

PHY 127 FS2024

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Lecture 13

May 31st, 2024

Last time (Lecture 12):

$$\text{Nuclear binding energy} = Z(m_p c^2) + N(m_n c^2) - m c^2$$

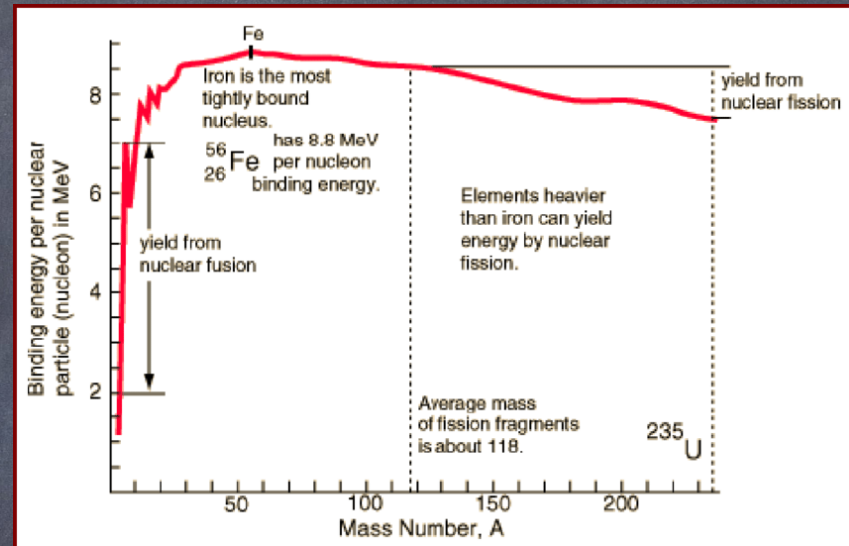
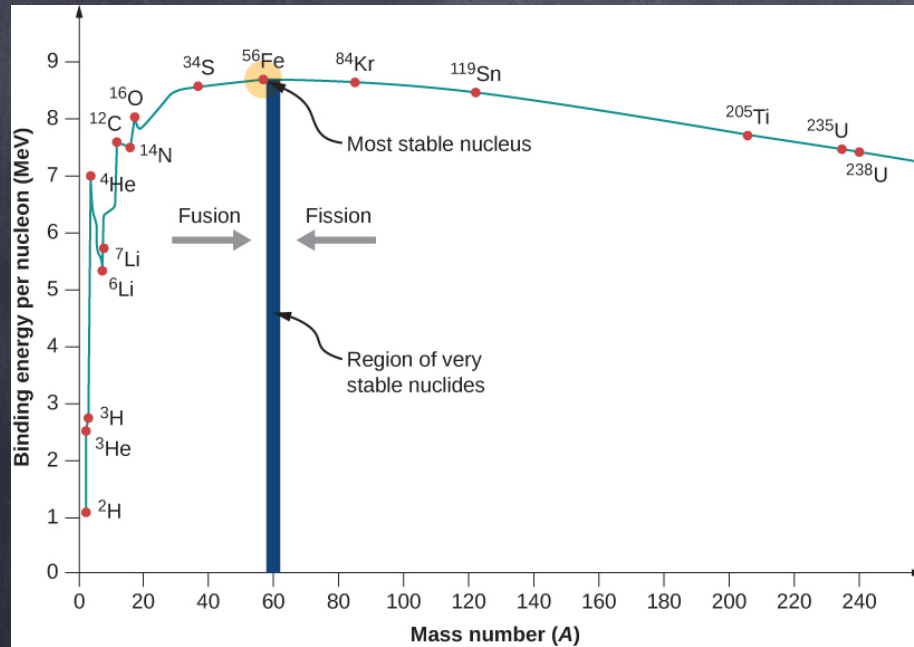
m_p : mass of proton
 m_n : mass of neutron
 $m c^2$: mass of the nucleus.

This binding energy is about 1% of the mass

$$\frac{8 \text{ MeV}}{1 \text{ u}} = \frac{8 \text{ MeV}}{930 \text{ MeV}} \sim 1\%$$

Binding energy per nucleon as a function of A

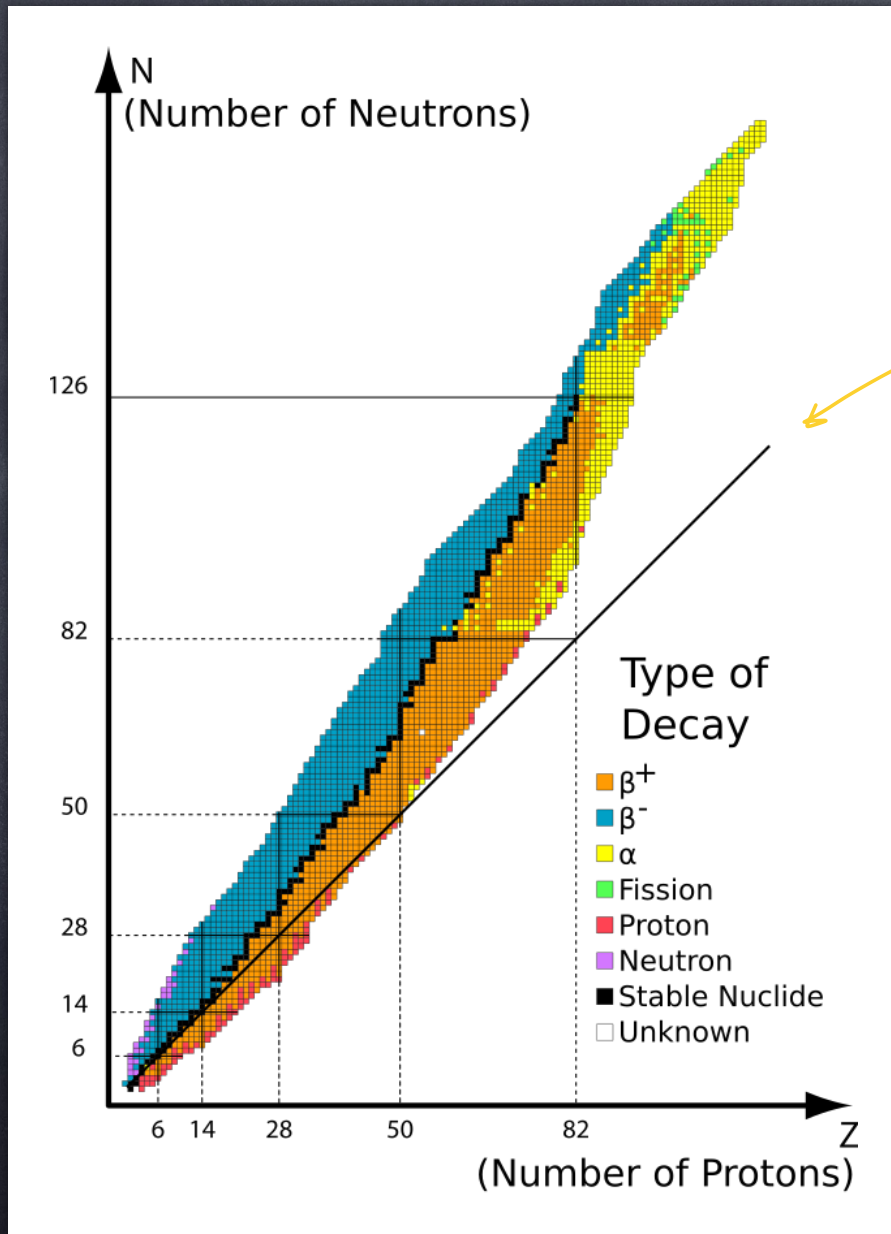
Release of energy occurs when binding energy per nucleon moves to higher energy



fusion from lighter elements to heavier elements produces energy below Fe

Fission from heavier elements to lighter elements produces energy above Fe.

Note! ^4He has a very high (relative) binding energy *



Black point are stable nuclides.

Line of $Z = N$

← stable: slightly more neutrons than protons

Pauli exclusion principle: the nucleus has protons + neutrons } Fermions with spin = $\frac{1}{2}$

As we add protons + neutrons to a nucleus, they occupy higher energy levels

But protons + neutrons do this separately.

Compare a) nucleus with Z protons, 0 neutrons
 b) nucleus with $\frac{Z}{2}$ protons, $\frac{Z}{2}$ neutrons.

Both have the same $A = Z + N$.

But the energy of (a) is larger than (b)

Example:

a) $Z=8, N=0$

b) $Z=4, N=4$



Nuclides with $Z \cong N$ tend to have lower energies & be more stable.

Atoms are more stable when electron shells (s, p, d, ...) are filled \rightarrow "closed shells"

Also true for nuclei with "magic" numbers of nucleons: 2, 8, 20, 28, ...

(Applies to both protons & neutrons separately)

For instance, ${}^4_2\text{He}$ ($Z=2, N=2$) is "doubly magic" \rightarrow extremely stable

Helium



(see binding energy on p. 3)

Types of radiation (from unstable nuclei decaying) are classified by their penetration power

α radiation: stopped by a few pieces of paper

β radiation: stopped by a few pieces of aluminum foil

γ radiation: can penetrate several cm of lead or a concrete wall.

Later, it was found that

α : ${}^4_2\text{He}$ nucleus

β : high-energy electron

γ : high-energy photon.

Energy released in a decay is called Q

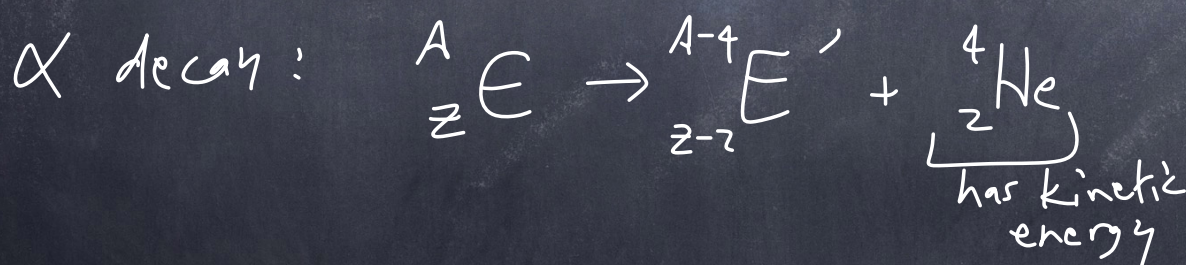
$$Q = \left(M_{\substack{\text{mass of} \\ \text{nucleus}}} - \sum_{\substack{\text{sum of} \\ Z + N}} m_i \right) c^2$$

For a radioactive decay to happen, Q must be > 0 .
(natural radioactivity)

An unstable nuclei will decay by α , β , or γ radiation

E : parent nucleus

E' : daughter nucleus



$$Q = (M_E - M_{E'} - M_{\text{He}}) c^2$$

$Q > 0$, energy becomes the energy of ${}^4_2 \text{He}$

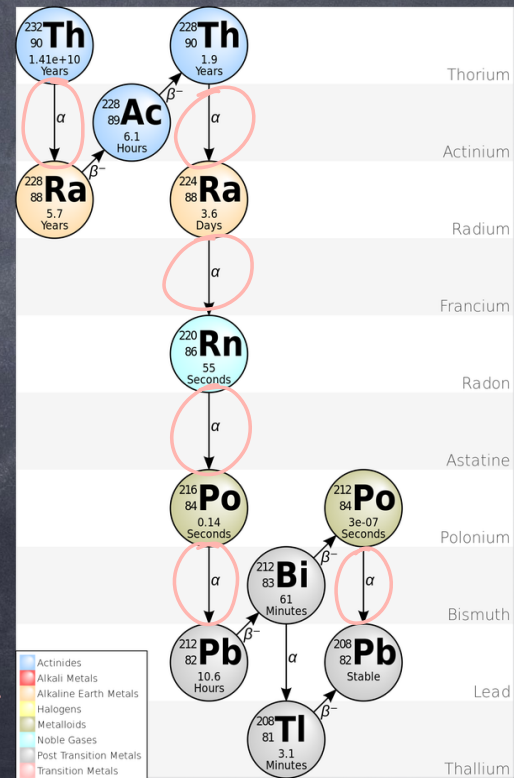
α particle: interacts very strongly with matter because $Z=2$ $q=+2e$
(feels stronger Coulomb force)

Often, E' also decays by α decay, causing a succession of α decays.

