Radiation / Radioactivity / Radioactive Decay

Radioactive Particles / Common Isotopes

Counting

History – Discovery of X-rays / Radioactivity /
Nuclear atom

Radioactive Decay – particles, half-life and equations

Radioactivity – the Nuclear atom
(side trip to the "Particle Zoo" and neutrinos)

Nuclear Energy

Hackert – CH370

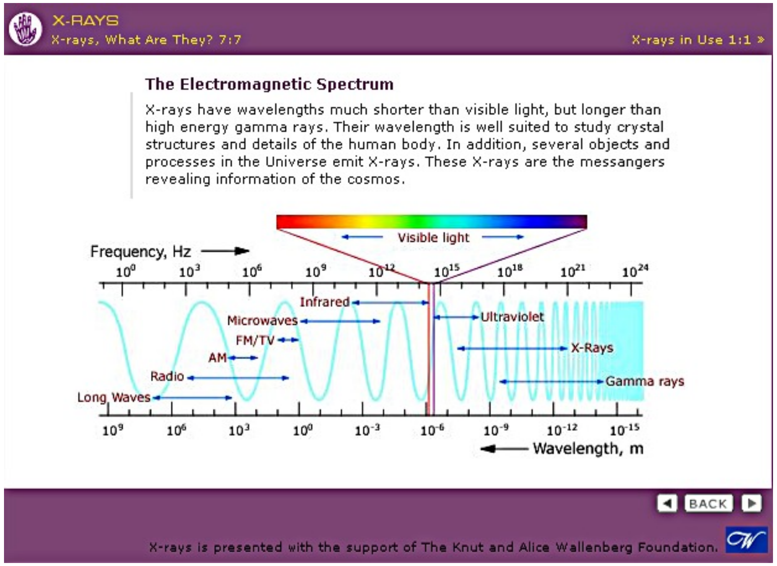
Goals for this unit:

Early History of the Nuclear Atom

Radioactive Decay –
know common forms of decay

Balance decay reactions

Nuclear Energy – fission rxns. vs. fusion

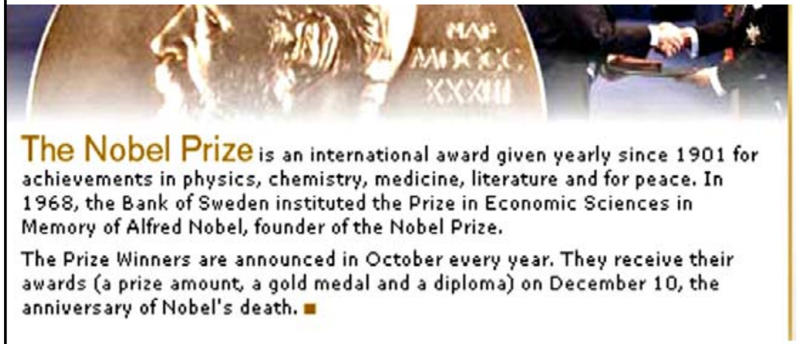


X-RAYS
X-rays, What Are They? 7:7
X-rays in Use 1:1 »

The Electromagnetic Spectrum

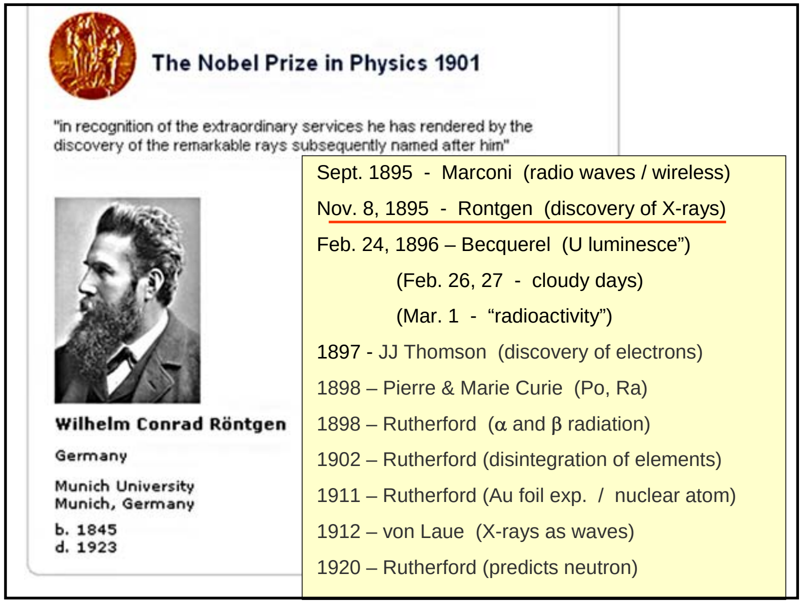
X-rays have wavelengths much shorter than visible light, but longer than high energy gamma rays. Their wavelength is well suited to study crystal structures and details of the human body. In addition, several objects and processes in the Universe emit X-rays. These X-rays are the messangers revealing information of the cosmos.

X-rays is presented with the support of The Knut and Alice Wallenberg Foundation.



The Nobel Prize is an international award given yearly since 1901 for achievements in physics, chemistry, medicine, literature and for peace. In 1968, the Bank of Sweden instituted the Prize in Economic Sciences in Memory of Alfred Nobel, founder of the Nobel Prize.

The Prize Winners are announced in October every year. They receive their awards (a prize amount, a gold medal and a diploma) on December 10, the anniversary of Nobel's death.



The Nobel Prize in Physics 1901

"in recognition of the extraordinary services he has rendered by the discovery of the remarkable rays subsequently named after him"

Wilhelm Conrad Röntgen

Germany

Munich University
Munich, Germany

b. 1845
d. 1923

Sept. 1895 - Marconi (radio waves / wireless)

Nov. 8, 1895 - Rontgen (discovery of X-rays)

Feb. 24, 1896 – Becquerel (U luminesce")

(Feb. 26, 27 - cloudy days)

(Mar. 1 - "radioactivity")

1897 - JJ Thomson (discovery of electrons)

1898 – Pierre & Marie Curie (Po, Ra)

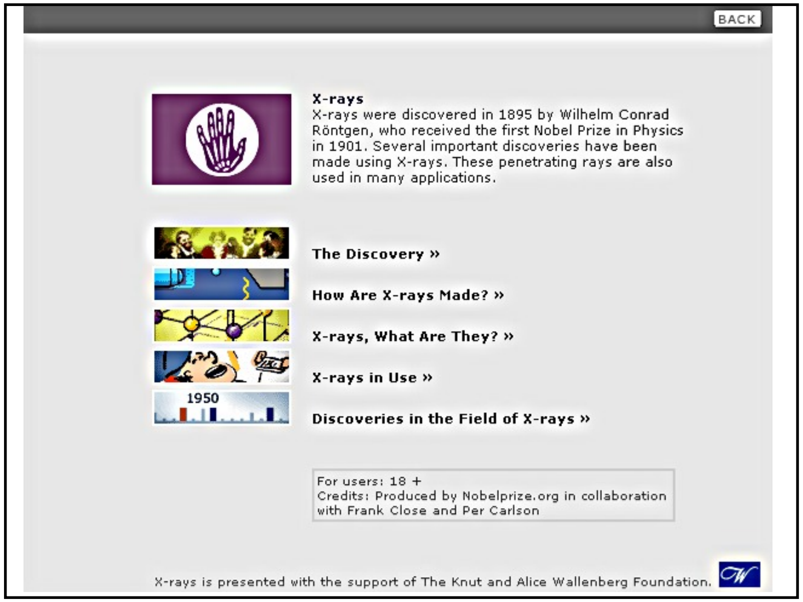
1898 – Rutherford (α and β radiation)

1902 – Rutherford (disintegration of elements)

1911 – Rutherford (Au foil exp. / nuclear atom)

1912 – von Laue (X-rays as waves)

1920 – Rutherford (predicts neutron)



X-rays
X-rays were discovered in 1895 by Wilhelm Conrad Röntgen, who received the first Nobel Prize in Physics in 1901. Several important discoveries have been made using X-rays. These penetrating rays are also used in many applications.

