Radiation Sources

Fall, 2017

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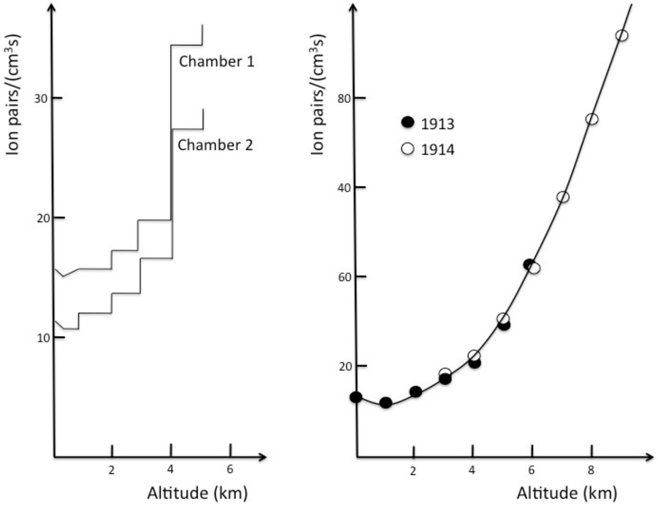
Natural sources

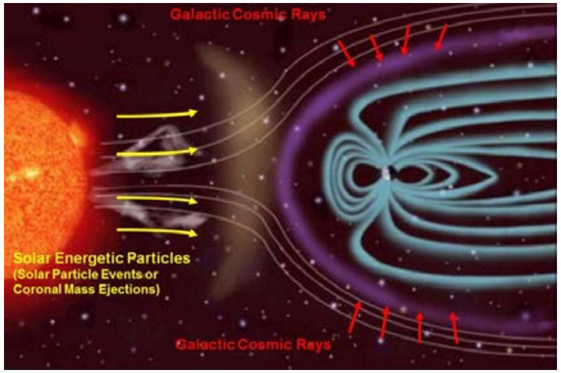
- Cosmic radiation sources:
  - After the discovery of radioactivity by Henri Becquerel and Marie Curie in 1896, it was generally believed that atmospheric electricity, ionization of the air, was caused only by radiation from radioactive elements in the ground or the radioactive gases or isotopes of 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.

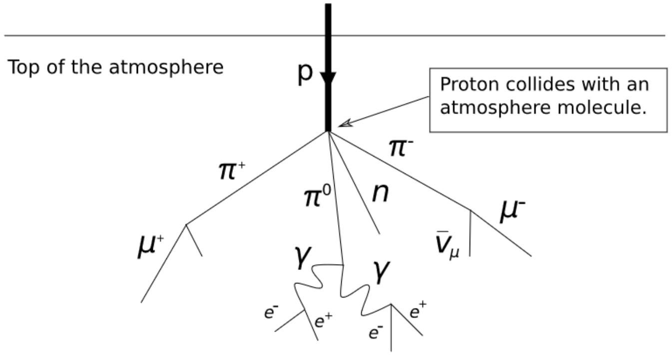
Victor Hess and his balloon (1912)



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.
    - Cosmic rays are high-energy radiation, mainly originating outside the solar system. Upon impact with the Earth's atmosphere, cosmic rays can produce showers of secondary particles that sometimes reach the surface.
    - 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 main source of terrestrial radiation is the element uranium and its decay products such as thorium, radium, and radon.
  - 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