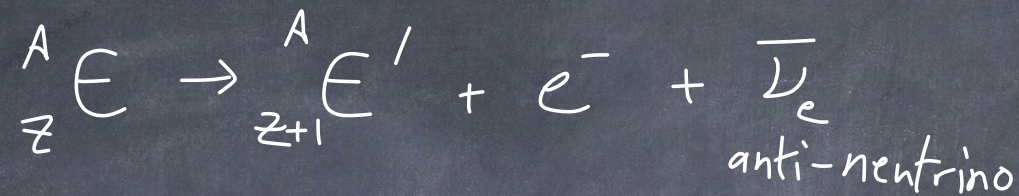
unstable
 Nuclides with $A=4n, 4n+1, 4n+2, \dots$
 (where n is an integer) typically exhibit multiple α decays.

For instance, ${}^{232}_{90}\text{Th}$.
 ($4 \cdot 58 = 232$)

We see ${}^{232}_{90}\text{Th}$ decays by α emission to ${}^{228}_{88}\text{Ra}$. Later ${}^{228}_{90}\text{Th}$ decays to ${}^{224}_{88}\text{Ra}$, \dots many α decays happen.



Beta decay: β

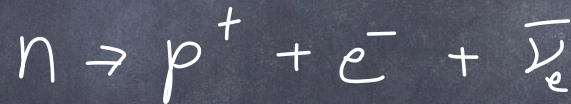


"-" means
anti-neutrino

Neutrinos interact extremely weakly so they are typically ignored.

A neutrino can travel through a light-year of lead and not interact

Note: A neutron is being converted into a proton.



This is happening because of the weak nuclear force.

What is a neutrino?

Symbol: ν ($\bar{\nu}$)

It is a neutral lepton, like the electron but with no electric charge. It only interacts through the weak nuclear interaction.



A lead tube one lightyear long (9 trillion km)
would only stop $\frac{1}{2}$ of
neutrinos. (9E12 km)

wow!

Sources of neutrinos:

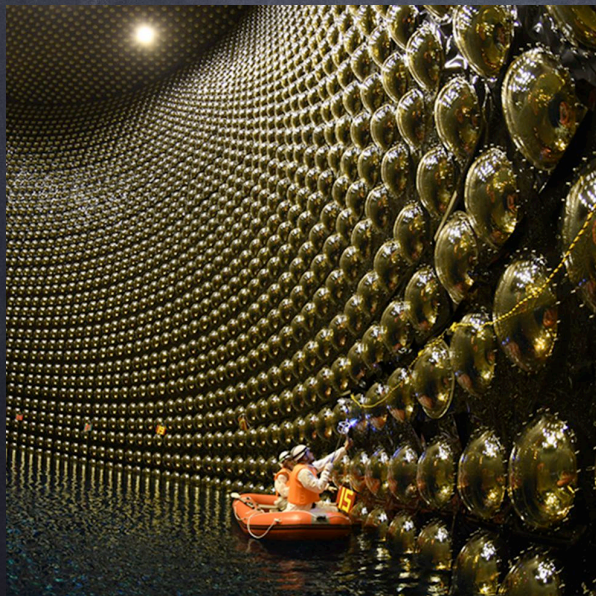
- radioactive decays
- neutrinos produced in sun (from fusion)
- neutrinos produced in nuclear reactors (fission)
- neutrinos produced in accelerators

10^{11} neutrinos from the sun travel through each of your fingernails each second.

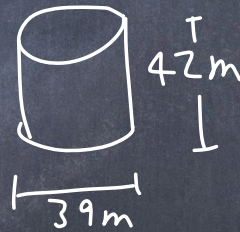


That's a lot!

Detecting neutrinos:



Super-Kamiokande: 50 kilotonnes of water



All of this water causes about 4000 neutrinos from sun to interact. Not so many!

weak nuclear force

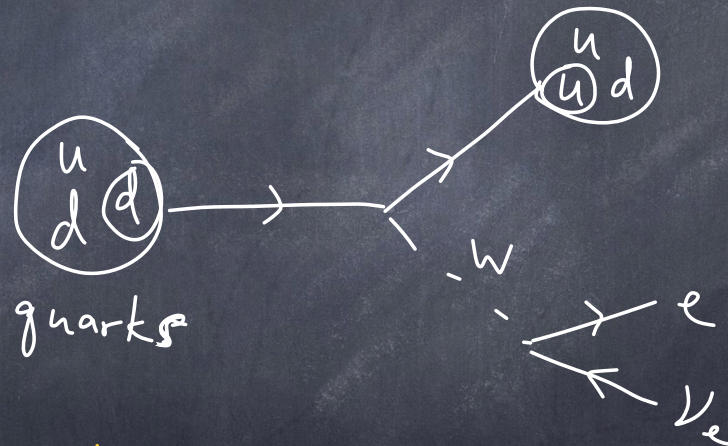
$$n \rightarrow p^+ + e^- + \bar{\nu}_e$$

W is a force carrier for the weak force.



↑ moving backward in time = anti-neutrino

$$d \rightarrow u + e^- + \bar{\nu}_e$$

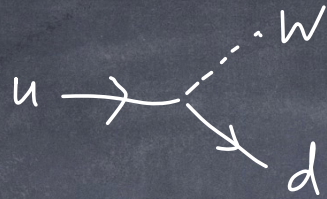


↑ fundamental interaction

relevant W interactions (affect matter)

remember

$p \rightarrow n$



$$u \rightarrow d + W^-$$

$$Q(u) = +\frac{2}{3}$$

$n \rightarrow p$

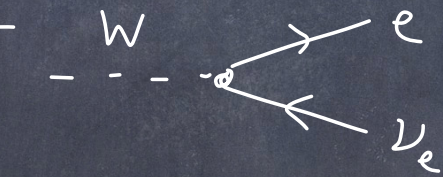


$$d \rightarrow u + W^+$$

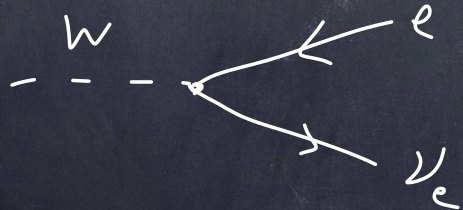
$$Q(d) = -\frac{1}{3}$$

produces

e^-
or
 e^+



$$W^- \rightarrow e^- + \bar{\nu}_e$$



$$W^+ \rightarrow e^+ + \nu_e$$

W is unstable and decays like this

so a $p \rightarrow n + e^+ + \nu_e$

But protons are stable by themselves
but can decay inside a nucleus

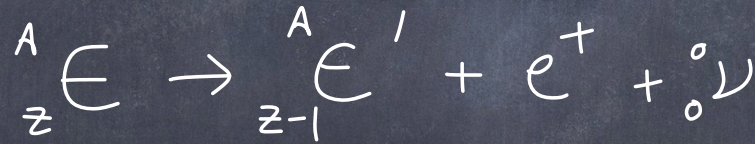
Free neutrons decay into a proton + $e^- + \bar{\nu}_e$
in ~ 15 minutes

Neutrinos were **hypothesized** because it was
found that $n \rightarrow p + e^-$

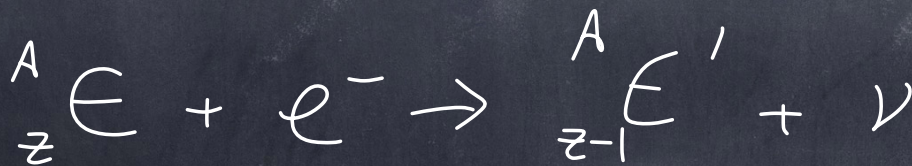
doesn't conserve energy
(so we need a neutrino
also)

Some **other** weak nuclear decays:

positron
emission



electron
capture

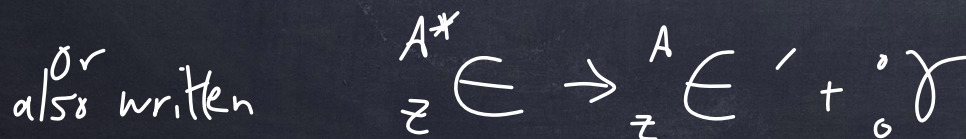
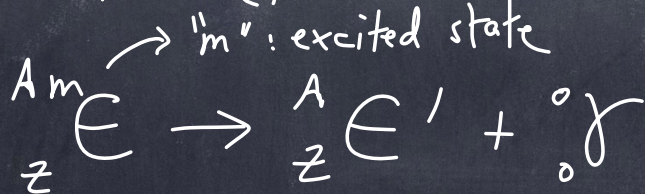


γ radiation (gamma)

Occurs when a nucleus makes a downward transition from one energy to a lower energy level (like in atoms). But nuclear transitions produce higher energy photons than atomic transitions (millions of times larger)

γ : used in medical applications (imaging) + radiation therapy.

γ process happens when a nuclei is left in an excited state following a α or β decay



Half-life of unstable nuclei:

$$N(t) = N_0 e^{-\lambda t}$$

λ : decay constant

N_0 : initial number
of radioactive
particles

$N(t)$: # of particles
remaining after
some time, t

$$T_{\frac{1}{2}} = t_{\frac{1}{2}} = \text{half-life}$$

$$T_{\frac{1}{2}} = \frac{\ln(2)}{\lambda}$$

$$\text{activity} = \frac{\Delta N}{\Delta t} = -\lambda N$$

(-) means N is
decreasing

This is explained more in next slides

Half-life principle:

The number of decays in a short period of time ΔN is proportional to the time interval Δt , and also to the number of particles, N .

Therefore, the formula is:

$$\Delta N = -\lambda N \Delta t \quad (1)$$

where λ is the decay constant, which depends on the particular radioactive nuclide.

The solution to this formula is solved with calculus:

As $\Delta t \rightarrow 0$, we use dt , and $\Delta N \rightarrow dN$.

$$\text{so } dN = -\lambda N dt$$

Integrating, $\int \frac{dN}{N} = \int -\lambda dt \Rightarrow \ln N = -\lambda t + \text{constant}$

Exponentiating) $e^{\ln N} = e^{-\lambda t + \text{constant}} = e^{-\lambda t} \cdot e^{\text{constant}}$

And since $e^{\text{constant}} = \text{another constant}$, then \Rightarrow

$$N = Ce^{-\lambda t}$$

Half-life

$$N(t) = N_0 e^{-\lambda t}$$

λ : decay constant

N_0 : initial # of radioactive particles

$N(t)$: # of ptcls after time, t .

How long does it take to decay half of the initial amount of isotope?

