Radiation and Radioactivity

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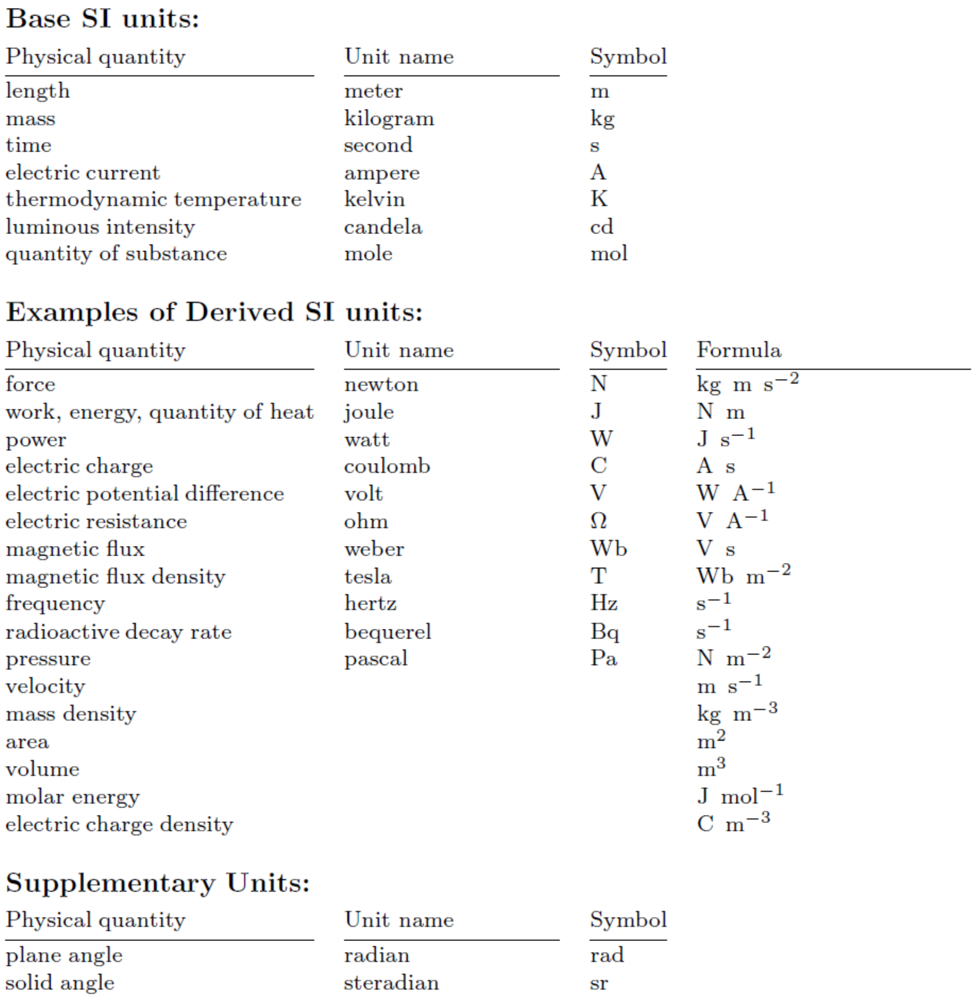
Modern units and prefixes

- With only a few exceptions, units used in nuclear science and engineering are those defined by the SI system of metric units.



Base SI units:

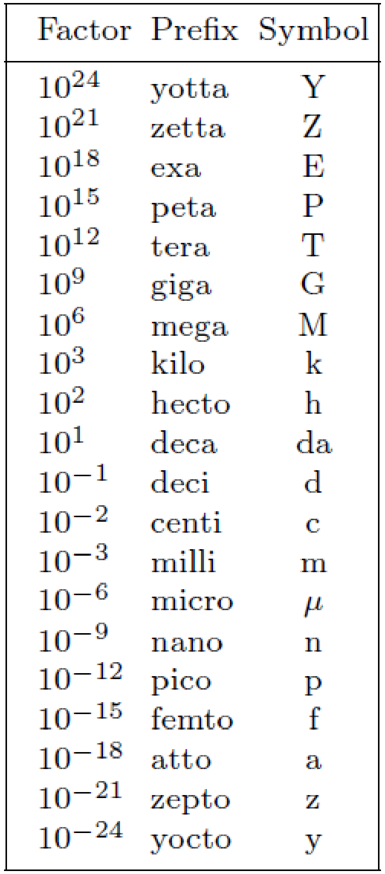
Physical quantity	Unit name	Symbol
length	meter	m
mass	kilogram	kg
time	second	s
electric current	ampere	A
thermodynamic temperature	kelvin	K
luminous intensity	candela	cd
quantity of substance	mole	mol

Examples of Derived SI units:

Physical quantity	Unit name	Symbol	Formula
force	newton	N	$\mathrm{kg\ m\ s^{-2}}$
work, energy, quantity of heat	joule	J	N m
power	watt	W	$\mathrm{J\ s^{-1}}$
electric charge	coulomb	C	A s
electric potential difference	volt	V	$\mathrm{W\ A^{-1}}$
electric resistance	ohm	Ω	$\mathrm{V\ A^{-1}}$
magnetic flux	weber	Wb	V s
magnetic flux density	tesla	T	$\mathrm{Wb\ m^{-2}}$
frequency	hertz	Hz	$\mathrm{s^{-1}}$
radioactive decay rate	bequerel	Bq	$\mathrm{s^{-1}}$
pressure	pascal	Pa	$\mathrm{N\ m^{-2}}$
velocity			$\mathrm{m\ s^{-1}}$
mass density			$\mathrm{kg\ m^{-3}}$
area			$\mathrm{m^2}$
volume			$\mathrm{m^3}$
molar energy			$\mathrm{J\ mol^{-1}}$
electric charge density			$\mathrm{C\ m^{-3}}$

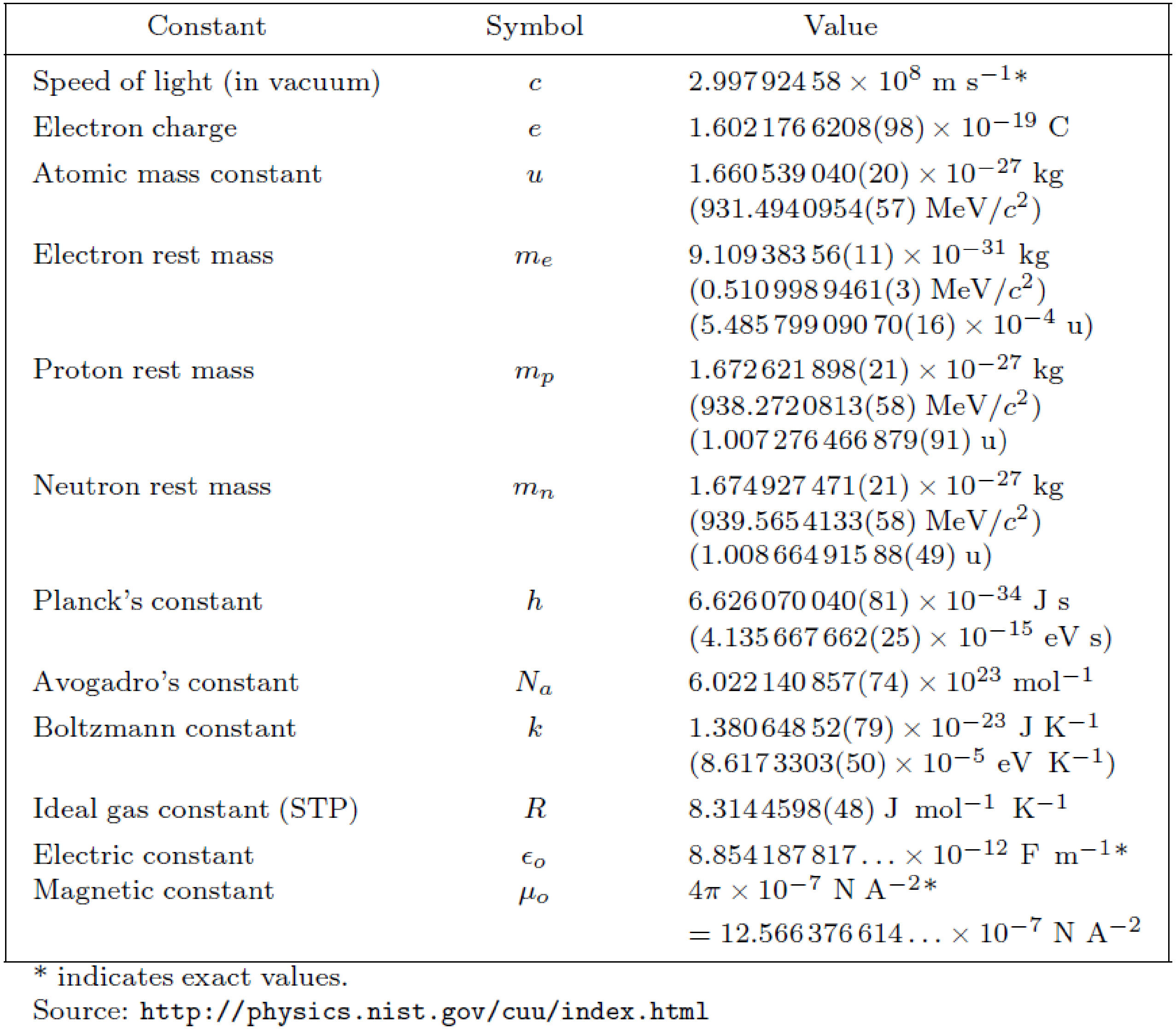
Supplementary Units:

Physical quantity	Unit name	Symbol
plane angle	radian	rad
solid angle	steradian	sr



Factor	Prefix	Symbol
10^{24}	yotta	Y
10^{21}	zetta	Z
10^{18}	exa	E
10^{15}	peta	P
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{2}	hecto	h
10^{1}	deca	da
10^{-1}	deci	d
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f
10^{-18}	atto	a
10^{-21}	zepto	z
10^{-24}	yocto	y

Values of some important physical constants



Constant	Symbol	Value
Speed of light (in vacuum)	c	$2.997\,924\,58 \times 10^{8}$ m s^{-1*}
Electron charge	e	$1.602\,176\,6208(98) \times 10^{-19}$ C
Atomic mass constant	u	$1.660\,539\,040(20) \times 10^{-27}$ kg $(931.494\,0954(57)$ MeV$/c^2)$
Electron rest mass	m_e	$9.109\,383\,56(11) \times 10^{-31}$ kg $(0.510\,998\,9461(3)$ MeV$/c^2)$ $(5.485\,799\,090\,70(16) \times 10^{-4}$ u$)$
Proton rest mass	m_p	$1.672\,621\,898(21) \times 10^{-27}$ kg $(938.272\,0813(58)$ MeV$/c^2)$ $(1.007\,276\,466\,879(91)$ u$)$
Neutron rest mass	m_n	$1.674\,927\,471(21) \times 10^{-27}$ kg $(939.565\,4133(58)$ MeV$/c^2)$ $(1.008\,664\,915\,88(49)$ u$)$
Planck's constant	h	$6.626\,070\,040(81) \times 10^{-34}$ J s $(4.135\,667\,662(25) \times 10^{-15}$ eV s$)$
Avogadro's constant	N_a	$6.022\,140\,857(74) \times 10^{23}$ mol^{-1}
Boltzmann constant	k	$1.380\,648\,52(79) \times 10^{-23}$ J K^{-1} $(8.617\,3303(50) \times 10^{-5}$ eV K$^{-1})$
Ideal gas constant (STP)	R	$8.314\,4598(48)$ J mol^{-1} K^{-1}
Electric constant	ϵ_o	$8.854\,187\,817\ldots \times 10^{-12}$ F m^{-1*}
Magnetic constant	μ_o	$4\pi \times 10^{-7}$ N A^{-2*} $= 12.566\,376\,614\ldots \times 10^{-7}$ N A^{-2}

* indicates exact values.

Source: `http://physics.nist.gov/cuu/index.html`

Special nuclear units

- When treating atomic and nuclear phenomena, physical quantities such as energies and masses are extremely small in SI units, and special units are almost always used.
- The electron volt (eV): the kinetic energy gained by an electron (mass m_e and charge $-e$) that is accelerated through a potential difference ΔV of one volt.

$$\boxed{1\ \mathrm{eV} = 1.602 \times 10^{-19}\ \mathrm{J}}$$

Q1. What is the speed of an electron with kinetic energy of 1 eV?
Q2. How about for proton or neutron?

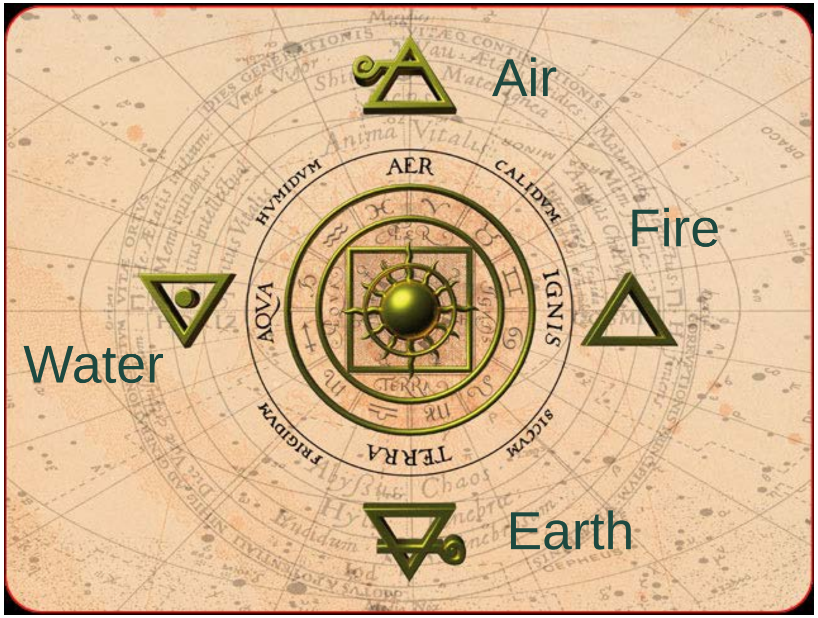
- The atomic mass unit (amu): 1 amu is defined to be 1/12 the mass of a neutral ground-state atom of ^{12}C.

$$\boxed{1\ \mathrm{amu} = \frac{1}{12}\frac{0.012\ \mathrm{kg/mole}}{N_a\ \mathrm{mole}^{-1}} = 1.66 \times 10^{-27}\ \mathrm{kg}\ \approx m_p}$$

Q1. What is the mass of argon atom?
Q2. What is the mass of ^{238}U?

Atom: philosophical approach

- The four elements (Empedocles, 490 BC ~ 430 BC and Aristotle, 384 BC ~ 322 BC)



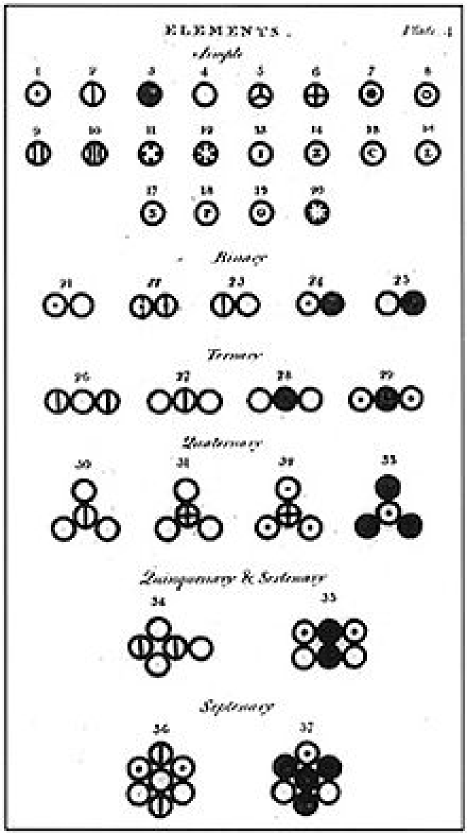
- Atomic hypothesis (“Atomos” = “unsplittable”, Democritus, 460 BC ~ 370 BC)

  Everything is composed of "atoms", which are physically, but not geometrically, indivisible; that between atoms, there lies empty space; that atoms are indestructible, and have always been and always will be in motion; that there is an infinite number of atoms and of kinds of atoms, which differ in shape and size.

