Interaction of Gamma-rays and Particles in Matter

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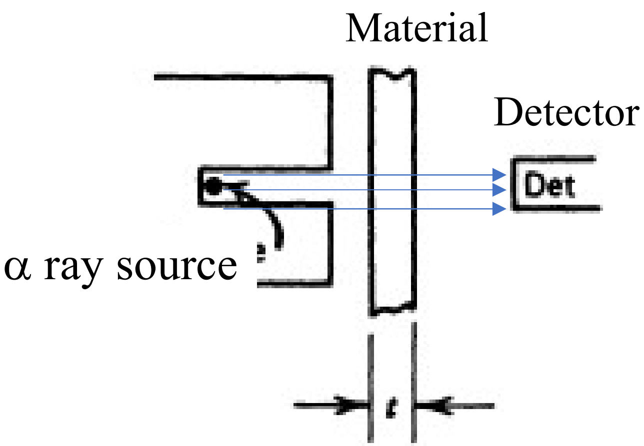
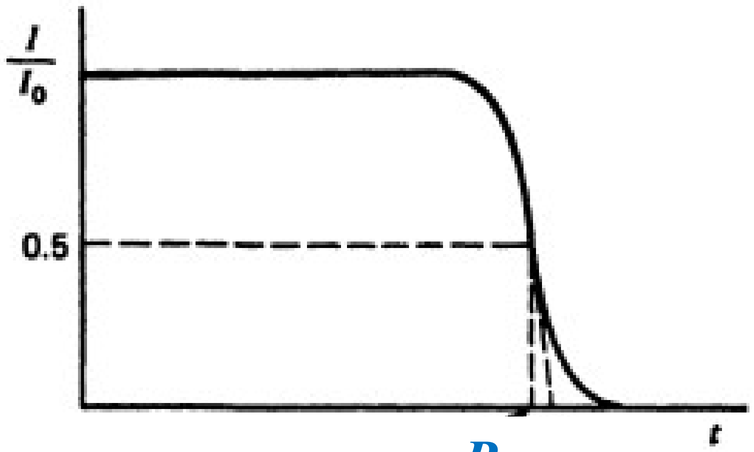
Radiation Interactions in Matter: 1. Charged particles

Charged particle : α rays, proton beam, Heavy ion beam → Material

Coulomb interaction b.w. electron in matter and charged particle
⇒ excitation, ionization
⇒ Lose the energy gradually through a lot of the interactions to electrons in matter
⇒ Stop

Range





Range

Calculation for Range → SRIM code (free soft)

http://www.srim.org/

======= Target Composition ========

Atom Name	Atom Numb	Atomic Percent	Mass Percent
C	6	100.00	100.00

====================

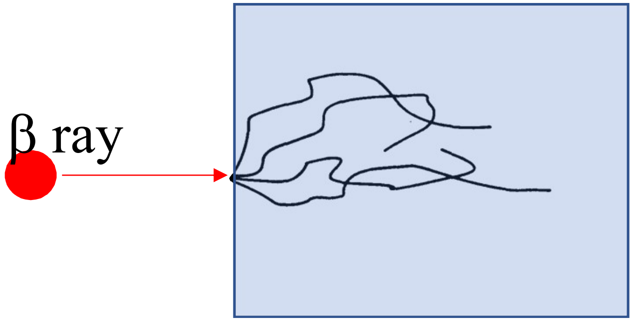
Proton beam in Carbon

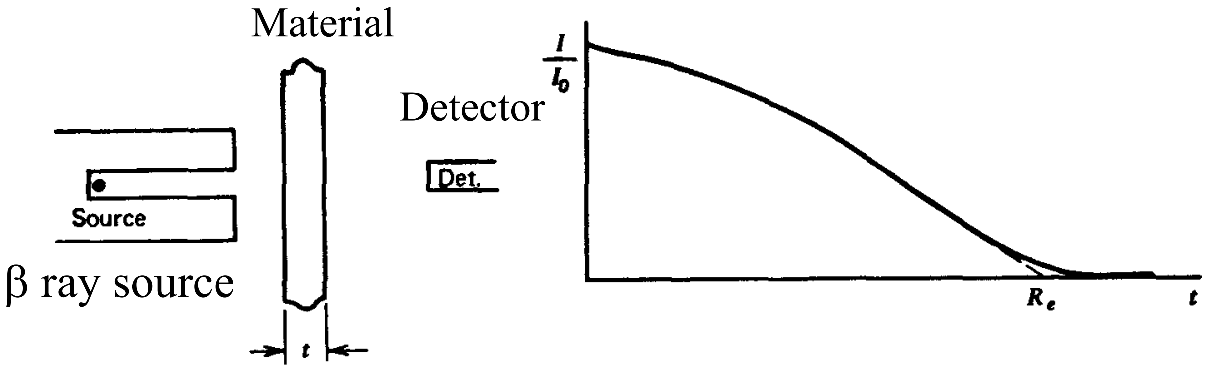
Bragg Correction = 0.00%
Stopping Units = MeV / (mg/cm2)
See bottom of Table for other Stopping units

Ion Energy	dE/dx Elec.	dE/dx Nuclear	Projected Range	Longitudinal Straggling	Lateral Straggling
500.00 keV	3.534E-01	2.738E-04	4.40 um	1837 A	1974 A
550.00 keV	3.334E-01	2.524E-04	5.04 um	2092 A	2182 A
600.00 keV	3.160E-01	2.342E-04	5.72 um	2347 A	2402 A
650.00 keV	3.007E-01	2.186E-04	6.44 um	2601 A	2632 A
700.00 keV	2.872E-01	2.051E-04	7.19 um	2856 A	2873 A
800.00 keV	2.640E-01	1.828E-04	8.80 um	3732 A	3385 A
900.00 keV	2.450E-01	1.651E-04	10.54 um	4553 A	3934 A
1.00 MeV	2.291E-01	1.507E-04	12.41 um	5350 A	4520 A
1.10 MeV	2.163E-01	1.387E-04	14.40 um	6134 A	5138 A
1.20 MeV	2.035E-01	1.286E-04	16.51 um	6915 A	5788 A
1.30 MeV	1.923E-01	1.199E-04	18.74 um	7703 A	6473 A
1.40 MeV	1.825E-01	1.124E-04	21.11 um	8501 A	7191 A
1.50 MeV	1.737E-01	1.058E-04	23.59 um	9309 A	7943 A
1.60 MeV	1.659E-01	9.998E-05	26.20 um	1.01 um	8727 A
1.70 MeV	1.588E-01	9.481E-05	28.93 um	1.10 um	9543 A
1.80 MeV	1.524E-01	9.017E-05	31.77 um	1.18 um	1.04 um
2.00 MeV	1.412E-01	8.219E-05	37.81 um	1.48 um	1.22 um

Radiation Interactions in Matter: 2. β ray (electron)

- β ray interacts electron in matter. Both have equal mass so that large energy transfer in a single encounter is possible and large deviations in the β ray path are also possible.





The β range is defined as maximum distance:
1 -2 mm / 1 MeV β ray

Radiation Interactions in Matter: 3. γ rays

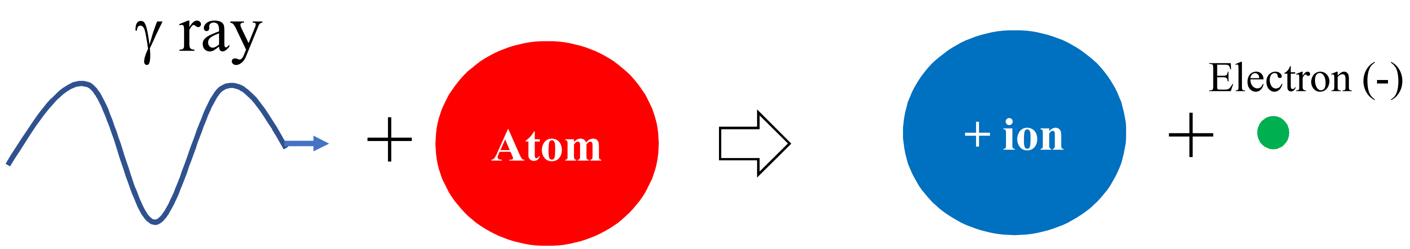
Main processes for radiation detection:

1. Photoelectric effect
2. Compton scattering
3. Pair creation

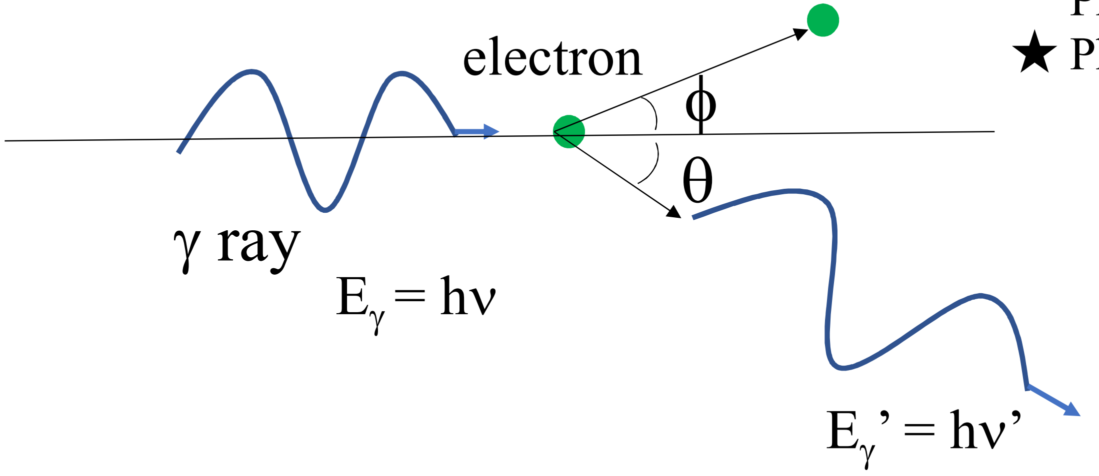
1. Photoelectric effect

- γ ray undergoes an interaction with absorbed atom in which the γ rays disappears.
- Energetic photo-electron is ejected.
- The energy:

$$E_e = E_\gamma - \text{binding energy of electron}$$



2. Compton Scattering



★ Incident photon collides with electron in the material. Photon is deflected through an angle θ.