The Discovery »

How Are X-rays Made? »

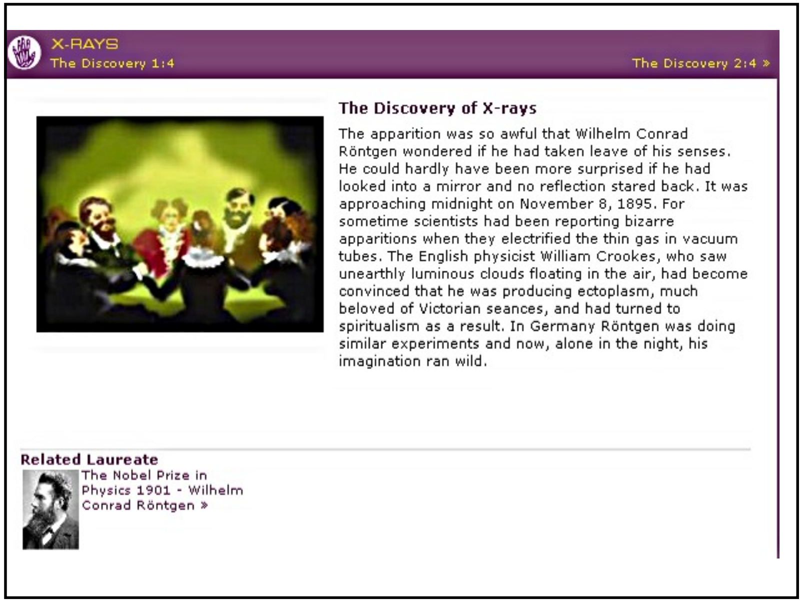
X-rays, What Are They? »

X-rays in Use »

Discoveries in the Field of X-rays »

For users: 18 +
Credits: Produced by Nobelprize.org in collaboration with Frank Close and Per Carlson

X-rays is presented with the support of The Knut and Alice Wallenberg Foundation.

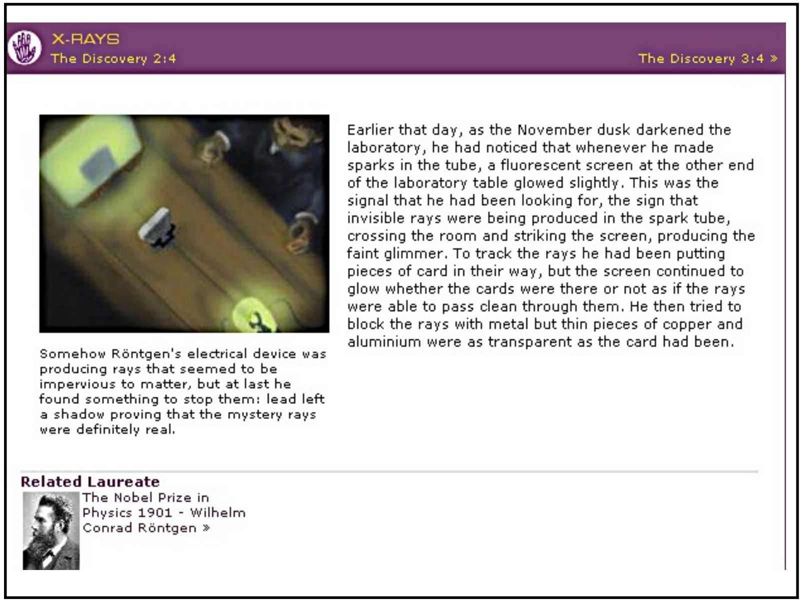


X-RAYS
The Discovery 1:4
The Discovery 2:4 »

The Discovery of X-rays

The apparition was so awful that Wilhelm Conrad Röntgen wondered if he had taken leave of his senses. He could hardly have been more surprised if he had looked into a mirror and no reflection stared back. It was approaching midnight on November 8, 1895. For sometime scientists had been reporting bizarre apparitions when they electrified the thin gas in vacuum tubes. The English physicist William Crookes, who saw unearthly luminous clouds floating in the air, had become convinced that he was producing ectoplasm, much beloved of Victorian seances, and had turned to spiritualism as a result. In Germany Röntgen was doing similar experiments and now, alone in the night, his imagination ran wild.

Related Laureate
The Nobel Prize in Physics 1901 - Wilhelm Conrad Röntgen »

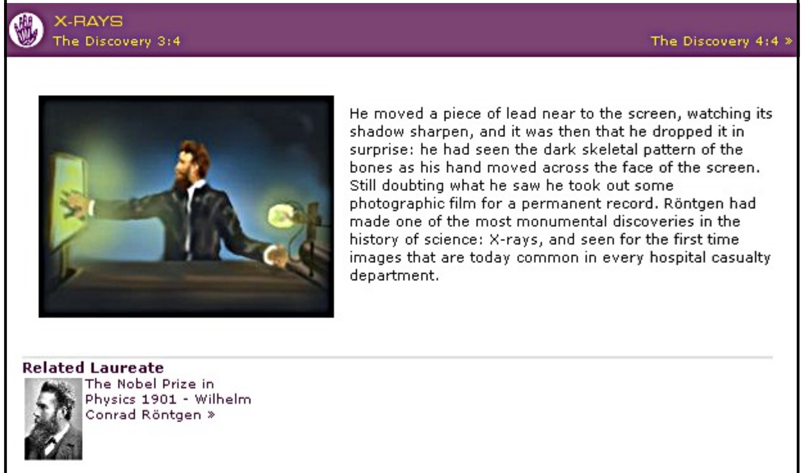


X-RAYS
The Discovery 2:4
The Discovery 3:4 »

Earlier that day, as the November dusk darkened the laboratory, he had noticed that whenever he made sparks in the tube, a fluorescent screen at the other end of the laboratory table glowed slightly. This was the signal that he had been looking for, the sign that invisible rays were being produced in the spark tube, crossing the room and striking the screen, producing the faint glimmer. To track the rays he had been putting pieces of card in their way, but the screen continued to glow whether the cards were there or not as if the rays were able to pass clean through them. He then tried to block the rays with metal but thin pieces of copper and aluminium were as transparent as the card had been.

Somehow Röntgen's electrical device was producing rays that seemed to be impervious to matter, but at last he found something to stop them: lead left a shadow proving that the mystery rays were definitely real.

Related Laureate
The Nobel Prize in Physics 1901 - Wilhelm Conrad Röntgen »



X-RAYS

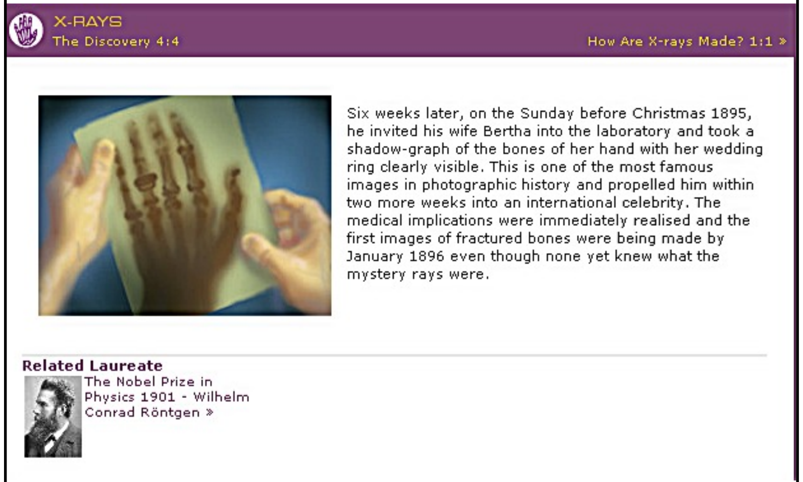
The Discovery 3:4

The Discovery 4:4 »

He moved a piece of lead near to the screen, watching its shadow sharpen, and it was then that he dropped it in surprise: he had seen the dark skeletal pattern of the bones as his hand moved across the face of the screen. Still doubting what he saw he took out some photographic film for a permanent record. Röntgen had made one of the most monumental discoveries in the history of science: X-rays, and seen for the first time images that are today common in every hospital casualty department.