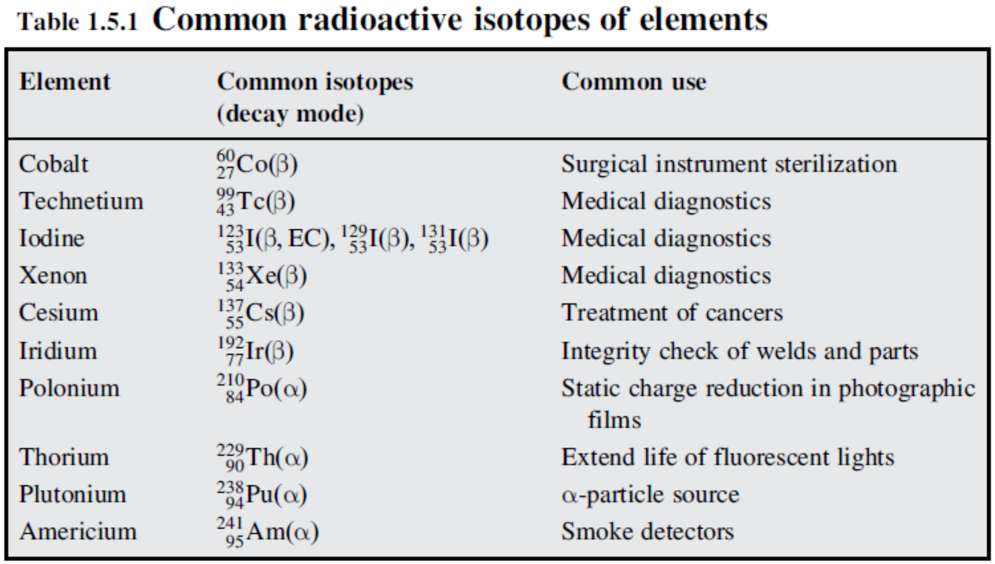
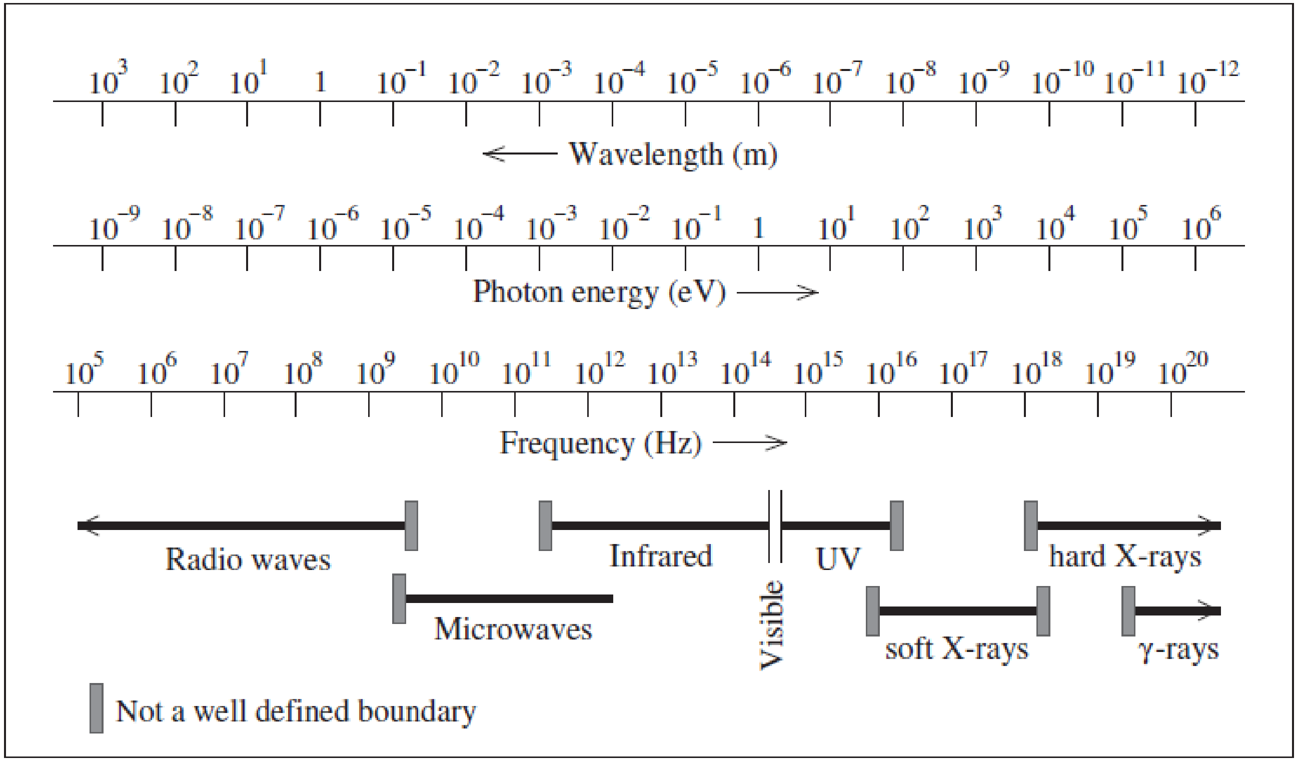


Table 1.5.1 Common radioactive isotopes of elements

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

Photons

- At the fundamental level, a photon is regarded as a quantum of excitation in the underlying electromagnetic field. For example, whenever a charged particle moves (such as a changing current in a wire), it creates electromagnetic waves around it that propagate in space. These waves are considered to be excitations in the underlying electromagnetic field, and a quantum of these excitations is called a photon.

