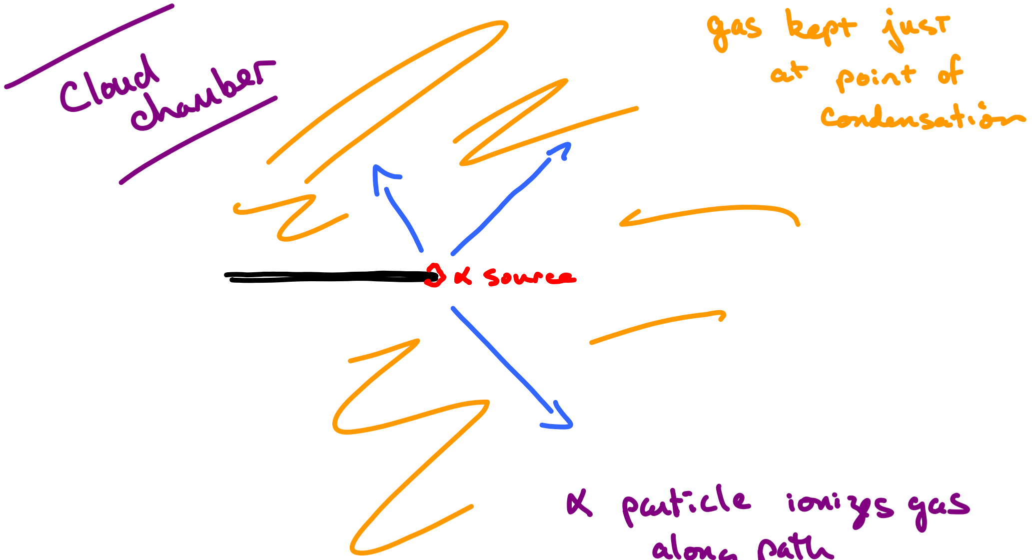
Physics 123 – April 29, 2013

Continuing with Nuclear Physics



gas kept just at point of condensation

α particle ionizes gas along path

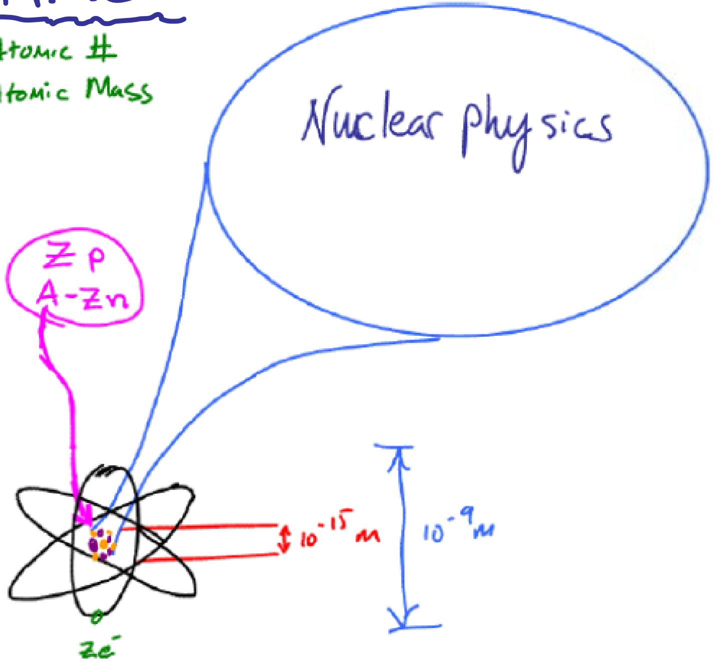
gas condenses at points of energy deposition

"See" track

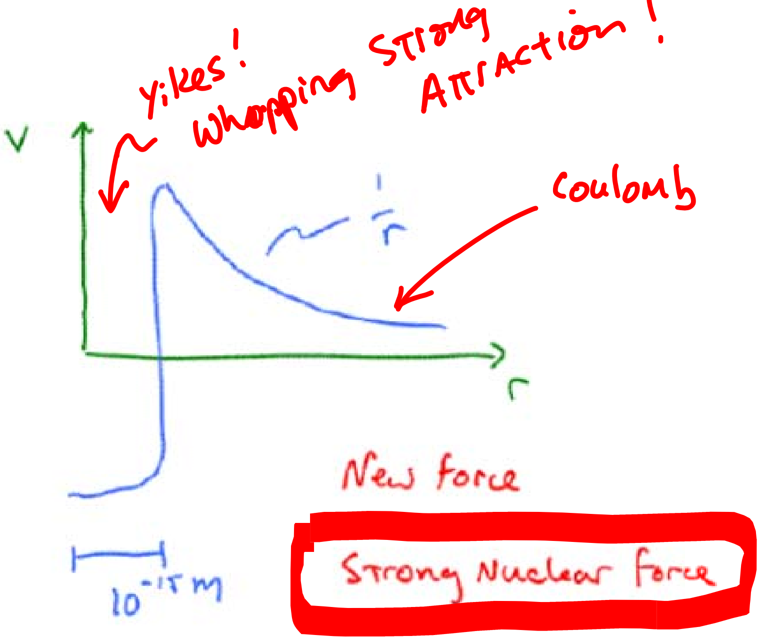
Last Time

Z ≡ Atomic #

A ≡ Atomic Mass



Particle	chg	Mass (MeV/c^2)	Spin
Proton, p	+e	938.28	½
neutron, n	0	939.37	½
electron, e	-e	0.511	½



Nuclear radius ~ 1-10 Fermi (10^{-15} m)