Related Laureate

The Nobel Prize in Physics 1901 - Wilhelm Conrad Röntgen »



X-RAYS

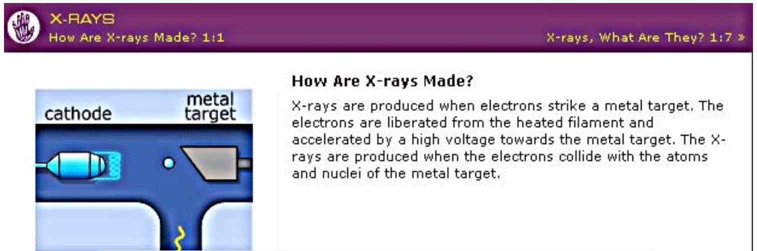
The Discovery 4:4

How Are X-rays Made? 1:1 »

Six weeks later, on the Sunday before Christmas 1895, he invited his wife Bertha into the laboratory and took a shadow-graph of the bones of her hand with her wedding ring clearly visible. This is one of the most famous images in photographic history and propelled him within two more weeks into an international celebrity. The medical implications were immediately realised and the first images of fractured bones were being made by January 1896 even though none yet knew what the mystery rays were.

Related Laureate

The Nobel Prize in Physics 1901 - Wilhelm Conrad Röntgen »



X-RAYS

How Are X-rays Made? 1:1

X-rays, What Are They? 1:7 »

How Are X-rays Made?

X-rays are produced when electrons strike a metal target. The electrons are liberated from the heated filament and accelerated by a high voltage towards the metal target. The X-rays are produced when the electrons collide with the atoms and nuclei of the metal target.

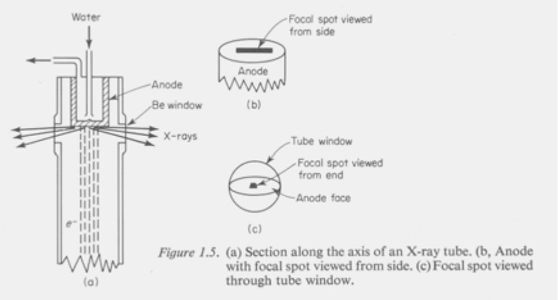
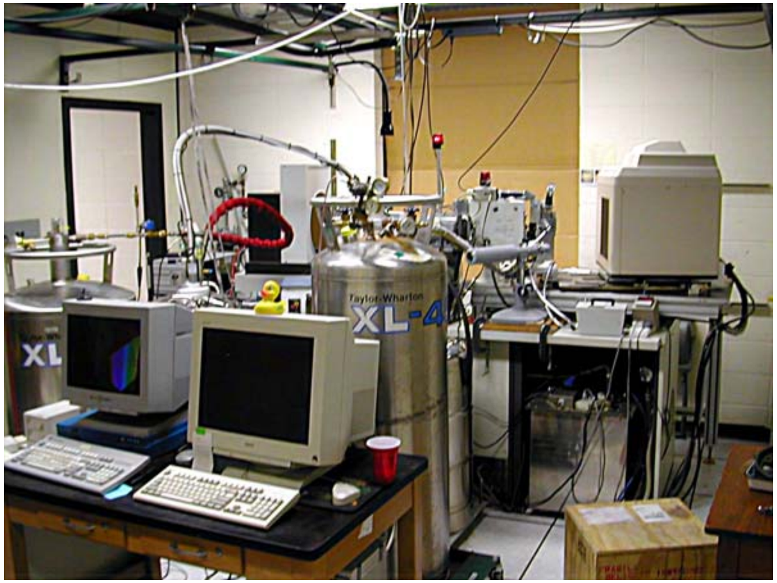


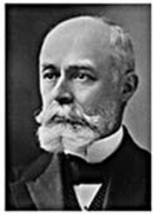
Figure 1.5. (a) Section along the axis of an X-ray tube. (b, Anode with focal spot viewed from side. (c) Focal spot viewed through tube window.



The Nobel Prize in Physics 1903

"in recognition of the extraordinary services he has rendered by his discovery of spontaneous radioactivity"

"in recognition of the extraordinary services they have rendered by their joint researches on the radiation phenomena discovered by Professor Henri Becquerel"



Antoine Henri Becquerel

◑ 1/2 of the prize

France

Pierre Curie

◔ 1/4 of the prize

France

Marie Curie, née Sklodowska

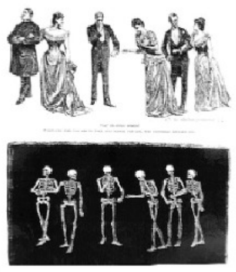
◔ 1/4 of the prize

France

Marie and Pierre Curie

Marie Sklodowska Curie
1867-1934

Pierre Curie
1859-1906



See "Women in Chemistry" in our S 2000 "Chemical Compositions" newsletter, p.4)

The Nobel Prize in Physics 1906

"in recognition of the great merits of his theoretical and experimental investigations on the conduction of electricity by gases"

Joseph John Thomson

United Kingdom

University of Cambridge
Cambridge, United Kingdom

b. 1856
d. 1940

The Nobel Prize in Chemistry 1908

"for his investigations into the disintegration of the elements, and the chemistry of radioactive substances"

Ernest Rutherford

United Kingdom and New Zealand

Victoria University
Manchester, United Kingdom

b. 1871
(in Nelson, New Zealand)
d. 1937

Sept. 1895 - Marconi (radio waves / wireless)
Nov. 8, 1895 - Rontgen (discovery of X-rays)
Feb. 24, 1896 – Becquerel (U luminesce")
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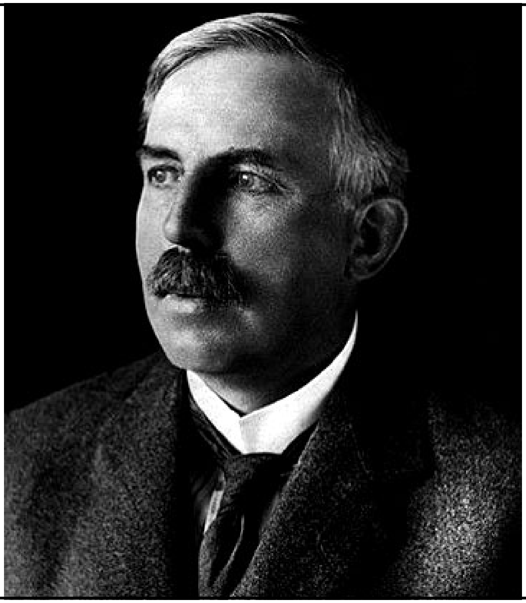
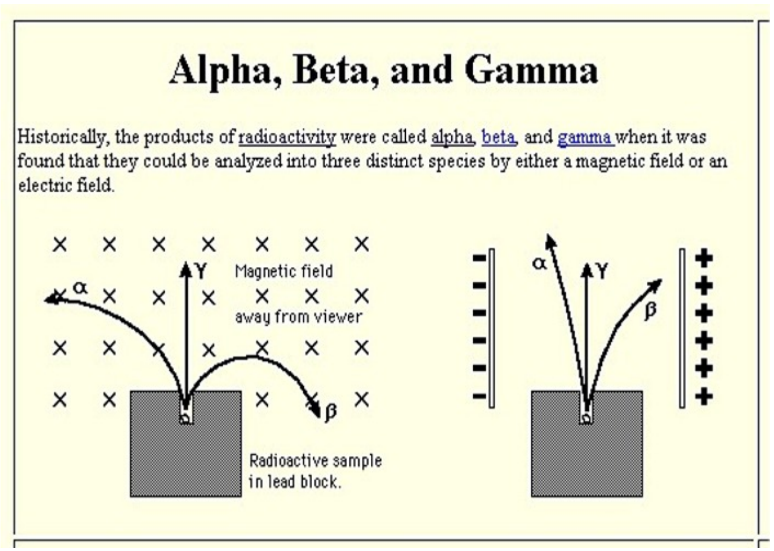
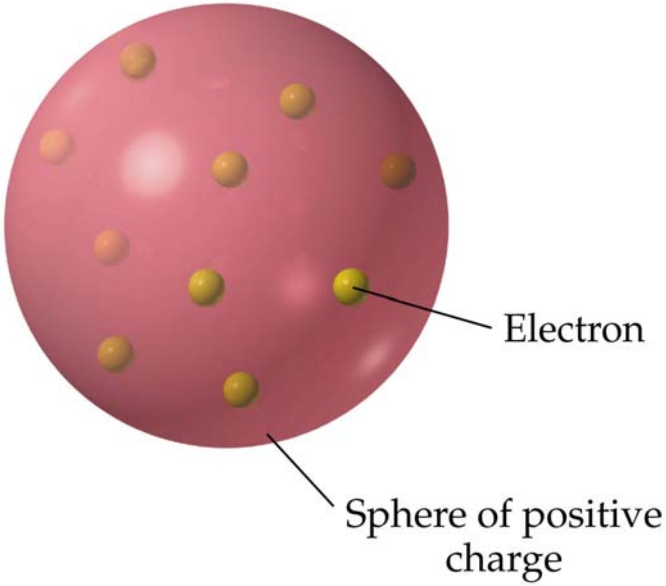
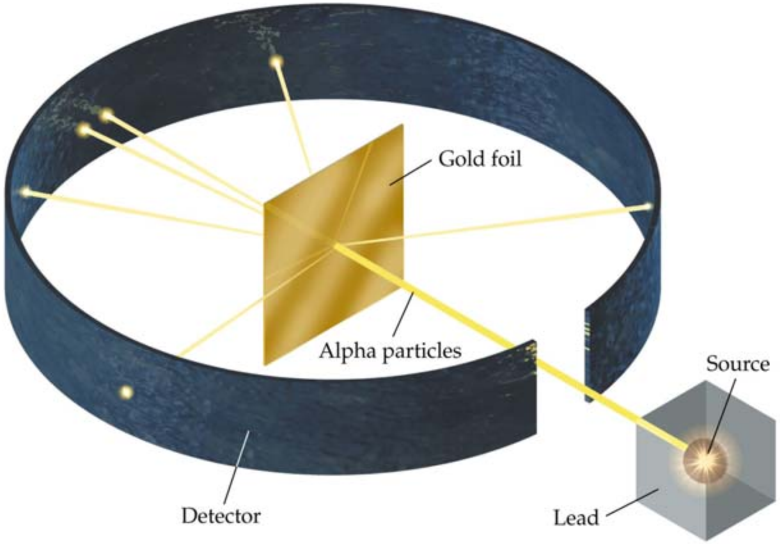


