PHY127 FS2026

Prof. Ben Kilminster
May 29th, 2026

Today: nuclear physics + some applications

- Try test exam (Actual exam may contain similar or different problems)
- Frau Brundler will arrange a special exercise session for last exercise sheet (potentially exam material)
- Formula sheet available for exam
- Exam June 26th, 10:00 - 12:00
- Lots of info today. Some material is marked as "Dive in deeper": won't be tested on exam.

Last time (Lecture 12):

$$\text{Nuclear binding energy} = Z(m_p c^2) + N(m_n c^2) - \underset{\substack{\uparrow \\ \text{mass of the nucleus.}}}{mc^2}$$

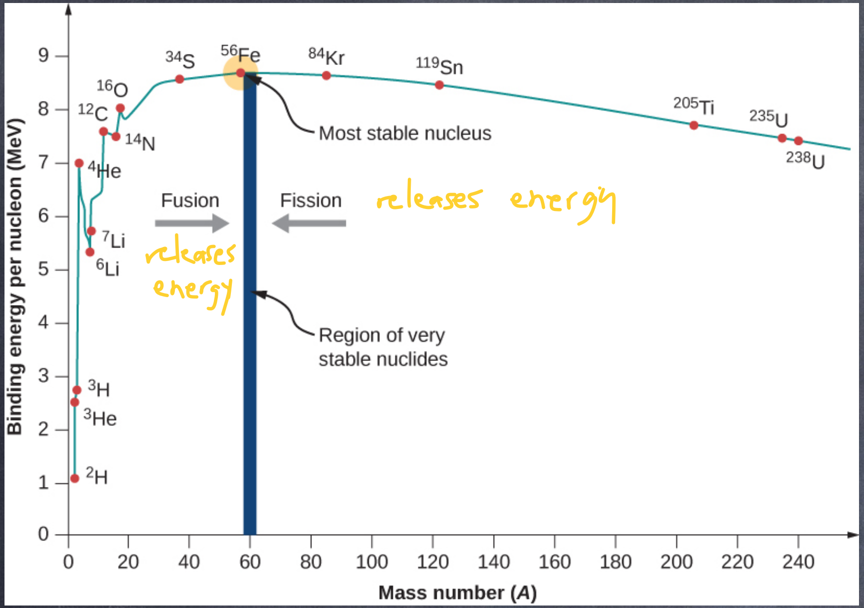
m_p : mass of proton
m_n : mass of neutron

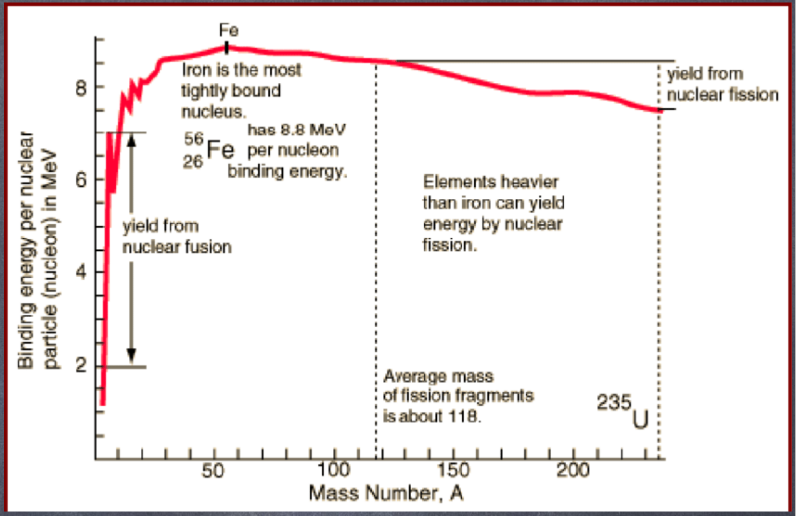
This binding energy is about 1% of the mass

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

Binding energy per nucleon as a function of A (A = Z+N)

Nucleons include all protons (Z) plus all neutrons (N)





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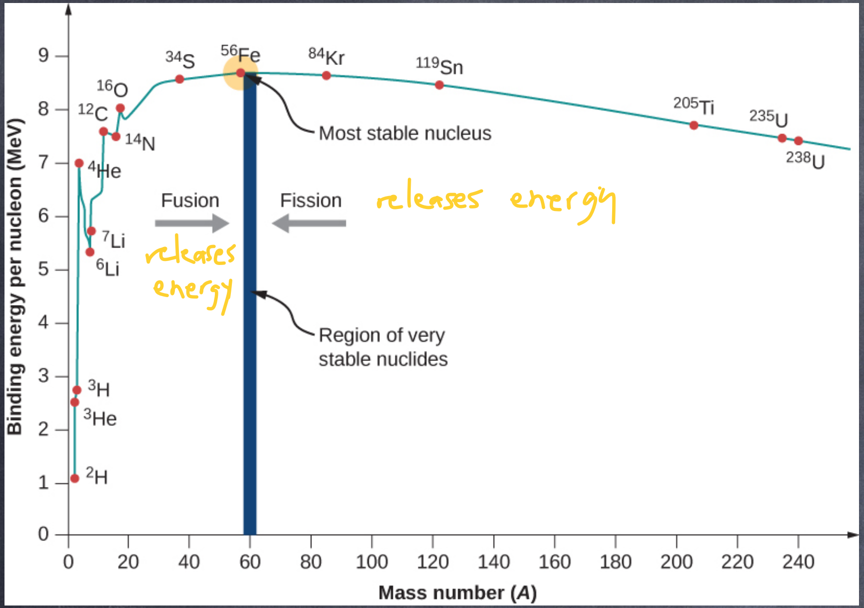

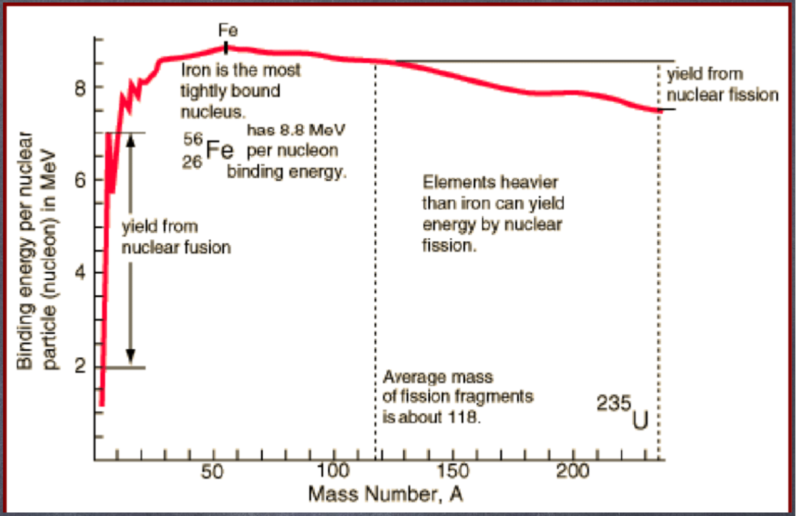

fusion from lighter elements to heavier elements
produces energy below Fe

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

Note: ^{4}He has a very high (relative) binding energy *

Previous slide:

1) Higher binding energy per nucleon = more stable nucleus
2) Iron is most stable nucleus
3) Very light or very heavy nuclei are less stable
4) Light elements combine to form heavier, more stable elements up to iron
    1) In this process they release energy
5) Heavy nuclei split into smaller ones
    1) In this process they release energy

6) Both 4&5 move nuclei towards higher binding energy per nucleon, towards stability

A reaction will release energy if binding energy increases

Examples! Which way?

$^{12}C + {}^{12}C \overset{?}{\leftrightarrow} {}^{24}Mg$

$^{235}U \overset{?}{\leftrightarrow} {}^{141}Ba + {}^{92}Kr + 3n$

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Nucleus	Binding energy per nucleon (MeV)	Total binding energy (MeV)
^{12}C	7.68	92.2
^{24}Mg	8.26	198.3
^{235}U	7.6	1786
^{141}Ba	8.3	1171
^{92}Kr	8.5	782
3 neutrons	0	0

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[MeV]

To figure it out, we can look at change in binding energy

$^{12}C + ^{12}C \overset{?}{\leftrightarrow} {}^{24}Mg$

$2 \cdot 92.2 = 184.4$ MeV $<$ 198.3 MeV

Reaction proceeds:

$^{12}C + ^{12}C \rightarrow {}^{24}Mg + 13.9$ MeV

$^{235}U \leftrightarrow {}^{141}Ba + {}^{92}Kr + 3n$

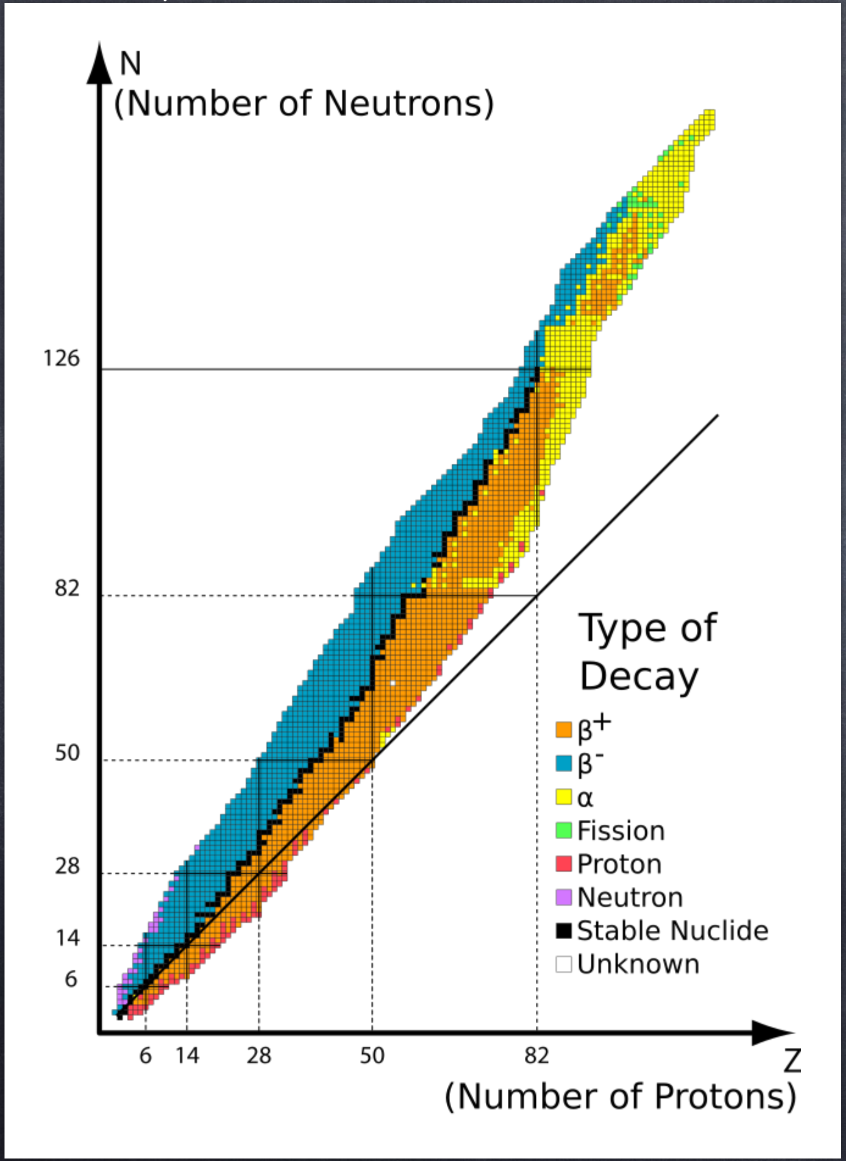
1786 MeV $<$ $1171 + 782 + 0 =$ 1953 MeV

Reaction proceeds:

$^{235}U \rightarrow {}^{141}Ba + {}^{92}Kr + 3n + 167$ MeV

Stability of nuclei with different Z and N

$(A = Z + N)$



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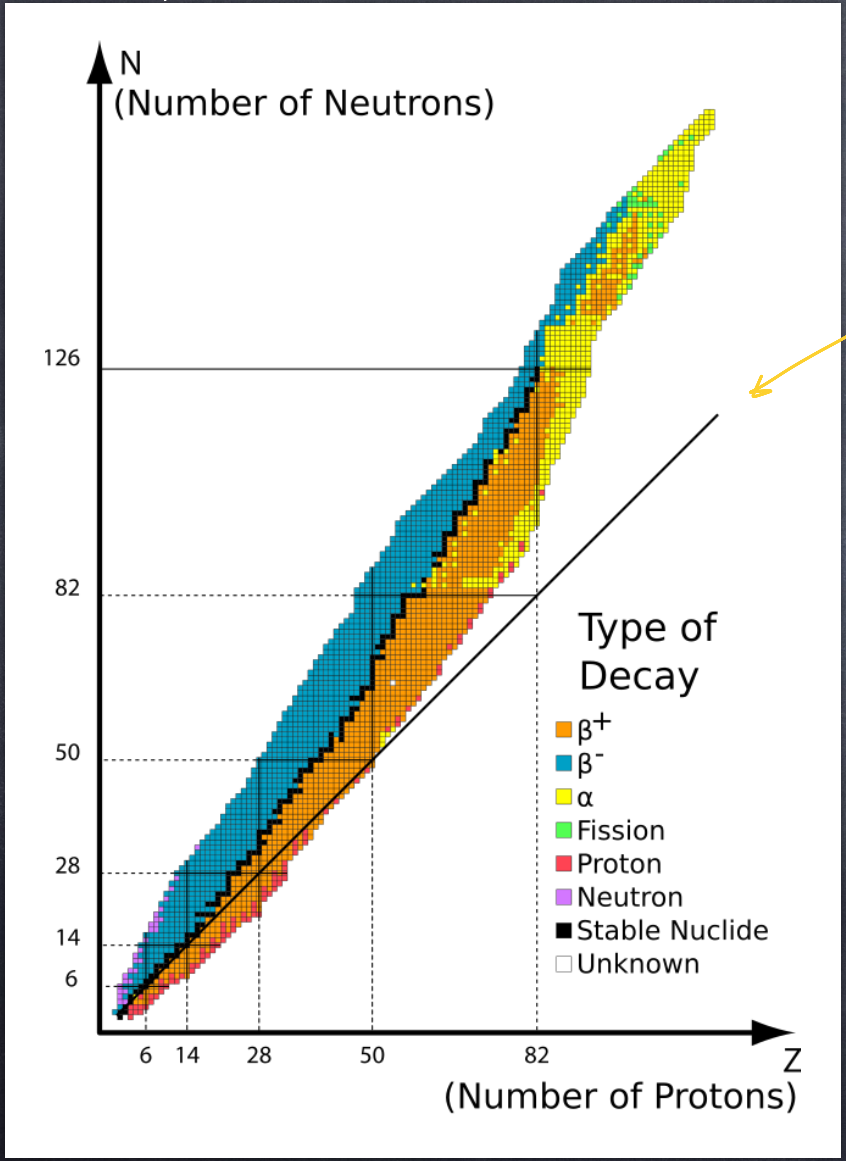
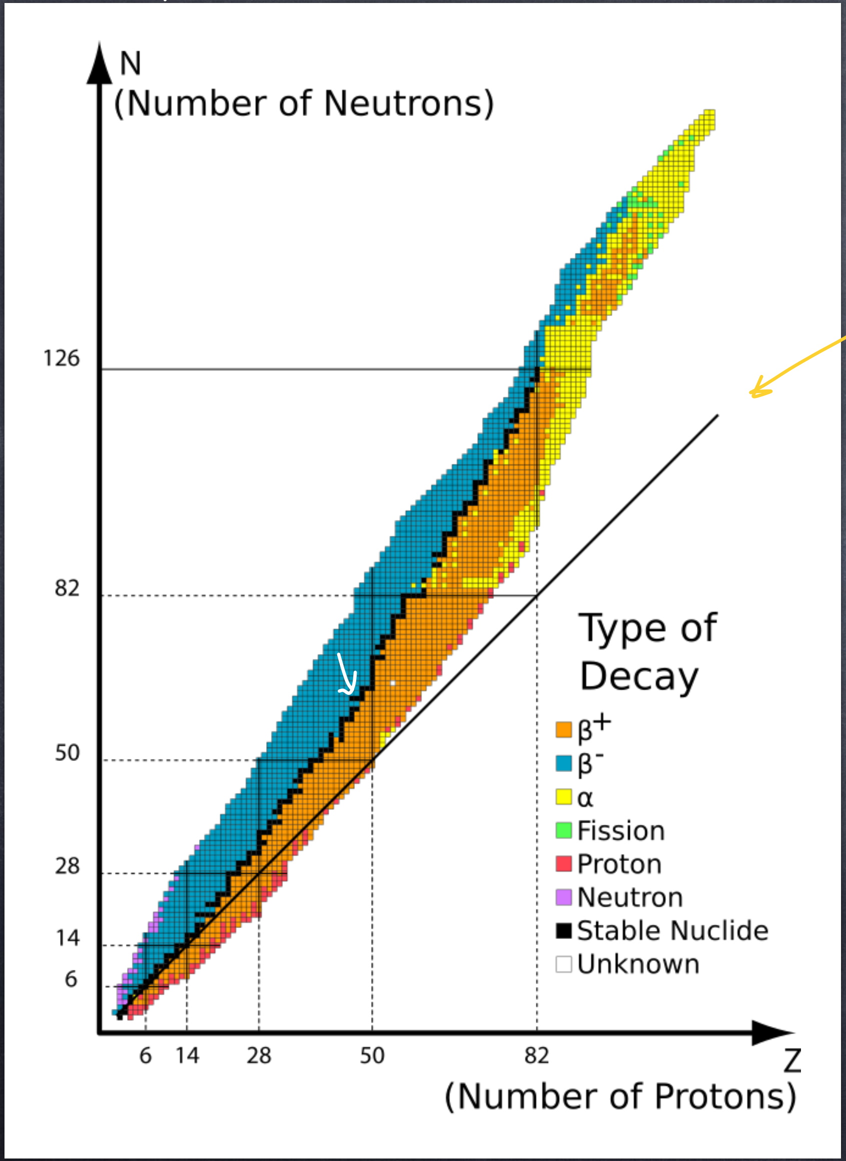


Colors represent how unstable nuclei decay
→ we will go through these

Line of $Z=N$

Stability of nuclei with different Z and N



Colors represent how unstable nuclei decay
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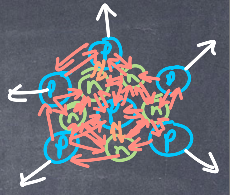
Line of Z=N

Black points are stable nuclides.

Note: slightly more stable when N>Z

Where does stability of nuclei come from?



Pauli exclusion principle: Spin-$\frac{1}{2}$ particles cannot occupy same state.

Nucleus has protons + neutrons with spin $\frac{1}{2}$ (like electrons in atomic shells)

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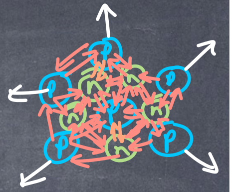

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As we add protons + neutrons to a nucleus, they occupy higher energy levels. But protons + neutrons do this separately.

Consider: 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)

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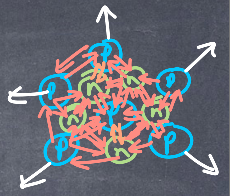

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Example:

a) $Z=8, N=0$

b) $Z=4, N=4$

a)

b)

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 → "closed shells"

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

(Applies to both protons & neutrons separately)

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+ be more stable.

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Also true for nuclei with "magic" numbers of nucleons: 2, 8, 20, 28, ...
(Applies to both protons + neutrons separately)

For instance, $^{4}_{2}\mathrm{He}$ ($Z=2$, $N=2$) is "doubly magic" → extremely stable
Helium

(see binding energy on p.3)

What happens if unstable?

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

1) α radiation: stopped by a few pieces of paper
2) β radiation: stopped by a few pieces of aluminum foil
3) γ radiation: can penetrate several cm of lead or a concrete wall.

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Later, it was found that

α : ${}^{4}_{2}\mathrm{He}$ nucleus

β : high-energy electron

γ : high-energy photon.

Energy released in a decay is called Q or "Q-value"

$$Q = \left(\underset{\text{mass of nucleus}}{M} - \underset{\text{sum of masses of } Z + N}{\sum m_i} \right) c^2$$

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For a radioactive decay to happen naturally (without stimulation) Q must be > 0. (natural radioactivity)

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

ϵ: parent nucleus

ϵ': daughter nucleus

1) α decay: $${}^{A}_{Z}E \rightarrow {}^{A-4}_{Z-2}E' + {}^{4}_{2}He$$

How much
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$$\begin{cases} Q = (M_E - M_{E'} - M_{He})\,c^2 \\ \text{when } Q>0,\ \text{kinetic energy mostly given to lighter particle } {}^{4}_{2}He \text{ because of momentum conservation.} \end{cases}$$

(Example: ${}^{238}U \rightarrow {}^{234}Th + \alpha \rightarrow Q \approx 4.27$ MeV
$K_\alpha \approx 4.2$ MeV (98%)
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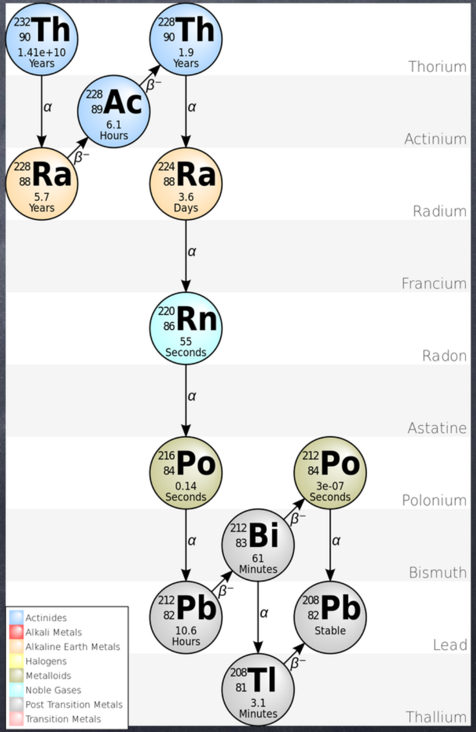
Note: Once α particle is produced, it interacts very strongly with matter because $Z=2$ so $q={+2e}$
(feels stronger Coulomb force, $F = \frac{kq_1q_2}{r^2}$)

Sometimes there are a succession of decays

$$\epsilon \to \epsilon' \to \epsilon'' \to \cdots$$

Often, if $\epsilon \to \epsilon'$ is α decay, other decays are also α

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



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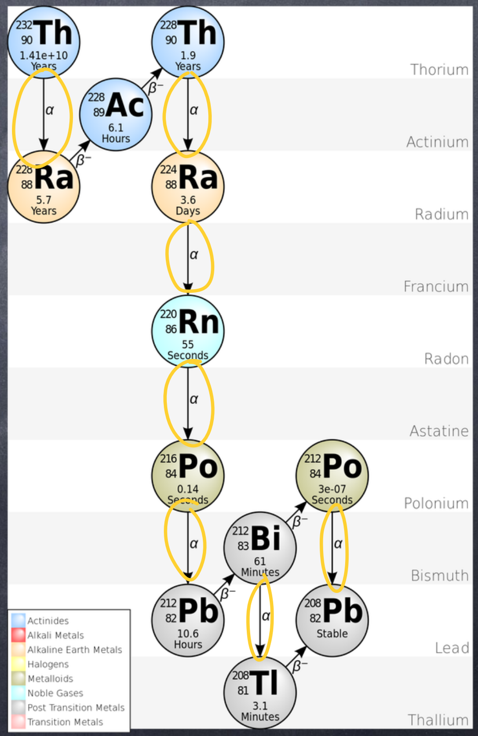
For instance, $^{232}_{90}\mathrm{Th}$. $(A = 232 = 4 \cdot 58)$

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



2) Beta decay: β

$$ {}^{A}_{Z}E \rightarrow {}^{A}_{Z+1}E' + e^{-} + \overline{\nu}_e $$

anti-neutrino

"—" means anti-particle

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anti-neutrino

Note: we start with Z protons and N neutrons and end with Z+1 protons and N-1 neutrons.

$\Longrightarrow$ A neutron is being converted into a proton.

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

This is happening because of the <u>weak nuclear force</u>.

Dive in deeper: what is a neutrino? Typically it is ignored...

Symbol : ν (nu)

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

A lead tube one lightyear long (9 trillion km 9E12 km) would only stop ½ of neutrinos.

wow!

(* we don't know if neutrinos are their own anti-particles. $\nu \stackrel{?}{=} \bar{\nu}$)

Dive in deeper :

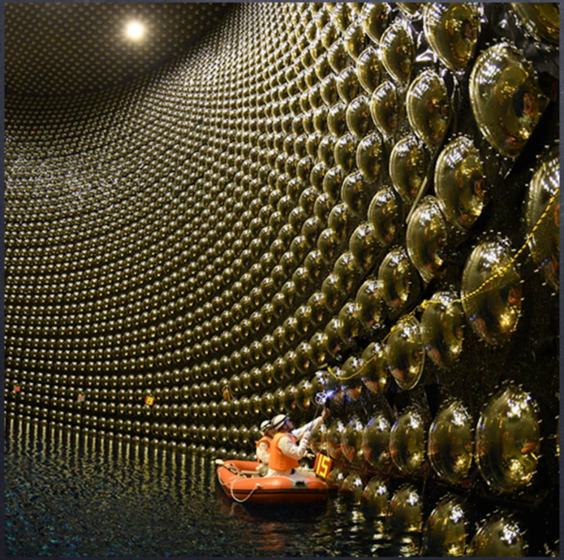
Sources of neutrinos :

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

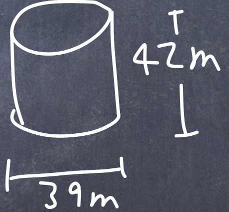
10^{11} neutrinos from the sun travel through each of your fingernails each second.

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!

Dive in deeper:

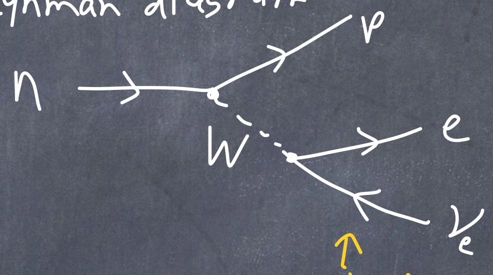
weak nuclear force

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

How does a neutron → proton?

(particle physics deals with this)

Feynman diagram



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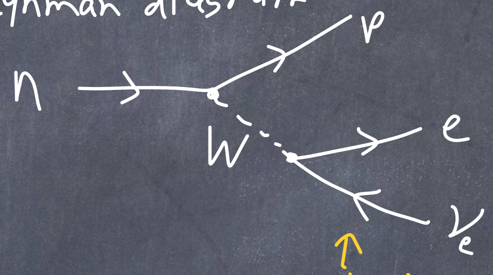

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The "W boson" is a massive particle.

W mass ≅ 85 · neutron mass

(W cannot be real, it is "virtual".
It exists momentarily according to uncertainty principle)

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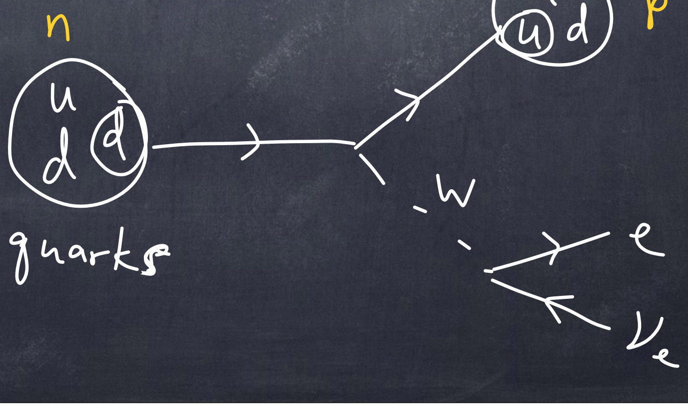
what is really happening is at the quark level.