Nuclear density is constant

$$\frac{A}{\frac{4}{3}\pi R^3} \sim \text{const.} \qquad A \sim R^3$$

$$R \sim A^{1/3}$$

$\rho \sim 10^{17}\ \mathrm{kg/m^3}$

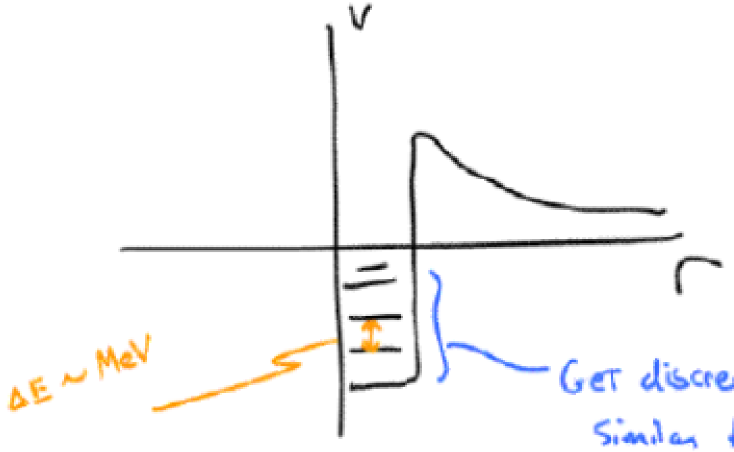
At this density

$M_{earth} \rightarrow$ ball 140 m in radius

for H ATOM

Strong nuclear interaction

Potential is attractive too



Get discrete energy levels
Similar to Atom

p, n spin ½

But separation $O(\text{MeV})$ instead of $O(10\,\text{eV})$

Why do you care?

fill shells w/ protons + neutrons in much the same way we fill atomic shells

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

X, Z same info

Symbol for a nucleus

X ≡ Atomic Symbol

Z ≡ # protons — Atomic #

A ≡ Atomic Mass

N ≡ A − Z ≡ # neutrons

Isotope → Same Z, Different A

Transitions between States Very Energetic

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

GAMMA radiation

γ

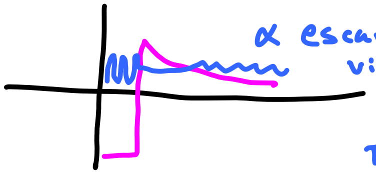
$${}^{A}_{Z}X' \longrightarrow {}^{A}_{Z+1}X + e^{-} + \bar{\nu}_e$$

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

β

β radiation

protons + neutrons collectively called "Nucleons"



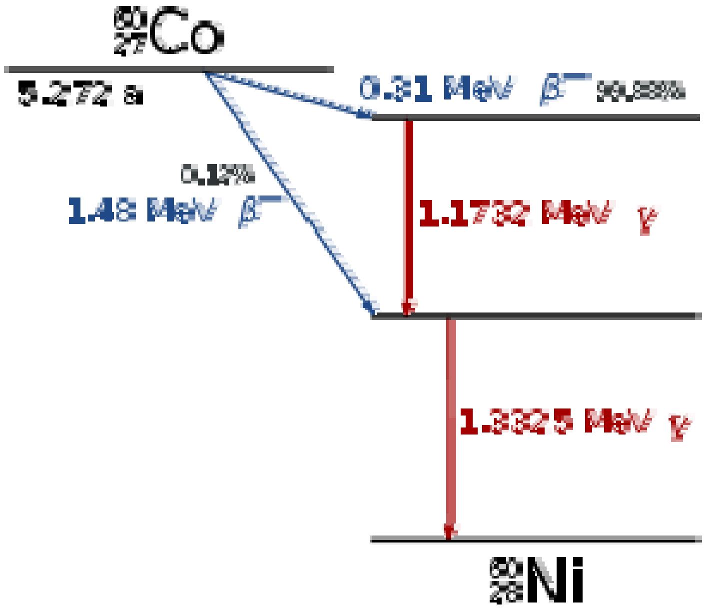
α escapes via quantum Tunneling

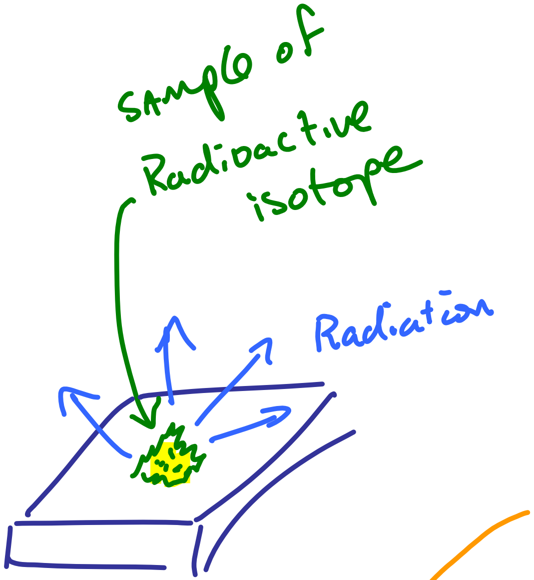
$${}^{A}_{Z}X' \longrightarrow {}^{A-4}_{Z-2}X + \alpha$$

Alpha radiation

${}^{4}_{2}He$

Example nuclear decay scheme





$$\frac{dN}{dt} = -\lambda N$$

decay constant

N ≡ # radioactive nuclei in sample

Activity ≡ # nuclei decaying per second

measured in Curies

$1\ \text{Ci} = 3.7\times10^{10}\ \frac{\text{dec.}}{\text{s}}$

$$\frac{dN}{N} = -\lambda\, dt$$

$$\int_{N_0}^{N} \frac{dN}{N} = -\int_{0}^{t} \lambda\, dt$$

$$\ln \frac{N}{N_0} = -\lambda t$$

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

$\lambda \equiv$ decay constant

$\#$ nuclei drop by $\frac{1}{e}$ when $t = \frac{1}{\lambda}$

"fast decay" → large λ

$$\boxed{t_{\frac{1}{2}} = \frac{0.693}{\lambda} \equiv \text{half-life} \equiv \text{time for } \tfrac{1}{2} \text{ the nuclei to decay}}$$