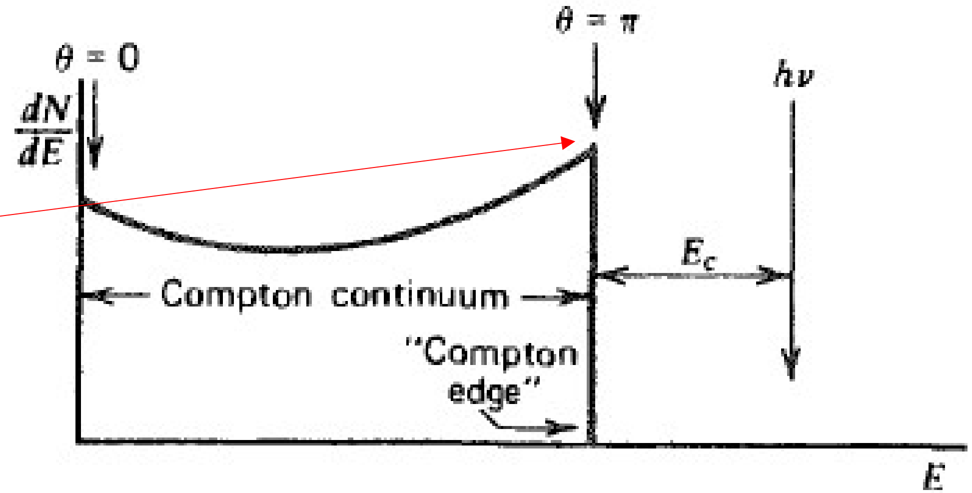
★ Photon transfers a portion of its energy to recoiled electron

$$h\nu' = \frac{h\nu}{1 + \frac{h\nu}{m_0c^2}(1 - \cos\theta)}$$

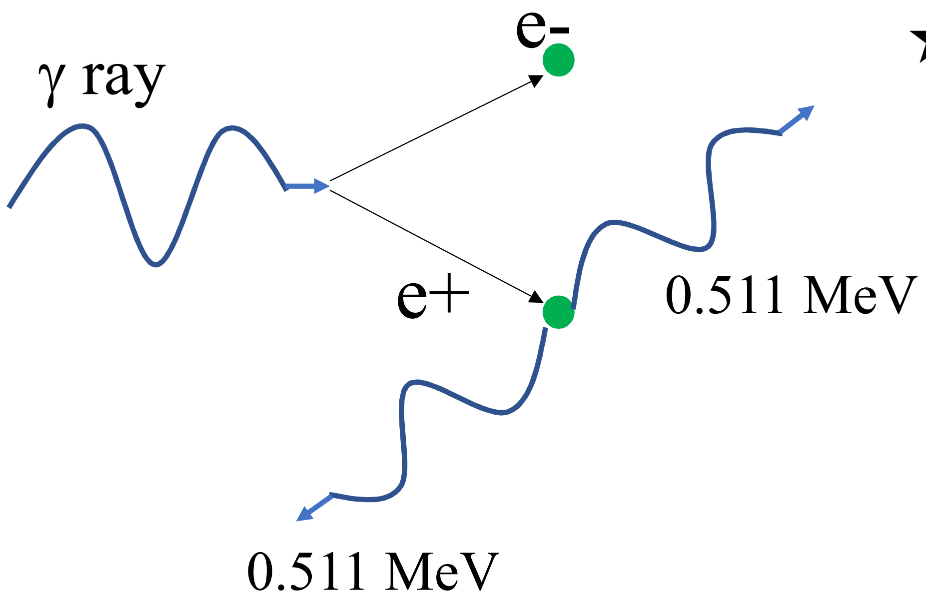
$m_0c^2 = 0.511$ MeV

E_e in max

$$E_{e^-}\Big|_{\theta = \pi} = h\nu\left(\frac{2h\nu/m_0c^2}{1 + 2h\nu/m_0c^2}\right)$$



3. Pair Production

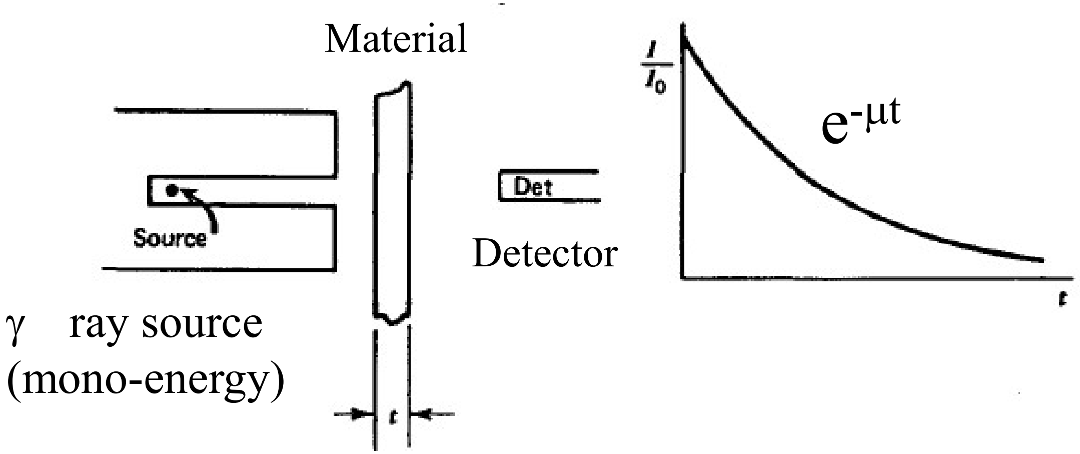


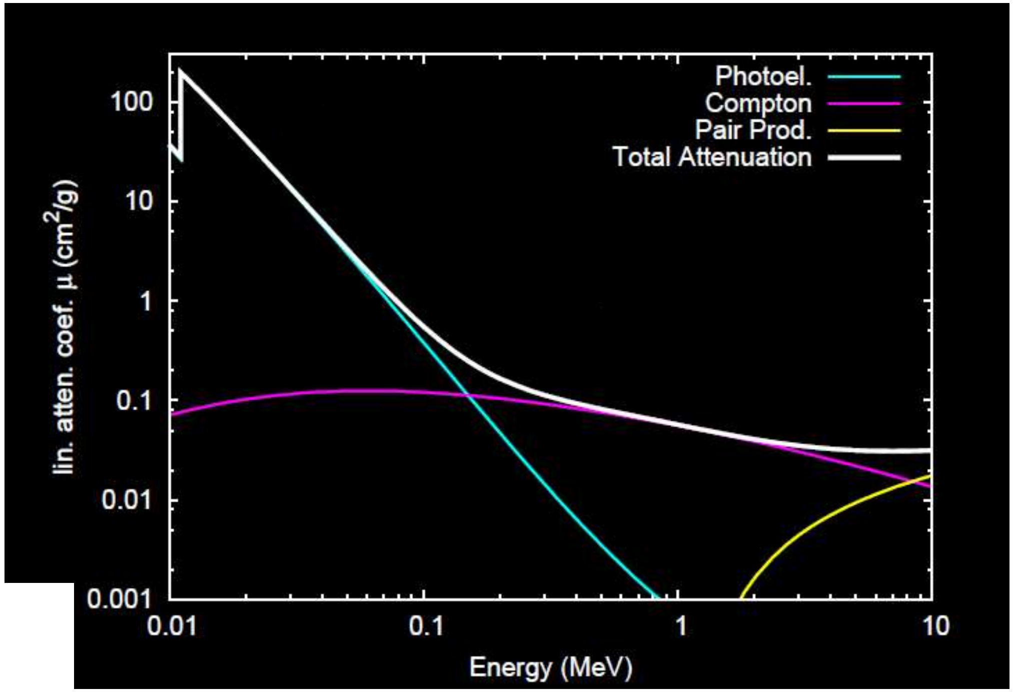
★ Require $E_\gamma > 2m_e = 1.022$ MeV
★ Occurs in strong electric field near nuclei.
★ Create electron and positron pair at the point of Complete disappearance of incident γ ray

$$E_{e-} + E_{e+} = h\nu - 2m_0c^2$$

★ Positron will annihilate → Two annihilation photons (γ rays) of 0.511 MeV appear
★ One or two g rays of 0.511 MeV may escape from absorbed material.

Attenuation coefficient





★ γ ray yield decreases exponentially according with absorber (material) thickness, since those process occur with a certain probability per unit path length in the absorber and γ ray photon is removed (absorbed or scattered).

⇒ μ: linear attenuation coefficient

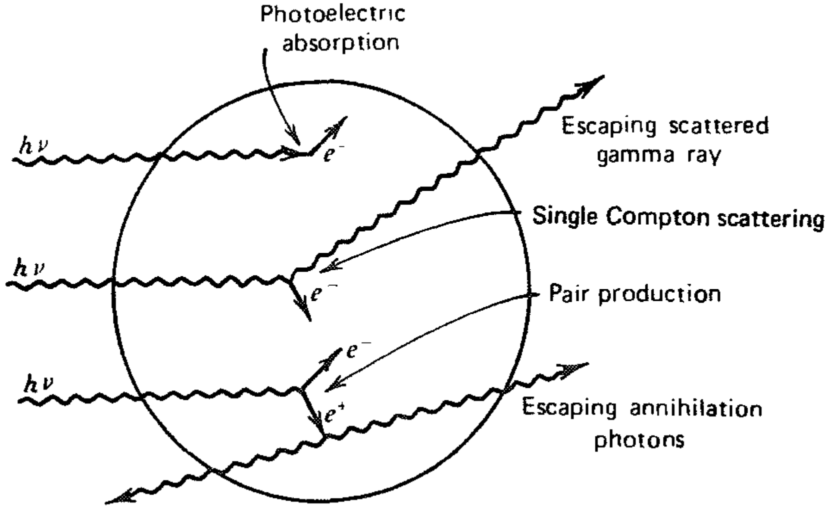
= photoelectric effect + Compton scattering + pair production

γ ray detection

★ A γ ray photon has no charge so that it does not create directly ionization and excitation of matter through which it passes.

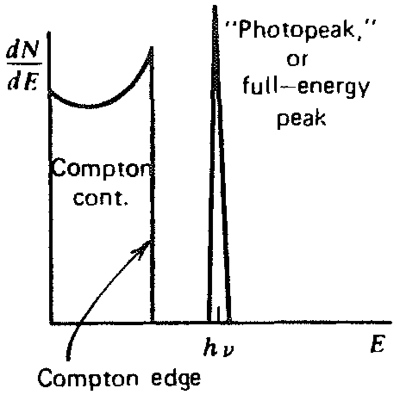
★ The (high energetic) electron generated as those processes has charge.
=> We can detect those electrons.

