Nuclear Physics

measure mass in energy equivalent of rest mass

e. g. for electron $m = 9.1\ (10)^{-31}$ kg

$mc^2 = 9.1\ (10)^{-31}$ kg $[3\ (10)^8$ m/s $]^2 = 8.19\ (10)^{-14}$ J

or

$mc^2 = 8.19\ (10)^{-14}$ J $[1.602\ (10)^{-19}$ J/eV $= 0.511$ MeV

$m \leftrightarrow 0.511$ MeV

matter $\Leftrightarrow$ energy

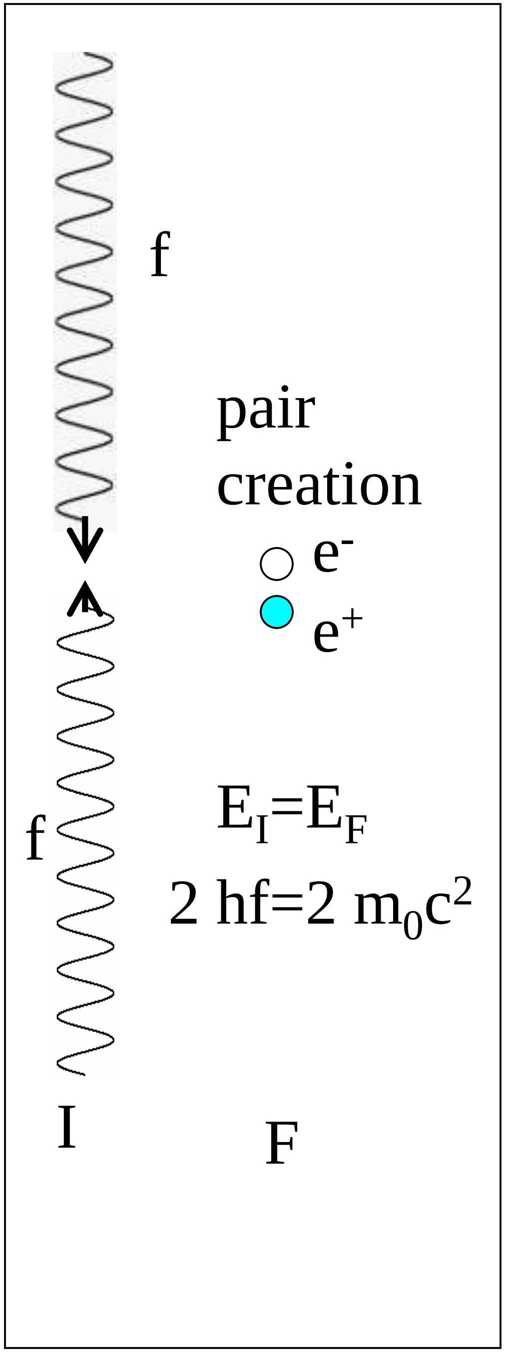
Nuclear Physics

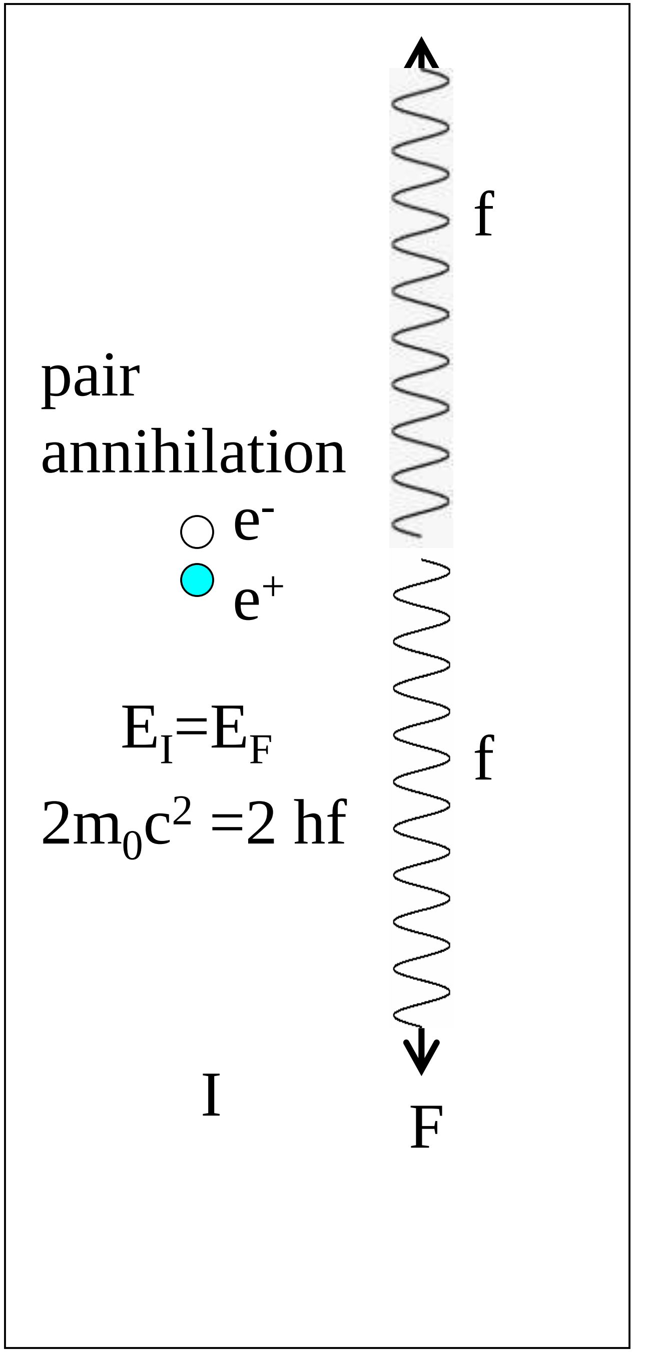
main actors and notation

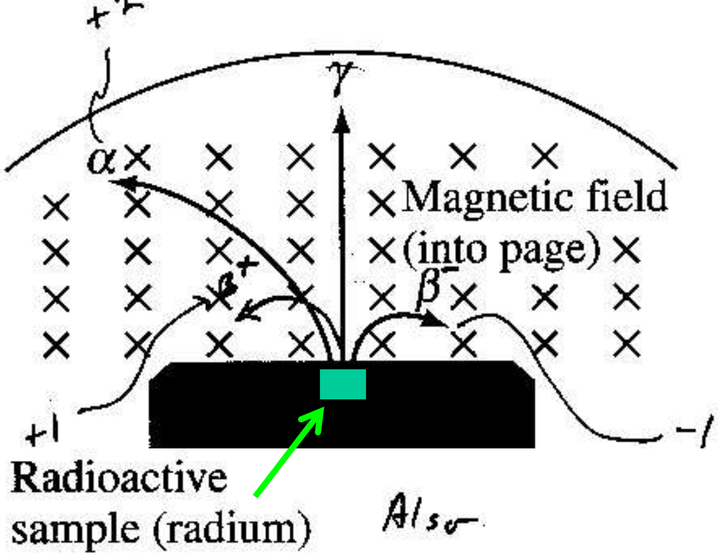
object/particle	charge	mc^2	comments
electron/beta-minus e^- / β^-	-e	0.511 MeV	
positron/beta-plus e^+ / β^+	+e	0.511 MeV	anti-particle of electron
proton p^+	+e	938.272 MeV	
neutron n	0	938.566 MeV	
α-particle = He nucleus α	+2e	3728.402 MeV	
neutrinos ν	0	> 1 eV	involved in weak force
gamma-ray γ	0	0	photon E=h f

13-1b

matter ⇔ energy







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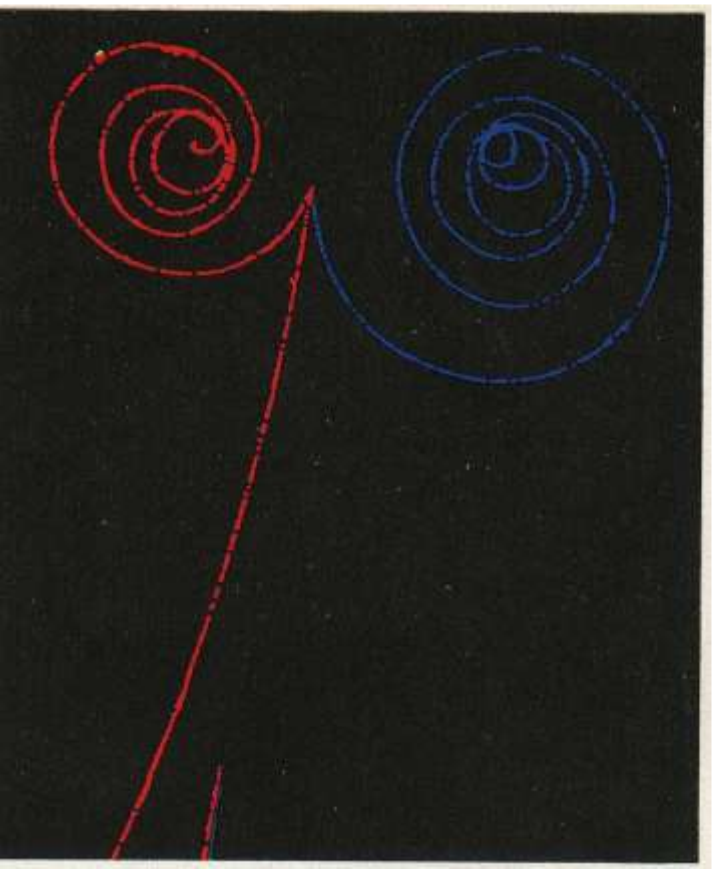


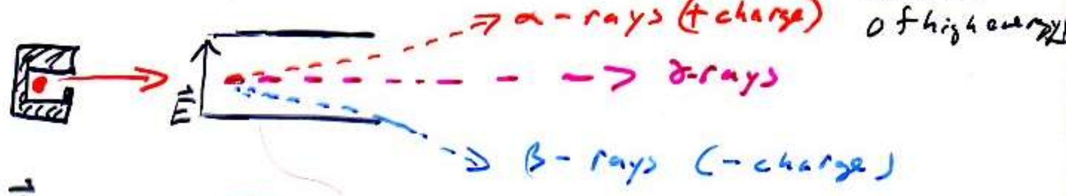
Radioactivity

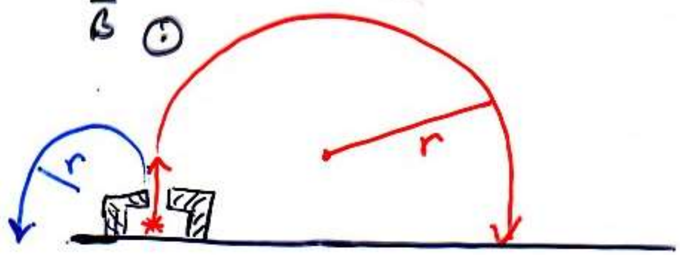
Rutherford

α - rays [He nucleus]

β - rays more penetrating [electron]

γ - rays still more penetrating [electromag radiation of high energy]





recall $\frac{mv^2}{r} = qvB$

$$\boxed{r = \frac{mv}{qB}}$$

$\frac{m}{q}$ for β particles $\frac{m}{e^-}$ → electrons

$\frac{m}{q}$ for α- particles $\begin{cases} m = 4 \times H \\ q = +e2 \end{cases}$