Fundamental interaction

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



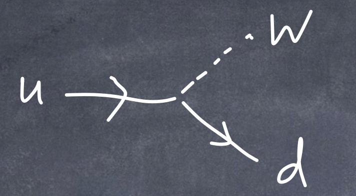
Dive in deeper: relevant W interactions (affect matter)

remember

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

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

p → n



$u \to d + W^+$

$+\frac{2}{3} \to -\frac{1}{3} \quad +1$

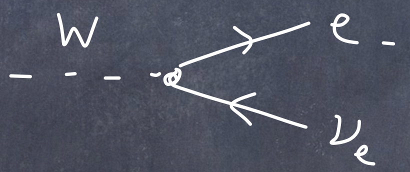
make a W

n → p

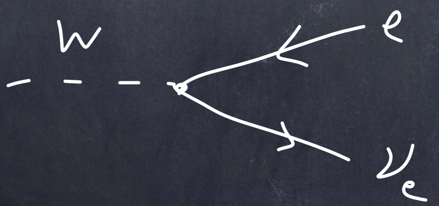
$d \to u + W^-$

$-\frac{1}{3} \to +\frac{2}{3} \quad -1$

produces e^- or e^+



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



$W^+ \to e^+ + \nu_e$

W produced above is virtual and must decay to particles lighter than the initial state

(W cannot be real, it is "virtual". It exists momentarily according to uncertainty principle)

Dive in deeper :

A proton is very stable. Super-K has set limits ($\tau_p > 10^{34}$ years)

So $p \to n + e^+ + \nu_e$ can only happen inside a nucleus when energetically favorable.

But Free neutrons decay into a proton $+ e^+ + \nu_e$ in ~15 minutes

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Note: Neutrinos were hypothesized because it was experimentally found that $n \to p + e^-$ doesn't conserve energy (so we need a neutrino also)

Some other weak nuclear decays:

$$\left.\begin{array}{ll} \text{positron emission} & {}^{A}_{Z}E \to {}^{A}_{Z-1}E' + e^+ + \nu \\ \\ \text{electron capture} & {}^{A}_{Z}E + e^- \to {}^{A}_{Z-1}E' + \nu \end{array}\right\} \; p \to n$$

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 ~ MeV)

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

γ process happens when a nuclei is decays from an excited state following a α or β decay

"m": excited state

$${}^{Am}_{Z}E \rightarrow {}^{A}_{Z}E' + {}^{0}_{0}\gamma$$

or also written $${}^{A*}_{Z}E \rightarrow {}^{A}_{Z}E' + {}^{0}_{0}\gamma$$

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

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

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

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

(–) means N is decreasing

$$\tau_{1/2} = t_{1/2} = t = \frac{\ln(2)}{\lambda} = \frac{0.693}{\lambda}$$

Dive in deeper:

Derivation of exponential decay formula

Decay 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:

$$\boxed{\Delta N = -\lambda N \Delta t}$$ ①

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

The solution to this formula is solved with calculus:

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

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^{constant} = another constant, then $\Rightarrow \boxed{N = Ce^{-\lambda t}}$

Dive in deeper:

Derivation of half-life formula

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

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?

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

(what is t)

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

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

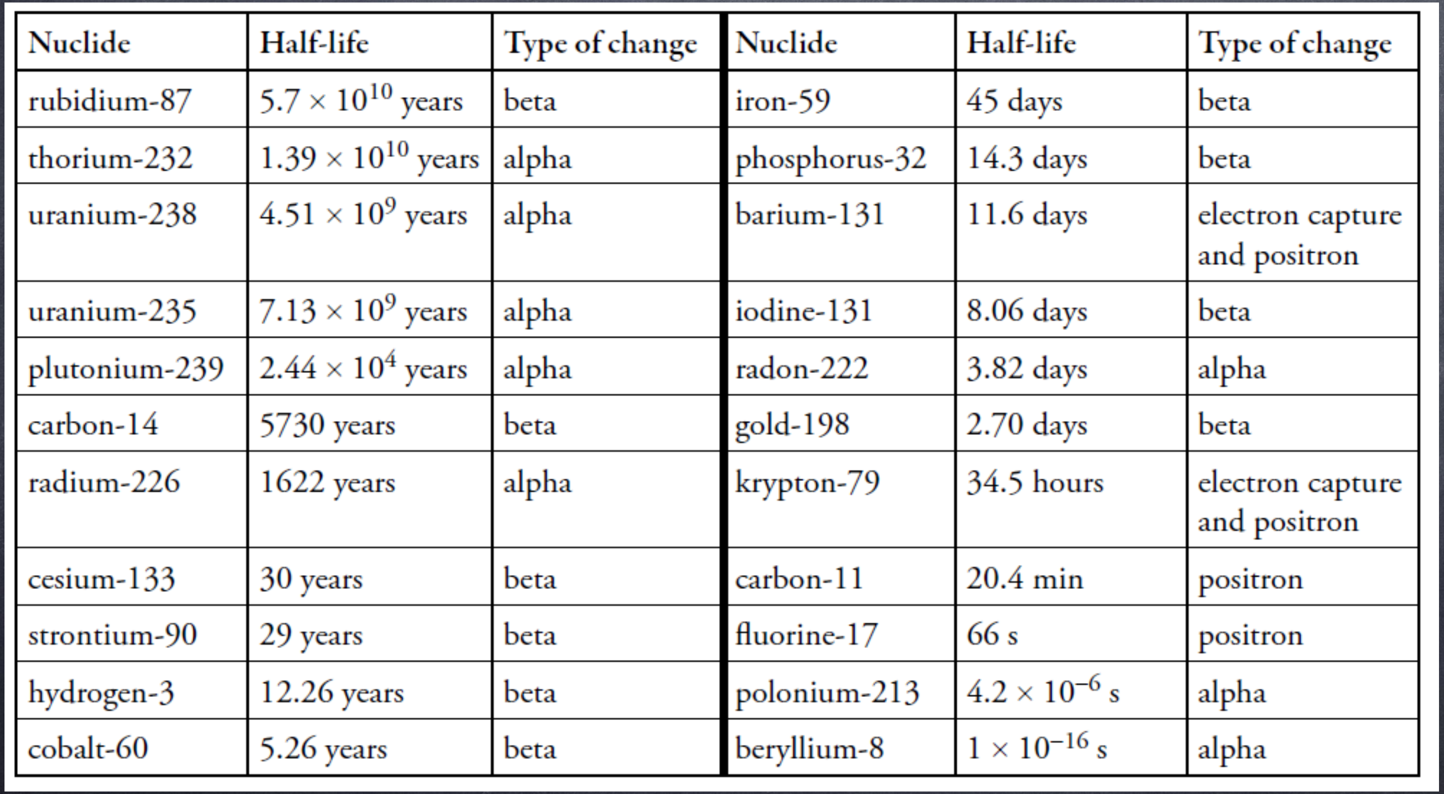
$$\tau_{1/2} = t_{1/2} = t = \frac{\ln(2)}{\lambda} = \frac{0.693}{\lambda}$$

half-life from decay constant

one half life : $N_0 \rightarrow N_0/2$

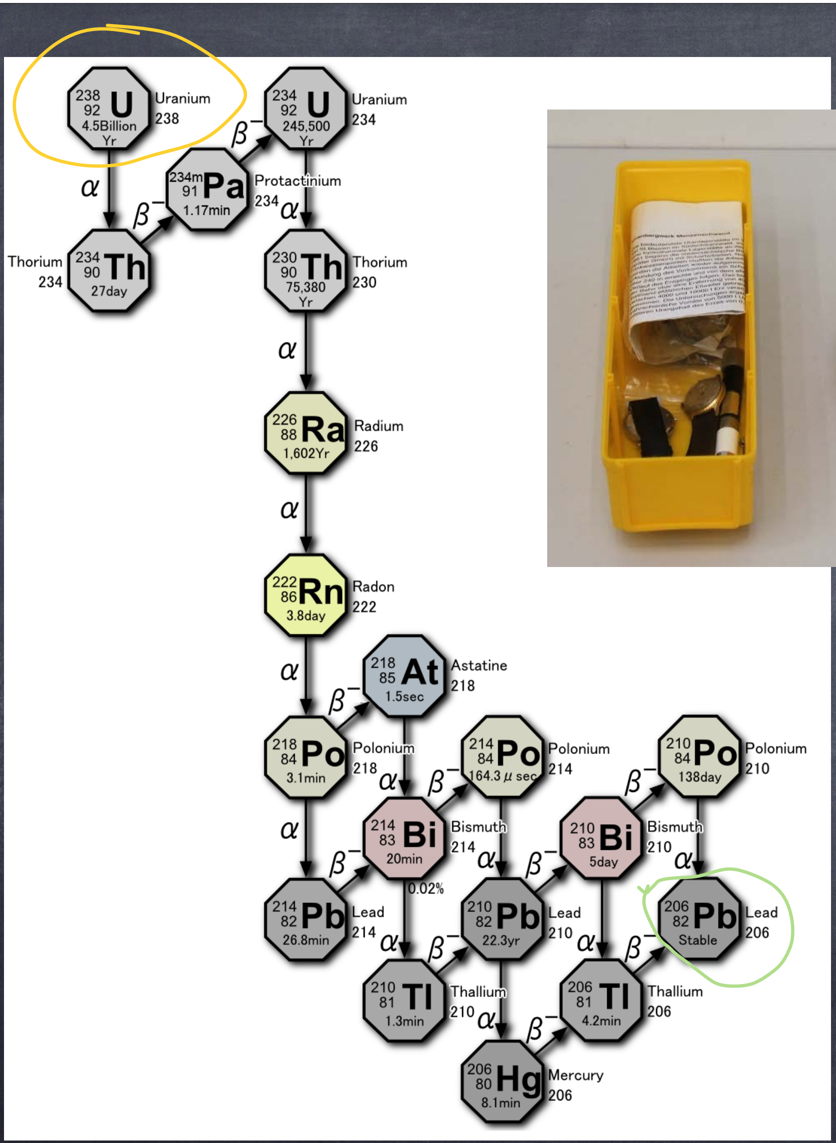
two half-lives : $N_0 \rightarrow N_0/4$

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

Examples of decays - experiments

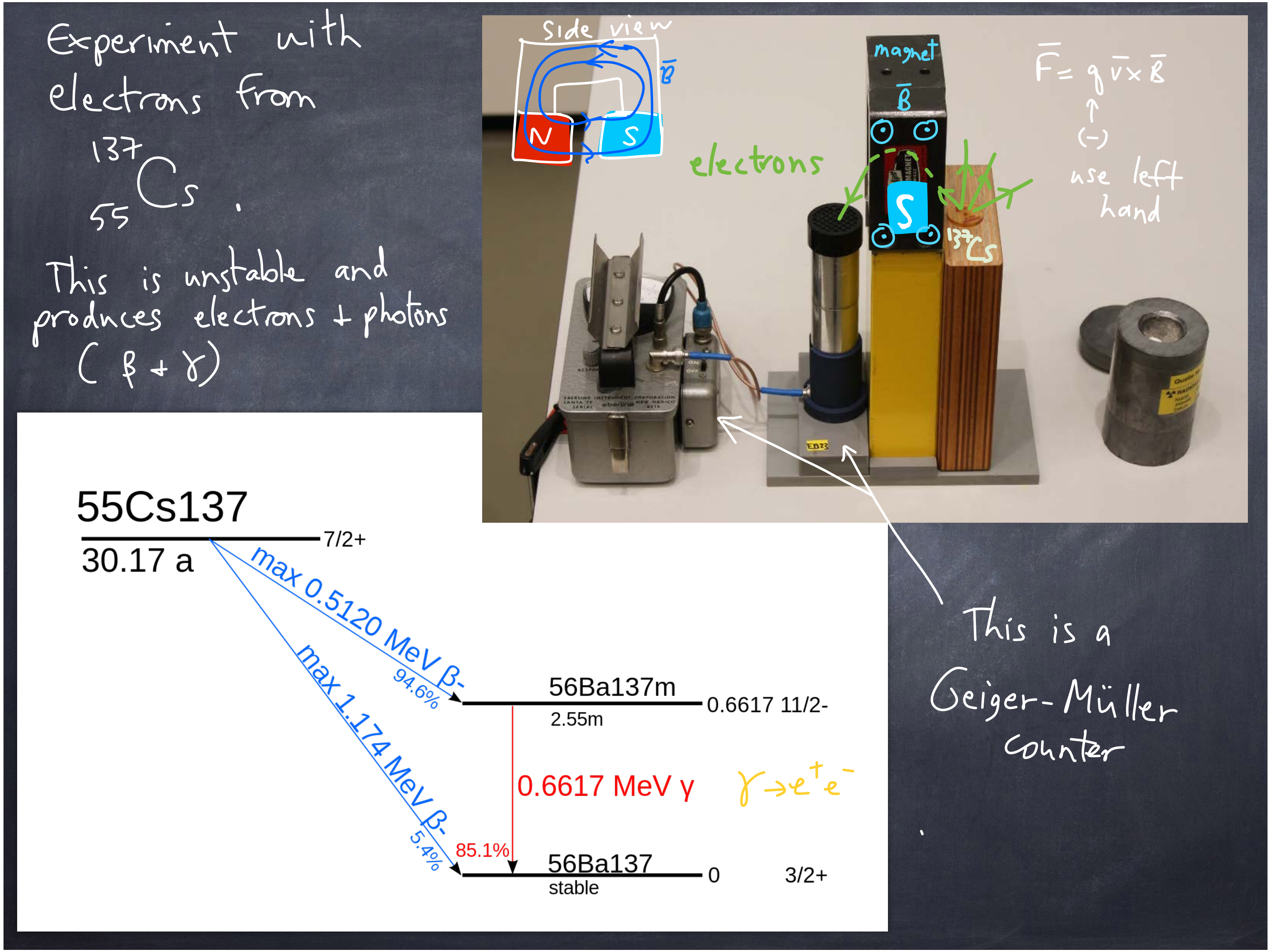


Experiment with uranium ore and radium.
These decay producing $\alpha + \beta$ radiation.

