Nuclear Physics

- The nucleus
- Nuclear stability
- Radioactive decay
- Standard model
- Radiation doses
- Medical physics

Nuclear medicine

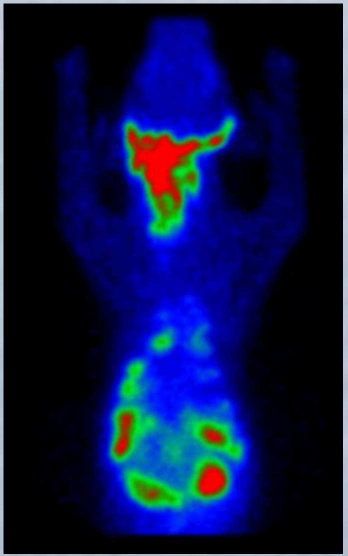
Scintigraphy

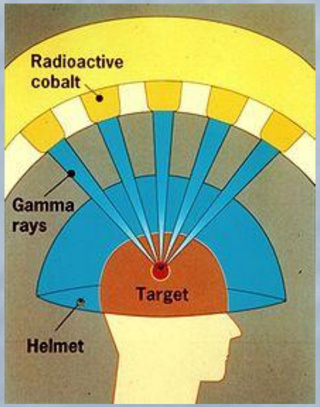
Positron emission tomography

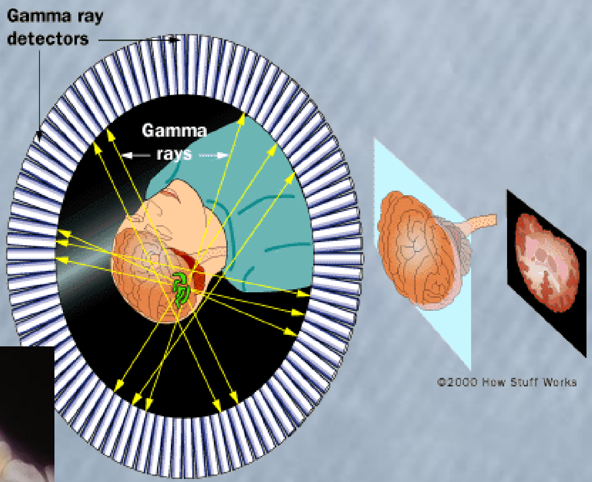
Brachytherapy

Gamma knife

Neutron therapy

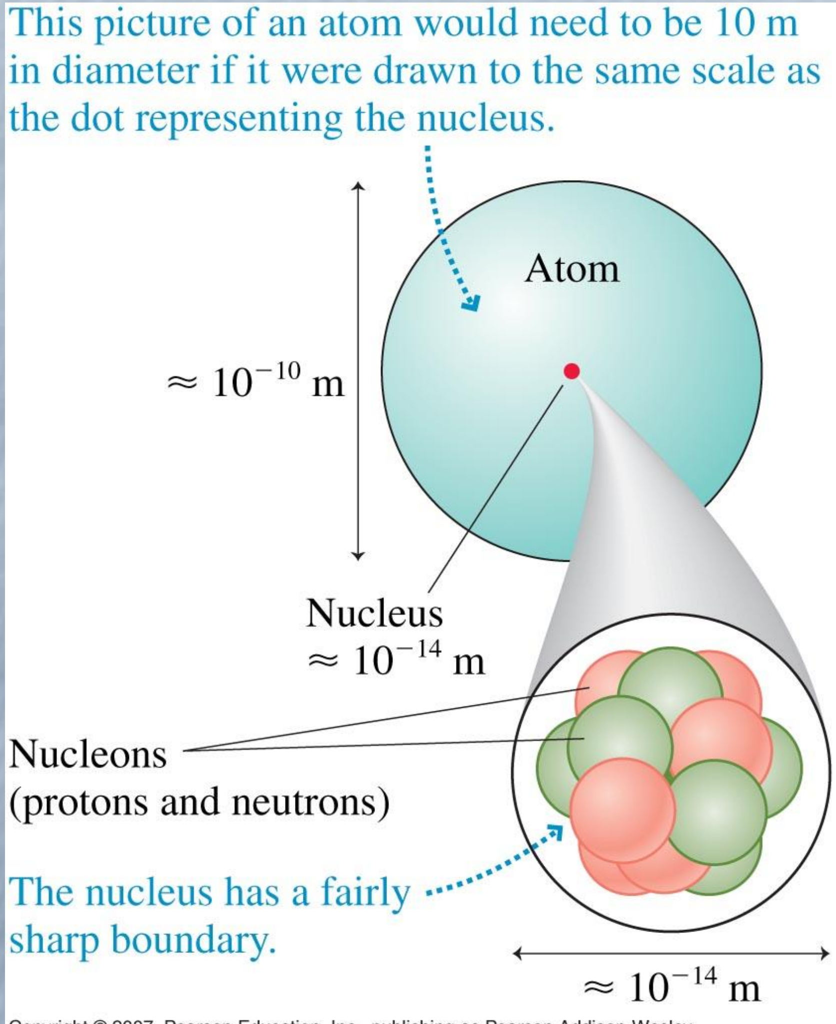






Nuclear structure

- Atoms – 10^{-10}m=0.1nm
- Made of point like electrons and the nucleus (10^{-14}m=10fm)
- Nucleus is made of **nucleons**, which are protons and neutrons



Nucleons

Nucleons is the generic name for neutrons and protons

Number of protons in a nucleus is Z (charge)

Number of neutrons in a nucleus is N

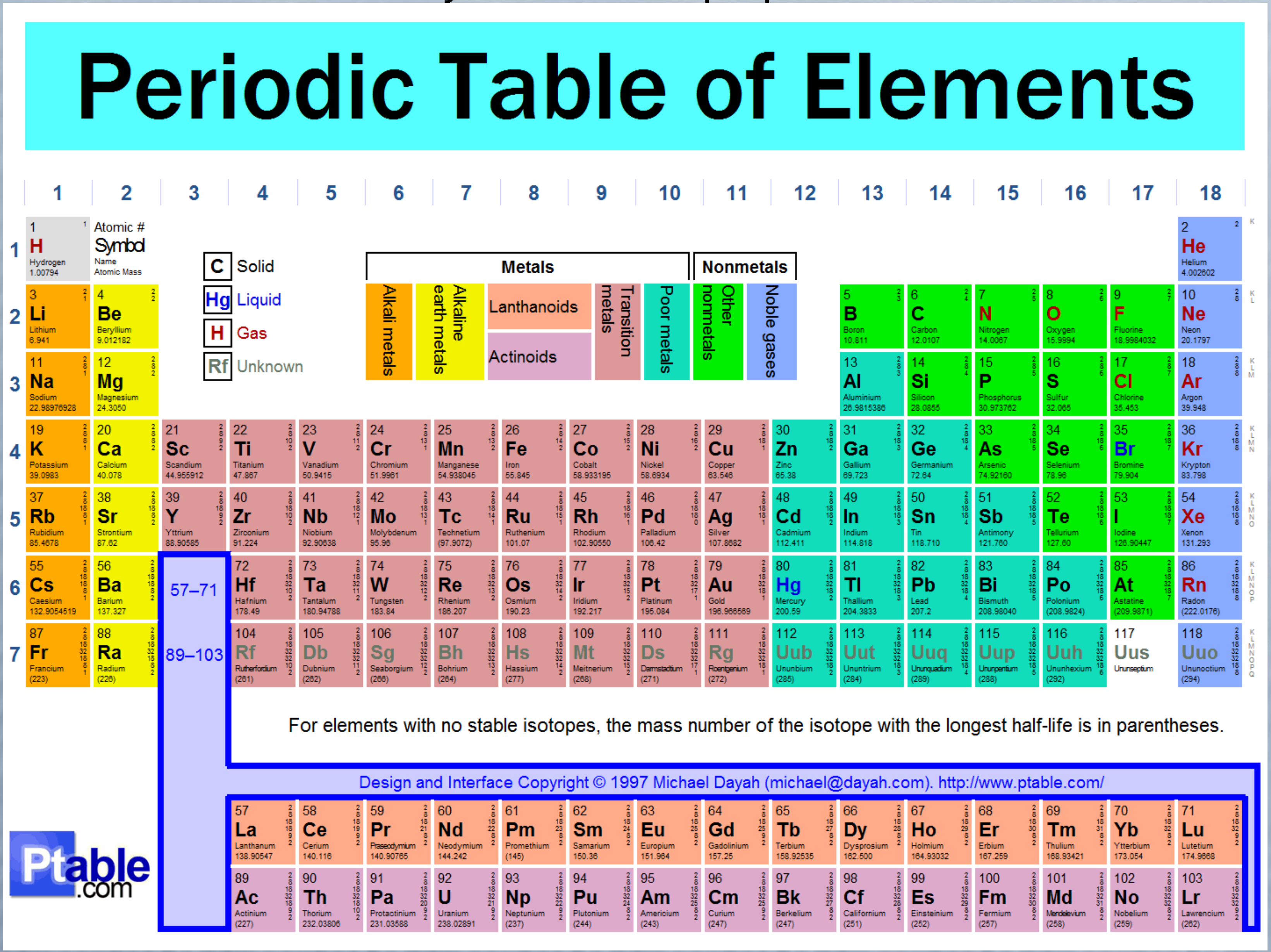
Total **atomic mass** is N+Z

TABLE 30.1 Protons and neutrons

	Proton	Neutron
Number	Z	N
Charge q	$+e$	0
Spin	$\frac{1}{2}$	$\frac{1}{2}$
Mass, in u	1.00728	1.00866