Atom: scientific approach

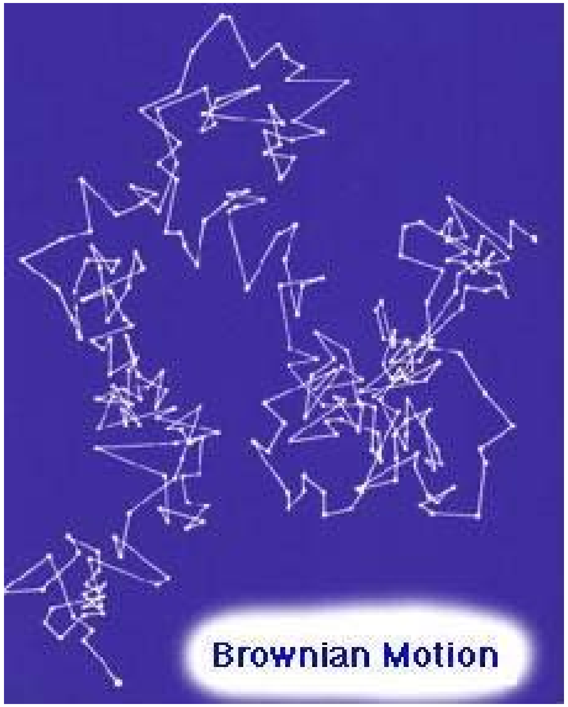
- Dalton’s atomic theory (John Dalton, 1808)

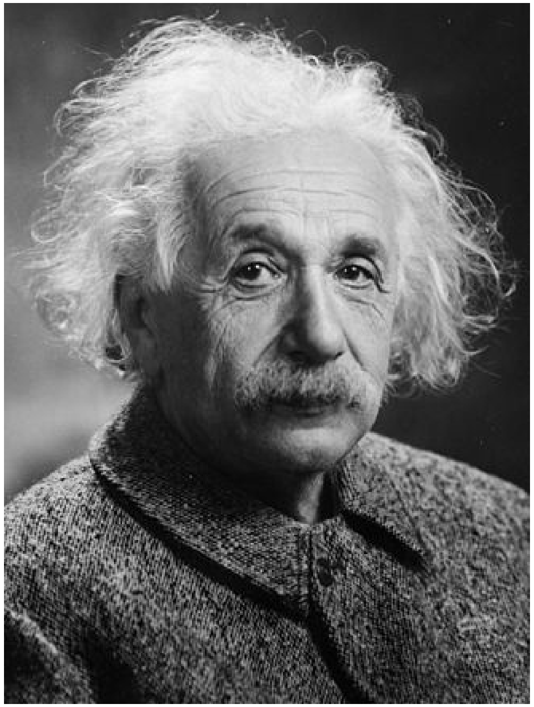
  1. Elements are made of extremely small particles called atoms.
  2. Atoms of a given element are identical in size, mass, and other properties; atoms of different elements differ in size, mass, and other properties.
  3. Atoms cannot be subdivided, created, or destroyed.
  4. Atoms of different elements combine in simple whole-number ratios to form chemical compounds.
  5. In chemical reactions, atoms are combined, separated, or rearranged.



Evidence that atoms and molecules exist

- Brownian motion (Robert Brown, 1827)

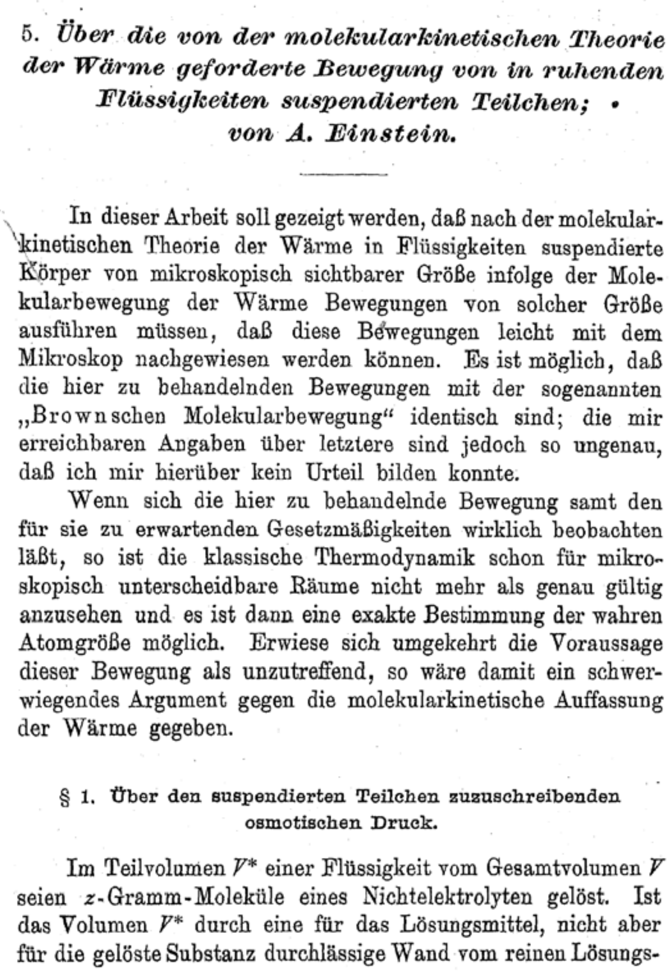




열 분자운동 이론이 필요한, 정지 상태의 액체 속에 떠 있는 작은 부유입자들의 운동에 관하여 (아인슈타인, 1905)

[H/W] Investigate the idea taken by A. Einstein to prove the Brownian motion.

Annalen der Physik 322, 549 (1905)



5. *Über die von der molekularkinetischen Theorie der Wärme geforderte Bewegung von in ruhenden Flüssigkeiten suspendierten Teilchen;*

von A. Einstein.

In dieser Arbeit soll gezeigt werden, daß nach der molekularkinetischen Theorie der Wärme in Flüssigkeiten suspendierte Körper von mikroskopisch sichtbarer Größe infolge der Molekularbewegung der Wärme Bewegungen von solcher Größe ausführen müssen, daß diese Bewegungen leicht mit dem Mikroskop nachgewiesen werden können. Es ist möglich, daß die hier zu behandelnden Bewegungen mit der sogenannten „Brownschen Molekularbewegung“ identisch sind; die mir erreichbaren Angaben über letztere sind jedoch so ungenau, daß ich mir hierüber kein Urteil bilden konnte.

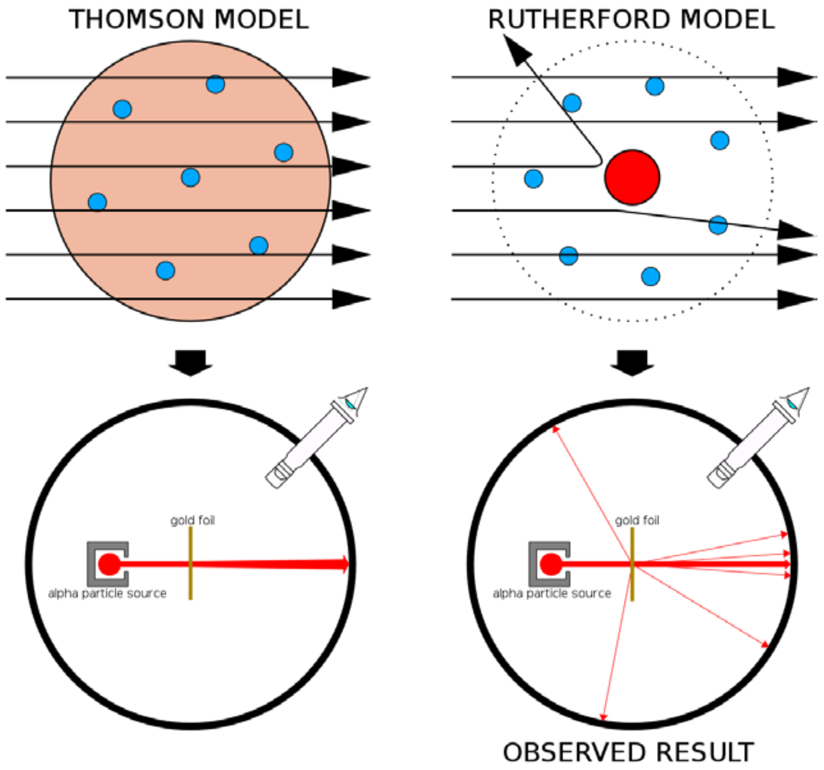
Wenn sich die hier zu behandelnde Bewegung samt den für sie zu erwartenden Gesetzmäßigkeiten wirklich beobachten läßt, so ist die klassische Thermodynamik schon für mikroskopisch unterscheidbare Räume nicht mehr als genau gültig anzusehen und es ist dann eine exakte Bestimmung der wahren Atomgröße möglich. Erwiese sich umgekehrt die Voraussage dieser Bewegung als unzutreffend, so wäre damit ein schwerwiegendes Argument gegen die molekularkinetische Auffassung der Wärme gegeben.

§ 1. Über den suspendierten Teilchen zuzuschreibenden osmotischen Druck.

Im Teilvolumen V^* einer Flüssigkeit vom Gesamtvolumen V seien z-Gramm-Moleküle eines Nichtelektrolyten gelöst. Ist das Volumen V^* durch eine für das Lösungsmittel, nicht aber für die gelöste Substanz durchlässige Wand vom reinen Lösungs-

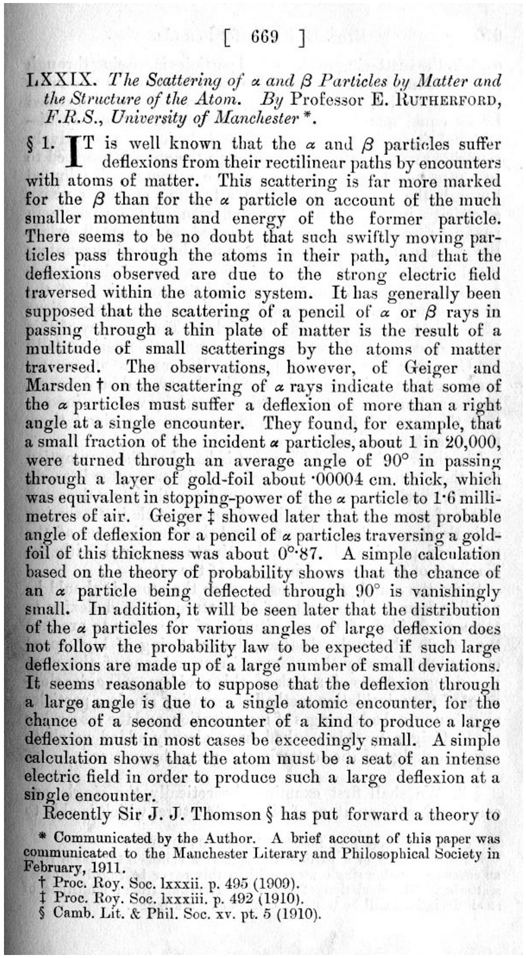
Gold foil experiment: Rutherford model (1911)

- Rutherford directed the famous Geiger–Marsden experiment in 1909 which suggested, upon Rutherford's 1911 analysis, that J. J. Thomson's plum pudding model of the atom was incorrect.



$$s = \frac{Xnt \csc^4\left(\frac{\phi}{2}\right)}{16r^2} \cdot \left(\frac{2Q_n Q_\alpha}{mv^2}\right)^2$$

Philosophical Magazine 21, 669 (1911)



[669]

LXXIX. *The Scattering of α and β Particles by Matter and the Structure of the Atom. By* Professor E. RUTHERFORD, *F.R.S., University of Manchester* *.

§ 1. IT is well known that the α and β particles suffer deflexions from their rectilinear paths by encounters with atoms of matter. This scattering is far more marked for the β than for the α particle on account of the much smaller momentum and energy of the former particle. There seems to be no doubt that such swiftly moving particles pass through the atoms in their path, and that the deflexions observed are due to the strong electric field traversed within the atomic system. It has generally been supposed that the scattering of a pencil of α or β rays in passing through a thin plate of matter is the result of a multitude of small scatterings by the atoms of matter traversed. The observations, however, of Geiger and Marsden † on the scattering of α rays indicate that some of the α particles must suffer a deflexion of more than a right angle at a single encounter. They found, for example, that a small fraction of the incident α particles, about 1 in 20,000, were turned through an average angle of 90° in passing through a layer of gold-foil about ·00004 cm. thick, which was equivalent in stopping-power of the α particle to 1·6 millimetres of air. Geiger ‡ showed later that the most probable angle of deflexion for a pencil of α particles traversing a gold-foil of this thickness was about 0°·87. A simple calculation based on the theory of probability shows that the chance of an α particle being deflected through 90° is vanishingly small. In addition, it will be seen later that the distribution of the α particles for various angles of large deflexion does not follow the probability law to be expected if such large deflexions are made up of a large number of small deviations. It seems reasonable to suppose that the deflexion through a large angle is due to a single atomic encounter, for the chance of a second encounter of a kind to produce a large deflexion must in most cases be exceedingly small. A simple calculation shows that the atom must be a seat of an intense electric field in order to produce such a large deflexion at a single encounter.

Recently Sir J. J. Thomson § has put forward a theory to

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* Communicated by the Author. A brief account of this paper was communicated to the Manchester Literary and Philosophical Society in February, 1911.

† Proc. Roy. Soc. lxxxii. p. 495 (1909).

‡ Proc. Roy. Soc. lxxxiii. p. 492 (1910).

§ Camb. Lit. & Phil. Soc. xv. pt. 5 (1910).

Bohr model (1913)

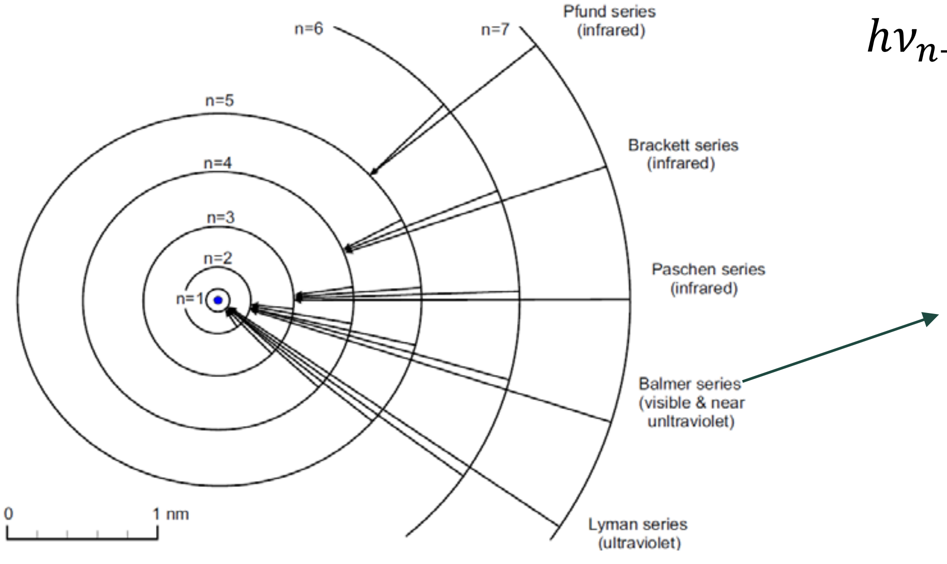
- Bohr model included several non-classical constraints (quantum nature).

