PAN-2016

Radiation detectors

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Grab the control of the universe!

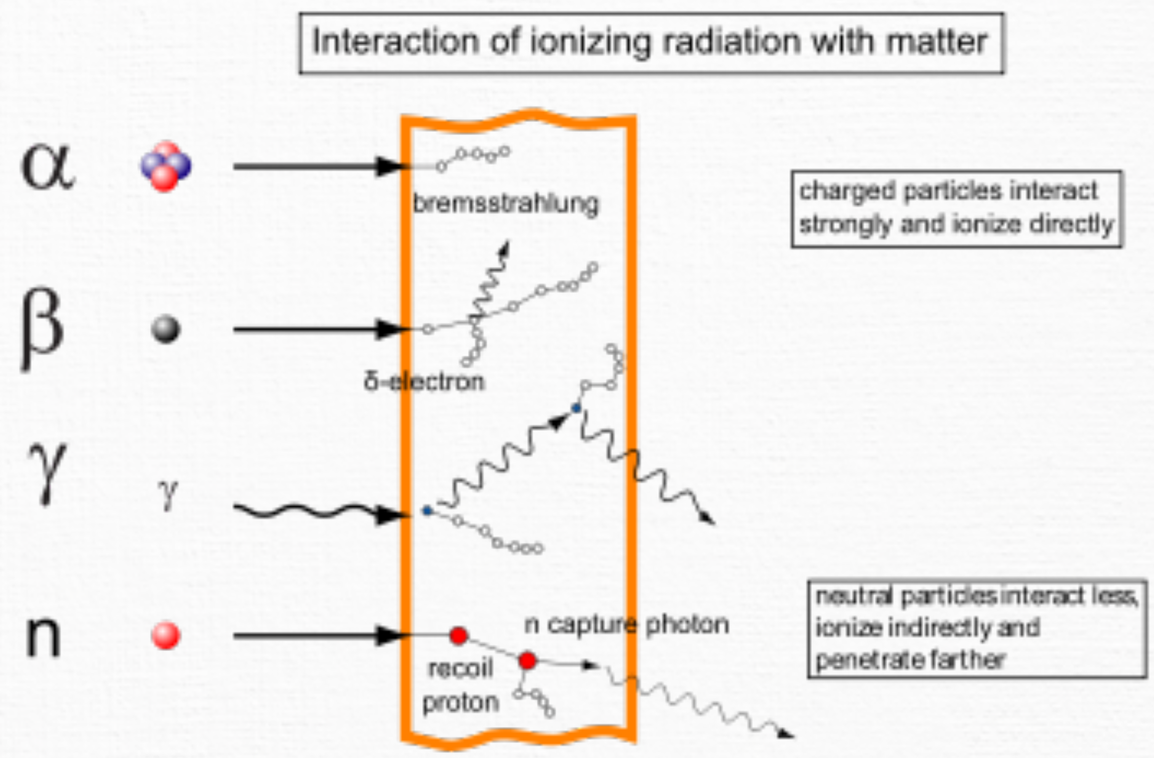
Types of radiation

Interaction of radiation with the matter

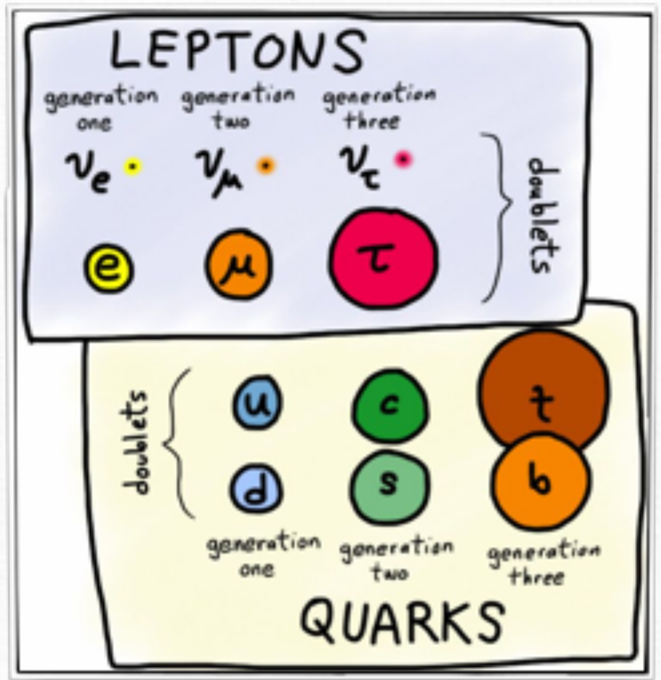
How we detect radiation and particles

Future…

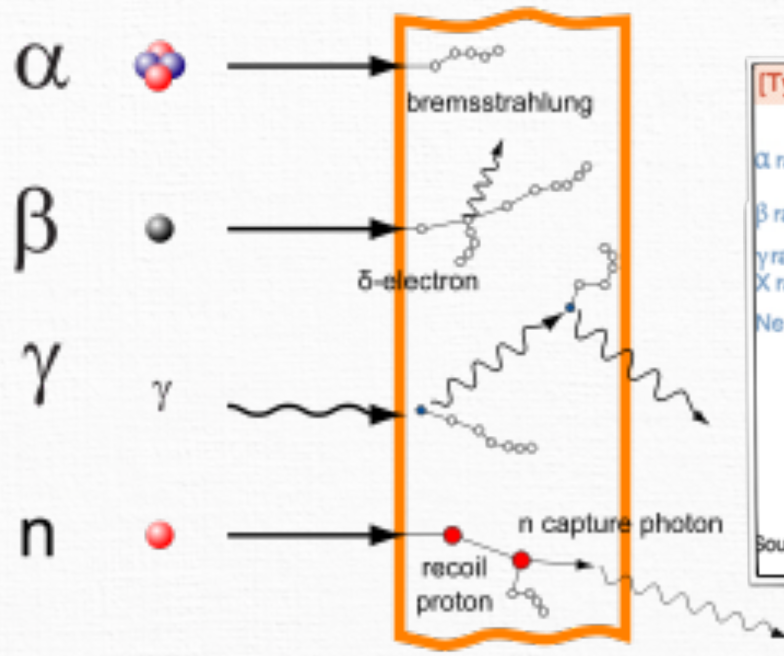
Types of radiation

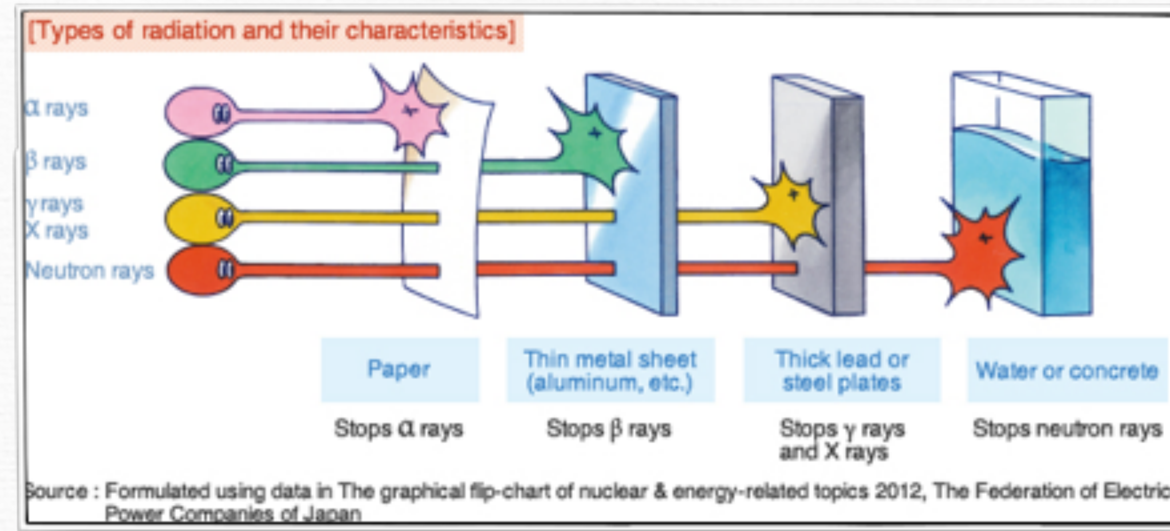


Types of radiation

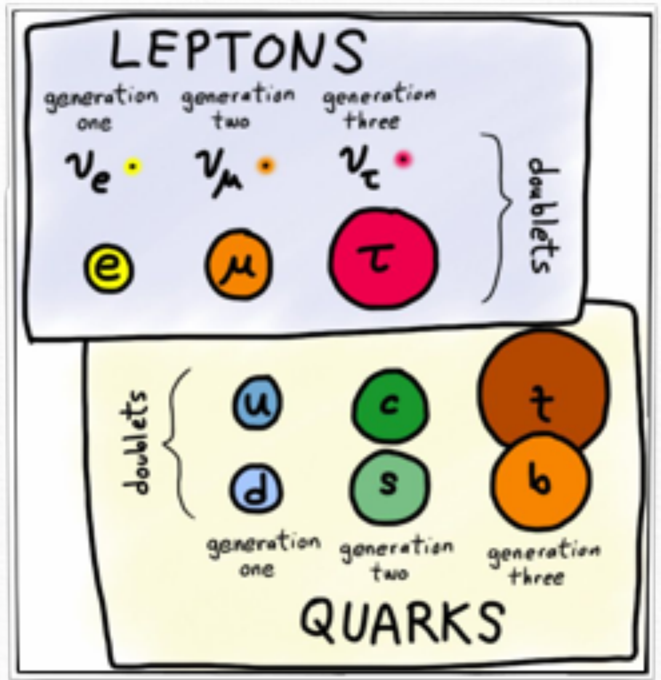


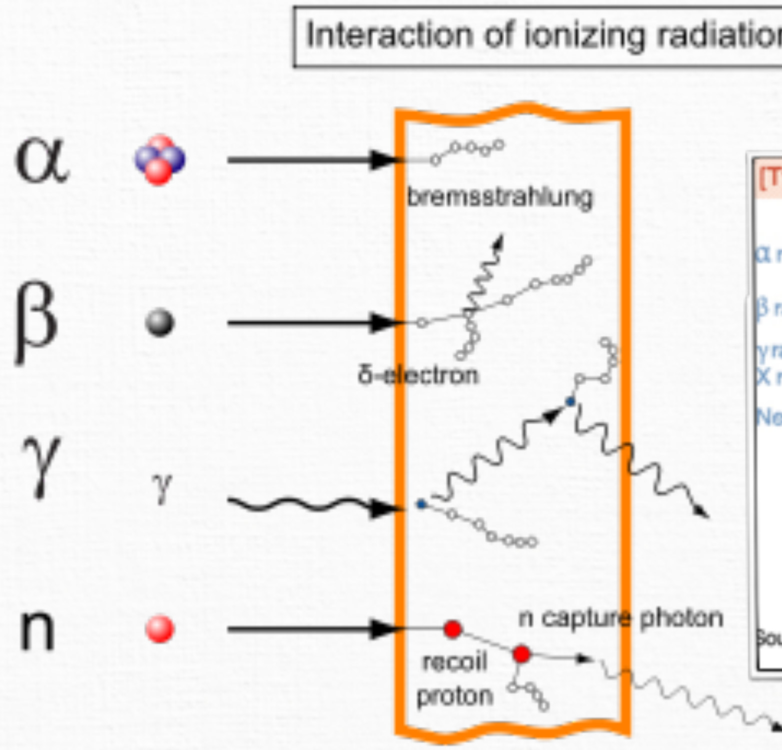
Interaction of ionizing radiation with matter

