Scintillation & scintillators

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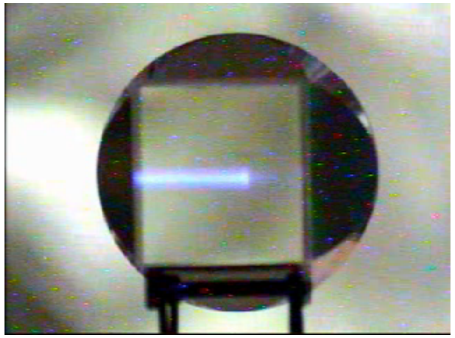
- Scintillation
  - When a charged particle passes in matter, it excites the atom (or molecules) in the medium. Some materials, call scintillators, releases the energy due to de-excitation by photons (scintillation).

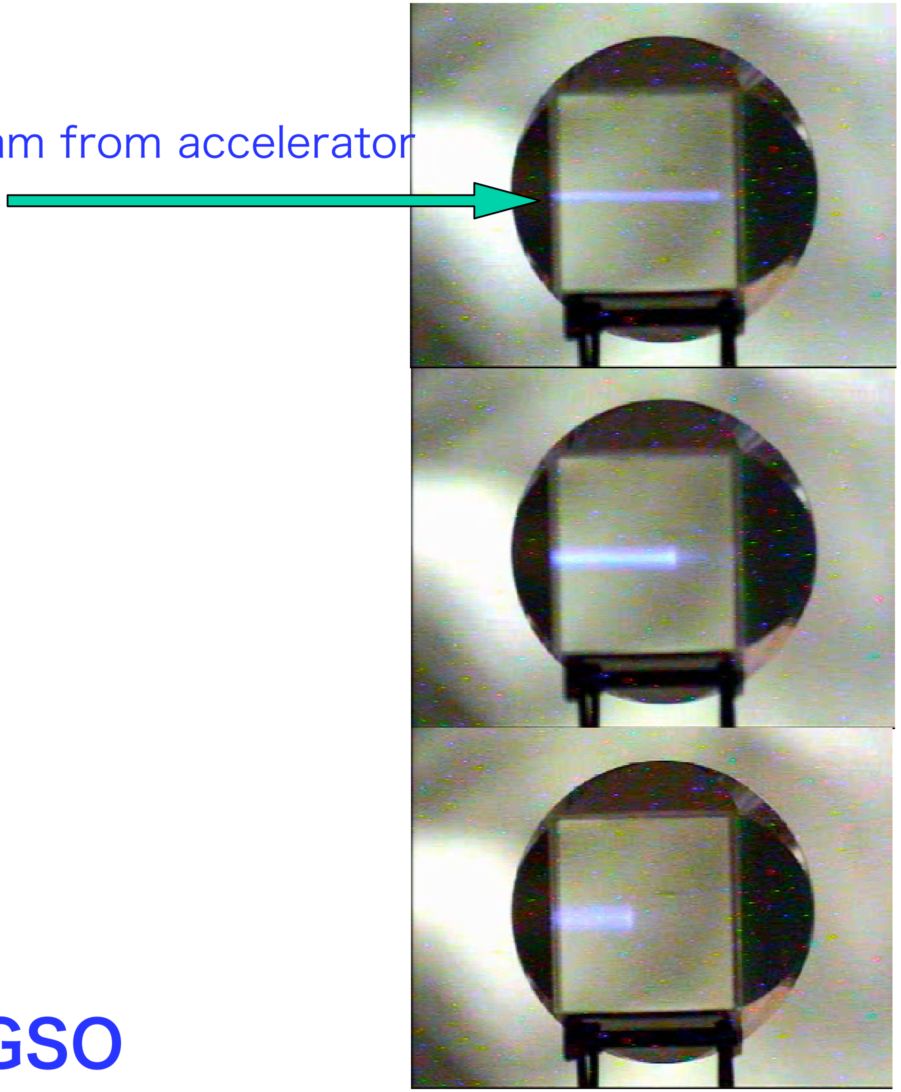


- the scintillation can be used as
  - presence of a charge particle
  - energy measurement
  - the measure of the time when it passes

- types of materials that scintillates (discussed in this lecture)
  - non-organic crystals
  - organic plastics (+ organic liquids)

high-energy heavy-ions (^{20}Ne) in a scintillator

^{20}Ne beam from accelerator



8 GeV
R=21g/cm^2

6.6 GeV
R=15g/cm^2

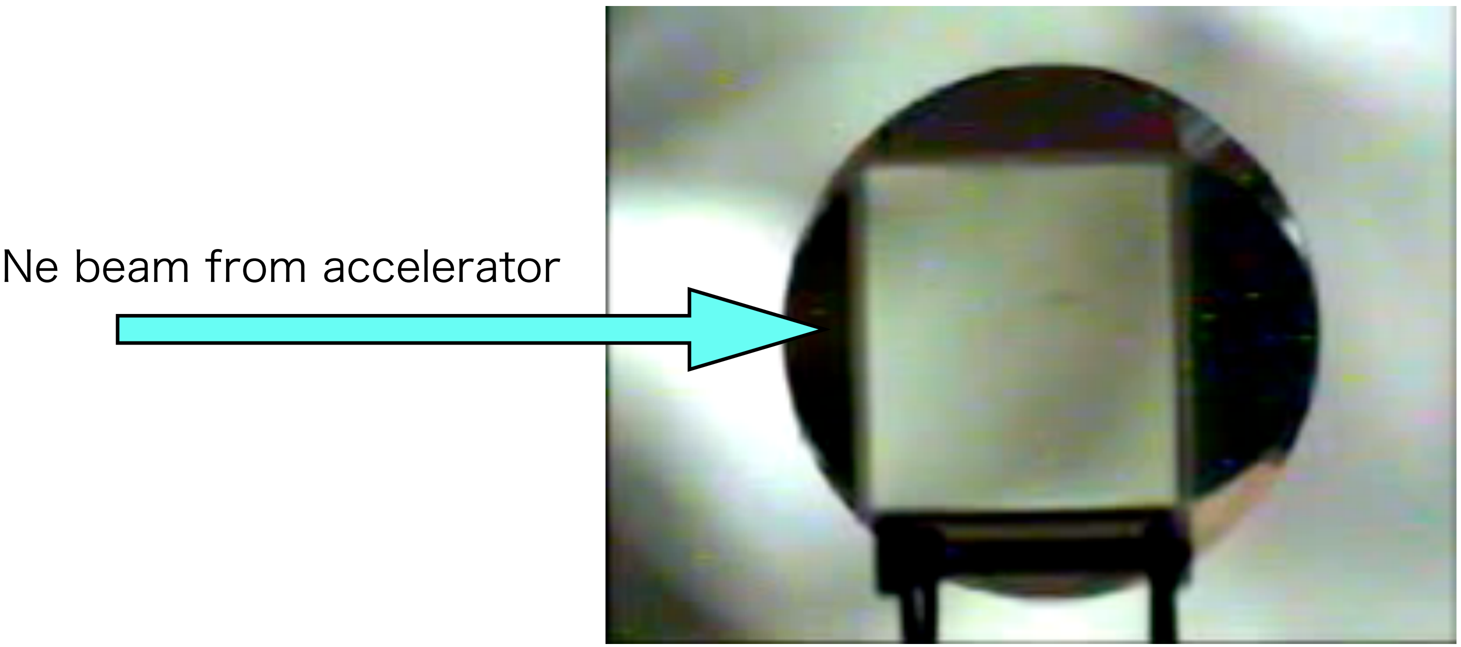
5 GeV
R=9.7g/cm^2

GSO

scintillation (movie)

intense high-energy heavy-ion beam

“beam” is injected every 3 seconds from a synchrotron



Ne beam from accelerator

My lecture on scintillation & scintillator

- Interaction of particles with matter
    - interaction of charged particles in matter
    - interaction of photons with matter
- scintillators
    - inorganic crystals
        - response to γ-ray
        - response to charged particle
    - organic scintillators
        - response to γ-ray
        - response to charge particle