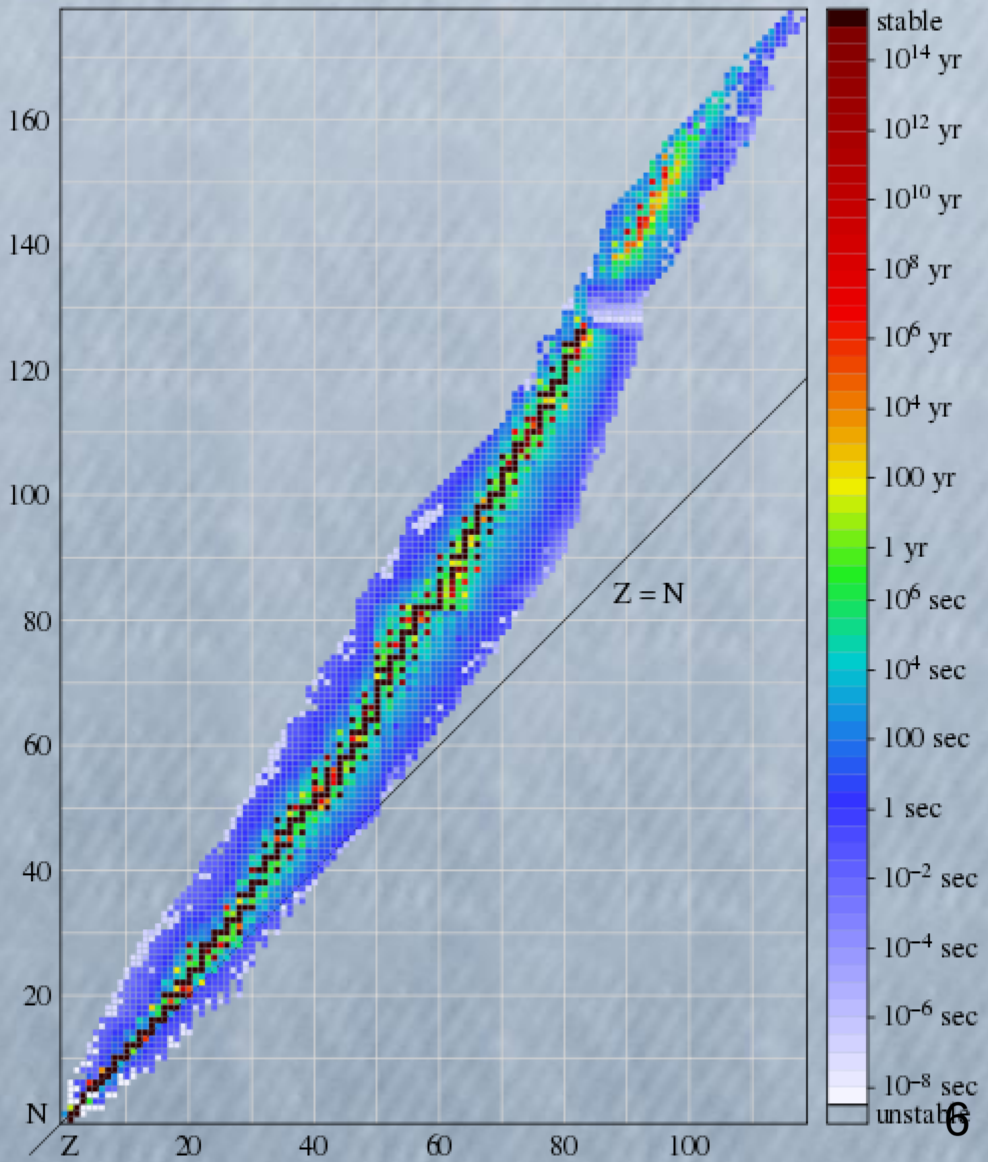
Elements and Isotopes

An element is determined by its chemical properties



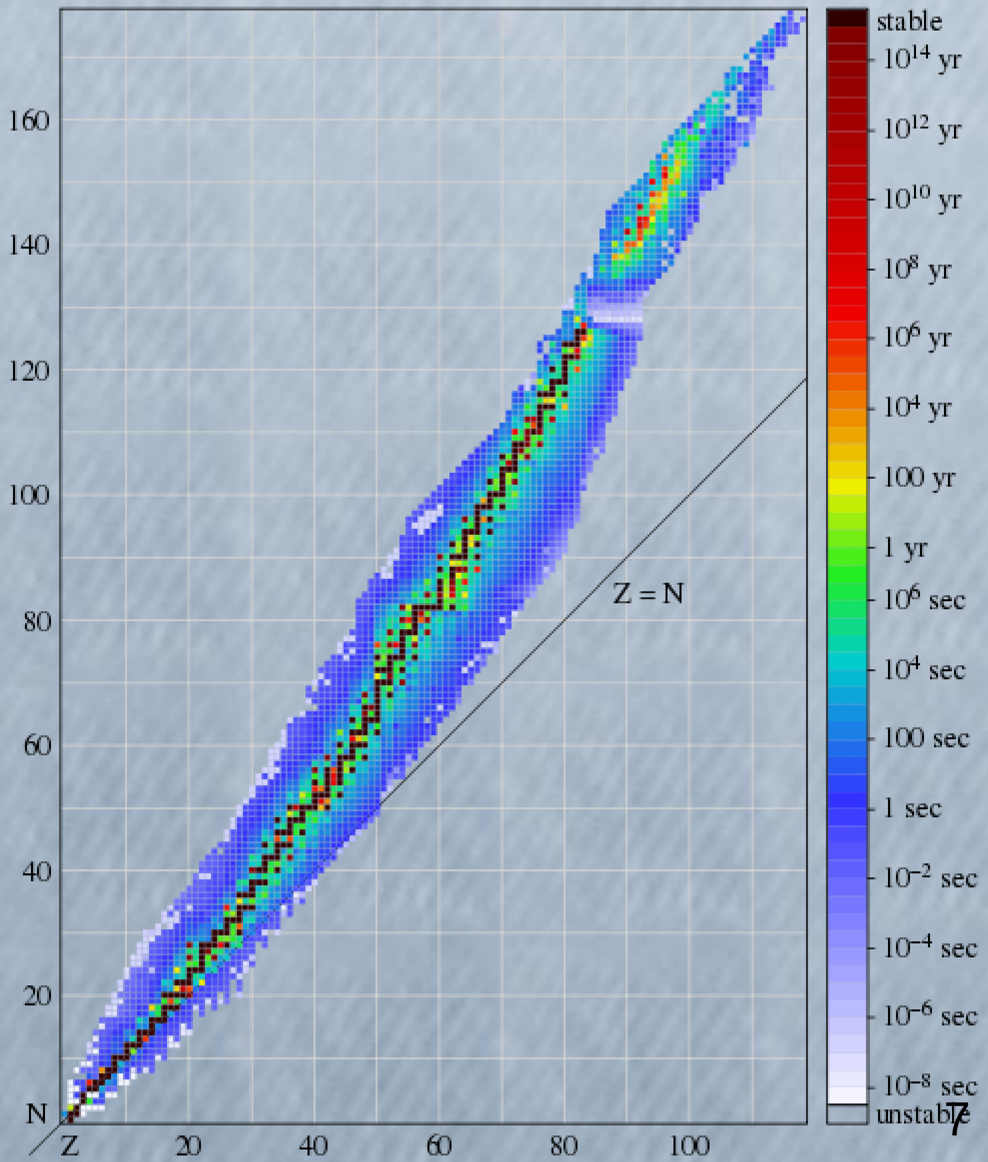
Isotopes

The number of protons in an atom is the same as the number of electrons. But an element may have a different number of neutrons – this are known as **isotopes**