N atoms in sample
at time =0

$$\text{Activity} \equiv \frac{\#\text{decays}}{\text{second}} = \frac{\Delta N}{\Delta t} = \underset{\uparrow}{\lambda} N$$

decay CONSTANT

halflife ≡ $t_{1/2}$ = time for ½ sample to decay

$$t_{1/2} = \frac{0.693}{\lambda}$$

Radioactive Dating

"Normal" carbon $^{12}_{6}C$

$^{14}_{6}C$ Produced by cosmic rays Hitting Atmosphere

^{14}C is naturally radioactive

β-emitter

$t_{1/2}$ = 5730 years

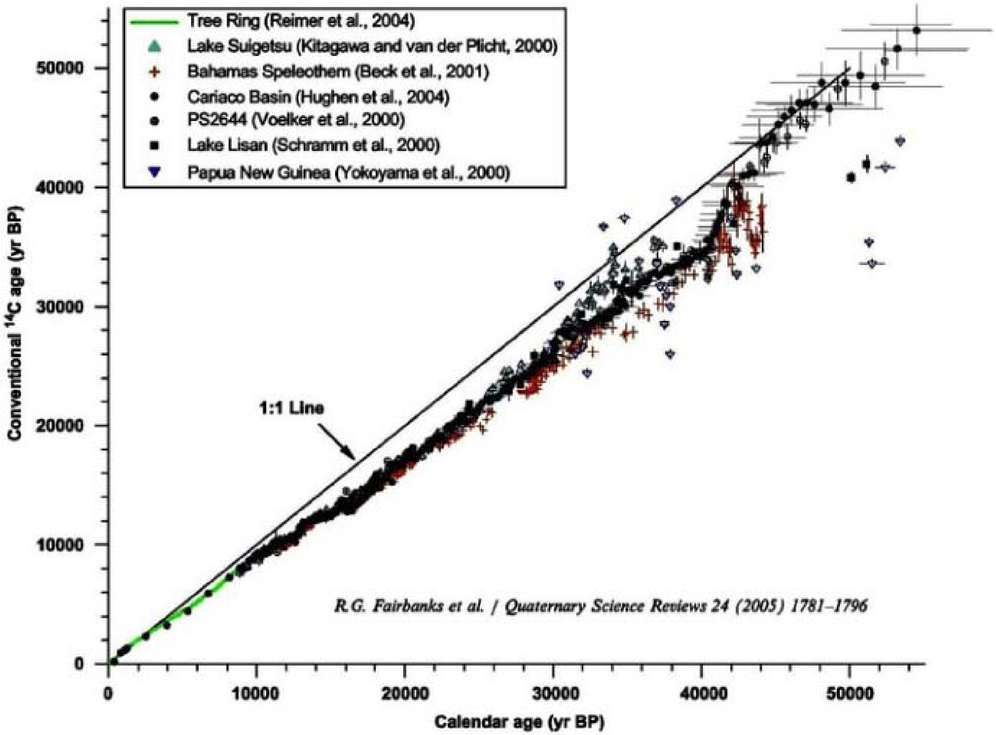
- ^{14}C incorporated into living tissue
- Stops at death
- $^{14}C/^{12}C$ ratio gives estimate of time since death
- ^{14}C concentration in atmosphere varies, calibrate w/ tree rings

A sample of bone

^{14}C activity to be 25 % of that in living material. How old is the bone?

^{14}C $t_{\frac{1}{2}} = 5730$

radiocarbon dating
Calibration
Data



R.G. Fairbanks et al. / Quaternary Science Reviews 24 (2005) 1781–1796

Fig. 1. Composite figure showing the range of radiocarbon calibration data from a variety of archives, including Bahamian speleothems (Beck et al., 2001), marine sediments (Hughen et al., 2000, 2004a; Voelker et al., 2000; lake sediments (Schramm et al., 2000; Kitagawa and van der Plicht, 2000), corals (Yokoyama, 2000), and tree rings (Reimer et al., 2004; Friedrich et al., 2004).

Nuclear Binding Energy

Consider atomic binding energy (ionization energy)

$$\underbrace{m_e c^2 + m_p c^2}_{\text{Energy of separate parts}} - \underbrace{M_H c^2}_{\text{energy of Bound beast}} = \underbrace{13.6\,\text{eV}}_{\text{Binding energy}}$$

For Atoms ... ionization energy is what we call it.

Nuclear Binding Energy

For a nucleus "x" with A, Z:

$$\boxed{(A-Z)M_n c^2 + Z M_p c^2 - M_x c^2 = \text{Total Nuclear Binding Energy}}$$

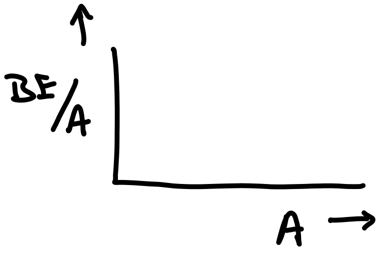
Binding Energy per Nucleon = Total BE/A

≡ Amount of E to remove a nucleon if you will
"ionization energy for a nucleon" sort of