He nucleus

Nuclear notation

atomic mass units $\quad 1\ u = 931.5\ MeV/c^2 \quad \{ M({}^{12}_{6}C) \equiv 12u \}$

$${}^{A}_{Z}X$$

atomic mass number = # n+p

chemical element (determined by # p)

atomic number = # p

A nucleons $\quad$ A-Z = # neutrons = N

examples

${}^{12}_{6}C \qquad {}^{16}_{8}O \qquad {}^{153}_{63}Eu$

isotopes

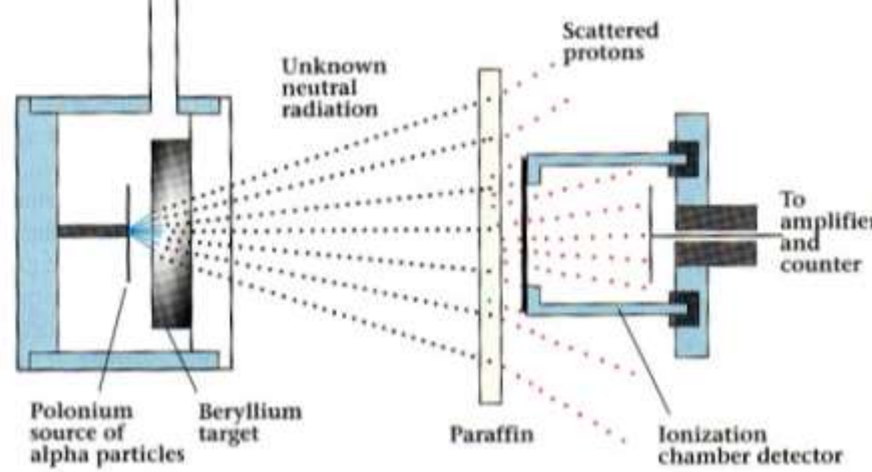
${}^{10}_{5}B \qquad {}^{11}_{5}B$

80.2 % $\qquad$ 19.8 % $\qquad$ abundance's in nature

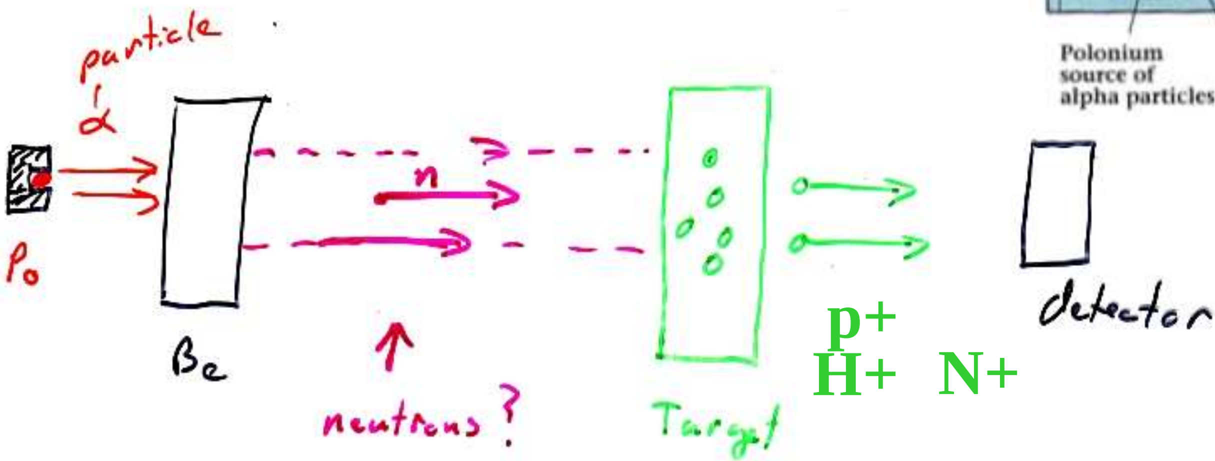
chemical mass = 10 (.802) + 11 (.198) = 10.80

note: nuclear stability favors $\#n = \#p^+$

$N = Z$



Chadwick's Experiment (n discovery)



① ⟶ not effected by $\vec{E}$ or $\vec{B}$ field
[no charge]

∴ $\underbrace{\text{photon } (\gamma\text{-ray})}_{\text{need 55 MeV (too much energy)}}$, or neutral particle

∴ neutral particle { n - Rutherford proposed, Chadwick discovered 1933 }

$\overset{V_n}{\underset{m_n}{o \longrightarrow}}$ $\quad \overset{T}{o}$ $\quad$ initial

$\overset{n}{\underset{V_n'}{\leftarrow \bullet}}$ $\quad \overset{T}{\underset{V_T}{o \longrightarrow}}$ $\quad$ final

Energy Conservation

$$\frac{1}{2} m_n V_n^2 = \frac{1}{2} m_n V_n'^2 + \frac{1}{2} m_T V_T^2$$

Momentum Conservation

$$m_n V_n = m_n V_n' + m_T V_T$$

$$\Rightarrow V_T' = \frac{2 m_n}{m_n + m_T} V_n$$

2 different targets.

Paraffin - H $\quad m_H$

Nitrogen - N $\quad m_N \simeq 14 m_H$

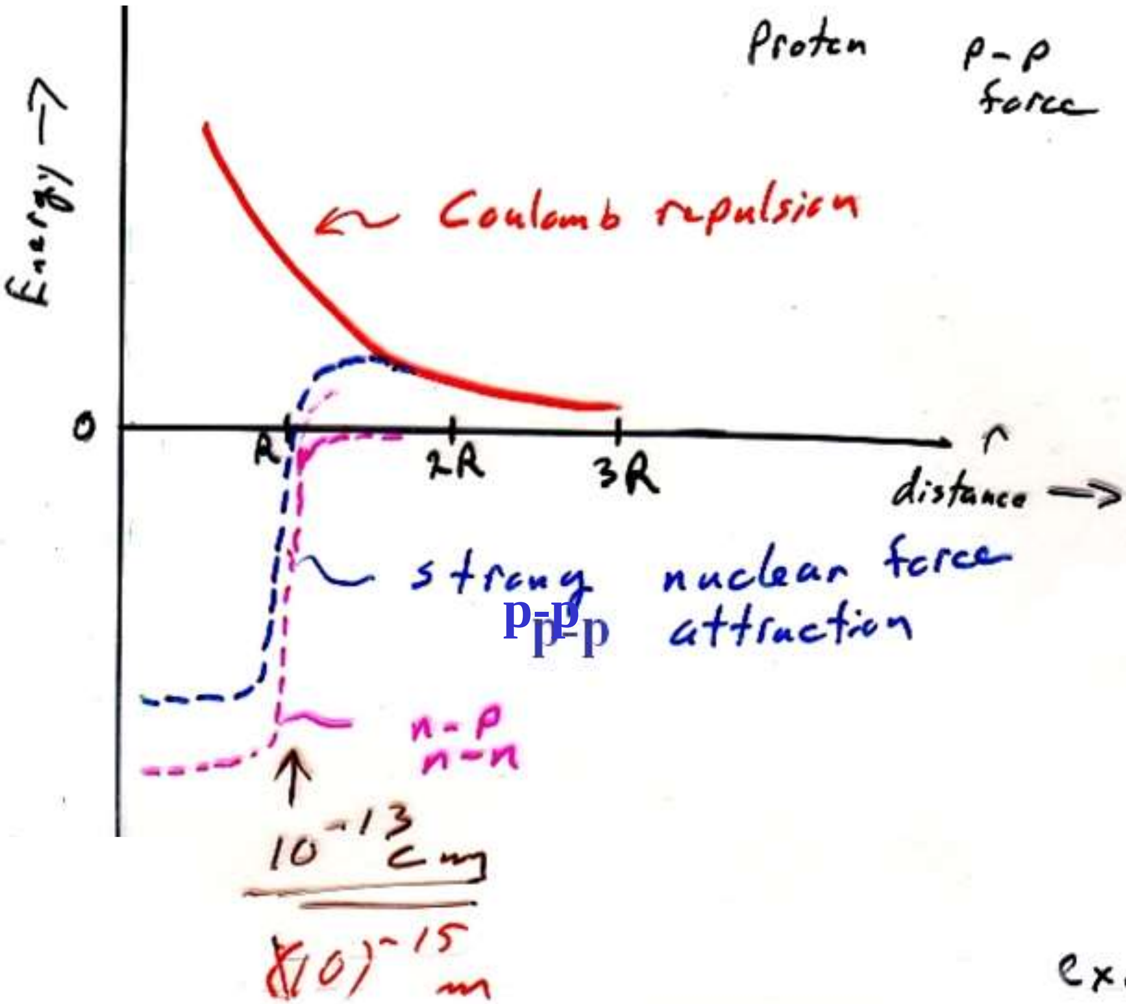
$$\frac{V_H}{V_N'} = \frac{\left[\frac{2 m_n}{m_n + m_H}\right] V_n}{\left[\frac{2 m_n}{m_n + 14 m_H}\right] V_n} = \frac{m_n + 14 m_H}{m_n + m_H} \simeq 7$$

Chadwick found $= \dfrac{3.3 (10)^7 \, m/s}{4.7 (10)^6 \, m/s} \simeq 7$

So. $(m_n + 14 m_H) = 7(m_n + m_H)$

$$\Longrightarrow \underline{m_n = \frac{7}{6} m_H \simeq 1.15 m_H}$$

Strong Nuclear Force



Nuclear size

V = Volume $\propto$ A (# nucleons)

V = Volume $\sim \left[\frac{4}{3}\pi\right] r^3$

$\therefore \quad r \propto V^{1/3}$

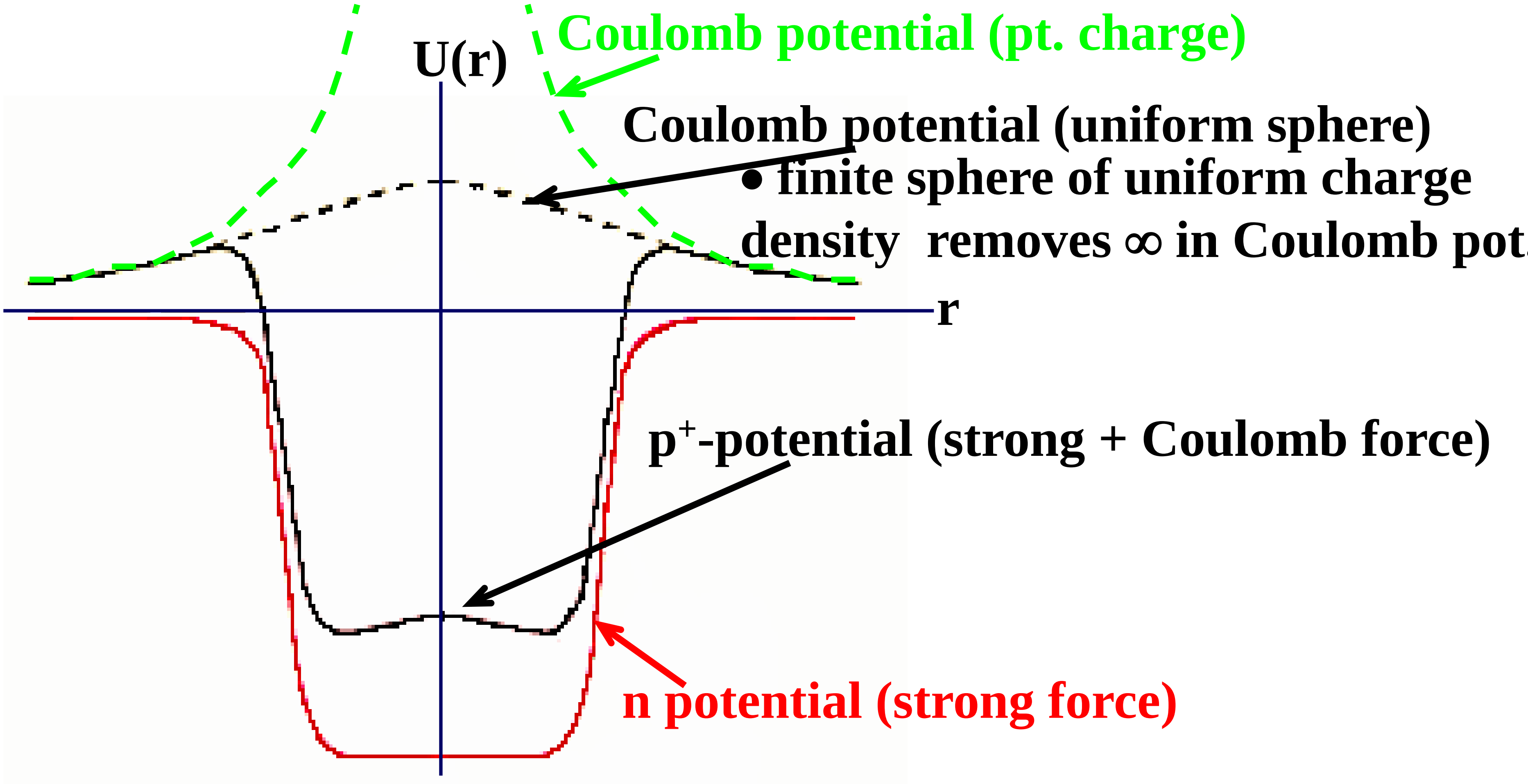
$$\boxed{r \propto A^{1/3}}$$

$$\boxed{r = R_0 A^{1/3}}$$

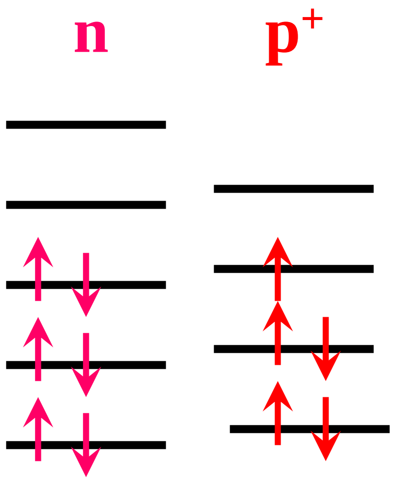
$R_0 = 1.2(10)^{-15}$ m

example ^{197}Au $\quad r = 7(10)^{-15}$

Nuclear size



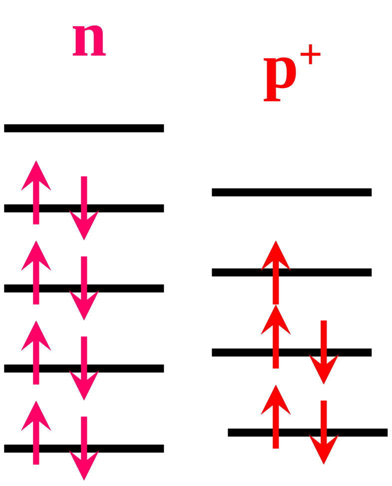
- nucleons feel effective potential due to all other nucleons combined
- n help lend stability – dilute repulsive Coulomb force
- square well-like potential (3-dimensional)
- nucleon – quantized standing matter waves (recall QM square well)
- nucleon – quantized energy levels