Isotopes

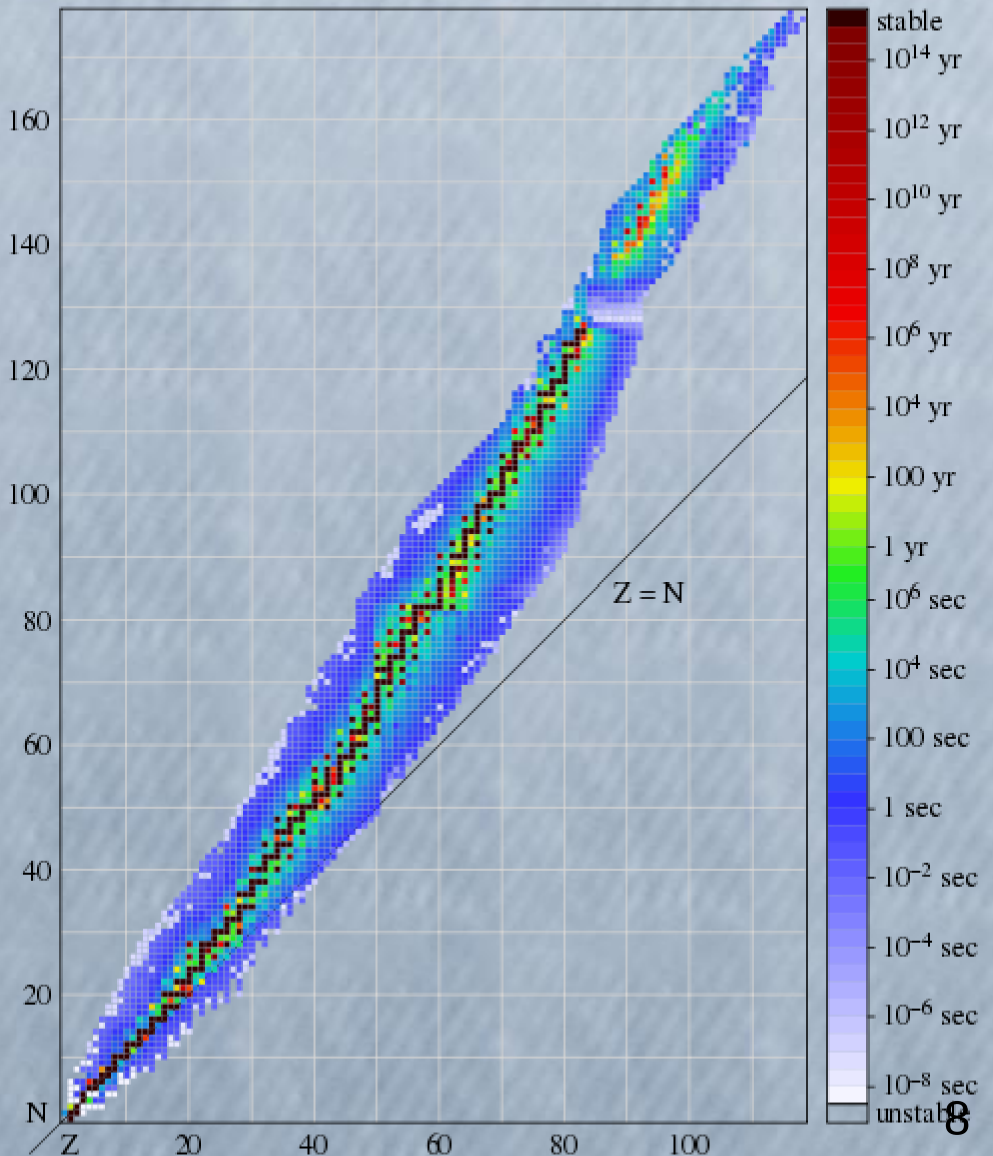
The isotopes of an element will have different atomic masses, e.g. oxygen occurs in nature with nucleons containing 8 protons and 8 neutrons ^{16}O, and 8 protons and 10 neutrons ^{18}O



Isotopes

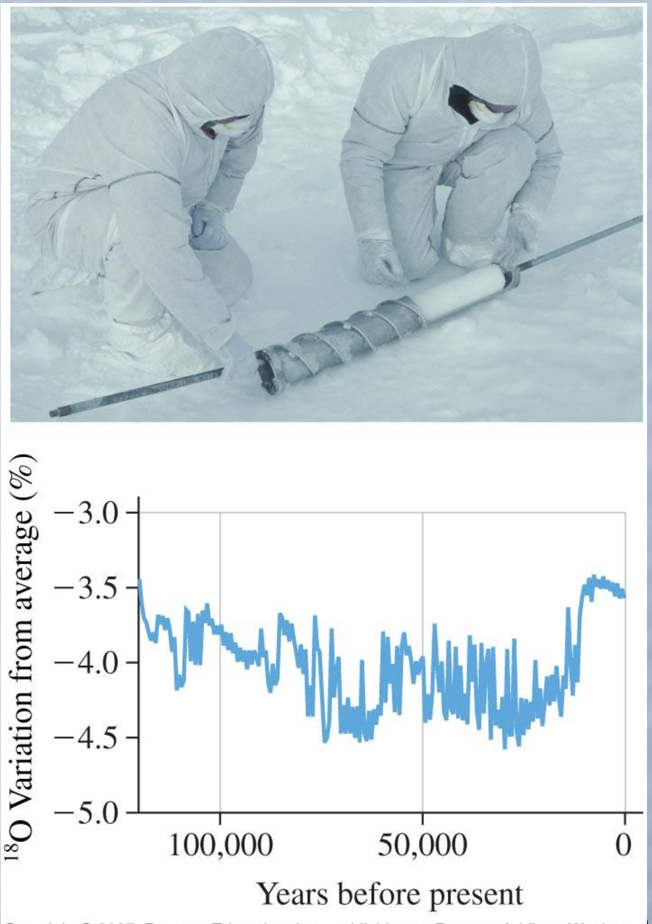
Although the chemical properties are the same for isotopes, the physical properties, such as boiling point, freezing point, rate of settling in a centrifuge, can be different.

Isotopes can be separated out by physical processes.



Global temperature change and isotopes of oxygen

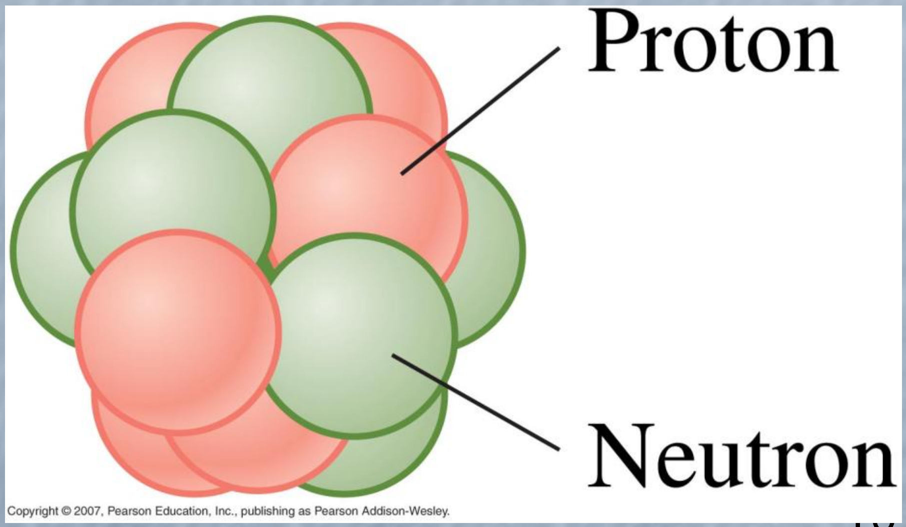
- ^{18}O is slightly more difficult to evaporate than ^{16}O, so there is deficiency in the earth's atmosphere of ^{18}O.
- The ratio of the two isotopes is a measure of the atmospheric water vapor content over time – measured in ice cores from the Antarctic.



Atomic Mass Number and Atomic Mass

- The atomic mass A, is the sum of the number of protons and neutrons A=Z+N.
- The atomic mass unit, u, is defined as 1/12 the mass of ^{12}C, u=1.6605×10^{-27}kg
- We can convert this mass to an energy