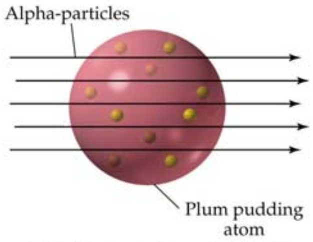


Alpha, Beta, and Gamma

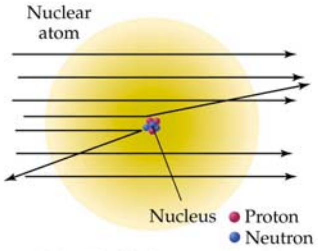
Historically, the products of radioactivity were called alpha, beta, and gamma when it was found that they could be analyzed into three distinct species by either a magnetic field or an electric field.



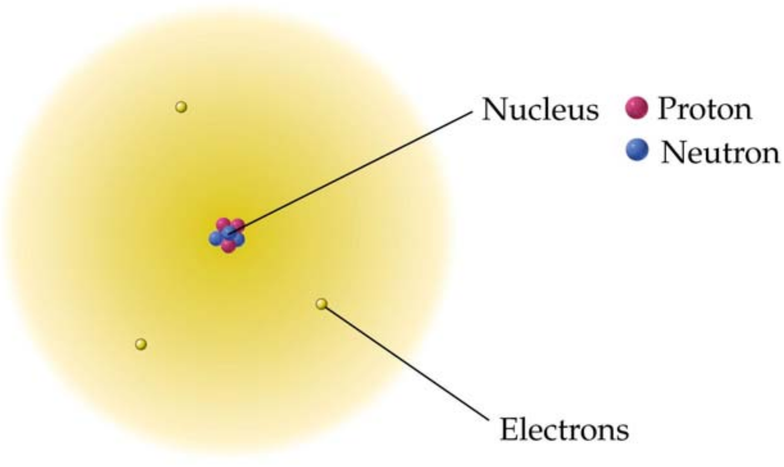


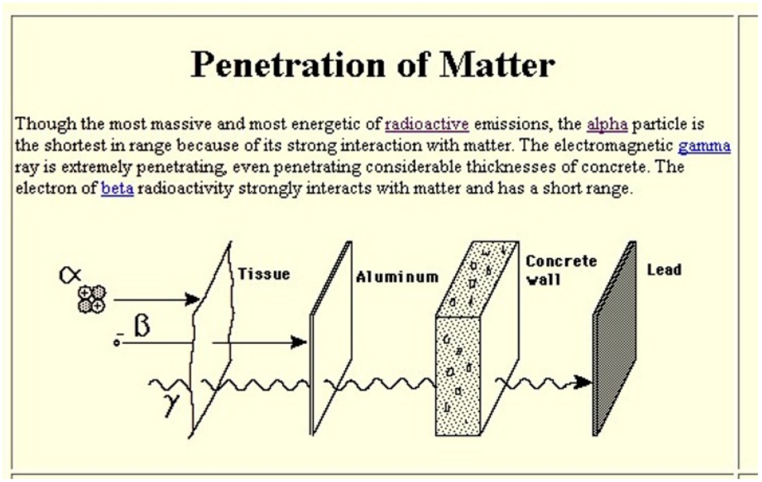


(a) Rutherford's Expected Result



(b) Rutherford's Actual Result



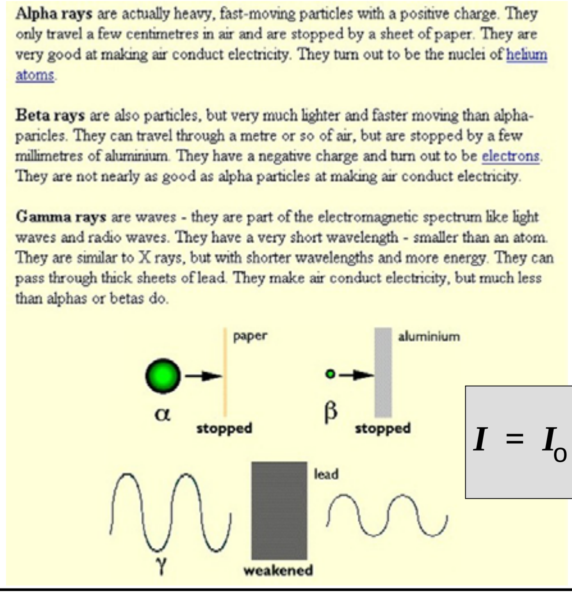


Penetration of Matter

Though the most massive and most energetic of radioactive emissions, the alpha particle is the shortest in range because of its strong interaction with matter. The electromagnetic gamma ray is extremely penetrating, even penetrating considerable thicknesses of concrete. The electron of beta radioactivity strongly interacts with matter and has a short range.

$$I = I_o e^{-\lambda t}$$

Rutherford – quantitative measurements



Alpha rays are actually heavy, fast-moving particles with a positive charge. They only travel a few centimetres in air and are stopped by a sheet of paper. They are very good at making air conduct electricity. They turn out to be the nuclei of helium atoms.

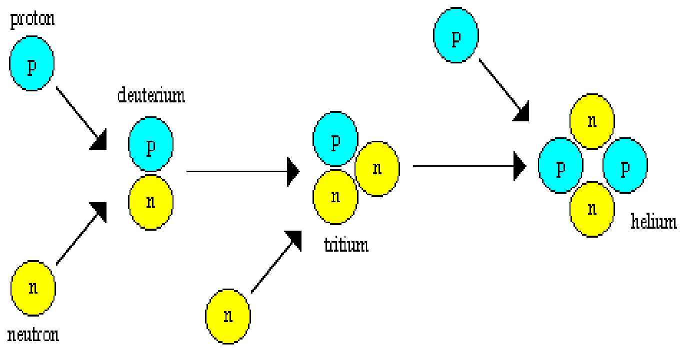
Beta rays are also particles, but very much lighter and faster moving than alpha-paricles. They can travel through a metre or so of air, but are stopped by a few millimetres of aluminium. They have a negative charge and turn out to be electrons. They are not nearly as good as alpha particles at making air conduct electricity.