Response Function in detector

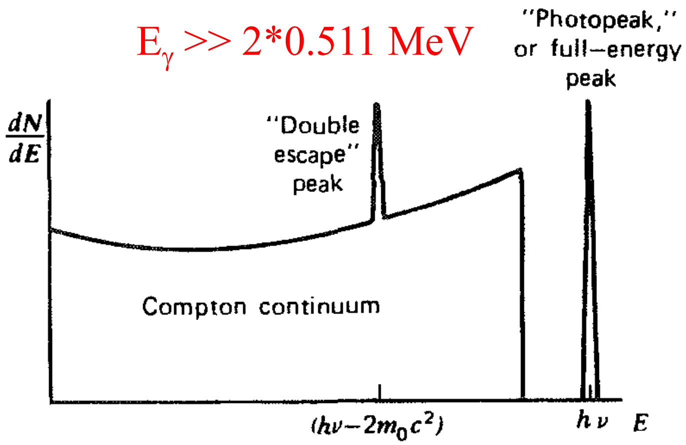


★ Photoelectric effect:
Full energy absorbed⇒ Photopeak
★ Compton scattering:
Only partial energy
★ Pair production
Full energy absorbed, but 2*0.511 MeV
γ rays emitted (one or two can be escaped)

$E_\gamma < 2*0.511$ MeV



$E_\gamma >> 2*0.511$ MeV

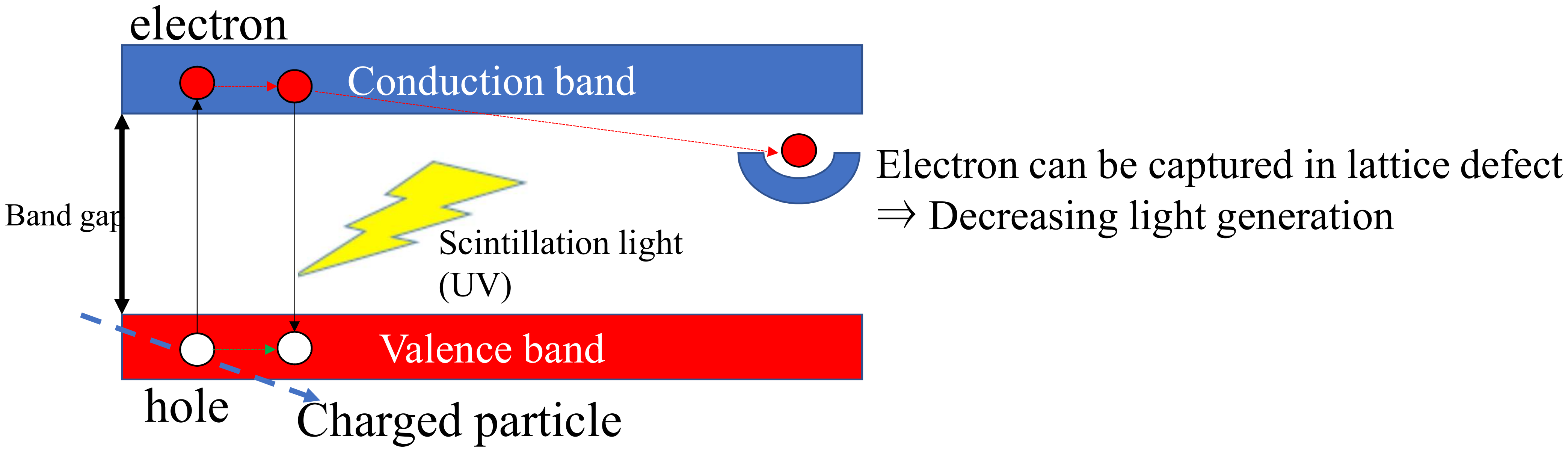


Detector types

★ Mainly two types of detectors for γ-ray measurements

1. Scintillation detectors
   Ionization by radiation -> Scintillation (visible photon)
   eg) **NaI(Tl) detector** (a kind of inorganic scintillator)
2. Semiconductor detectors
   electrons generated by ionization
   eg) Ge detector (expensive)

Scintillation mechanize in inorganic (pure)crystal



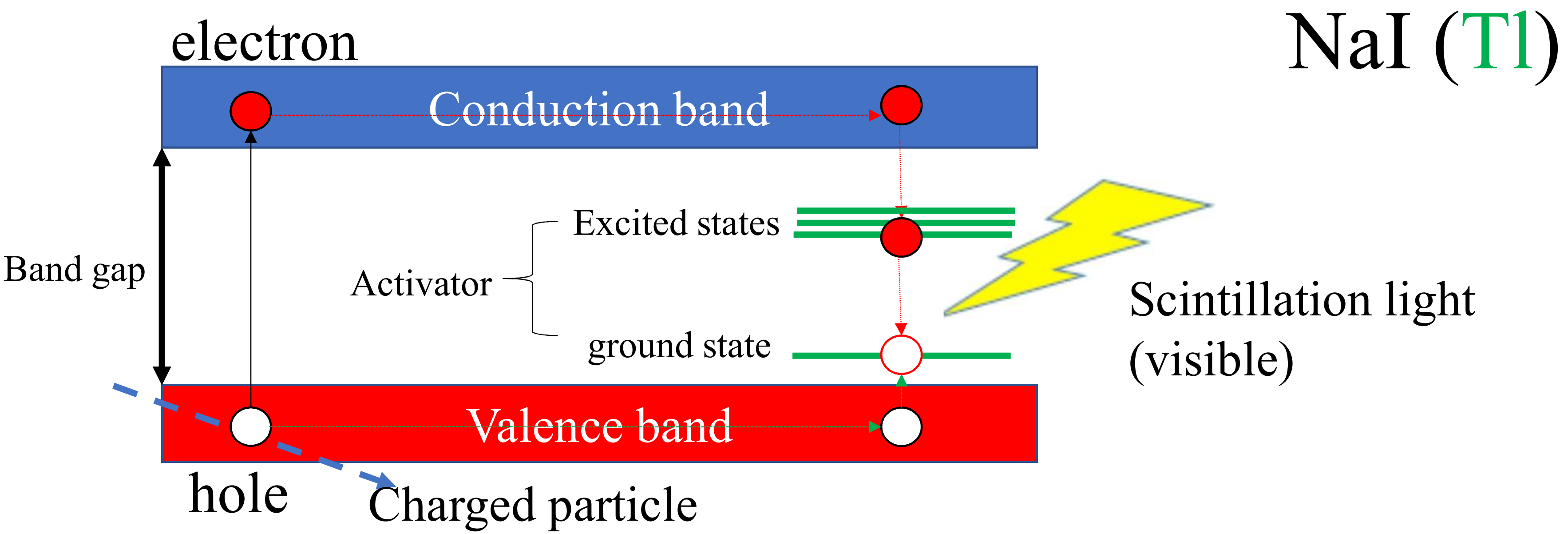
★ Charged particle hit a valence electron in the lattice, transferring the energy to electron. Electron goes up into conduction band. Also a hole (+) is generated in valence band.

★ The electron in conduction band and the hole in valence band move freely.

★ Electron meets a hole so that electron goes down to valance band so that the energy is released as light. -> Scintillation

Not good efficiency for light generation & Too high energy for visible light

Scintillation mechanize in inorganic crystal with activator



★ Intentionally, a small amount of impurity (Tl) add into the scintillator material (NaI). New energy bands inside the band gap are generated.

★ The excitation energy in activator is smaller than band gap. → Visible light is generated

★ The hole is captured in ground state in activator and the electron is captured in excited state in activator efficiently.

⇒ **Efficient light generation**

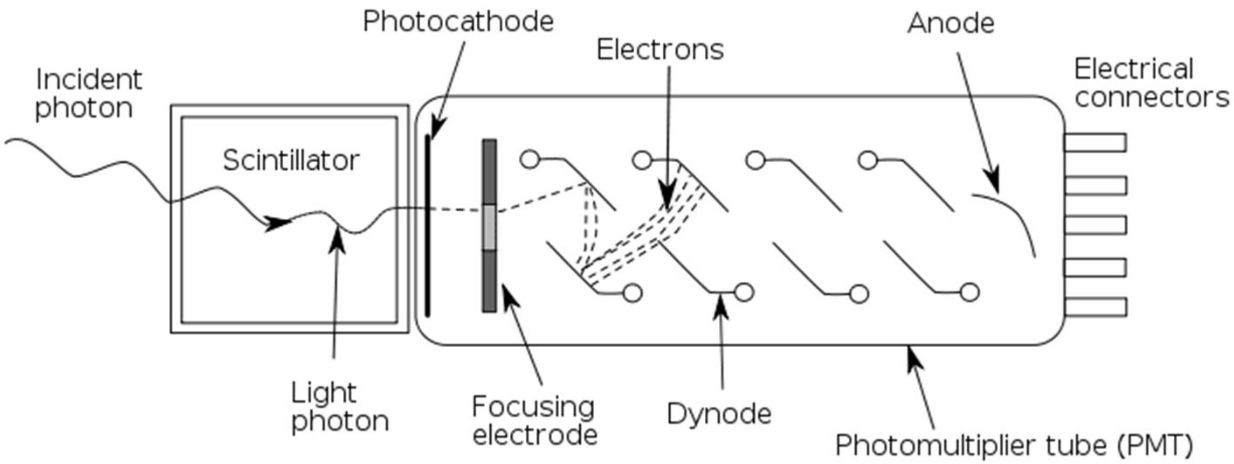
Number of photons in NaI(Tl) / MeV = 38,000