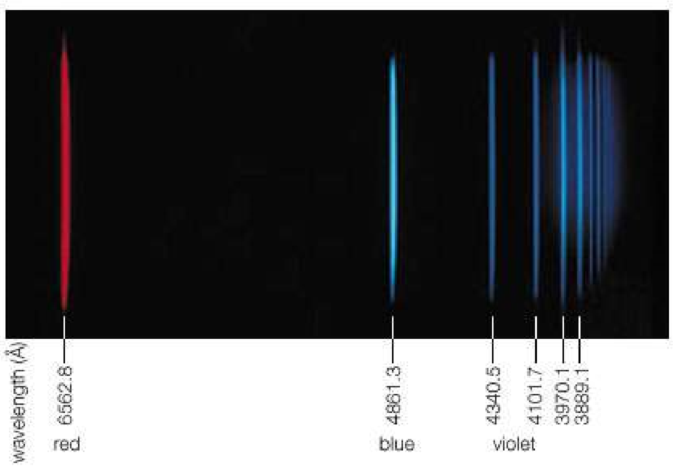
$$\frac{m_e v^2}{r} = \frac{Ze^2}{4\pi\epsilon_0 r^2} \qquad L = m_e v r = n\frac{h}{2\pi}$$

⇨ $$r_n = \frac{n^2 h^2 \epsilon_0}{\pi m_e Z e^2} \qquad E_n = T_n + V_n = -\frac{m_e Z^2 e^4}{8h^2\epsilon_0^2}\frac{1}{n^2}$$

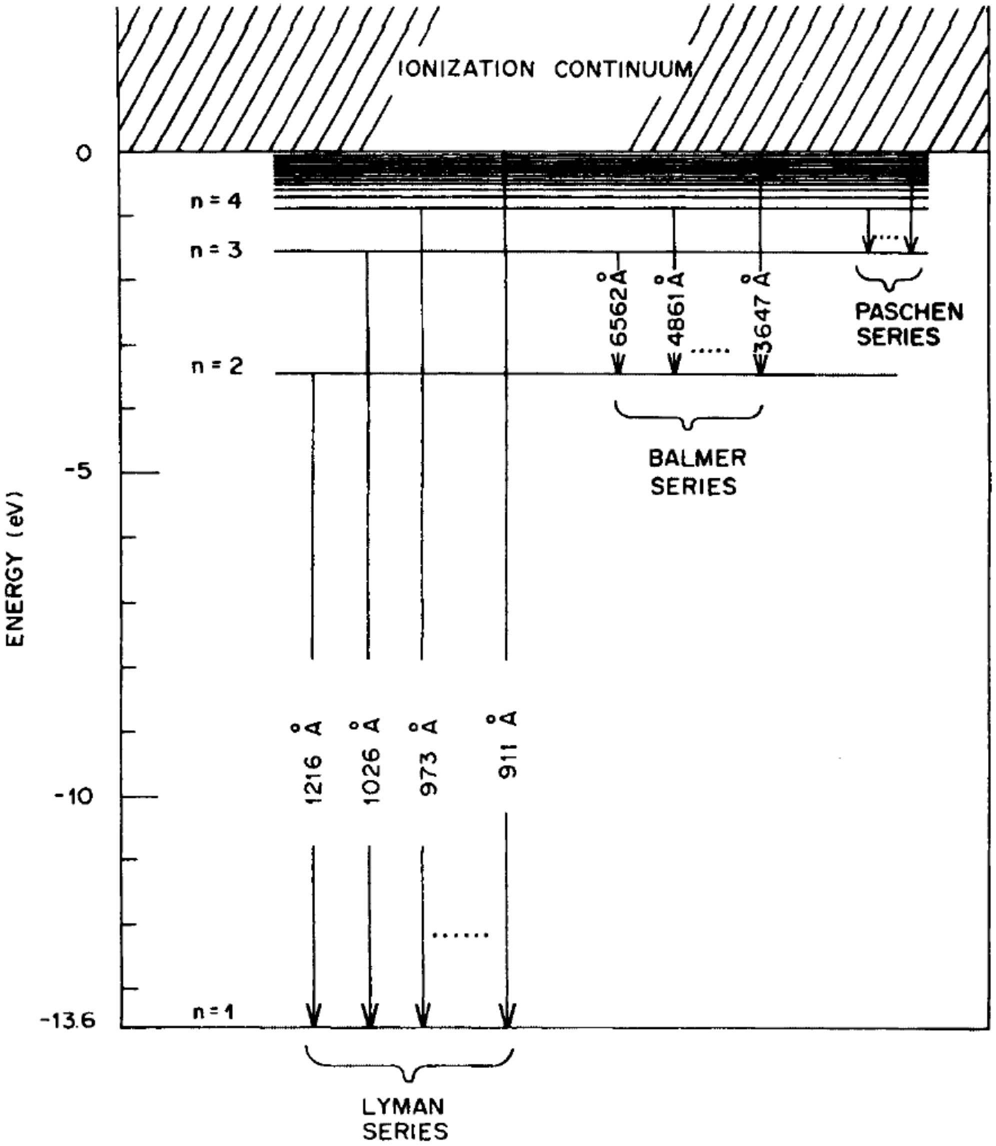
- Bohr model explains the lime emissions well.

$$h\nu_{n\to n_0} = E_n - E_{n0} = \frac{m_e Z^2 e^4}{8h^2\epsilon_0^2}\left[\frac{1}{n_0^2} - \frac{1}{n^2}\right]$$

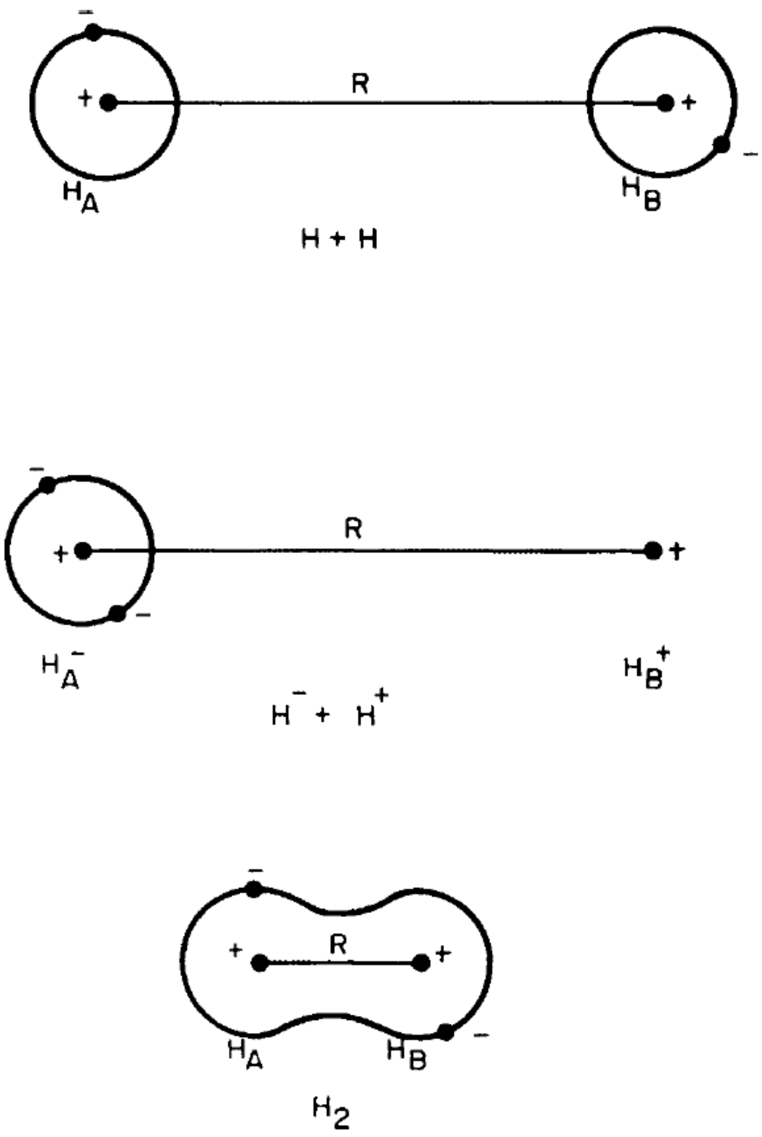


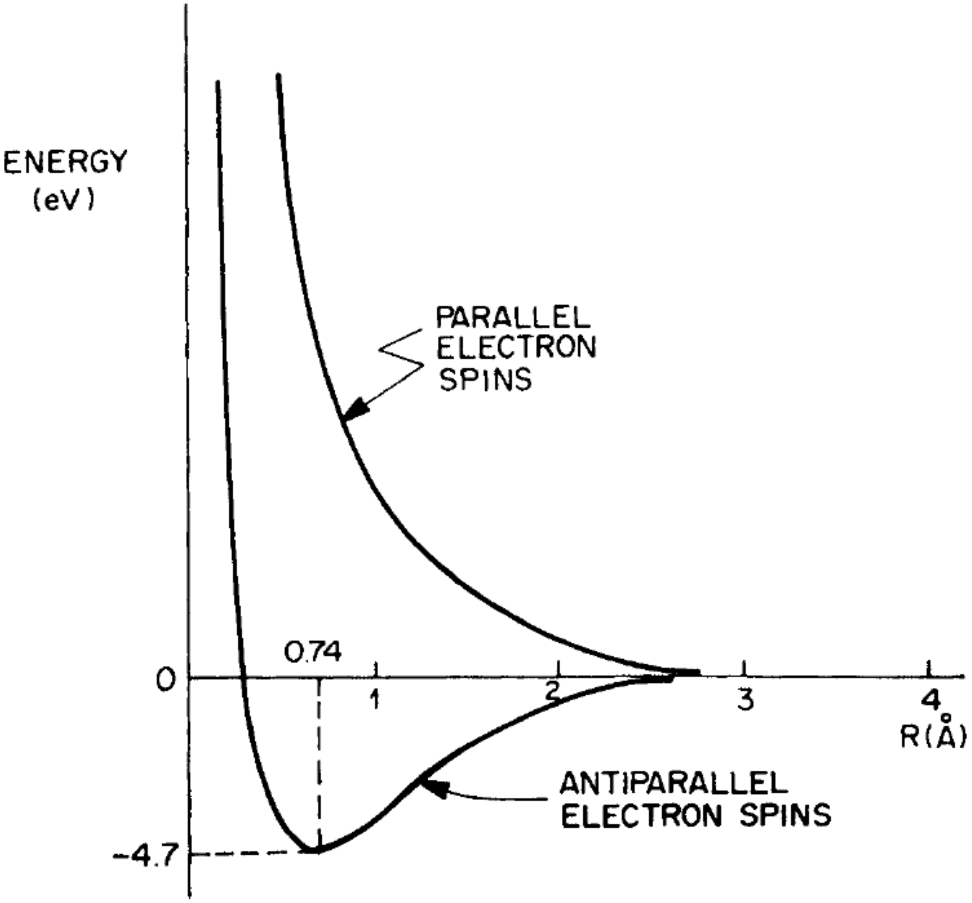


Energy levels of hydrogen atom



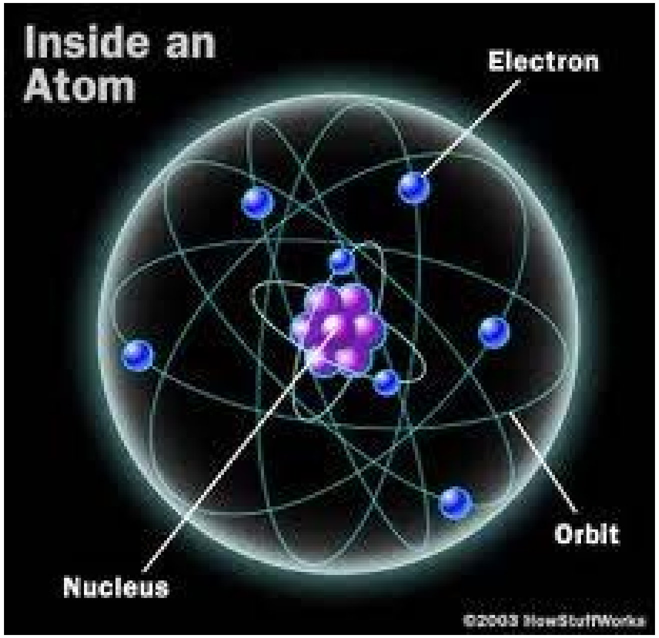
Molecules


R
H_A
H_B
H + H
R
H_A^-
H_B^+
$H^- + H^+$
R
H_A
H_B
H_2

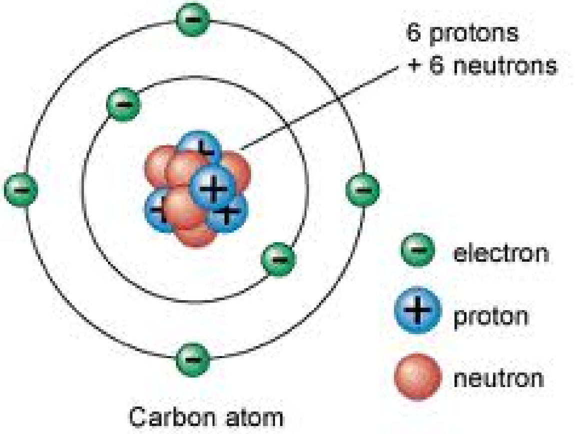

ENERGY (eV)
PARALLEL ELECTRON SPINS
ANTIPARALLEL ELECTRON SPINS
0.74
0
−4.7
1
2
3
4
R(Å)

The structure of atom

- Every atom is composed of a nucleus and one or more electrons bound to the nucleus. The nucleus is made of one or more protons and typically a similar number of neutrons. Protons and neutrons are called nucleons.
- More than 99.94% of an atom's mass is in the nucleus.



- Proton (p, H^+)
  - mass (m_p) = 1.67×10^{-27} kg
  - charge (q_p) = $+1.6 \times 10^{-19}$ C (+e)
- Electron (e)
  - mass (m_e) = 9.11×10^{-31} kg
  - charge (q_e) = -1.6×10^{-19} C (-e)



$$^{12}_{6}\mathrm{C}$$

$$\frac{m_p}{m_e} \approx 1837$$

$$\left|\frac{q_p}{q_e}\right| = 1$$

Nuclear dimensions

- An effective spherical nuclear radius is

$$R = R_0 A^{1/3} \quad (R_0 \approx 1.2 \times 10^{-13}\ \mathrm{cm})$$

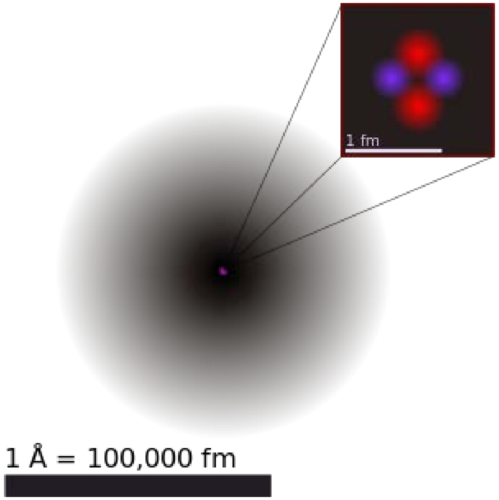
- Then the associated volume is

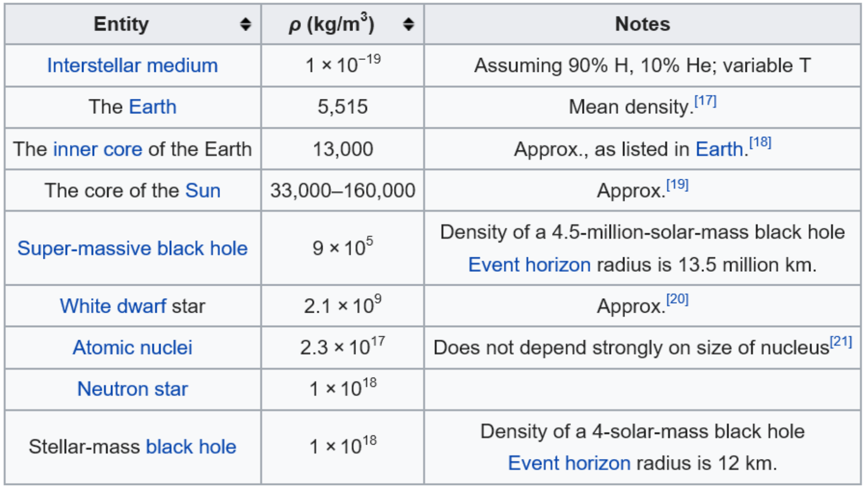
$$V_{nucleus} = \frac{4}{3}\pi R^3 \approx 7.2 \times 10^{-39}\, A\ \ \mathrm{cm}^3$$

- The mass density of a nucleus is

$$\rho_{nucleus} = \frac{m_{nucleus}}{V_{nucleus}} = \frac{A/N_a}{(4/3)\pi R^3} \approx 2.3 \times 10^{14}\ \mathrm{g/cm}^3$$

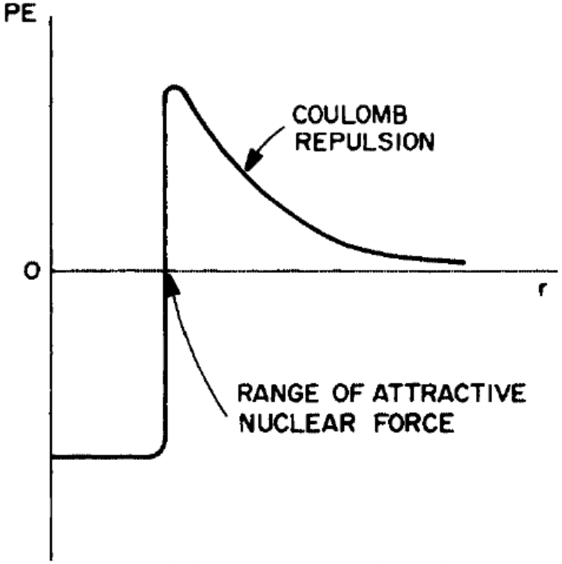
  - ➢ This is equivalent to the density of the earth if it were compressed to a ball 200 m in radius.