$$E = mc^2$$



Atomic Mass Number and Atomic Mass

- From E=mc², we get

$$1u = 1.6605 \times 10^{-27} kg$$

$$= 1.4924 \times 10^{-10} J / c^2$$

$$= 931.49 MeV / c^2$$

$$\approx 1 GeV / c^2$$

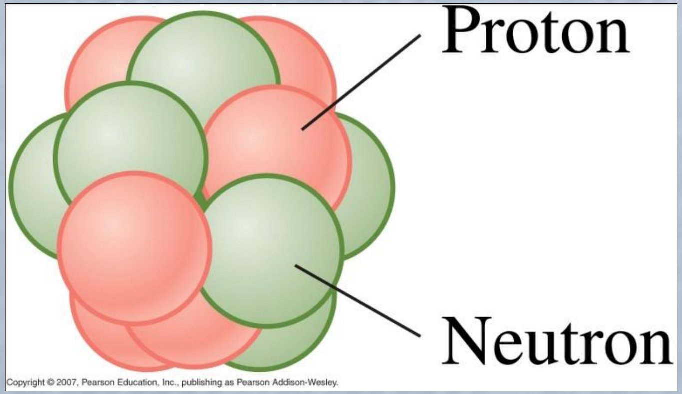


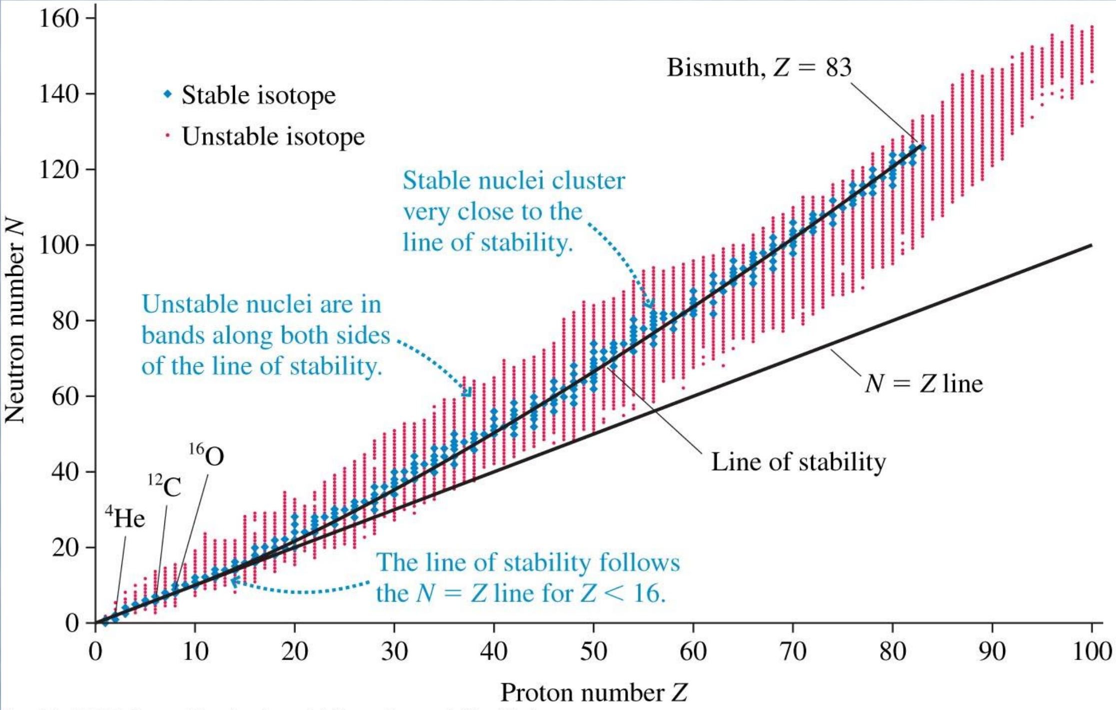
TABLE 30.2 Some atomic masses

Particle	Symbol	Mass (u)	Mass (MeV/c^2)
Electron	e	0.00055	0.51
Proton	p	1.00728	938.28
Neutron	n	1.00866	939.57
Hydrogen	^1H	1.00783	938.79
Helium	^4He	4.00260	3728.40

Nuclear stability

- Back to the isotope chart, the N and Z are related.
- The ratio N/Z changes from ≈1 to ≈1.5, along a **line of stability**

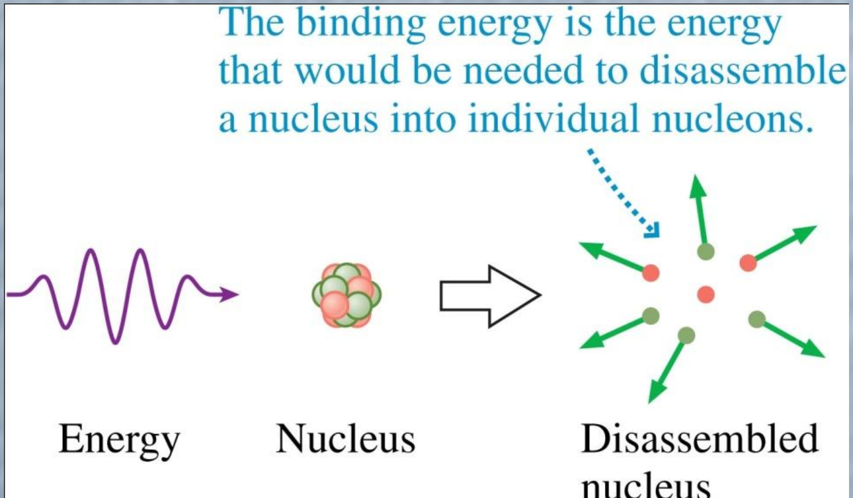
- Nature likes to have more neutrons than protons
- The red dots represent unstable isotopes which decay through radioactivity



Binding energy

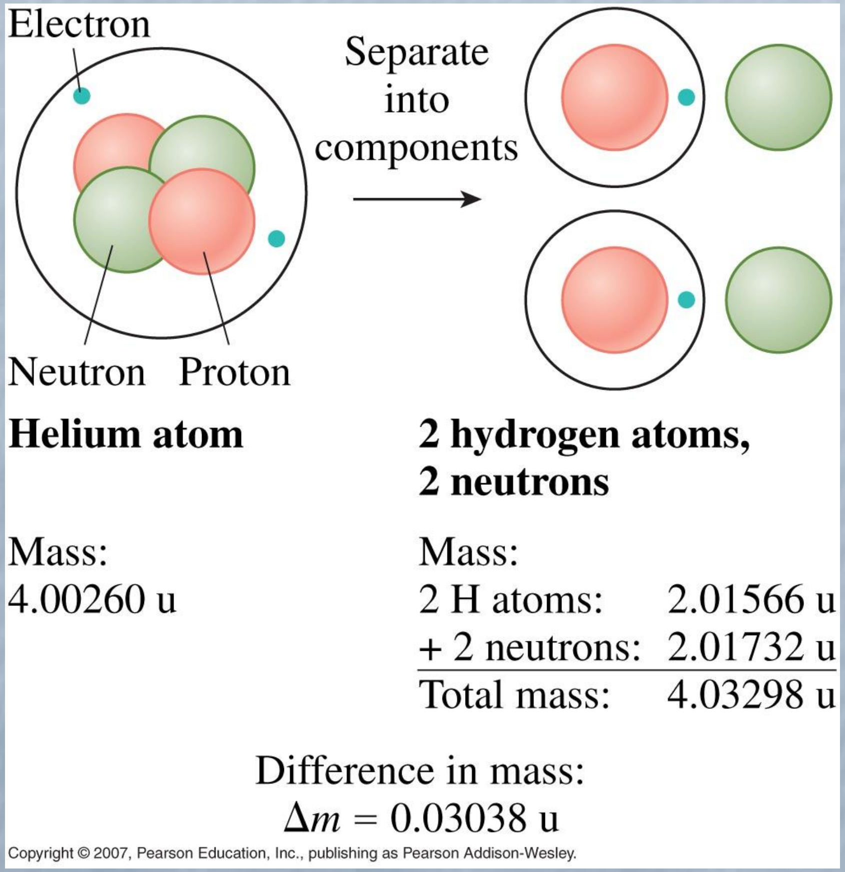
- Binding energy is the energy used in bonding the nucleons together.
- The binding forces and bond energy is so great in a nucleus that we can measure it as a fraction of the mass of the system.

- From Einstein's special theory of relativity (1905) $E=mc^2$, we can measure the mass which goes into forming the nucleon bonds



Binding energy of the Helium nucleus

- We can calculate the different in mass between the constituent parts and the measured mass of the ^{4}He nucleus
- Δu=28.30MeV, or 0.75% of its mass.



Binding energy

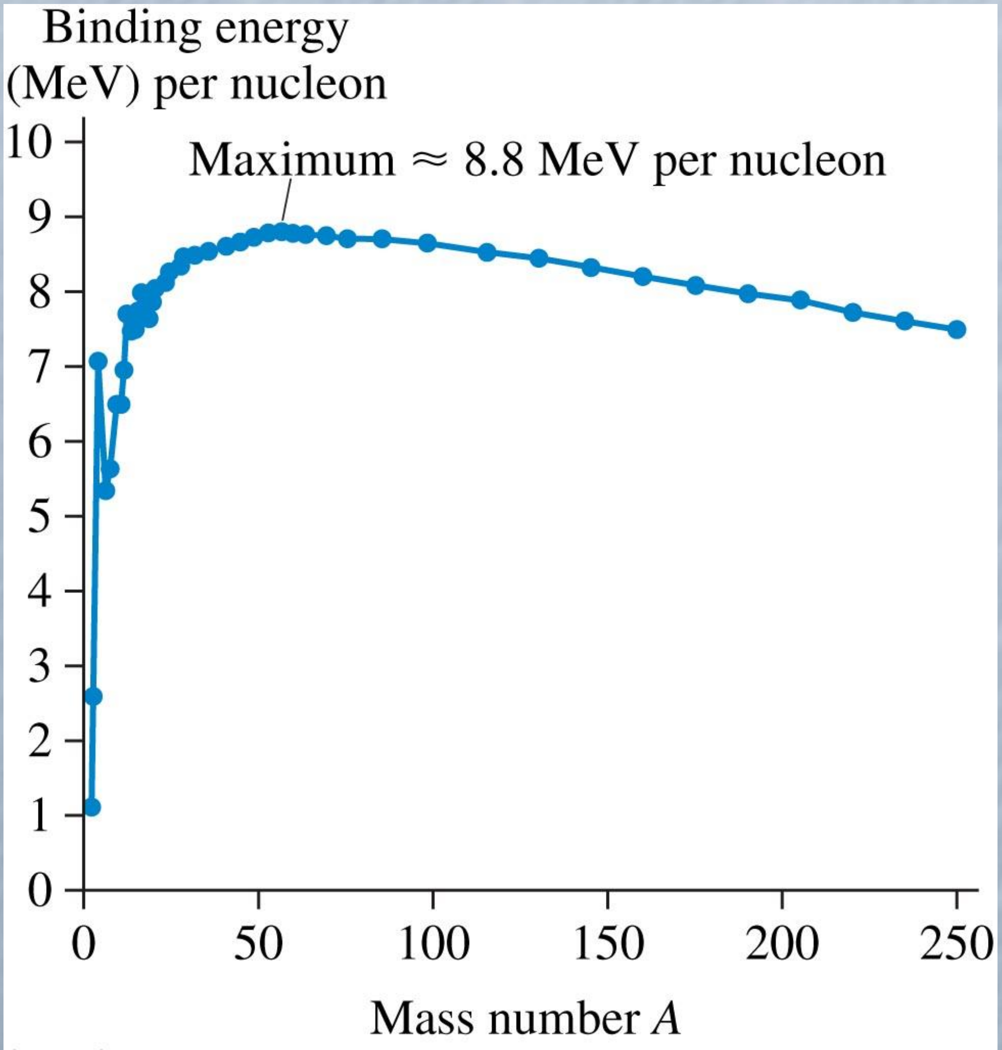
In general, the binding energy, B, of a nucleus can be calculated from the measured atomic mass, m_{atom}, and the number of protons, Z and neutrons, N.

$$B = (Zm_H + Nm_n - m_{atom}) \times 931.49 MeV$$

Where m_H, m_n and m_{atom} are in units of the atomic mass unit, u.