How to convert photons to electric pulse signal?
~ Photo Multipliers (PMT)~

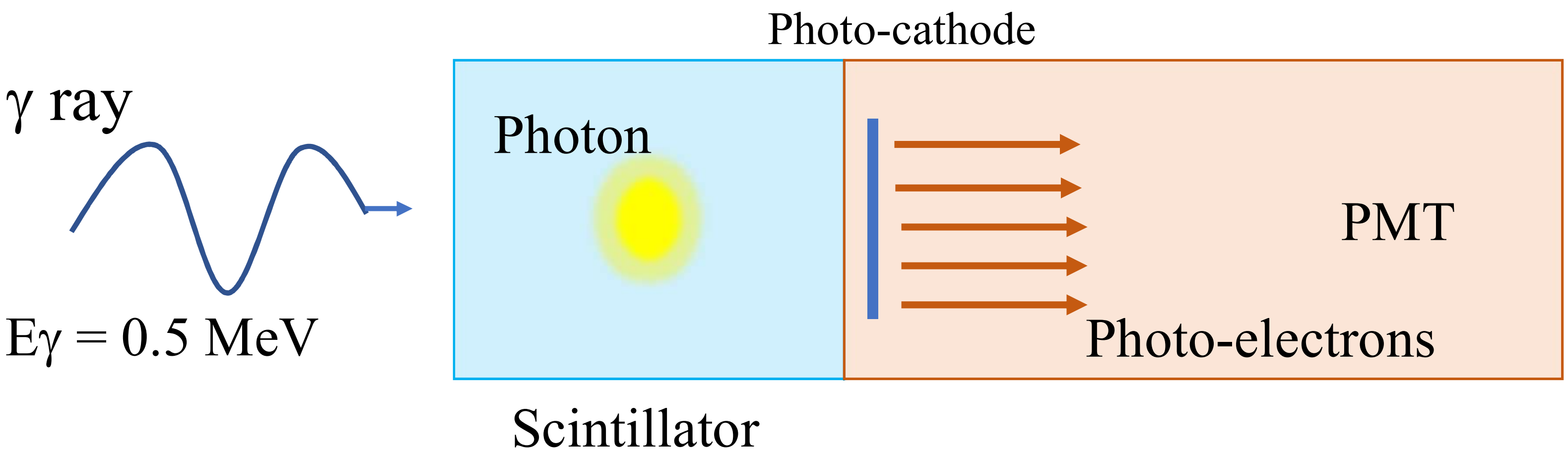
★ Scintillation light hits photocathode in PMT.
Light is converted to electron on photocathode thanks to Photoelectric effect.
★ Electron is accelerated with electric potential on dynode and hits dynode, leading to generating several electrons which are emitted from the dynode.
-> Repeat on multi-dynodes.

Gain ~ δ^N : typically $\delta \sim 5$
If 10 electrodes, Gain ~ 10^7

★ Finally, electrons are collected on Anode.
=> Enough charges for pulse height



Statistics for photo-electrons



★ Scintillation efficiency ~ 12%

- 0.5 *0.12 = 60 keV for scintillation ⇒ converted with 3 eV energy photon: 60,000/3 = 20,000 photons
- loss during transportation (surface of crystal, crystal-PMT interface, etc.): ~ 25% ⇒ 15,000 photons

★ Quantum efficiency on photo-cathode (= number of photo-electrons/number of photons) ~ 20%

⇒ 15,000 photons *0.2 = 3,000 electrons   3,000 * $10^{6\text{-}7}$ = 3*$10^{9\text{-}10}$ e ***Detectable***

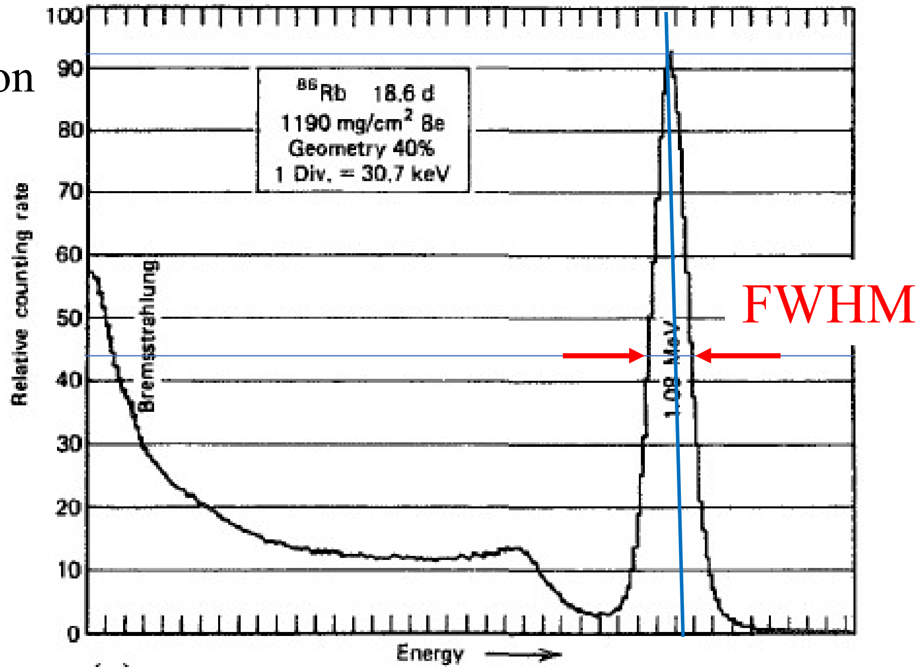
Energy resolution (one of main features for detector)

★ Assuming radiation, for a single energy is recorded, a Gaussian distribution is expected. The energy resolution is defined as:

R ≡ Full Width of Half Maximum/Peak position

★ Origins for resolution loss

- Charge collection statistic (Photo-electron statistics)
- Electronic noise
- Variations in the detector response
- Drifts in operating parameters



★ Resolution from the statistics

number of photo-electrons ~ 3,000 for 0.5 MeV γ ray

⇒ Standard deviation (Assuming Poisson distribution) $\sigma = \sqrt{3000}/3000 \sim 1.8\%$

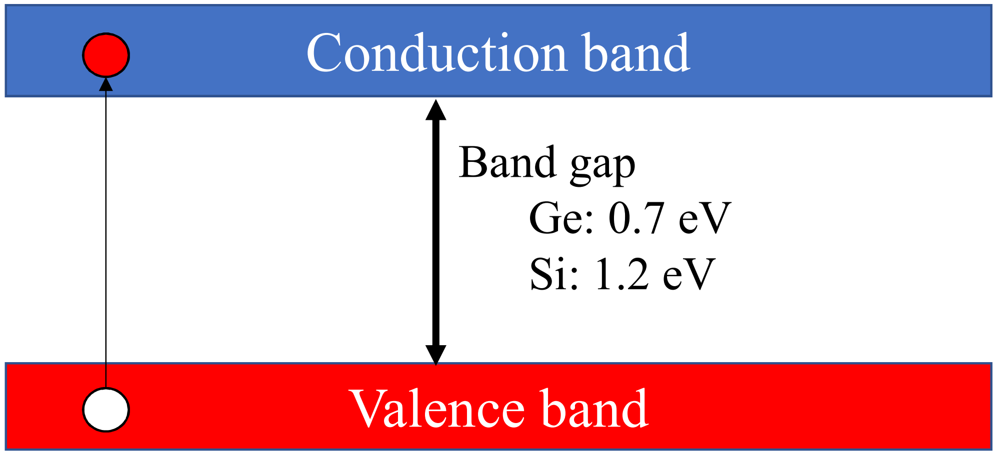
FWHM = 2.35σ

R ~ 4.3% from photo-electron statistics at 0.5 MeV γ ray detection (main)

How about semi-conductor detectors (Ge detector)?

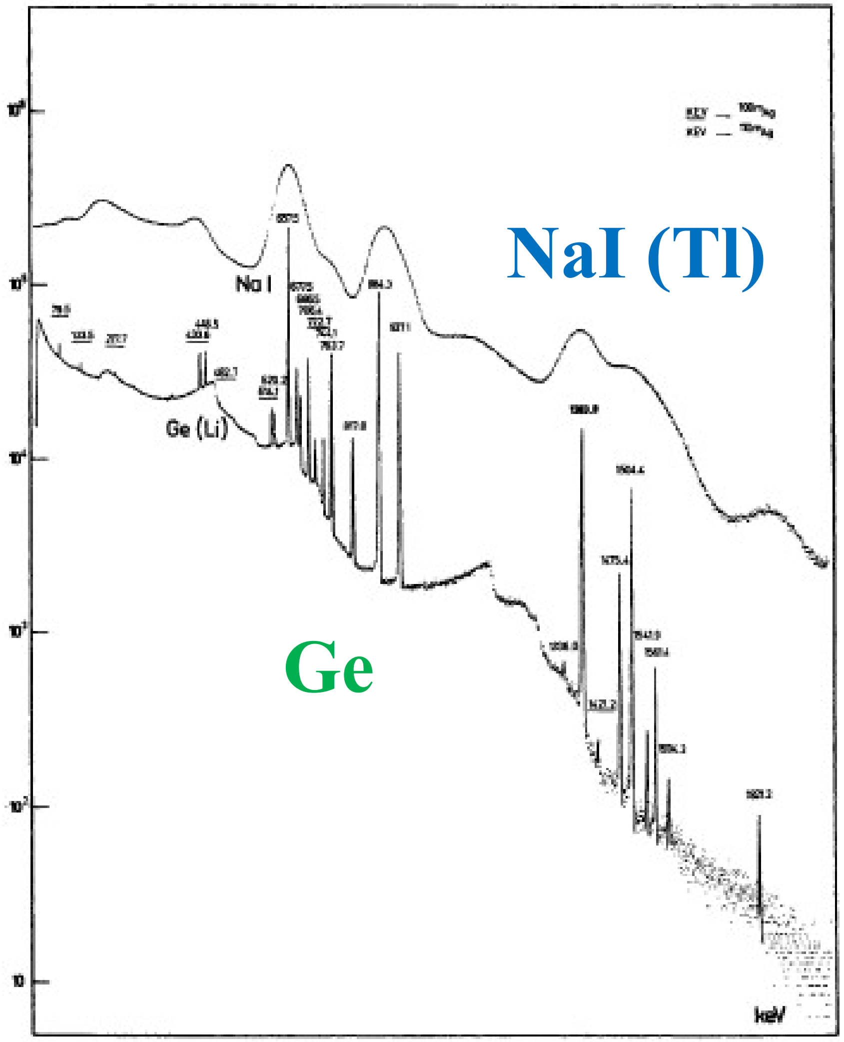
★ To create one photo-electrons, we need (energy) cost about:
0.5 MeV/ 3,000 ~ 160 eV

★ Basic concept of semiconductor
Due to narrow band structure it costs on a few eV to create an electron-hole pair.