Interaction of particles with matter

(for detecting particles, they must interact with matter)

- **photons**
  - photoelectric
  - Compton
  - pair production

- **charged particles**
  - losing energy due to ionization
  - losing energy due to photon emission
    - bremsstrahlung (mainly electron, positron)
  - nuclear reaction

- **other important electromagnetic processes**
  - Cerenkov radiation, transition radiation
  - (multiple scattering)

Energy loss in matter

- particle loses its energy by ionization and excitation
  - energy transfer in each collision is tiny (~ eV order)
  - cross section ~ $10^{-17\sim16}$ cm^2
    - 10 MeV (10^7 eV) proton stops in 0.25 mm copper
  - Beth-Bloch formula (a few % accuracy)

$$-\frac{dE}{dx} = \underbrace{2\pi N_a r_e^2 m_e c^2}_{0.154\ \mathrm{MeV\ cm^2/g}}\rho\frac{Z}{A}\frac{z^2}{\beta^2}\left[\ln\left(\frac{2m_e\gamma^2 v^2 W_{max}}{I^2}\right) - 2\beta^2\right]$$

r_e=classical radius of electron
m_e=mass of electron
N_a=Avogadro's number
c=speed of light
z=charge of incident particle
β=v/c of incident particle
$\gamma=(1-\beta^2)^{-1/2}$
W_{max}=max. energy transfer in one collision

- corrections for density and shell effects, in addition. refer to the Leo's textbook.

- Some useful formula and scales (exclude electron/positron)

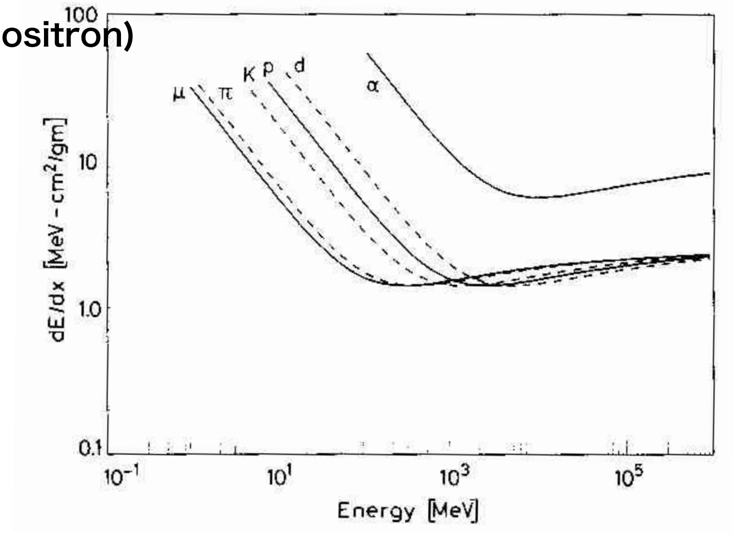
$$-\frac{dE}{\rho dx} = z^2\frac{Z}{A}f(\beta, I) \Rightarrow \approx \frac{1}{\beta^2} = 1/E$$

ΔE in ρdx is nearly the same

$$Range \propto \frac{E^{1.75}}{Z^2}$$

for estimation of the range of particles

$$-\frac{dE}{dx} \approx 2MeV/(g/cm^2)@\beta \sim 0.95$$

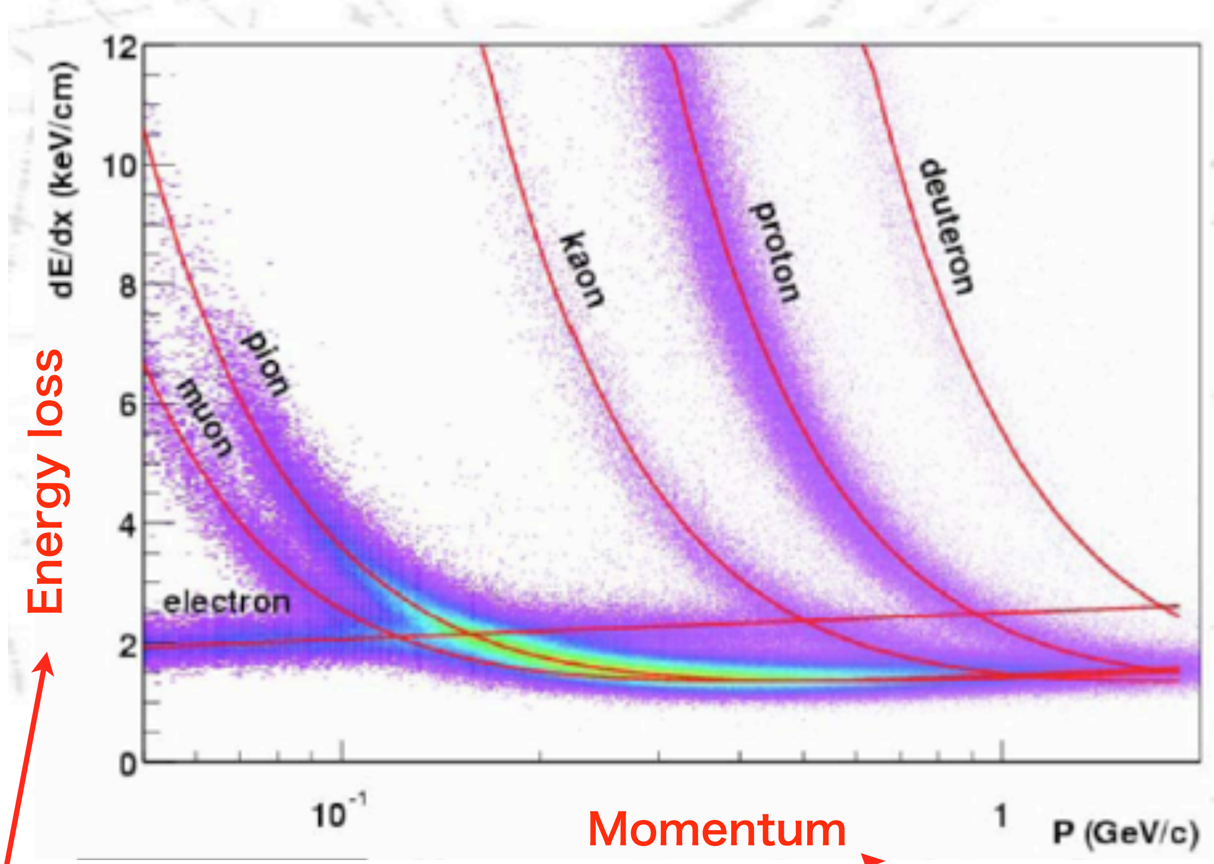


Particle identification

- one must determine their mass (m) and charge (z)
- what one can measure are ...
  - momentum $$p = \frac{m\beta}{\sqrt{1-\beta^2}}$$
  - velocity (time-of-flight for a certain distance) $$\beta = \frac{v}{c}$$
  - energy loss $$-\frac{dE}{dx} \propto \frac{z^2}{\beta^2}$$
  - total energy $$E = \frac{m}{\sqrt{1-\beta^2}}$$

an example of particle identification

for z=1 particles, the measurement of energy loss and momentum gives their mass



particle		mass (MeV/c^2)
electron	e	0.511
muon	μ	106
pion	π	140
kaon	K	494
proton	p	938
duetron	d	1876

$$-\frac{dE}{dx} \propto \frac{z^2}{\beta^2}$$

z=1

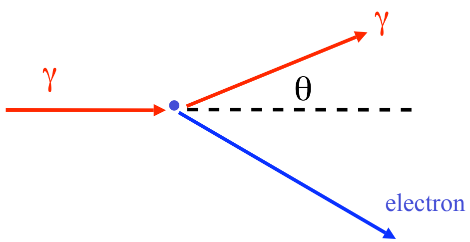
$$p = \frac{m\beta}{\sqrt{1-\beta^2}}$$

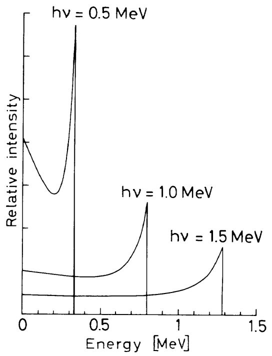
interaction of photons with matter

- photoelectric (Eg < a few MeV)
  - a photon is absorbed by an atom, and an electron is ejected.
    - Ee = Eγ - BE(binding energy : ~ a few eV)
    - cross section ~ f(E$_\gamma{}^{-7/2}$, Z^5)
    - higher Z is favored for γ-ray detection