Binding energy per nucleon

- We can look at the binding energy per nucleon for all the elements.
- The most stable nucleus is Fe.
- In a high energy environment (like a star) lighter nuclei will undergo fusion, heavier will undergo fission, until we're left with iron.



Nucleon force

The force which keeps neutrons and protons together is called the **strong force** and must

- Be attractive
- Have no effect on electrons
- Be a short range force (not seen at atomic distances)
- Be stronger than the electrostatic repulsion of protons

Calculations are difficult, (F=kx), and is described by Quantum Chromodynamics (QCD)

History of Radioactivity

1894 - J.J.Thomson identified electrons

1896 - Uranium salts were found to ruin photographic paper by Henri Becquerel.

1898 - Investigated by Marie Curie who published data naming the rays radioactivity, and discovered the radioactive elements polonium and radium.

1899-1903, Ernest Rutherford identified 3 different types of radiation – alpha, beta and gamma

1911 – Rutherford published the nucleus/electron model

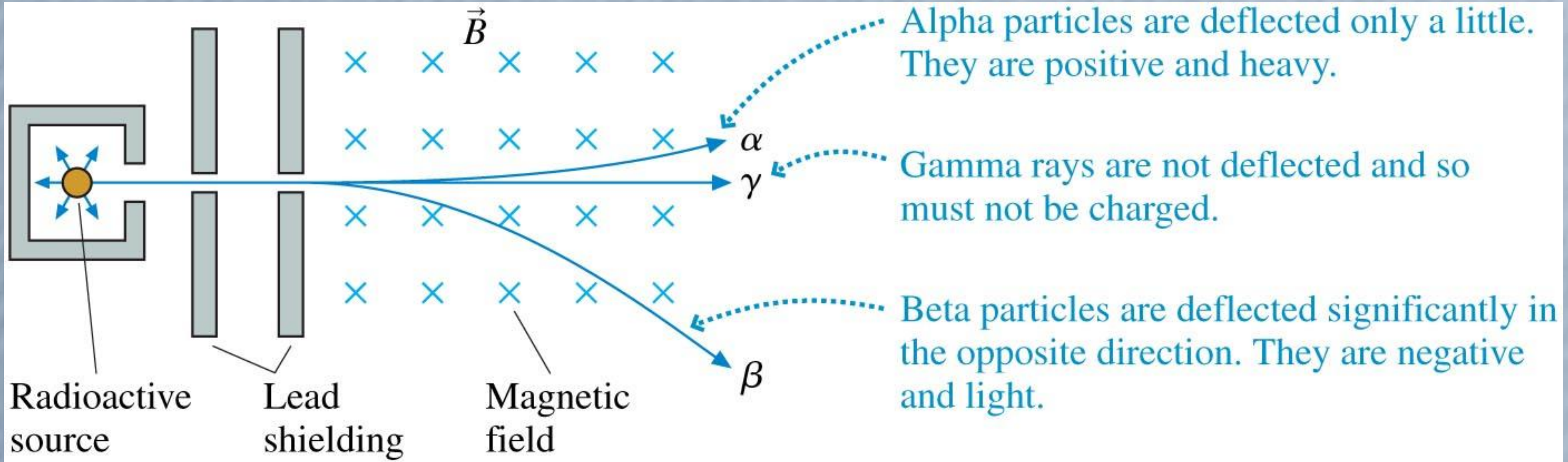
1913 – J.J.Thomson identified isotopes

Three types of radiation

In a magnetic field, the 3 types of radiation act have different charge.

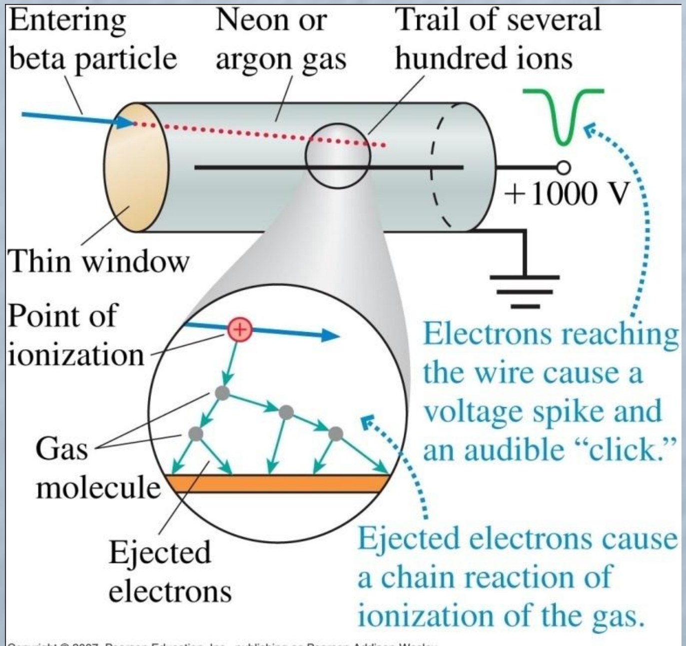
TABLE 30.3 Three types of radiation

Radiation	Identification	Charge
Alpha, α	^{4}He nucleus	$+2e$
Beta, β	Electron	$-e$
Gamma, γ	High-energy photon	0



Ionizing properties of radiation

- All 3 types of nuclear radiation can be detected by its ionization of atoms in its path.
- A Geiger counter uses a high voltage E field to accelerate and amplify the electrons from ionization.
- Damages cell tissue, free ions disrupt biochemical reactions, and breaks up DNA leading to tumors.



Ionizing properties of radiation

- Irradiating stable isotopes does not make them radioactive
- Used to sterilize food, US mail, hamburger patties and medical equipment
- A large dose of radiation can cause long term biological effects in living tissue.

Nuclear decay

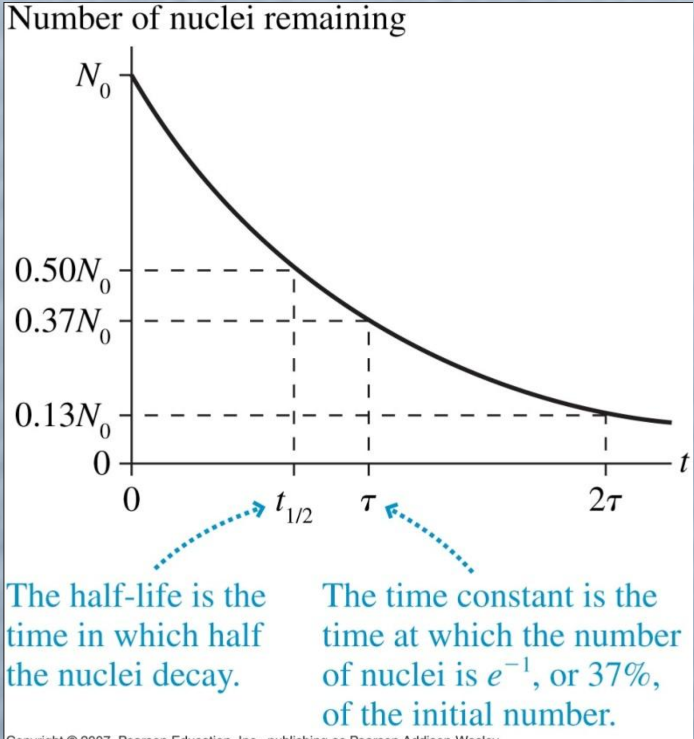
- Radioactive isotopes decay over time.
- The probability of the decay of an individual nucleus is constant, it does not depend on time.
- The rate of decays will depend only on the number of nuclei left in the sample

$$\frac{\Delta N}{\Delta t} \propto N$$

Nuclear decay

- The solution of this equation is an exponential
- The symbol τ, is a time which represents the time it takes for the fraction of the nuclei to be reduced by 1/e=0.37
- Note the probability of decay of an individual nucleus does not change, but the rate of the sample drops as fewer nuclei remain.

$$N = N_0 e^{-t/\tau}$$



Half-life

- The decay probability is often described as a half-life.
- The half life is the time for which a sample (and so rate) will drop by a factor 2.

$$N = N_0 e^{-t/\tau} = \frac{N_0}{2}$$

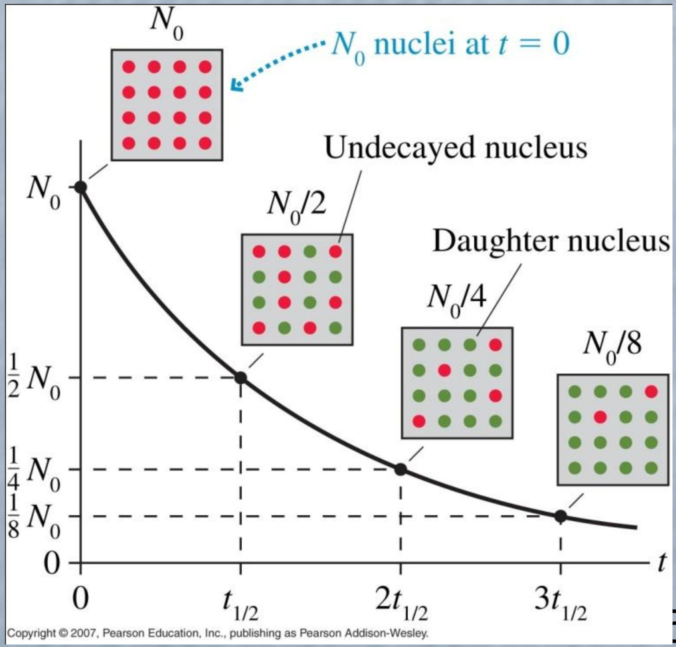
$$\frac{1}{2} = e^{-t_{1/2}/\tau}$$

$$t_{1/2} = \tau \ln 2 = 0.693\tau$$

Half-life

Half lives range wildly, ^{238}U has a half-life of 10^9 years, ^{214}Po has a half life of 160μs.