Initial # : N_0
Final # : $\frac{N_0}{2}$

$$\left. \begin{array}{l} \text{Initial \# : } N_0 \\ \text{Final \# : } \frac{N_0}{2} \end{array} \right\} \rightarrow \frac{N_0}{2} = N_0 e^{-\lambda t} \quad (\text{what is } t)$$

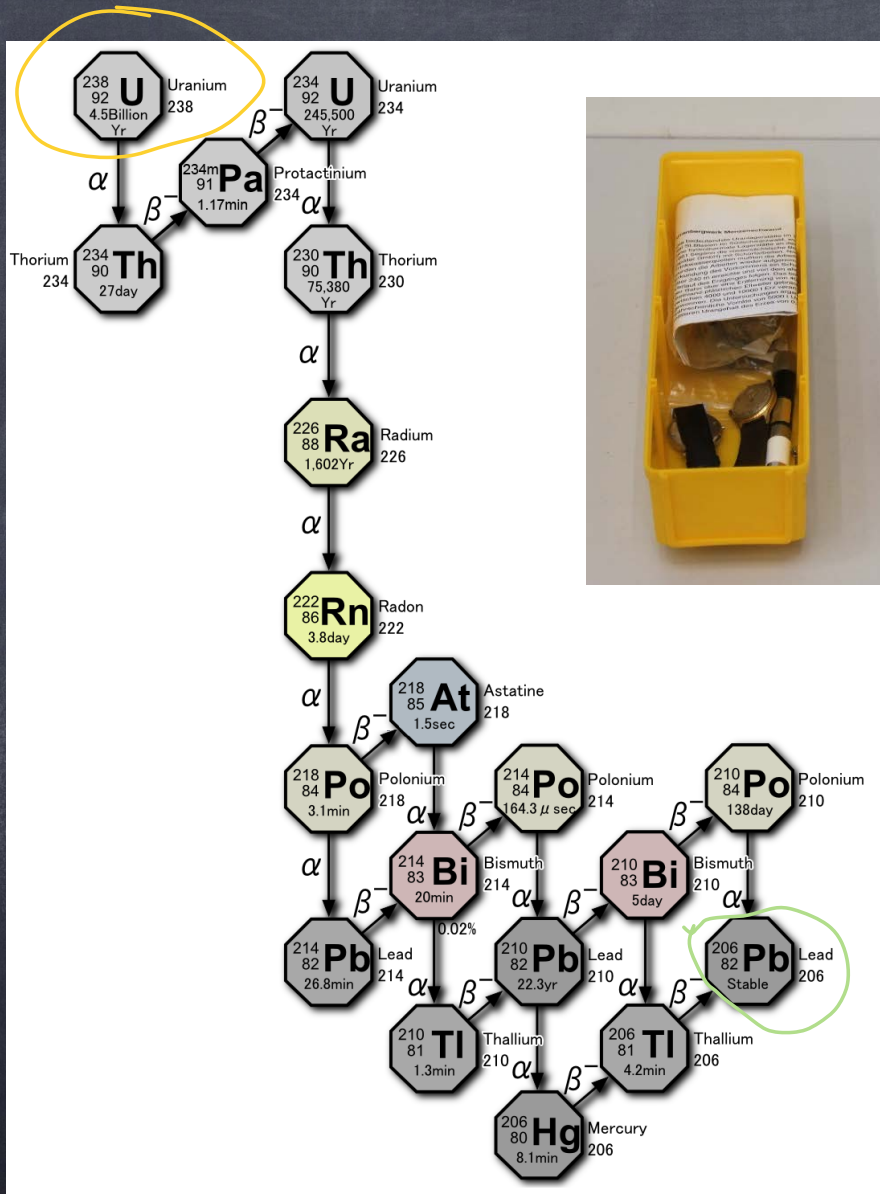
$$\frac{1}{2} = e^{-\lambda t}$$

$$\log_e\left(\frac{1}{2}\right) = \ln \frac{1}{2} = \ln(e^{-\lambda t}) = -\lambda t$$

$$T_{1/2} = t_{1/2} = t = \frac{\ln(2)}{\lambda} = \frac{0.693}{\lambda} \quad \text{half-life}$$

one half life : $N_0 \rightarrow N_0/2$
 two half-lives : $N_0 \rightarrow N_0/4$
 three - - - : $N_0 \rightarrow N_0/8$

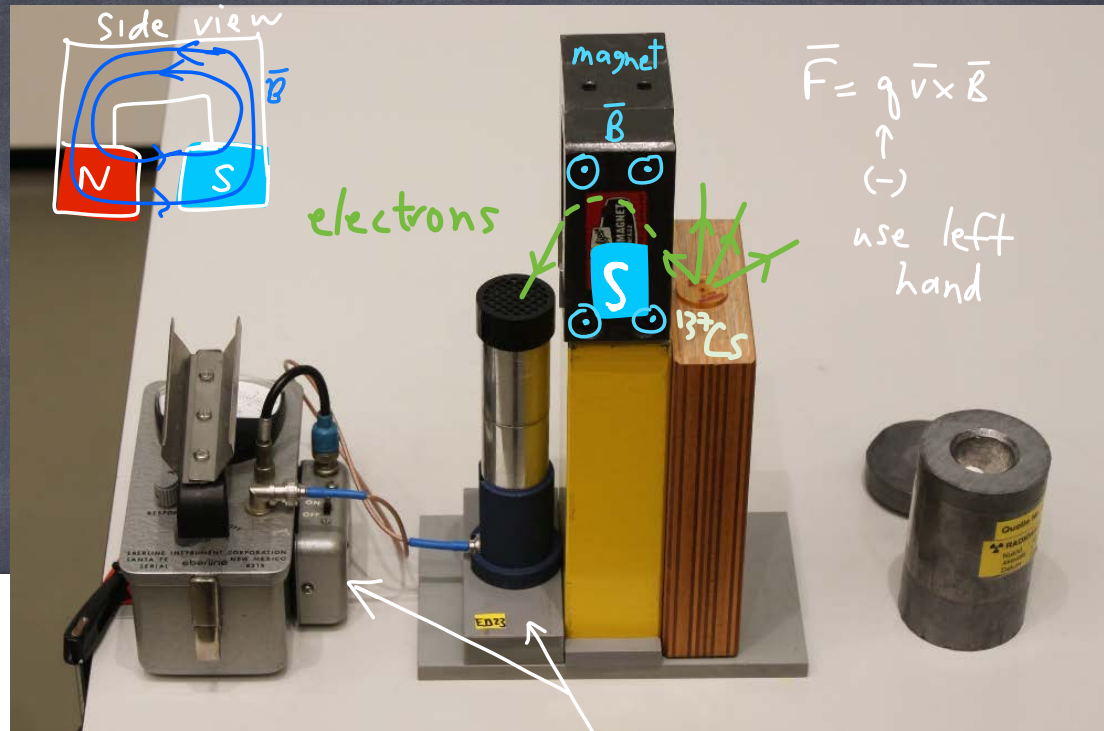
| Nuclide | Half-life | Type of change | Nuclide | Half-life | Type of change |
|---------------|-----------------------------|----------------|---------------|------------------------|-------------------------------|
| rubidium-87 | 5.7×10^{10} years | beta | iron-59 | 45 days | beta |
| thorium-232 | 1.39×10^{10} years | alpha | phosphorus-32 | 14.3 days | beta |
| uranium-238 | 4.51×10^9 years | alpha | barium-131 | 11.6 days | electron capture and positron |
| uranium-235 | 7.13×10^9 years | alpha | iodine-131 | 8.06 days | beta |
| plutonium-239 | 2.44×10^4 years | alpha | radon-222 | 3.82 days | alpha |
| carbon-14 | 5730 years | beta | gold-198 | 2.70 days | beta |
| radium-226 | 1622 years | alpha | krypton-79 | 34.5 hours | electron capture and positron |
| cesium-133 | 30 years | beta | carbon-11 | 20.4 min | positron |
| strontium-90 | 29 years | beta | fluorine-17 | 66 s | positron |
| hydrogen-3 | 12.26 years | beta | polonium-213 | 4.2×10^{-6} s | alpha |
| cobalt-60 | 5.26 years | beta | beryllium-8 | 1×10^{-16} s | alpha |



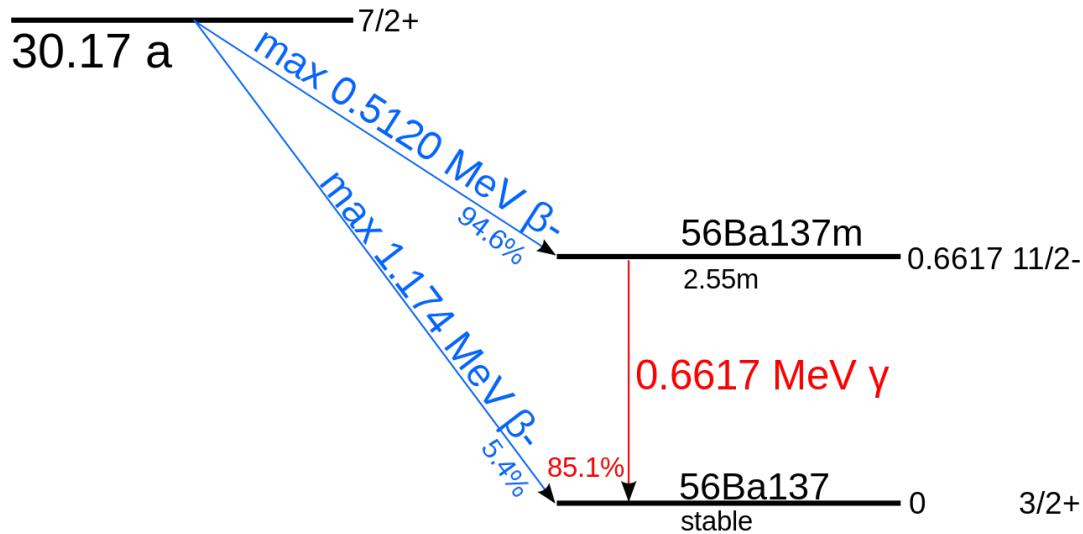
Experiment with uranium ore and radium. These decay producing $\alpha + \beta$ radiation. \leftarrow ^{206}Pb is finally stable

Experiment with electrons from $^{137}_{55}\text{Cs}$.

This is unstable and produces electrons + photons ($\beta + \gamma$)

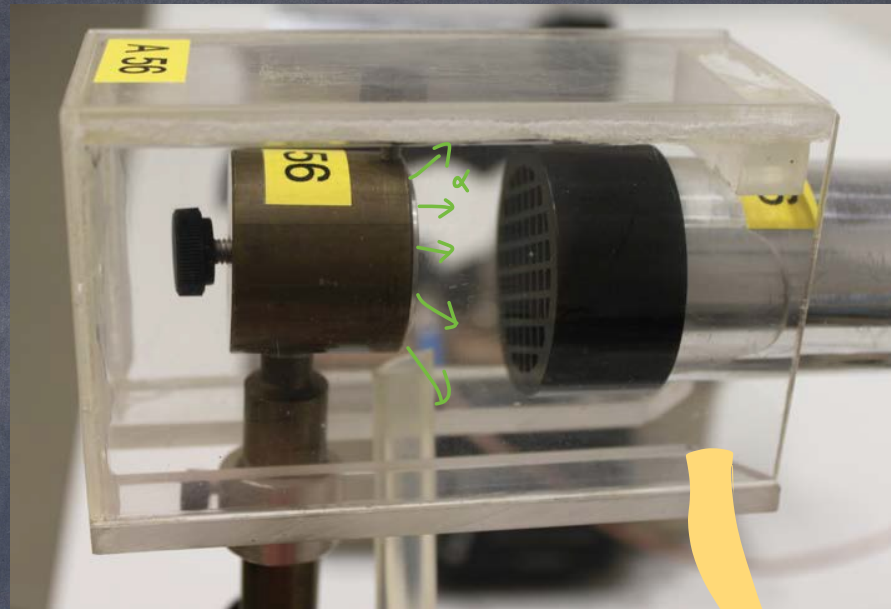
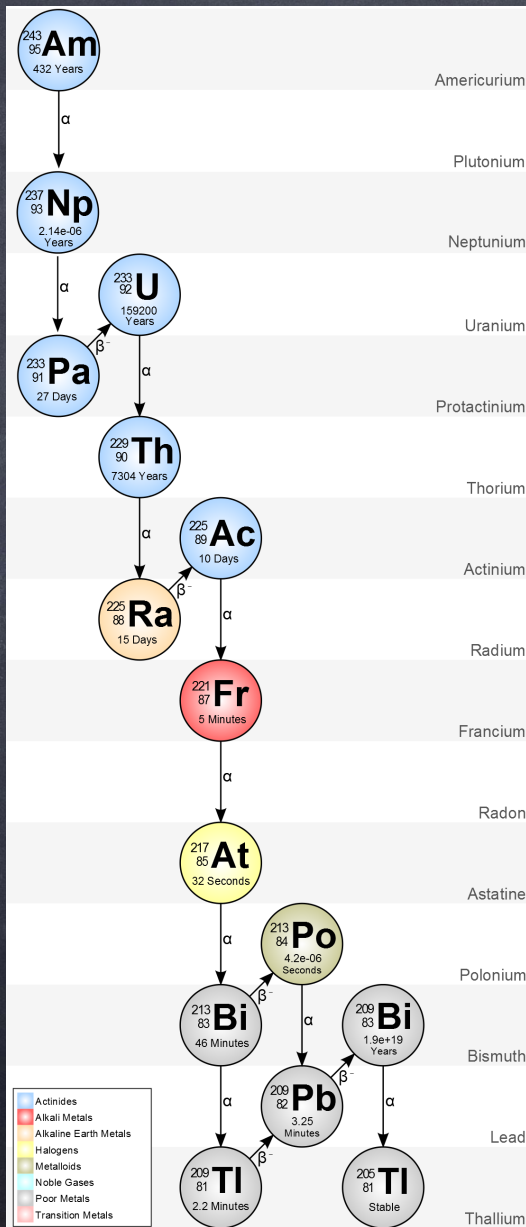