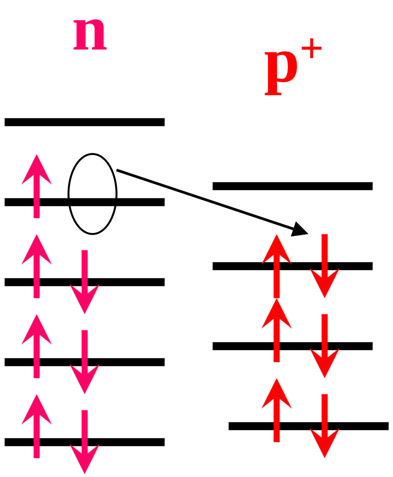
n

- have lower energy (no Coulomb repulsion)
- dilute Coulomb energy

$\Rightarrow$ extra n lower energy = stabilize

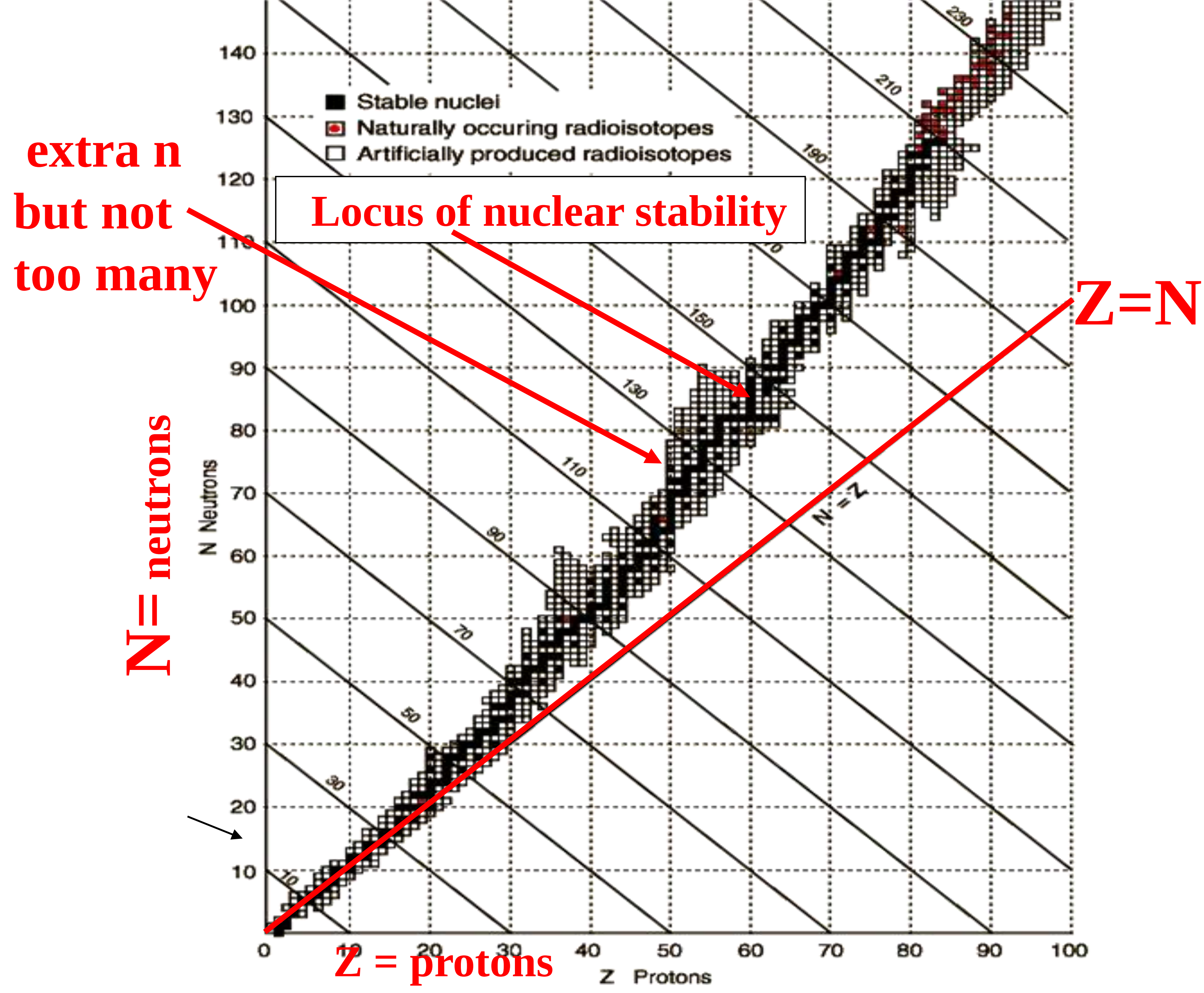


n and p+ obey Pauli Exclusion Principal



- too many n, energy to high
- unstable $\Rightarrow$ decays to lower energy

e.g. $n \Rightarrow p^{+} + e^{-} + \bar{\nu}$



Stable nuclei
Naturally occuring radioisotopes
Artificially produced radioisotopes
Locus of nuclear stability
extra n but not too many
Z=N
N = Z
N= neutrons
N Neutrons
Z = protons
Z Protons

Nuclear Binding

$$M_{^4He} < 2M_H + 2M_n$$

$${}_2^4He$$

$\therefore$ **ΔM is in binding energy**

$$E_{binding} = \Delta M\, c^2$$

$$E_{binding} = [(2m_H + 2m_n) - M_{^4He}]\, c^2$$

in u

$$2m_H + 2m_n = 2.01560 + 2.017330 = 4.03298$$

$$M_{^4He} = 4.002603$$

$$\Delta M = 0.030377\ u$$

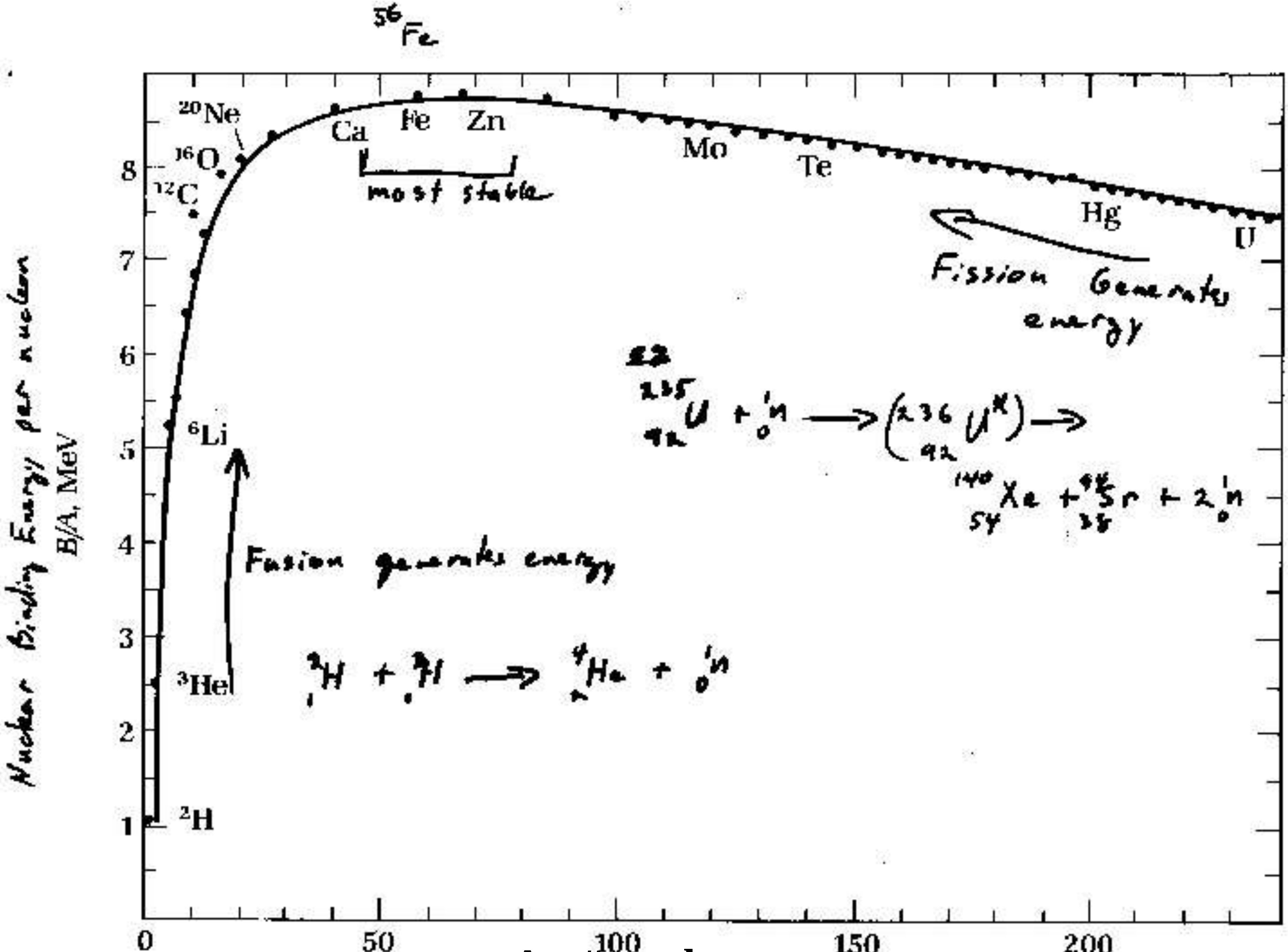
$$E_{binding} = (0.03077\ u)(931.5\ MeV/u)$$

$$\underbrace{= 28.3\ MeV}_{^4He}$$

this is 10^6 times atomic binding!!

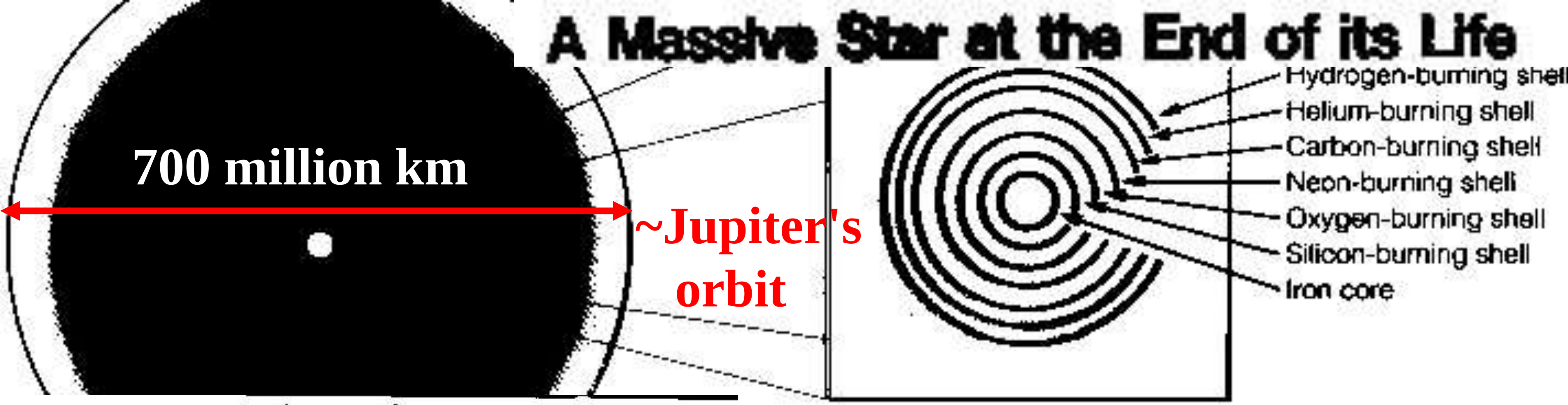
chemical reactions (Coulomb force) ~ eV

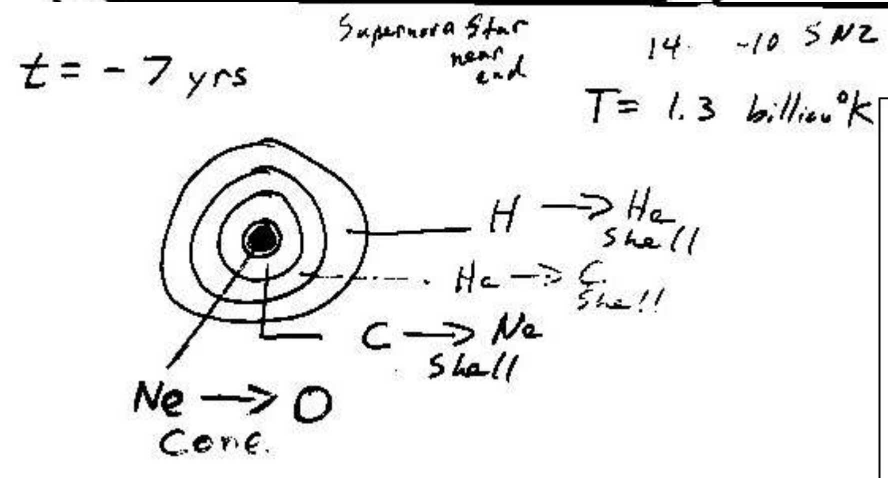
nuclear reactions (strong nuclear force) ~ 10^6 eV