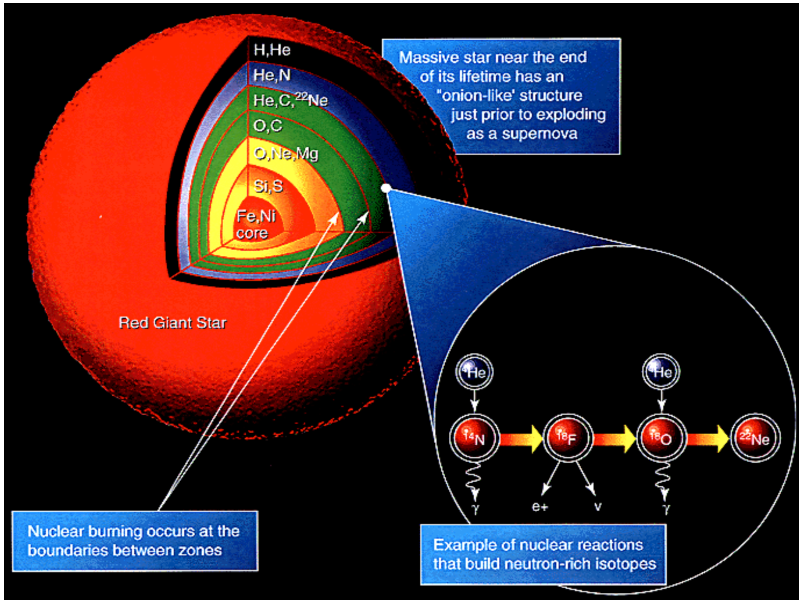
Gamma rays are waves - they are part of the electromagnetic spectrum like light waves and radio waves. They have a very short wavelength - smaller than an atom. They are similar to X rays, but with shorter wavelengths and more energy. They can pass through thick sheets of lead. They make air conduct electricity, but much less than alphas or betas do.

$$I = I_o e^{-\lambda t}$$

Nucleosynthesis

as the Universe cools, protons and neutrons can fuse to form heavier atomic nuclei

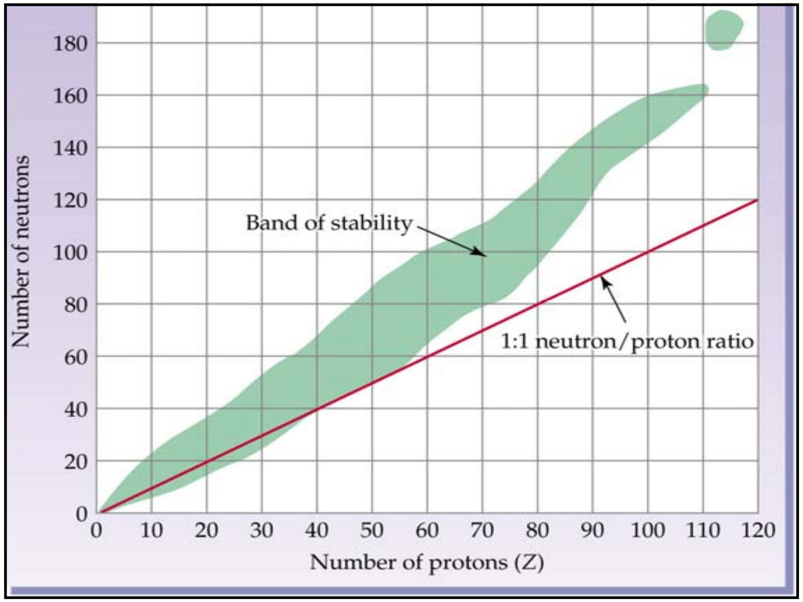


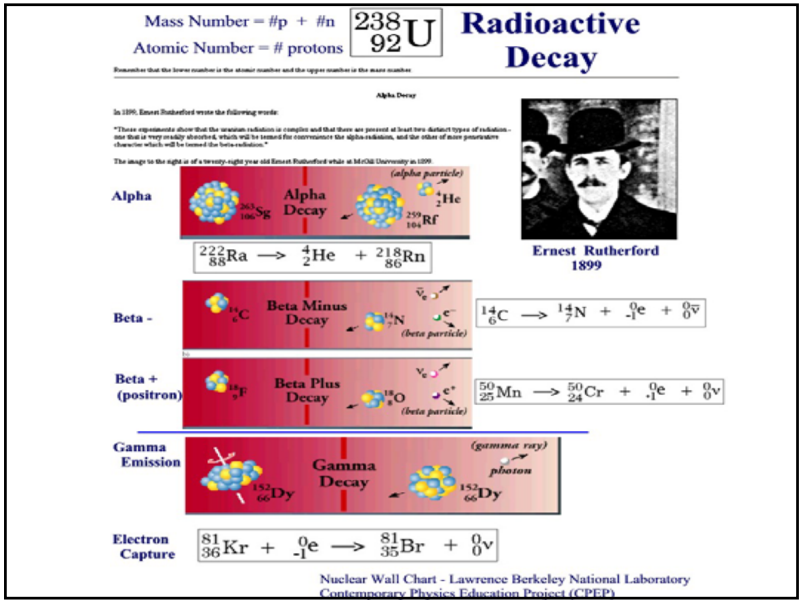


Massive star near the end of its lifetime has an "onion-like" structure just prior to exploding as a supernova

Nuclear burning occurs at the boundaries between zones

Example of nuclear reactions that build neutron-rich isotopes





Mass Number = #p + #n

Atomic Number = # protons

$^{238}_{92}U$

Radioactive Decay

Remember that the lower number is the atomic number and the upper number is the mass number

Alpha Decay

In 1899, Ernest Rutherford wrote the following words:

"These experiments show that the uranium radiation is complex and that there are present at least two distinct types of radiation - one that is very readily absorbed, which will be termed for convenience the alpha-radiation, and the other of more penetrative character which will be termed the beta-radiation."

The image to the right is of a twenty-eight year old Ernest Rutherford while at McGill University in 1899.

Alpha

$^{222}_{88}Ra \longrightarrow {}^{4}_{2}He + {}^{218}_{86}Rn$

Ernest Rutherford
1899

Beta -

$^{14}_{6}C \longrightarrow {}^{14}_{7}N + {}^{0}_{-1}e + {}^{0}_{0}\bar{\nu}$

Beta +
(positron)

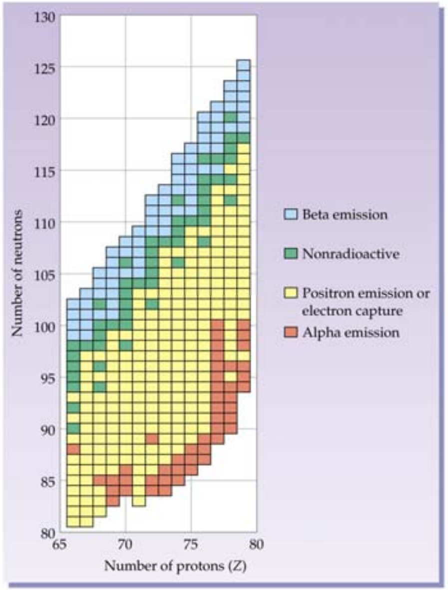
$^{50}_{25}Mn \longrightarrow {}^{50}_{24}Cr + {}^{0}_{+1}e + {}^{0}_{0}\nu$