$^{55}\text{Cs}^{137}$



This is a Geiger-Müller counter

2.14e+6 years →

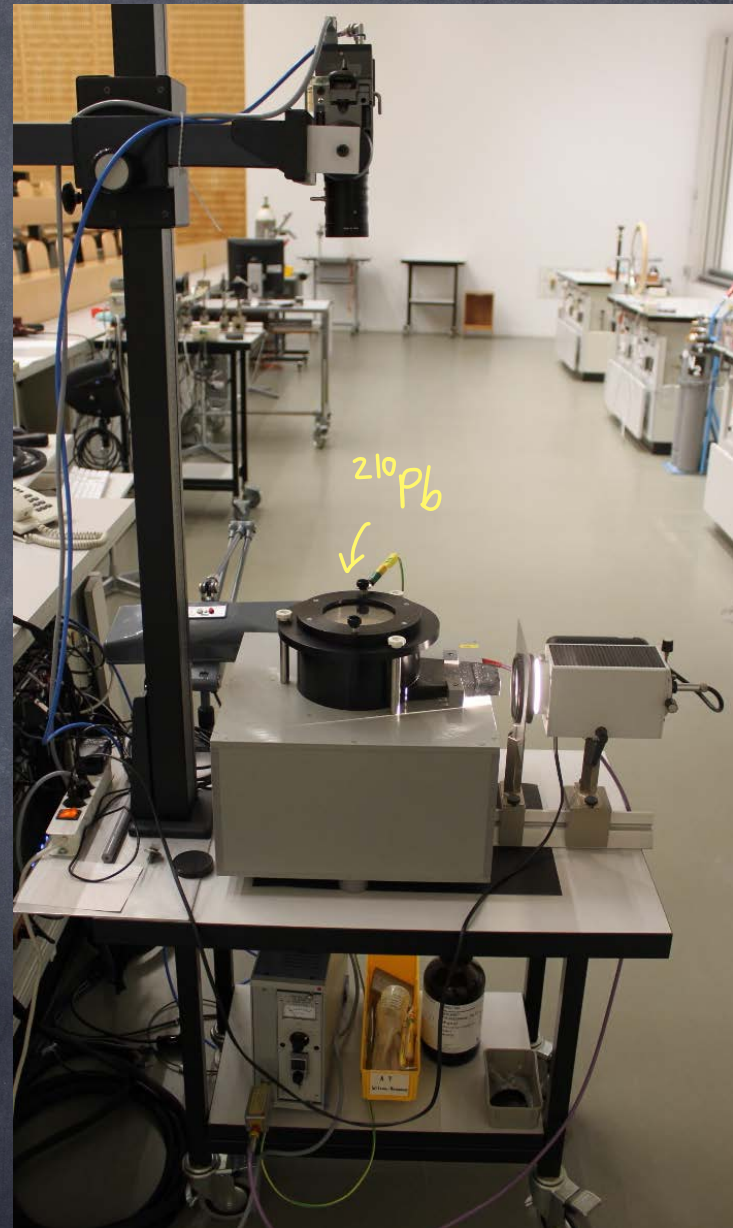
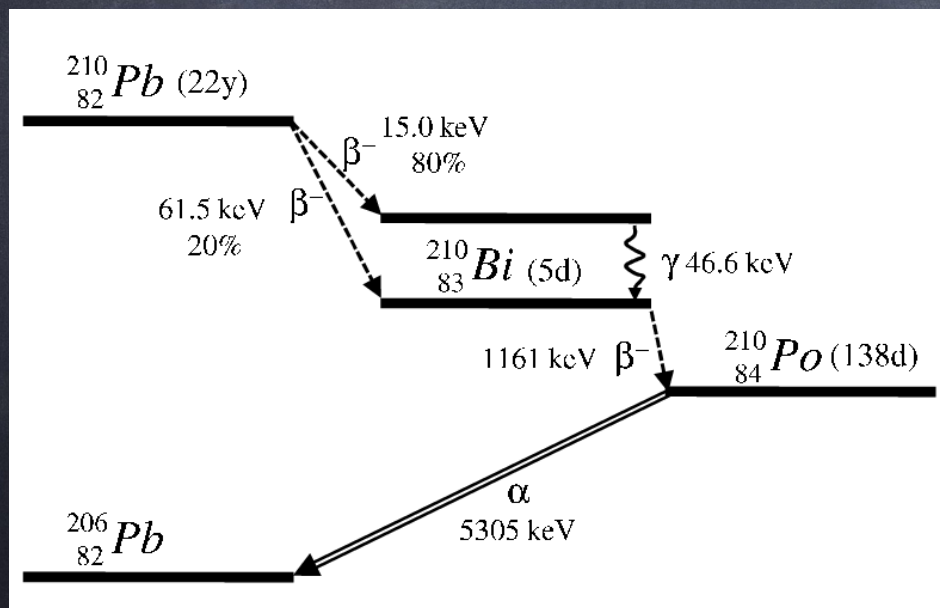


Experiment with ^{243}Am

$\alpha \rightarrow$ molecules

CO_2 or He
denser gas less dense gas

Experiment: cloud chamber
showing ^{210}Pb decaying



$\frac{\Delta N}{\Delta t}$: activity level

measured in $\frac{\text{disintegrations}}{\text{seconds}} = [\text{Bq}]$
Becquerel

$$1 \text{ Bq} = \frac{1 \text{ decay}}{\text{second}}$$

$$\text{or } [\text{Curie}] = [\text{Ci}] \quad 1 \text{ Ci} = 3.7 \times 10^{10} \text{ Bq}$$

Applications : ^{14}C dating.

Living things are carbon-based.

^{14}C produced in the upper atmosphere
by cosmic radiation.

Living things incorporate carbon (^{12}C , ^{13}C , ^{14}C)
until they die.

One can measure the fraction of ^{14}C left in a sample from a (previously) living organism to see how much is left.

$\tau_{\frac{1}{2}}$ of ^{14}C is 5730 years

^{14}C dating works well for objects < 60,000 years old

60,000 years is 10 half-lives

$$\left(\frac{1}{2}\right)^{10} \sim 0.001$$

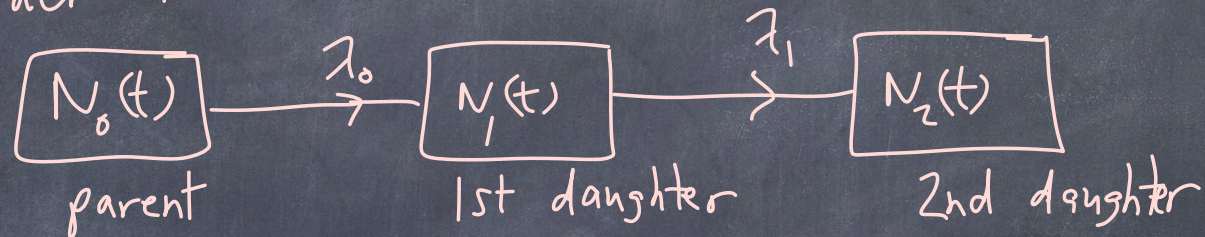
Geological dating uses ^{238}U

$\tau_{\frac{1}{2}} \sim 4.5 \text{ E } 9$ years

First fossils are 3 billion years old, found using ^{238}U dating

Some isotopes can reach equilibrium levels if they are produced by a long-lived parent and then decay themselves.

Consider this case.



The number of 1st daughter particles increases due to the parent decays, but also decreases due to its own decay to 2nd daughters.

The number of N_1 particles can therefore reach an equilibrium.

The total change in ΔN in some time Δt

$$\Delta N_1(t) = [N_0(t)\lambda_0 - N_1(t)\lambda_1]\Delta t \quad (2)$$

IF λ_1 is much smaller (faster) than λ_0 , then $N_0(t)$ and $N_1(t)$ are approximately constant in time.

So equation ② becomes

$$\Delta N_1(t) = 0 = [N_0 \lambda_0 - N_1 \lambda_1] \Delta t$$

Since $\Delta t \neq 0$, $N_0 \lambda_0 = N_1 \lambda_1$

and therefore, we can predict that the equilibrium number of

N_1 daughters is $N_1 = \frac{\lambda_0}{\lambda_1} N_0$

→ The number of isotopes coming from long-lived parents is \sim constant and related to $\lambda_0, \lambda_1, \pm N_0$.

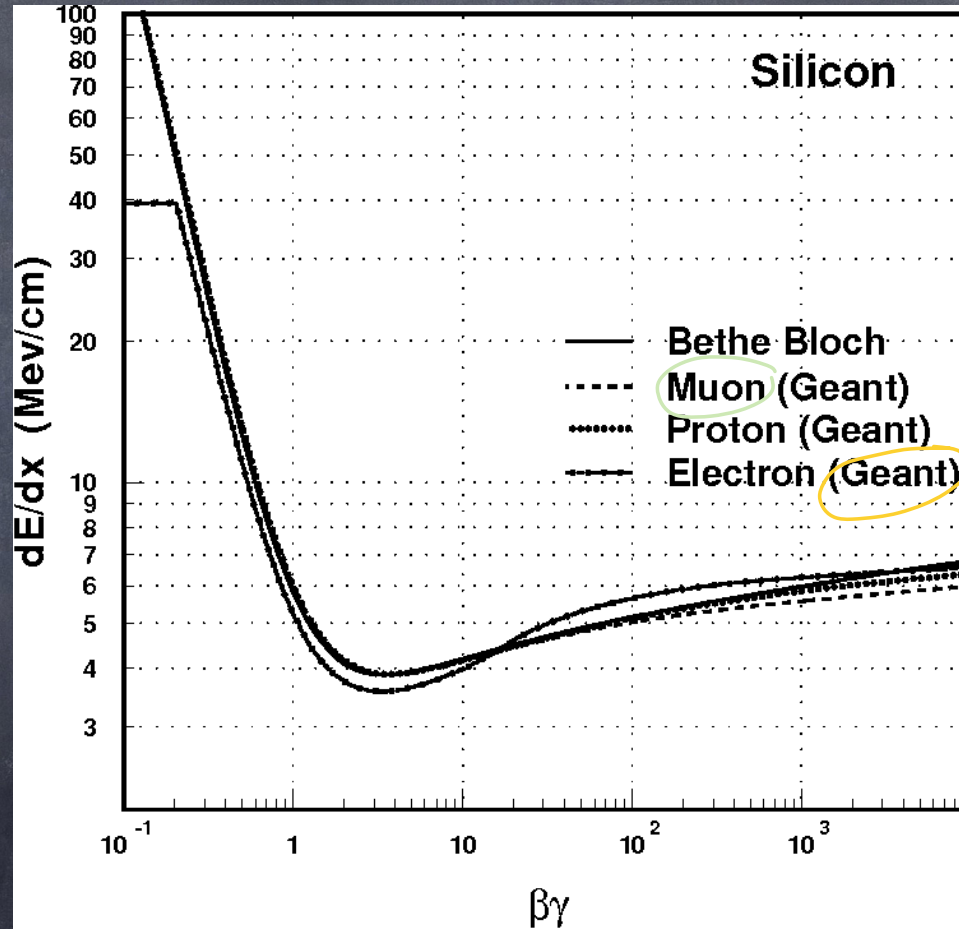
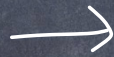
Radiation (here, charged particles) lose energy moving through materials.