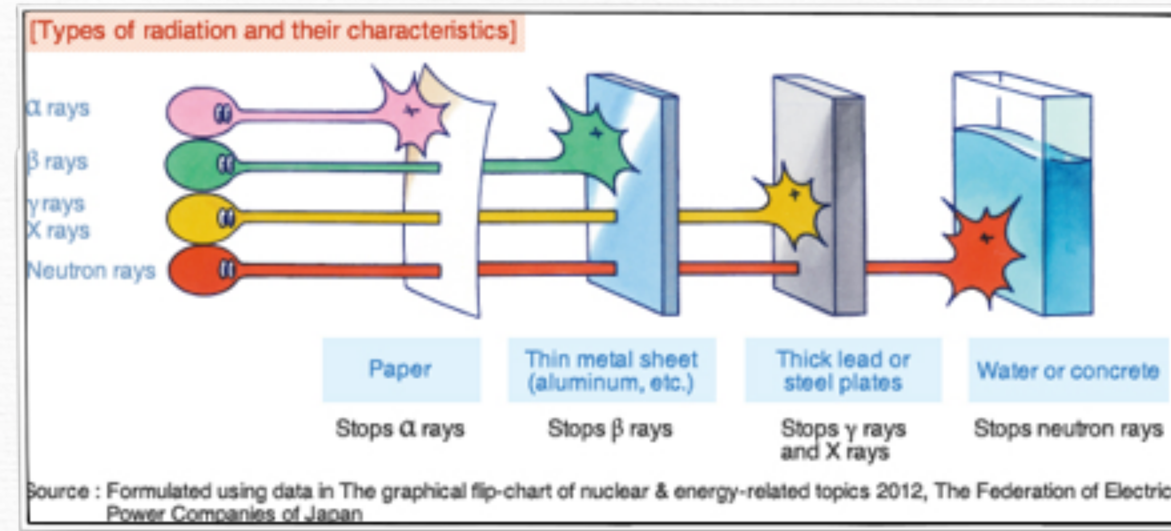




Types of radiation







Sources of radiation

Natural sources: Cosmic rays (μ, e, ν) and natural radiation (^{40}K, U, Th … ^{222}Rn)

Artificial sources: Accelerators for research in nuclear physics, materials, medicine
Reactors for nuclear power generation (or research)
and atomic bombs…

Types of radiation

Interaction of ionizing radiation with matter

1 Sv = 1 joule/kilogram (of human tissue)
- a biological effect.

Banana Equivalent Dose

Bananas are a natural source of radioactive isotopes.

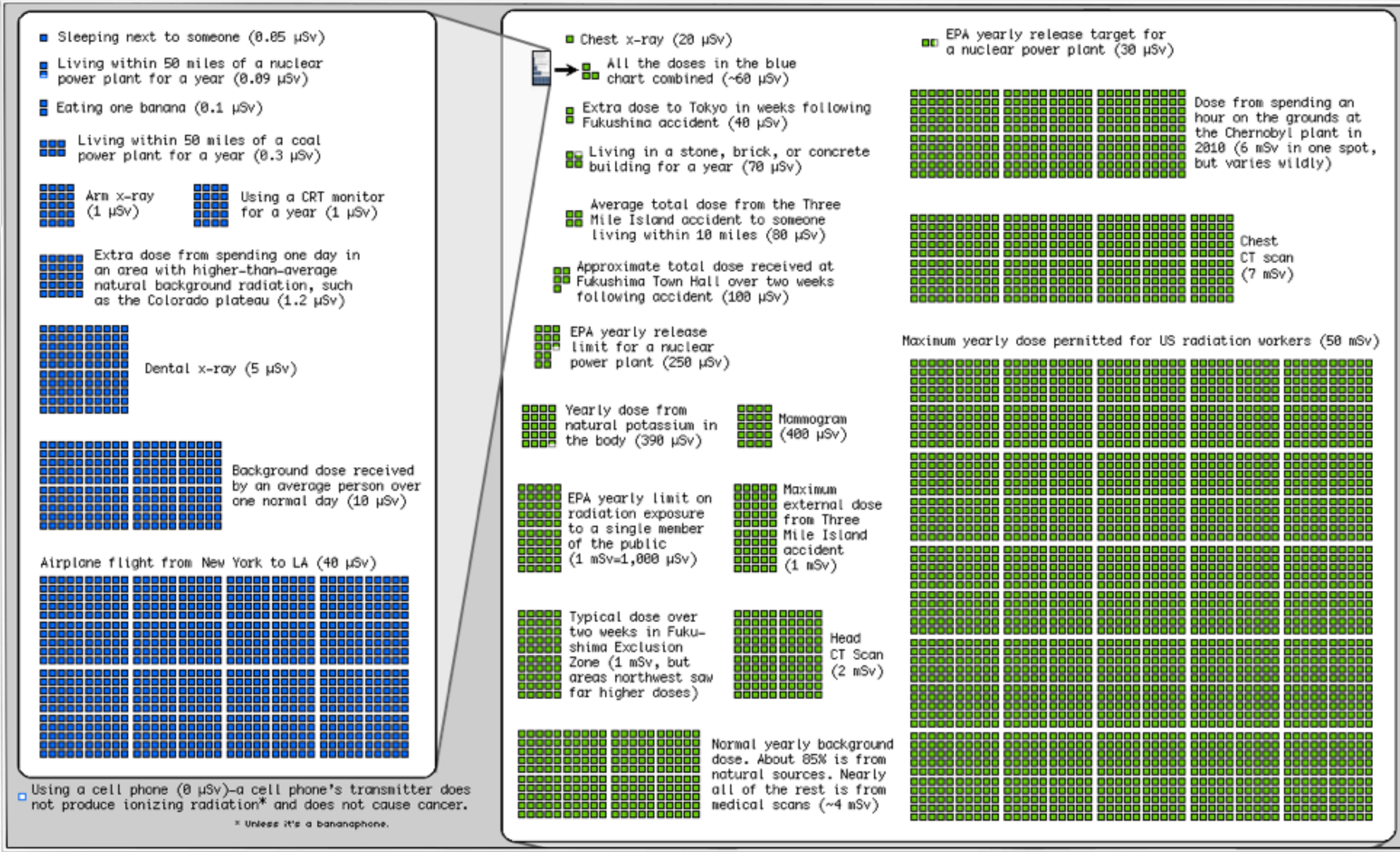
Eating one banana = 1 BED = 0.1 μSv = 0.01 mrem

Number of bananas	Equivalent exposure
100,000,000	Fatal dose (death within 2 weeks)
20,000,000	Typical targeted dose used in radiotherapy (one session)
70,000	Chest CT scan
20,000	Mammogram (single exposure)
200 - 1000	Chest X-ray
700	Living in a stone, brick or concrete building for one year
400	Flight from London to New York
100	Average daily background dose
50	Dental X-ray
1 - 100	Yearly dose from living near a nuclear power station

Nat … ^{222}Rn)