- Compton scattering
  - scattering of photons by an electron

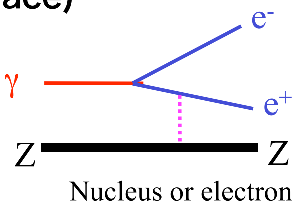
$$E_{\gamma,out} = \frac{E_{\gamma,in}}{1+\gamma(1-\cos\theta)}$$

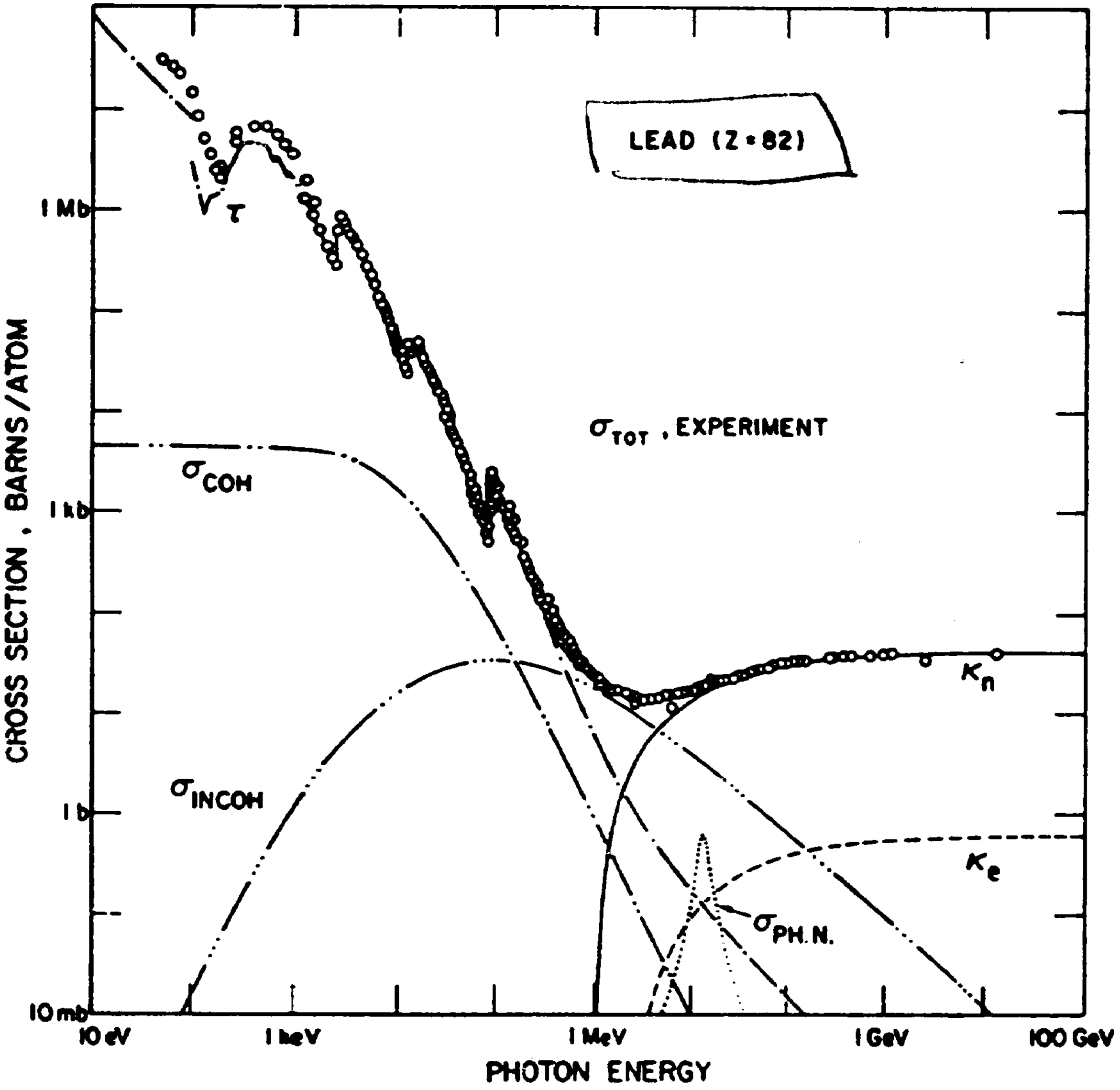




  - cross section : Klein-Nishina formula
  - cross section ~ f(Z) : number of electrons

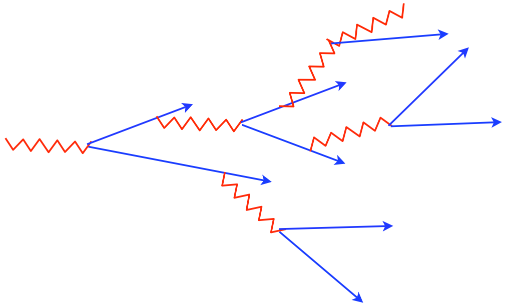
- Pair production (Eg > a few MeV)
  - e-e+ creation (kinematically forbidden in free space)
  - Coulomb field of nucleus or electron
  - cross section ~ f(Z^2) (nucleus)
  - ~ f(Z) (electron)




LEAD (Z = 82)
CROSS SECTION, BARNS/ATOM
PHOTON ENERGY
1 Mb
1 kb
1 b
10 mb
10 eV
1 keV
1 MeV
1 GeV
100 GeV
τ
σ_{TOT}, EXPERIMENT
σ_{COH}
σ_{INCOH}
κ_n
κ_e
$\sigma_{PH.N.}$

for high energy photons and electrons

- **pair production + bremsstrahlung emitted from electron(positron)**
  - electromagetic showers in matter