Bethe-Bloch Function

The Bethe-Bloch Function describes this interaction

$$\frac{dE}{dx}$$

energy loss per distance



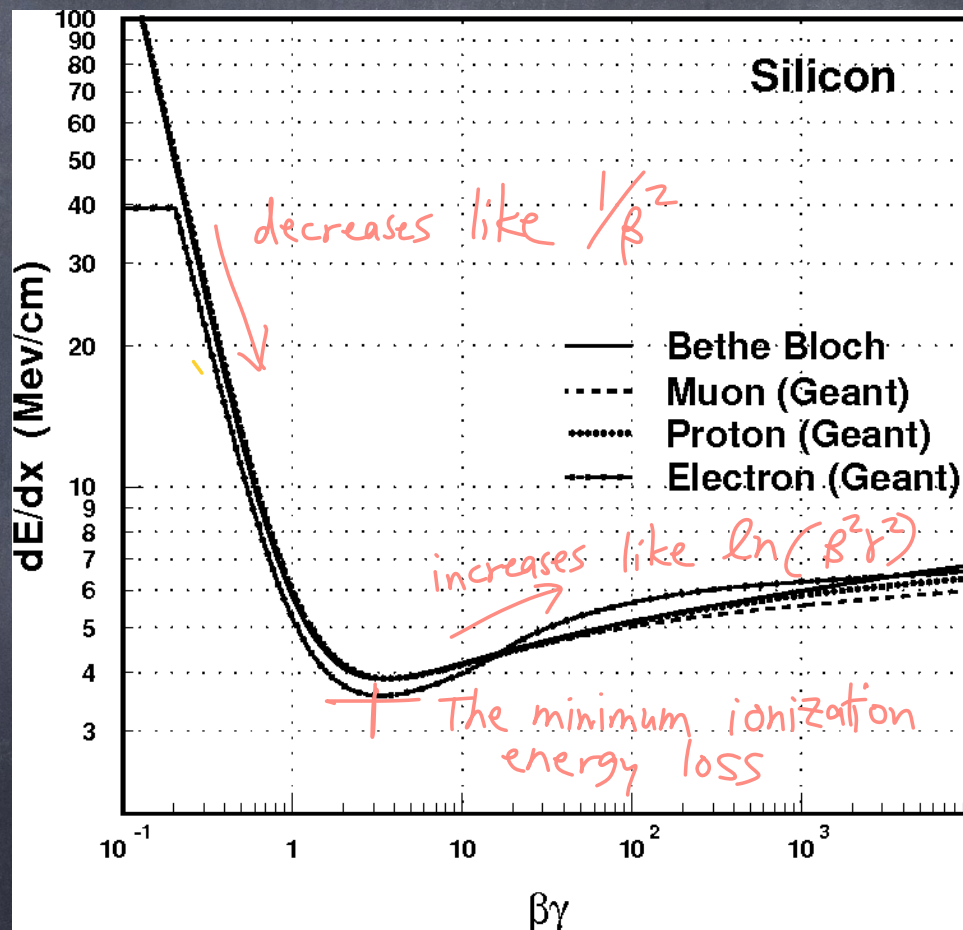
have the same shape curve

Muons come from cosmic rays. (10,000 go through your body every minute)

Geant is a simulation software for particle interactions

β related to velocity

Note that over a significant range of velocities (or $\beta\gamma$), dE/dx doesn't change much. (From $1 < \beta\gamma < 10^4$)



$\beta = \frac{v}{c}$ speed relative to light speed.

$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$
 not photon, this γ is related to velocity (called the Lorentz Factor)

Note: dE/dx typically has units of $\frac{\text{MeV}}{\text{cm}}$
since it is energy deposited
per length in a material.

However, often people divide it by the
density of the material, so it has units
of $\text{MeV/g/cm}^2 = \text{MeV} \cdot \text{g}^{-1} \cdot \text{cm}^2$

IF you have a dE/dx in units of $\text{MeV} \cdot \text{g}^{-1} \cdot \text{cm}^2$,
multiply by the density of the material
to get an energy deposition per length.

dE/dx

Particle Data Group:
pdg.lbl.gov/2016/reviews/rp2016-rev-passage-particles-matter.pdf

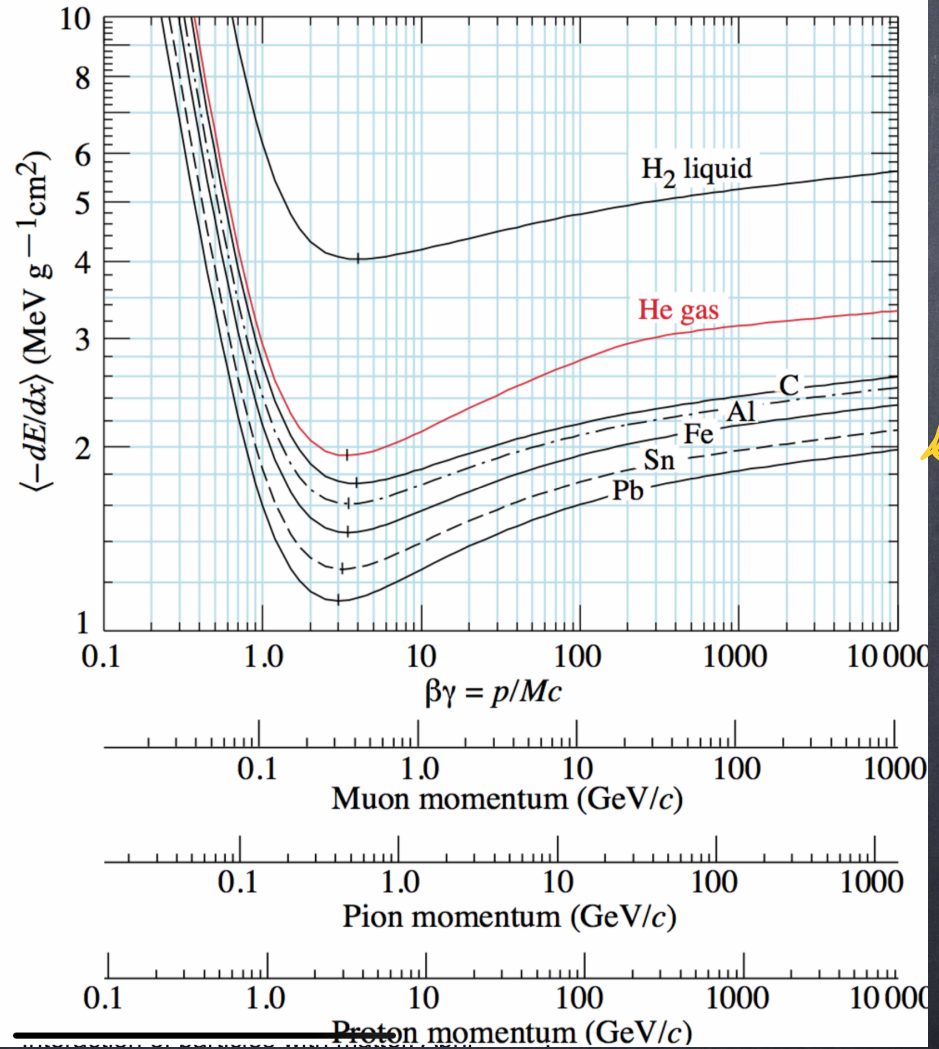
Different detector materials

$$\frac{dE}{dx} \approx \frac{Z}{A}$$

(remember density!)

dE/dx depends on
 $\beta\gamma = p/(Mc)$

→ at a given p, dE/dx is different for particles with different mass M



Here $\frac{dE}{dx}$ is divided by density of material

$$\left[\frac{\text{MeV}}{\text{cm}} \cdot \frac{\text{g}}{\text{cm}^3} \right] = \left[\frac{\text{MeV}}{\text{g}} \text{cm}^2 \right]$$

Bethe-Bloch equation

Considering quantum mechanical effects:

$$-\left\langle \frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

[·ρ]

density

$$K = 4\pi N_A r_e^2 m_e c^2 = 0.307 \text{ MeV g}^{-1} \text{ cm}^2$$

$$N_A = 6.022 \cdot 10^{23}$$

[Avogadro's number]

$$T_{\max} = 2m_e c^2 \beta^2 \gamma^2 / (1 + 2\gamma m_e/M + (m_e/M)^2)$$

[Max. energy transfer in single collision]

$$r_e = e^2 / 4\pi \epsilon_0 m_e c^2 = 2.8 \text{ fm}$$

[Classical electron radius]

$$m_e = 511 \text{ keV}$$

[Electron mass]

z : Charge of incident particle

M : Mass of incident particle

$$\beta = v/c$$

[Velocity]

Z : Charge number of medium

A : Atomic mass of medium

$$\gamma = (1 - \beta^2)^{-2}$$

[Lorentz factor]

I : Mean excitation energy of medium

δ : Density correction [transv. extension of electric field]

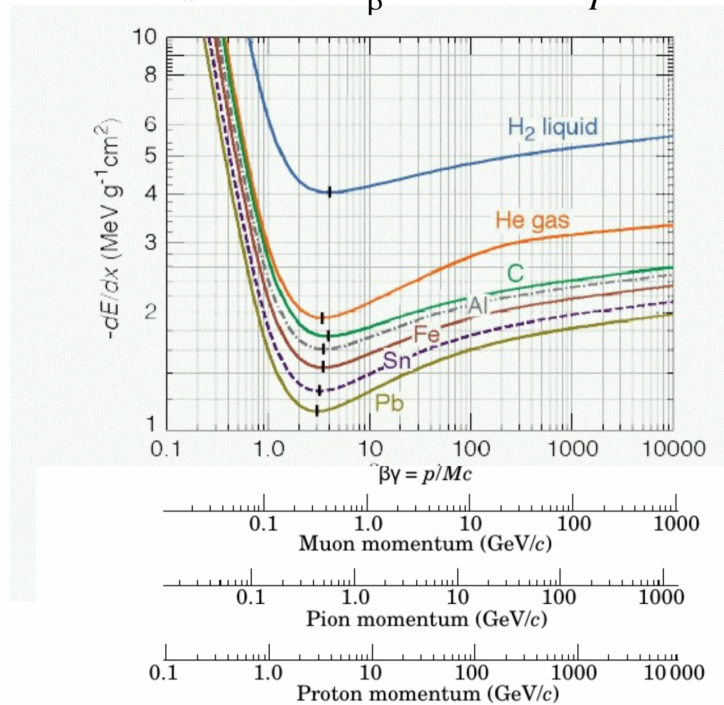
Validity:

$$.05 < \beta\gamma < 500$$

$$M > m_\mu$$

dE/dx_{min} different materials

$$\frac{-dE}{dX} = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta}{2} - \frac{C}{Z} \right]$$



dE/dX depends on A, Z of target material

$\beta\gamma \approx 3.5$ broad minimum

→ minimum ionising particles (MIP)

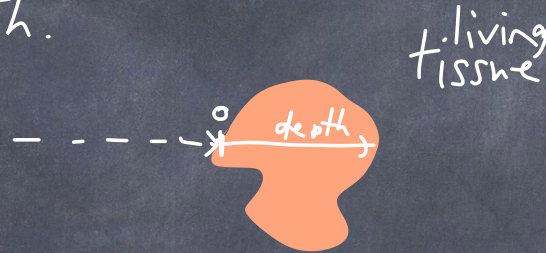
H_2 $Z/A \approx 1$ $dE/dX_{min} \approx 4 \text{ MeV}/(\text{g}/\text{cm}^2)$

others $Z/A \approx 0.5$ $dE/dX_{min} \approx 2 \text{ MeV}/(\text{g}/\text{cm}^2)$

$dE/dX_{min} \approx 1-1.7 \text{ MeV}/(\text{g}/\text{cm}^2)$
only weak material dependence

PDG <http://pdg.lbl.gov/pdg.html>

What is most important in understanding radiation damage to tissue is the dose delivered at each depth.



This depends on the type of radiation and its energy.