The number of nuclei left is always reduced by a factor 2 after $t_{1/2}$, and so some nuclei remain for practically ever.



Activity of a sample

- The rate is proportional to the number of nuclei left.
- The decay rate will change exponentially with time, with the same time constant, τ, and same half-life $t_{1/2}$
- Measured in becquerels, and curies

1 becquerel = 1Bq = 1decay per sec

1 curie = 1Ci = 3.7×10^{10}Bq

$$R = \frac{\Delta N}{\Delta t} \propto N$$

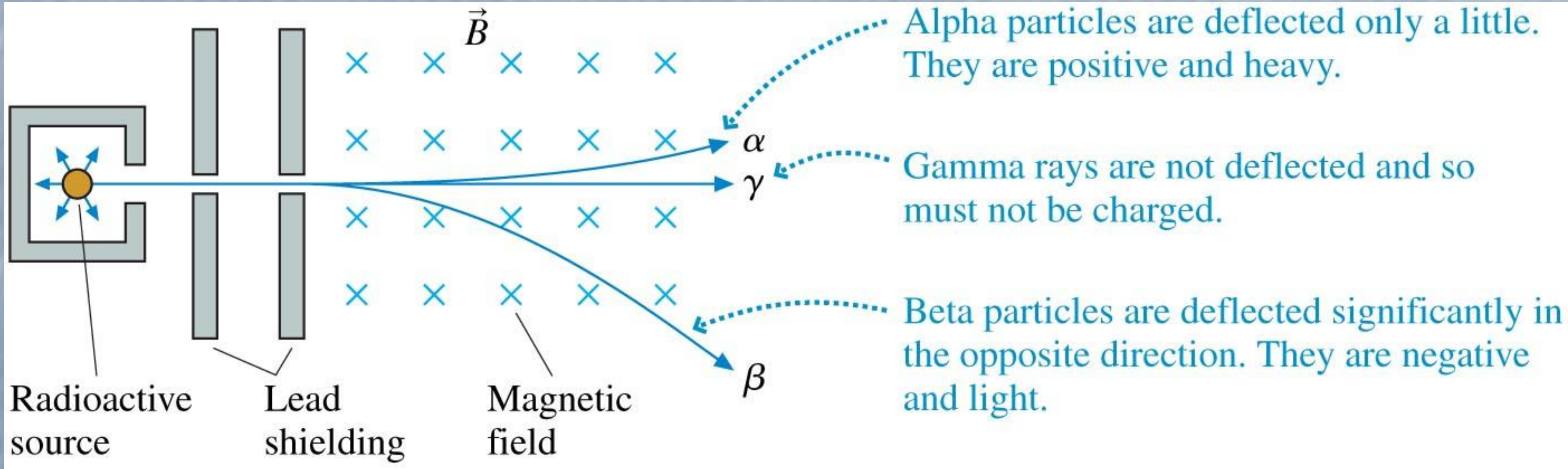
$$R \propto N_0 e^{-t/\tau}$$

$$R = R_0 e^{-t/\tau}$$

Types of radiation

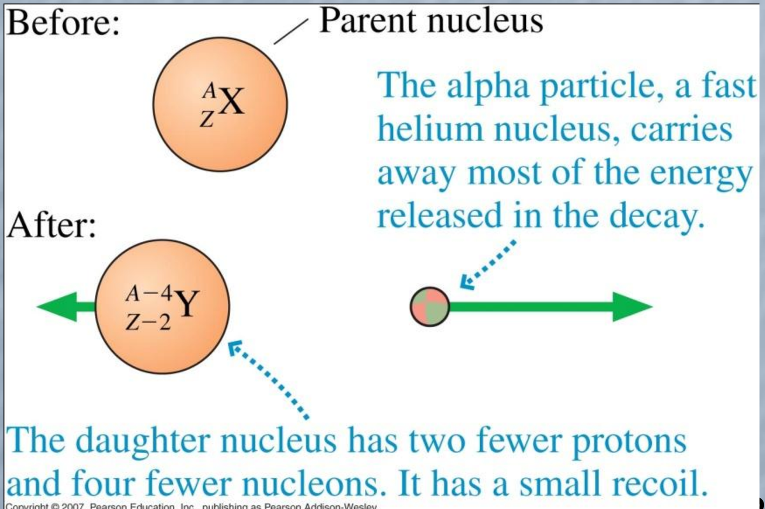
Three types of radiation

- Alpha – low penetration, high tissue ionization
- Beta – medium penetration, medium ionization
- Gamma – high penetration, low ionization
- And others



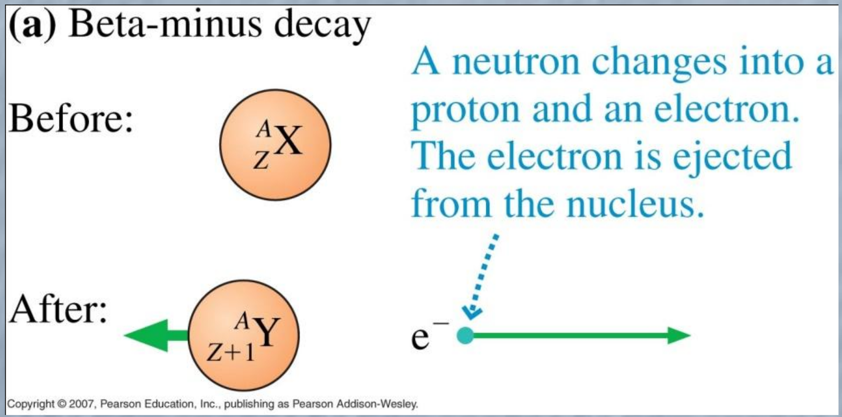
Alpha radiation α

- Nucleus ejects 2 protons and 2 neutrons (Helium nucleus)
- $Z \rightarrow Z\text{-}2$, $N \rightarrow N\text{-}2$, $A \rightarrow A\text{-}4$.
- Alpha particles are easily stopped as they are heavy.
- They lose their energy quickly, causing large amounts of ionization in a short distance.



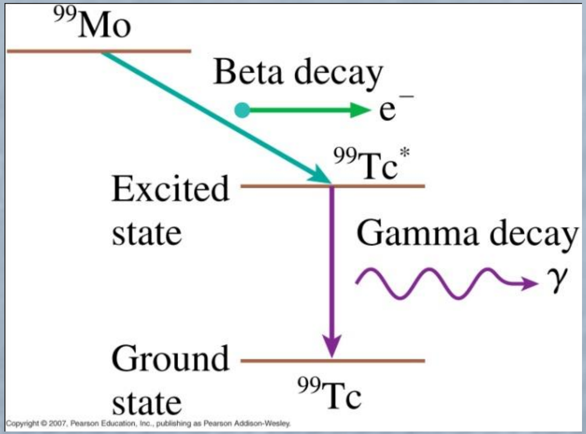
Beta radiation β

- Neutron decays to a proton and electron (and anti-neutrino), electron (and anti-neutrino) get ejected
- $Z \rightarrow Z+1$, $N \rightarrow N-1$, A is unchanged
- Beta particles are stopped by a few cm of tissue.
- They lose energy in the tissue via ionization, causing damage to DNA and cell reproduction.