Charges can be collected directly thanks for semiconductor feature

NaI (Tl) vs. Ge detector



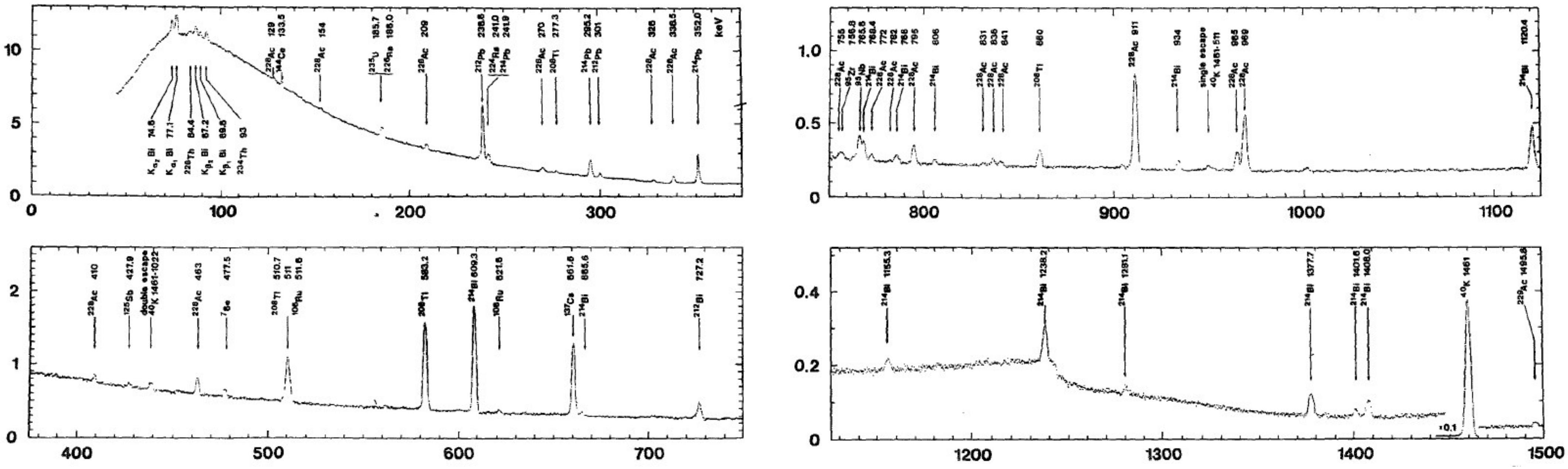
★ Energy resolution for Ge detector
~ about Factor 30 better than NaI

Why do we want to use NaI?
- Ge is extremely expensive.
- Lage volume of NaI detector
  ⇒ higher efficiency
- Simple handling (Ge detector has to be cooled)
- Better time resolution for NaI

Digression…

Natural radioactivity (background)

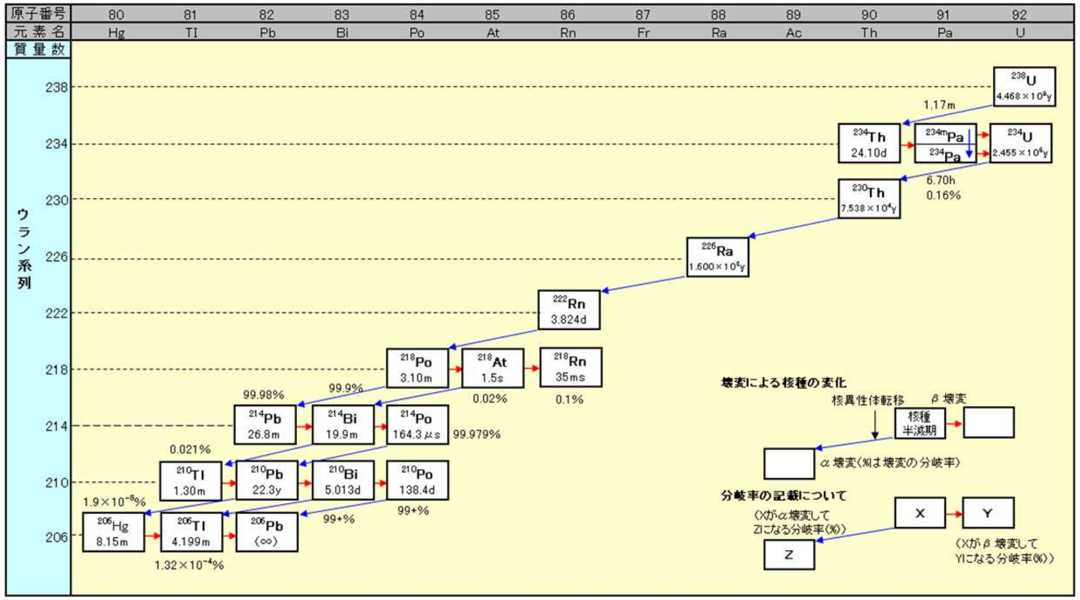
Ge detector



^{40}K, Thorium, Uranium and long decay chains of Thorium and Uranium

Decay chains

Uranium chain

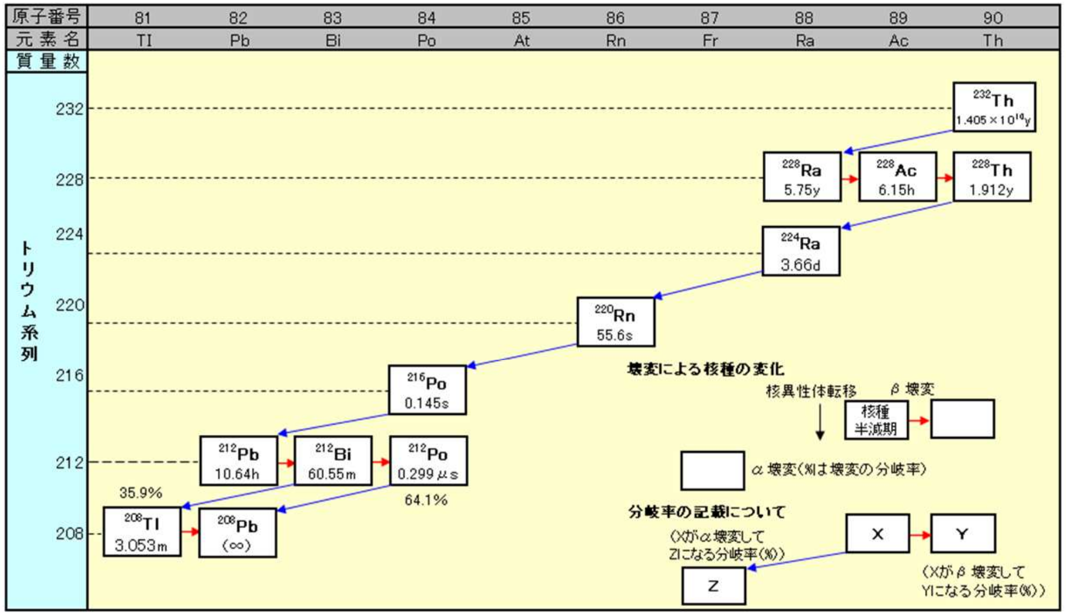


半減期の記号;s(秒), ms(10⁻³秒), μs(10−6秒), m(分), h(時), d(日), y(年)

図1-1　天然放射性核種の壊変系列図(ウラン系列)(1/4)

[出典] 国立天文台(編):理科年表 2010年版、丸善(2009年10月)、p.468-469

Thorium chain



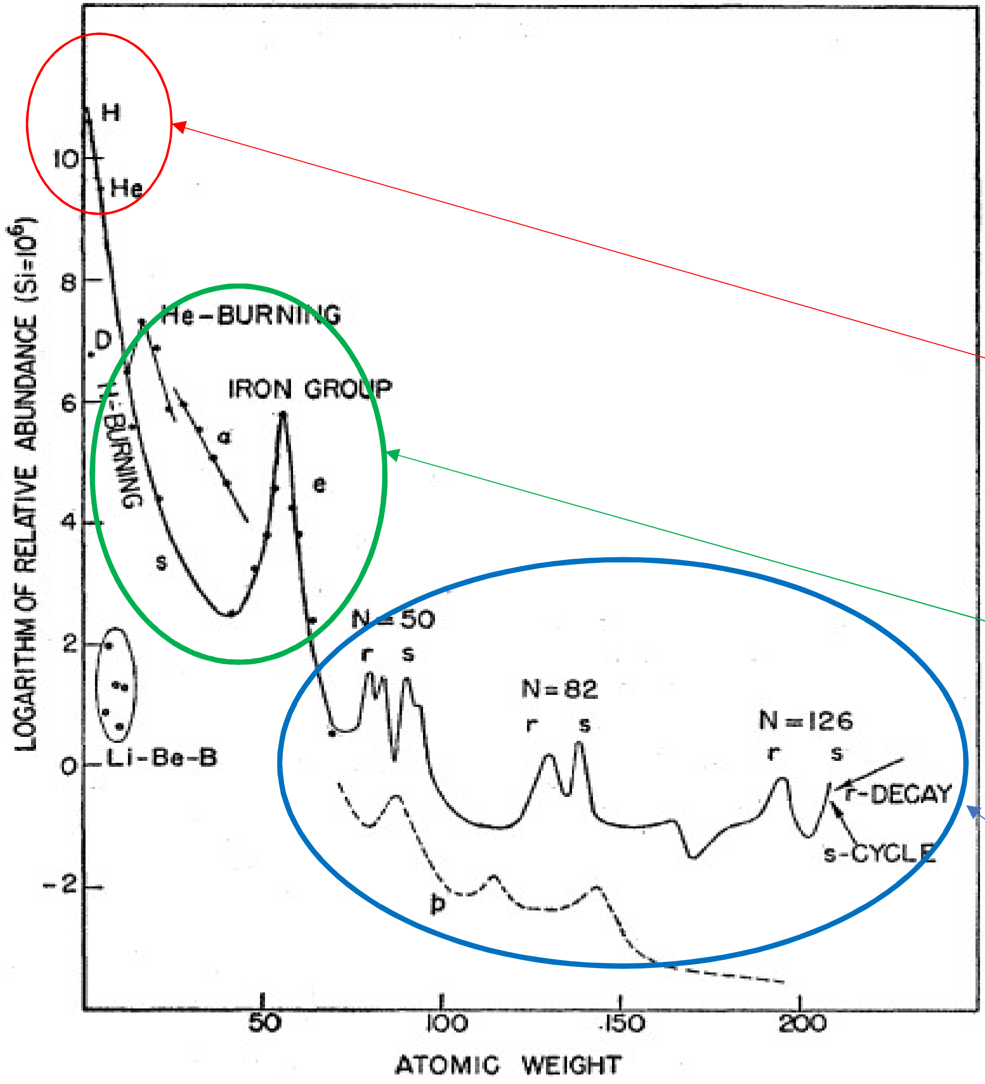
半減期の記号;s(秒), ms(10⁻³秒), μs(10⁻⁶秒), m(分), h(時), d(日), y(年)

図1-3　天然放射性核種の壊変系列図(トリウム系列)(3/4)

[出典] 国立天文台(編):理科年表 2010年版、丸善(2009年10月)、p.468-469

When and Where were U & Th generated?