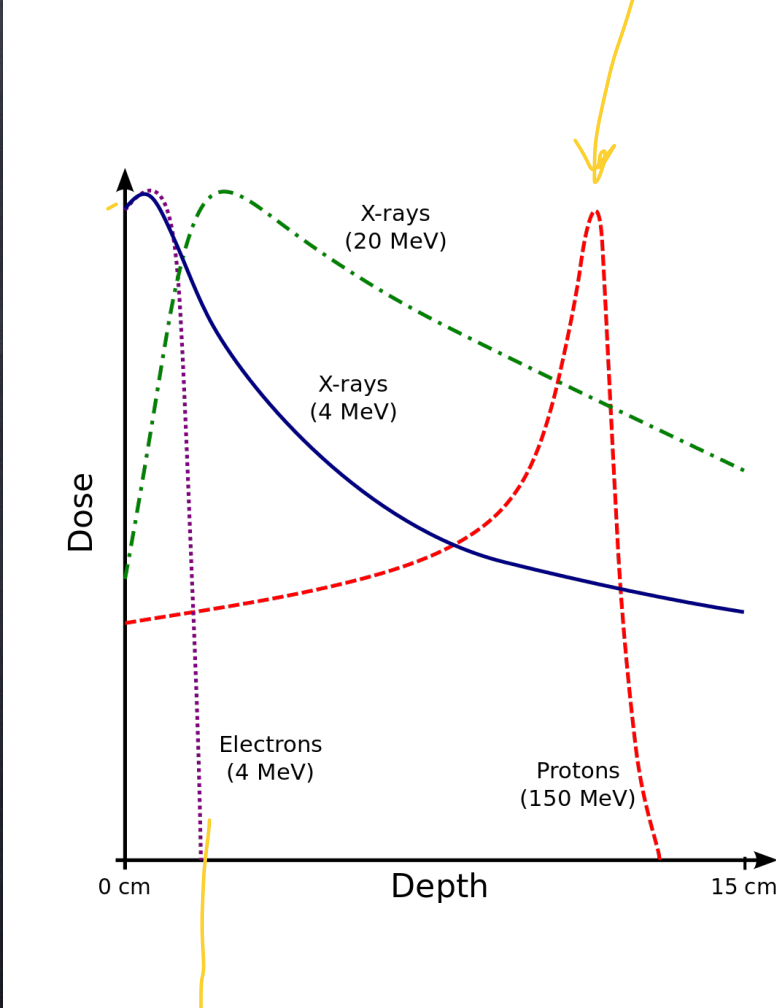
TABLE 23.1

Range of various forms of radiation in biological tissue or water

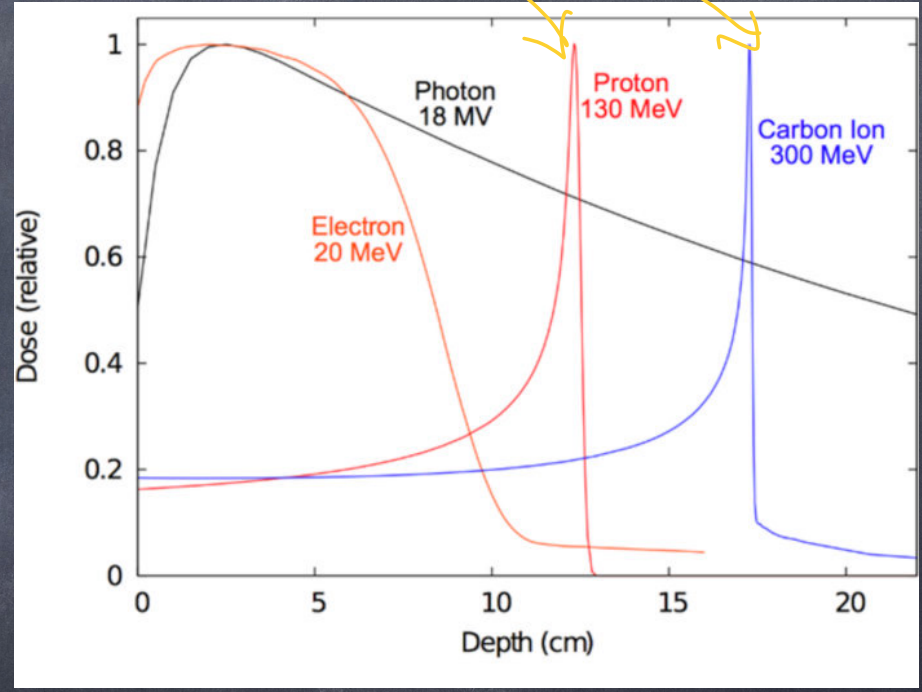
| Radiation type | Energy | Range |
|---------------------|--------|------------------|
| α -particles | 5 MeV | 40 μm |
| β -radiation | 20 keV | 10 μm |
| β -radiation | 1 MeV | 7 mm |
| γ -radiation | 20 keV | 6.4 cm |
| γ -radiation | 1 MeV | 65 cm |
| neutrons | 1 MeV | 20 cm |

Range:
 ← how far the radiation can travel before stopping

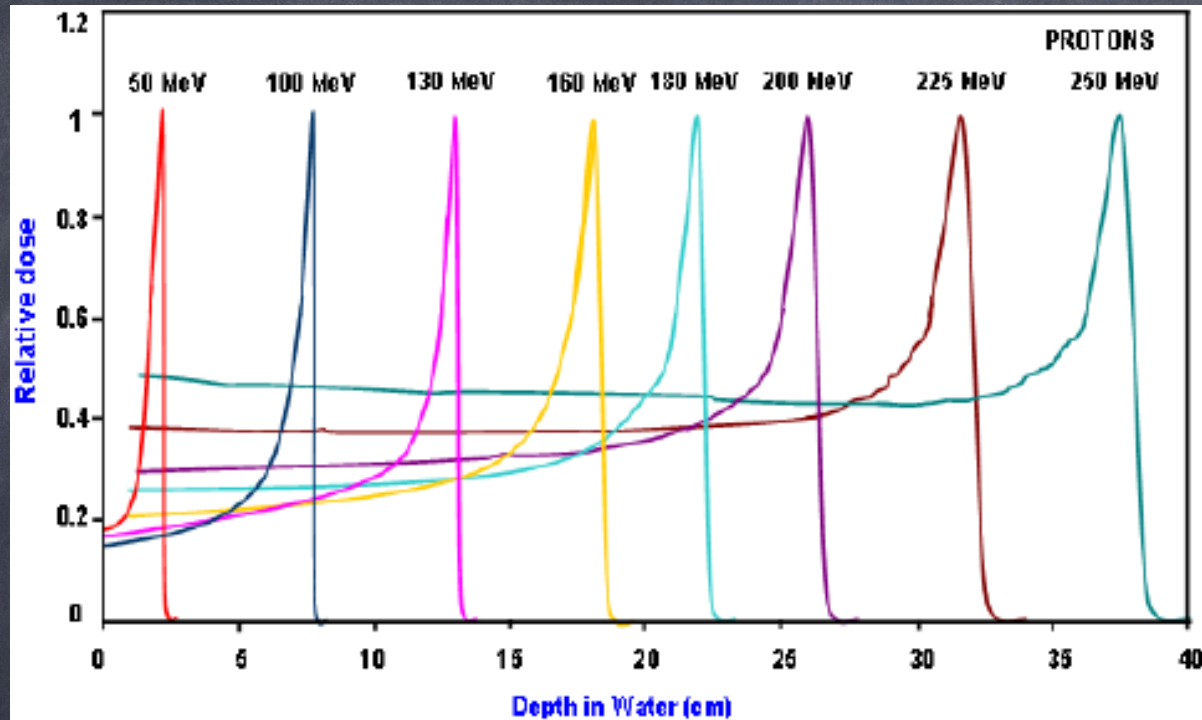
Bragg peak: shows that most of the energy is deposited when the proton or ion stops.



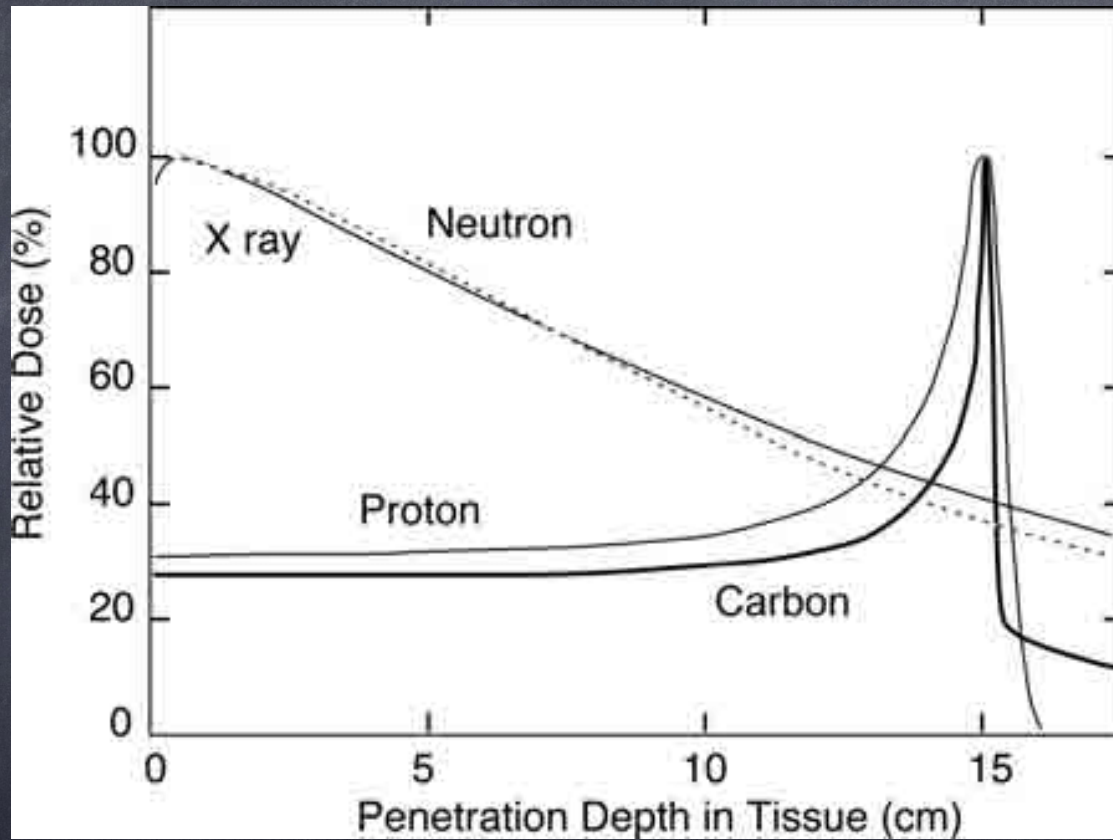
few cm



proton dose vs. depth for different energies.



we can tune the energy of protons to deposit energy at a certain depth.



Radiopharmaceuticals

Incorporation of radioactive isotopes into cells or in organs of body allows radioactive tracing or radiolabeling of a particular molecule as it passes through an organism.

For instance, hydrogen ${}^1_1\text{H}$ and ${}^3_1\text{H}$ (tritium) have the same chemistry, but tritium is radioactive ($T_{1/2} = 12$ years): ${}^3_1\text{H} \rightarrow {}^3_2\text{He} + e^- + \bar{\nu}_e$

Since its lifetime is long, you wouldn't necessarily put it in a human body, but it could be used as a radiolabel for investigating hydrogen molecules in a sample. Also, electrons don't travel very far...

So other radioactive nuclides are often used.

(See next page)

Table 26.4 Some Commonly Used Radioisotopes in Medicine

| <i>Radioisotope</i> | <i>Half-Life</i> | <i>Radiation</i> | <i>Applications</i> |
|---------------------|------------------|------------------|---|
| Technetium-99m | *6 h | γ | Most widely used |
| Iodine-123 | 13 h | γ | SPECT brain imaging |
| Carbon-11 | 20 min | e^+ | PET |
| Iodine-131 | *8.1 days | β, γ | Thyroid disorders |
| Phosphorus-32 | *14 days | β | Large variety of uses in biology and medicine |
| Thallium-201 | 74 h | γ | Heart imaging |
| Gallium-67 | 78 h | γ | Tumor imaging |
| Chromium-51 | *28 days | γ | Red blood cell survival |

*Produced in nuclear reactors; otherwise produced in an accelerator.

Center for Radiopharmacy (CRP)

The CRP is since 1993 the Swiss leading manufacturer of radioactive pharmaceuticals which are used in the nuclear medicine diagnostic by positron emission tomography (PET). These so-called PET-Tracers are molecules containing a very short lived radionuclide which decays by emission of positrons. Immediately after their manufacturing, they are intravenously administered to the patient and they rapidly distribute through the body. Because the radionuclides contained in PET-Tracers decay very fast, in most cases there will be no radioactivity left in the body after a few hours of their administration.