Gamma radiation γ

- Nucleon decays to a lower energy state, ejecting a high energy electromagnetic photon
- Z,N and A are unchanged
- Gamma particles are stopped by a few cm of lead.
- They lose energy in the tissue, but only higher intensities will damage tissues via ionization



Other types of radiation

Are rarer

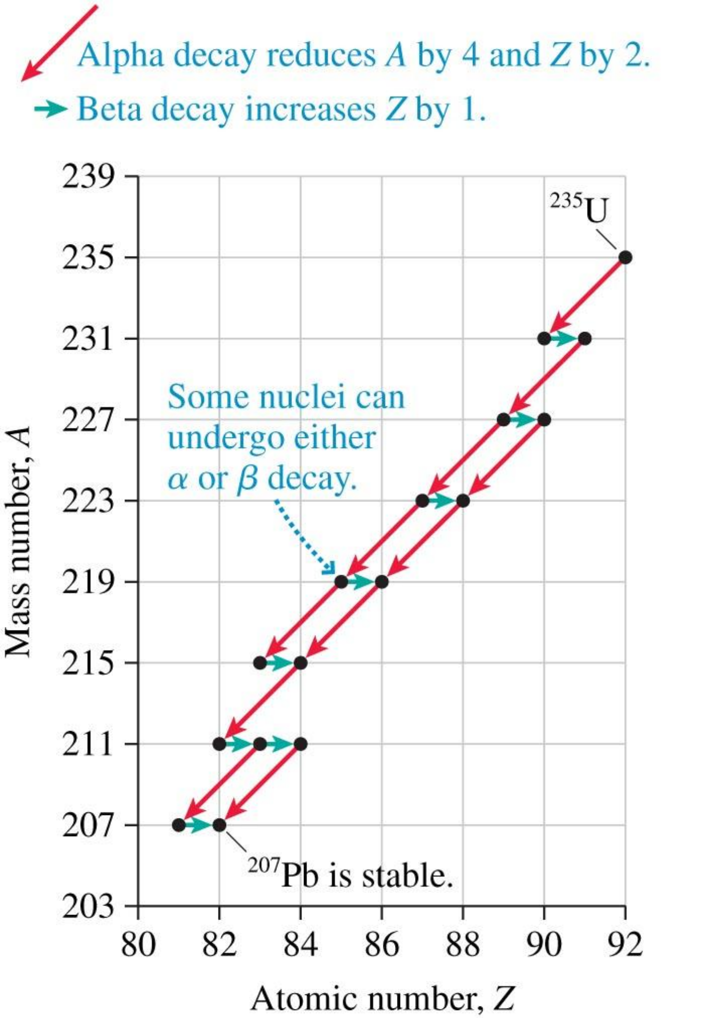
- Proton emission
- Beta-plus decay (positron emission)
- Cluster decay (emission of proton & neutron clusters)

They are all mechanisms for nuclei to get closer to iron

Decay series

Usually a radioactive nucleus decays into another nucleus which is also radioactive.

The ratio of elements found inside minerals can tell us about the age of the rock



Subatomic particles

- Electron has never been split (since 1894)
- Nucleons have been split – found 3 quarks per nucleon, bound by gluons (**strong force**).
- Understand how neutrons change into protons (**weak force**)
- All particles found to have antiparticles
- Electrons (and quarks) found to have excited states with a larger mass
- All the forces we see can be boiled down to only three
- We have two basic types: point-like particles and the force carriers.

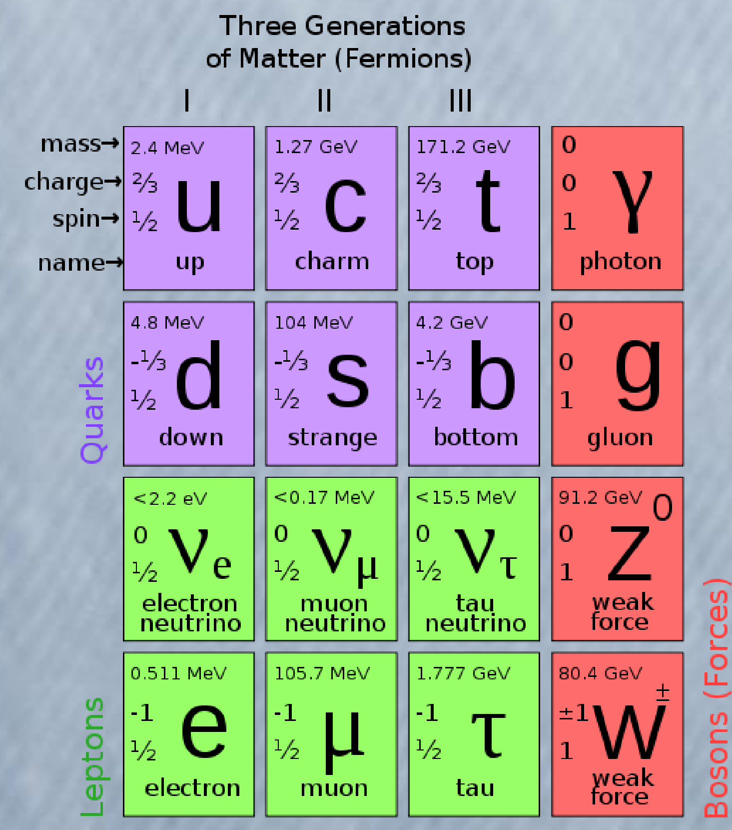
Standard Model

All of nature can be built from 12 particles, and all interactions can be described by 3 forces:

- Quantum chromodynamics
- Electroweak
- Gravity

Gravity is not as well understood.

Looking for the Higg’s boson in Geneva



Radiation dose

- All radiation ionizes tissue, the more the energy left behind, the worse it is.
- Radiation dose is a measures of how much damage the tissue will sustain.

1 gray = 1Gy = 1.00J/kg of absorbed energy

Also used - 1 rad = 0.01Gy

- 1Gy is a huge unit – 1Gy causes a chance of 5% death within a month.

Relative biological effectiveness

- The different types of radiation are found to cause different types of radiation sickness, even after accounting for the amount of energy left behind.
- The gray is multiplied by the RBE to get the unit sievert.

TABLE 30.6 Relative biological effectiveness of radiation

Radiation type	RBE
X rays	1
Gamma rays	1
Beta particles	1–2
Alpha particles	10–20

Dose equivalent in sievert Sv = dose in Gy x RBE.

(Also rem (Rontgen equivalent man), 100rem = 1Sv)

Radiation doses

- Federal regulations limit annual work dose as 50mSv (5rem) for full body radiation or 500mSv (50rems) to an individual organ
- Average background is around 4mSv per year, from ^{40}K inside your body, radon & cosmic rays

TABLE 30.7 Radiation exposure

Radiation source	Typical exposure (mSv)
PET scan	7.0
Natural background (1 year)	3.0
Mammogram	0.70
Chest x ray	0.30
Transatlantic airplane flight	0.050
Dental x ray	0.030

Nuclear medicine

Scintigraphy

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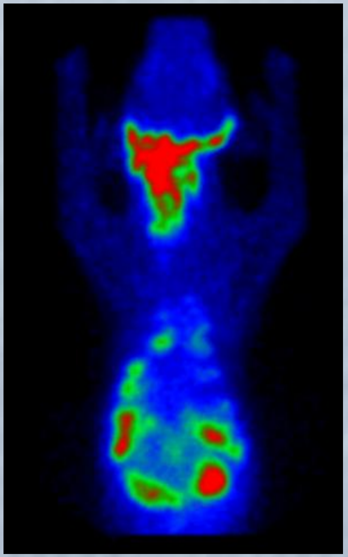
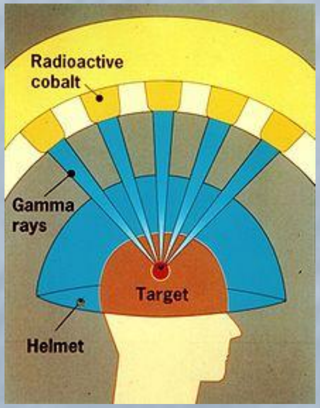
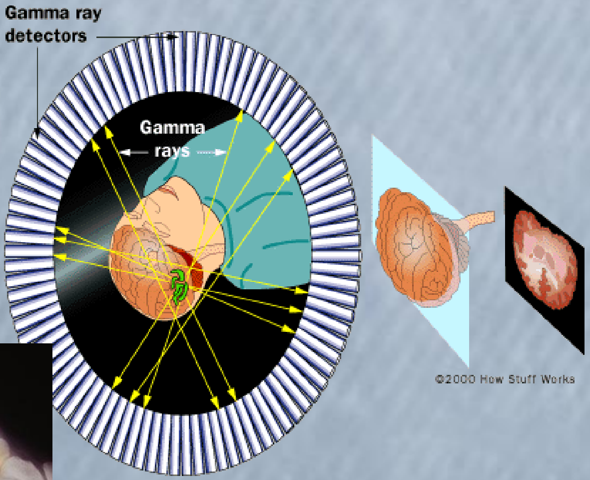
Brachytherapy

Gamma knife

Neutron therapy

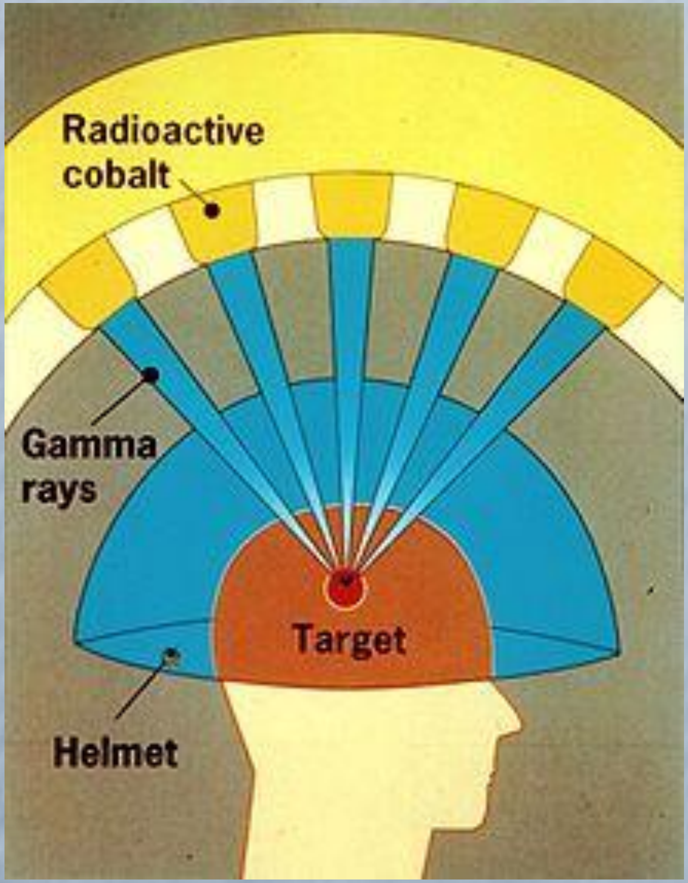






Gamma Knife therapy

- Huge ^{60}Co source (1.1TBq)
- Focuses γ rays into tumors in the brain
- Kill cancer, shrink tumors