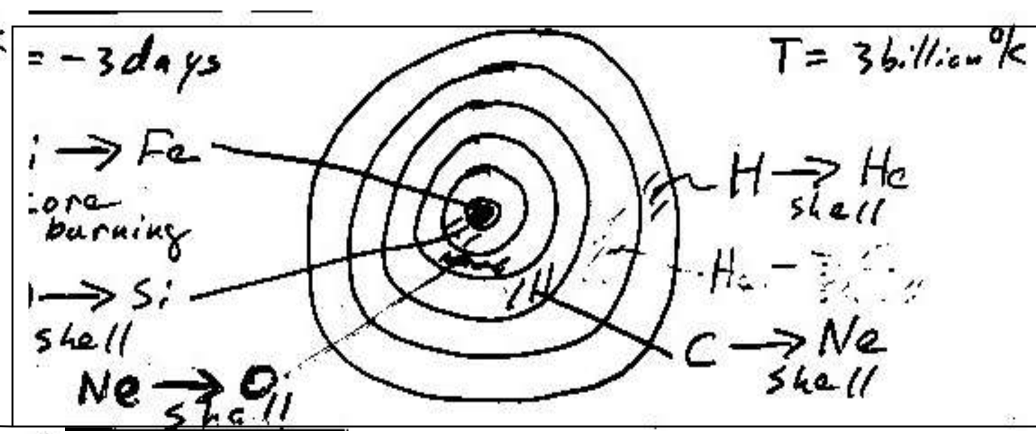


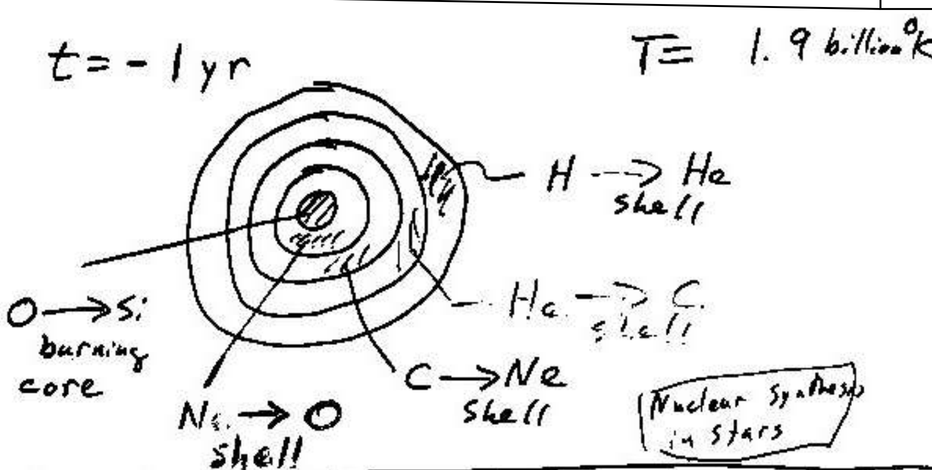
A= # nucleons 13-9a

A Massive Star at the End of its Life



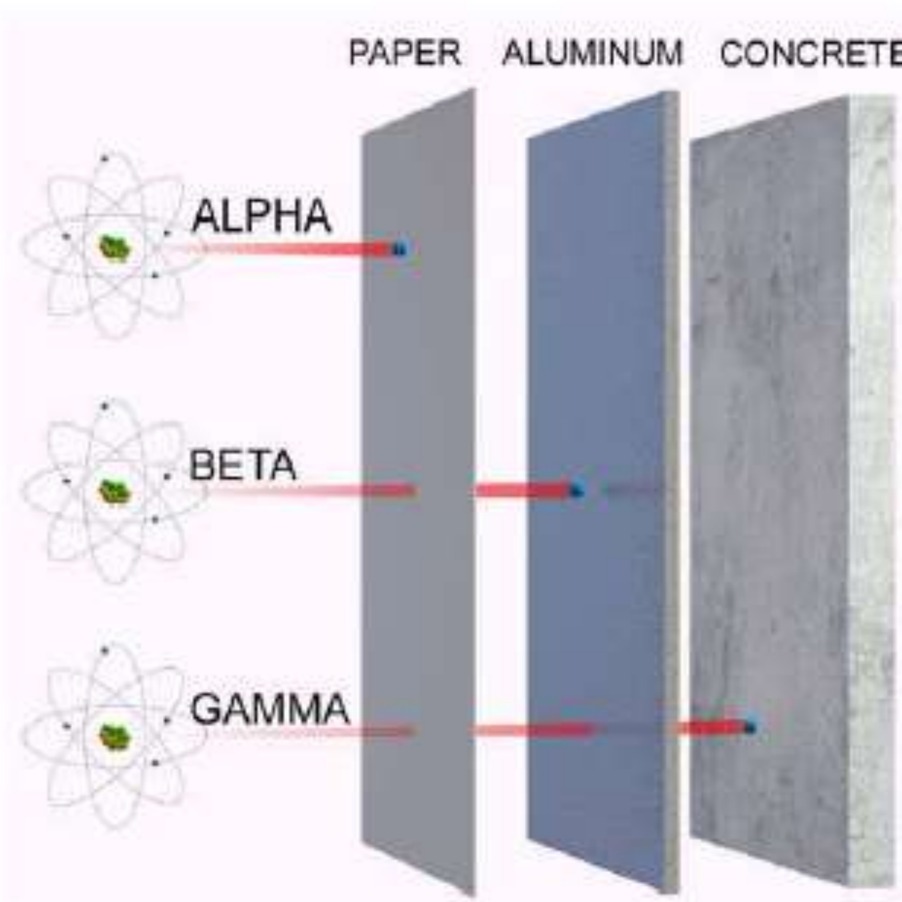






13-9b

Relative Stopping Power



Pb better

Nuclear decay channels

α emission

$${}^{A}_{Z}X \longrightarrow {}^{A-4}_{Z-2}X' + {}^{4}_{2}He$$

$${}^{214}_{84}Po \longrightarrow {}^{210}_{82}Pb + {}^{4}_{2}He \qquad {}^{226}_{88}Ra \longrightarrow {}^{222}_{86}Rn + {}^{4}_{2}He$$

$${}^{238}_{92}U \longrightarrow {}^{234}_{90}Th + {}^{4}_{2}He$$

γ emission

$${}^{A}_{Z}X^{*} \longrightarrow {}^{A}_{Z}X + \gamma$$

$${}^{61}_{28}Ni^{*} \longrightarrow {}^{61}_{28}Ni + \gamma$$

$${}^{12}_{6}C^{*} \longrightarrow {}^{12}_{6}C + \gamma$$

β (e) decay

$\beta^{-} = e^{-}$ emission

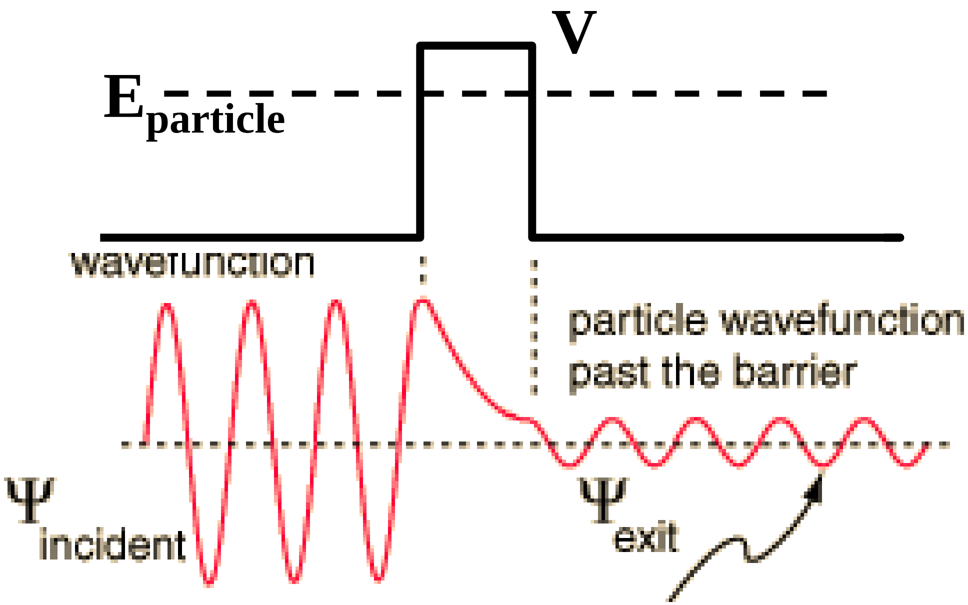
$${}^{A}_{Z}X \longrightarrow {}^{A}_{Z+1}X' + {}^{0}_{-1}e$$

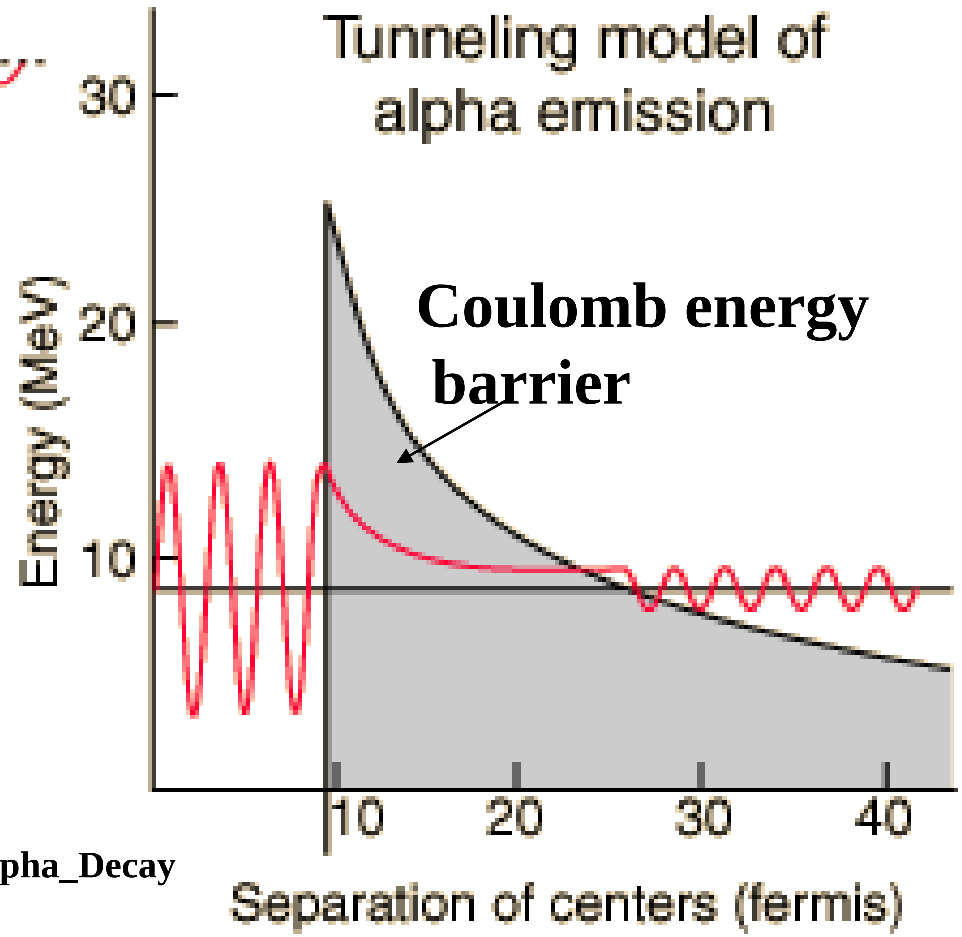
$${}^{14}_{6}C \longrightarrow {}^{14}_{7}N + {}^{0}_{-1}e + \bar{\nu}_{e}$$