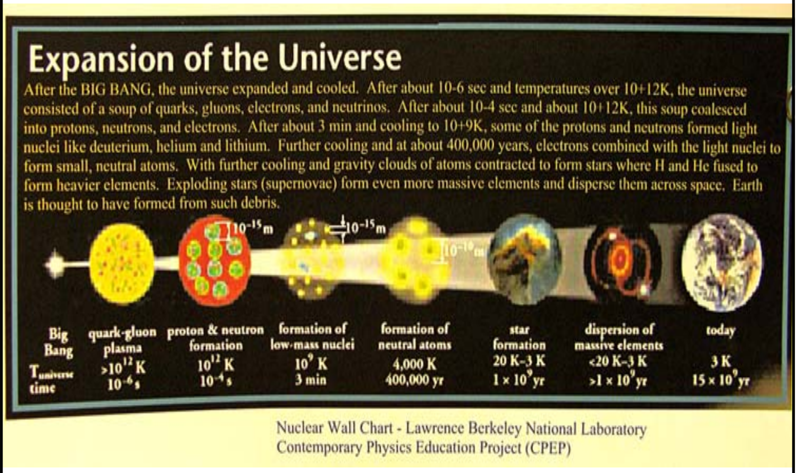
Gamma Emission

Electron Capture

$^{81}_{36}Kr + {}^{0}_{-1}e \longrightarrow {}^{81}_{35}Br + {}^{0}_{0}\nu$

Nuclear Wall Chart - Lawrence Berkeley National Laboratory
Contemporary Physics Education Project (CPEP)



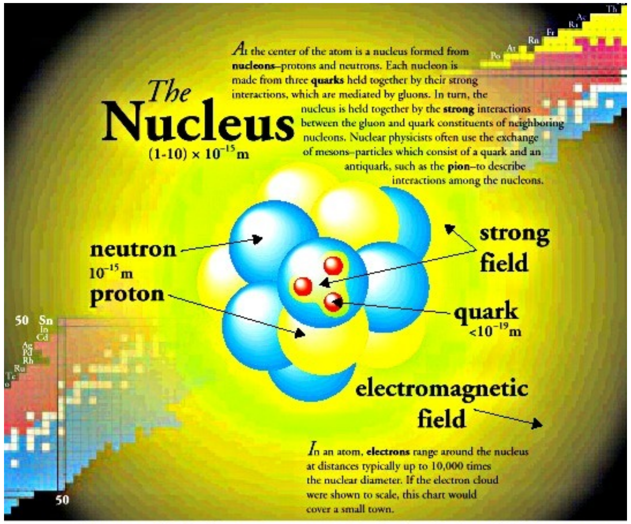


Expansion of the Universe

After the BIG BANG, the universe expanded and cooled. After about 10-6 sec and temperatures over 10+12K, the universe consisted of a soup of quarks, gluons, electrons, and neutrinos. After about 10-4 sec and about 10+12K, this soup coalesced into protons, neutrons, and electrons. After about 3 min and cooling to 10+9K, some of the protons and neutrons formed light nuclei like deuterium, helium and lithium. Further cooling and at about 400,000 years, electrons combined with the light nuclei to form small, neutral atoms. With further cooling and gravity clouds of atoms contracted to form stars where H and He fused to form heavier elements. Exploding stars (supernovae) form even more massive elements and disperse them across space. Earth is thought to have formed from such debris.

Big Bang	quark-gluon plasma	proton & neutron formation	formation of low-mass nuclei	formation of neutral atoms	star formation	dispersion of massive elements	today
$T_{universe}$	$>10^{12}$ K	10^{12} K	10^{9} K	4,000 K	20 K-3 K	<20 K-3 K	3 K
time	10^{-6} s	10^{-4} s	3 min	400,000 yr	1×10^{9} yr	$>1 \times 10^{9}$ yr	15×10^{9} yr

Nuclear Wall Chart - Lawrence Berkeley National Laboratory
Contemporary Physics Education Project (CPEP)



The Nucleus

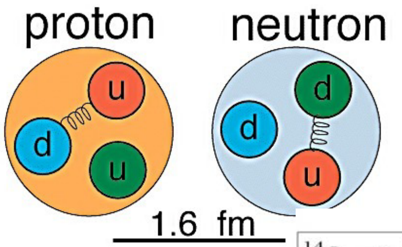
$(1\text{-}10) \times 10^{-15}$m

At the center of the atom is a nucleus formed from **nucleons**–protons and neutrons. Each nucleon is made from three **quarks** held together by their strong interactions, which are mediated by gluons. In turn, the nucleus is held together by the **strong** interactions between the gluon and quark constituents of neighboring nucleons. Nuclear physicists often use the exchange of mesons–particles which consist of a quark and an antiquark, such as the **pion**–to describe interactions among the nucleons.

In an atom, **electrons** range around the nucleus at distances typically up to 10,000 times the nuclear diameter. If the electron cloud were shown to scale, this chart would cover a small town.

Nuclear Wall Chart - Lawrence Berkeley National Laboratory
Contemporary Physics Education Project (CPEP)

Protons and Neutrons are both made up of Quarks. In the Quark Model the only difference between a Proton and a Neutron is that an "up" Quark has been replaced by a "down" Quark.

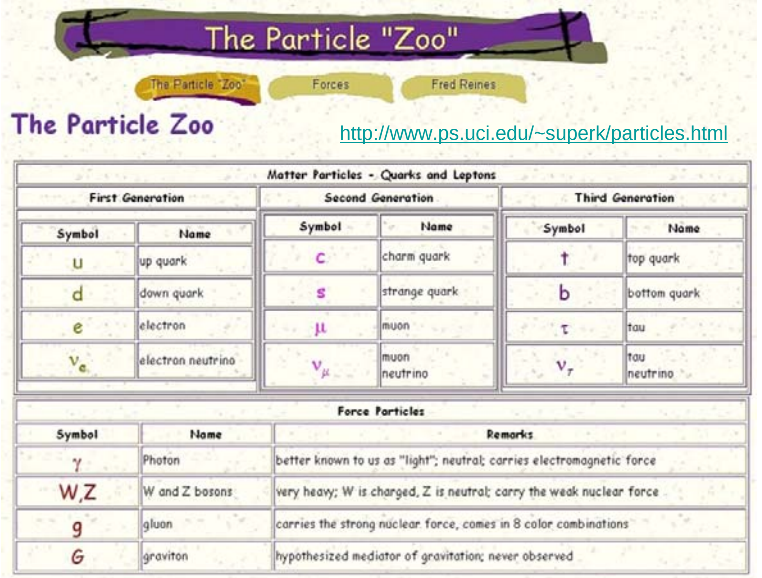


$$^{14}_{6}C \longrightarrow {}^{14}_{7}N + {}^{0}_{-1}e + {}^{0}_{0}\bar{\nu}$$

The little spring in the drawing is used
to indicate that the quarks inside a nucleon
are held together by a force we call gluon exchange.

Size of Nucleons

Nuclear Wall Chart - Lawrence Berkeley National Laboratory
Contemporary Physics Education Project (CPEP)



The Particle Zoo

http://www.ps.uci.edu/~superk/particles.html

Matter Particles - Quarks and Leptons

First Generation		Second Generation		Third Generation	
Symbol	**Name**	**Symbol**	**Name**	**Symbol**	**Name**
u	up quark	c	charm quark	t	top quark
d	down quark	s	strange quark	b	bottom quark
e	electron	μ	muon	τ	tau
ν_e	electron neutrino	ν_μ	muon neutrino	ν_τ	tau neutrino

Force Particles

Symbol	Name	Remarks
γ	Photon	better known to us as "light"; neutral; carries electromagnetic force
W,Z	W and Z bosons	very heavy; W is charged, Z is neutral; carry the weak nuclear force
g	gluon	carries the strong nuclear force, comes in 8 color combinations
G	graviton	hypothesized mediator of gravitation; never observed