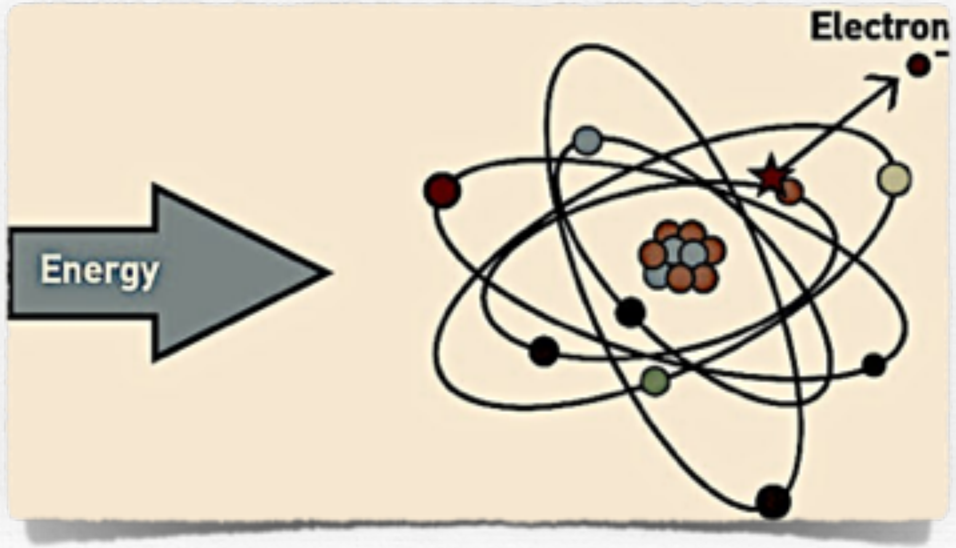
Artific … edicine

Interaction of light charged particles with the matter

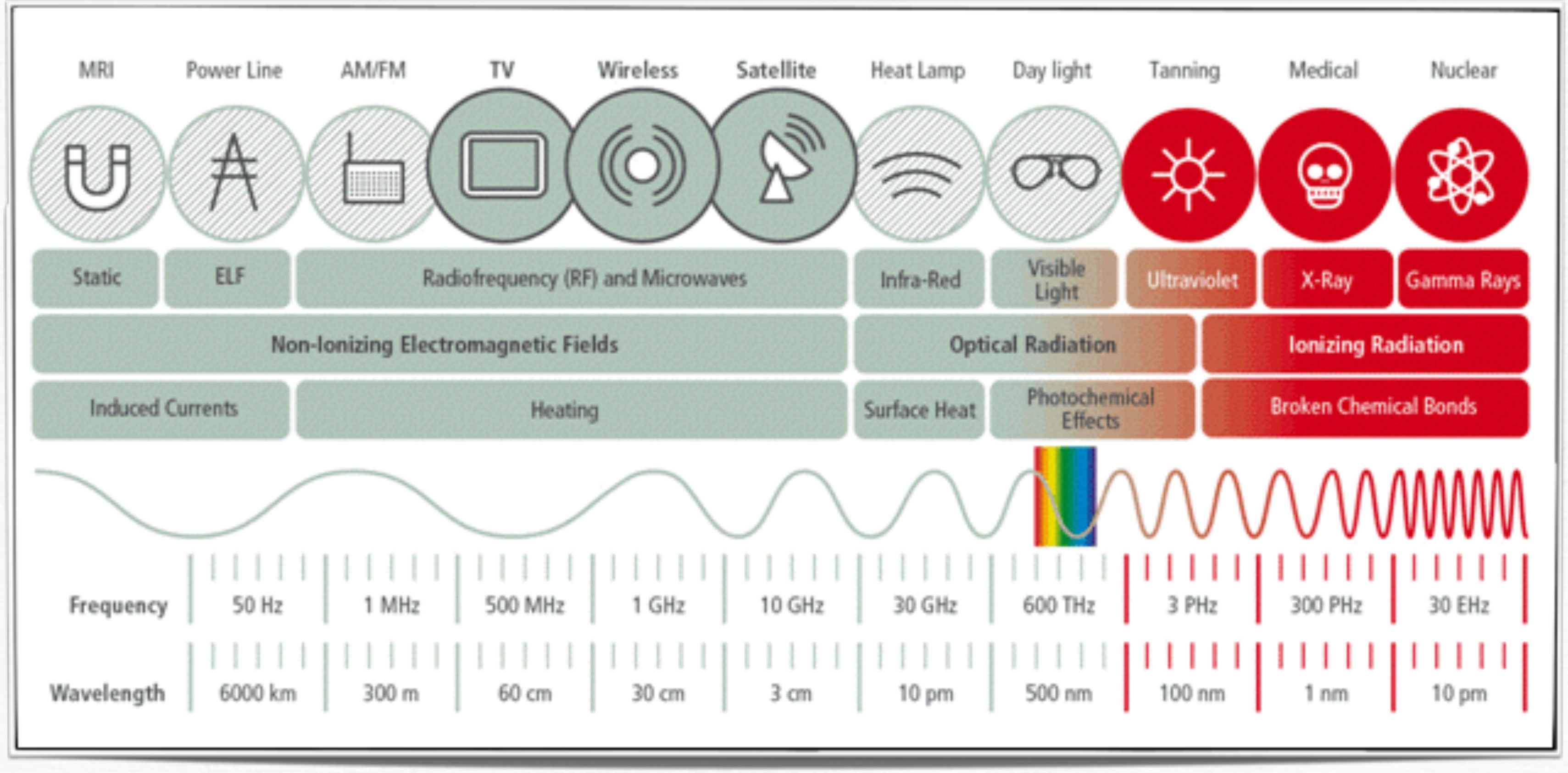


Interaction of radiation with the matter

Ionizing radiation has enough energy to ionize (kick off) electrons from atoms
Depends on the energy and the nature of the radiation



Energy at least equal to the binding energy of the electron



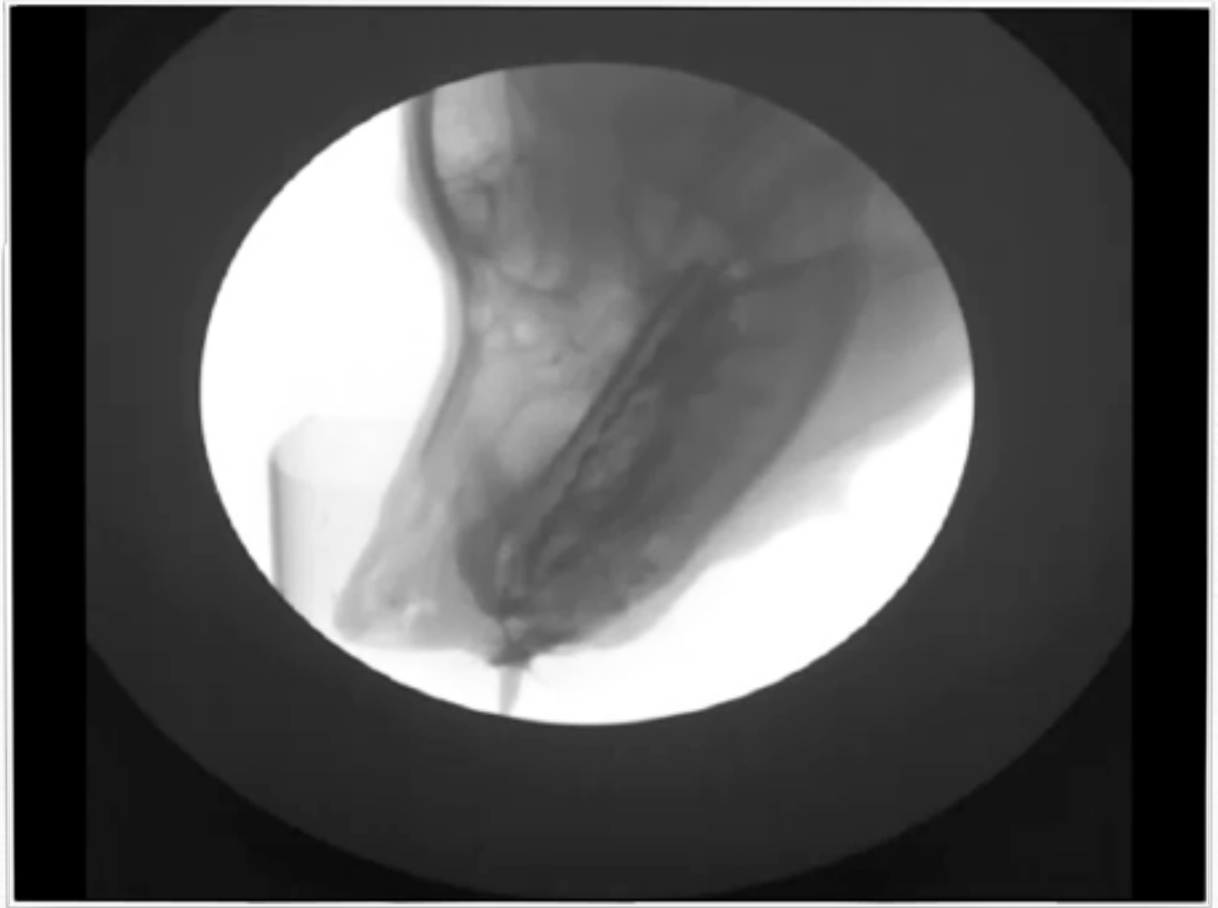
Why MeV?

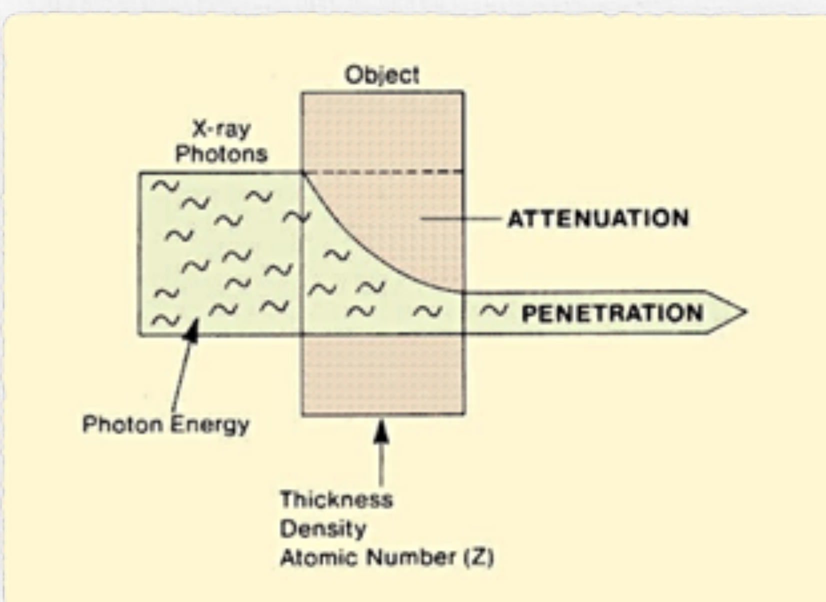
In physics, the electron volt (symbol eV; also written electronvolt) is a unit of energy equal to approximately 1.602×10−19 joule (symbol J). By definition, it is the amount of energy gained by the charge of a single electron moved across an electric potential difference of one volt.