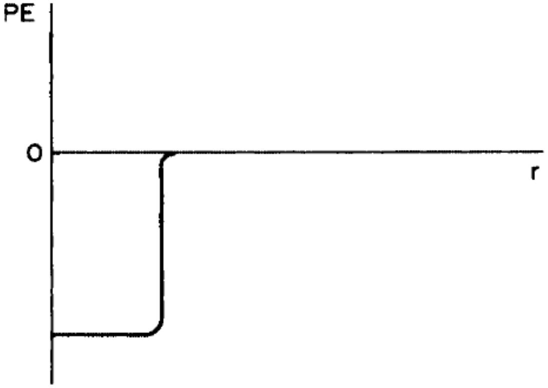


Entity	ρ (kg/m^3)	Notes
Interstellar medium	1×10^{-19}	Assuming 90% H, 10% He; variable T
The Earth	5,515	Mean density.[17]
The inner core of the Earth	13,000	Approx., as listed in Earth.[18]
The core of the Sun	33,000–160,000	Approx.[19]
Super-massive black hole	9×10^5	Density of a 4.5-million-solar-mass black hole Event horizon radius is 13.5 million km.
White dwarf star	2.1×10^9	Approx.[20]
Atomic nuclei	2.3×10^{17}	Does not depend strongly on size of nucleus[21]
Neutron star	1×10^{18}	
Stellar-mass black hole	1×10^{18}	Density of a 4-solar-mass black hole Event horizon radius is 12 km.

Nuclear potential and energy levels



(a) PROTON - NUCLEUS



(b) NEUTRON - NUCLEUS

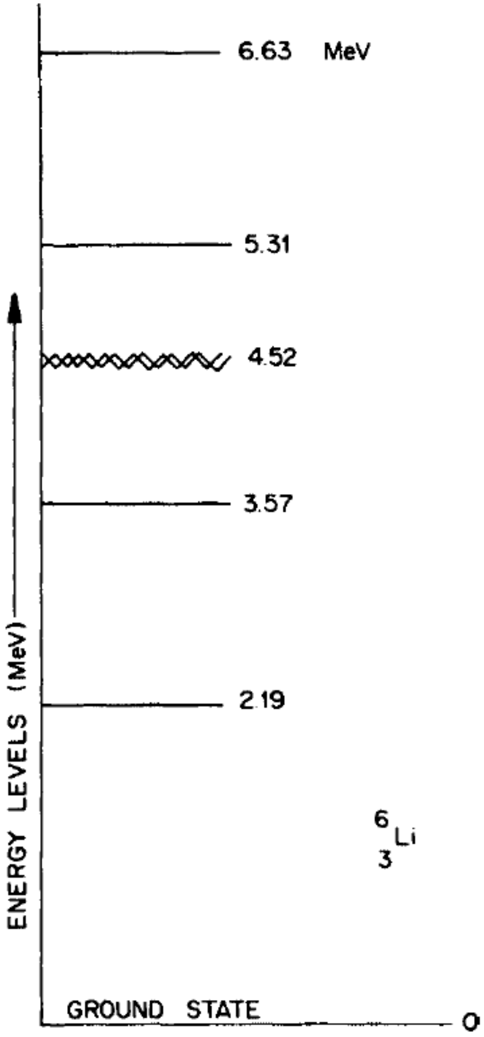
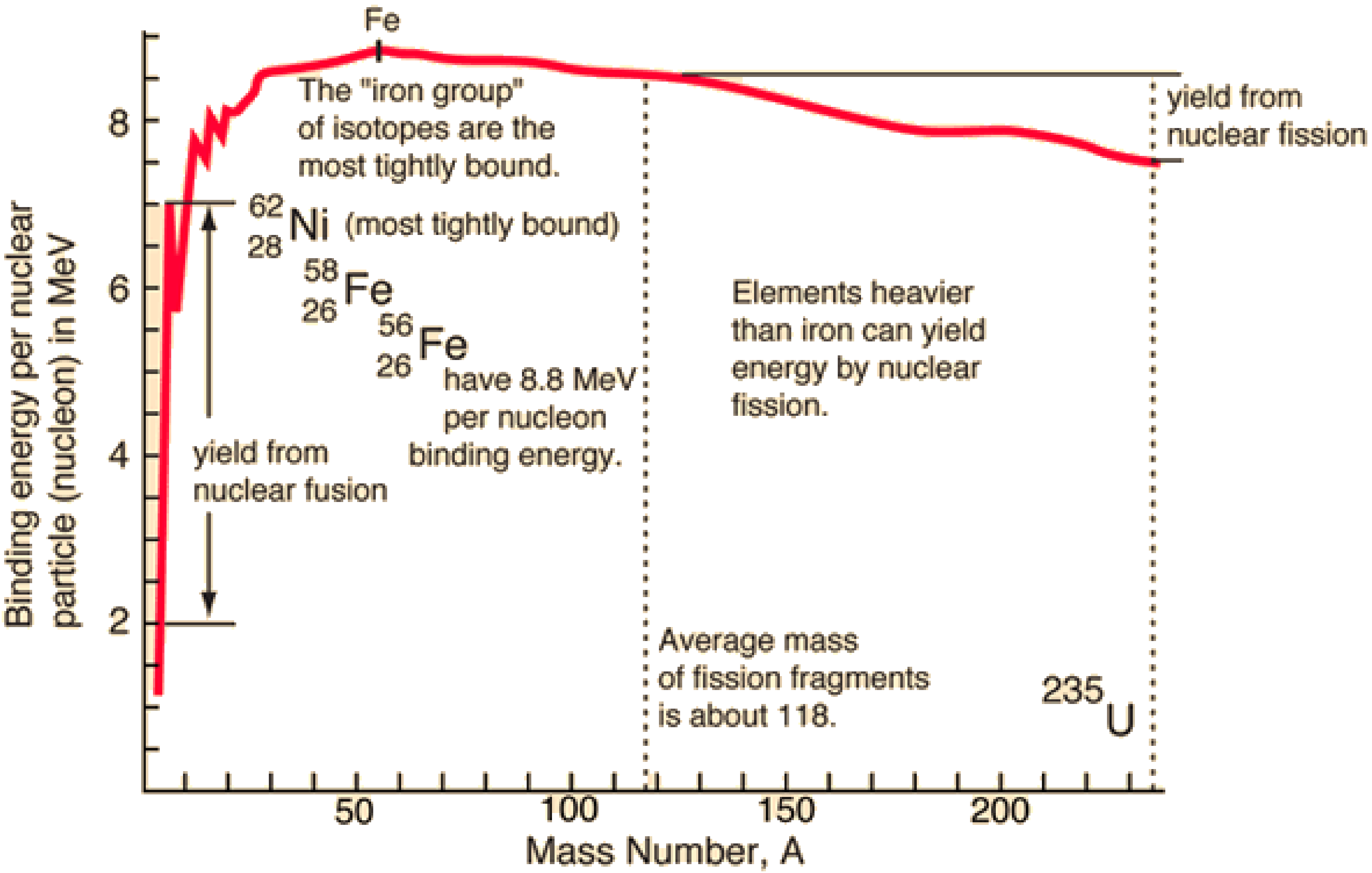


Fig. 3.2 Energy levels of the $^6_3$Li nucleus, relative to the ground state of zero energy.

Nuclear binding energy



Fusion vs. Fission

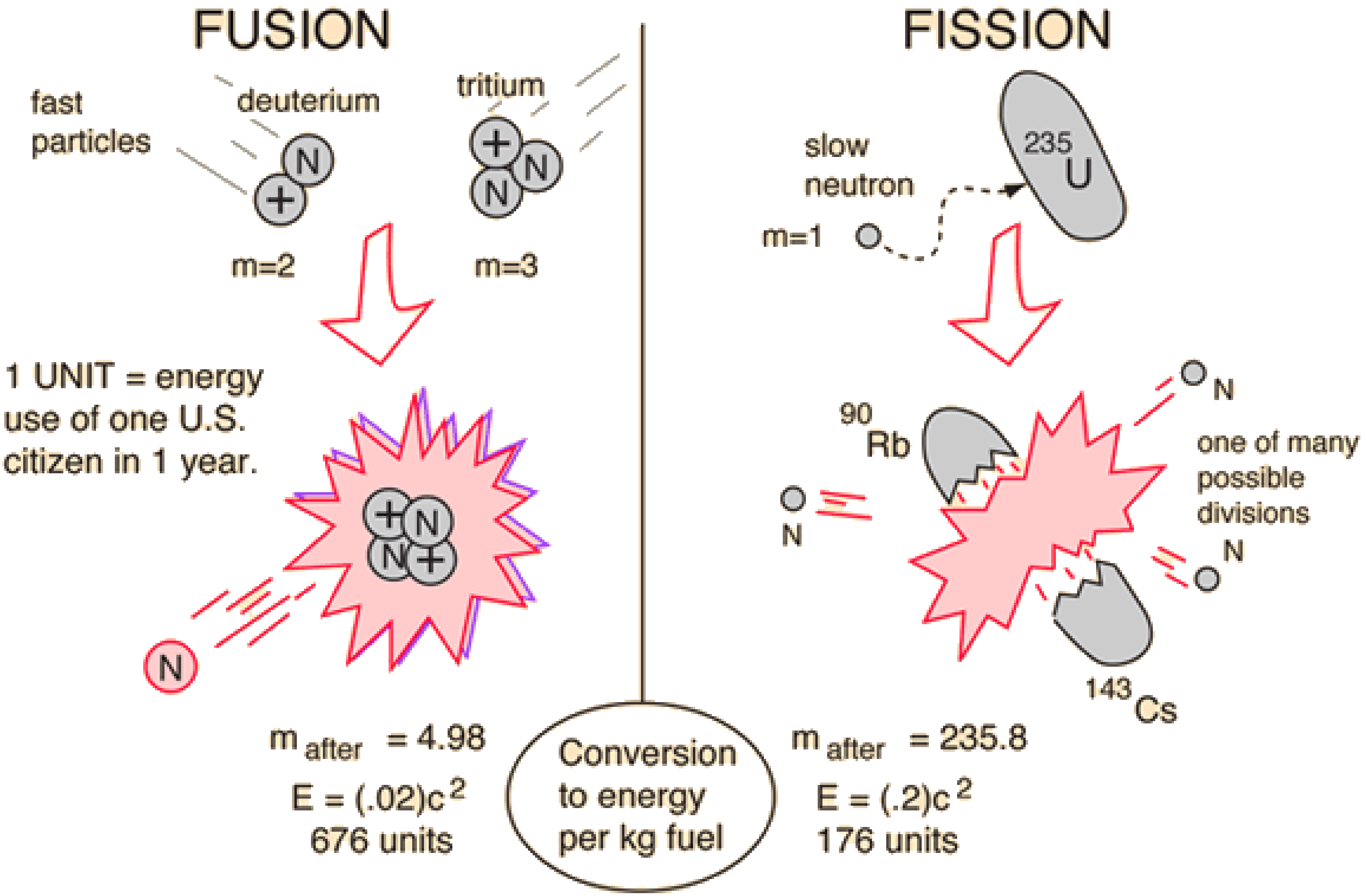
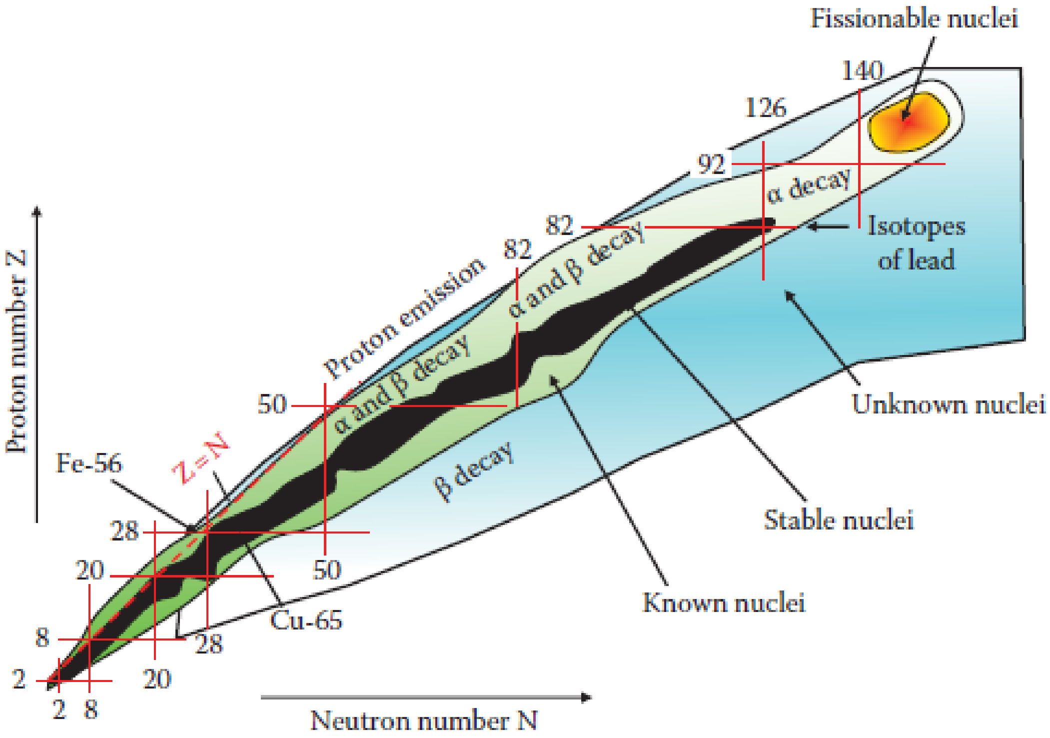


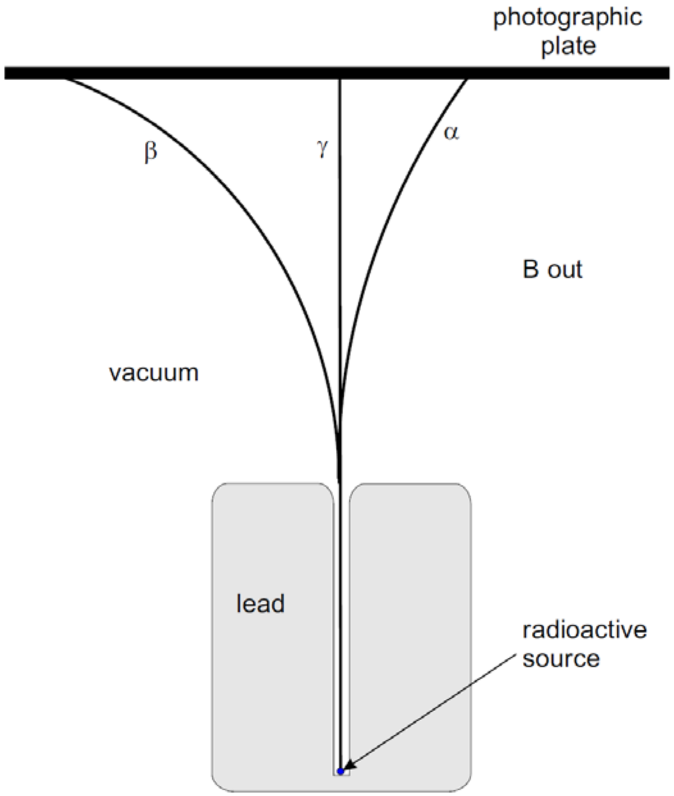
Chart of the nuclide

- The number of known different atoms, each with a distinct combination of Z and A, is large, numbering over 3200 nuclides. Of these, 266 are stable (i.e., non-radioactive) and are found in nature. There are also 65 long-lived radioisotopes found in nature.
- The remaining nuclides have been made by humans and are radioactive with lifetimes much shorter than the age of the solar system.