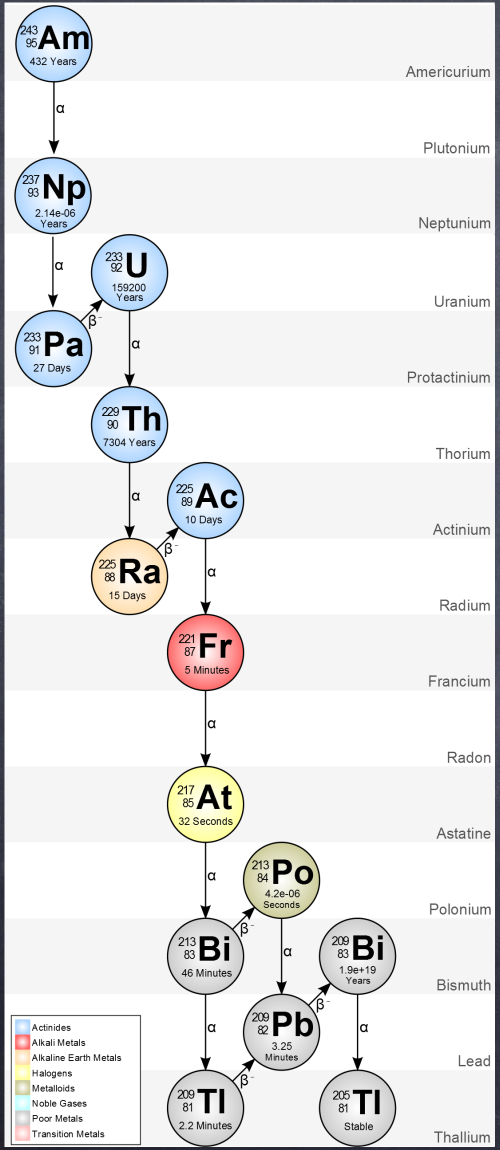
← ^{206}Pb is finally stable

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

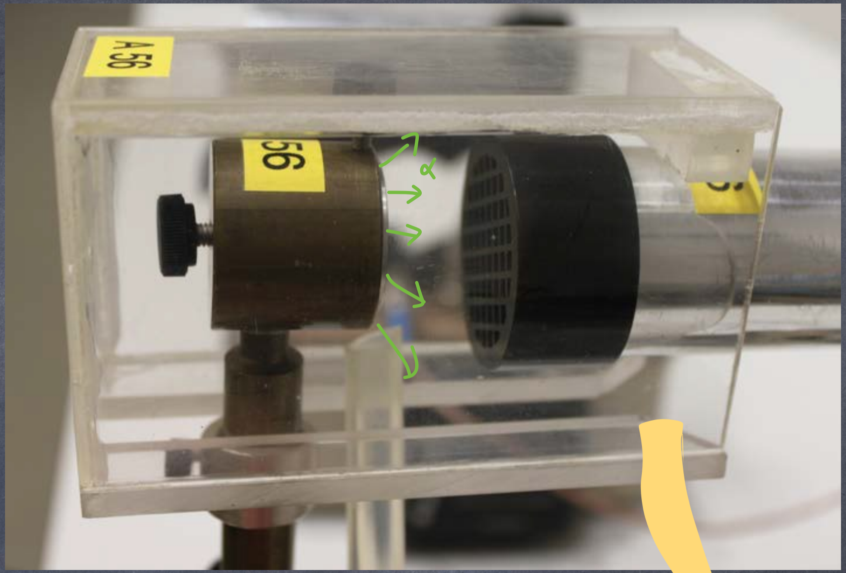
This is unstable and produces electrons + photons (β + γ)



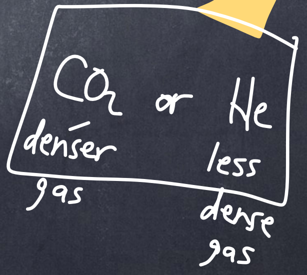
This is a Geiger-Müller counter



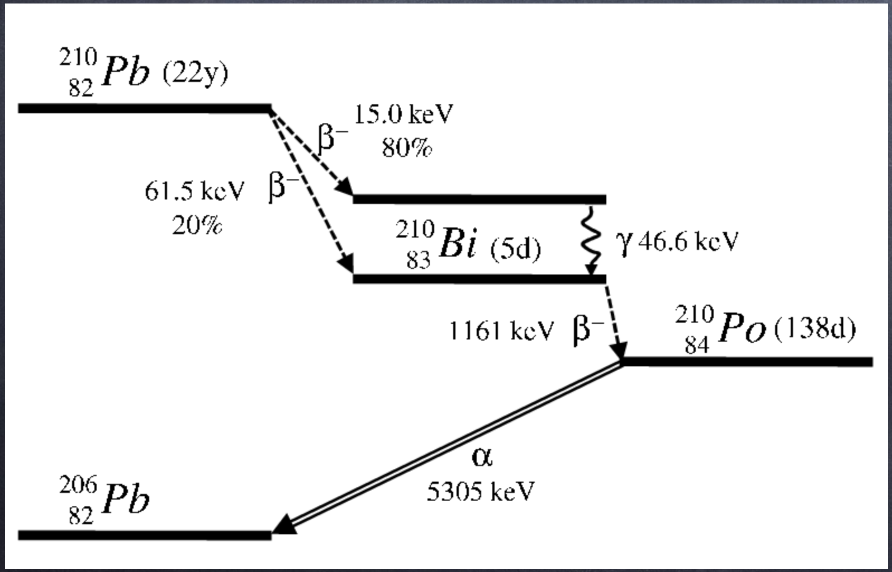
2.14e+6 years

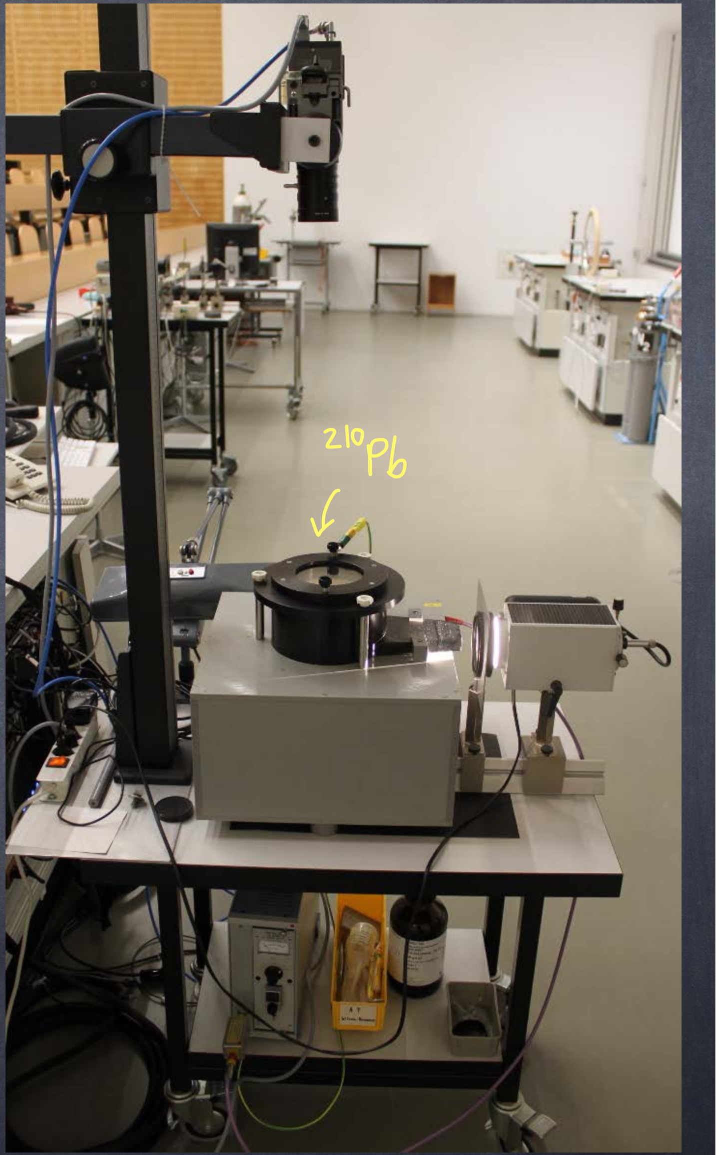


Experiment with ^{243}Am

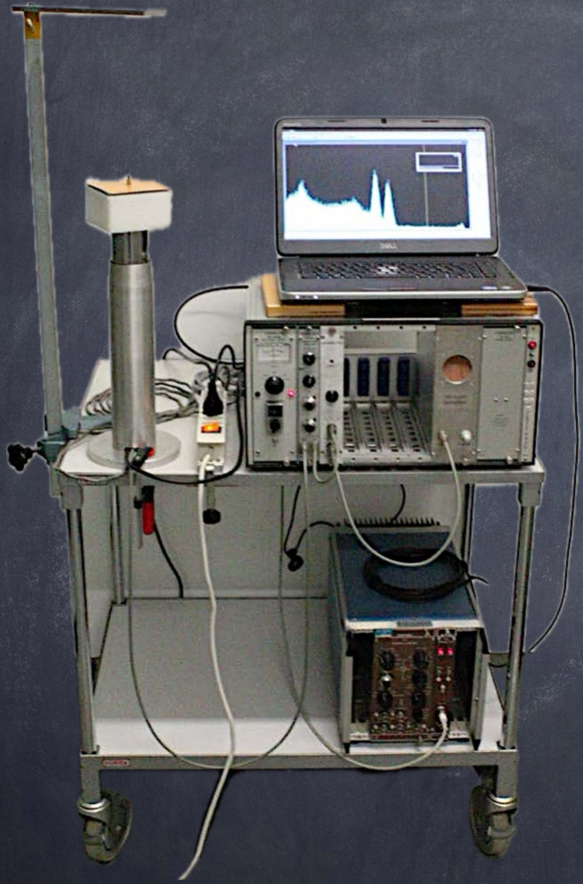


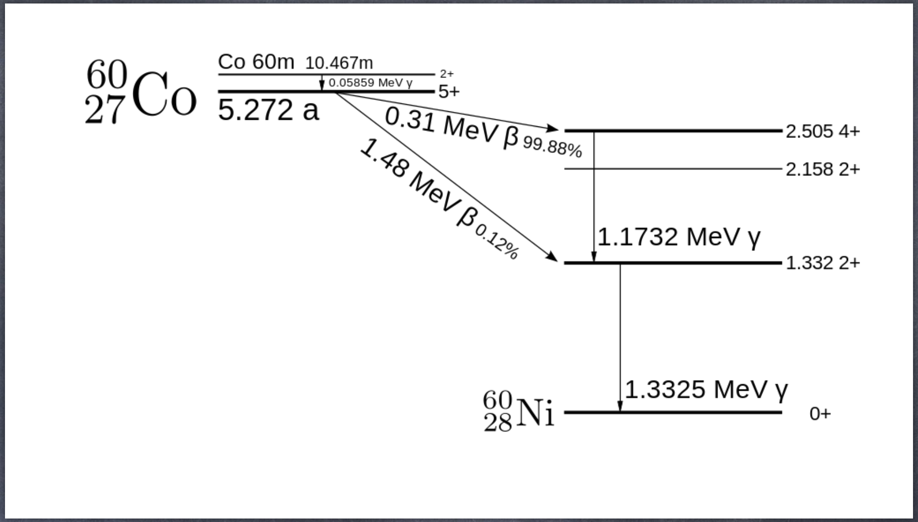
Experiment : cloud chamber showing ^{210}Pb decaying





Gamma radiator from Cobalt-60 source





we observe the gamma spectrum

The quantity $\frac{\Delta N}{\Delta t}$ is known as the activity level

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

Becquerel

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

or $[\text{Curie}] = [Ci]$ $1\ Ci = 3.7e10\ Bq$

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

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

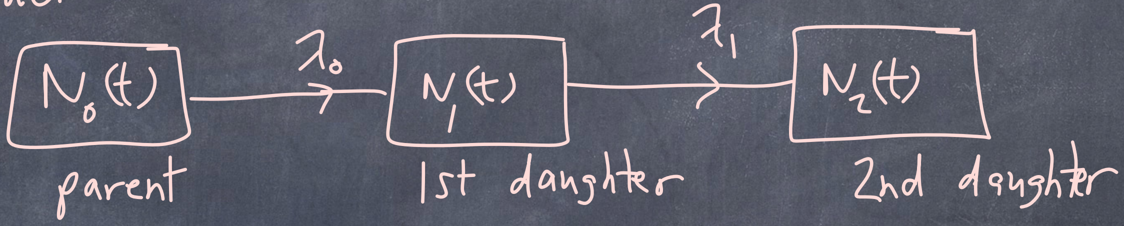
Geological dating uses ^{238}U

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

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

Dive in deeper: Some isotopes can reach equilibrium levels if they are produced by a long-lived parent and then decay themself.

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

$$\boxed{\Delta N_1(t) = \left[N_0(t)\lambda_0 - N_1(t)\lambda_1\right]\Delta t}$$ 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

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

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 $\boxed{\frac{N_1}{N_0} = \frac{\lambda_0}{\lambda_1}}$ when $\lambda_1 << \lambda_0$

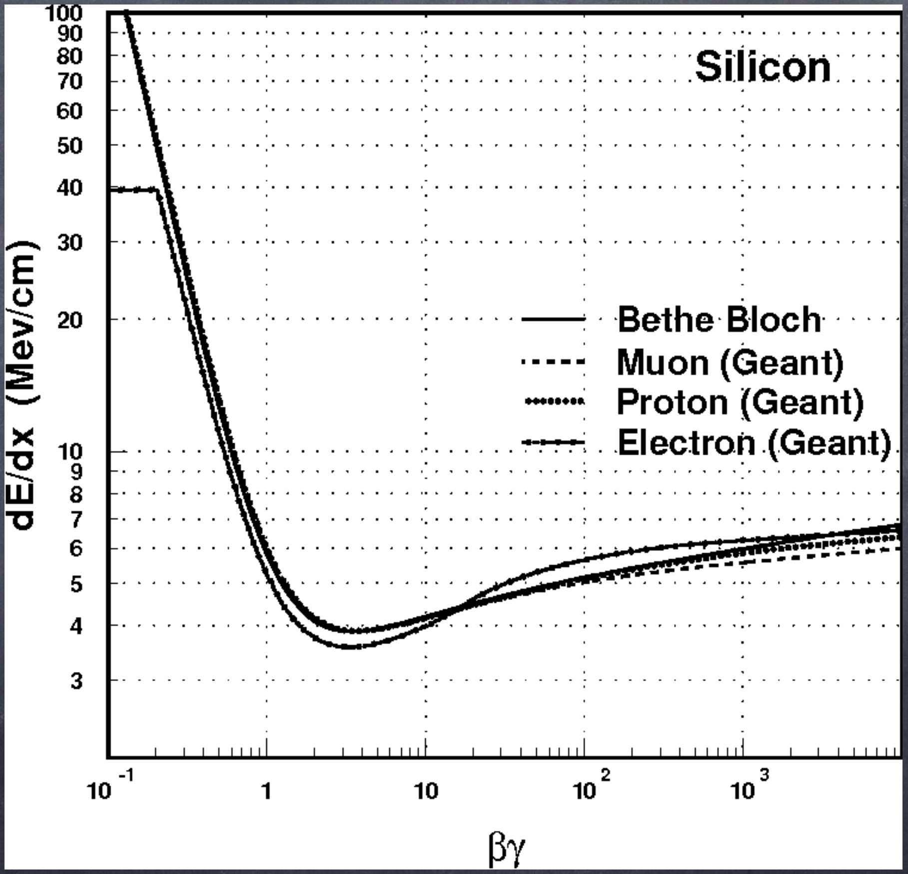
→ The number N_1 then is ~ constant and related to $\lambda_0, \lambda_1,$ & N_0, (for cases when $\lambda_1 << \lambda_0$)