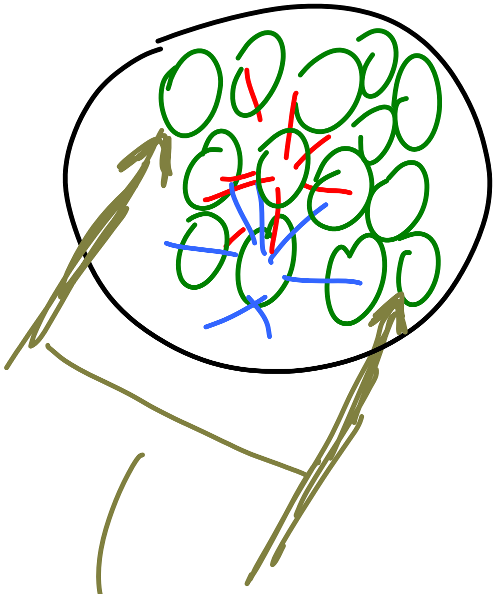
High BE/A → Very stable nucleus

Low BE/A → less stable nucleus

let's look at



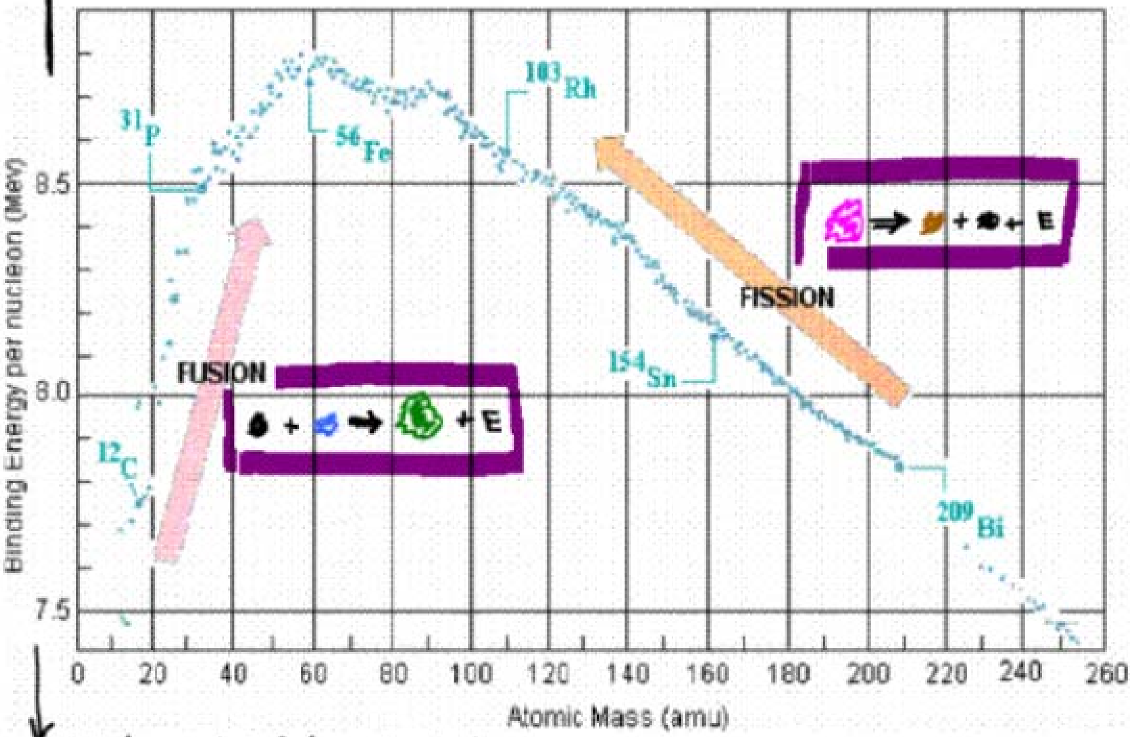
recall range of str. force $O(10^{-15} m)$