Radiation and radioactivity

- Radiation: transportation of mass and energy through space
- Type of radiation
    - Particle vs wave
    - Ionizing vs non-ionizing
    - Hazardous vs non-hazardous
- Radioactivity: the process through which nuclei spontaneously emit subatomic particles
    - Radioactivity was discovered by the French scientist Henri Becquerel in 1896.
    - The terms radioactivity was suggested by Marie Curie about four years later.
- Activity: the number of radioactive decays in a particular time
    - SI unit: becquerel (Bq), 1 decay per second
    - Old unit: curie (Ci), the activity of 1 g of radium-226



1 Ci = 3.7×10^{10} Bq

Radioactive decay

- Radioactive decay is a random process and has been observed to follow Poisson distribution. What this essentially means is that the rate of decay of radioactive nuclei in a large sample depends only on the number of decaying nuclei in the sample:

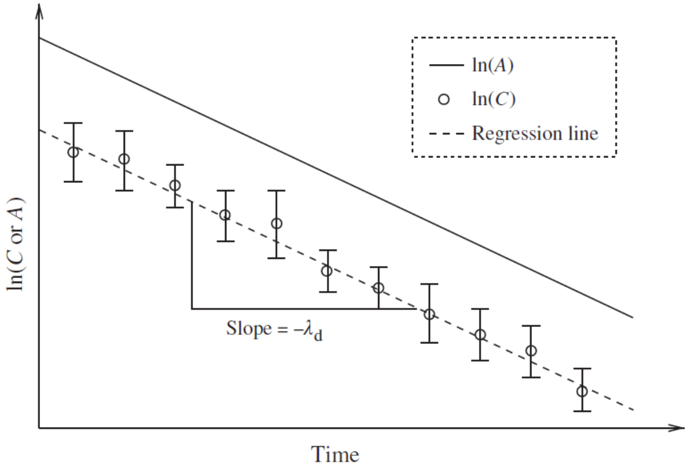
$$-\frac{dN}{dt} \propto N \quad \Rightarrow \quad \frac{dN}{dt} = -\lambda_d N$$

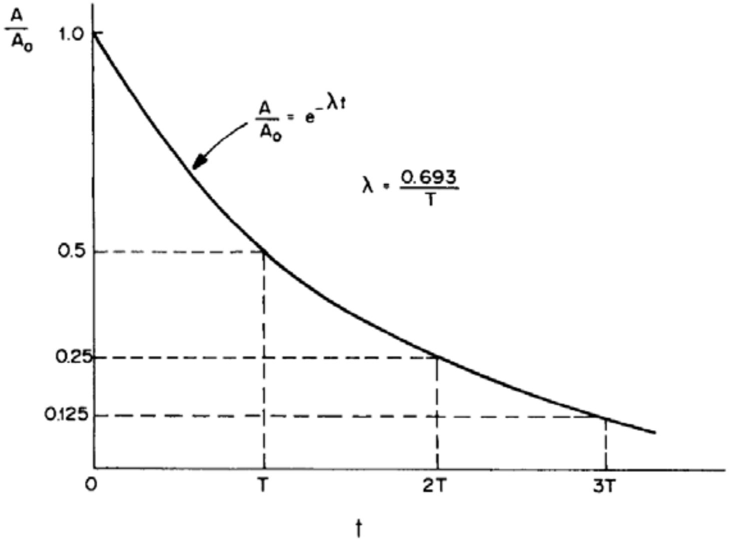
λ_d : decay constant

- Activity $A = -\dfrac{dN}{dt} = \lambda_d N \quad \Rightarrow \quad A = A_0 e^{-\lambda_d t} = A_0 e^{-t/\tau}$

τ : decay time

- Half-life $T_{1/2} = \dfrac{\ln 2}{\lambda_d} = 0.693\tau$





Mean lifetime

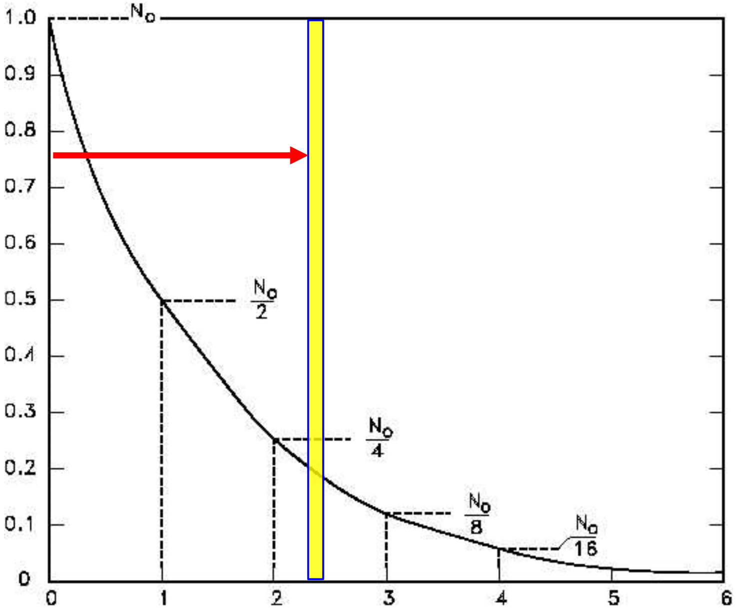
- Given an assembly of elements, the number of which decreases ultimately to zero, the mean lifetime, τ (also called simply the lifetime) is the expected value of the amount of time before an object is removed from the assembly. The mean lifetime is the arithmetic mean of the individual lifetimes.

$$\tau = \langle T \rangle = \int_0^\infty t \, \underline{\exp(-\lambda_d t)} \, \lambda_d dt = \frac{1}{\lambda_d}$$

Decay probability between t and $t + dt$

Expectation

Probability of surviving until time t



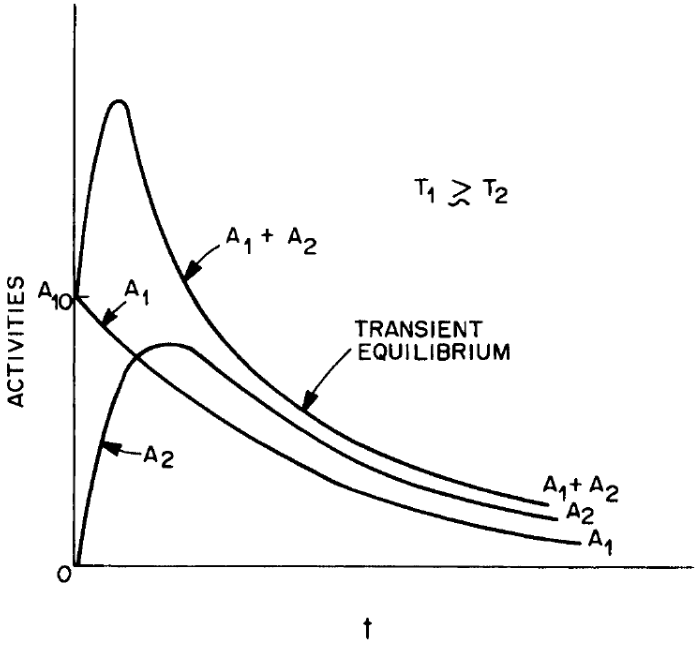
Serial radioactive decay

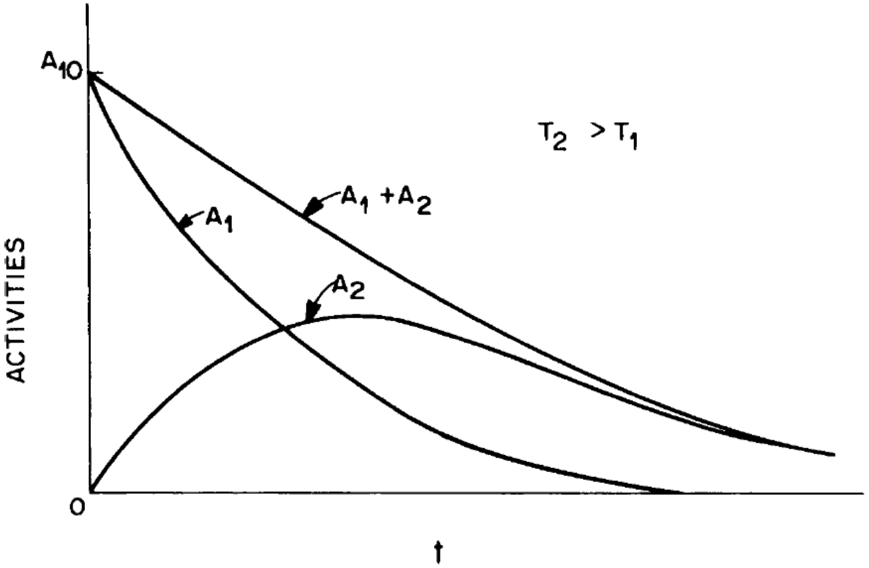
- We can calculate the activity of a sample in which one radionuclide produces one or more radioactive offspring in a chain.

$$\frac{dN_1}{dt} = -\lambda_1 N_1$$

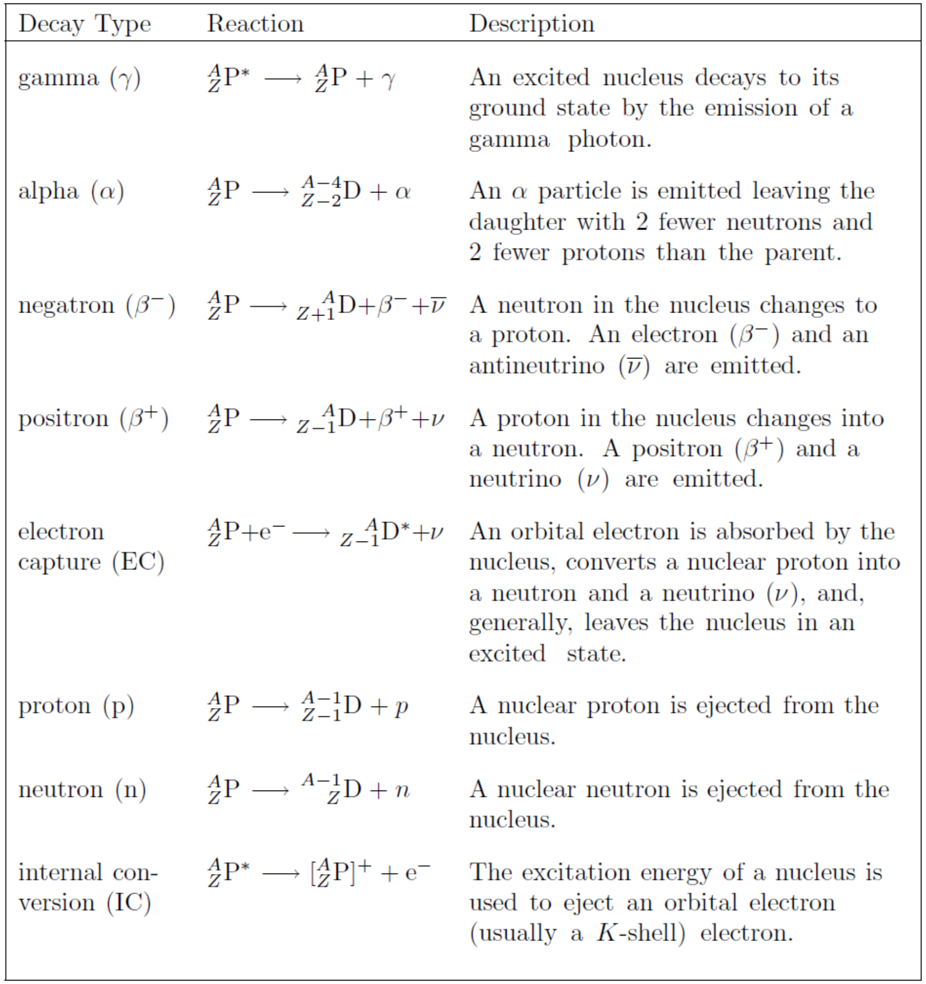
$$\frac{dN_2}{dt} = \lambda_1 N_1 - \lambda_2 N_2$$

[H/W] Show the followings with an initial condition of $N_2(t = 0) = 0$.