Dive in
deeper :

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

Bethe - Bloch Function

The Bethe-Bloch Function describes this interaction



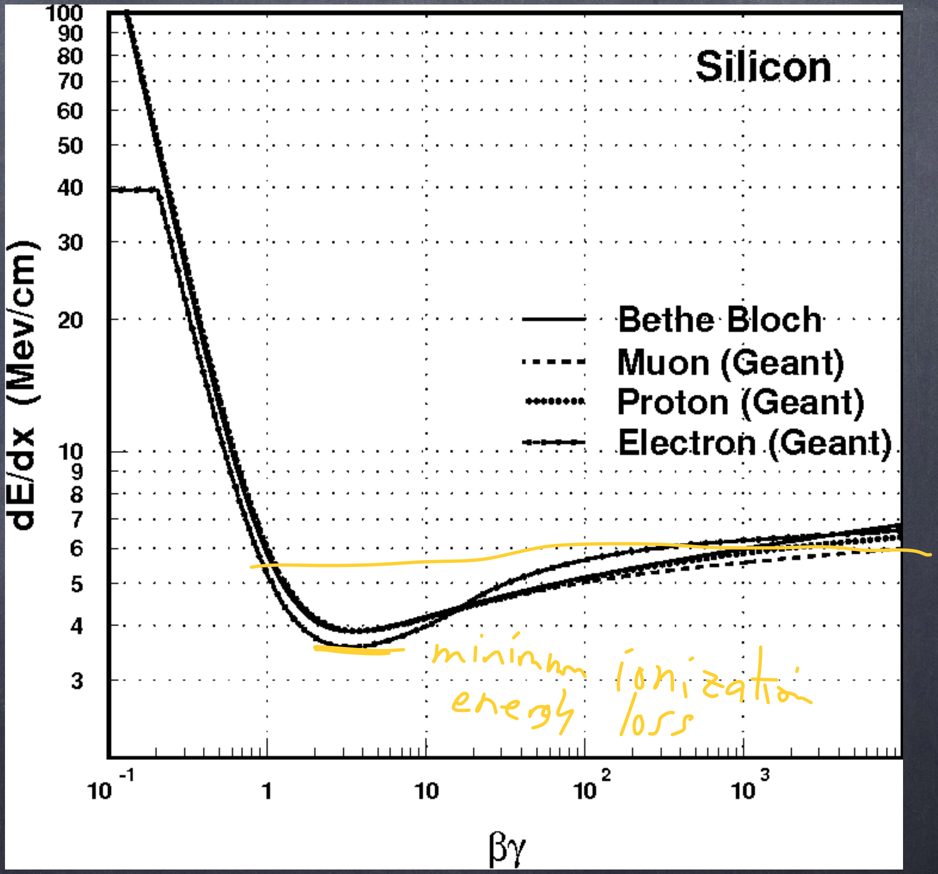
Geant: simulation program

↑ related to velocity

$\beta = \frac{v}{c}$

$\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$

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



minimum ionization energy loss

$\beta = \frac{v}{c}$ 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 $\text{MeV}/_{\text{g}/\text{cm}^2} = \text{MeV}\cdot\text{g}^{-1}\cdot\text{cm}^2$

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.

Bethe-Bloch equation

Considering quantum mechanical effects:

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

density

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

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

[Max. energy transfer in single collision]

z : Charge of incident particle
M : Mass of incident particle

Z : Charge number of medium
A : Atomic mass of medium

I : Mean excitation energy of medium
δ : Density correction [transv. extension of electric field]

$N_A = 6.022 \cdot 10^{23}$
[Avogardo's number]

$r_e = e^2/4\pi\varepsilon_0 m_e c^2 = 2.8$ fm
[Classical electron radius]

$m_e = 511$ keV
[Electron mass]

$\beta = v/c$
[Velocity]

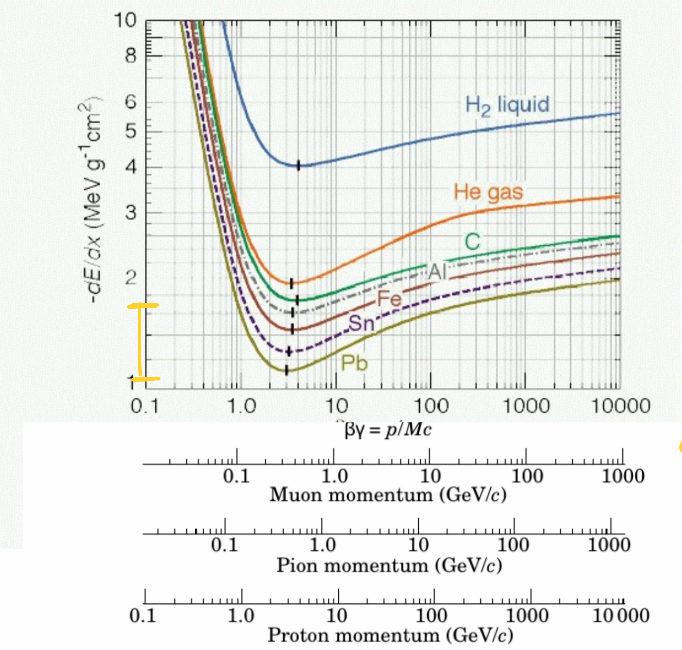
$\gamma = (1-\beta^2)^{-2}$
[Lorentz factor]

Validity:

$.05 < \beta\gamma < 500$
$M > m_\mu$

dE/dx_{min} different materials

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



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

dE/dX depends on A, Z of target material

βγ≅ 3.5 broad minimum
→ minimum ionising particles (MIP)

H_2 Z/A≅ 1 dE/dX_{min} ≅ 4 MeV /(g/cm^2)
others Z/A≅ 0.5 dE/dX_{min} ≅ 2 MeV /(g/cm^2)

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

key point

Katharina Müller, Autumn 14

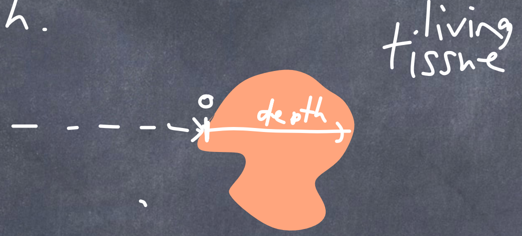
Key point:

There is a roughly constant energy deposit as energetic charged particle traverse matter of $1-1.7$ MeV/(g/cm^2)

(Multiply by density in $\frac{g}{cm^3}$ to get dE/dx)

This is applicable for a variety of particles with a variety of energies.

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.

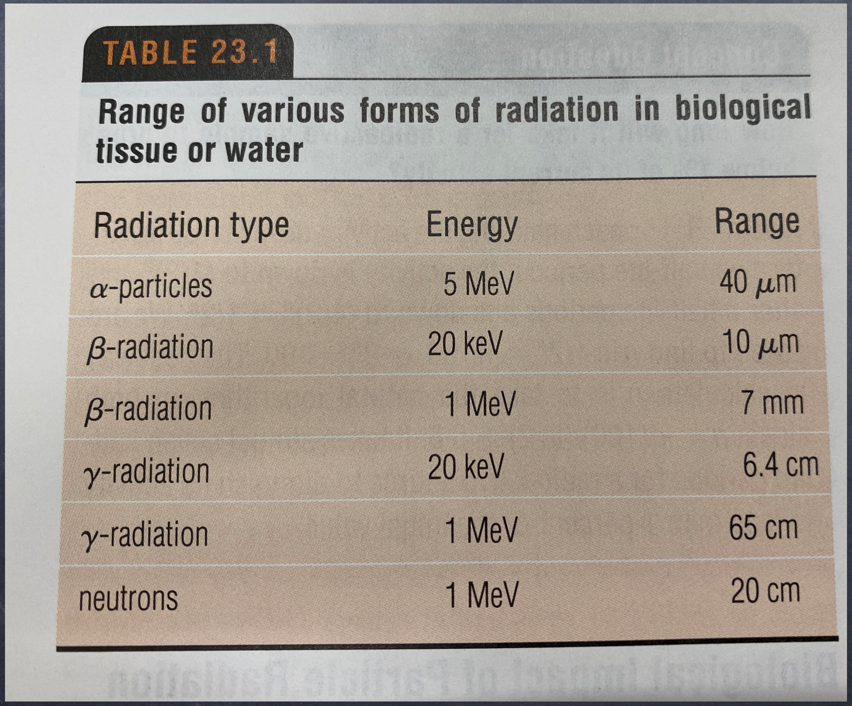


TABLE 23.1

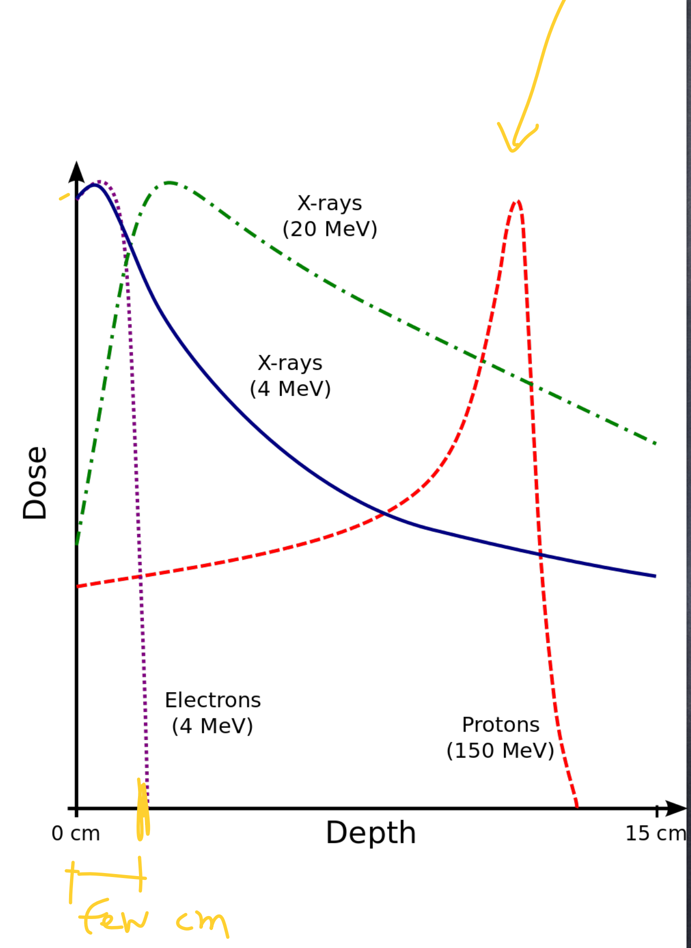
Range of various forms of radiation in biological tissue or water

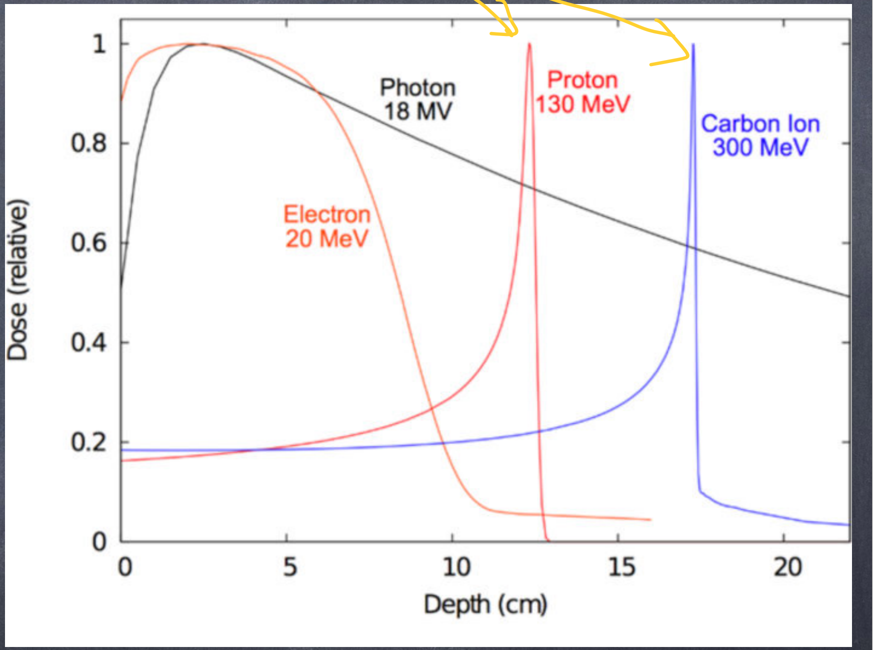
Radiation type	Energy	Range
α-particles	5 MeV	40 μm
β-radiation	20 keV	10 μm
β-radiation	1 MeV	7 mm
γ-radiation	20 keV	6.4 cm
γ-radiation	1 MeV	65 cm
neutrons	1 MeV	20 cm

← Range: how far the radiation can travel before stopping

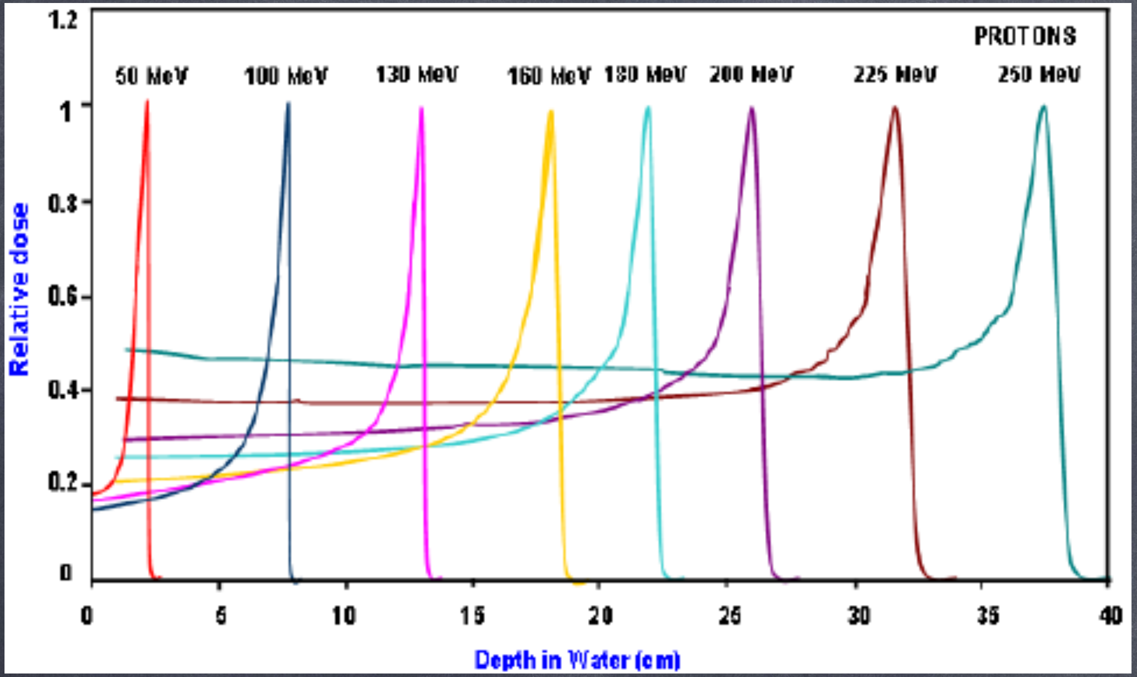
Particles deposit energy differently:

"Bragg peak" : shows that most of the energy is deposited just before it stops.