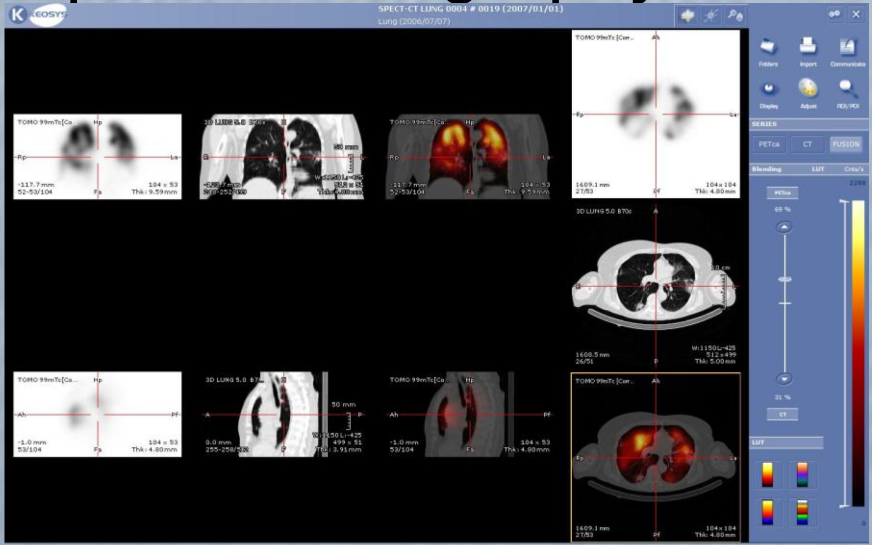


Brachytherapy therapy

- Insert small radioactive seeds into a tumor.
- 2 to 12 Gy/hr
- Uses γ and β sources (^{137}Cs, ^{60}Co ^{125}I, etc)

Scintigraphy, SPECT

- Radioisotopes injected or taken orally. (20-1000MBq)
- Picked up preferentially by a rapidly growing tumor
- Radiation focused and recorded with gamma cameras (crystals which flash when hit by γ's)
- Single photon emission computed tomography

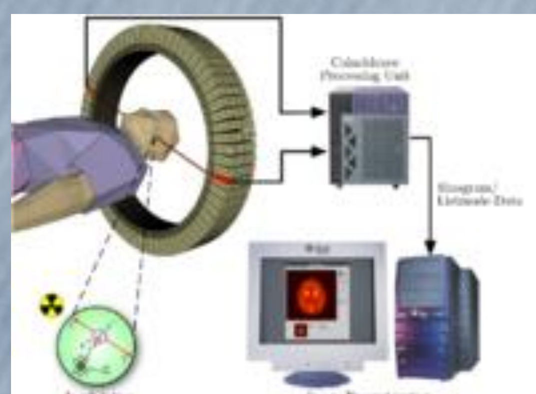


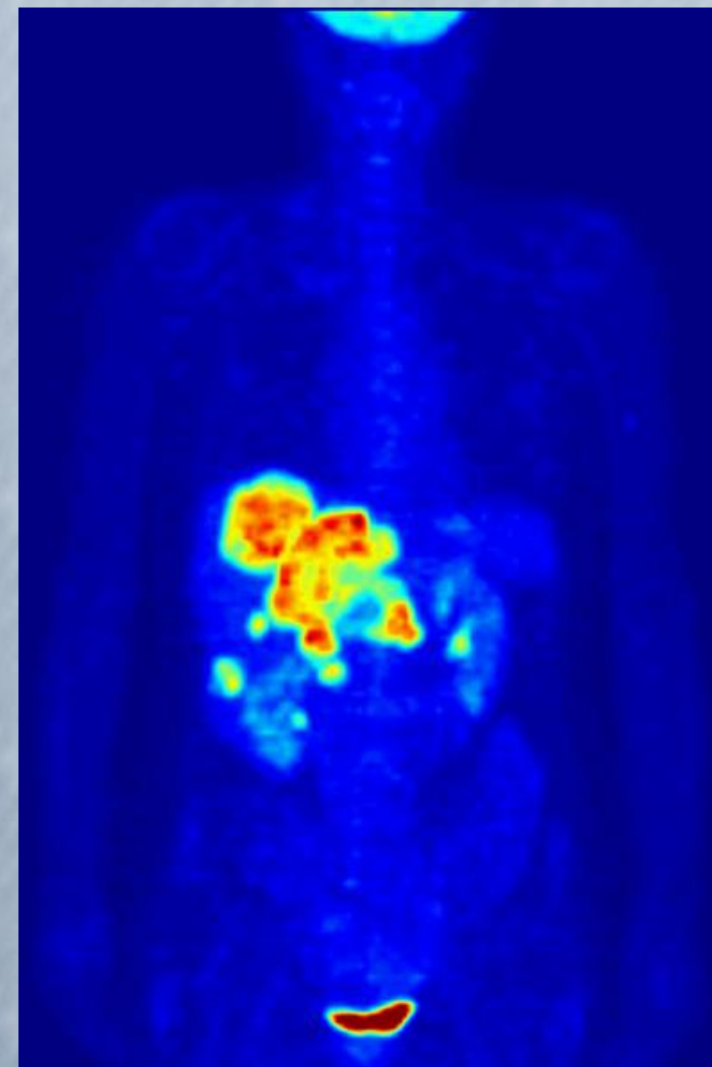
Positron-Electron Tomography

Inject ^{18}F compounds, nucleus ejects a positron after beta-plus decay.

Positron annihilates with an electron to form 2 back-to-back 511keV photons.

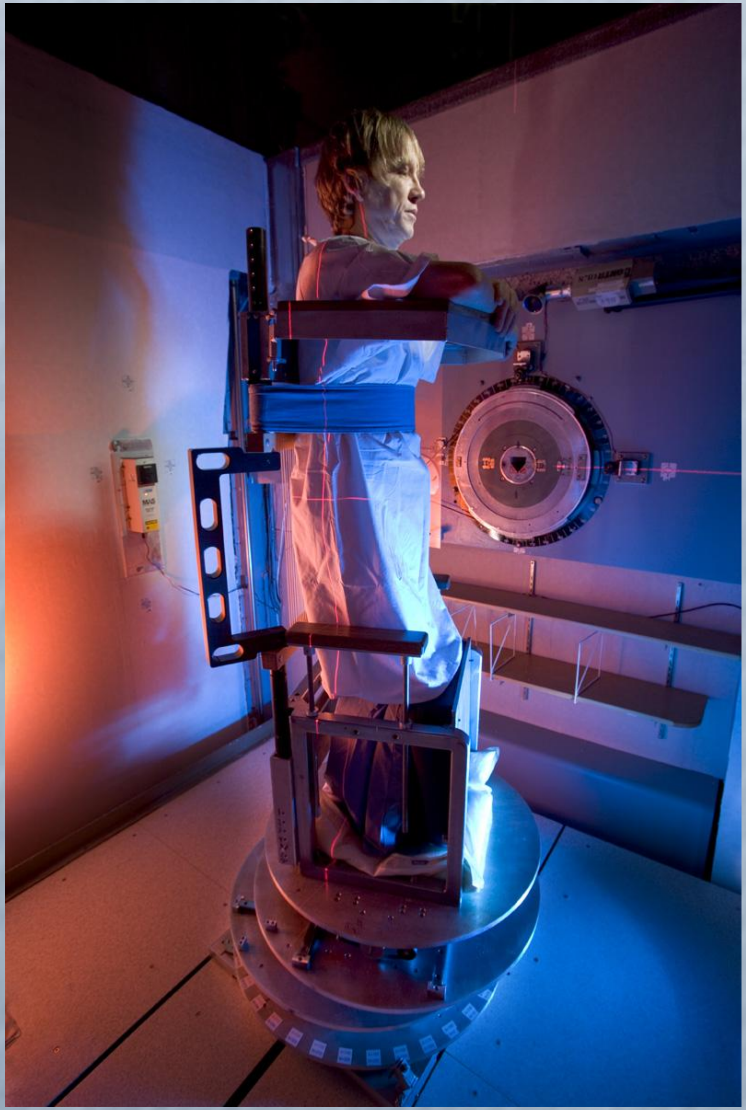
Needs a nuclear physics lab to make ^{18}F





Neutron therapy

- Neutrons produced from firing protons into a beryllium target
- Directed into the patient, and patient is revolved to maximize the irradiation of the tumor.



Summary

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- Nuclear stability
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- Radiation doses
- Medical physics