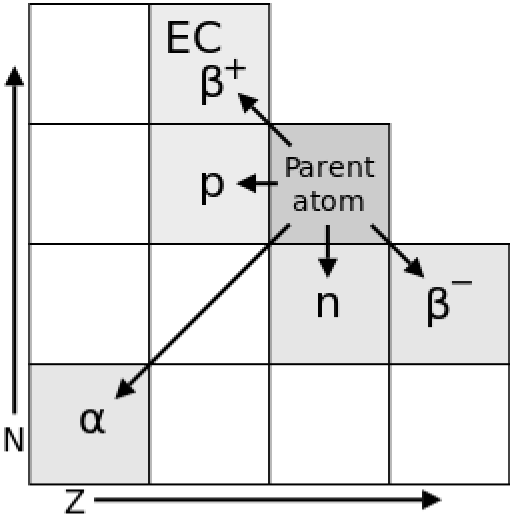


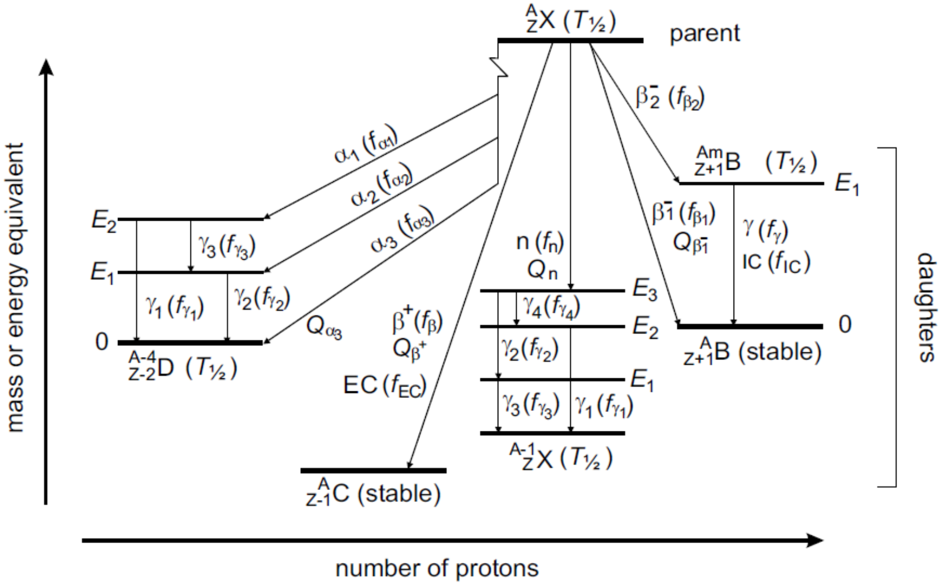


Important types of radioactive decay

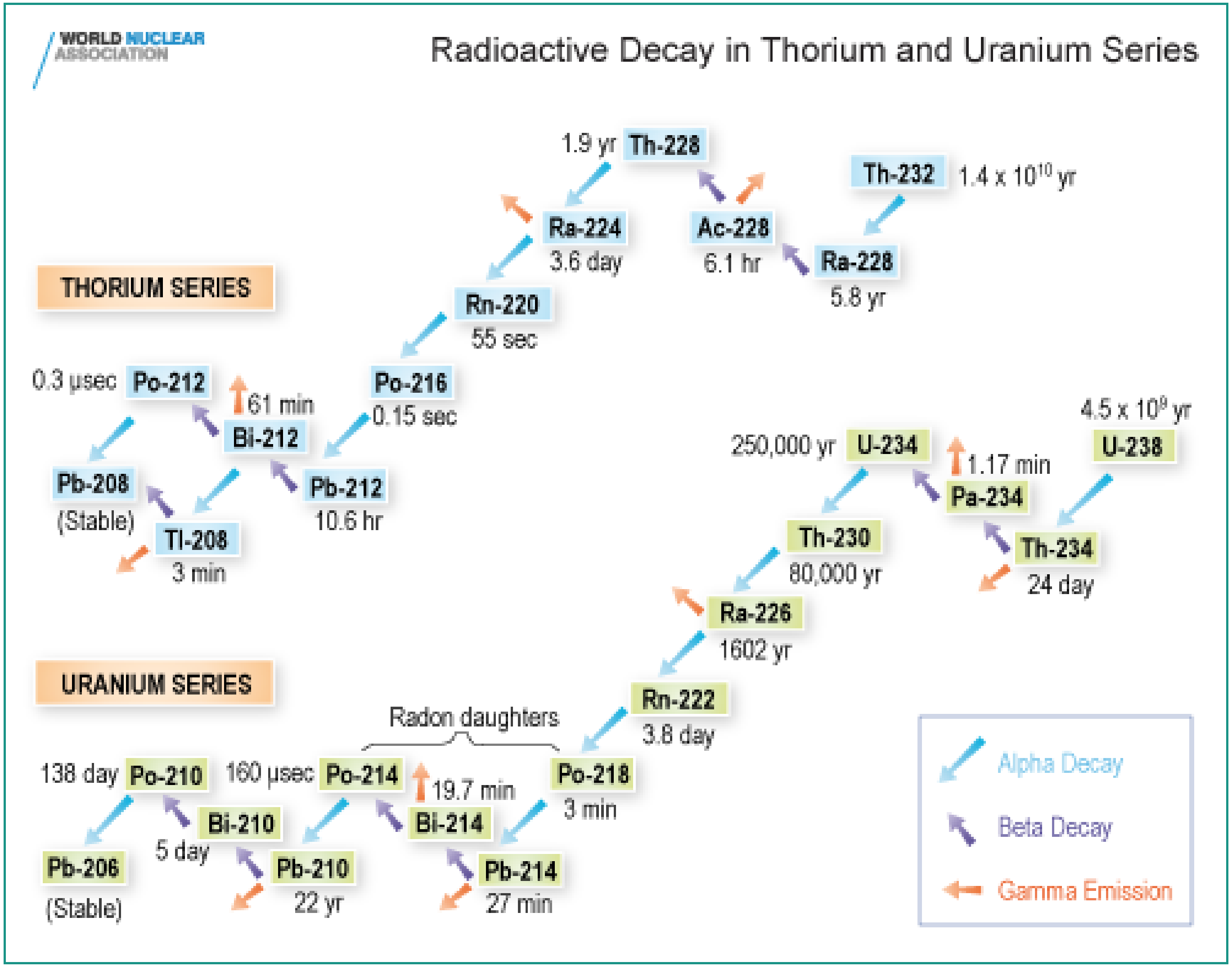


Decay Type	Reaction	Description
gamma (γ)	${}^A_Z\mathrm{P}^* \longrightarrow {}^A_Z\mathrm{P} + \gamma$	An excited nucleus decays to its ground state by the emission of a gamma photon.
alpha (α)	${}^A_Z\mathrm{P} \longrightarrow {}^{A-4}_{Z-2}\mathrm{D} + \alpha$	An α particle is emitted leaving the daughter with 2 fewer neutrons and 2 fewer protons than the parent.
negatron (β^-)	${}^A_Z\mathrm{P} \longrightarrow {}_{Z+1}^{A}\mathrm{D}+\beta^-+\overline{\nu}$	A neutron in the nucleus changes to a proton. An electron (β^-) and an antineutrino ($\overline{\nu}$) are emitted.
positron (β^+)	${}^A_Z\mathrm{P} \longrightarrow {}_{Z-1}^{A}\mathrm{D}+\beta^++\nu$	A proton in the nucleus changes into a neutron. A positron (β^+) and a neutrino (ν) are emitted.
electron capture (EC)	${}^A_Z\mathrm{P}+\mathrm{e}^- \longrightarrow {}_{Z-1}^{A}\mathrm{D}^*+\nu$	An orbital electron is absorbed by the nucleus, converts a nuclear proton into a neutron and a neutrino (ν), and, generally, leaves the nucleus in an excited state.
proton (p)	${}^A_Z\mathrm{P} \longrightarrow {}^{A-1}_{Z-1}\mathrm{D} + p$	A nuclear proton is ejected from the nucleus.
neutron (n)	${}^A_Z\mathrm{P} \longrightarrow {}^{A-1}_{Z}\mathrm{D} + n$	A nuclear neutron is ejected from the nucleus.
internal conversion (IC)	${}^A_Z\mathrm{P}^* \longrightarrow [{}^A_Z\mathrm{P}]^+ + \mathrm{e}^-$	The excitation energy of a nucleus is used to eject an orbital electron (usually a K-shell) electron.





Radioactive decay of Th-232 and U-238



Activation

- It is possible to induce radioactivity into materials by letting them interact with radiation. This process is known as activation and is extensively used to produce radioactive particle sources and activation detectors.
- To activate a material, it must be irradiated. As soon as the irradiation starts, the material starts decaying. This means that both processes of irradiation and decay are happening at the same time.

$$\frac{dN}{dt} = R_{act} - \lambda_d N \qquad \Rightarrow \qquad A = \lambda_d N = R_{act}\left(1 - e^{-\lambda_d t}\right)$$

- In activation detectors, a thin foil of an activation material is placed in the radiation field for a time longer than the half-life of the activated material. The foil is then removed and placed in a setup to detect the decaying particles. The count of decaying particles is used to determine the activation rate and thus the radiation field.

$$R_{act} = V\Phi\sigma_{act}$$

Volume of sample

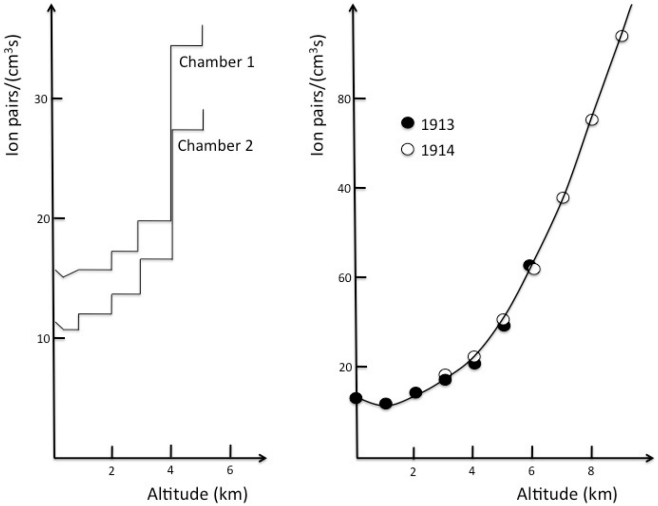
Radiation flux

Activation cross section

Natural sources

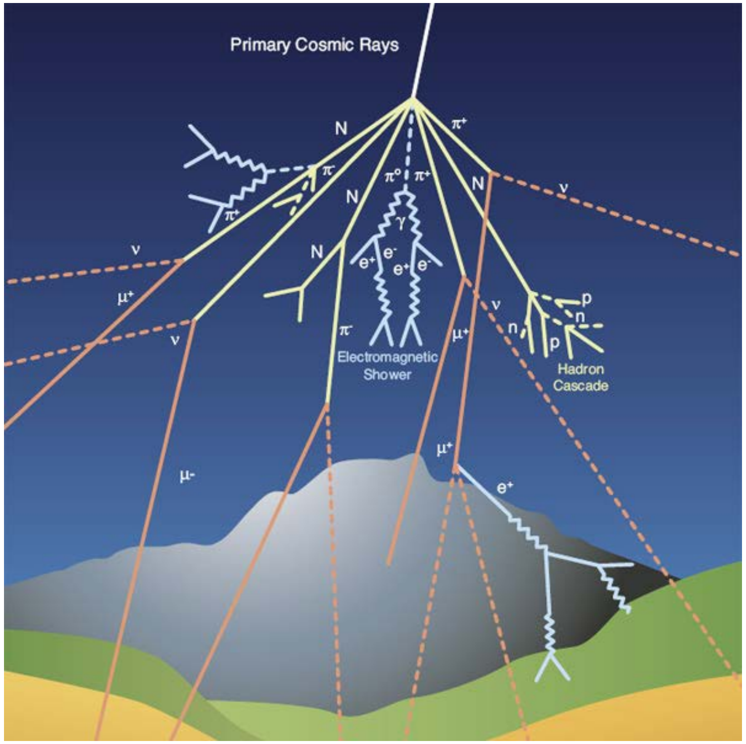
- Cosmic radiation sources:
  - After the discovery of radioactivity by Henri Becquerel and Marie Curie in 1896, it was generally believed that atmospheric electricity, ionization of the air, was caused only by radiation from radioactive elements in the ground or the radioactive gases or isotopes of radon they produce.
  - Measurements of ionization rates by Victor Hess (Nobel prize in physics in 1936) at increasing heights above the ground showed a decrease that could be explained as due to absorption of the ionizing radiation by the intervening air.

Victor Hess and his balloon (1912)



Natural sources

- Cosmic radiation sources:
  - Outer space is filled with radiation that comes from a variety of sources such as burning (e.g., our Sun) and exploding (e.g., supernovae) stars.
  - Primary cosmic rays are composed primarily of protons and alpha particles (99%), with a small amount of heavier nuclei (~1%) and an extremely minute proportion of positrons and antiprotons.
  - Secondary cosmic rays, caused by a decay of primary cosmic rays as they impact an atmosphere, include neutrons, pions, positrons, and muons.



Natural sources

- Terrestrial radiation sources:
  - This type of radiation is present in small quantities all around us and is more or less inescapable. Our surroundings, the water we drink, the air we breathe, and the food we consume, all are contaminated with minute quantities of radiation-emitting isotopes.
  - The two isotopes of radon, ^{222}Rn and ^{220}Rn, and their daughter products are the most commonly found hazardous radioactive elements in our surroundings. The main cause of concern with respect to these α-emitting isotopes is their inhalation or digestion, in which case the short-range α-particles continuously cause damage to internal organs that can lead to cell mutations and ultimately cancer.
- Internal radiation sources:
  - Our bodies contain some traces of radioactive elements that continuously expose our tissues to low levels of radiation. This internal radiation primarily comes from potassium-40 and carbon-14 isotopes. However, the absorbed dose and damage to tissues due to this radiation are minimal.

Man-made sources

- Right after the discovery of radiation and realization of its potential, scientists started working on developing sources that can be used to produce radiation in controlled laboratory environments. Common examples of such sources are:
  - Medical X-ray machine
  - Airport X-ray scanner
  - Isotopes used in nuclear medicine
  - Particle accelerators
  - lasers

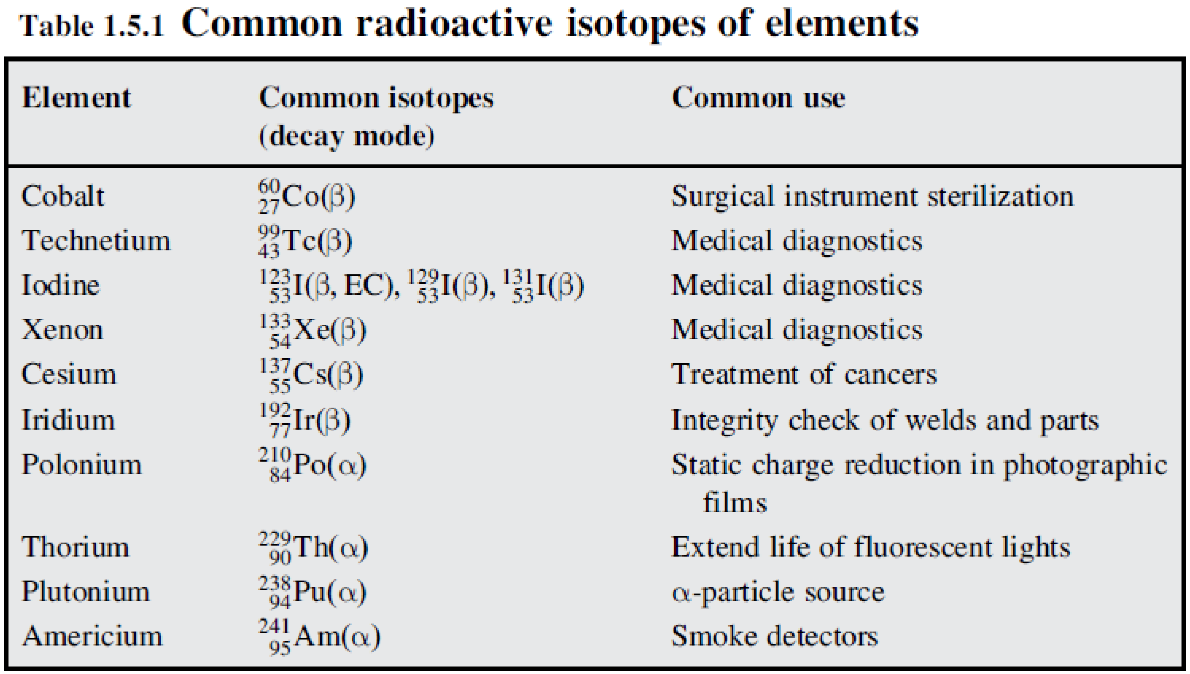


Table 1.5.1 Common radioactive isotopes of elements

Element	Common isotopes (decay mode)	Common use
Cobalt	$^{60}_{27}$Co(β)	Surgical instrument sterilization
Technetium	$^{99}_{43}$Tc(β)	Medical diagnostics
Iodine	$^{123}_{53}$I(β, EC), $^{129}_{53}$I(β), $^{131}_{53}$I(β)	Medical diagnostics
Xenon	$^{133}_{54}$Xe(β)	Medical diagnostics
Cesium	$^{137}_{55}$Cs(β)	Treatment of cancers
Iridium	$^{192}_{77}$Ir(β)	Integrity check of welds and parts
Polonium	$^{210}_{84}$Po(α)	Static charge reduction in photographic films
Thorium	$^{229}_{90}$Th(α)	Extend life of fluorescent lights
Plutonium	$^{238}_{94}$Pu(α)	α-particle source
Americium	$^{241}_{95}$Am(α)	Smoke detectors

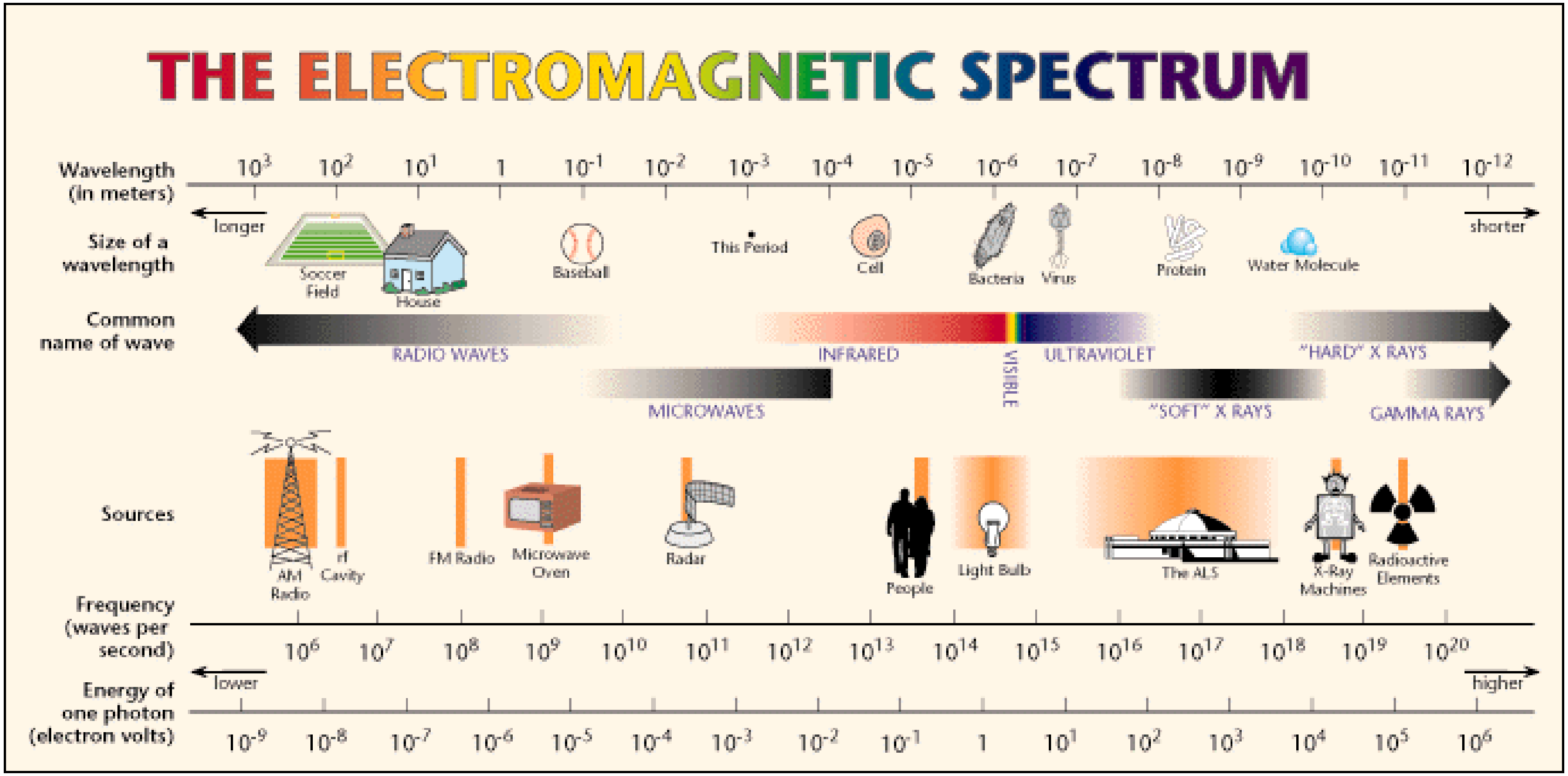
Photons

- A photon is regarded as a quantum of excitation in the underlying electromagnetic field.