over large distances
→ coulomb

Inherent Nuclear stability as function of nuclear size

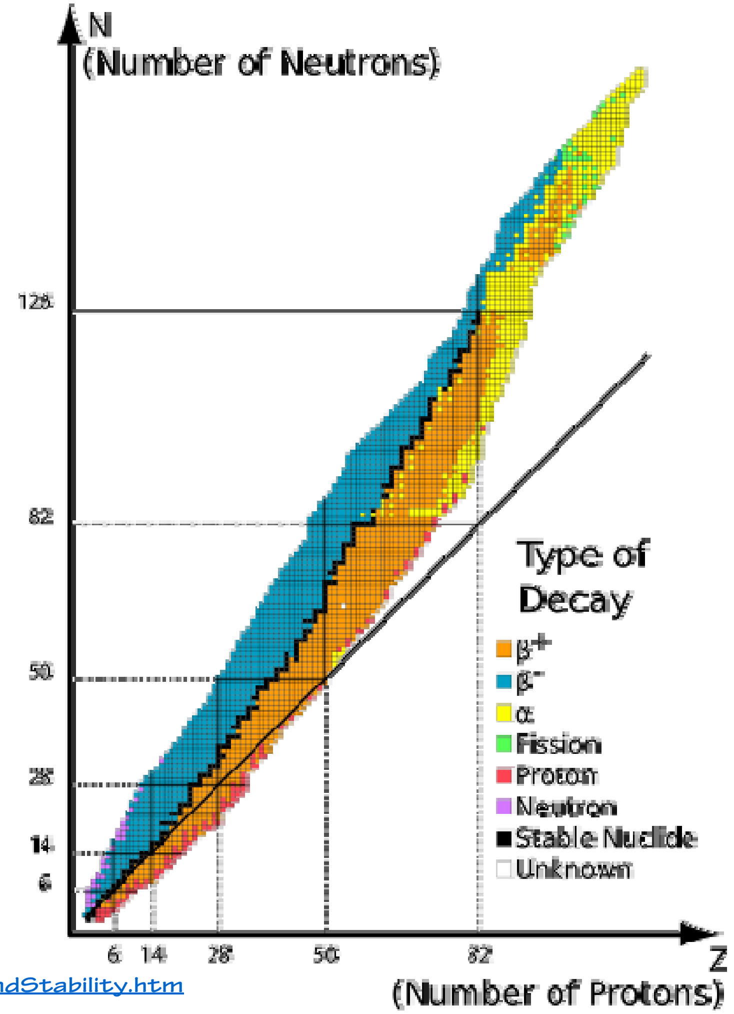
nucleons held more tightly



nucleons held less tightly

line of Stability

$\#_n > \#_p$



Nice figure from http://www.kentchemistry.com/links/Nuclear/BandStability.htm

Fun with Fission

Woohoo!

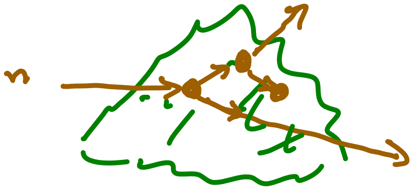
A very important nuclear process ...

$$\underbrace{{}^{235}_{92}U}_{\Sigma\,\text{mass} = M_{initial}} + n \longrightarrow {}^{93}_{37}Rb + {}^{141}_{58}Cs + 2n$$

$$\gamma \quad \gamma \qquad \gamma \quad \gamma$$

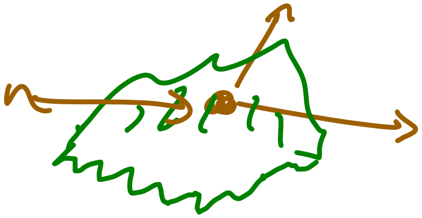
$$\underbrace{\text{cascade of decays}}_{\Sigma\,\text{mass} = M_{final}}$$

$$M_{initial} - M_{final} > 0$$



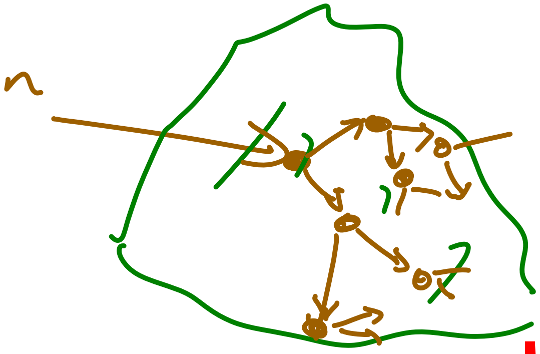
Critical

1 Split per Split



Subcritical

<1 Split per split



Supercritical

>1 split per split

Watch out!

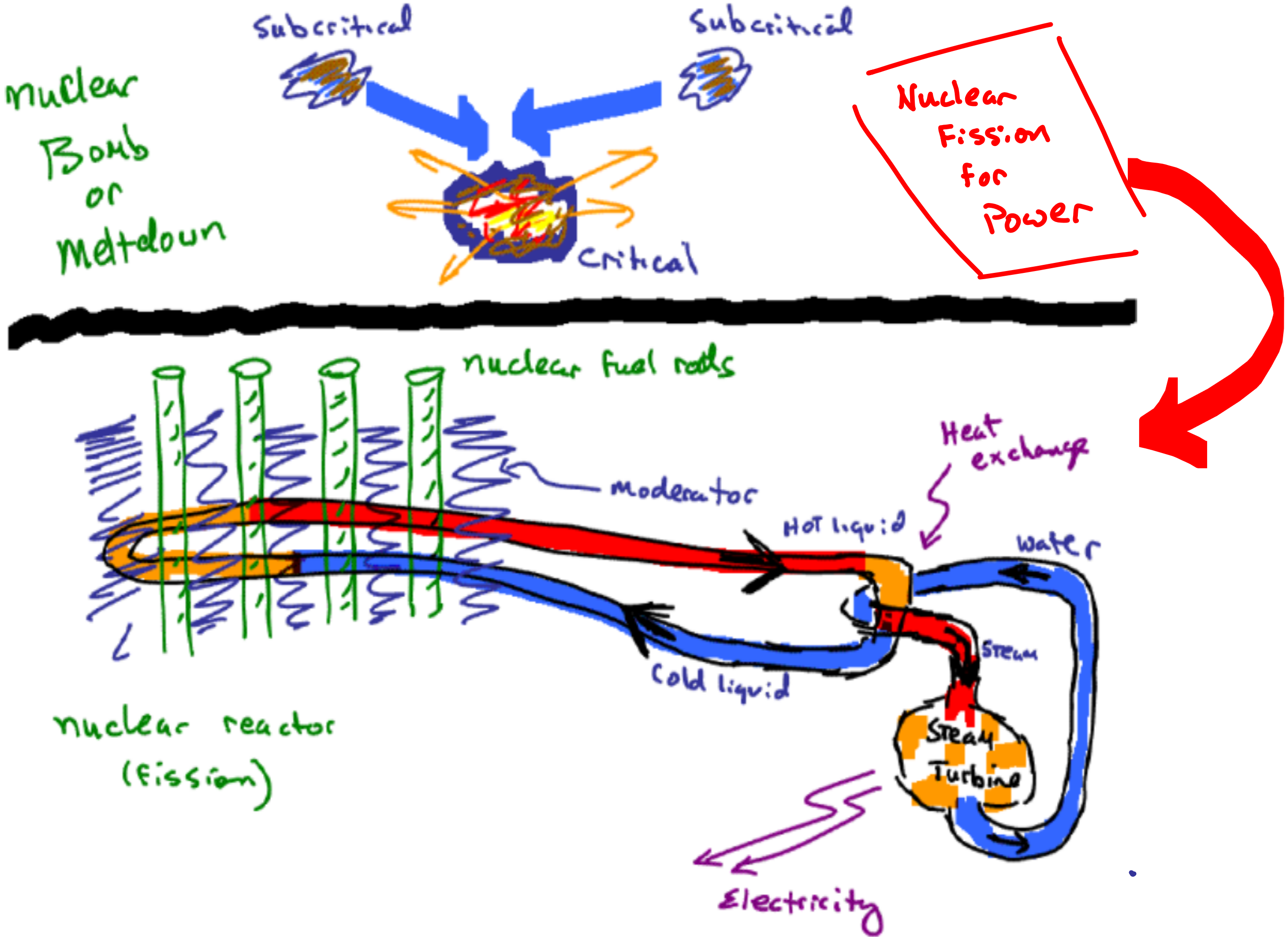
Kablooey!

