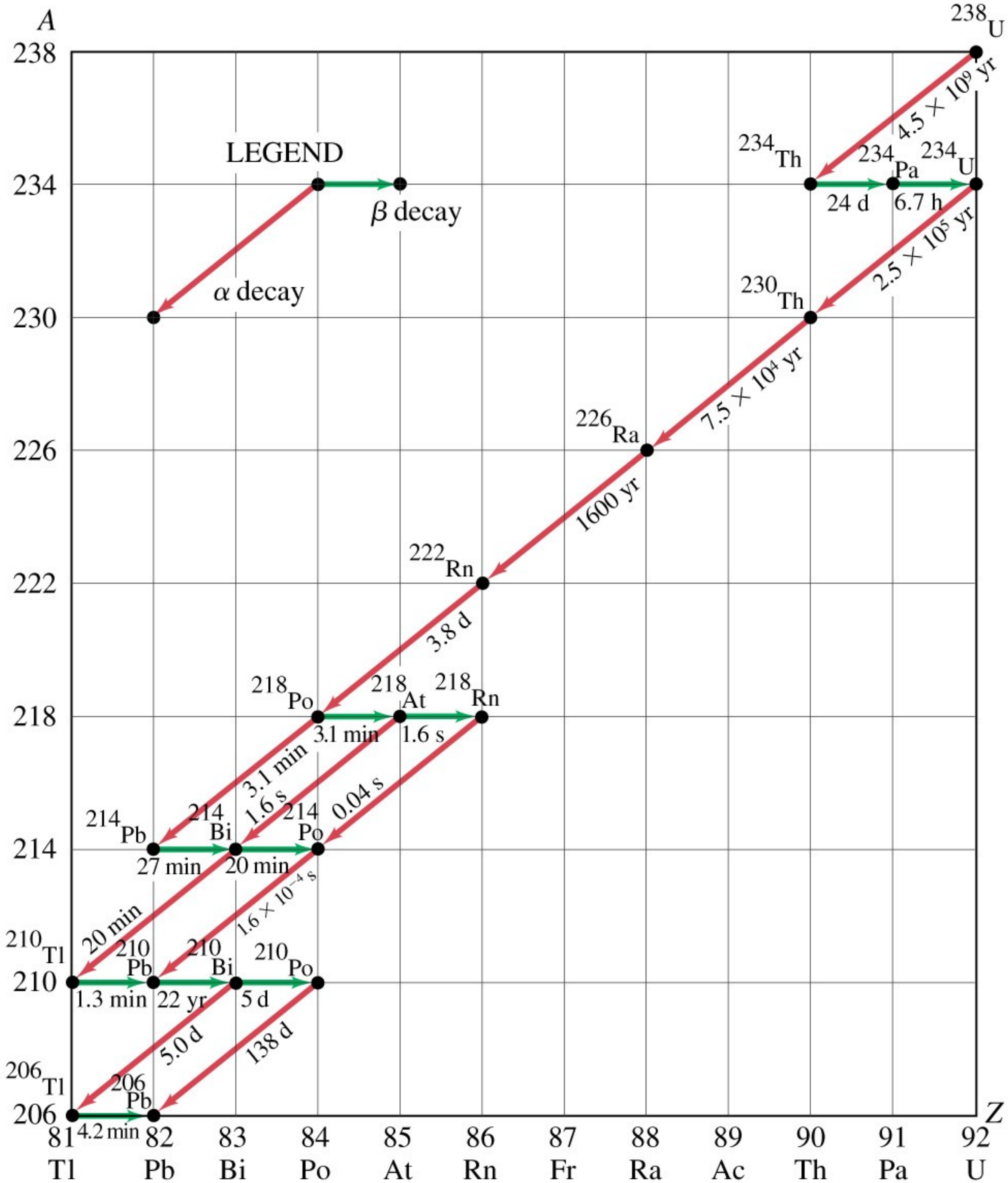
The half-life is the time it takes for half the nuclei in a given sample to decay. It is related to the decay constant:

$$T_{\frac{1}{2}} = \frac{\ln 2}{\lambda} = \frac{0.693}{\lambda} \qquad \textbf{(30-6)}$$

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.