- 5.25×10^{32} eV: total energy released from a 20 kt nuclear fission device
- 1.22×10^{28} eV: the Planck energy
- 1×10^{25} eV: the approximate grand unification energy
- ~624 EeV (6.24×10^{20} eV): energy consumed by a single 100-watt light bulb in one second (100 W = 100 J/s ≈ 6.24×10^{20} eV/s)
- 300 EeV (3×10^{20} eV = ~50 J):[13] the so-called Oh-My-God particle (the most energetic cosmic ray particle ever observed)
- 2 PeV: two petaelectronvolts, the most high-energetic neutrino detected by the IceCube neutrino telescope in Antarctica[14]
- 14 TeV: the designed proton collision energy at the Large Hadron Collider (operated at about half of this energy since 30 March 2010, reached 13TeV in May 2015)
- 1 TeV: a trillion electronvolts, or 1.602×10^{-7} J, about the kinetic energy of a flying mosquito[15]
- 125.1±0.2 GeV: the energy corresponding to the mass of the Higgs boson, as measured by two separate detectors at the LHC to a certainty better than 5 sigma[16]
- 210 MeV: the average energy released in fission of one Pu-239 atom
- 200 MeV: the average energy released in nuclear fission of one U-235 atom
- 17.6 MeV: the average energy released in the fusion of deuterium and tritium to form He-4; this is 0.41 PJ per kilogram of product produced
- 1 MeV (1.602×10^{-13} J): about twice the rest energy of an electron
- 13.6 eV: the energy required to ionize atomic hydrogen; molecular bond energies are on the order of 1 eV to 10 eV per bond
- 1.6 eV to 3.4 eV: the photon energy of visible light
- 25 meV: the thermal energy $k_B T$ at room temperature; one air molecule has an average kinetic energy 38 meV
- 230 μeV: the thermal energy $k_B T$ of the cosmic microwave background

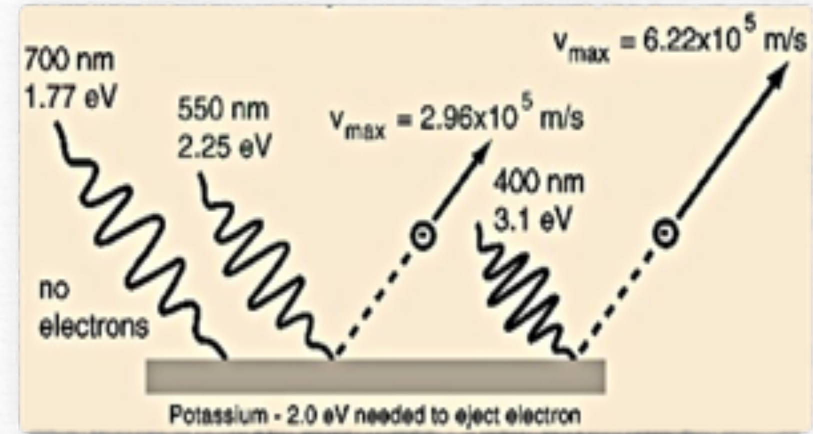
mass-energy equivalence!