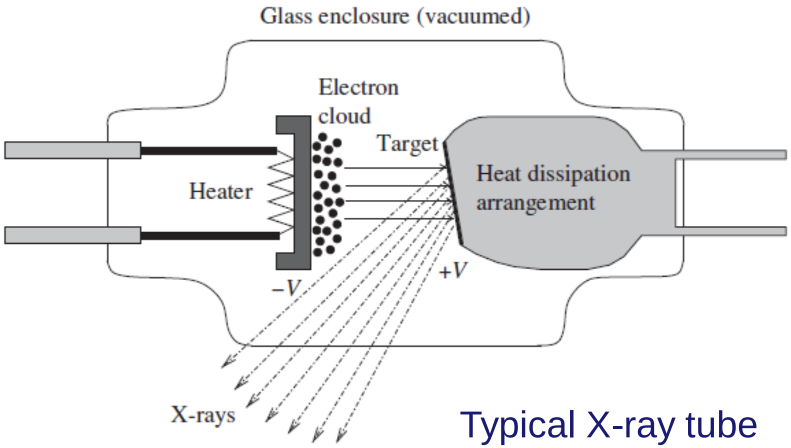


$$\boxed{E = h\nu = \frac{hc}{\lambda}}$$

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

Sources of photons: X-ray machine

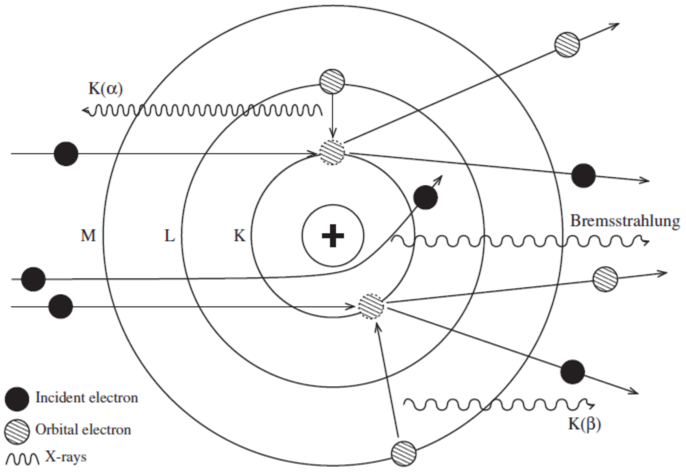
- Production of X-rays is a relatively simple process in which a high Z target (i.e., an element having a large number of protons, such as tungsten or molybdenum) is bombarded with high-velocity electrons. This results in the production of two types of X-rays: Bremsstrahlung and characteristic X-rays.
- 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.

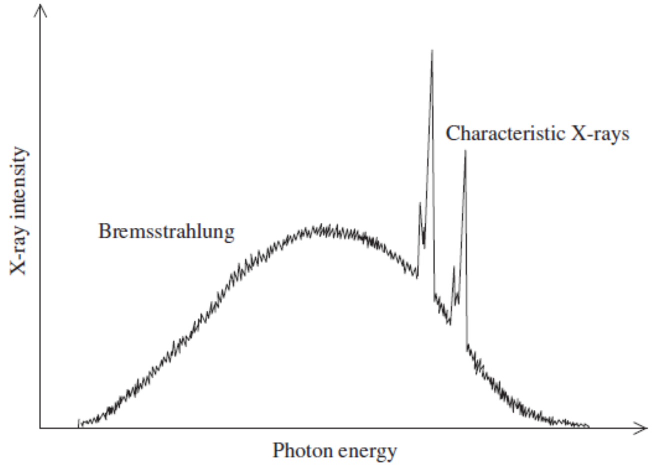


Typical X-ray tube

Bremsstrahlung and characteristic X-rays

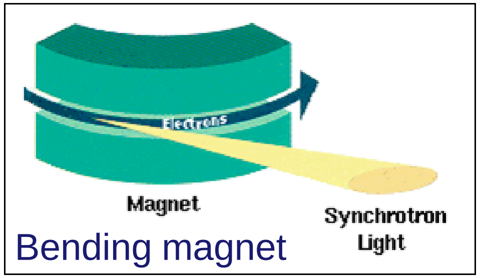
- Bremsstrahlung (braking radiation) refers to the radiation emitted by charged particles when they decelerate in a medium. In the case of X-rays, the high-energy electrons decelerate quickly in the target material and hence emit Bremsstrahlung. The emitted X-ray photons have a continuous energy spectrum 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.