Decay Series



Radioactive Dating

Radioactive dating can be done by analyzing the fraction of carbon in organic material that is carbon-14.

Radioactive Dating

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 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.

Radioactive Dating

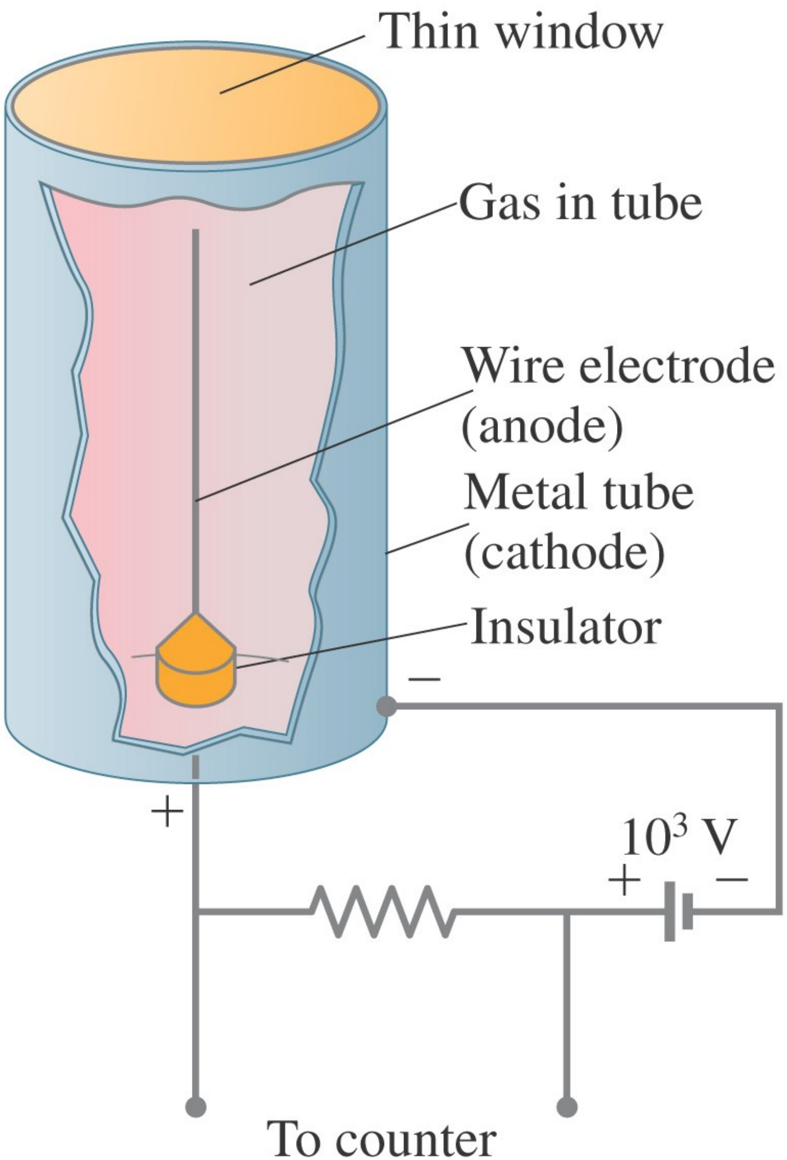
Other isotopes are useful for geologic time scale dating.

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.