$\beta^{+} = e^{+}$ emission (decay)

$${}^{A}_{Z}X \longrightarrow {}^{A}_{Z-1}X' + {}^{0}_{+1}e$$

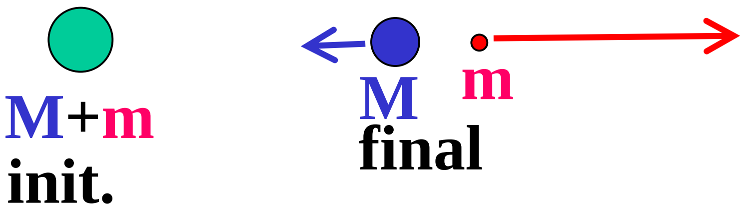
Quantum tunneling through energy barrier





http://phet.colorado.edu/simulations/sims.php?sim=Alpha_Decay

Particle decay α and β emission



momentum conservation

$$0 = MV - mv \quad (1)$$

or

$$V = \frac{m}{M} v \quad (1a)^*$$

*(1a-student corr)

energy

$$\Delta E = \tfrac{1}{2} MV^2 + \tfrac{1}{2} mv^2 \qquad (2)$$

(1a) into (2)

$$\Delta E = \frac{1}{2} M\left(\frac{m}{M} v\right)^2 + \frac{1}{2} mv^2$$

$$\Delta E = \frac{1}{2} mv^2 \left\{1 + \frac{m}{M}\right\}$$

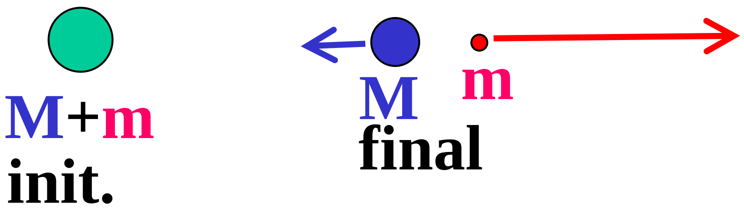
nuclear energy change

energy of emitted m particle

Note: most of energy goes to KE of light (m) particle

$$\frac{KE(M)}{KE(m)} = \frac{\tfrac{1}{2} MV^2}{\tfrac{1}{2} mv^2} = \frac{\tfrac{1}{2} mv^2 \left(\frac{m}{M}\right)}{\tfrac{1}{2} mv^2} \Rightarrow \frac{KE(M)}{KE(m)} = \frac{m}{M}$$

Particle decay α and β emission



Energy

$$\Delta E = \underbrace{\tfrac{1}{2} m v^2}_{\text{energy of exiting particle}} \left\{ 1 + \frac{m}{M} \right\}$$

nuclear energy change

α emission

$$^{210}_{84}\text{Po} \rightarrow {}^{206}_{82}\text{Pb} + {}^{4}_{2}\text{He} \qquad \frac{m}{M} = \frac{4}{206} = 0.0194 \sim 2\%$$

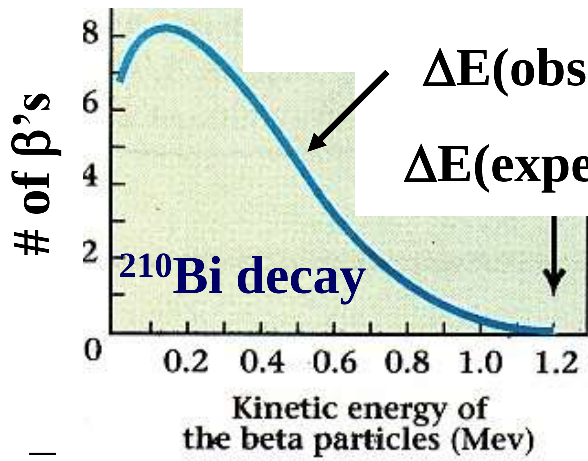
*(corr) *(corr)

β (e) decay $\beta^- = e^-$ **emission**

$$^{14}_{6}\text{C} \rightarrow {}^{14}_{7}\text{N} + {}^{0}_{-1}\text{e} + \bar{\nu}_e \qquad \frac{m}{M} = \frac{5.5\,(10)^{-4}}{14} \sim 0.003\,\%$$

neutrino complication

weak nuclear force in β decay



ΔE(observed)

ΔE(expected)

$\bar{\nu}_e$ energy distribution

$$ {}^{1}_{0}\mathrm{n} \rightarrow {}^{1}_{+1}\mathrm{p} + {}^{0}_{-1}\mathrm{e} + \bar{\nu}_e $$

electron antineutrino

inverse β decay

$$ {}^{1}_{+1}\mathrm{p} + {}^{0}_{-1}\mathrm{e} \rightarrow {}^{1}_{0}\mathrm{n} + \nu_e $$

β (e) decay **β^- = e^- emission**

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

neutrino complication

http://phet.colorado.edu/simulations/sims.php?sim=Beta_Decay

γ-ray emission

momentum conservation

$$c = \lambda f$$

$$0 = MV - \frac{h}{\lambda} \quad \Rightarrow V = \frac{h}{M\lambda} = \frac{hf}{Mc}$$

energy liberated

$$\Delta E = hf + \frac{1}{2}MV^2$$

$$\Delta E = hf + \frac{1}{2}M\left(\frac{hf}{Mc}\right)^2$$

$$\Delta E = hf\,[1 + \{\frac{hf}{2Mc^2}\}]$$

$$\{\frac{hf}{2Mc^2}\} \sim \frac{1}{10{,}000} \text{ or } \frac{1}{200{,}000}$$

almost all energy to γ

$$hf \sim< 1\,\text{MeV}$$

$$2Mc^2 \sim> 2\,A\,[1000\,\text{MeV}] \sim 200{,}000\,\text{MeV}$$

$$A \sim 4 \text{ to } 300$$

Tc used in nuclear stress tests to look at distribution of blood flow in heart

Activate Mo in reactor $\mathbf{{}^{98}_{42}Mo} + {}^{1}_{0}\mathbf{n} \rightarrow {}^{99}_{42}\mathbf{Mo}$

$$\mathbf{{}^{99}_{42}Mo} \rightarrow {}^{99\boldsymbol{m}}_{43}\mathbf{Tc} + {}^{0}_{-1}\mathbf{e} + \bar{\boldsymbol{\nu}}$$

m=excited daughter nucleus

^{99}Mo has a half-life of 66 hours

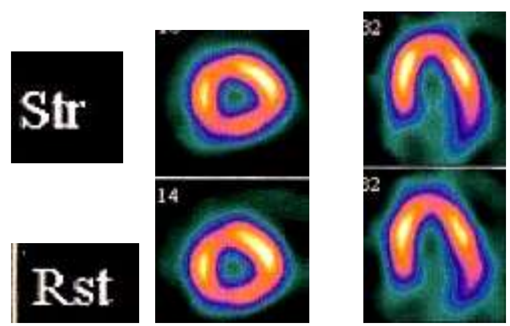
$$^{99\boldsymbol{m}}_{43}\mathbf{Tc} \rightarrow {}^{99}_{43}\mathbf{Tc} + \boldsymbol{\gamma}$$

excited nucleus decays

γ Energy =140 keV (escapes body)

$^{99\boldsymbol{m}}_{43}\mathbf{Tc}$ ½-life of 6.01 hours {15/16 =93.7% done in 24 hr}

Transport and inject in patient blood stream
Image gamma rays emanating from heart to measure blood flow



Example KE of

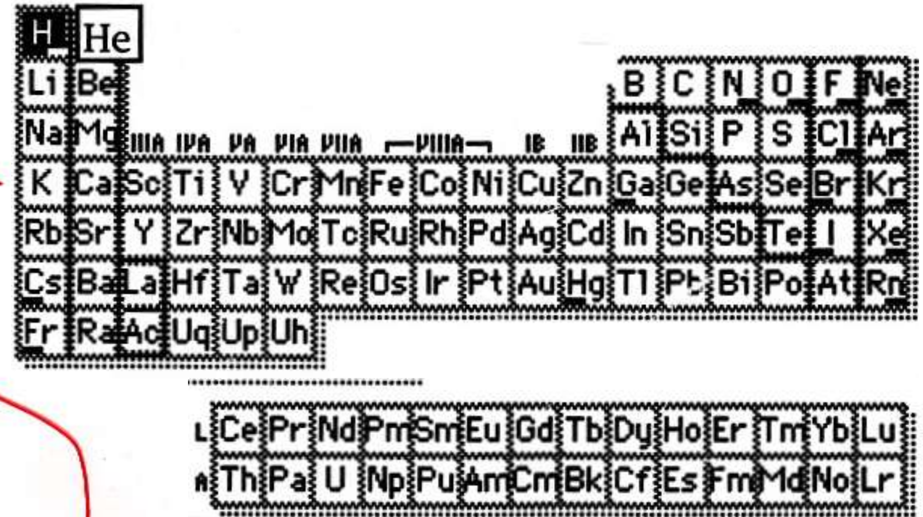
$$ {}^{232}_{92}U \longrightarrow \underbrace{{}^{228}_{90}Th + {}^{4}He}_{M(Th)\,+\,m(He)} + \underbrace{KE_{tot}}_{} $$

$m(U)$ = 232.037131 u (larger)

$M(Th)$ + $m(He)$ = 228.028716 u + 4.002602 u = 232.031318 u (smaller)

difference

$$ .005813\ u \cdot 931.5\ \frac{MeV}{u} = 5.4\ MeV $$



$$ KE_{Th} + KE_{He} = KE_{tot} = 5.4\ MeV $$

(Th 228) 4/232 (He 4) 228/232 232/232] fraction of total

$$ \frac{KE_{Th}}{KE_{He}} = \frac{m}{M} = \frac{4}{228} $$ inverse

$$ KE_{He} = \left(\frac{228}{232}\right) 5.4\ MeV = 5.3\ MeV $$

$$ KE_{Th} = \frac{4}{232}\ 5.4\ MeV \approx 0.1\ MeV $$

Radioactive decay: a stochastic statistical process

-a given nuclei decays randomly and independently of others

-constant statistical decay rate (probability per unit time)

{short time compared to time when ~ nothing left)

$\Rightarrow$1) the more nuclei the more decays

2) the longer the time the more decays.

1) $\Rightarrow$ N radioactive nuclei at time t , then $\Delta N \sim N$

2) $\Rightarrow$ $\Delta N \sim \Delta t$

$$\Rightarrow \quad \Delta N = -\lambda N \, \Delta t$$

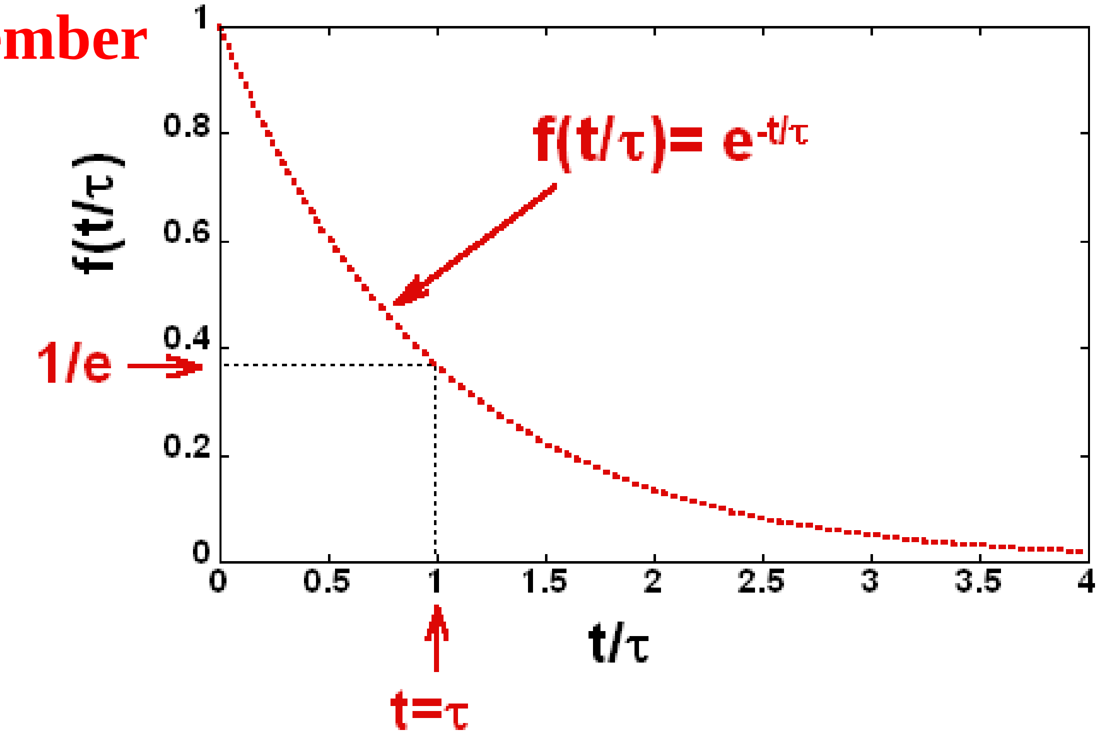
$$\Rightarrow \quad dN = -\lambda N \, dt$$

$$\Rightarrow \quad \boxed{\begin{array}{c} \dfrac{dN}{dt} = -\lambda N \\ \Rightarrow \quad \dfrac{dN}{dt} + \lambda N = 0 \end{array}}$$

Have seen this before !!

Poisson process: every object has a fixed probability of decaying in a given time [Remember the Fr. mathematician Siméon Denis Poisson (1781 – 1840) who was wrong about “ Poissions’ bright spot”.]