Element abundance in solar system



B2FH, Rev. Mod. Phys. 29 (1957) 547.

Mass ratio
H: 70.7%
He: 27.4%
Others: 1.9%
Heavy elements (> Ni): 4E-4%

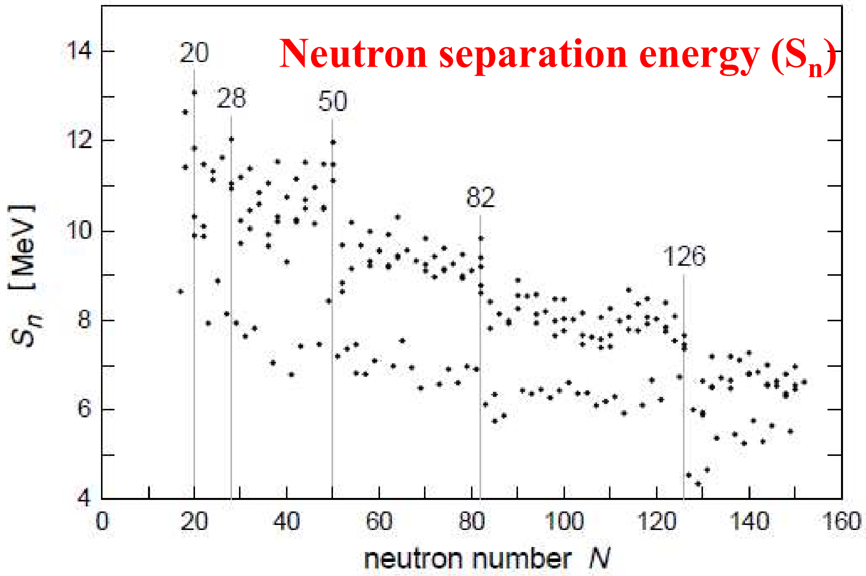
Big Bang Nucleosynthesis:
Main production of H, He (Li, Be)
No stable isotope : A = 5, 8

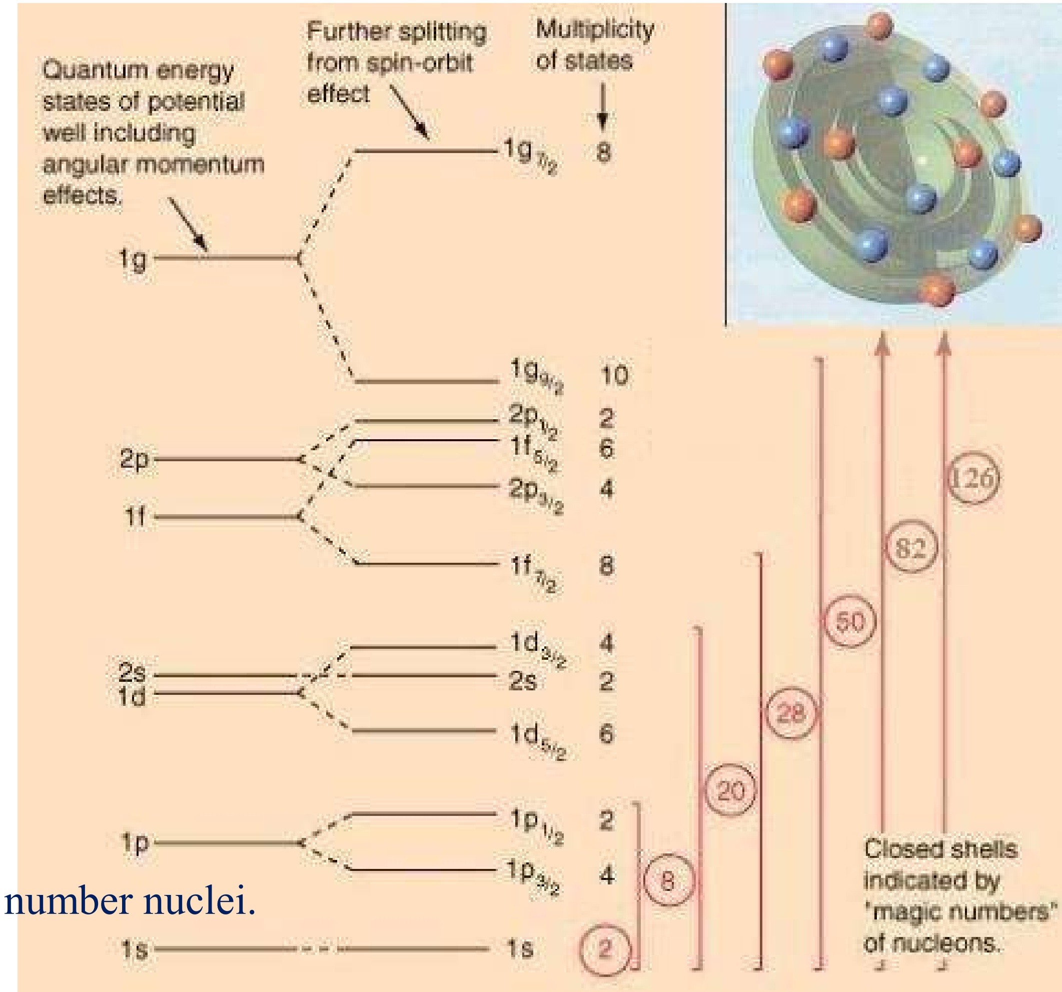
Thermo-nuclear reactions (charged particle) in Stars:
Up to Fe
Fe: Maximal binding energy / nucleon ⇒ Stable

Beyond Fe ⇒ neutron capture reactions: (n, γ)
Why do two peaks exist?
Slow (s-) process
Rapid (r-) process

Beyond Fe, why do several peaks exist? (before double peaks problem)

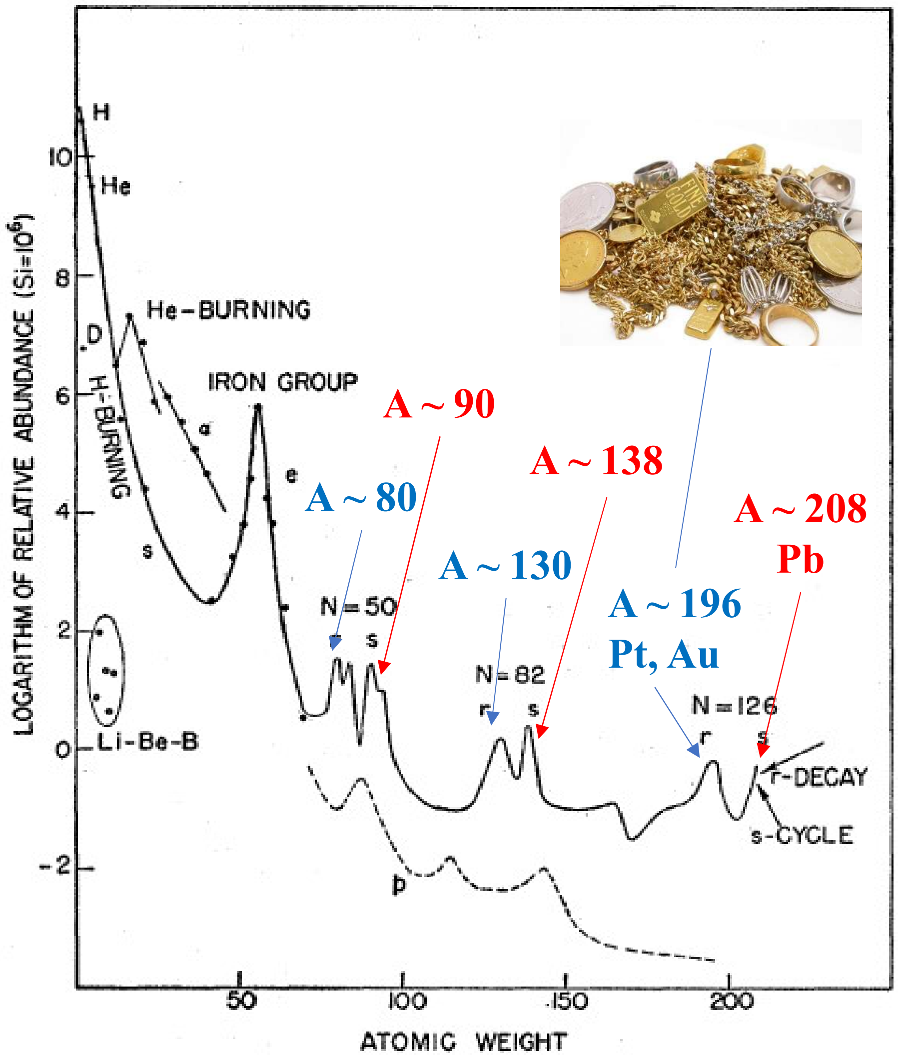
Shell model
⇒ Magic number = 2, 8, 20, 28, 50, 82, 126,..
We call ‘Shell closure’.
Typically, ^{4}He, ^{16}O, ^{20}Ne, ^{40}Ca (double magic nuclei)



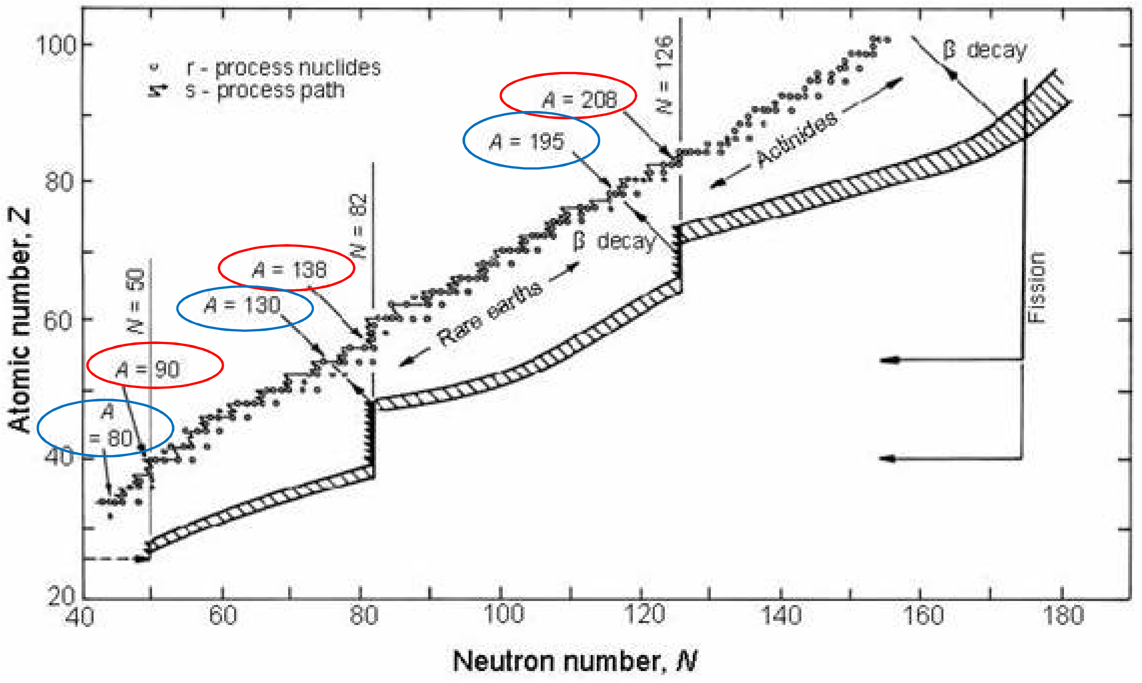


High S_n around magic numbers = stable
⇒ Reversely speaking, neutron capture is not easy after magic number nuclei.
⇒ Suppression of neutron capture reaction
⇒ Peak formation (accumulation at around magic number)

Why are double peaks generated?