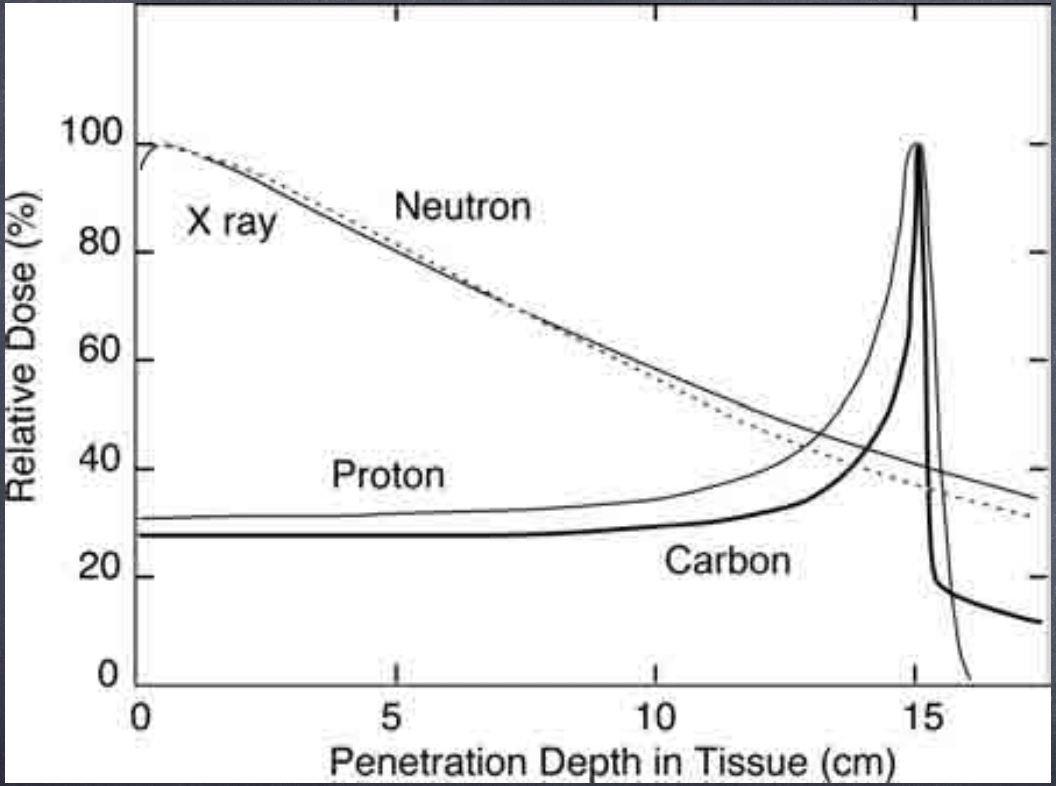




proton dose vs. depth for different energies.



Comparison



Relative Dose (%)
100
80
60
40
20
0
X ray
Neutron
Proton
Carbon
0
5
10
15
Penetration Depth in Tissue (cm)

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 $^{1}_{1}H$ and $^{3}_{1}H$ (tritium) have the same chemistry, but tritium is radioactive ($\tau_{1/2} = 12$ years): $^{3}_{1}H \rightarrow {}^{3}_{2}He + e^{-} + \bar{\nu}_e$

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)

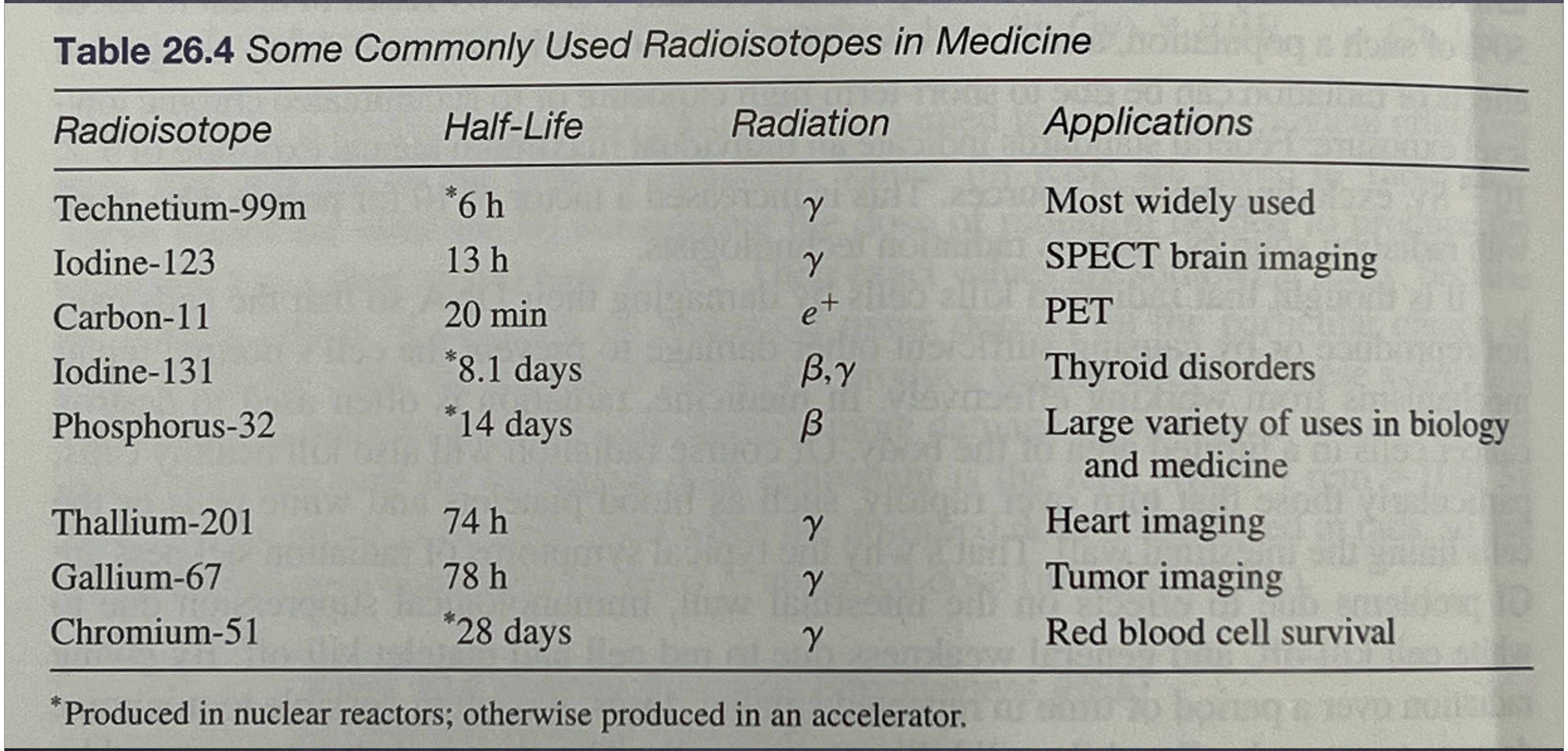
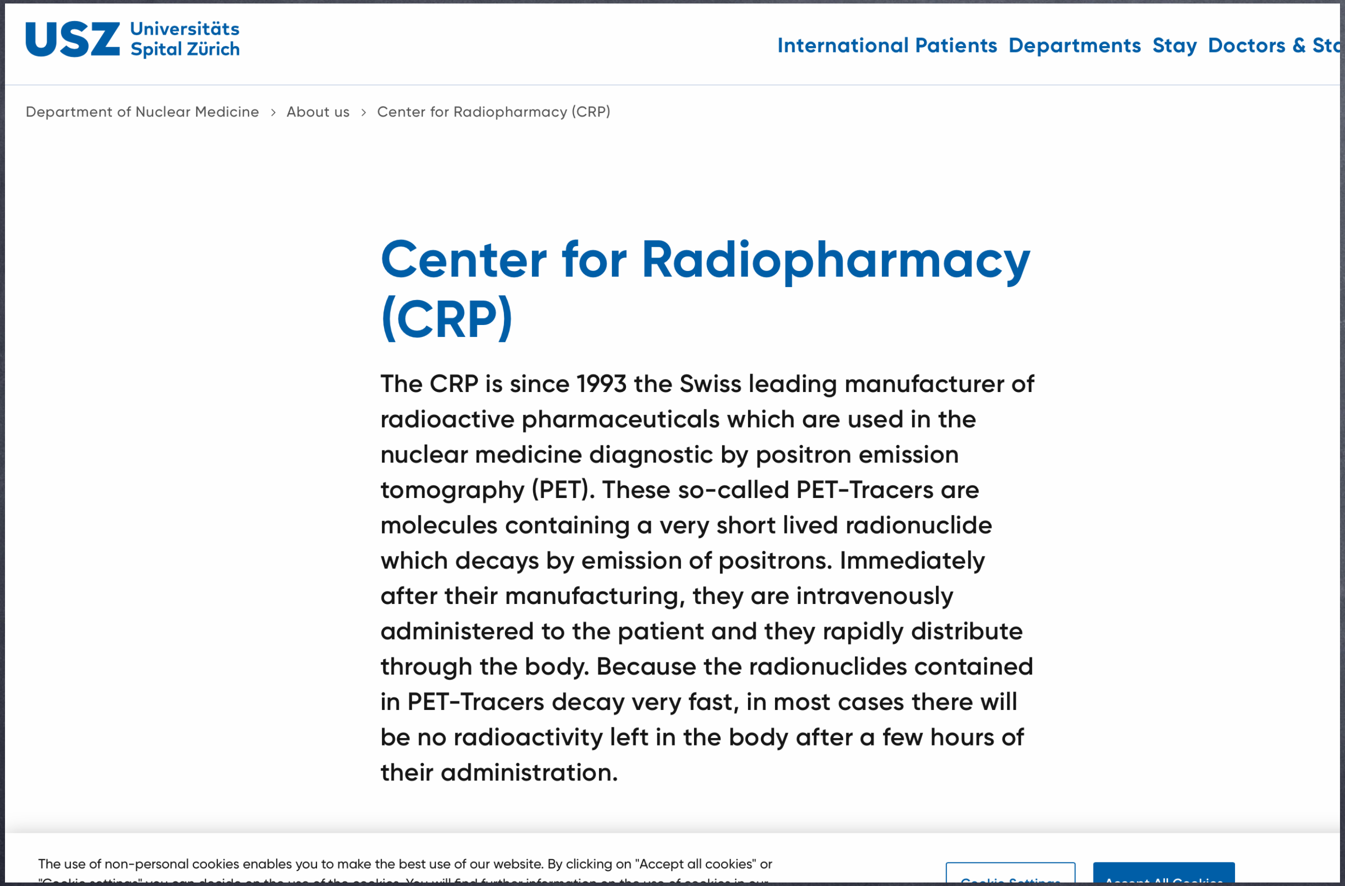


Table 26.4 *Some Commonly Used Radioisotopes in Medicine*

Radioisotope	*Half-Life*	*Radiation*	*Applications*
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.

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- ^{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-Fluoethyltyrosine 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

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- ^{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

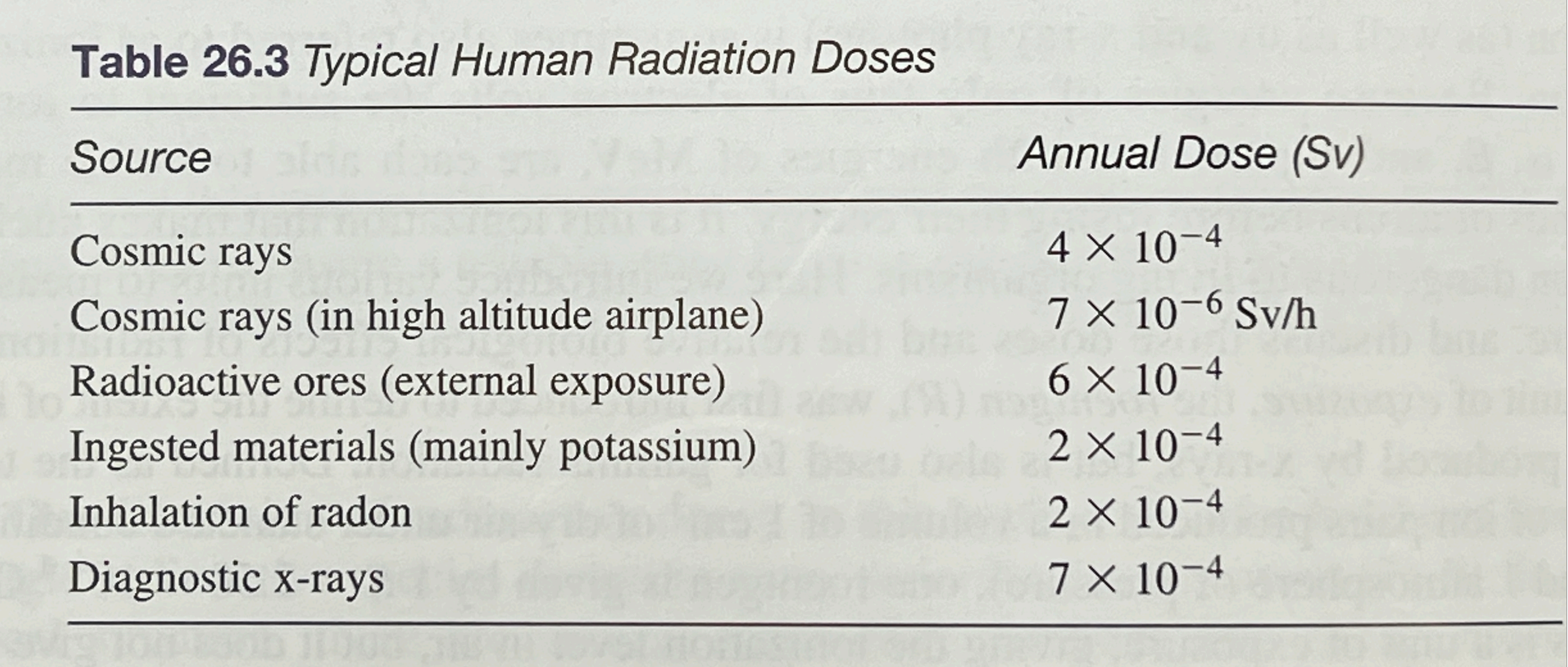


Table 26.3 *Typical Human Radiation Doses*

Source	*Annual Dose (Sv)*
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 [Gy] * RBE factor