Exponential Function **remember**



$$f(t) = e^{-\frac{t}{\tau}}$$

τ = time constant

$$f(t=\tau) = e^{-1} = \frac{1}{e} = \frac{1}{2.732}$$

$$\boxed{\frac{df}{dt} = -\frac{1}{\tau} f}$$

or

$$\frac{\Delta f}{\Delta t} = -\frac{1}{\tau} f$$

$$\frac{df}{f} = -\frac{1}{\tau} dt \qquad \int \frac{df}{f} = -\frac{1}{\tau} \int dt$$

$$\ln(f) = -\frac{t}{\tau} \qquad f(t) = e^{-\frac{t}{\tau}}$$

Note: gen. soln. $f(t) = f_o \ e^{-\frac{t}{\tau}}$ (f_0= constant)

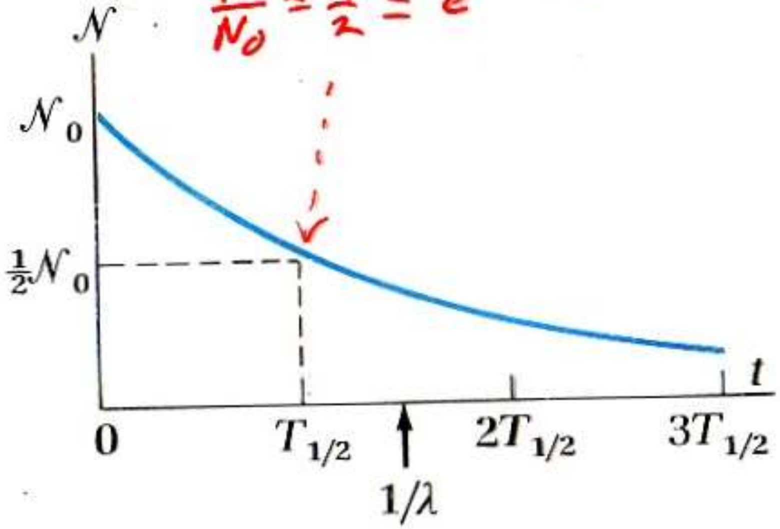
$$\boxed{T_{1/2} = \frac{.693}{\lambda}} \quad \boxed{\lambda = \frac{.693}{T_{1/2}}} \Rightarrow \therefore N = N_0 \, e^{-.693 \frac{t}{T_{1/2}}} = N_0 (e^{-.693})^{t/T_{1/2}}$$

$$\ln 2 = \lambda T_{1/2}$$

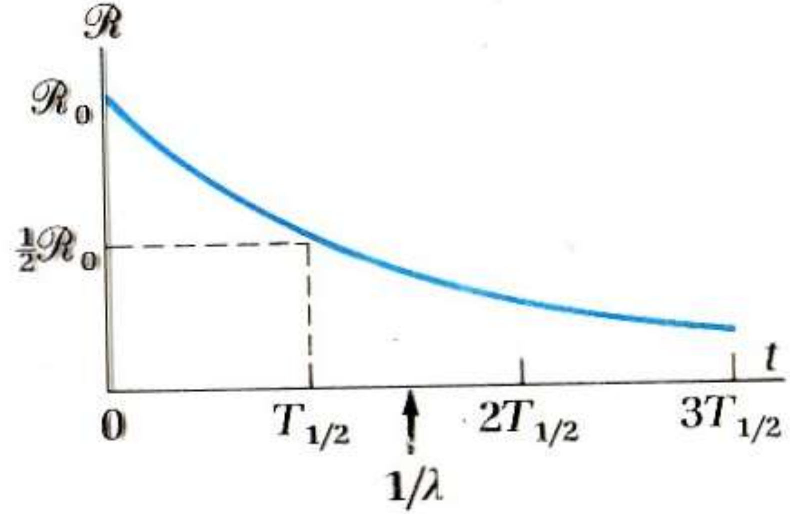
$$2 = e^{\lambda T_{1/2}}$$

$$\boxed{N = N_0 \left(\frac{1}{2}\right)^{t/T_{1/2}}}$$

$$\frac{N}{N_0} = \frac{1}{2} = e^{-\lambda T_{1/2}}$$



(a)



(b)

$$\boxed{N = N_0 \, e^{-\lambda t}}$$

$$\boxed{R = \frac{\Delta N}{\Delta t} = \left(\frac{\Delta N}{\Delta t}\right)_0 e^{-\lambda t}}$$

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

Radioactivity illustration: carbon dating

cosmic rays (at high altitudes)

$$n + {}^{14}_{7}N \rightarrow {}^{14}_{6}C + {}^{1}_{1}p$$

Constantly creates ${}^{14}_{6}C$

${}^{14}_{6}C$ is incorporated into CO_2 in the atmosphere with stable ${}^{12}_{6}C$

photosynthesis incorporates ${}^{14}_{6}CO_2$ into plants

animals eat plants (and each other)

but ${}^{14}_{6}C \rightarrow {}^{14}_{7}N + e^{-} + \bar{\nu}_e$ $\tau_{1/2} = 5730$ years

Constantly decaying ${}^{14}_{6}C$

so $\dfrac{N\,({}^{14}C)}{N\,({}^{12}C)} = 1.3 \text{ x } 10^{-12}$ equilibrium isotope ratio in <u>atmosphere and all living things</u>

organism dies $\Rightarrow$ ${}^{14}_{6}C$ content decays as

$$\frac{N\,({}^{14}C)}{N\,({}^{12}C)} = 1.3 \text{ x } 10^{-12}\ e^{-t[.693/5730]}$$

$$\frac{N_{{}^{14}C}(t)}{N_{{}^{12}C}} = 1.3\,(10)^{-12}\left(\tfrac{1}{2}\right)^{t/5700}$$

$$\frac{N_{^{14}C}(t)}{N_{^{12}C}} = 1.3\,(10)^{-12}\ e^{-.693\,t/5700}$$

$$\frac{N_{^{14}C}(t)}{N_{^{12}C}} = 1.3\,(10)^{-12}\left(\tfrac{1}{2}\right)^{t/5700}$$

suppose

$$\frac{N_{^{14}C}}{N_{^{12}C}} = 1.3\,(10)^{-12}\ \left(\frac{1}{10}\right)$$

$$\Rightarrow \frac{1}{10} = e^{-.693\,t/5700}$$

$$\ln\left(\frac{1}{10}\right) = -.693\,t\,/\,5700$$

$$t = -\frac{5700}{.693}\ln\left(\frac{1}{10}\right) \sim 3.3\,(5700)$$

$$t = 18,939\ \text{yrs}$$

between

$$\Rightarrow \frac{1}{10} = \left(\tfrac{1}{2}\right)^{t/5700}$$

$$\left(\frac{1}{2}\right)^0 = 1$$

$$\left(\frac{1}{2}\right)^1 = \frac{1}{2} = 0.5 \qquad 1(5700) = 5700$$

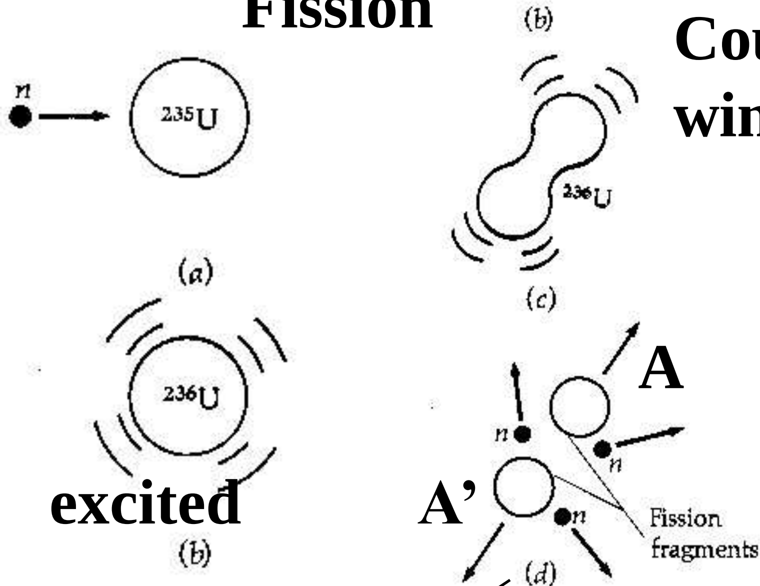
$$\left(\frac{1}{2}\right)^2 = \frac{1}{4} = 0.25 \qquad 2(5700) = 11400$$

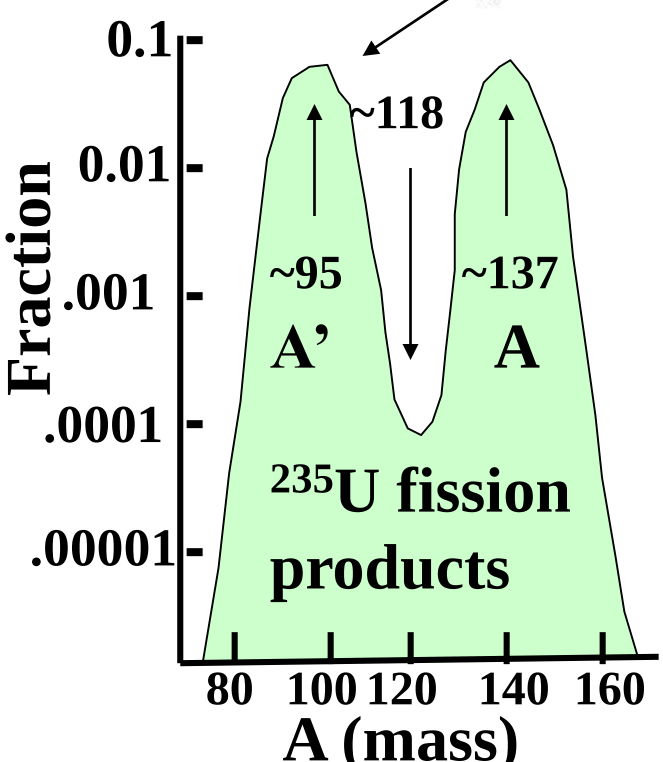
$$\left(\frac{1}{2}\right)^3 = \frac{1}{8} = 0.125 \qquad 3(5700) = 17100$$