Licensed products

- ^{18}F -Fluoroglucose ZRP: Imaging of regional glucose consumption in cardiology, neurology and oncology
- ^{18}F -Fluorocholine ZRP: imaging of prostate or parathyroid cancer
- ^{18}F -Fluoroethyltyrosine ZRP: Imaging of amino acid metabolism in the diagnosis of brain tumors
- ^{18}F -Sodium fluoride ZRP: Imaging of bone to detect abnormally altered bone formation activity
- ^{18}F -Vizamyl: Imaging of the density of neuritic β -amyloid plaques in the brain of adult patients with cognitive impairment who are being evaluated for Alzheimer's disease

Non licensed

- ^{13}N -ammonia: Imaging of myocardial perfusion
- ^{15}O -Water: Imaging of regional brain perfusion
- ^{68}Ga -DOTATATE ZRP: Imaging of neuroendocrine tumors with somatostatin receptors
- ^{68}Ga -PSMA 11: Imaging of prostate cancer
- ^{18}F -PSMA 1007 ZRP: Imaging of prostate cancer

Table 26.3 *Typical Human Radiation Doses*

| <i>Source</i> | <i>Annual Dose (Sv)</i> |
|---|-------------------------|
| Cosmic rays | 4×10^{-4} |
| Cosmic rays (in high altitude airplane) | 7×10^{-6} Sv/h |
| Radioactive ores (external exposure) | 6×10^{-4} |
| Ingested materials (mainly potassium) | 2×10^{-4} |
| Inhalation of radon | 2×10^{-4} |
| Diagnostic x-rays | 7×10^{-4} |

A Sv is equivalent dose of 1 J/kg (see previous notes)

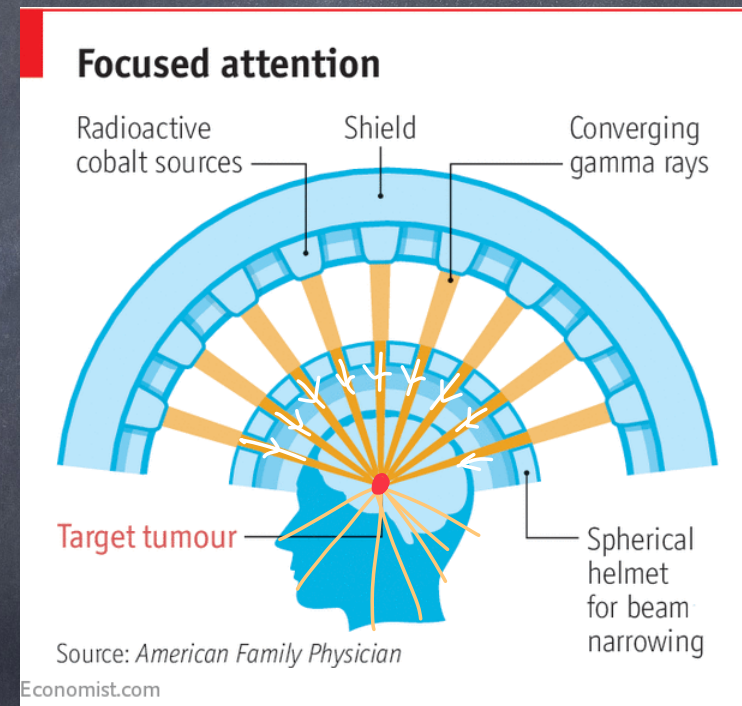
Dose in Sieverts : biological dose =
absorbed dose \times RBE Factor
[Gy]

Table 26.2 Relative Biological Effectiveness (RBE)
of Different Types of Radiation

| Type of Radiation | RBE |
|-------------------|-----|
| 200 KeV x-rays | 1 |
| γ | 1 |
| β | 1 |
| α | 20 |
| Neutrons (fast) | 10 |
| Protons | 10 |

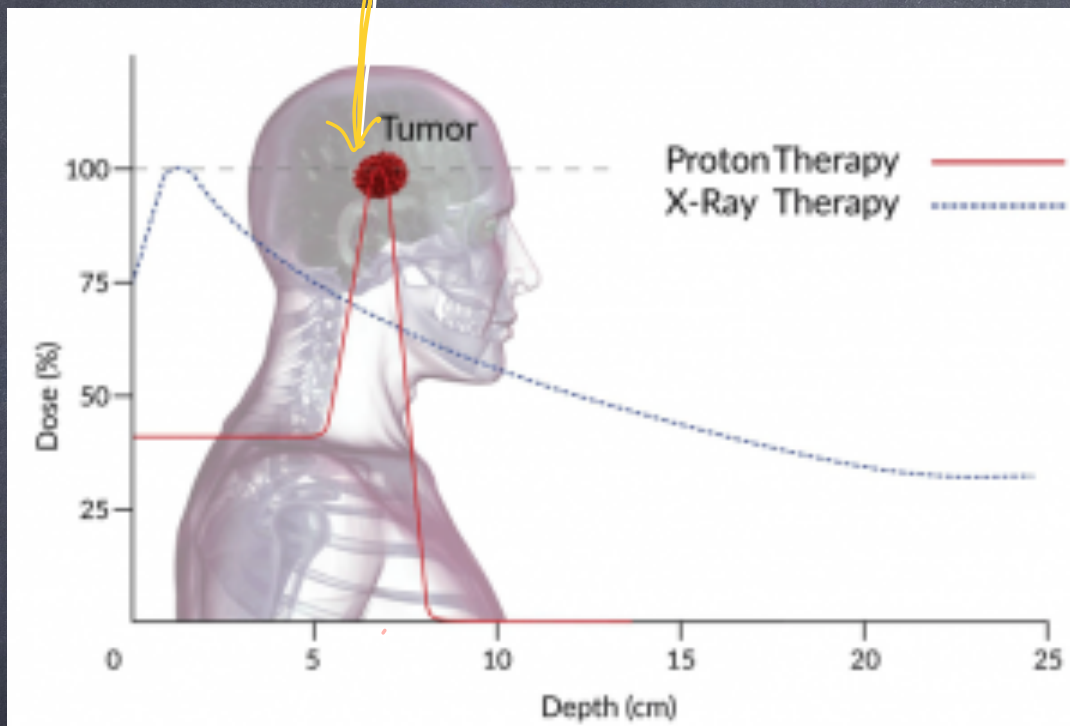
Dose depends on type of radiation.
 α : largest because it interacts so quickly
 p : also quite large

Gamma therapy radiation



By attacking tumor from many angles, the intersection gets more dose, while healthy tissue damage is minimized.

proton can target just the tumor, and
destroy less tissue before & after
the tumor

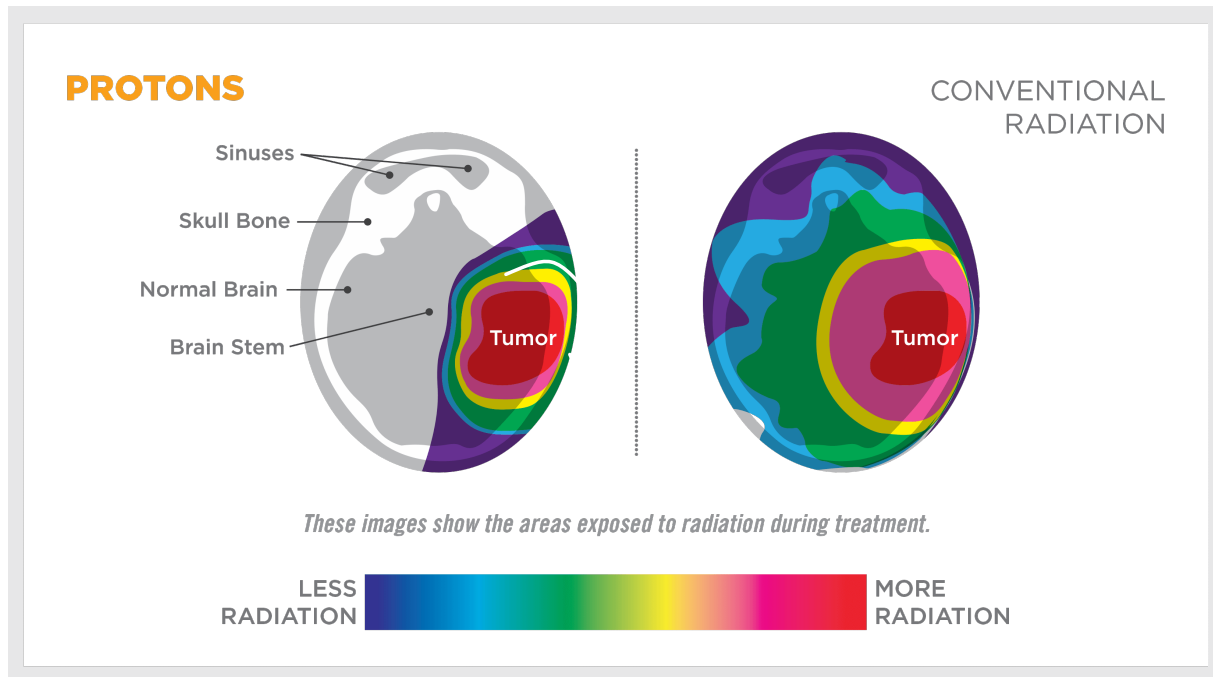


↑
Bragg peak tuned to a depth of 7 cm

Comparison

proton therapy

gamma therapy

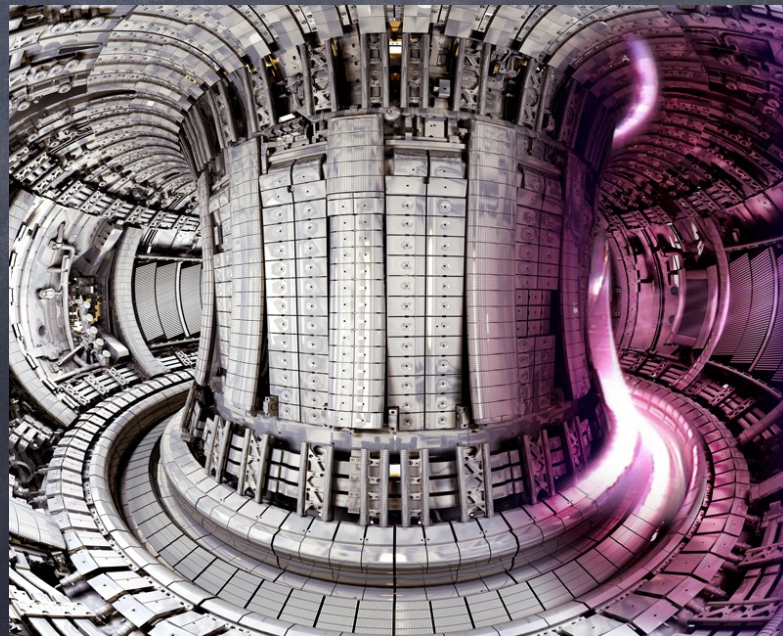
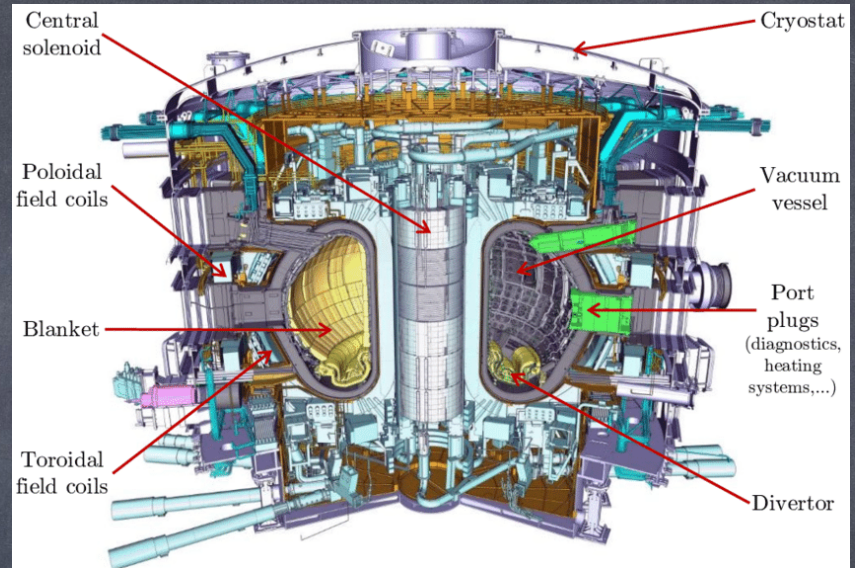
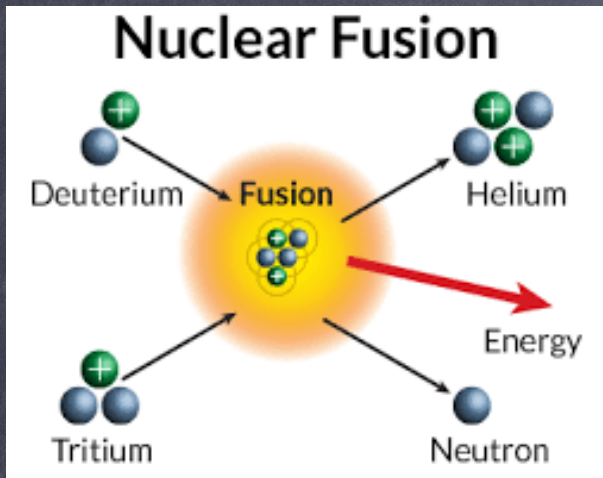


proton therapy facilities.