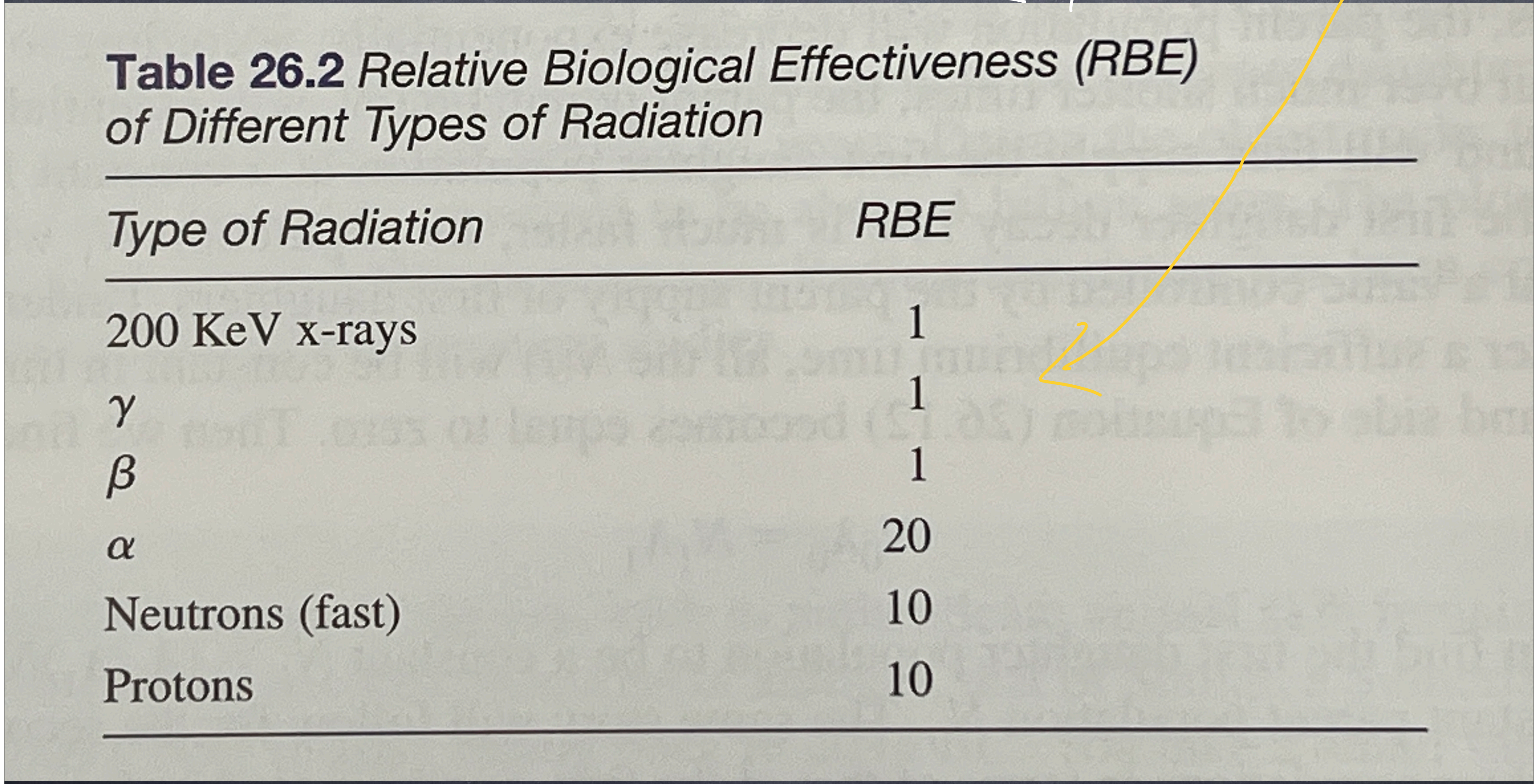


Table 26.2 *Relative Biological Effectiveness (RBE) of Different Types of Radiation*

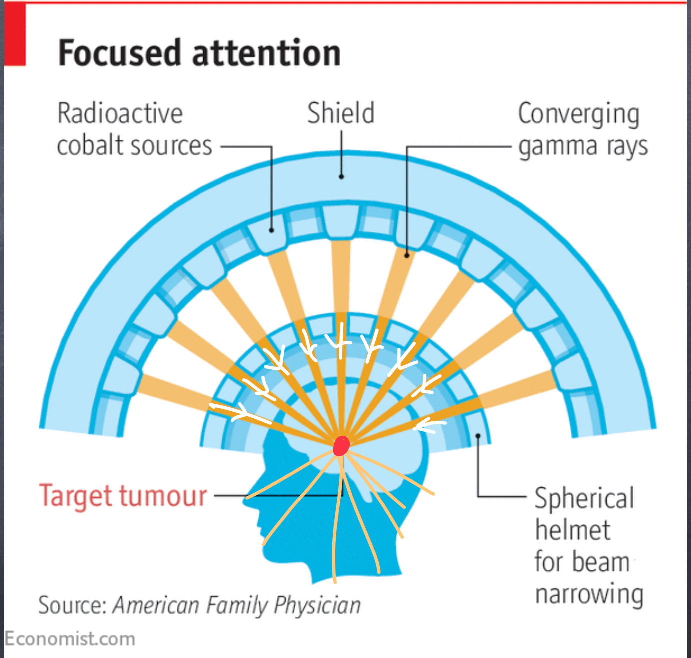
Type of Radiation	*RBE*
200 KeV x-rays	1
γ	1
β	1
α	20
Neutrons (fast)	10
Protons	10

Dose depends on type of radiation.

α : largest because it interacts so quickly

p : also quite large

Gamma therapy
radiation

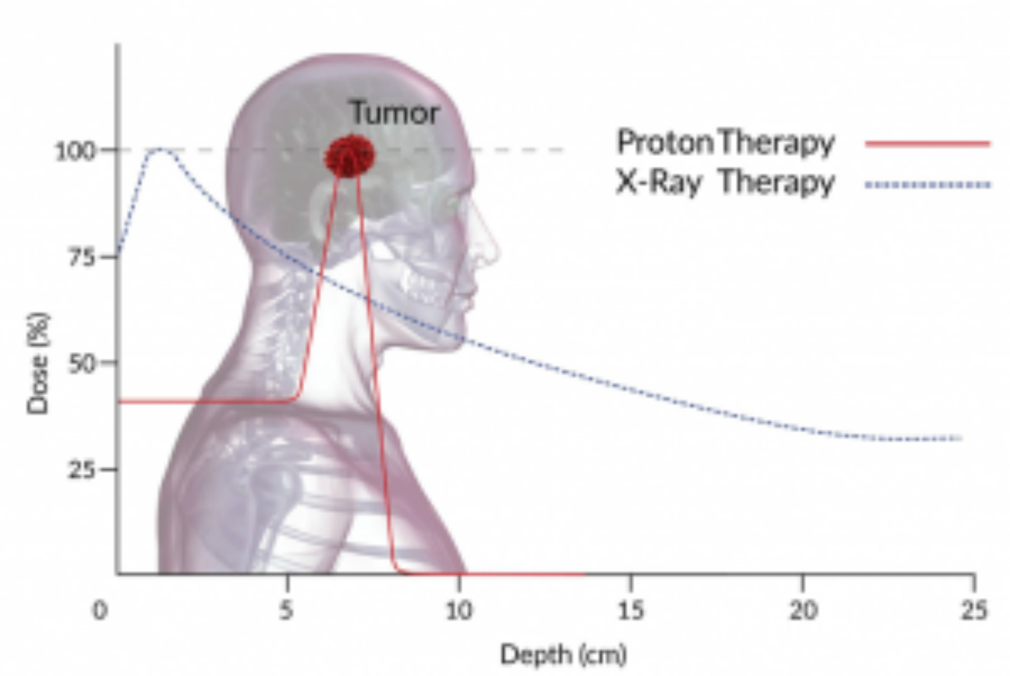


Source: *American Family Physician*

Economist.com

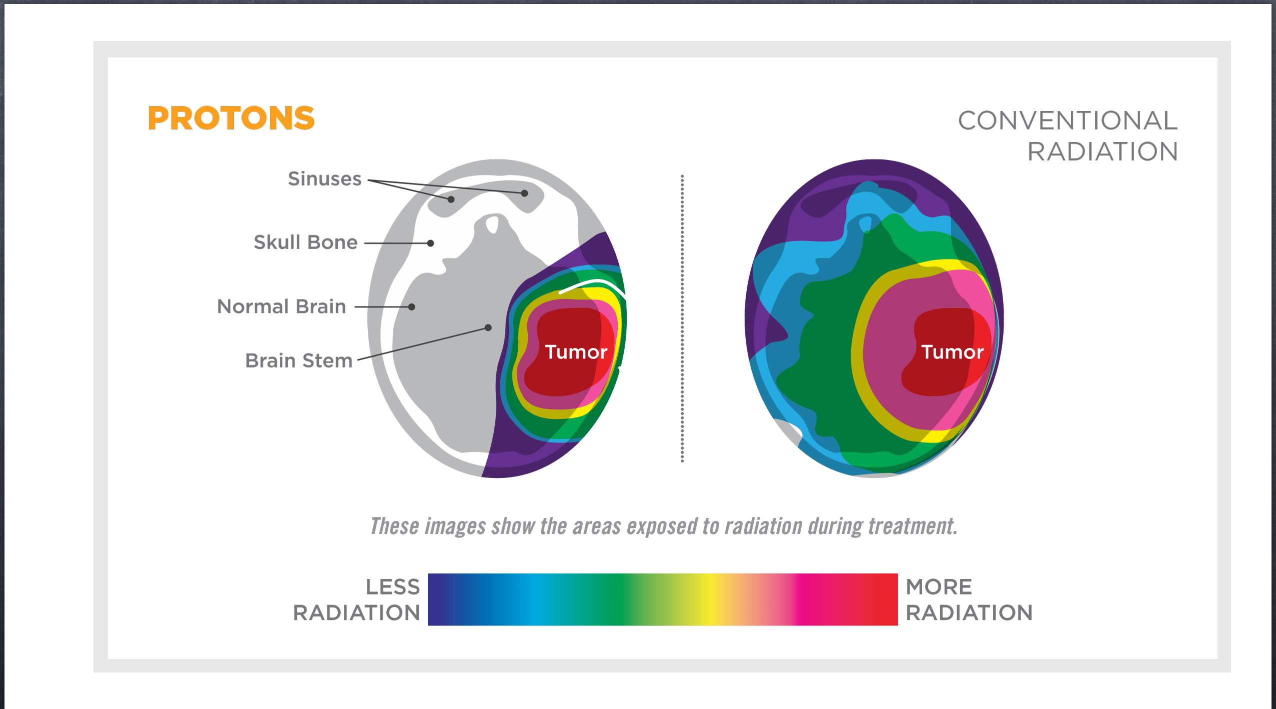
By attacking tumor from many angles, the intersection gets more dose, while heathy tissue damage is minimized.

Comparison of 2 types of radiation



comparison

proton therapy gamma therapy

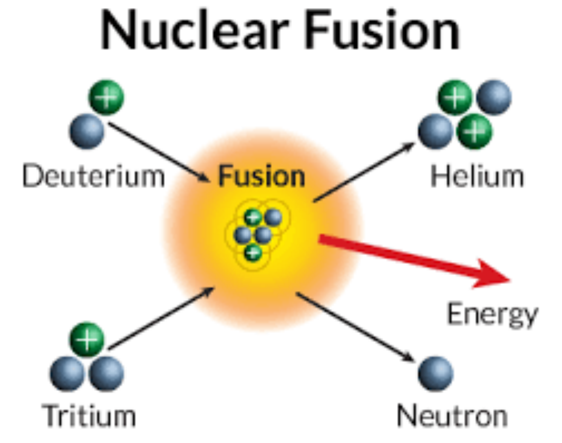


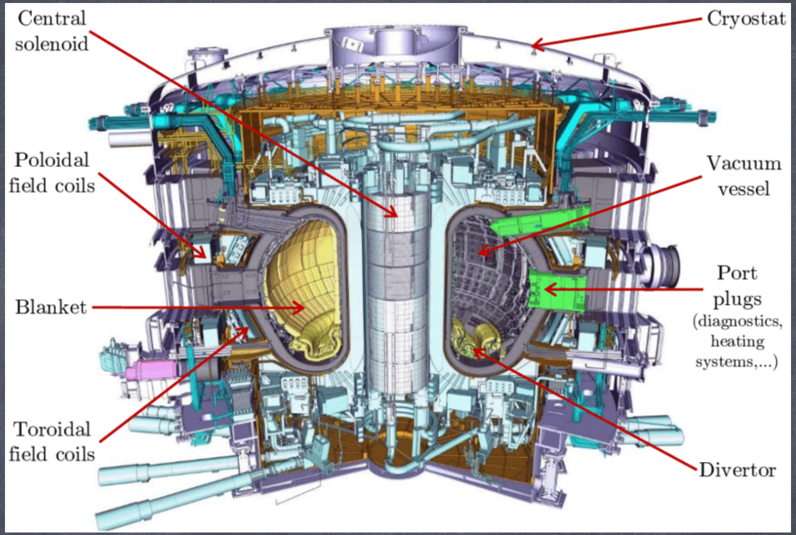
These images show the areas exposed to radiation during treatment.