Interaction of photons with the matter

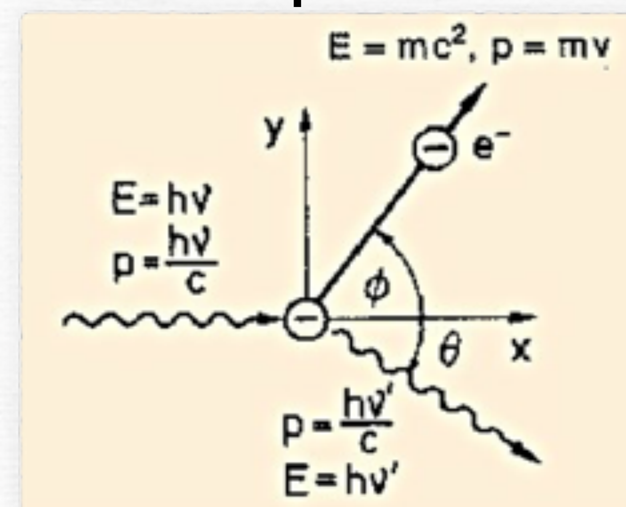




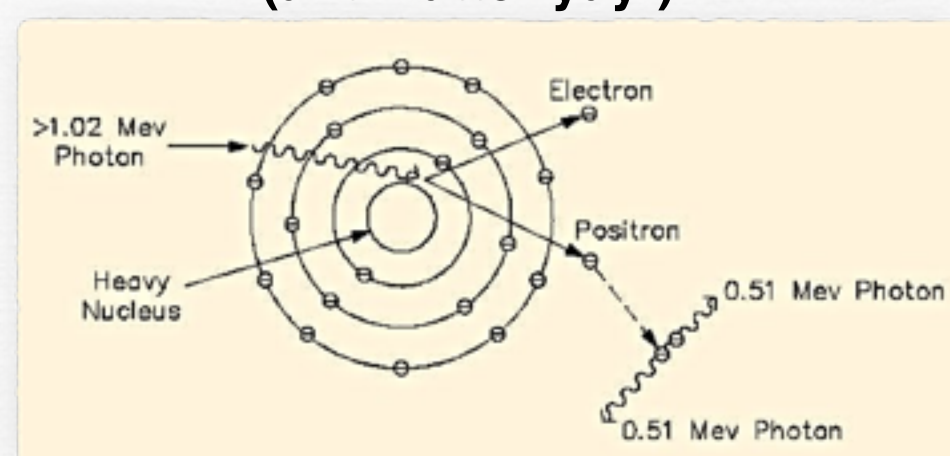
I- Photoelectric effect



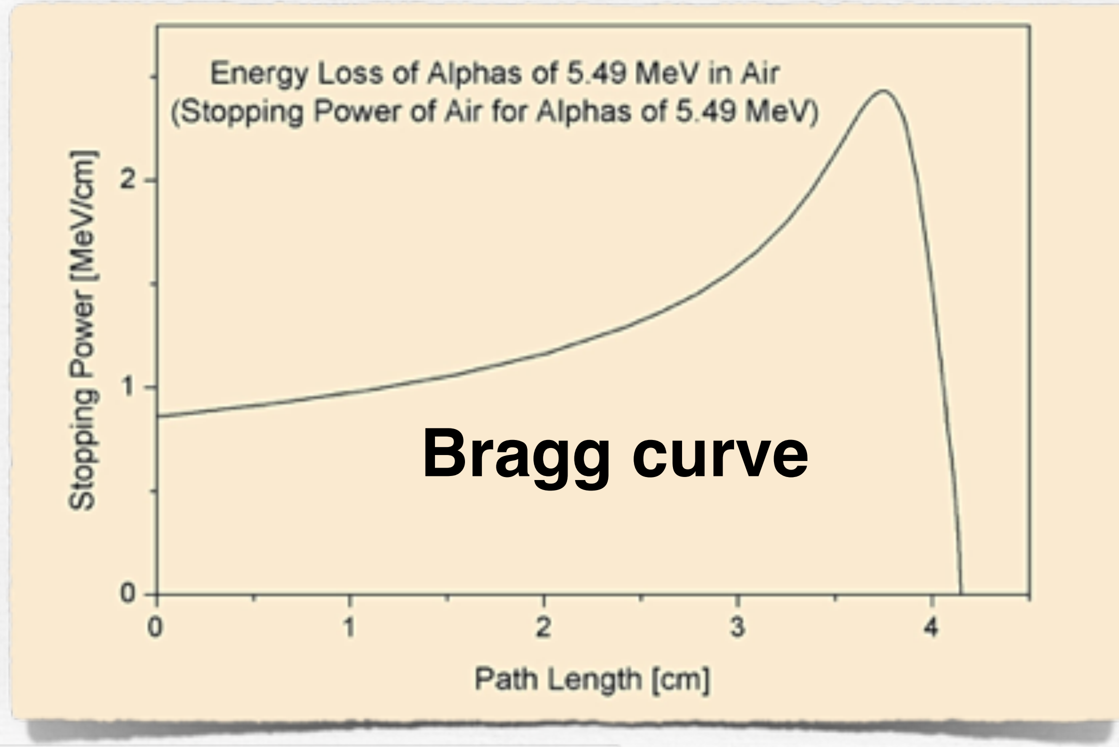
II- Compton effect

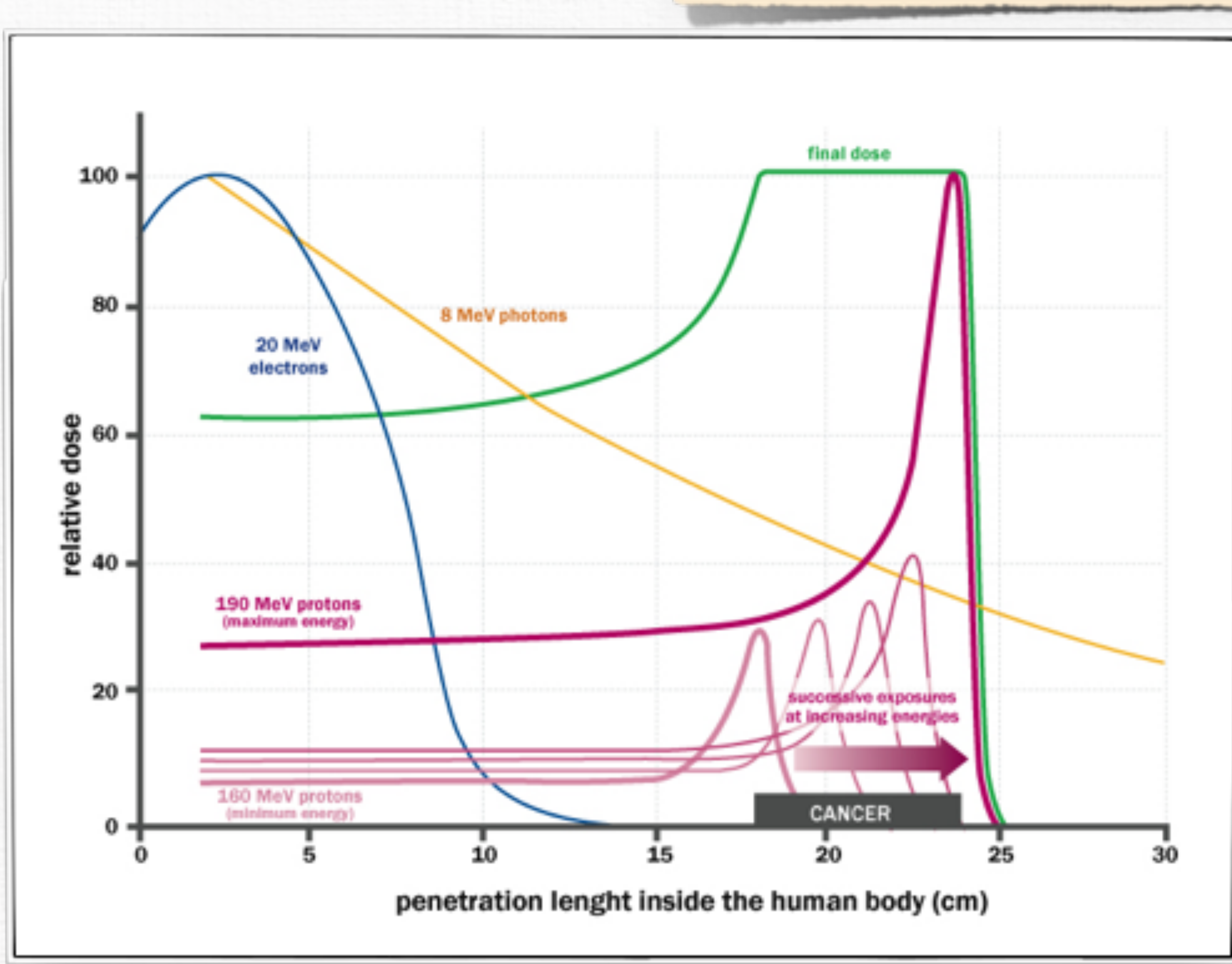


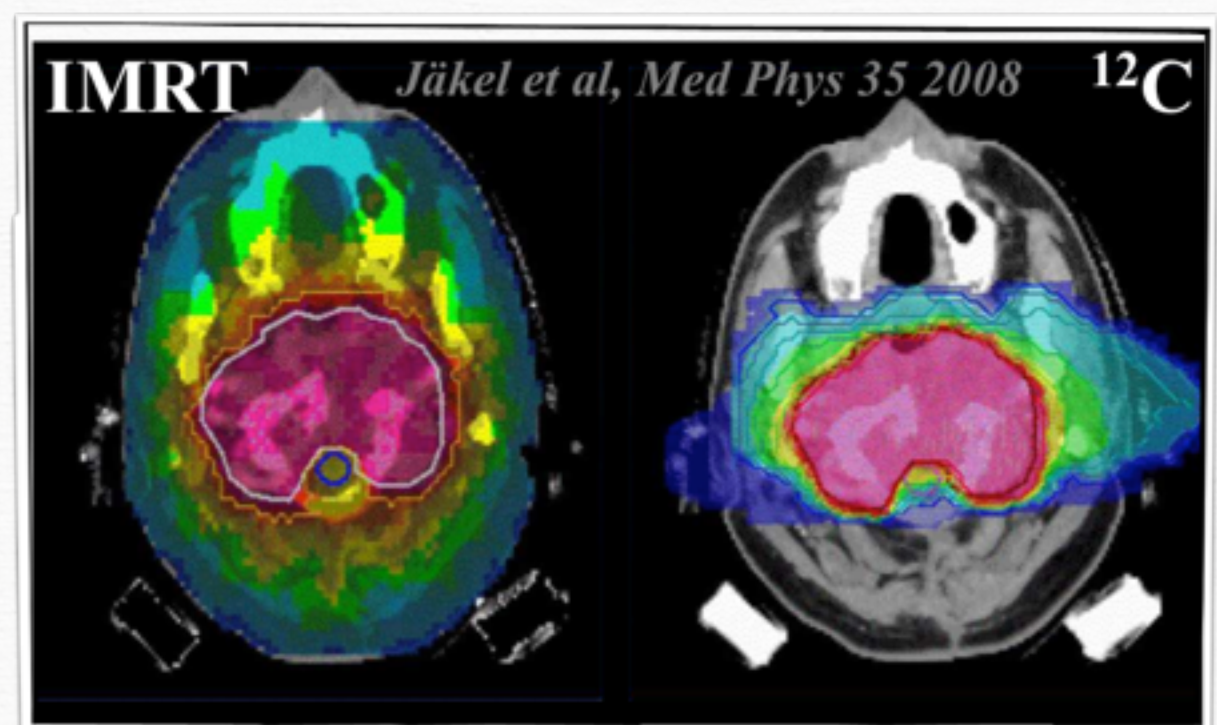
III- Pair production (antimatter yay!)