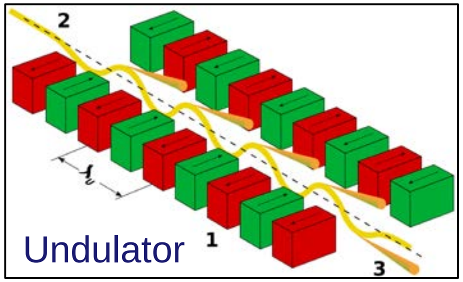


Sources of photons: Synchrotron radiation

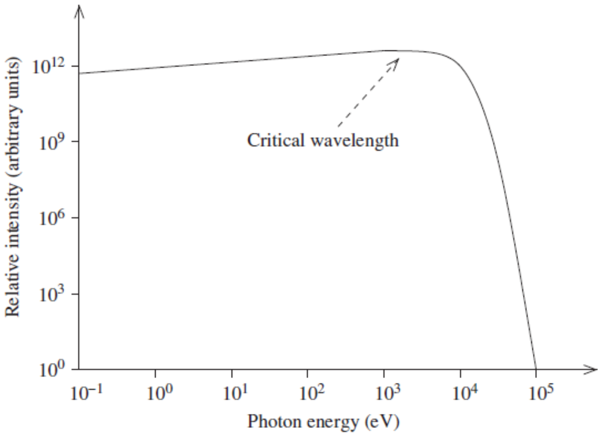
- In high-energy particle physics facilities, where particles are accelerated in curved paths at relativistic velocities using magnetic fields, highly intense beams of photons, called synchrotron radiation, are naturally produced.
- Differently from Bremsstrahlung radiation, the synchrotron radiation 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.



Bending magnet



Undulator

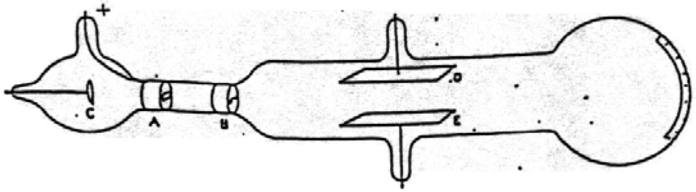


Sources of photons: Laser

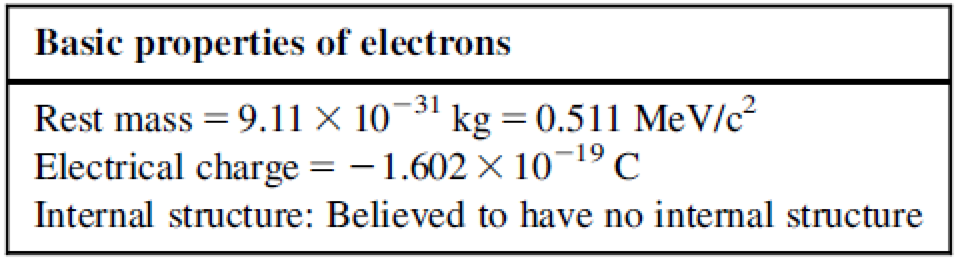
- Laser (Light Amplification by Stimulated Emission of Radiation) is generated by exploiting a quantum mechanical phenomenon called stimulated emission of photons.
- In essence, the trick of producing laser is to somehow increase the population of atoms or molecules in the excited state and maintain 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), CO2 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.

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.