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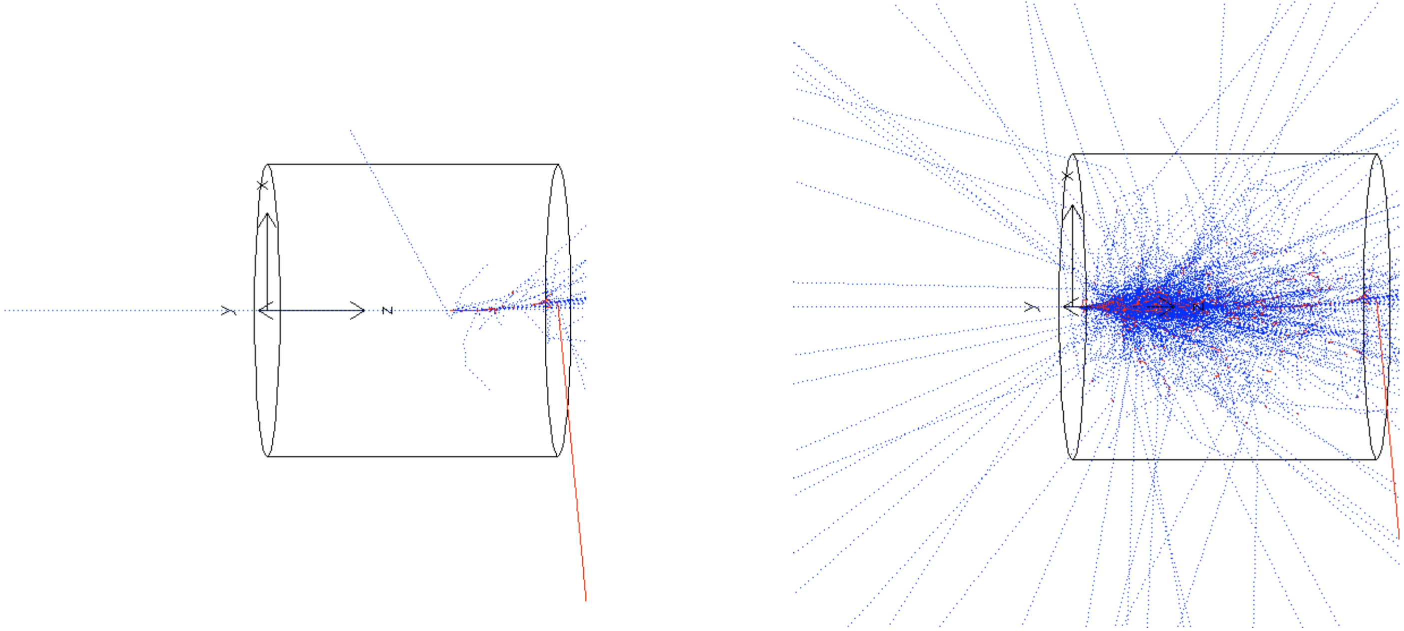


a GEANT simulation for electromagnetic shower of 300 MeV in material (CsI)

scintillators

- **inorganic scintillators : NaI(Tl), CsI(Tl), BaF2, BGO, GSO etc.**
    - response is generally slower (~a few 100 ns)
    - some crystals are hygroscopic
    - high Z, high density : larger stopping power, photon detection
    - large light output

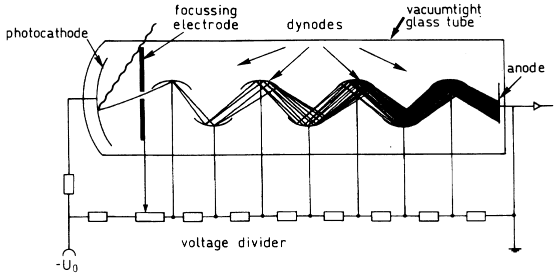
- **organic scintillator (mostly plastic, but liquid is also used)**
    - smaller Z
    - fast response (~ a few ns)
    - large light output
    - very flexible (thickness, size, shape etc.)

training using detectors in this Nishina School

- **NaI(Tl) scintillator (inorganic)**
  - scintillation yields : ~ 1/25 eV
  - decay time ~ 250 ns
  - scintillation yield is still the largest among various scintillators

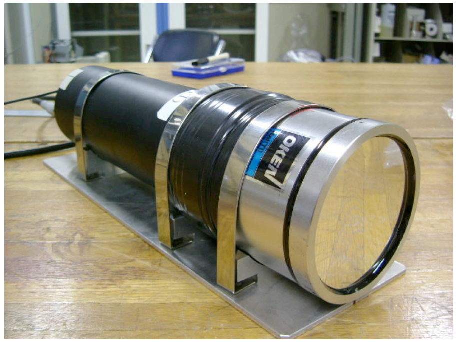
- **plastic scintillator (organic)**
  - scintillation yields : ~ 1/100 eV
  - decay time ~ a few ns
  - cheap,

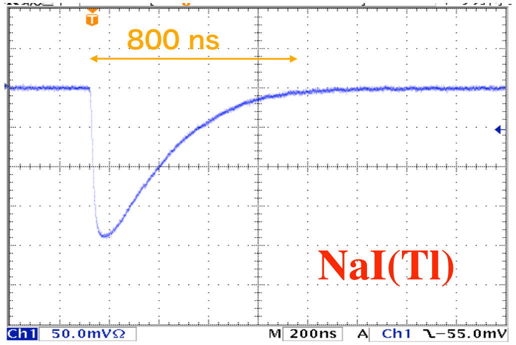
  - **photomultiplier tube**
    - scintillation-to-(electric signal) converter (with ~10^6 amplification)
      - high gain (>10^{6-7}) (even single photon counting)
      - variety of choices (size, gain, sensitivity)
      - cost (~10^{4-5} JY)



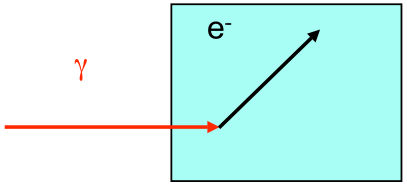
inorganic scintillator (NaI(Tl))

- **widely used for (low energy) γ-ray measurement**
  - high Z : enhancing photoelectric effect
  - NaI(Tl) + PMT -> scintillation to electric signal