Interaction of charged particles with the matter

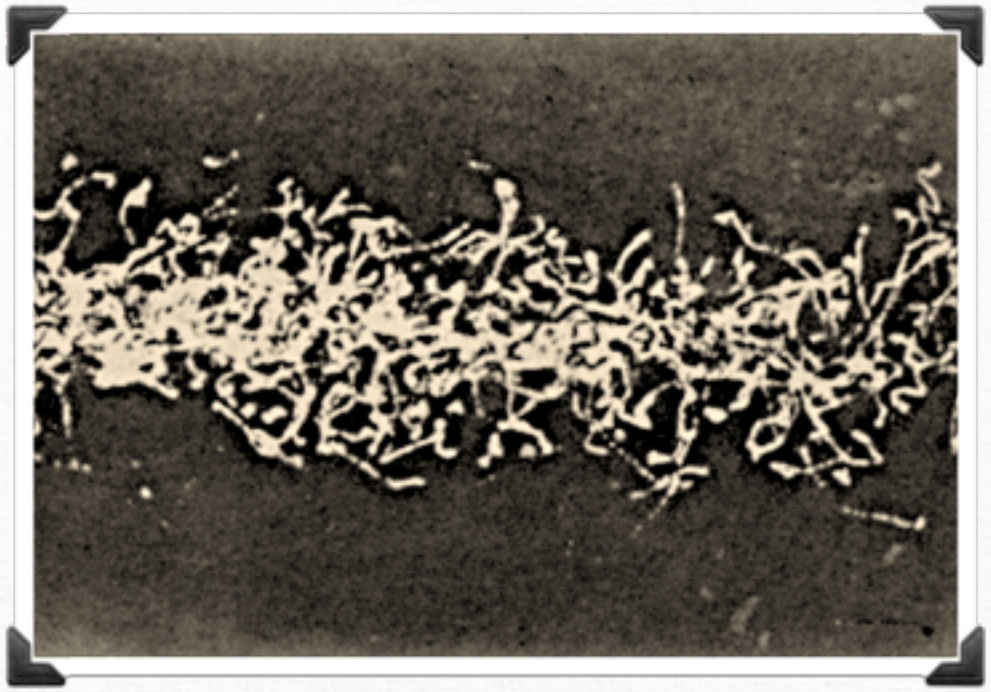


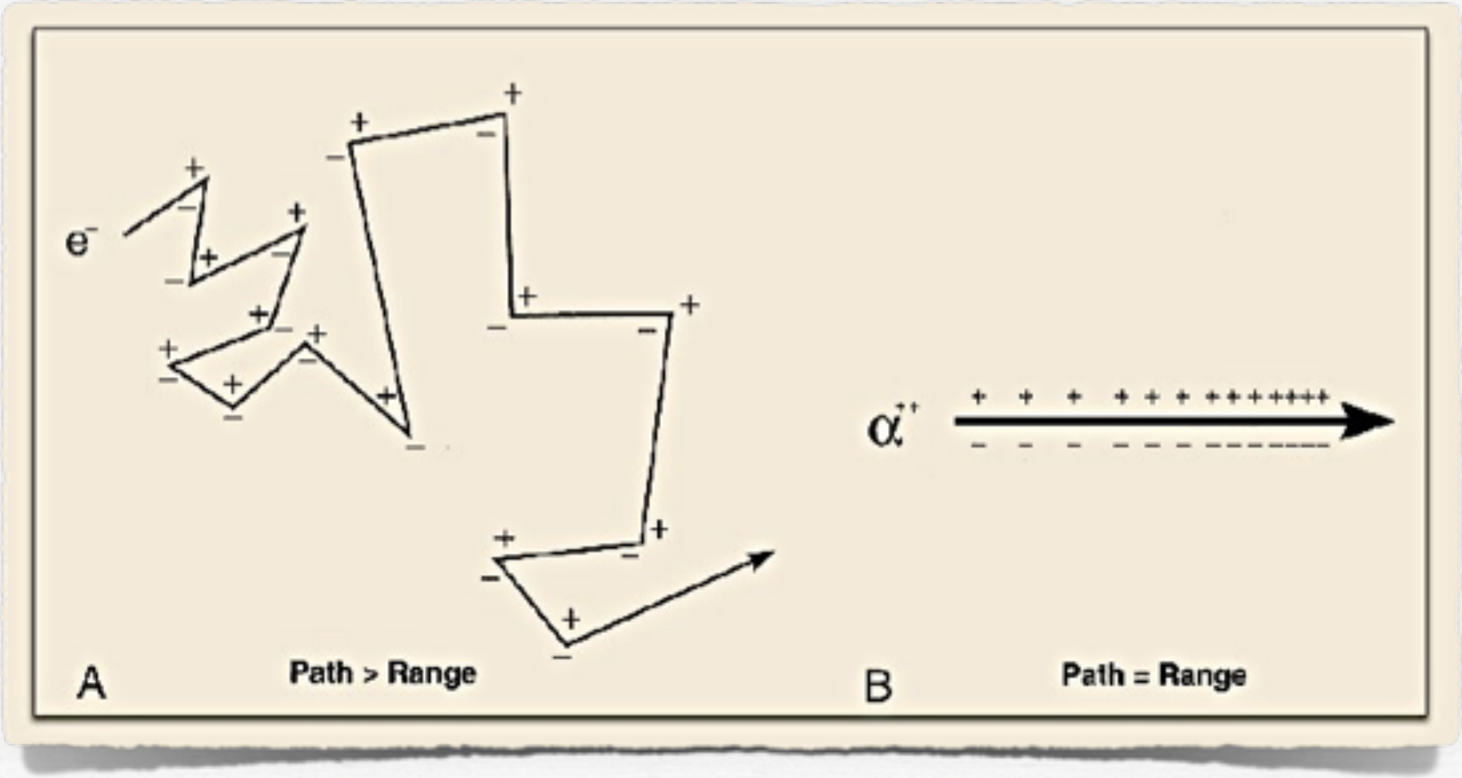




Interaction of light-charged particles with the matter

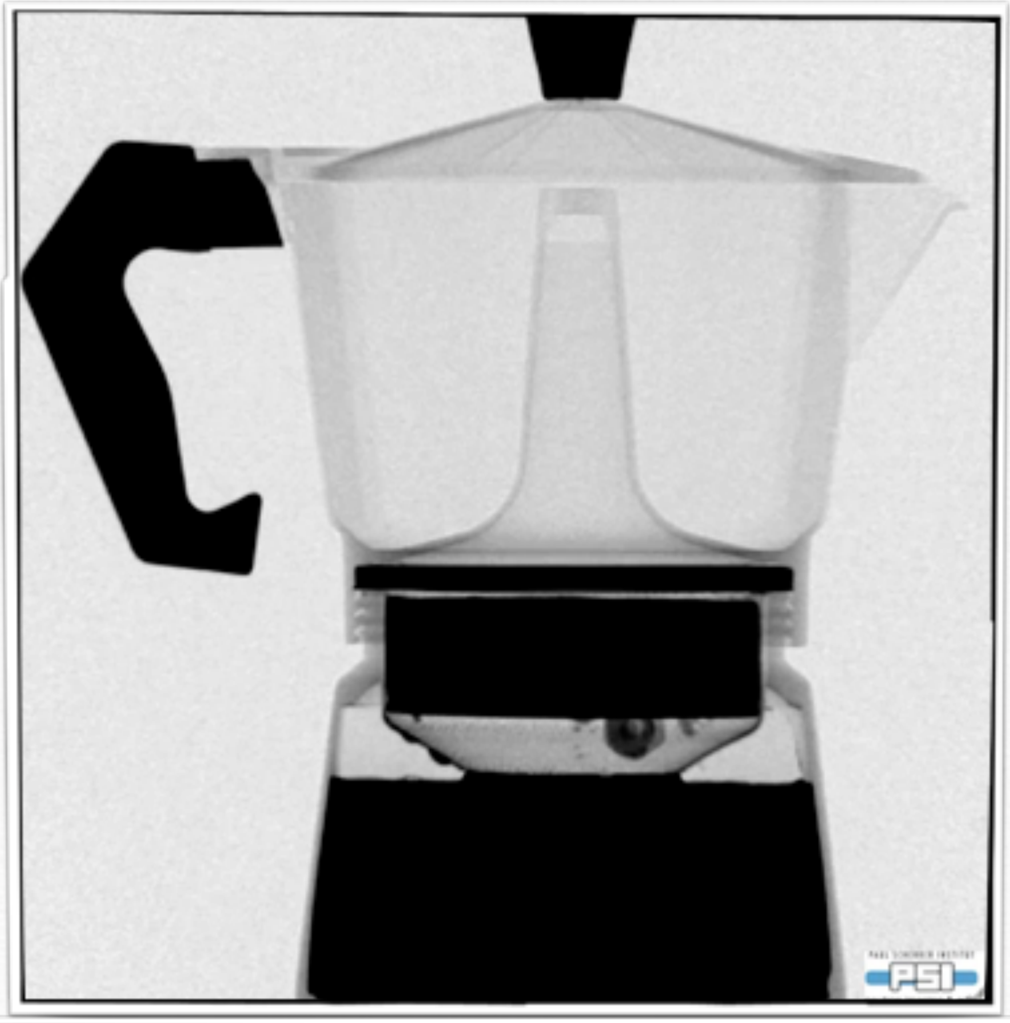
Electrons produced by X-rays in air

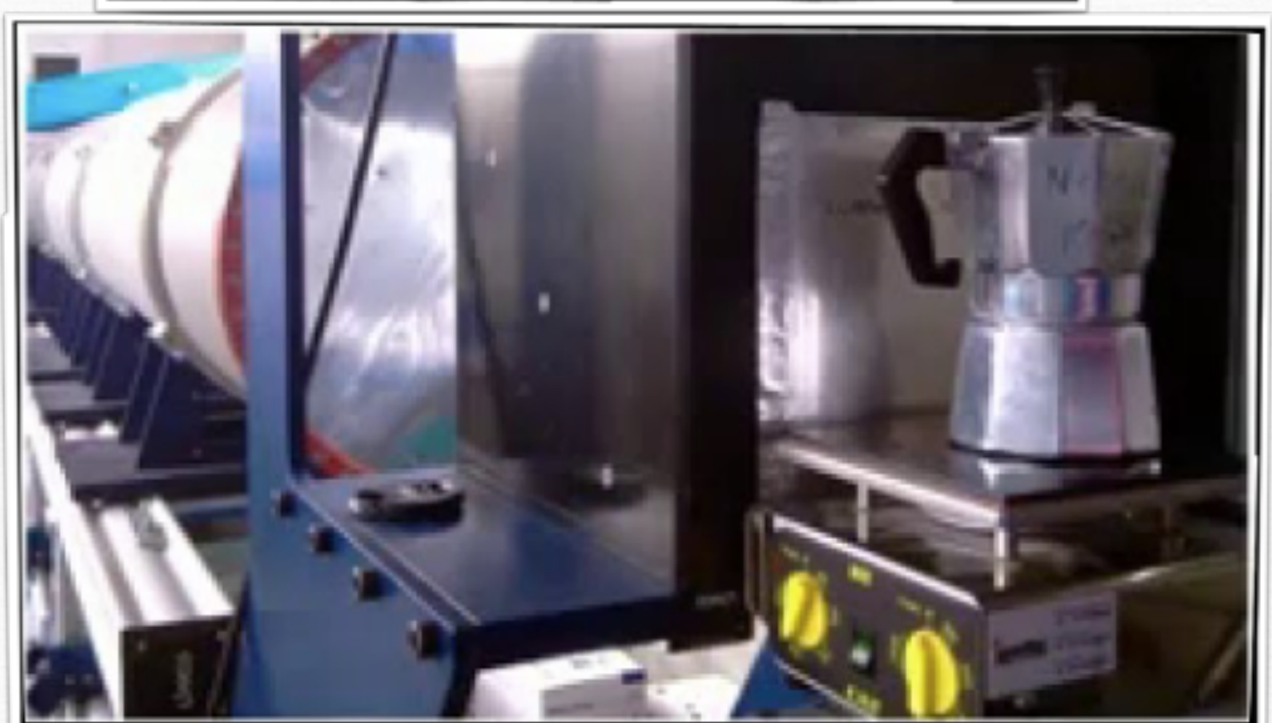


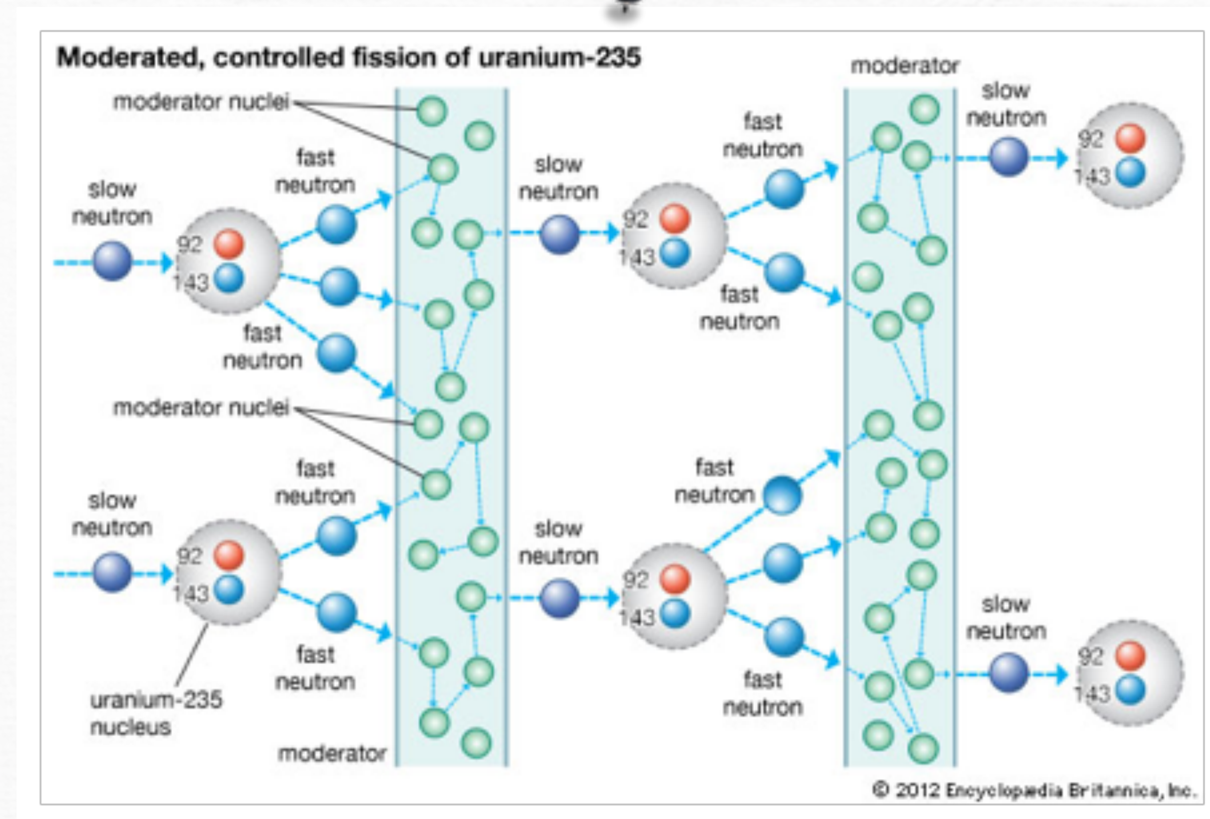


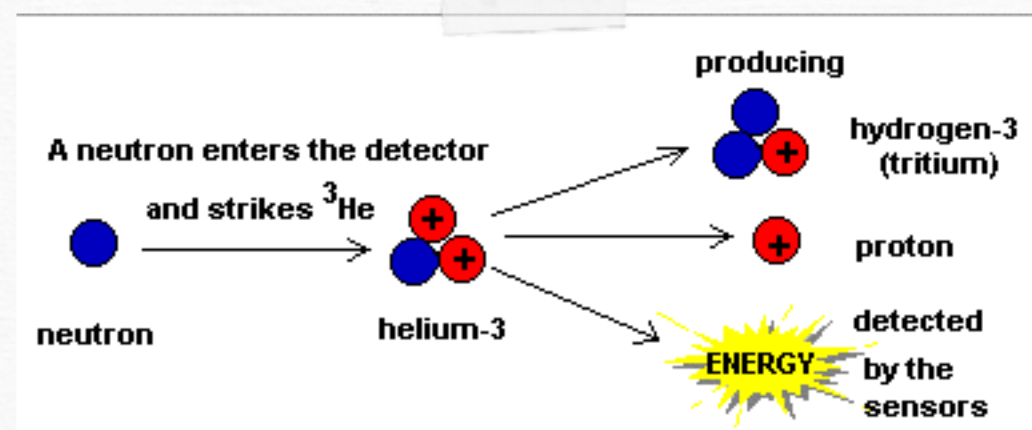
Energy loss by ionization and radiation!