$$\boxed{E = h\nu = \frac{hc}{\lambda}}$$

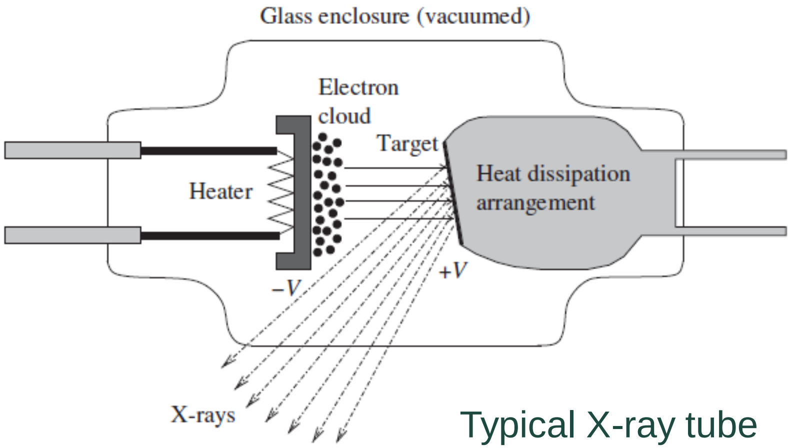
$$\boxed{p = \frac{h\nu}{c} = \frac{h}{\lambda}}$$

1 eV ~ 1,240 nm



Sources of photons: X-ray machine

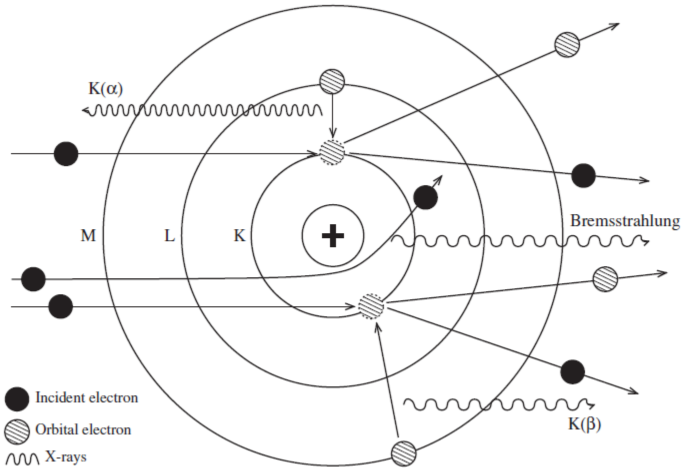
- Production of X-rays is a relatively simple process in which a high Z target (i.e., an element having a large number of protons, such as tungsten or molybdenum) is bombarded with high-velocity electrons. This results in the production of two types of X-rays: Bremsstrahlung and characteristic X-rays.
- In an X-ray tube the target (anode) is kept very close (typically 1-3 cm) to the source of electrons (cathode). A high electric potential between cathode and anode accelerates the electrons to high velocities. The maximum kinetic energy in electron volts attained by these electrons is equal to the electric potential (in volts) applied between the two electrodes.
- X-ray machines are extremely inefficient in the sense that 99% of their energy is converted into heat and only 1% is used to generate X-rays.

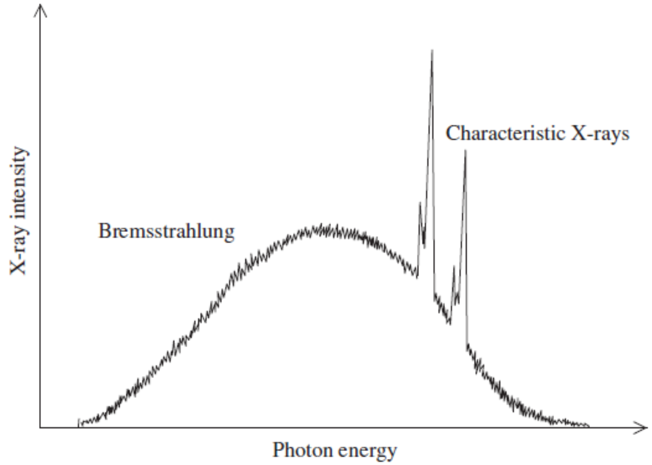


Typical X-ray tube

Bremsstrahlung and characteristic X-rays

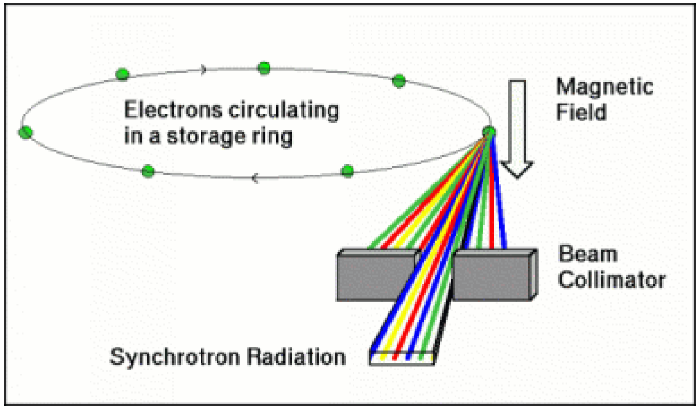
- Bremsstrahlung (braking radiation) refers to the radiation emitted by charged particles when they decelerate in a medium. In the case of X-rays, the high-energy electrons decelerate quickly in the target material and hence emit Bremsstrahlung. The emitted X-ray photons have a continuous energy spectrum since there are no quantized energy transitions involved in this process.
- The electrons incident on a target may also attain sufficient energies to knock off electrons from the internal atomic shells of target atoms, leaving them in unstable states. To regain atomic stability, the electrons from higher energy levels quickly fill these gaps. During this, so-called characteristic X-ray photons have energies equal to the difference between the two energy levels are emitted. The energy of emitted photons does not depend on the energy or intensity of the incident electron.

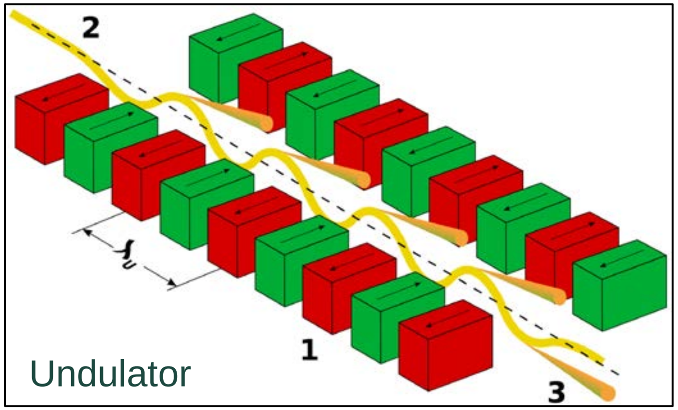




Sources of photons: Synchrotron radiation

- In high-energy particle physics facilities, where particles are accelerated in curved paths at relativistic velocities using magnetic fields, highly intense beams of photons, called synchrotron radiation, are naturally produced.
- Differently from Bremsstrahlung radiation, the synchrotron radiation is produced when charged particles are accelerated in curved paths. Although conceptually they represent the same physical phenomenon, they can be distinguished by noting that Bremsstrahlung is a product of tangential acceleration, while synchrotron radiation is produced by centripetal acceleration of charged particles.
- The spectrum of synchrotron radiation is continuous and extends over a broad energy range, from infrared to hard X-rays. In general, the spectral distribution is smooth, with a maximum near the so-called critical wavelength, which divides the energy carried by the synchrotron radiation into two halves.





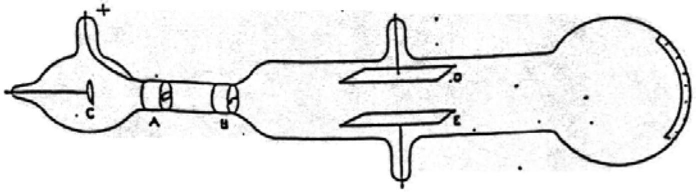
Sources of photons: Laser

- Laser (Light Amplification by Stimulated Emission of Radiation) is generated by exploiting a quantum mechanical phenomenon called stimulated emission of photons.
- In essence, the trick of producing laser is to somehow increase the population of atoms or molecules in the excited state and maintain it through external means (pumping). If more atoms or molecules are in an excited state than in a ground state, the system is said to have reached population inversion. Laser light is emitted for as long as this population inversion is maintained.
- Gas laser: He-Ne laser (632.8, 1152, 543.5 nm), CO_2 laser (IR), Excimer laser
- Liquid laser (dye laser): use liquid organic dye. pumped by Nd-YAG laser
- Solid-state laser: Ruby, Nd-YAG, Ti-sapphire
- Free electron laser (FEL): a kind of laser whose lasing medium consists of very-high-speed electrons moving freely through a magnetic structure, hence the term free electron. The free-electron laser is tunable and has the widest frequency range of any laser type, currently ranging in wavelength from microwaves, through terahertz radiation and infrared, to the visible spectrum, ultraviolet, and X-ray.

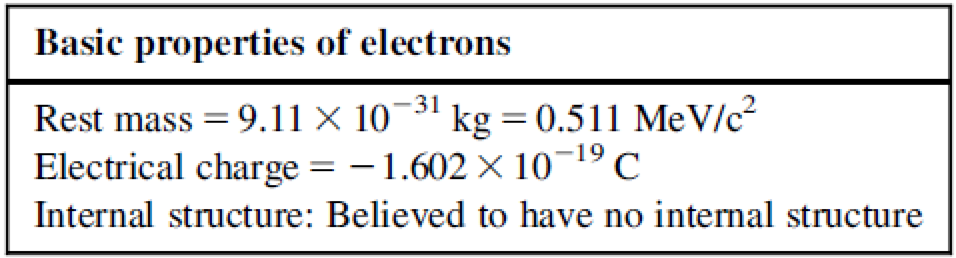
[H/W] Investigate the stimulated emission mechanism and Einstein coefficients.

Electrons

- According to our understanding so far, the electron is one of the fundamental particles of nature. It carries negative electrical charge and has a very small mass. Although we sometimes talk of electron radius, none of the experiments so far has been able to associate any particular structure to electrons. Interestingly enough, even though it appears to have no structure, it seems to be spinning in well-defined ways.
- Electrons were first discovered by J. J. Thompson in 1897 (Nobel prize in physics in 1906), about six years after their presence was hypothesized, and they were named electrons by an Irish physicist, George Stoney.



Thomson's illustration of the Crookes tube by which he observed the deflection of cathode rays by an electric field.



Basic properties of electrons

Rest mass = 9.11×10^{-31} kg = 0.511 MeV/c^2
Electrical charge = -1.602×10^{-19} C
Internal structure: Believed to have no internal structure

Sources of electrons: Electron gun

- Three types of electron guns are in common use: the thermionic electron gun, the field emission electron gun, and the photo-emission electron gun.
- *Thermionic emission* (Owen W. Richardson, 1901, Nobel prize in physics in 1928): the thermally induced flow of charge carriers from a surface or over a potential-energy barrier. This occurs because the thermal energy given to the carrier overcomes the work function of the material.

$$J = AT^2 \exp\left(-\frac{W}{kT}\right)$$

- *Field emission* (Fowler and Nordheim, 1928): the extraction of electrons from a solid by tunneling through the surface potential barrier. The emitted current depends directly on the local electric field at the emitting surface and on its work function.

$$J = C\frac{E^2}{W}\exp\left(-D\frac{W^{3/2}}{E}\right)$$

- *Photoelectric emission* (A. Einstein, 1905): electrons are emitted from matter as a consequence of their absorption of energy from electromagnetic radiation of very short wavelength, such as visible or ultraviolet light.

$$K_{max} = h\nu - W$$

[H/W] Investigate other electron emission mechanisms such as Auger electron and secondary electron emissions.

Sources of electrons: Radioactive sources

- The emission of a β-particle by a radionuclide through the reaction:

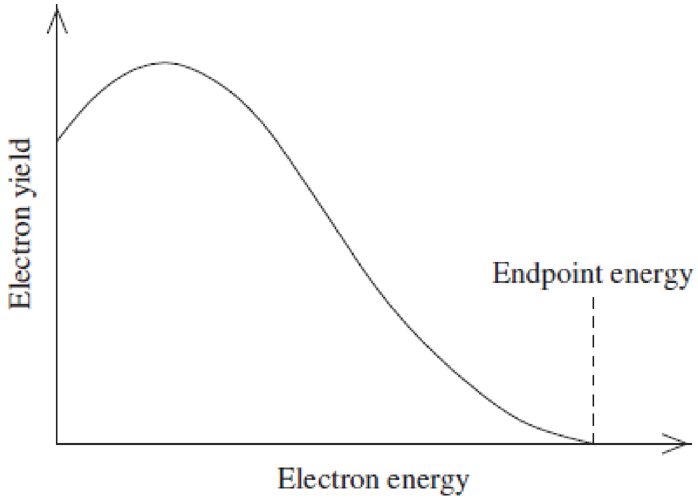
$$ {}^{n+p}_{p}X \rightarrow {}^{n+p}_{p+1}Y + e + \overline{\nu}. $$

- Due to mass difference between emitted particles and daughter nucleus, most of the energy is distributed between the electron and the neutrino. There is no restriction on either of these particles as to the amount of energy they can carry.
- The electrons can carry energy from almost zero up to the endpoint energy, which is essentially the decay Q-value.