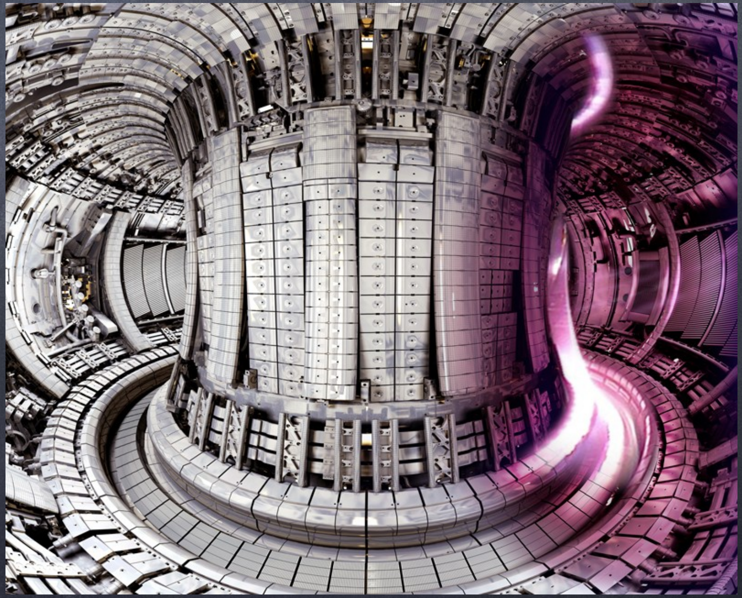
proton therapy facilities.

PSI :

Nuclear Fusion



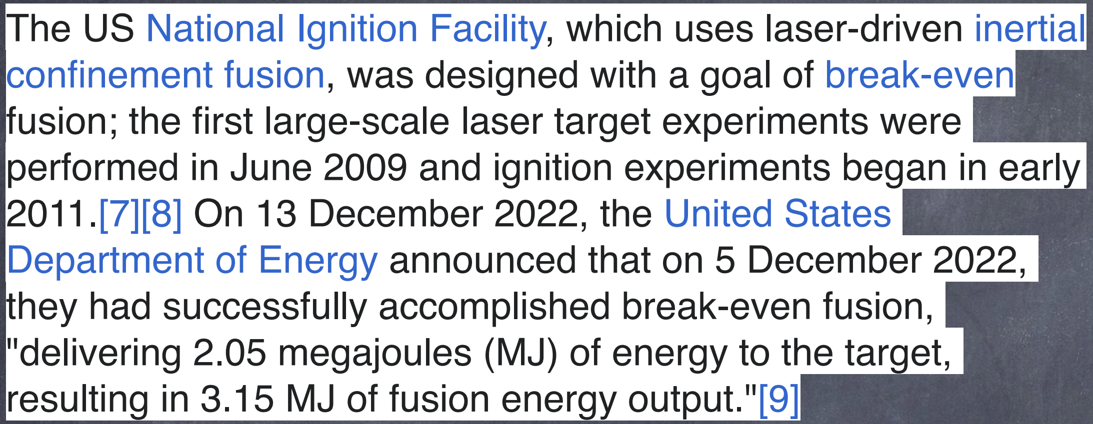




ITER

(Fusion not possible yet)

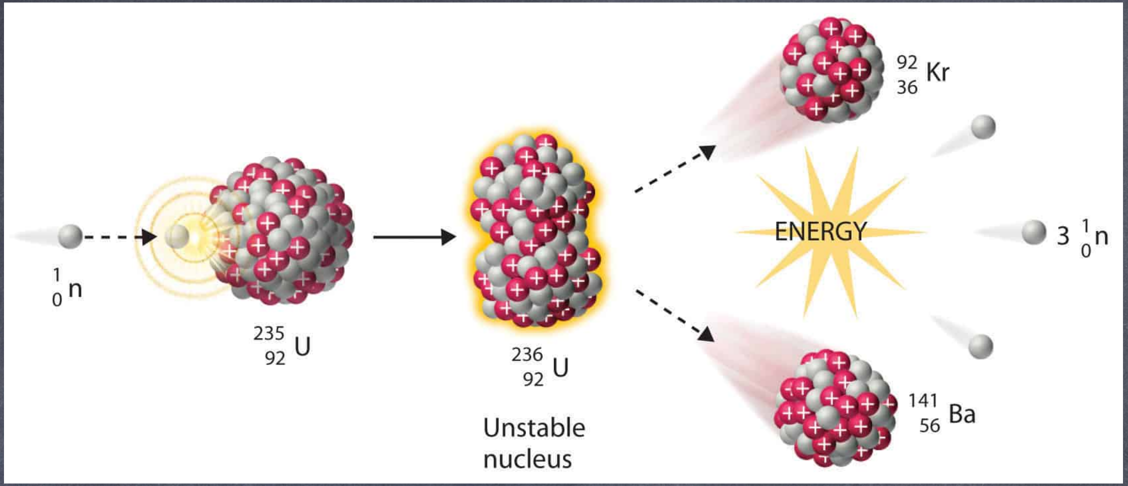
Recent progress:


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.

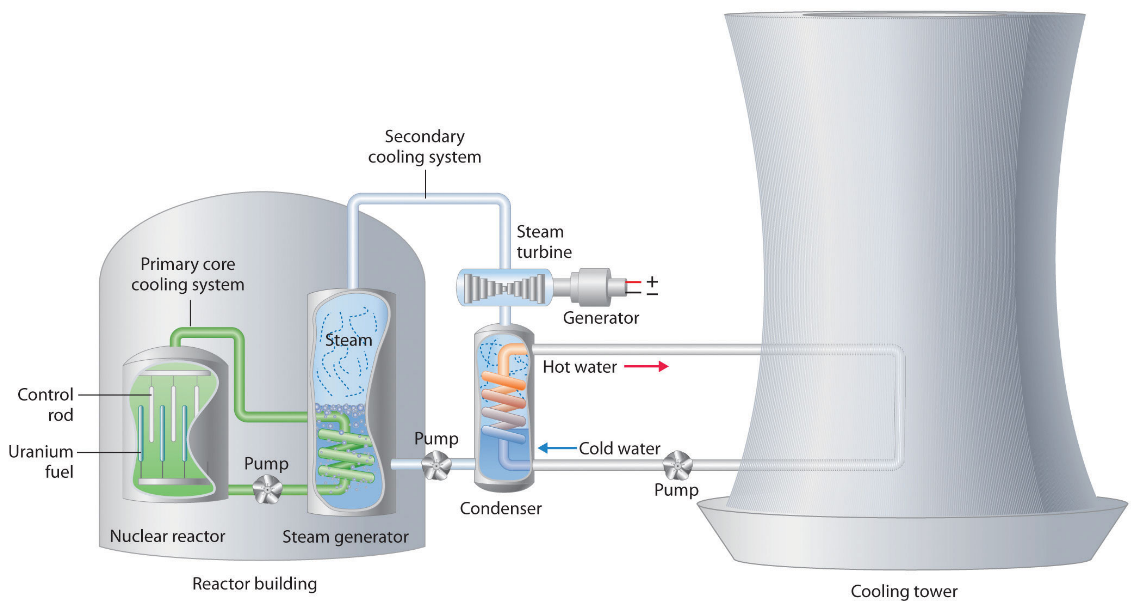
Fission

1n

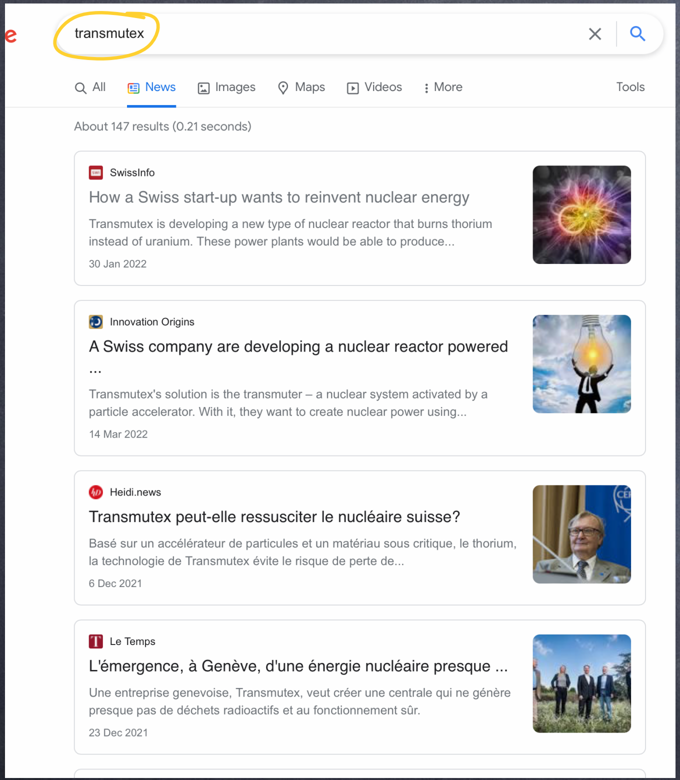


3n

chain reaction



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



About 147 results (0.21 seconds)

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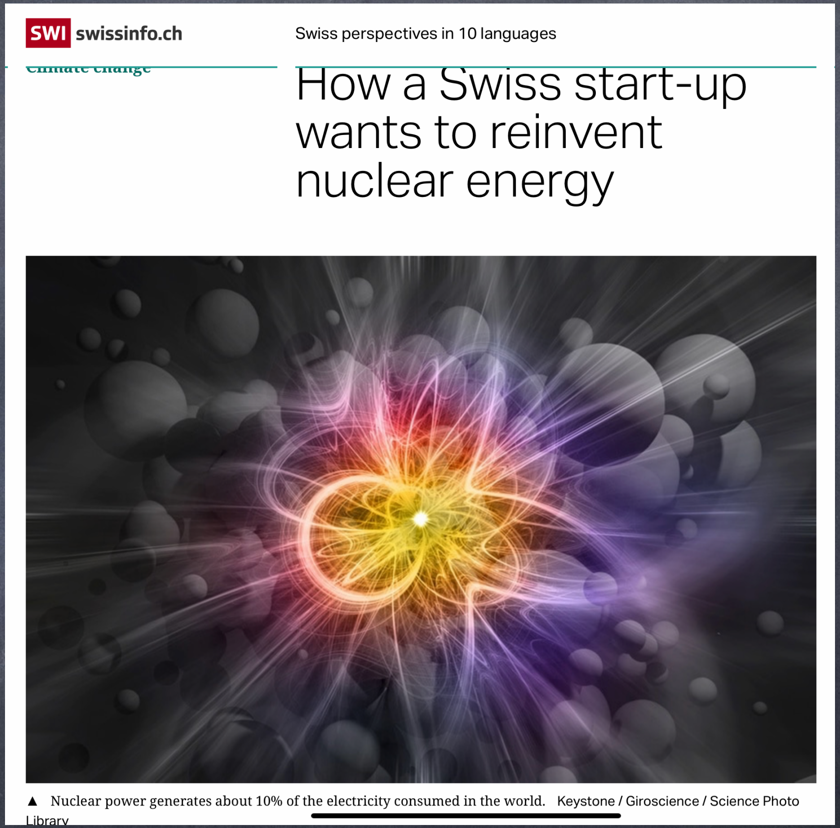


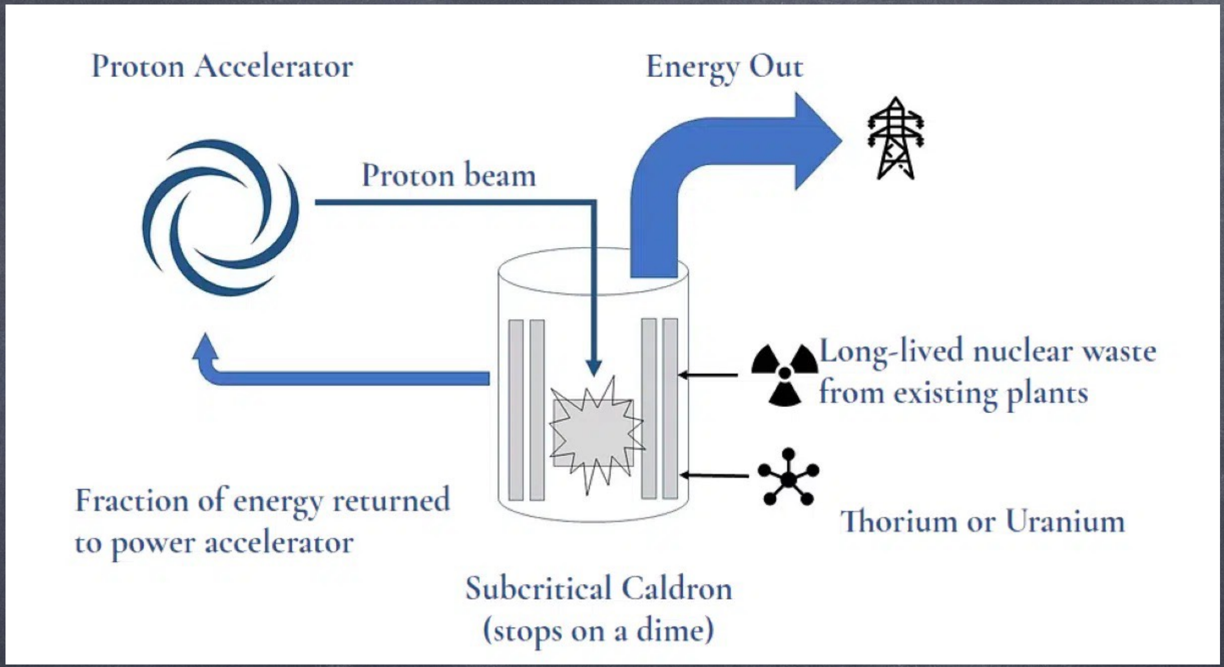
How a Swiss start-up wants to reinvent nuclear energy

▲ Nuclear power generates about 10% of the electricity consumed in the world. Keystone / Giroscience / 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.
↓

produces energy and eliminates previous radioactive waste.



Proton Accelerator

Proton beam

Energy Out

Long-lived nuclear waste from existing plants

Thorium or Uranium

Fraction of energy returned to power accelerator

Subcritical Caldron (stops on a dime)

No risk of "meltdown" (uncontrolled reactions)

SAFE

- burns radioactive waste or thorium (thorium is abundant)

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