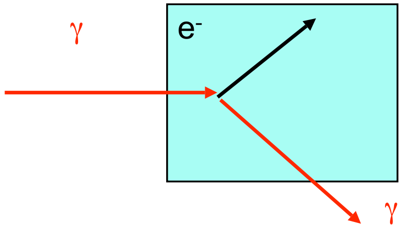




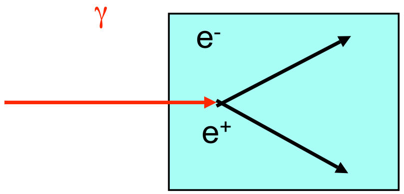
Photoelectric

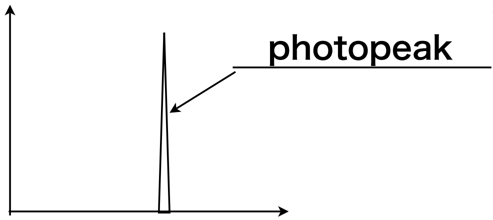


Compton

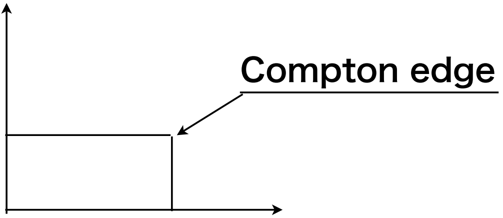


Pair production





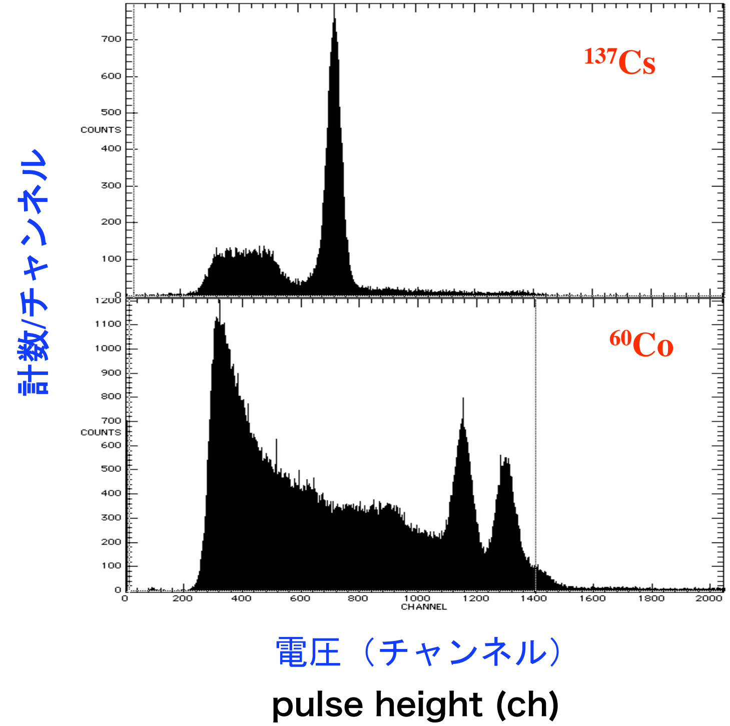
Pulse Height

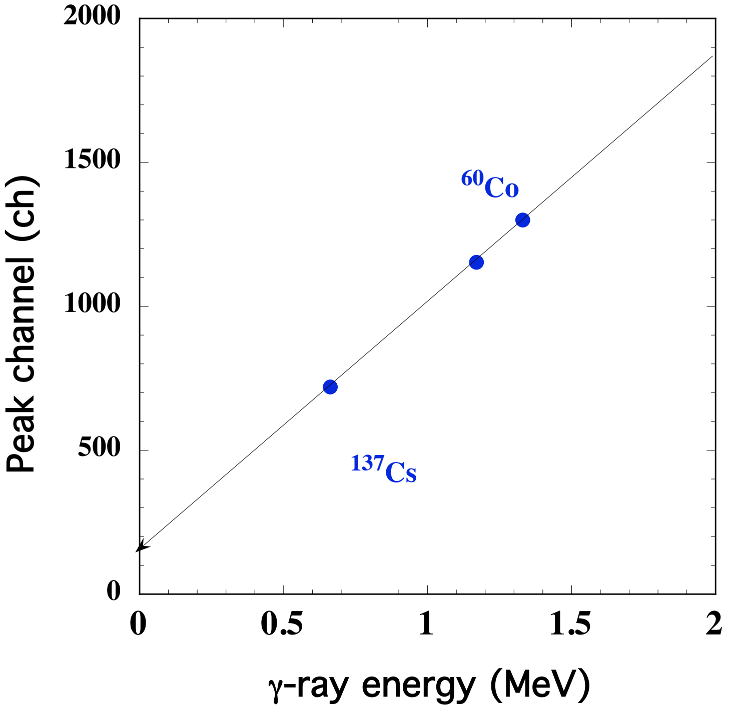


Pulse Height

γ-ray energy and pulse height

- pulse height is proportional to the γ-ray energy
  - ex. radiation sources such as
    - ^{137}Cs : 0.662 MeV
    - ^{60}Co : 1.17, 1.33 MeV

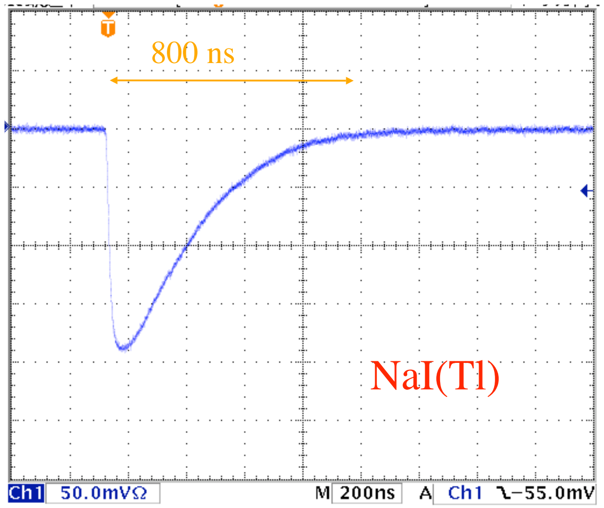


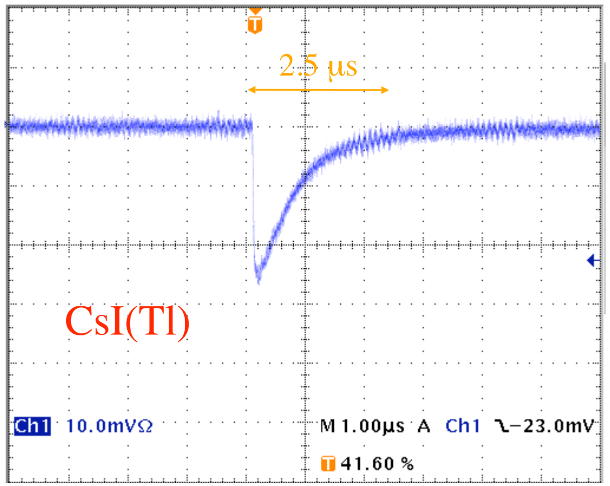


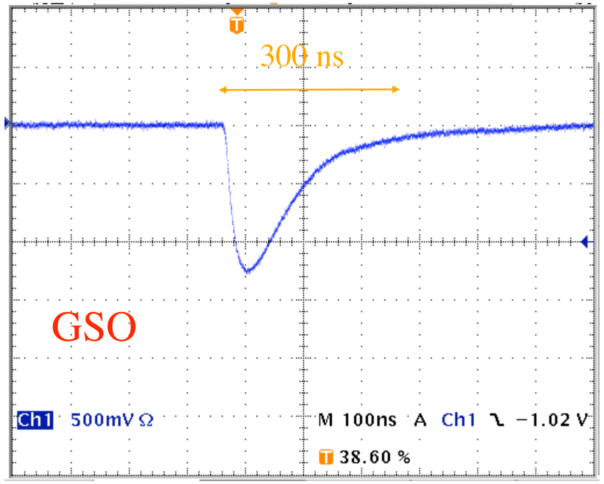
various inorganic crystals

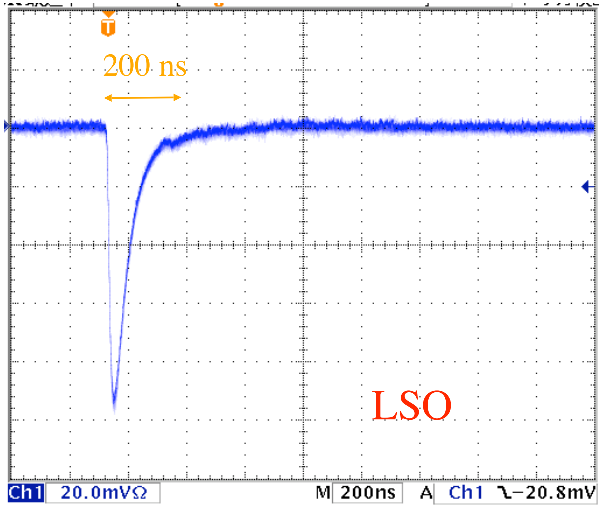
Crystal	NaI(Tl)	CsI(Tl)	CsI	BaF_2	BGO	LSO(Ce)	GSO(Ce)
Density (g/cm^3)	3.67	4.51	4.51	4.89	7.13	7.40	6.71
Melting Point (°C)	651	621	621	1280	1050	2050	1950
Radiation Length (cm)	2.59	1.85	1.85	2.06	1.12	1.14	1.37
Interaction Length (cm)	41.4	37.0	37.0	29.9	21.8	21	22
Refractive Index	1.85	1.79	1.95	1.50	2.15	1.82	1.85
Hygroscopicity	Yes	Slight	Slight	No	No	No	No
Luminescence (nm)	410	560	420 310	300 220	480	420	440
Decay Time (ns)	230	1300	35 6	630 0.9	300	40	60
Light Yield (%)	100	45	5.6 2.3	21 2.7	9	75	30