$$\left(\frac{1}{2}\right)^4 = \frac{1}{16} = 0.0625 \qquad 4(5700) = 22800$$

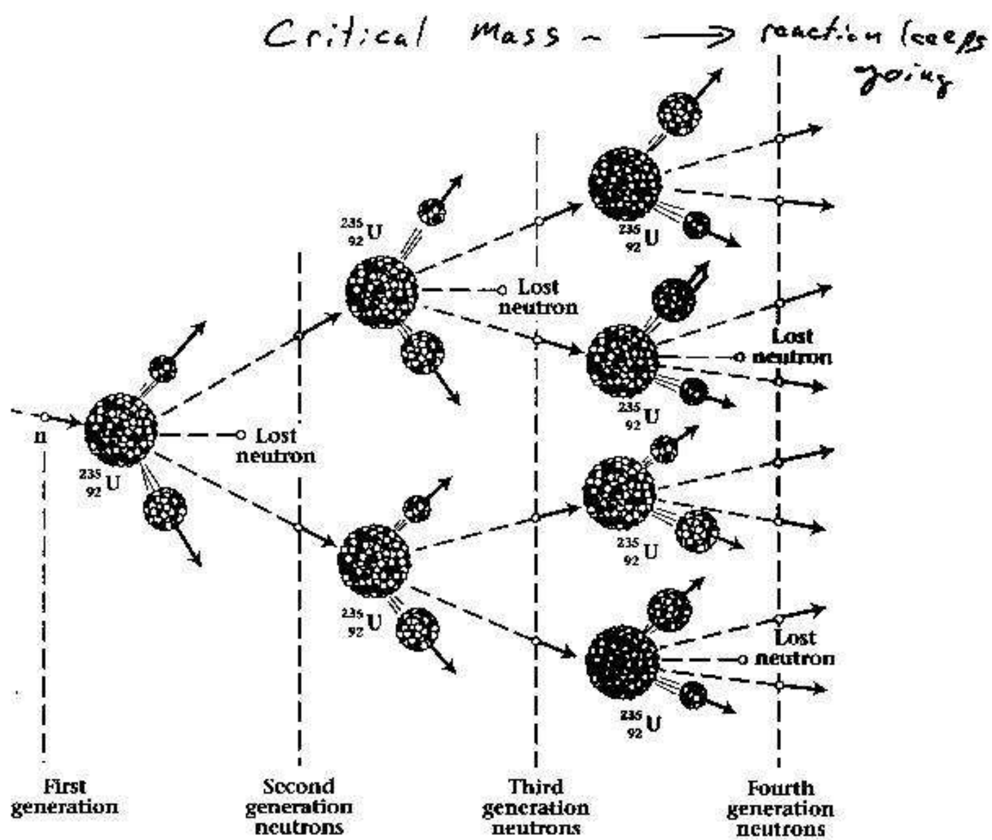
Fission

Coulomb repulsion wins





chain reaction



Atomic weapons: fission bombs : U-bomb

^{235}U 0.7 % natural abundance

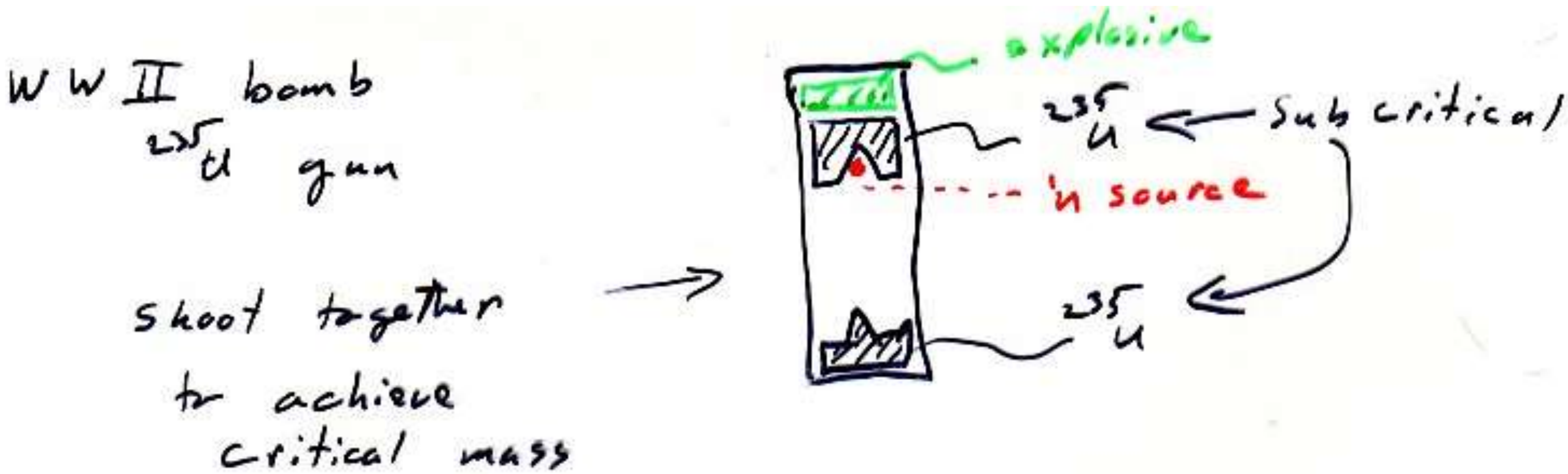
Weapons grade of enrichment 99% ^{235}U

Reactor grade of enrichment 3-4% ^{235}U

τ= time for spontaneous ^1n emission to initiate chain reaction

$\tau \sim 1\ \mu s$ for ^{235}U

time to assemble critical mass must be τ <



uranium gun-type atomic bomb (Little Boy) - Hiroshima

Atomic weapons: fission bombs : Pu-bomb

^{239}Pu man made in reactors

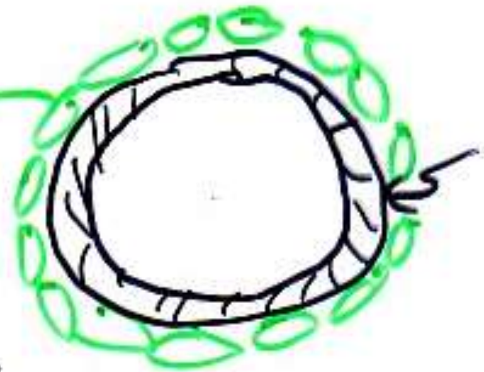
τ= time for spontaneous ^{1}n emission to initiate chain reaction

time to assemble critical mass must be τ <

2nd WWII bomb ^{239}Pu

τ - smaller
must assemble faster

explosive



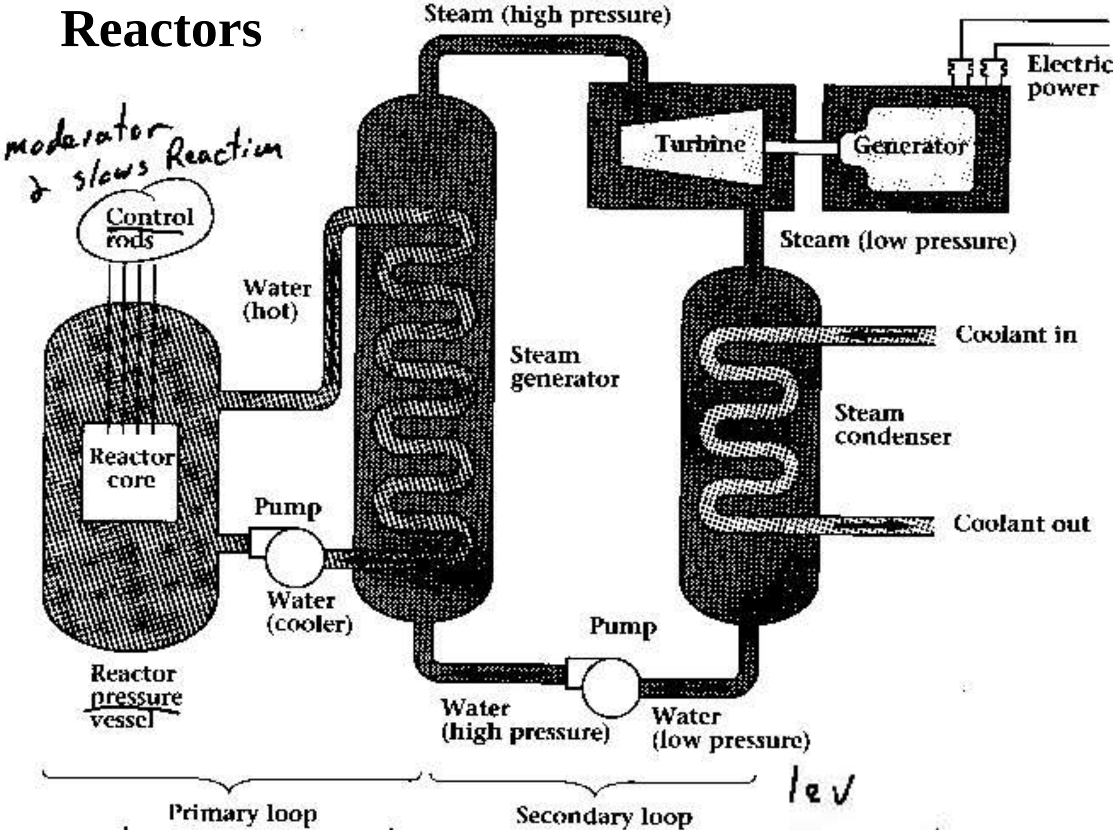
sphere of ^{239}Pu

detonate
simotaneously
to implode ^{239}Pu into lump critical mass.

timing of explosive detonation crucial

implosion-type bomb (Fat Man) on the city of Nagasaki

Reactors



1 eV slow ^{1}n best

$$^1n + {}^{235}U \Rightarrow {}^{236}U^*$$

$$^{236}U^* \Rightarrow {}^{140}Xe + {}^{94}Sr + 2\,{}^1n$$

$$^{236}U^* \Rightarrow {}^{141}Ba + {}^{92}Kr + 3\,{}^1n$$

$$^{236}U^* \Rightarrow {}^{150}Nd + {}^{81}Ge + 5\,{}^1n$$

1eV
slow neutrons
best

fast neutrons

Moderator
H_2O
or C
Slows down n

also
Controle C rods - absorb n
slow down or stop chain reaction

Heat → work

Note: T of reactor is low

→ low thermodynamic efficiency

→ large waste heat loss to surroundings

Problems that can occur with nuclear reactors

^{92}Kr gas-radioactive-overpressure develops
-released and controlled way (or blow out)

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cooling system breakdown or coolant loss
"China syndrome" – fuel melts - concentrates
- burns through reactor containment floor
- molten fuel burns into earth below reactor
- hits ground water – blast of dirty radioactive steam emitted

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Chernobyl (C-moderator- Russian design)
- test of reactors ability to run its own cooling system-
- undetected problems – local heating
- C- rods fracture – blocked at 33% insertion - steam blow outs
- C moderator ignited and burns
- fuel rods melt – steam explosion – C rod fire blow roof off
- smoke carries away radioactivity

Radioactive isotopes released
^{137}Cs **particles - aerosol**
^{92}Sr **radioactive released - Sr^{2+} like Ca^{2+} -- concentrates in bones**
^{129}I **- long half life released I gets in grass – cows eat – into milk supply**

Breeder Reactor

takes advantage of

$$^{1}n + {}^{238}U \rightarrow {}^{239}U \xrightarrow[T_{1/2}=23\text{ min}]{e^-} {}^{239}Np \xrightarrow[T_{1/2}=2.3\text{ d}]{e^-} {}^{239}Pu \nearrow \text{fission fuel}$$

^{1}n: fast

^{239}Pu: $T_{1/2}$=24,000 yr

∴ decrease moderator in reactor

^{238}U : 15-30% ^{235}U → ^{239}Pu fuel created

~20% ^{239}Pu → $^{1}n \rightarrow {}^{235}U$ energy generated

$^{1}n \rightarrow {}^{239}Pu$ energy generated

reactor lasts 10-20 yr – creates enough fuel for another reactor

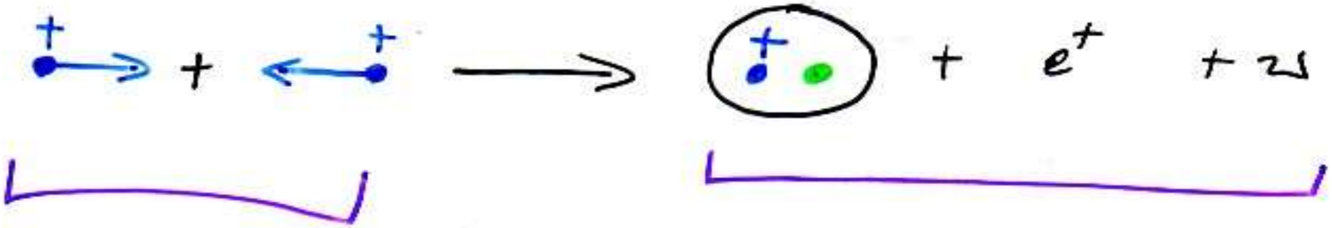
Common in Europe (France)

fear – generates ^{239}Pu weapons product

What to do with nuclear waste ?

Fusion

$$\underbrace{{}^1H + {}^1H}_{\text{hydrogen / proton}} \longrightarrow \underbrace{{}^2H}_{\text{Deuterium}} + \underbrace{e^+}_{\text{positron}} + \underbrace{\nu}_{\text{neutrino}}$$



mass in - - - - · —— . less mass out

$$E = mc^2$$

E ← energy, m ← mass, c^2 ← speed of light squared

$$E_{fusion} = m_{(in)}c^2 - m_{(out)}c^2$$

- mass converted to energy
- c^2 is a big # $\therefore$ little mass gives lots of energy !

Core of sun

High pressure & density $\Rightarrow$ lots of p^+ p^+ collisions

(opportunities to fuse)

High temperature : ~ 15 million K

High temperature $\Rightarrow$ high p^+ velocity $$< \frac{1}{2}mv^2 >= \frac{3}{2}kT$$

∴ very fast speeds

$$p^+ \xrightarrow{\quad v \quad} \qquad\qquad \xleftarrow{\quad v \quad} p^+$$

Speed (v) high enough: overcome coulomb potential (repulsion). Nuclei get close enough for strong nuclear force to win & fusion to occur.