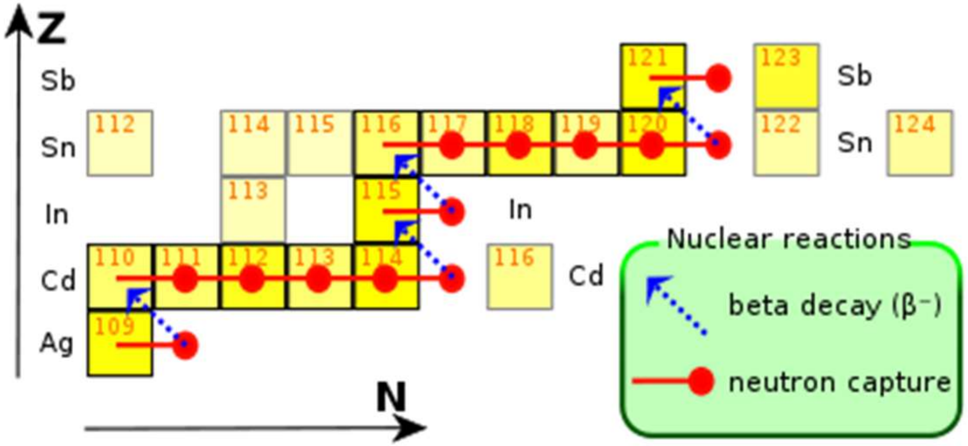
Clayton, Principles of stellar Evolution
And Nucleosynthesis (1983)

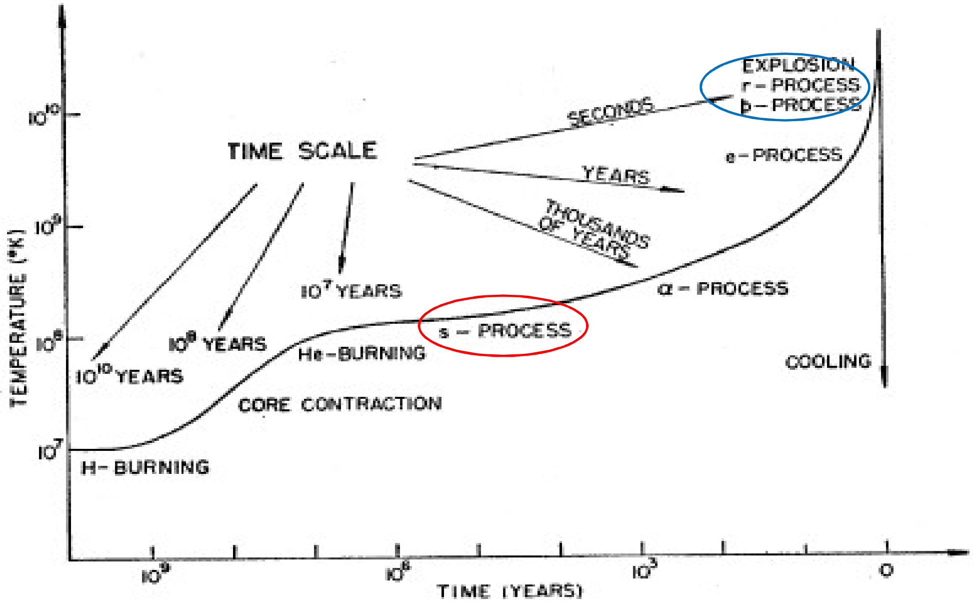


Neutron capture process along stable nuclei
⇒ - slower than β-decay, Slow(s-) process

Neutron capture process on radioactive nuclei
⇒ faster than β-decay, Rapid (r-) process

r-process vs. s-process





s-process

To proceed toward heavier nuclei

Neutron capture rates should be slower than β-decay rate.

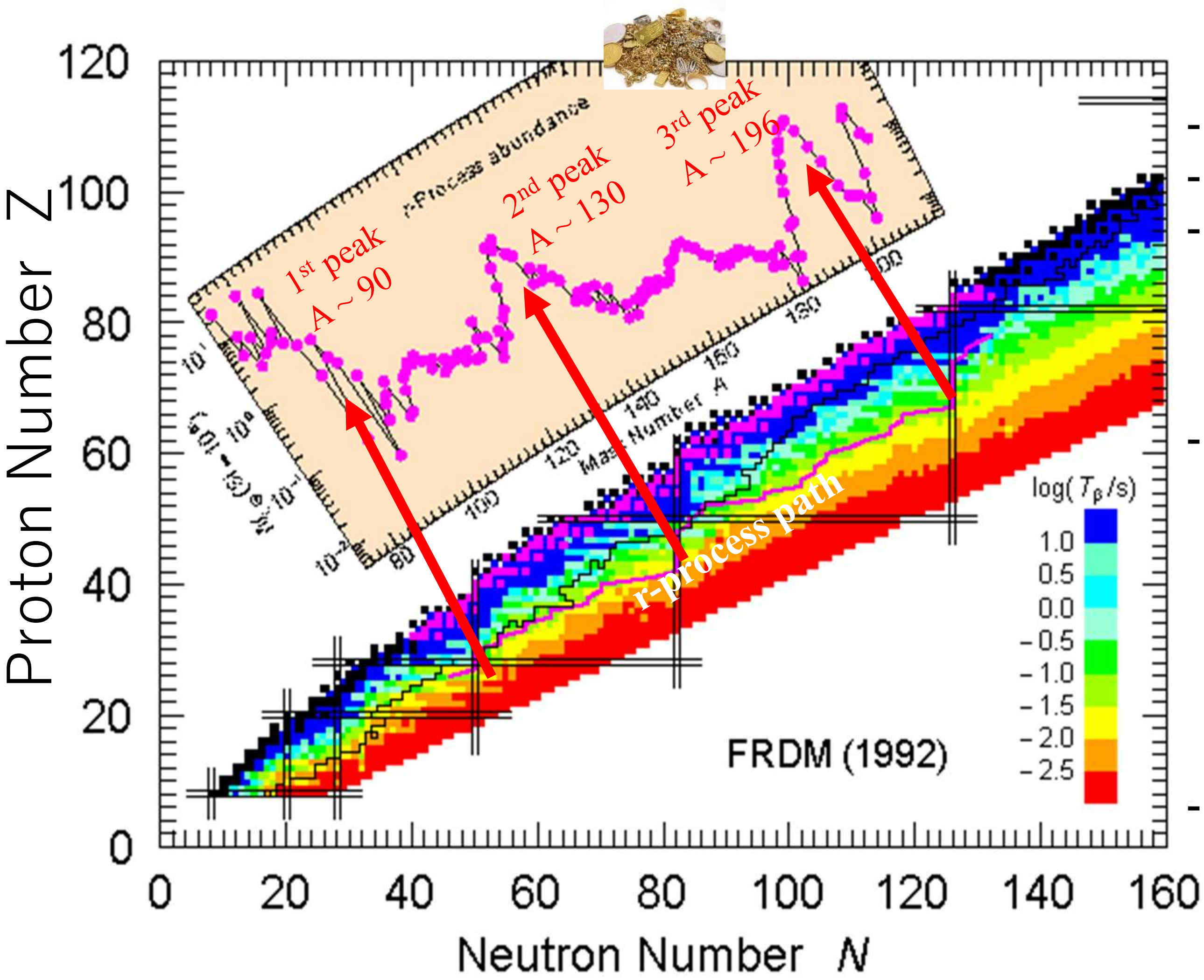
Low neutron density & Long time scale (~ 10^5 year)

r-process

To proceed toward heavier nuclei along radioactive nuclei, neutron capture rates should be faster than β-decay rate.

High neutron density & short time scale (~ seconds)

Features of r-process



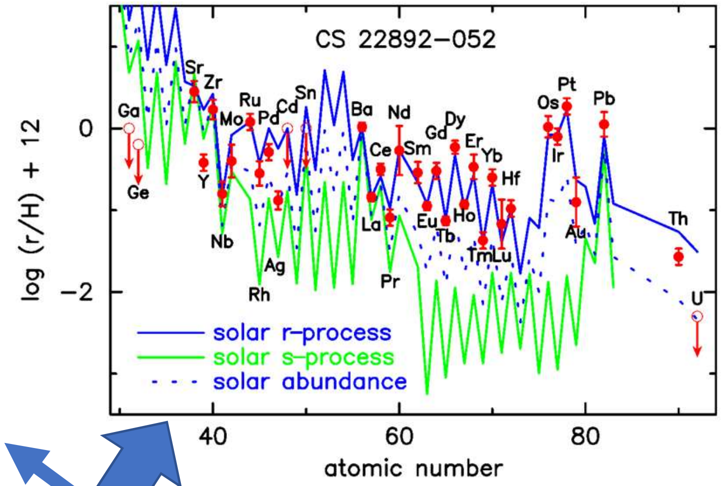
- Neuron capture is faster than beta decay
- Uranium, Th, etc. productions beyond Bi
- (n, γ) – (γ, n) equilibrium @ high temperature
  T ~ 10^9 K
  neutron capture reactions & photo-distinguish reactions equilibrium
- Waiting point nuclei
  N = 50, 82, 126 : Sn ⇒ high,
  Magic number + 1: Sn ⇒ low
  ⇒ Neutron capture reaction ceases on those nuclei have to wait for β-decay
  'Waiting point nuclei'
  ⇒ Peak formation
- High neutron density > 10^{20} cm^{-3}

Candidates for r-process site

Rapid neutron capture
- high temperature ($T_9 \sim 1$)
- High neutron number density ($10^{20} \sim 10^{30}/cm^3$)
- Short time scale (several seconds)

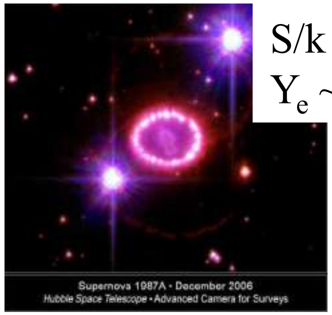
➔ Stellar explosion ?