or

meltdown

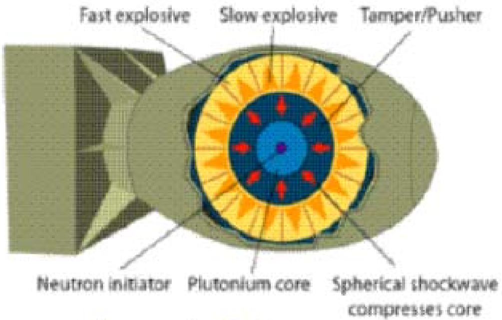
+

Fire


nuclear Bomb or Meltdown
Subcritical
Subcritical
Critical
Nuclear Fission for Power
nuclear fuel rods
moderator
Heat exchange
Hot liquid
water
steam
Steam Turbine
Cold liquid
nuclear reactor (Fission)
Electricity

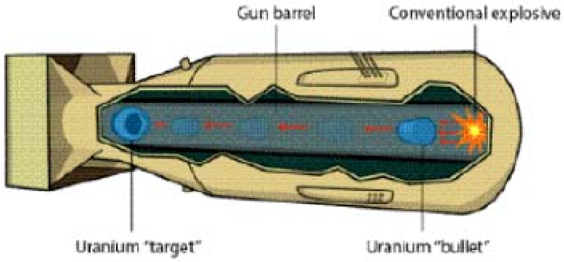
Implosive-type

Technically harder than Gun-type



Similar to Fat Man
used on Nagasaki
Aug. 9, 1945

Similar to "Little Boy"
used on Hiroshima
August 6, 1945



Gun-type

Diagrams
from
Wikipedia

Natural U
~99% ^{238}U
Must enrich
in ^{235}U to
use as fuel
Nuclear
or bomb

isotopes
very difficult
to impossible
to separate
chemically

Stars - from dust to dust

Stars form from
condensation of gas/dust
due to gravitation