Electric signals from some inorganic scintillators





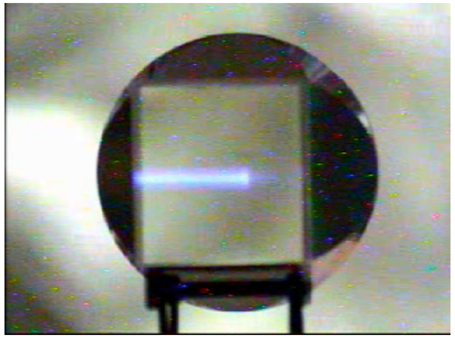


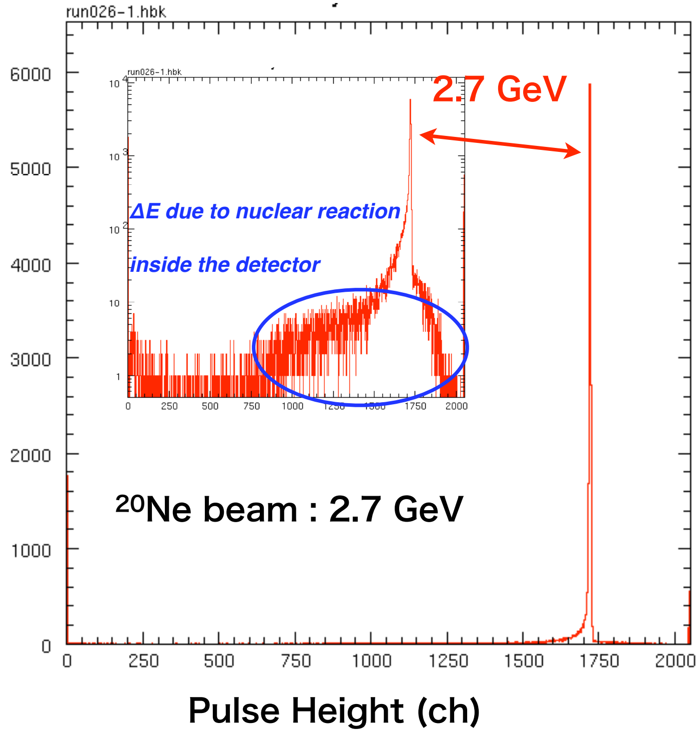


NaI(Tl) response to (heavy-ion) charged particle

- **NaI(Tl) response to heavy-ion beam**
  - **total energy is large -> number of scintillation is huge**
  - **(the range in the NaI(Tl) is not long)**
    - $\Delta E/E \sim 10^{-3}$
      - $N_{ph}(1\mathrm{MeV}) \sim 4\times10^{4}$
      - $N_{ph}(3\mathrm{GeV}) \sim 1\times10^{8}$ (neglect “quenching” here)
      - $N_{ph}(3\mathrm{GeV})/N_{ph}(1\mathrm{MeV}) = 3\times10^{3}$

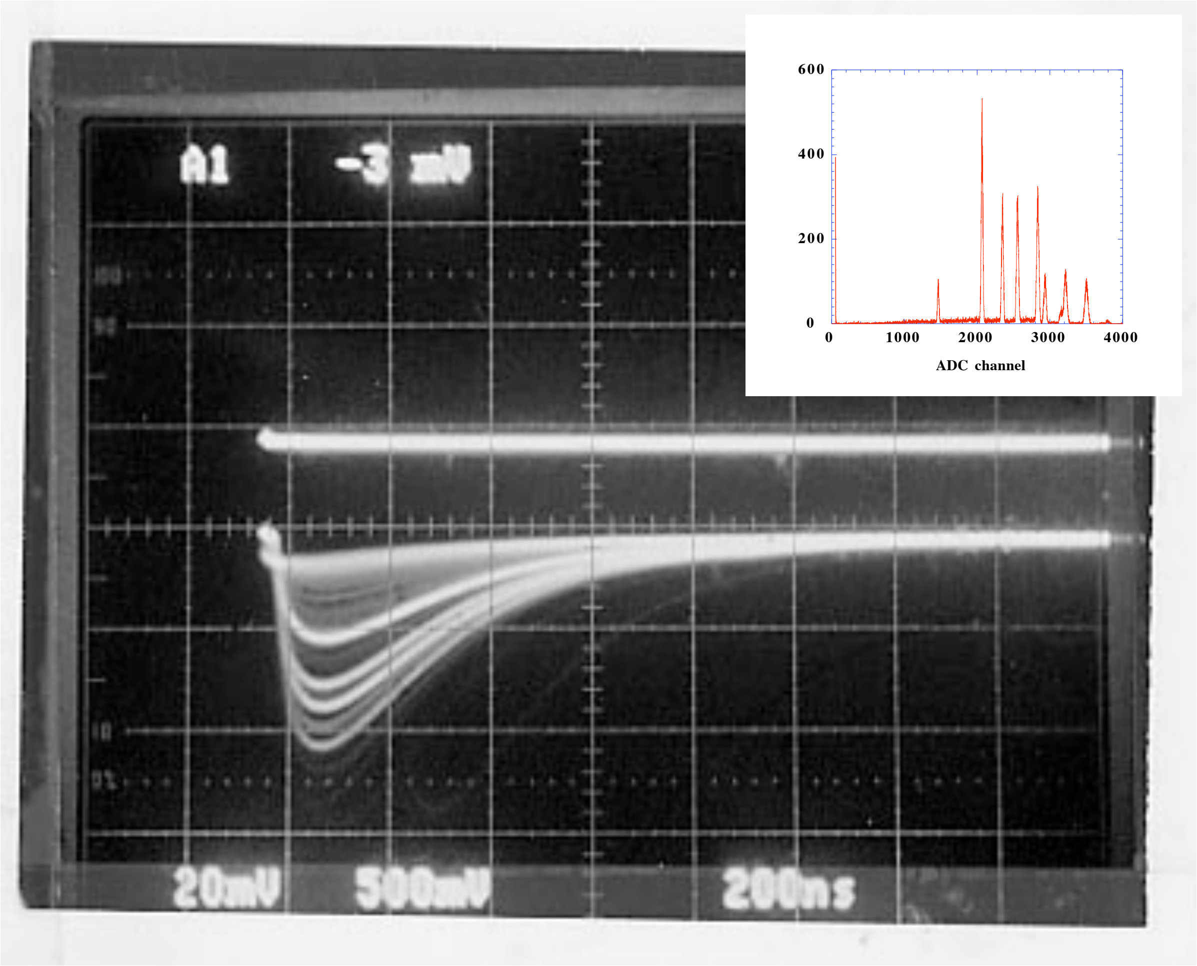
$$\boxed{\frac{\Delta E}{E} \propto \frac{1}{\sqrt{N_{photon}}}}$$