Site parameters
- Ye (electron fraction):
  Yp = Ye, Yn = 1-Ye
- S/k (entropy)
  $\propto$ T^3/ρ (density @ same T)
- τ_{dyn} (dynamic time scale)
  ~ duration time for α-process & r-process



High S/k site

Neutrino driven wind in type II Sne (NDW)

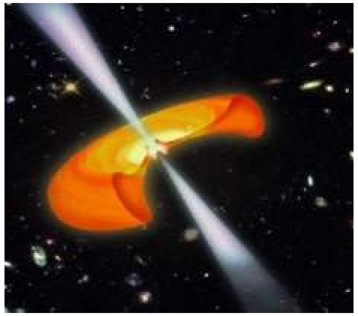


S/k ~ several 100
$Y_e \sim 0.45$

High Ye value?
High S/k ?

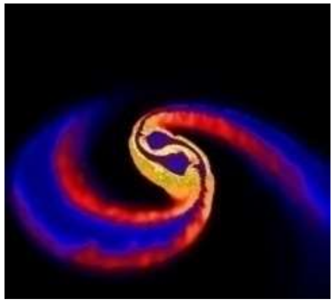
Low Ye site

MHD jet /Collapsar



S/k < several 10
$Y_e < 0.2$

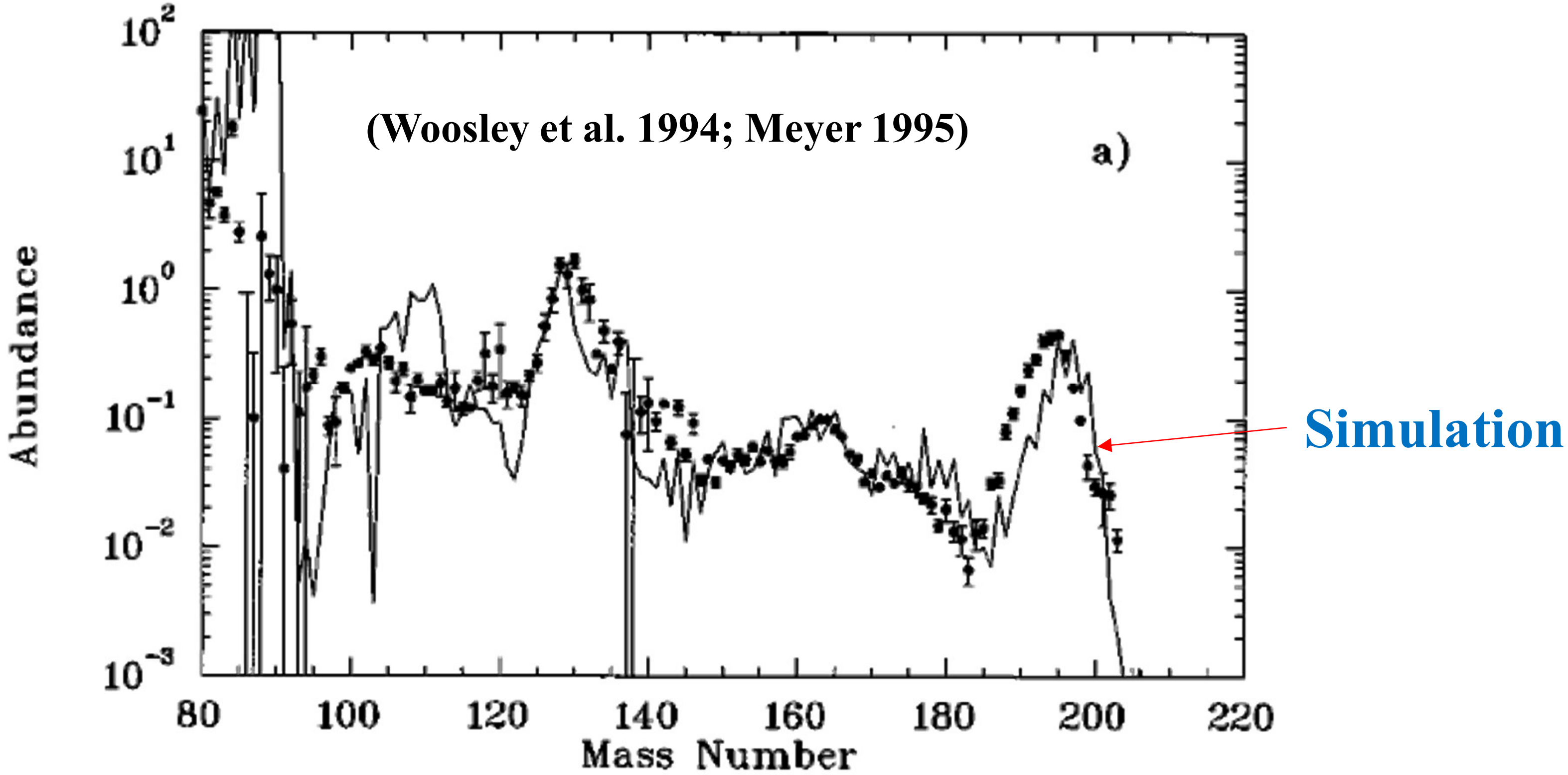
Neutron star merger



Event rate, early universe ?

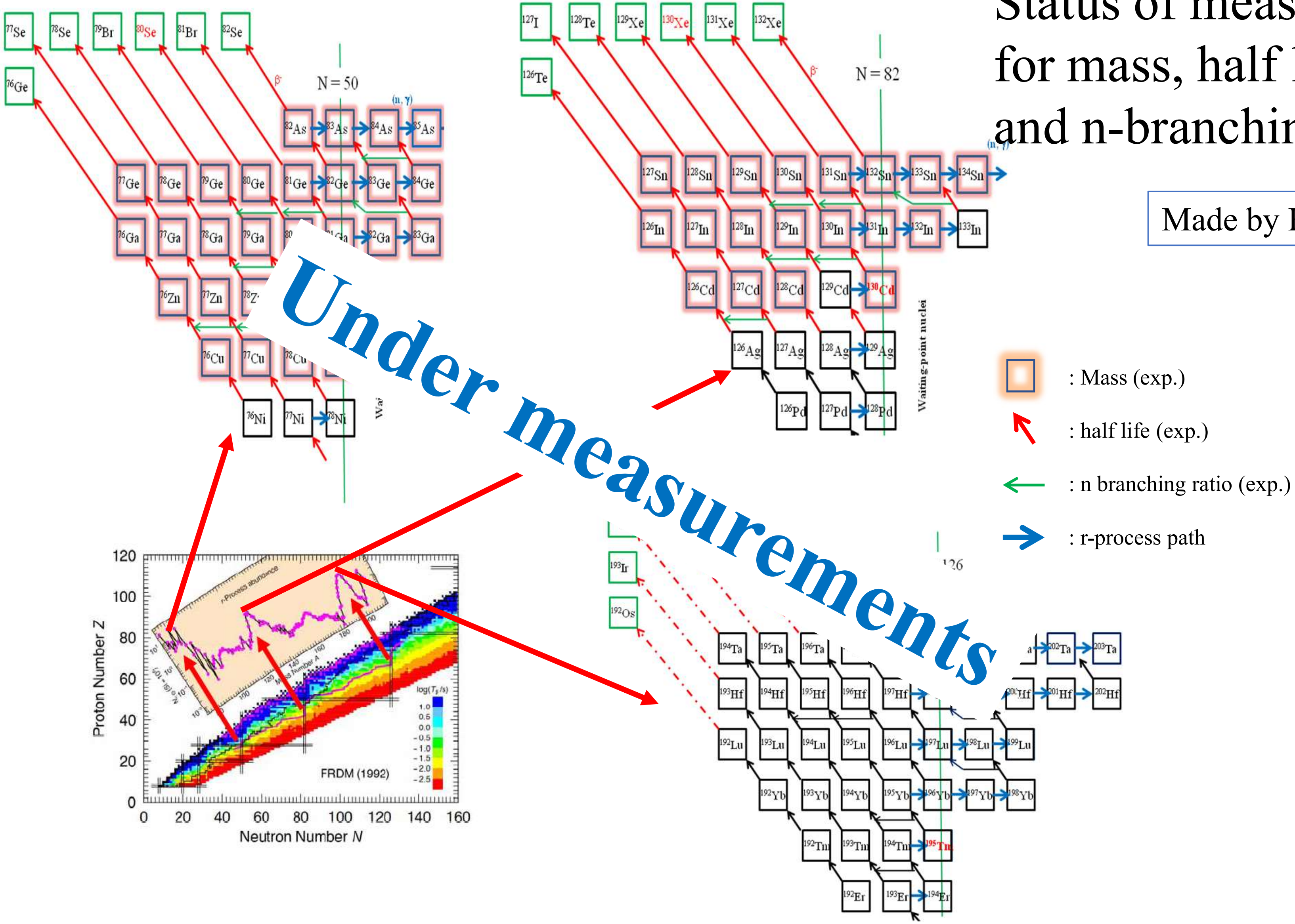
Nuclear physics inputs
- **Nuclear mass**
-> Sn, r-process path
- **Half life**
-> r-process speed, waiting point
- **neutron branching ratio**
-> r-process abundance pattern
- **neutron capture rate & other reaction**
-> r-process path when the equilibrium is broken

Network calculation for r-process nucleosynthesis



Status of measurements for mass, half life and n-branching ratio

Made by HI in 2009



Let's start γ ray measurement with NaI detector

To Do List

- Watch the signals with Oscilloscope
- Measure γ ray energy spectrum
    - Co source, Cs source, Room back ground
        - Full energy peak, Compton-edge,….
    - Energy resolution on each peak
    - Energy calibration
    - Efficiency measurement
    - …..