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

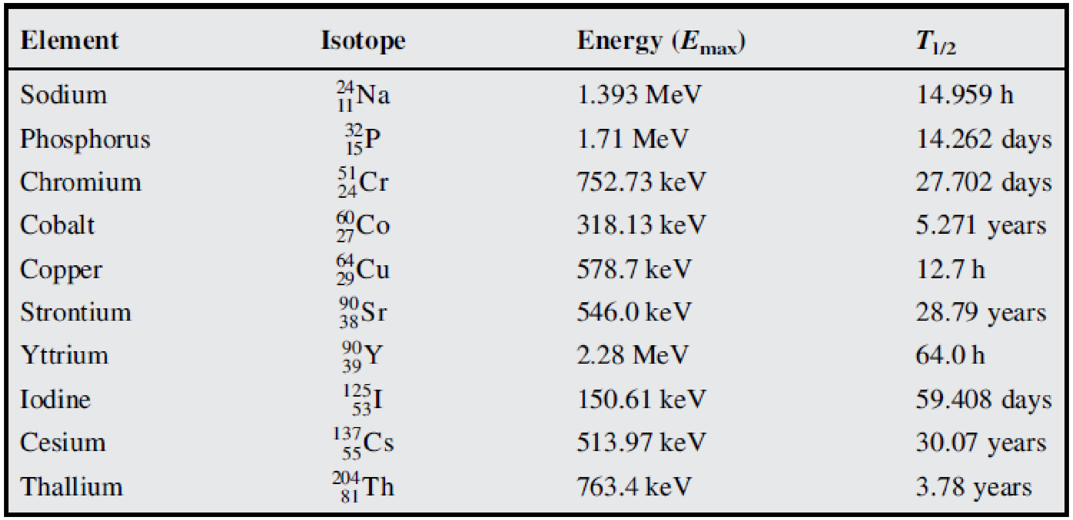
Sources of electrons: Radioactive sources

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

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

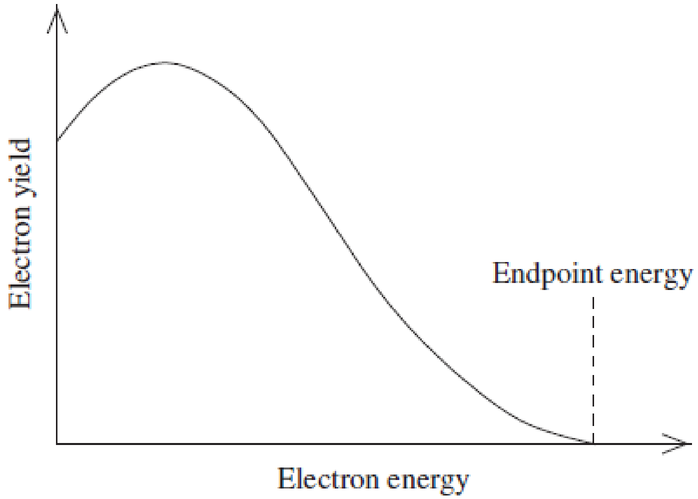
- Due to mass difference between emitted particles and daughter nucleus, most of the energy is distributed between the electron and the neutrino. There is no restriction on either of these particles as to the amount of energy they can carry.
- The electrons can carry energy from almost zero up to the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