Common electron emitters and their half-lives

Element	Isotope	Energy (E_{max})	$T_{1/2}$
Sodium	${}^{24}_{11}$Na	1.393 MeV	14.959 h
Phosphorus	${}^{32}_{15}$P	1.71 MeV	14.262 days
Chromium	${}^{51}_{24}$Cr	752.73 keV	27.702 days
Cobalt	${}^{60}_{27}$Co	318.13 keV	5.271 years
Copper	${}^{64}_{29}$Cu	578.7 keV	12.7 h
Strontium	${}^{90}_{38}$Sr	546.0 keV	28.79 years
Yttrium	${}^{90}_{39}$Y	2.28 MeV	64.0 h
Iodine	${}^{125}_{53}$I	150.61 keV	59.408 days
Cesium	${}^{137}_{55}$Cs	513.97 keV	30.07 years
Thallium	${}^{204}_{81}$Th	763.4 keV	3.78 years

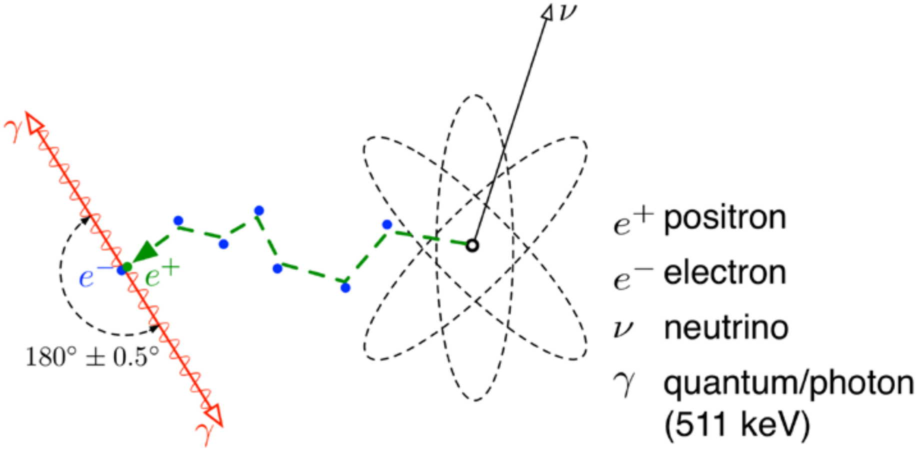
Typical β-particle energy spectrum

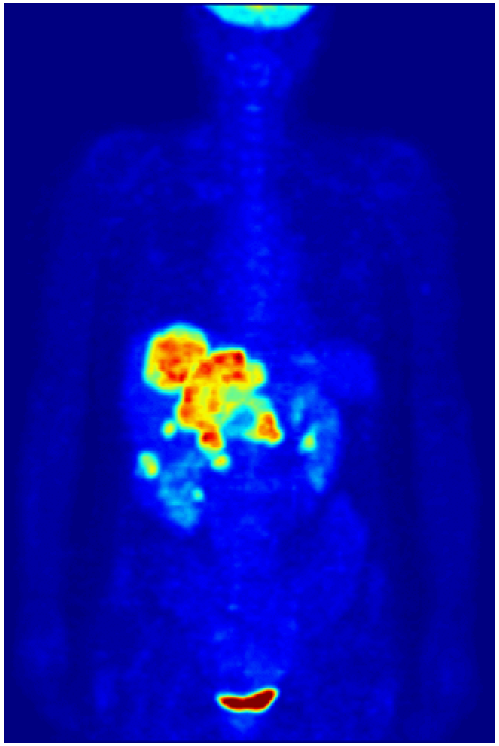


Positrons

- A positron is the antiparticle of an electron. It has all the properties of an electron except for the polarity of the electrical charge, which is positive. Therefore, a positron can simply be considered an electron having positive unit electrical charge. Whenever an electron and a positron come close, they annihilate each other and produce energy in the form of photons. In medical imaging, they are employed in so-called positron emission tomography (PET).

$$e + e^{+} \rightarrow 2\gamma$$



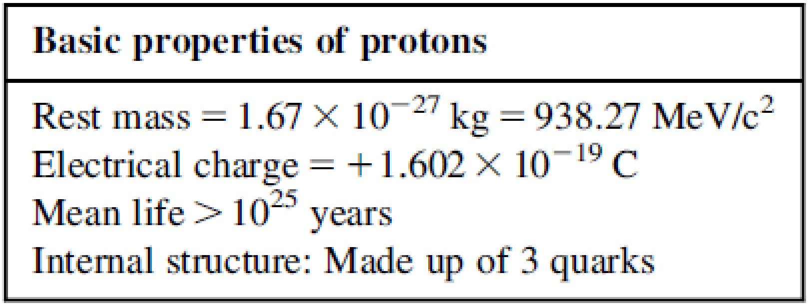


Common positron emitters and their half-lives

Element	Isotope	$T_{1/2}$
Carbon	$^{11}_{6}C$	20.39 min
Nitrogen	$^{13}_{7}N$	9.96 min
Oxygen	$^{15}_{8}O$	122.24 s
Fluorine	$^{18}_{9}F$	109.77 min

Protons

- Protons are extremely stable composite particles made up of three quarks. They carry the same amount of electric charge as electrons but in positive polarity. However, they are about 1836 times heavier than electrons.
- It was Ernest Rutherford who, in 1911, proposed the idea of the atom being composed of a positively charged nucleus and separate negative charges. After a series of experiments he reached the conclusion that the nuclei of different elements were always integral multiples of the nucleus of hydrogen atom. He called this basic unit the “proton.”
- Protons have found many useful applications in medicine and research. For example, proton beams are used to destroy cancerous tumors. They are also extensively used in high-energy physics experiments to explore the fundamental particles and their properties.

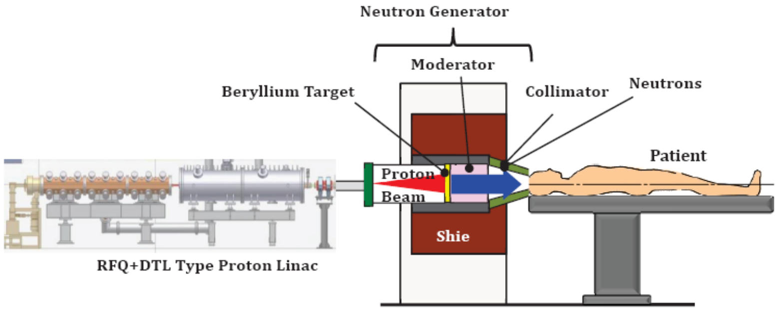


Basic properties of protons

Rest mass $= 1.67 \times 10^{-27}$ kg $= 938.27$ MeV/c^2
Electrical charge $= +1.602 \times 10^{-19}$ C
Mean life $> 10^{25}$ years
Internal structure: Made up of 3 quarks

Sources of protons: Particle accelerators

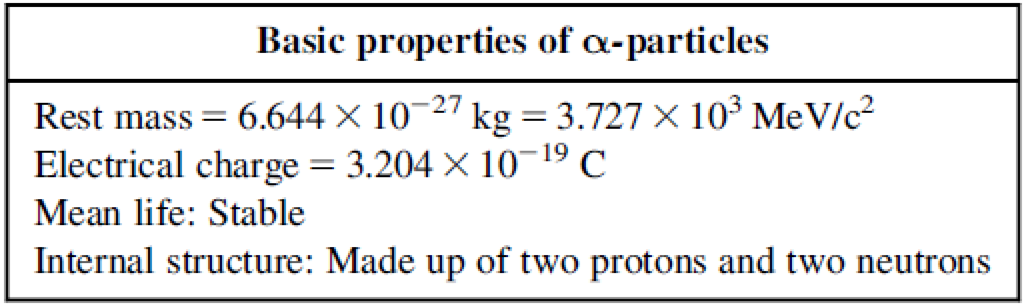
- Most of high-energy protons are generated by particle accelerators.
- Particle accelerators are the most important tools of fundamental particle physics research. The discoveries of the different quarks making up protons and neutrons have all been made at particle colliders. In some of these facilities, particles are first accelerated to very high energies and then made to collide with some target material. There are also colliders where different particles are first accelerated to very high energies in opposite directions and then allowed to collide at certain points.
- Apart from fundamental physics research, particle accelerators are also extensively used in medicine. For example, high-energy protons produced in a particle accelerator are used to destroy cancerous cells. They are also used to produce radioisotopes such as ^{18}F which is widely used in PET.
- Most of high-flux neutrons are produced by high-energy protons colliding with high Z materials.



Accelerator-based neutron source for BNCT

Alpha particles

- Alpha particles are essentially helium nuclei with two protons and two neutrons bound together.
- The consequence of their high mass and electrical charge is their inability to penetrate as deep as other particles such as protons and electrons. In fact, a typical alpha particle emitted with a kinetic energy of around 5 MeV is not able to penetrate even the outer layer of our skin. On the other hand, due to their positive charge, alpha particles interact very strongly with the atoms they encounter on their way. Hence α-particle sources pose significantly higher risk than other types of sources of equal strength if the particles are able to reach the internal organs. This can happen, for example, if the source is somehow inhaled or ingested.
- Alpha particles cannot travel more than a few centimeters in air and readily capture two electrons to become ordinary helium.

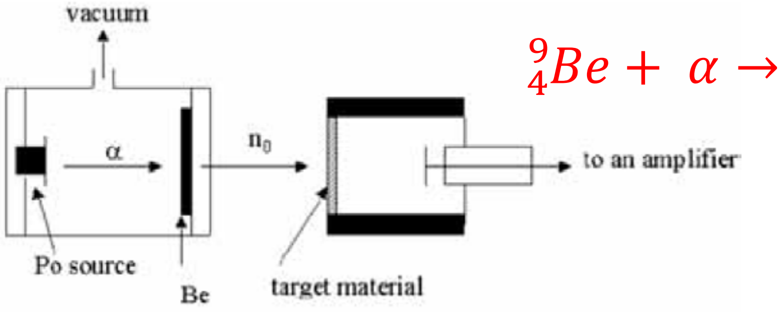


Basic properties of α-particles

Rest mass = 6.644×10^{-27} kg = 3.727×10^{3} MeV/c^2
Electrical charge = 3.204×10^{-19} C
Mean life: Stable
Internal structure: Made up of two protons and two neutrons

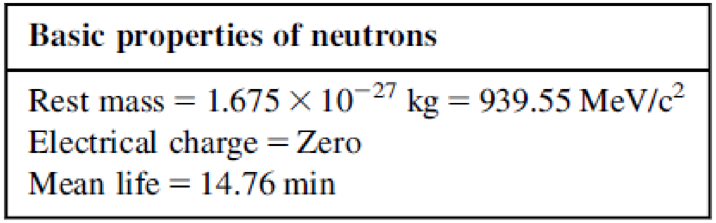
Neutrons: discovery

- In 1920, Rutherford postulated that there were neutral, massive particles in the nucleus of atoms. James Chadwick (Nobel prize in physics in 1935), a colleague of Rutherford, discovered the neutron in 1932.
- Chadwick bombarded a beryllium target with alpha particles producing neutrons that recoiled into a block of paraffin. The produced neutrons were detected when they knocked protons of paraffin wax. By measuring protons emerging from the paraffin with a Geiger counter, Chadwick inferred that the neutron had a mass comparable to that of the proton.



$${}^{9}_{4}Be + \alpha \rightarrow {}^{12}_{6}C + n$$

Chadwick's apparatus: 1st neutron generator

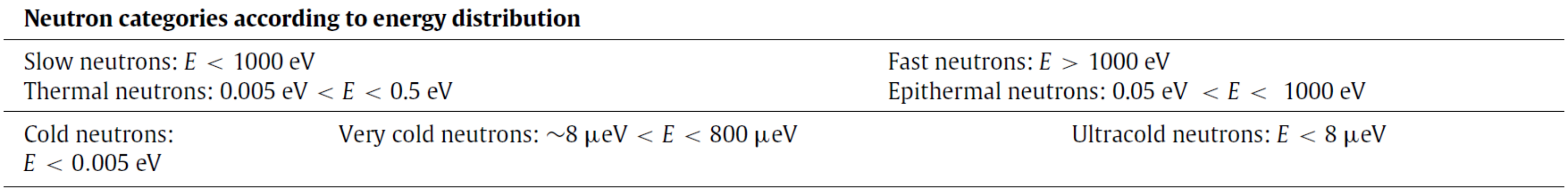


Basic properties of neutrons

Rest mass $= 1.675 \times 10^{-27}$ kg $= 939.55$ MeV/c^2
Electrical charge = Zero
Mean life = 14.76 min

$$n \xrightarrow{t_{1/2}=611\ \mathrm{s}} e^- + p + \bar{\nu}_e + 782\ \mathrm{keV}$$

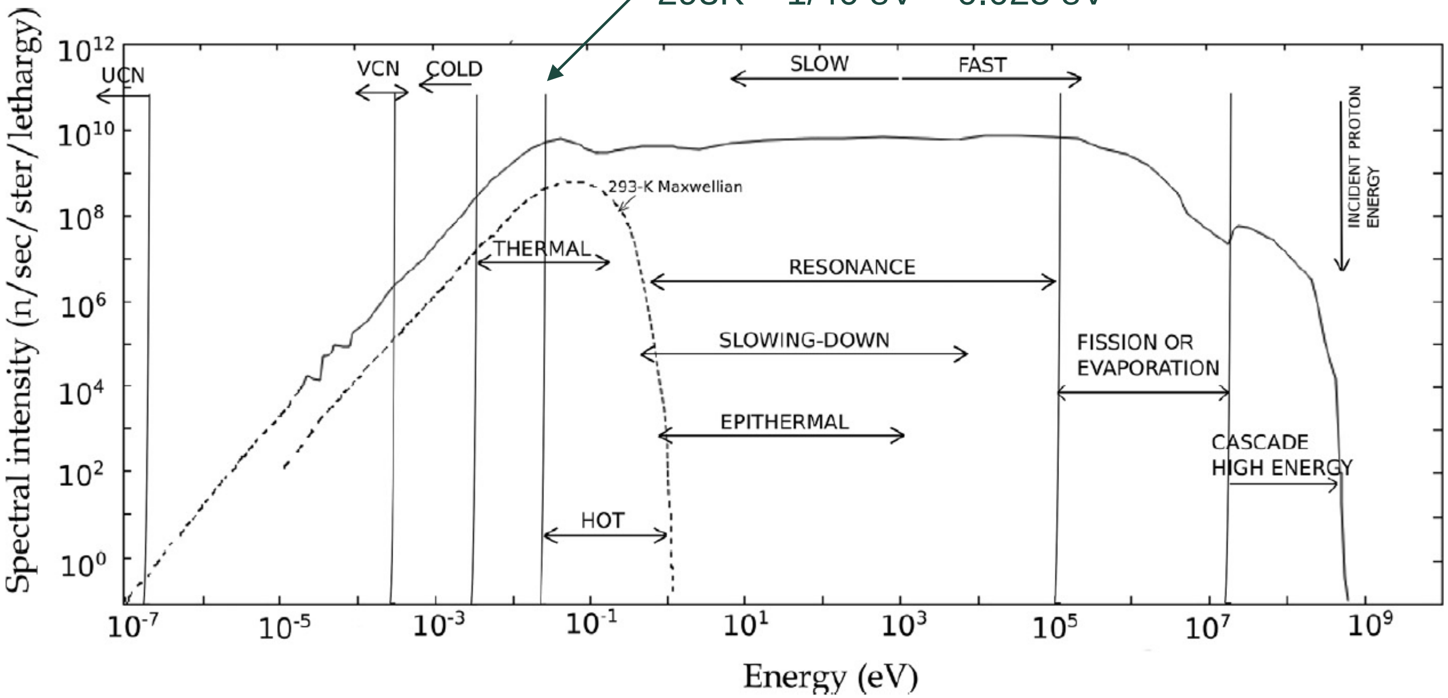
Classification of free neutrons according to kinetic energies



Neutron categories according to energy distribution

Slow neutrons: $E < 1000$ eV Thermal neutrons: 0.005 eV $< E < 0.5$ eV		Fast neutrons: $E > 1000$ eV Epithermal neutrons: 0.05 eV $< E <$ 1000 eV
Cold neutrons: $E < 0.005$ eV	Very cold neutrons: ~ 8 μeV $< E < 800$ μeV	Ultracold neutrons: $E < 8$ μeV

293K ~ 1/40 eV ~ 0.025 eV



The expected neutron spectrum emitted from a 100 K liquid methane moderator of the Intense Pulsed Neutron Source (IPNS) at Argonne National Laboratory (ANL)

Radioisotope neutron sources

- **Radioisotopes which undergo spontaneous fission**: Certain isotopes undergo spontaneous fission with emission of neutrons. The most commonly used spontaneous fission source is the radioactive isotope californium-252. When purchased new a typical Cf-252 neutron source emits between 1×10^7 to 1×10^9 neutrons per second but, with a half life of 2.6 years. The price of a typical Cf-252 neutron source is from $15,000 to $20,000.

- **Radioisotopes which decay with alpha particles packed in a low-Z elemental matrix**: Neutrons are produced when alpha particles impinge upon any of several low-atomic-weight isotopes including isotopes of beryllium, carbon, and oxygen. This nuclear reaction can be used to construct a neutron source by mixing a radioisotope that emits alpha particles such as radium, polonium, or americium with a low-atomic-weight isotope, usually by blending powders of the two materials. Typical emission rates for alpha reaction neutron sources range from 1×10^6 to 1×10^8 neutrons per second. The size and cost of these neutron sources are comparable to spontaneous fission sources. Usual combinations of materials are plutonium-beryllium (PuBe), americium-beryllium (AmBe), or americium-lithium (AmLi).