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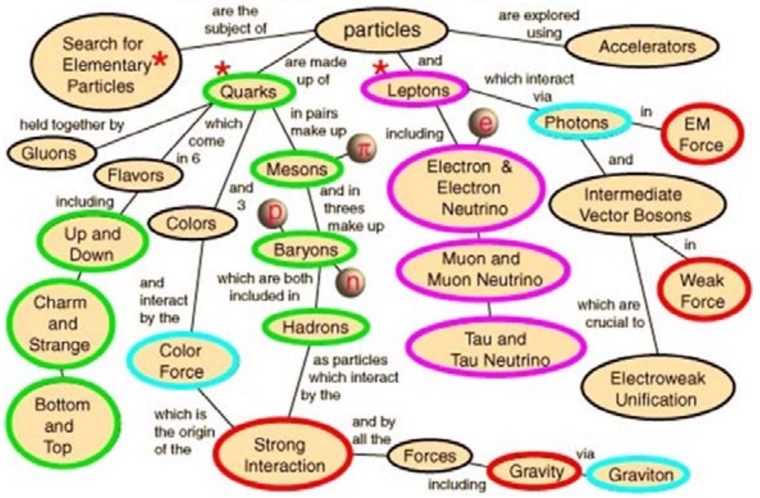
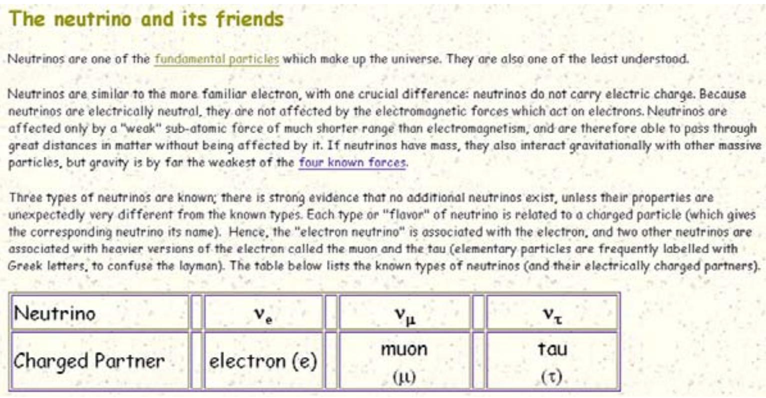
Particle Concepts Roadmap

http://hyperphysics.phy-astr.gsu.edu/Hbase/particles/parcon.html





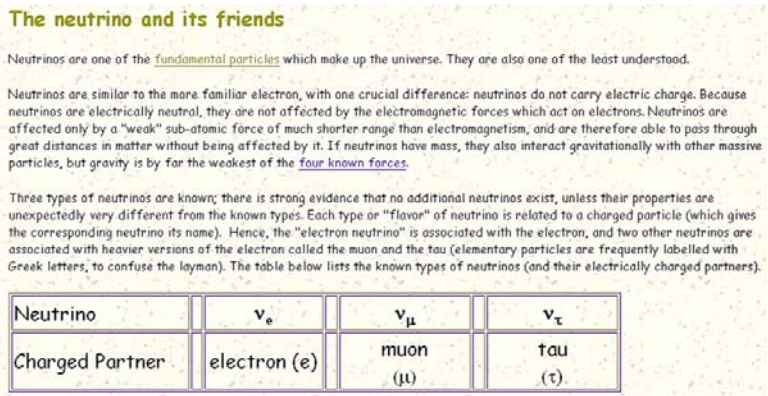
The neutrino and its friends

Neutrinos are one of the fundamental particles which make up the universe. They are also one of the least understood.

Neutrinos are similar to the more familiar electron, with one crucial difference: neutrinos do not carry electric charge. Because neutrinos are electrically neutral, they are not affected by the electromagnetic forces which act on electrons. Neutrinos are affected only by a "weak" sub-atomic force of much shorter range than electromagnetism, and are therefore able to pass through great distances in matter without being affected by it. If neutrinos have mass, they also interact gravitationally with other massive particles, but gravity is by far the weakest of the four known forces.

Three types of neutrinos are known; there is strong evidence that no additional neutrinos exist, unless their properties are unexpectedly very different from the known types. Each type or "flavor" of neutrino is related to a charged particle (which gives the corresponding neutrino its name). Hence, the "electron neutrino" is associated with the electron, and two other neutrinos are associated with heavier versions of the electron called the muon and the tau (elementary particles are frequently labelled with Greek letters, to confuse the layman). The table below lists the known types of neutrinos (and their electrically charged partners).

Neutrino	ν_e	ν_μ	ν_τ
Charged Partner	electron (e)	muon (μ)	tau (τ)



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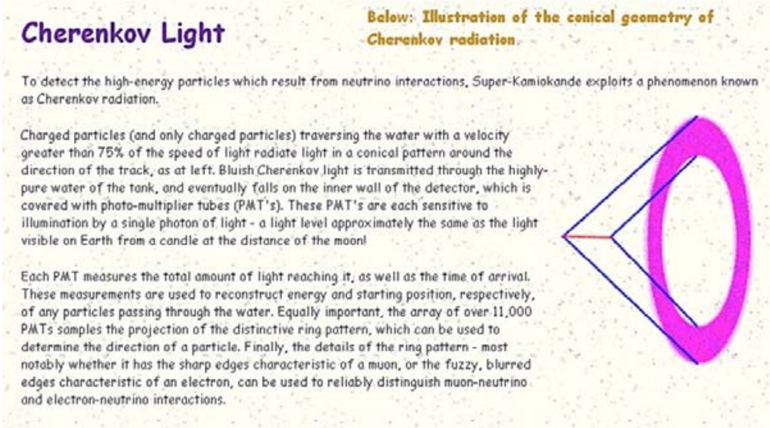
Neutrino	ν_e	ν_μ	ν_τ
Charged Partner	electron (e)	muon (μ)	tau (τ)

The electron neutrino (a lepton) was postulated in 1930 by Fermi to avoid a violation of conservation of energy and momentum during beta decay. It was not experimentally observed until 1953. It is thought that neutrinos left over from the Big Bang are the most abundant particles in the universe. Solar neutrino flux is estimated at 5,000,000 /cm^2/s. With no charge and almost no mass, the mean free path of a neutrino in matter is about 22 light years in lead!!!! ***"Solar neutrinos shine down on us during the day, and shine up on us during the night."***



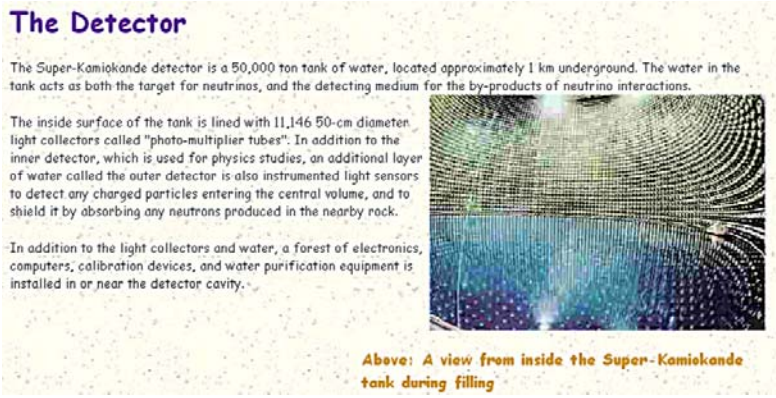
Cherenkov Light

Below: Illustration of the conical geometry of Cherenkov radiation.

To detect the high-energy particles which result from neutrino interactions, Super-Kamiokande exploits a phenomenon known as Cherenkov radiation.

Charged particles (and only charged particles) traversing the water with a velocity greater than 75% of the speed of light radiate light in a conical pattern around the direction of the track, as at left. Bluish Cherenkov light is transmitted through the highly-pure water of the tank, and eventually falls on the inner wall of the detector, which is covered with photo-multiplier tubes (PMT's). These PMT's are each sensitive to illumination by a single photon of light - a light level approximately the same as the light visible on Earth from a candle at the distance of the moon!

Each PMT measures the total amount of light reaching it, as well as the time of arrival. These measurements are used to reconstruct energy and starting position, respectively, of any particles passing through the water. Equally important, the array of over 11,000 PMTs samples the projection of the distinctive ring pattern, which can be used to determine the direction of a particle. Finally, the details of the ring pattern - most notably whether it has the sharp edges characteristic of a muon, or the fuzzy, blurred edges characteristic of an electron, can be used to reliably distinguish muon-neutrino and electron-neutrino interactions.



The Detector

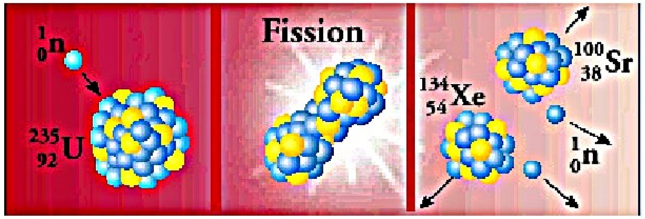
The Super-Kamiokande detector is a 50,000 ton tank of water, located approximately 1 km underground. The water in the tank acts as both the target for neutrinos, and the detecting medium for the by-products of neutrino interactions.