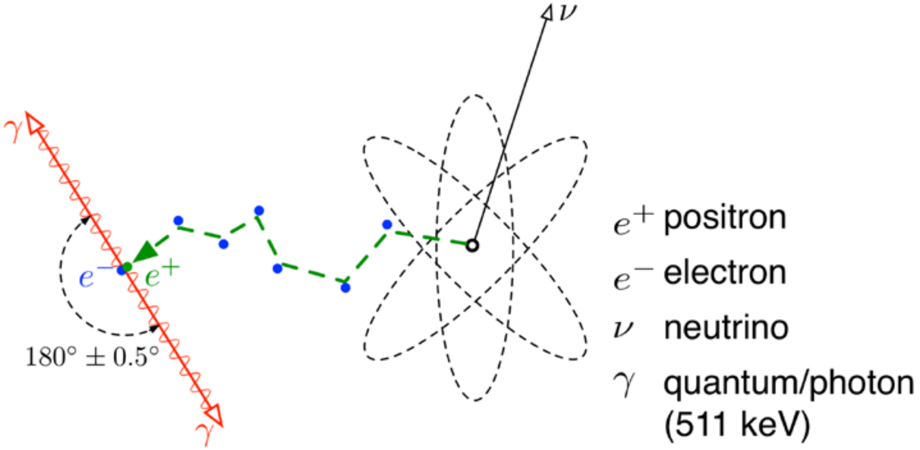
Typical β-particle energy spectrum

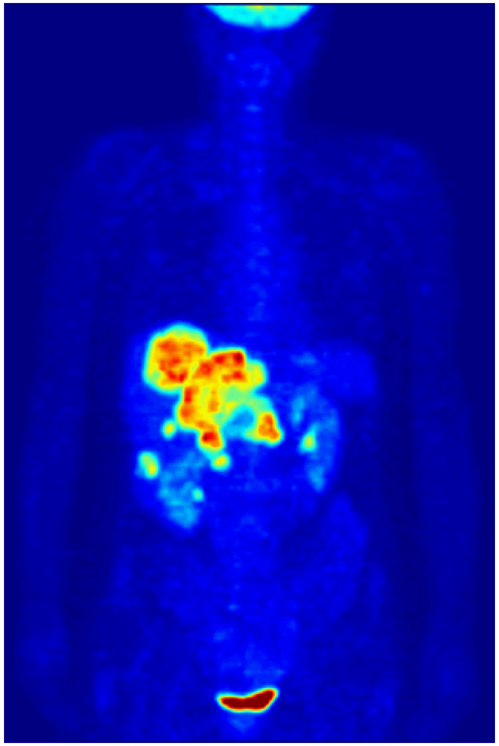


Positrons

- 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).

$$e + e^+ \to 2\gamma$$



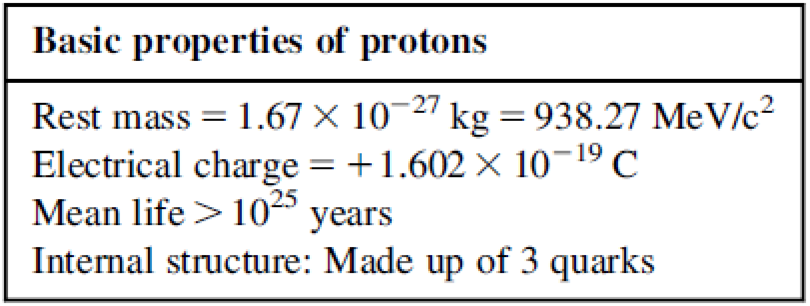


Common positron emitters and their half-lives

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

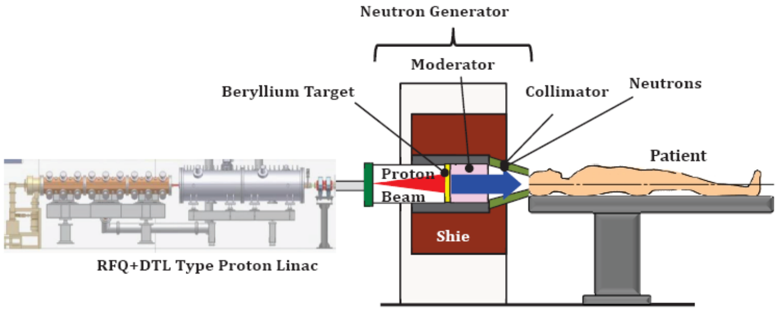
Electrical charge $= +1.602 \times 10^{-19}$ C

Mean life $> 10^{25}$ years

Internal structure: Made up of 3 quarks

Sources of protons: Particle accelerators

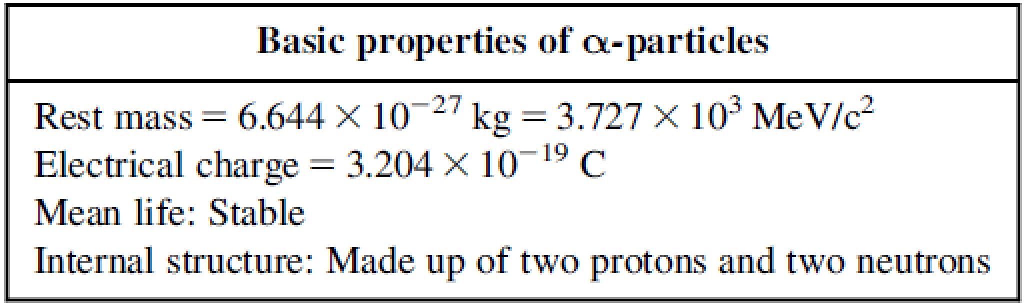
- Most of high-energy protons are generated by particle accelerators.
- Particle accelerators are the most important tools of fundamental particle physics research. The discoveries of the different quarks making up protons and neutrons have all been made at particle colliders. In some of these facilities, 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