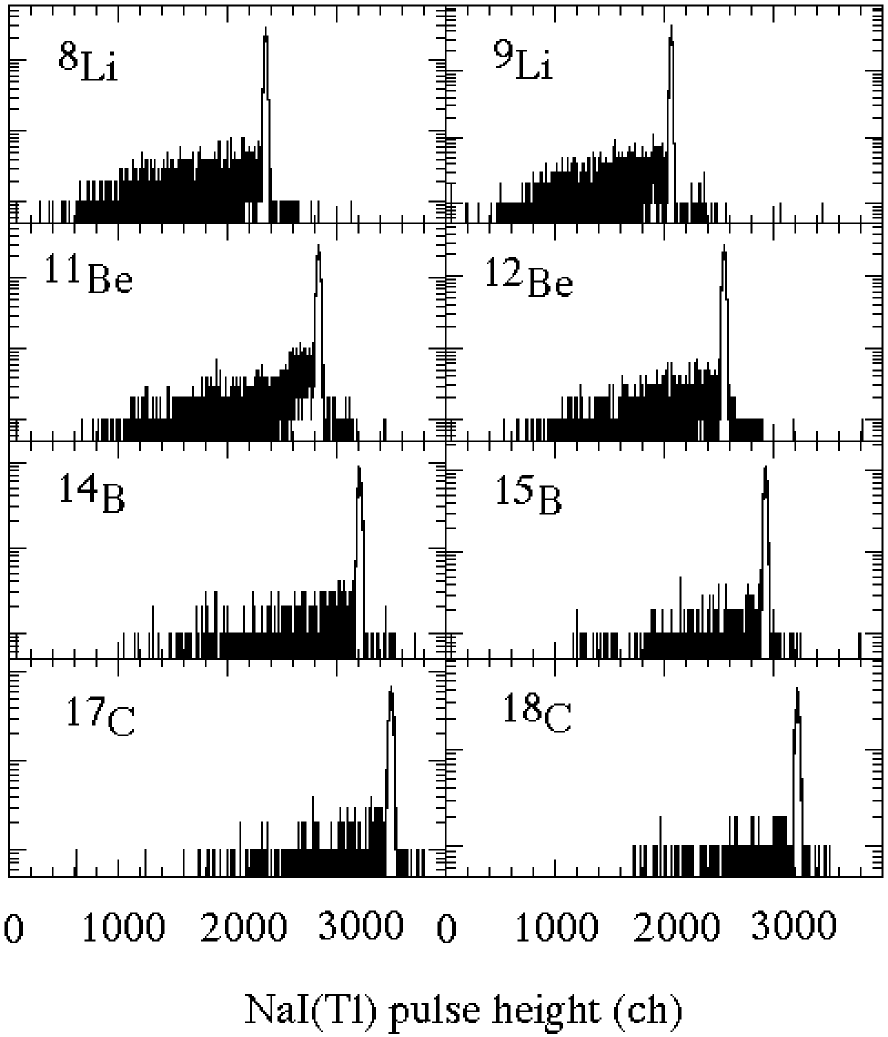


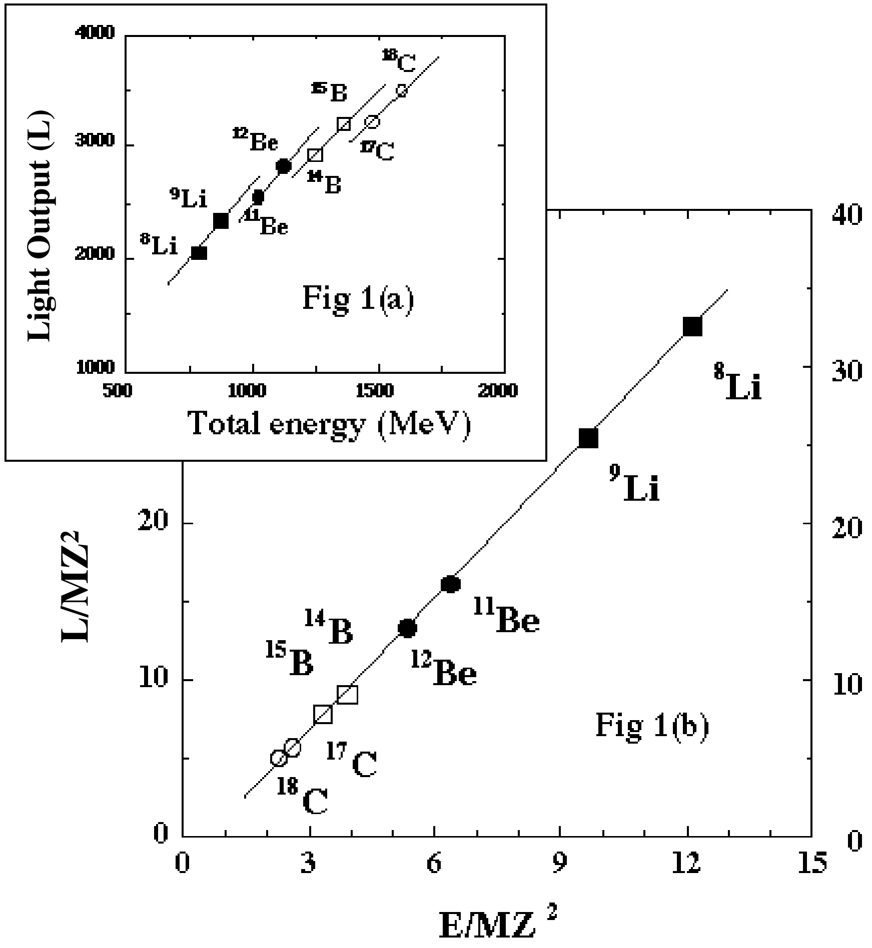
responses of NaI(Tl) to various heavy-ion beams

^{7,8}Li,^{11,12}Be,^{14,15}B and ^{17,18}C using RIPS



重イオンビームに対するNaI(Tl) の応答

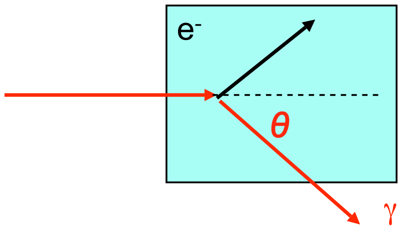


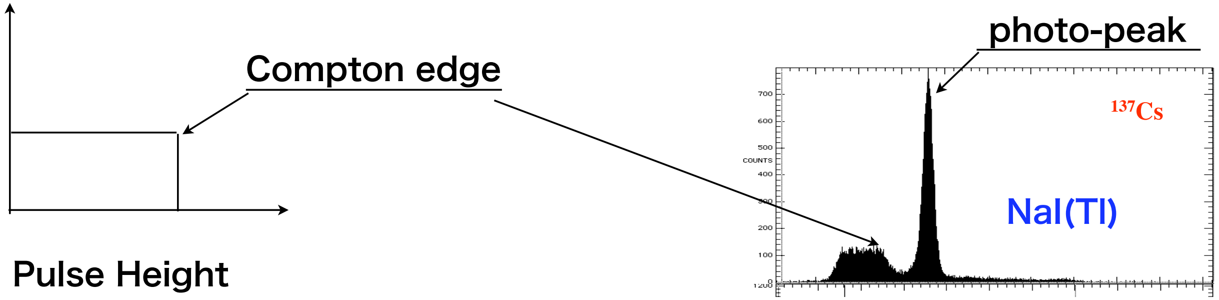


organic scintillator

- low Z materials
  - γ (~1MeV) interacts mostly via Compton scattering
    - pulse height is determined by Compton-scattered electron energy

Compton scattering





$$E^e = E_\gamma \left(\frac{\frac{2E_\gamma}{m_e}(1-\cos\theta)}{1+\frac{2E_\gamma}{m_e}(1-\cos\theta)} \right)$$

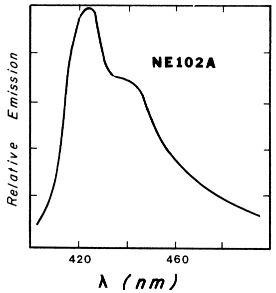
θ=180°

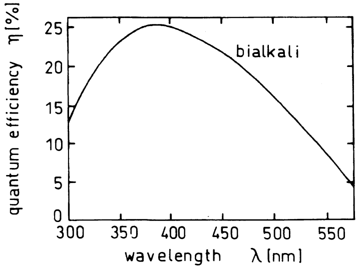
$$E^e_{Comp.Edge} = E_\gamma \left(\frac{2E_\gamma / m_e}{1 + 2E_\gamma / m_e} \right)$$