The inside surface of the tank is lined with 11,146 50-cm diameter light collectors called "photo-multiplier tubes". In addition to the inner detector, which is used for physics studies, an additional layer of water called the outer detector is also instrumented light sensors to detect any charged particles entering the central volume, and to shield it by absorbing any neutrons produced in the nearby rock.

In addition to the light collectors and water, a forest of electronics, computers, calibration devices, and water purification equipment is installed in or near the detector cavity.

Above: A view from inside the Super-Kamiokande tank during filling

Nuclear Fission Energy



Fission of ^{235}U after absorption of a thermal neutron.

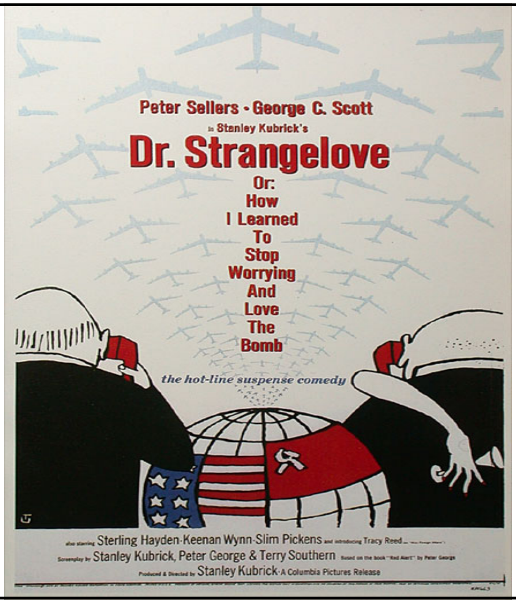
The relevant nuclear reactions can be written as follows:

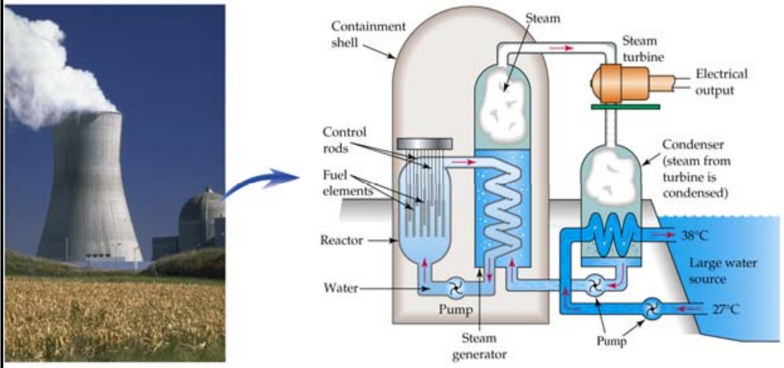
$$^{235}\text{U} + {}^{1}\text{n} \rightarrow \text{fission products + neutrons + energy (\textasciitilde 200 MeV)} \qquad (1)$$

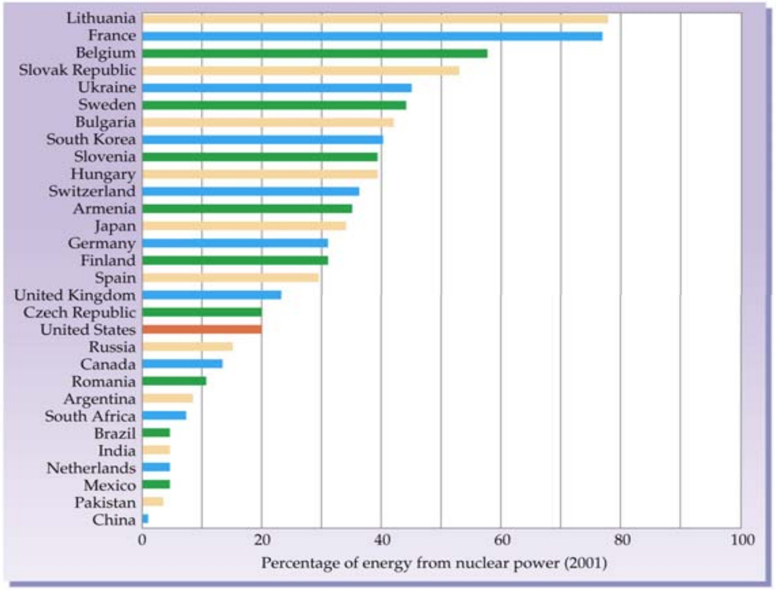
$$^{238}\text{U} + {}^{1}\text{n} \rightarrow {}^{239}\text{U} + \text{gamma rays} \qquad (2)$$

$$^{239}\text{U} \rightarrow {}^{239}\text{Np} \rightarrow {}^{239}\text{Pu} \qquad \text{(a series of beta decays).} \qquad (3)$$

Nuclear Wall Chart - Lawrence Berkeley National Laboratory
Contemporary Physics Education Project (CPEP)







Characteristics of Biologically Significant Isotopes

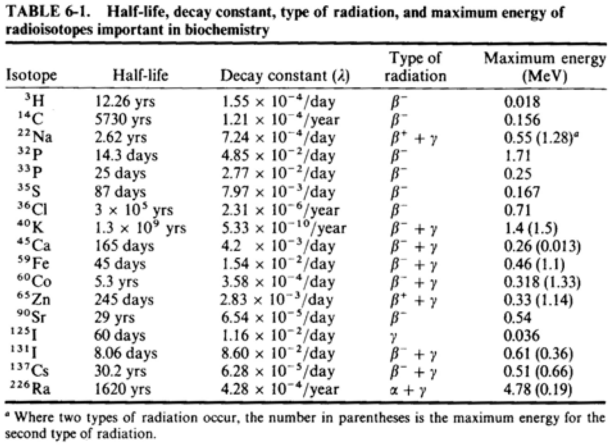


TABLE 6-1. Half-life, decay constant, type of radiation, and maximum energy of radioisotopes important in biochemistry

Isotope	Half-life	Decay constant (λ)	Type of radiation	Maximum energy (MeV)
^{3}H	12.26 yrs	1.55×10^{-4}/day	β^-	0.018
^{14}C	5730 yrs	1.21×10^{-4}/year	β^-	0.156
^{22}Na	2.62 yrs	7.24×10^{-4}/day	$\beta^+ + \gamma$	0.55 (1.28)[a]
^{32}P	14.3 days	4.85×10^{-2}/day	β^-	1.71
^{33}P	25 days	2.77×10^{-2}/day	β^-	0.25
^{35}S	87 days	7.97×10^{-3}/day	β^-	0.167
^{36}Cl	3×10^{5} yrs	2.31×10^{-6}/year	β^-	0.71
^{40}K	1.3×10^{9} yrs	5.33×10^{-10}/year	$\beta^- + \gamma$	1.4 (1.5)
^{45}Ca	165 days	4.2×10^{-3}/day	$\beta^- + \gamma$	0.26 (0.013)
^{59}Fe	45 days	1.54×10^{-2}/day	$\beta^- + \gamma$	0.46 (1.1)
^{60}Co	5.3 yrs	3.58×10^{-4}/day	$\beta^- + \gamma$	0.318 (1.33)
^{65}Zn	245 days	2.83×10^{-3}/day	$\beta^+ + \gamma$	0.33 (1.14)
^{90}Sr	29 yrs	6.54×10^{-5}/day	β^-	0.54
^{125}I	60 days	1.16×10^{-2}/day	γ	0.036
^{131}I	8.06 days	8.60×10^{-2}/day	$\beta^- + \gamma$	0.61 (0.36)
^{137}Cs	30.2 yrs	6.28×10^{-5}/day	$\beta^- + \gamma$	0.51 (0.66)
^{226}Ra	1620 yrs	4.28×10^{-4}/year	$\alpha + \gamma$	4.78 (0.19)

[a] Where two types of radiation occur, the number in parentheses is the maximum energy for the second type of radiation.

$$\boxed{t_{1/2} = \frac{0.693}{\lambda}} \qquad I = I_o\, e^{-\lambda t}$$