PSI:





ITER
(Fusion not possible yet)

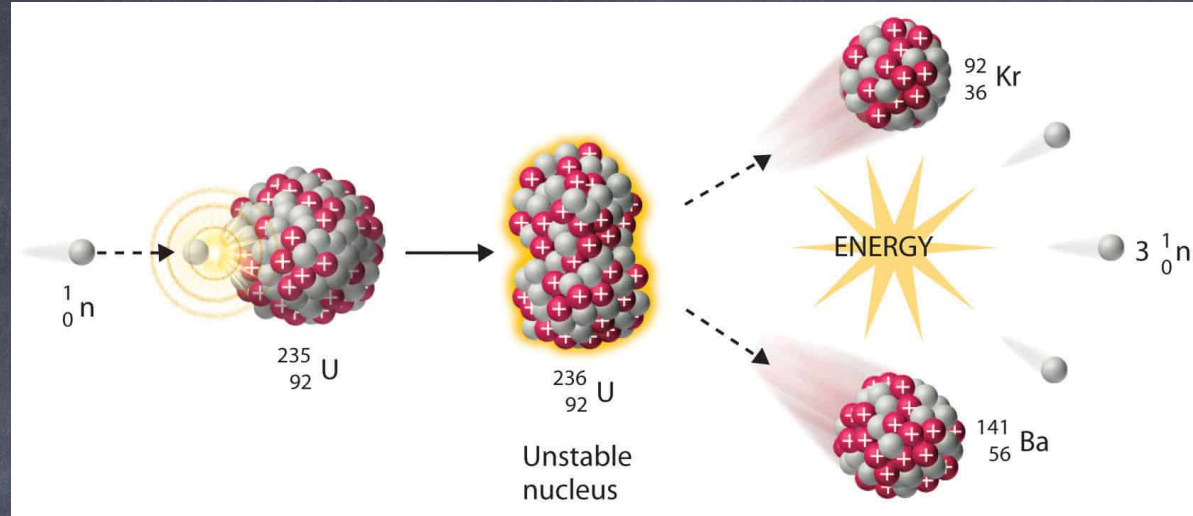
Recent progress:

The US [National Ignition Facility](#), which uses laser-driven [inertial confinement fusion](#), was designed with a goal of [break-even fusion](#); the first large-scale laser target experiments were performed in June 2009 and ignition experiments began in early 2011.^{[7][8]} On 13 December 2022, the [United States Department of Energy](#) announced that on 5 December 2022, they had successfully accomplished break-even fusion, "delivering 2.05 megajoules (MJ) of energy to the target, resulting in 3.15 MJ of fusion energy output."^[9]

Still a long time to go before commercial reactors possible, but this is a huge milestone.

nuclear fission

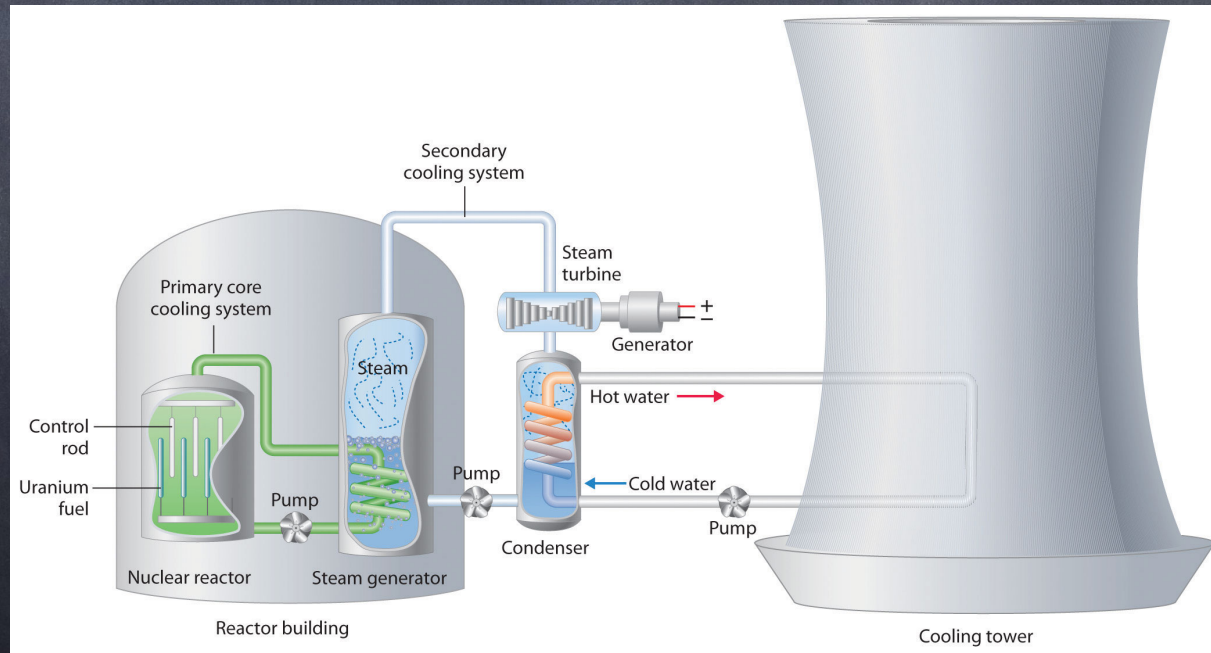
one neutron starts the reaction



3 neutrons are produced.

A chain reaction starts.

This gets hot!
(needs cooling)



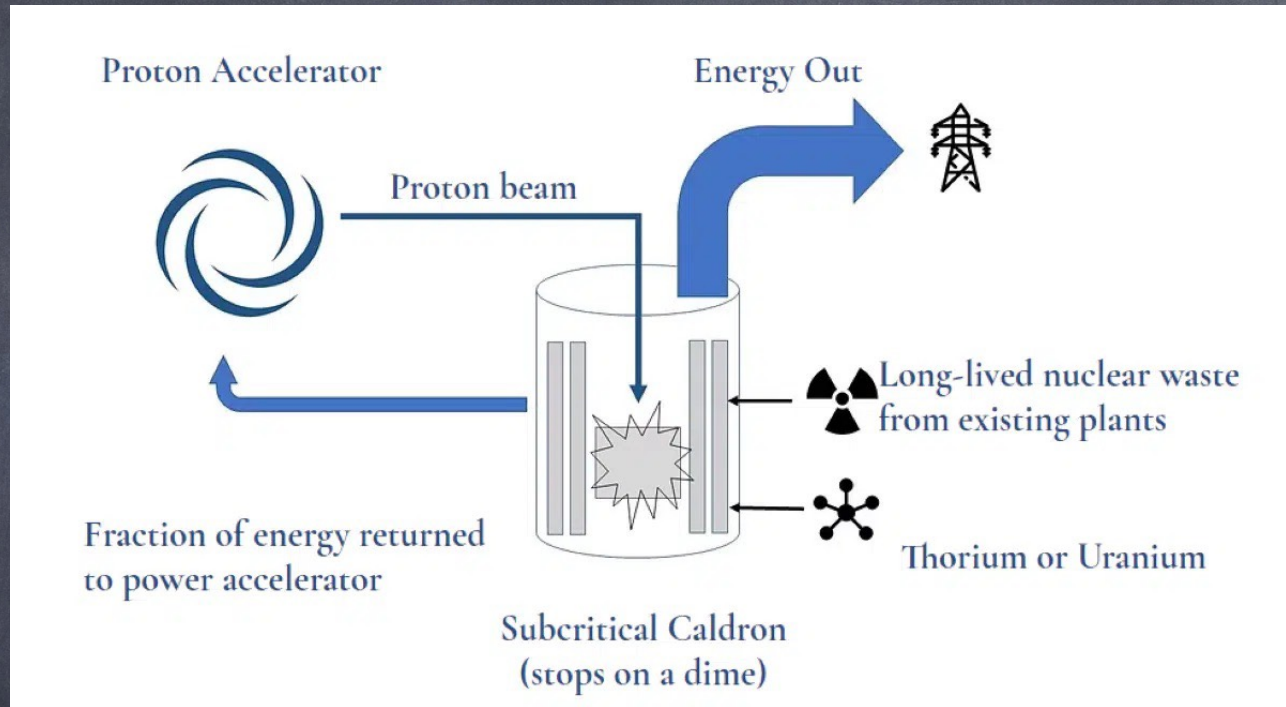
subcritical nuclear fission reactor
can use nuclear waste as a fuel (Thorium)

A screenshot of a search engine results page for the query "transmutex". The search bar at the top shows the query and a search icon. Below the search bar, there are navigation options for "All", "News", "Images", "Maps", "Videos", and "More". The results section shows "About 147 results (0.21 seconds)". The first result is from SwissInfo, titled "How a Swiss start-up wants to reinvent nuclear energy", with a sub-headline "Transmutex is developing a new type of nuclear reactor that burns thorium instead of uranium. These power plants would be able to produce..." and a date of "30 Jan 2022". The second result is from Innovation Origins, titled "A Swiss company are developing a nuclear reactor powered ...", with a sub-headline "Transmutex's solution is the transmuter – a nuclear system activated by a particle accelerator. With it, they want to create nuclear power using..." and a date of "14 Mar 2022". The third result is from Heidi.news, titled "Transmutex peut-elle ressusciter le nucléaire suisse?", with a sub-headline "Basé sur un accélérateur de particules et un matériau sous critique, le thorium, la technologie de Transmutex évite le risque de perte de..." and a date of "6 Dec 2021". The fourth result is from Le Temps, titled "L'émergence, à Genève, d'une énergie nucléaire presque ...", with a sub-headline "Une entreprise genevoise, Transmutex, veut créer une centrale qui ne génère presque pas de déchets radioactifs et au fonctionnement sûr." and a date of "23 Dec 2021".

The article header from swissinfo.ch features the logo and the text "Swiss perspectives in 10 languages". Below this, the title "How a Swiss start-up wants to reinvent nuclear energy" is displayed. A large, vibrant image of a nuclear fission reaction, showing a central yellow core with radiating purple and red energy waves, is the main visual. Below the image, a caption reads: "▲ Nuclear power generates about 10% of the electricity consumed in the world. Keystone / Gioscience / Science Photo Library".

No risk of meltdown because fission only happens when beam of particles is on.
Transmutex aims to produce a proof of concept in ~ 25 years.

principle of subcritical nuclear fusion reactor
proton beam keeps chain reaction going.



No risk of
"melt down"
(uncontrolled
reactions)

SAFE

- burns radioactive waste
- thorium is abundant

Need to support R&D for these safe
nuclear reactors since they will
take decades to develop.