Interaction of neutrons with the matter







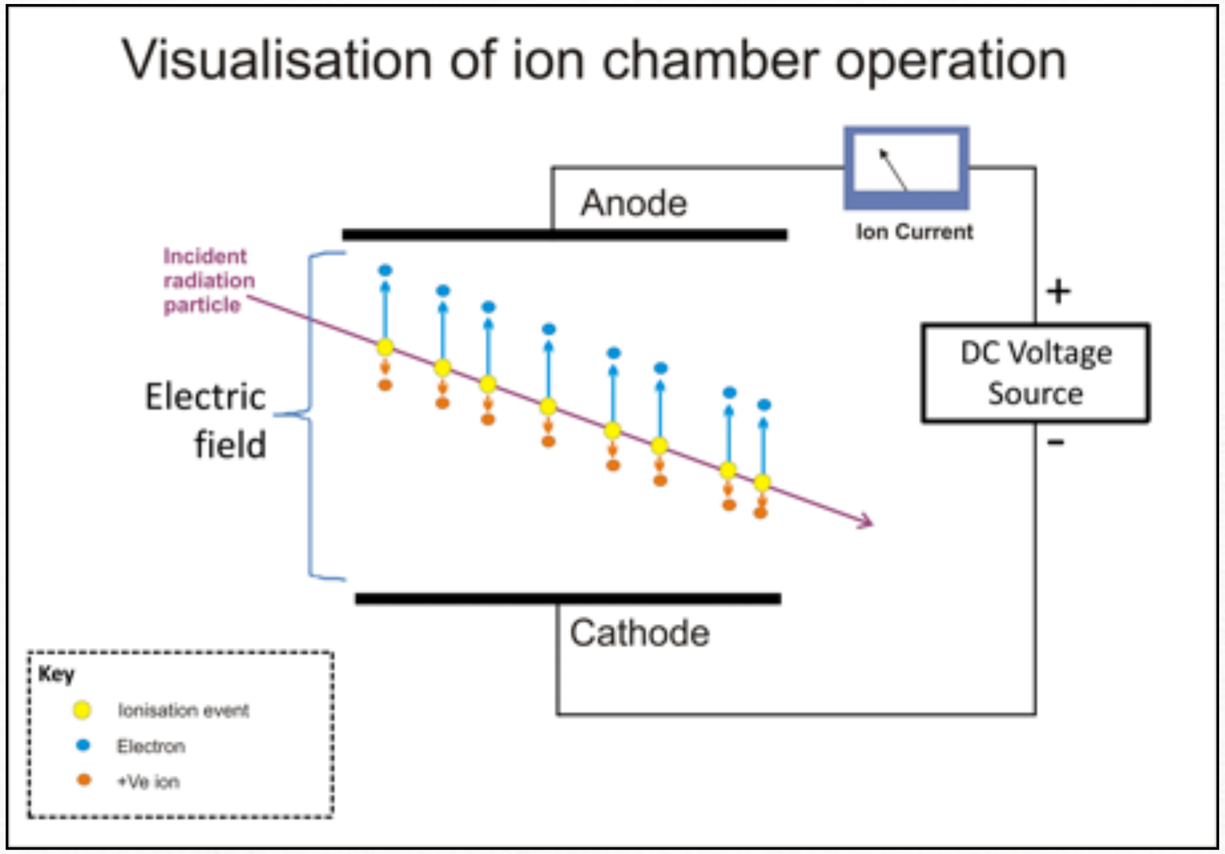


Moderate

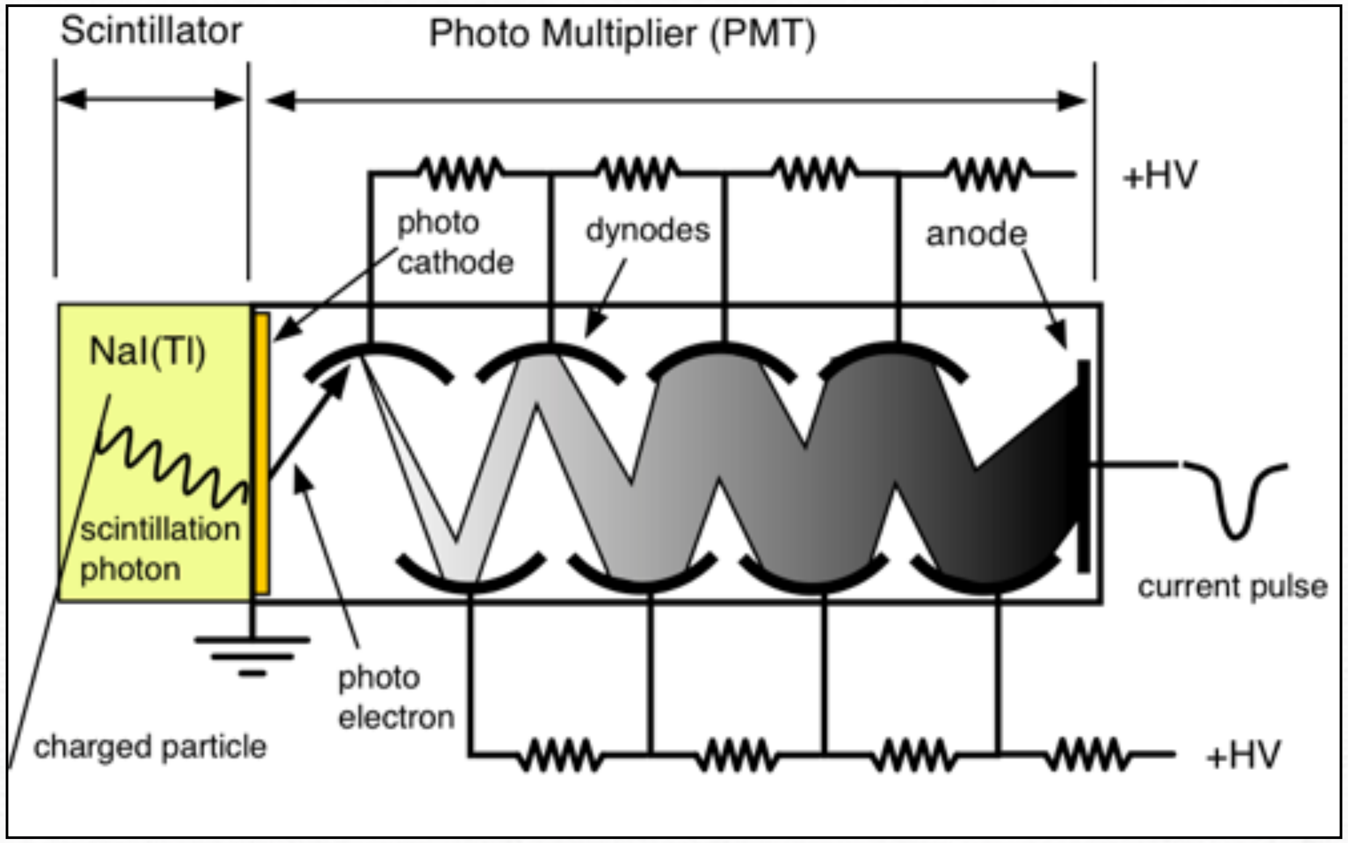
Capture — **Ionize (light target)** — **Elastic (heavy target)**