Detection of Radiation

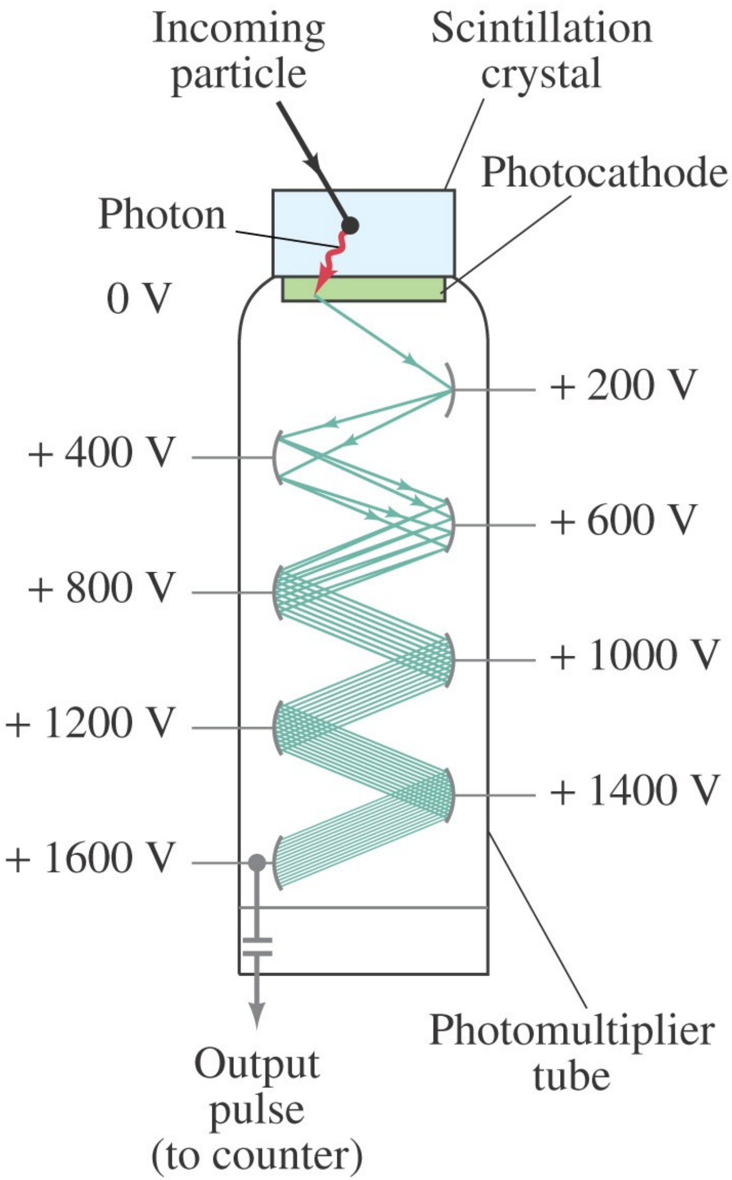
Individual particles such as electrons, neutrons, and protons cannot be seen directly, so their existence must be inferred through measurements. Many different devices, of varying levels of sophistication, have been developed to do this.

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.