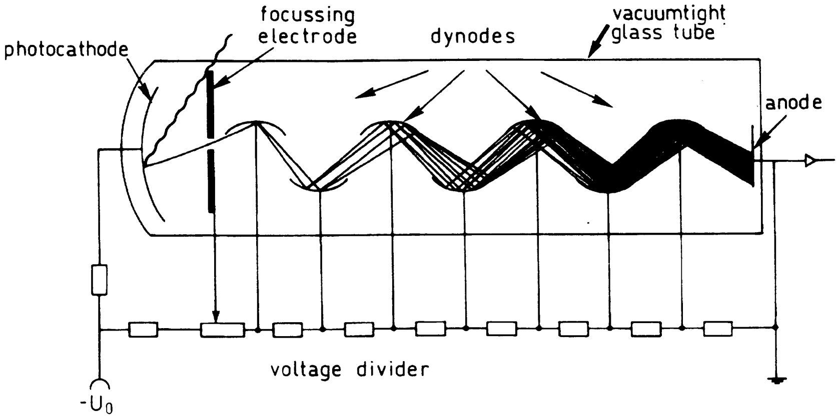
	Eγ (MeV)	Compton Edge (MeV)
^{137}Cs	0.662	0.478
^{60}Co	1.17, 1.33	0.960,1.12

plastic scintillator for charged particle

- **charged particles**
  - 1 photon/100 eV
  - minimum ionizing particle (~2MeV/(g/cm^2))
    - ~2 x 10^4 photons
    - collection eff. * Quantum eff ~ 0.1*0.25 = 2.5%
    - gain ~ 10^6
    - photo-electron : 2x10^4 x 0.025 x 10^6 ~ 5x10^8 = 8x10^{-11}C = Q
    - time duration ~ 50 ns : I = dQ/dt =8x10^{-11}/5x10^{-8} =1.6x10^{-3}A
    - electric signal (pulse height) : V=IR = 1.6x10^{-3}x50(Ω) = 80 mV

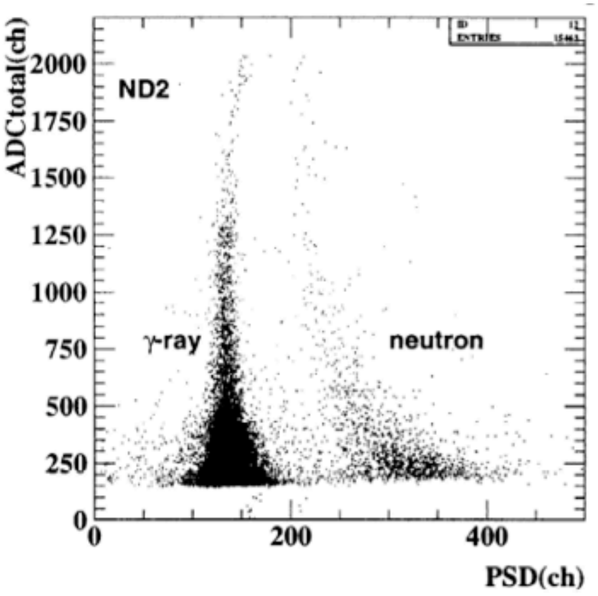


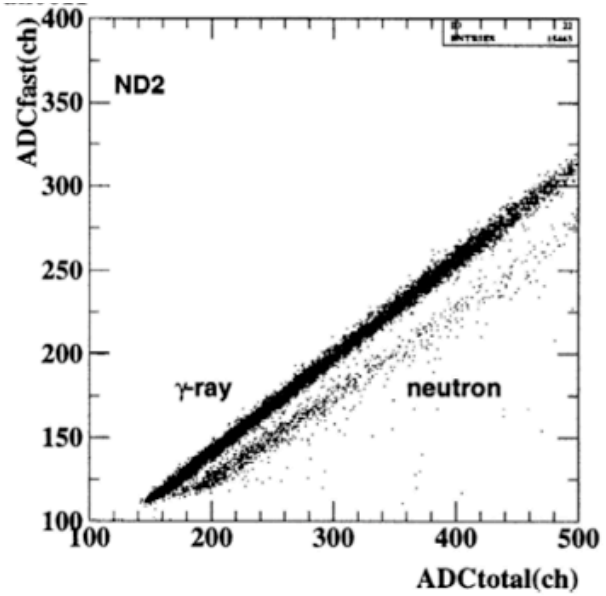




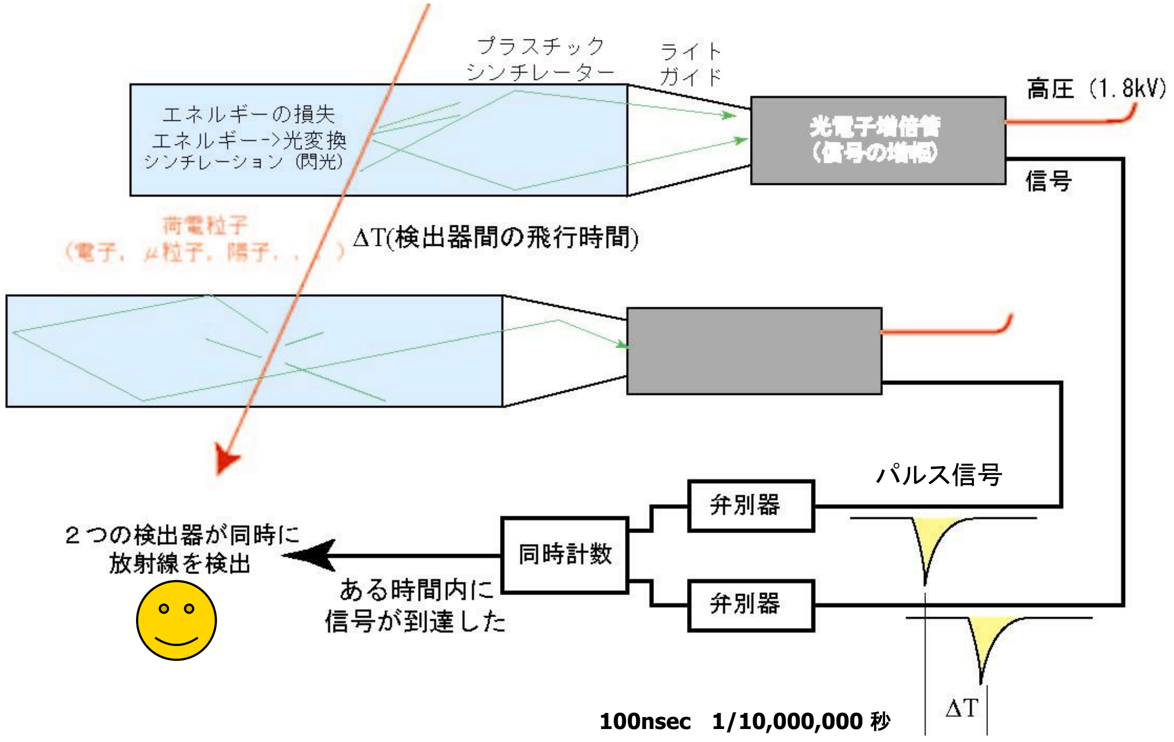
another type of organic scintillator

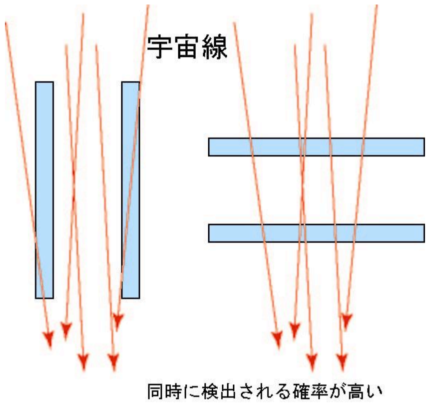
- **liquid scintillator**
  - similar properties as plastic scintillator
  - ex. a special feature of the liquid scintillator
    - fast and slow decay components of scintillation having different sensitivity to the energy loss densities
    - analyzing the pulse shape -> particle identification





ex. Velocity measurement using plastic scintillators





useful scale

cosmic ray (μ) can be safely assumed as “minimum ionizing particles”. Their energy loss in a 1cm-thick plastic scintillator (~1g/cm^2) is ~ 2 MeV.