Nuclear reaction in sun

Proton – Proton Chain

Fusion bomb (H-bomb)

$$^{2}H \quad + \quad ^{3}H \quad \Rightarrow \quad ^{4}He \quad + \quad ^{1}n$$

deuterium **tritium**

(natural isotope) **(1/2 life = 12.3 yr)**

Needs to be replenished every~ 12 yrs or so

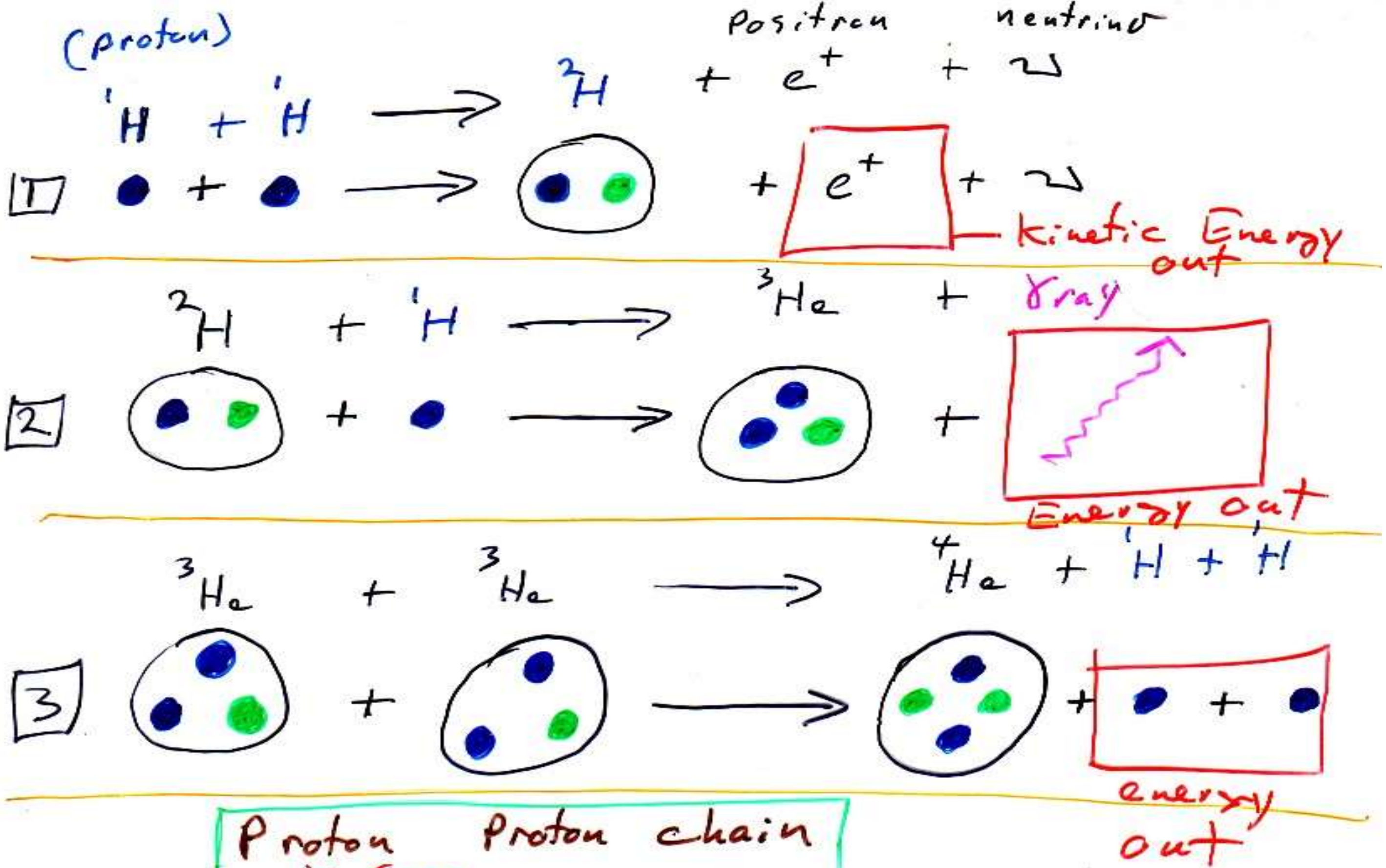
- bomb yield will decay

To drive this reaction high H velocities required (to overcome the coulomb repulsion)

T~ 1-10 million ^{0}K needed to get right H velocities

Use fission bomb (U or Pu) to trigger/heat-up fission bomb

It is this fission trigger that makes H-bomb dirty (radioactive)



Proton Proton chain in Sun

- Energy out to heat up soroundings at each step $\underbrace{\text{6 protons in}} \rightarrow \underbrace{^4He + \text{2 protons out}}$
- Change in mass in $\rightarrow$ out $\rightarrow$
  - $\hookrightarrow$ about 0.07%

$E = mc^2$ ← [Einstein]

still lots of energy

[Fussion Energy source in Sun]

Fusion bomb (H-bomb) cont.

$$^{2}H + {}^{3}H \Rightarrow {}^{3}He + {}^{1}n$$

nuclear weapon needs to keep lump of nuclear reacting material together long enough to react (like to blow apart with partial reaction)

T(H-fusion-reaction)~ 1-10 million ^{0}K –nothing strong enough to contain

(even steel turns to vapor ~ 1/10,000' th of this temperature)

inertial confinement

high Z material resists expansion by virtue of the inertia of its mass (tamper)

"bright idea"- use left over "scrap" ^{238}U for tamper

Actually - ^{238}U tamper used to get more "bang for $"

$^{1}n + {}^{238}U \Rightarrow {}^{239}U \rightarrow {}^{239}Np \rightarrow {}^{239}Pu$ fissionable

1/2 life 24,000 yrs

nuclear reaction activated $^{238}U \rightarrow {}^{239}Pu$ which fissioned

results—they get a bigger dirtier blast

Tsar Bomb- 1961 largest test 50 to 58 megatons of TNT used Pb tamper – so one of the "cleanest" nuclear explosions

Fusion bomb (H-bomb) cont.

$$^{2}H + ^{3}H \Rightarrow ^{3}He + ^{1}n$$

Castle Bravo a dry fuel hydrogen bomb, 1954, at Bikini Atoll, Marshall Islands

fuel **$^{6\text{-}7}Li^{2}H = ^{6\text{-}7}LiD$** Natural Li 7.5% ^{6}Li + 92.5% ^{7}Li

bomb enriched to 40% ^{6}Li + 60% ^{7}Li

$\boxed{^{6}Li + ^{1}n \Rightarrow ^{4}He + ^{3}H}$ Expected ^{6}Li to yield fusion fuel

Expected ^{7}Li to do $^{7}Li + ^{1}n \Rightarrow ^{8}Li \Rightarrow e^{-} + ^{8}Be$ $^{8}Be \Rightarrow 2\ ^{4}He$

With fast n they got

$\boxed{^{7}Li + ^{1}n \Rightarrow ^{8}Li \Rightarrow ^{4}He + ^{3}H + ^{1}n}$ **increased fast n flux !**

more fission fuel !

- fireball ~ 4.5 mi (~7 km) across within ~1 s

- mushroom cloud – 1 min height 14 km, diameter 11 km)

-10 min 40 km height, 100 km diameter

Expected 5 M tom – got 15 M ton yield

neutronization in core instant before supernova

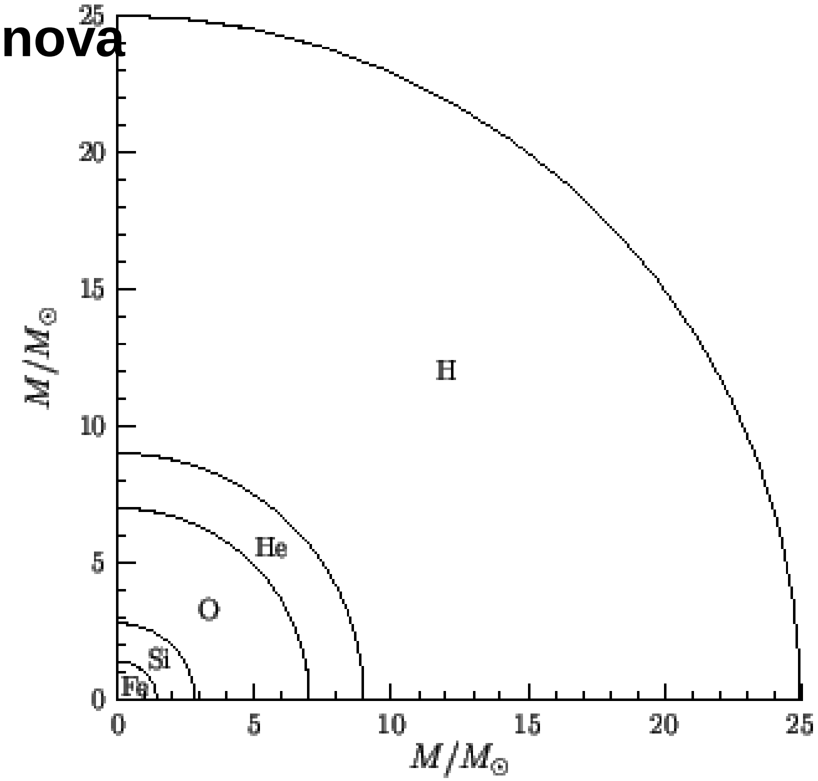


Figure: Onion-like interior structure of a Population I star of $25\ M_\odot$ just before the onset of collapse (see Ref. [249]).

Fe represents assorted iron-peak elements: ^{48}Ca, ^{50}Ti, ^{54}Fe, ^{56}Fe, ^{58}Fe, ^{66}Ni. The Si shell contains less abundant amounts of S, O, Ar, Ca, the O shell contains less abundant amounts of Ne, C, Mg, Si, the He shell contains less abundant amounts of C, Ne, O, and the H shell contains less abundant amounts of He, Ne, O, N, C.

Fusion energy burns out – star collapses violently
– gravitational energy heats core to 13 billion K – tremendous pressures

Fe nuclei cook apart – decompose (photo dissociate)

$$\gamma + {}^{56}\mathrm{Fe} \rightarrow 13\,\alpha + 4\,n\,.$$

Electrons capture occurs and nuclei decompose to neutrons (neutronization)

$$e^- + p \rightarrow n + \nu_e\,,$$ **This neutrino blast escapes !!!!**

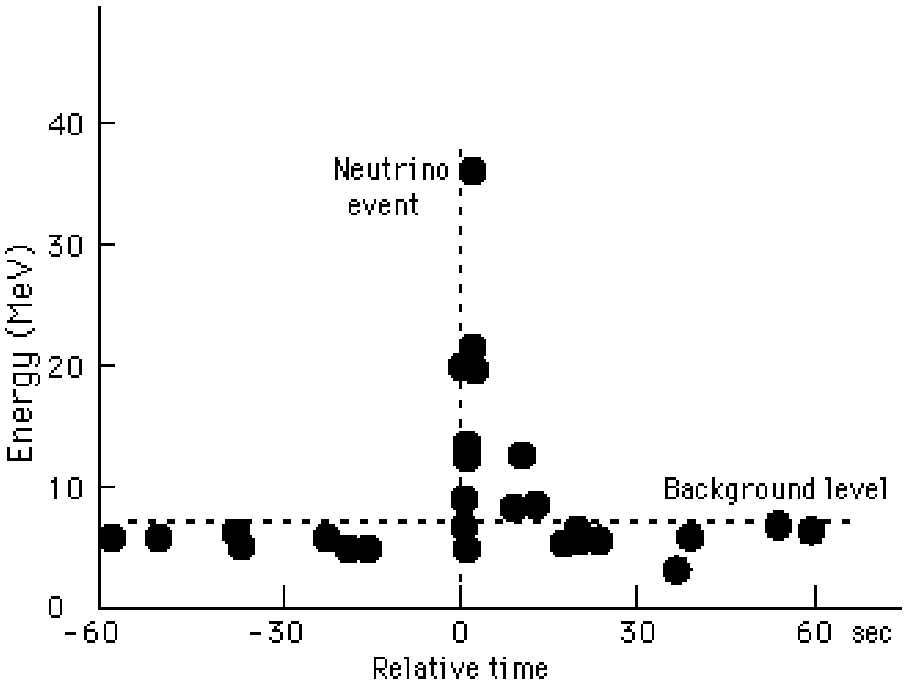
Collapsing star rebounds off of hard core of neutron star and explodes in supernova
(if massive enough neutron core collapses to gravitational black hole)

Electrons capture occurs and nuclei decompose to neutrons (neutronization)

$$e^- + p \rightarrow n + \nu_e \,,$$ **This neutrino blast escapes !!!!**

Collapsing star rebounds off of hard core of neutron star and explodes in supernova (if massive enough neutron core collapses to gravitational black hole)

Neutrino's from Supernova 1987A (Shelton)



^{210}Po

1897 discovered Marie & Pierre Curie - named after Marie's home Poland

mg ^{210}Po emits as many alpha particles as 5 g of radium

1/2 g quickly reaching a temperature above 750 K.

^{210}Po emit a blue glow by excitation of surrounding air.

1 g ^{210}Po generates energy at the rate of 150 watts

applications: space craft – antistatic

lethal dose of only 0.12 micrograms

1934 $\quad$ $\mathbf{n + {}^{209}Bi \Rightarrow {}^{210}Bi}$

mg amounts producible using high n flux nuclear reactors -100 g/yr

$$\mathbf{n + {}^{209}Bi \Rightarrow {}^{210}Bi}$$

$\mathbf{{}^{210}Bi \Rightarrow \beta^- + {}^{210}Po}$ $\quad$ **τ = 5.01 days.**

$\mathbf{{}^{210}Po \Rightarrow \alpha + {}^{206}Pb}$ $\quad$ **τ = 138.38 days.**

^{206}Pb non-radioactive

$^{222}Rn \Rightarrow \alpha + {}^{218}Po$ τ = 3.824 days.

$^{218}Po \Rightarrow \alpha + {}^{214}Pb$ τ = 3.05 minutes.

$^{214}Pb \Rightarrow \beta^+ + {}^{214}Bi$ τ = 26.8 minutes.

$^{214}Bi \Rightarrow \beta^- + {}^{214}Po$ τ = 19.8 minutes

$^{214}Po \Rightarrow \alpha + {}^{210}Pb$ τ = 164 microseconds.

$^{210}Pb \Rightarrow \beta^- + {}^{210}Bi$ τ = 22.3 years.

$^{210}Bi \Rightarrow \beta^- + {}^{210}Po$ τ = 5.01 days.

$^{210}Po \Rightarrow \alpha + {}^{206}Pb$ τ = 138.38 days.

^{206}Pb stable ^{206}Pb non-radioactive

Liquid Metal cooled Fast Breeder Reactors (LMFBR)