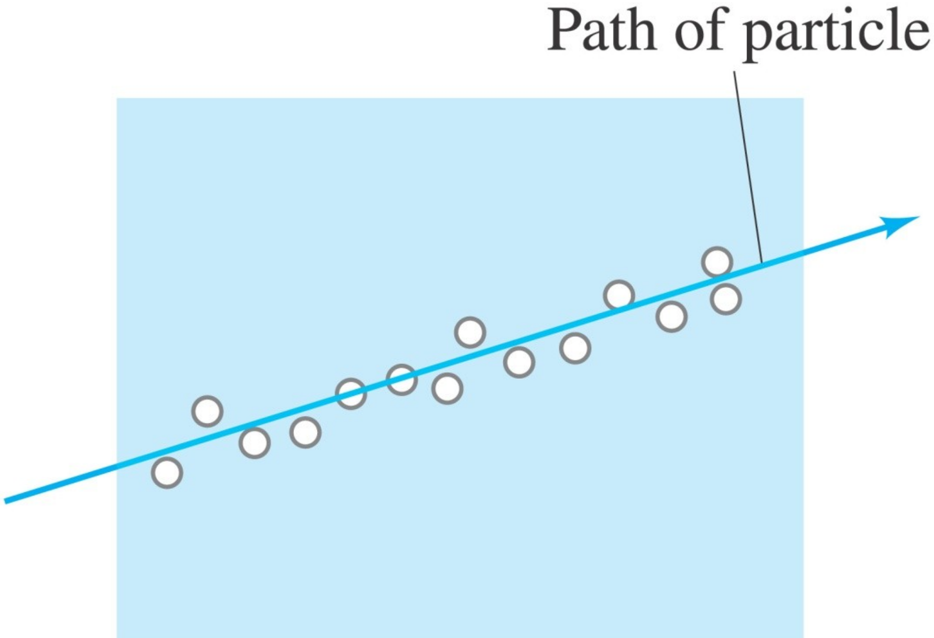
Detection of Radiation



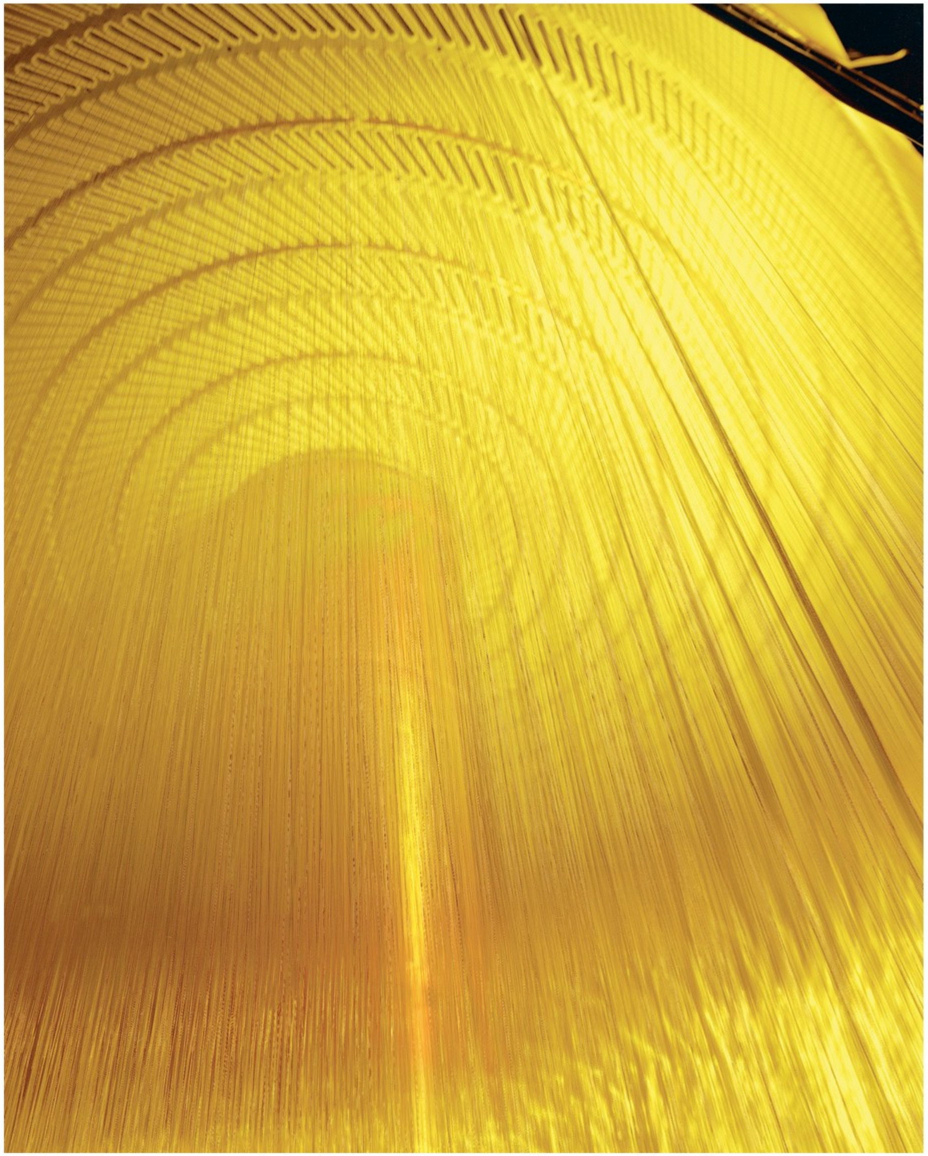
A scintillation counter uses a scintillator – a material that emits light when a charged particle goes through it. The scintillator is made light-tight, and the light flashes are viewed with a photomultiplier tube, which has a photocathode that emits an electron when struck by a photon and then a series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