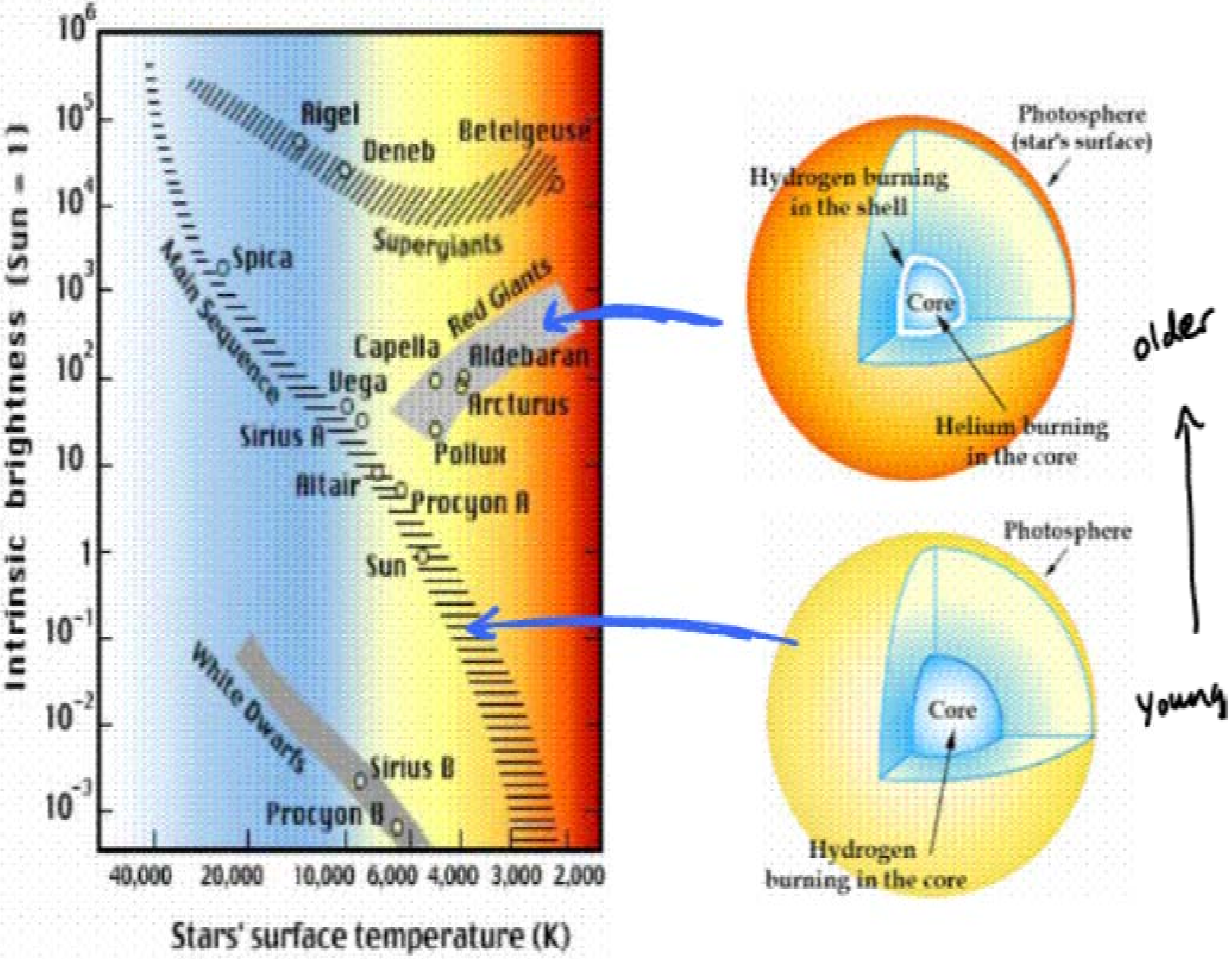
mostly hydrogen gas

Star-Birth Clouds · M16 HST · WFPC2

PRC95-44b · ST ScI OPO · November 2, 1995
J. Hester and P. Scowen (AZ State Univ.), NASA

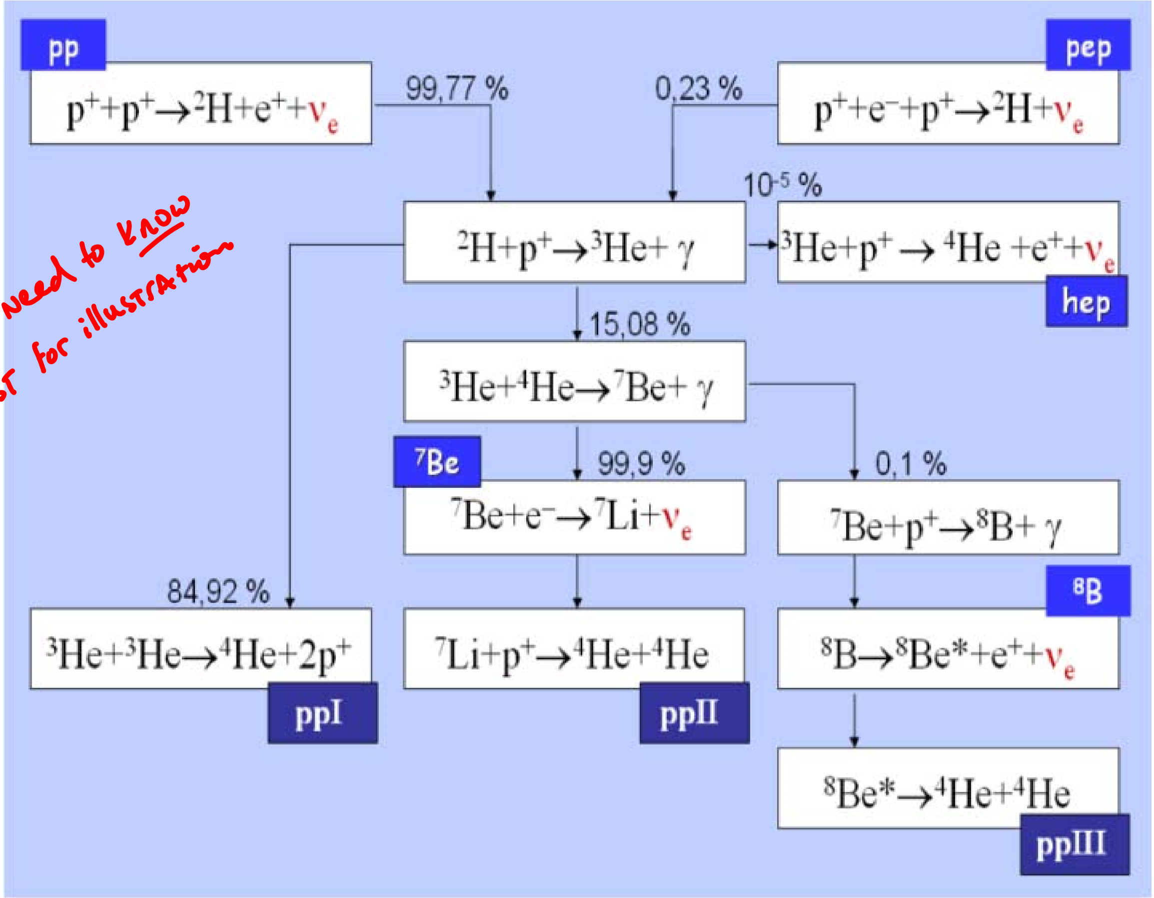
The Pleiades

Young stars residual dust
surrounding them



Intrinsic brightness (Sun = 1)
10^6
10^5
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
Rigel
Deneb
Betelgeuse
Supergiants
Spica
Main Sequence
Red Giants
Capella
Aldebaran
Vega
Arcturus
Sirius A
Pollux
Altair
Procyon A
Sun
White Dwarfs
Sirius B
Procyon B
40,000
20,000
10,000
6,000
4,000
3,000
2,000
Stars' surface temperature (K)
Photosphere (star's surface)
Hydrogen burning in the shell
Core
Helium burning in the core
Photosphere
Core
Hydrogen burning in the core
older
young

Primary Fusion Processes in the Sun



pp

$p^+ + p^+ \rightarrow {}^2H + e^+ + \nu_e$

99,77 %

0,23 %

pep

$p^+ + e^- + p^+ \rightarrow {}^2H + \nu_e$

10^{-5} %

${}^2H + p^+ \rightarrow {}^3He + \gamma$

${}^3He + p^+ \rightarrow {}^4He + e^+ + \nu_e$

hep

15,08 %

${}^3He + {}^4He \rightarrow {}^7Be + \gamma$

84,92 %

^{7}Be

99,9 %

${}^7Be + e^- \rightarrow {}^7Li + \nu_e$

0,1 %

${}^7Be + p^+ \rightarrow {}^8B + \gamma$

^{8}B

${}^3He + {}^3He \rightarrow {}^4He + 2p^+$

ppI

${}^7Li + p^+ \rightarrow {}^4He + {}^4He$

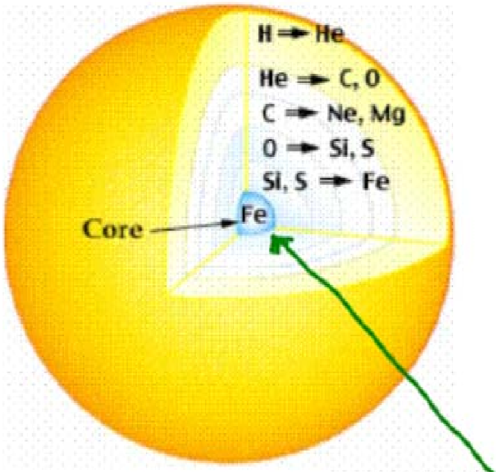
ppII

${}^8B \rightarrow {}^8Be^* + e^+ + \nu_e$

${}^8Be^* \rightarrow {}^4He + {}^4He$

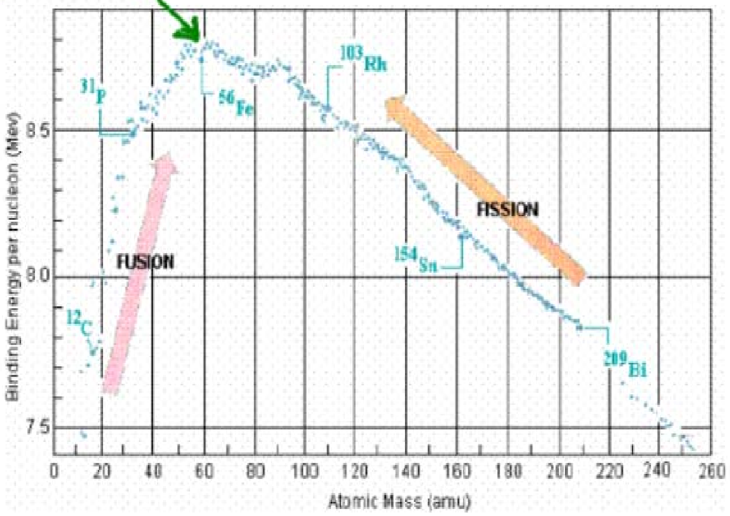
ppIII

No need to know
just for illustration

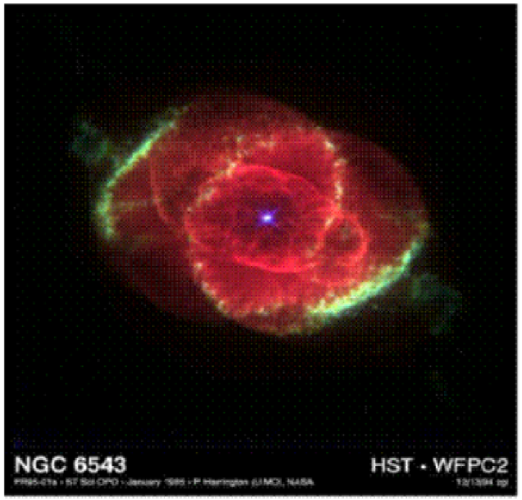


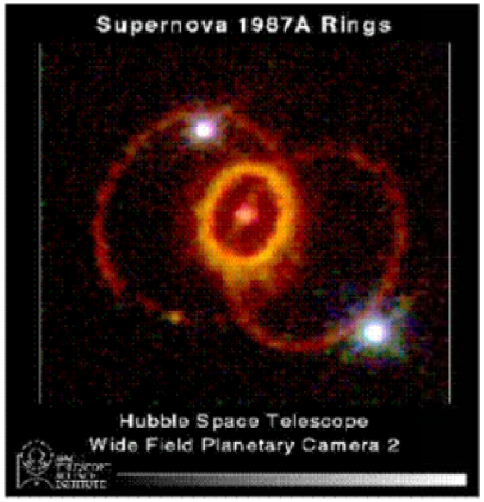
late life massive star

Fusion process into nuclei larger than ^{56}Fe takes energy rather than releasing energy

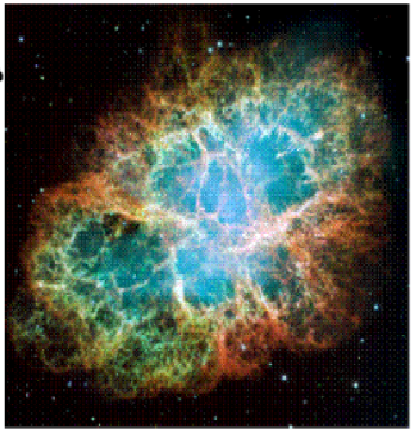


- Early universe almost entirely Hydrogen
- normal stellar evolution
  ↳ fusion A up to ~57
- Supernova processes
  ↳ fusion A > 57





STAR went Supernova in day
1054 – observed during
by Chinese and Arab
Astronomers



Crab
Nebula

Star went
Supernova in
1054