Radiation detectors

Charge carriers

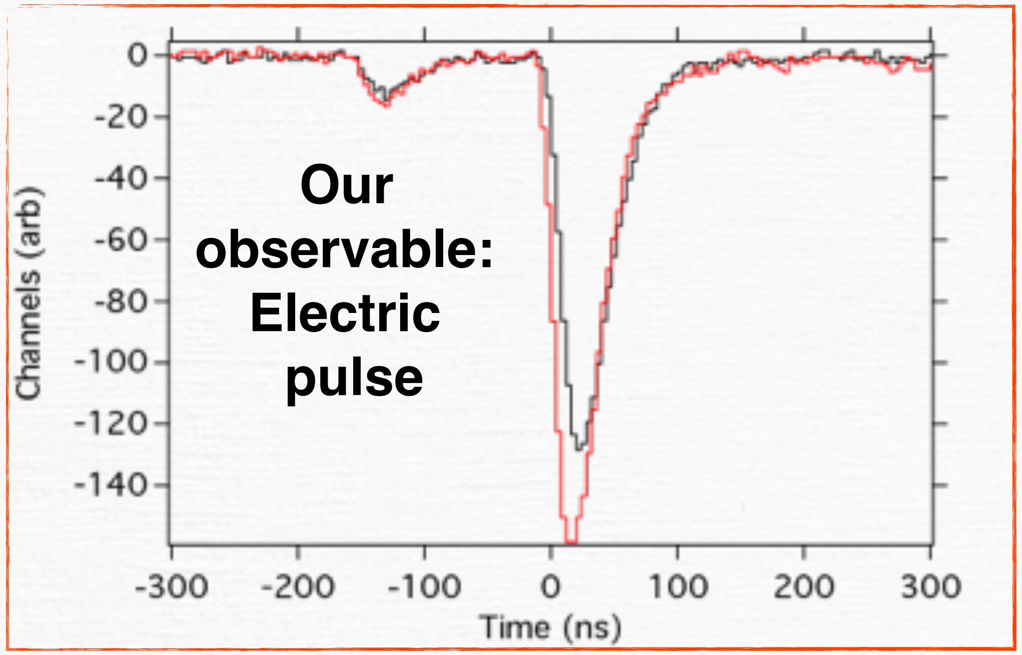


Light emission



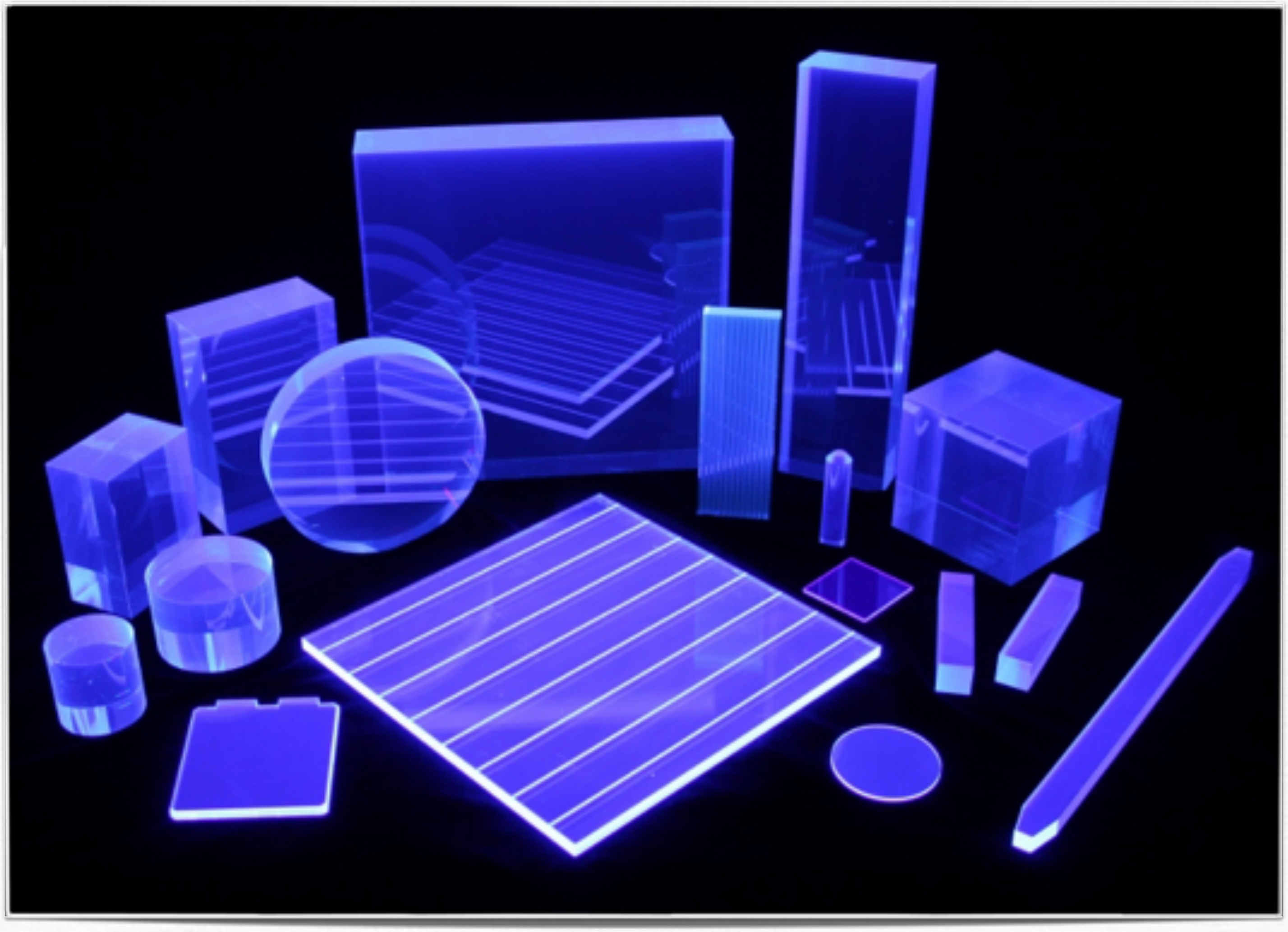
Solid state detectors

Gas detectors

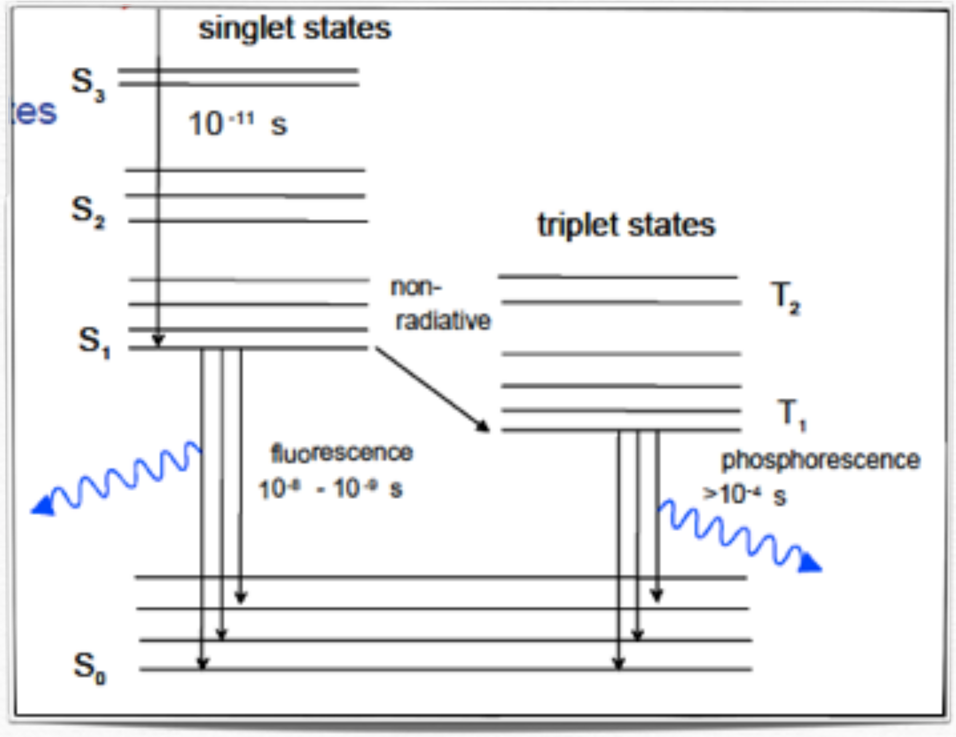


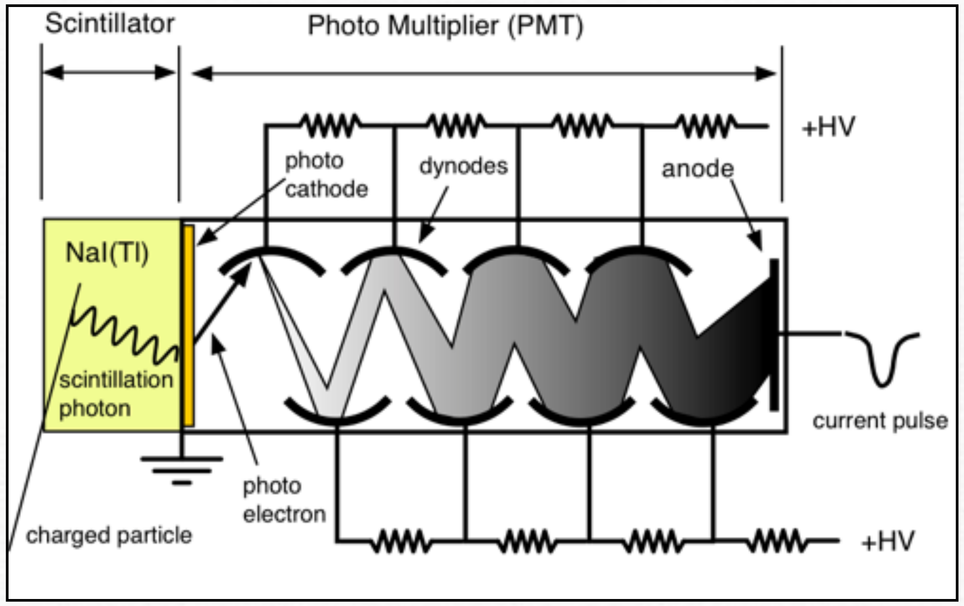
Organic and inorganic scintillators

Plastic scintillators (Organic)



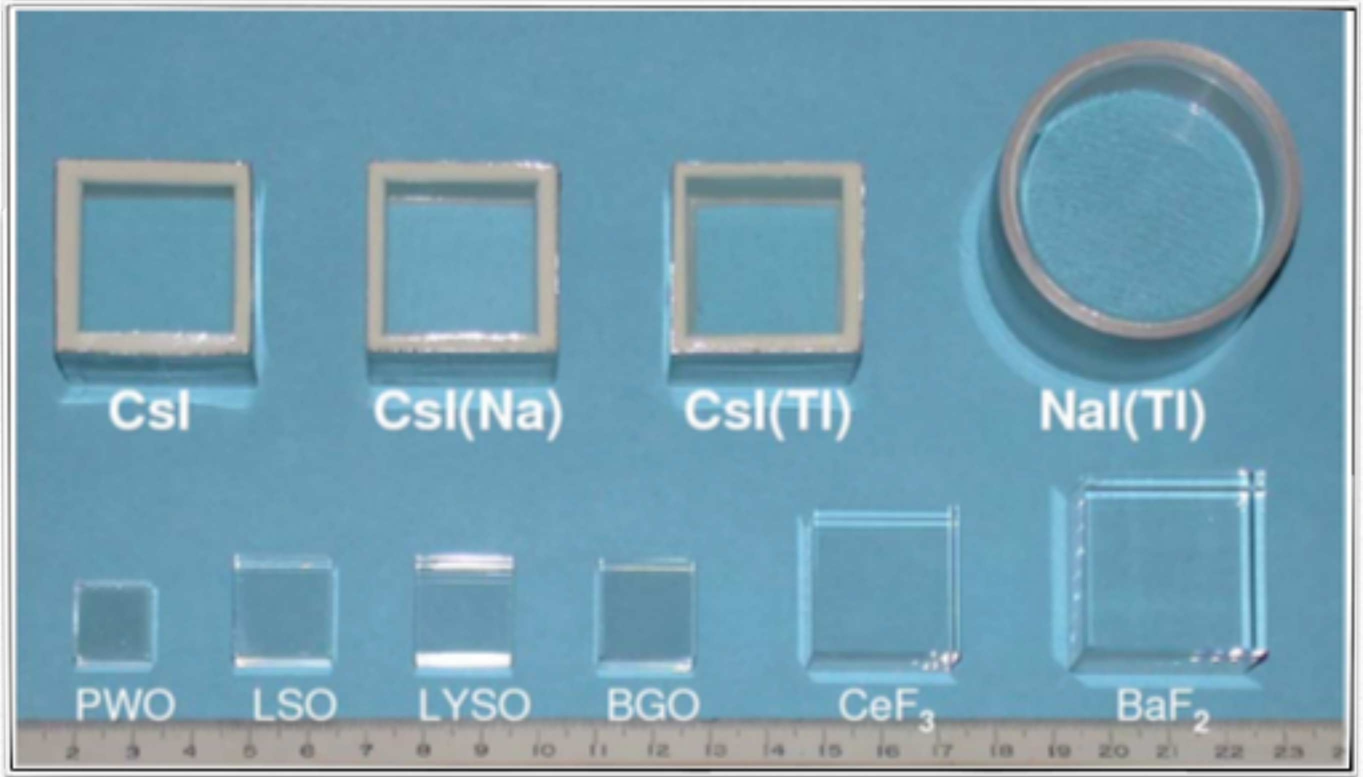
Molecular states: de-excitation by emitting photons



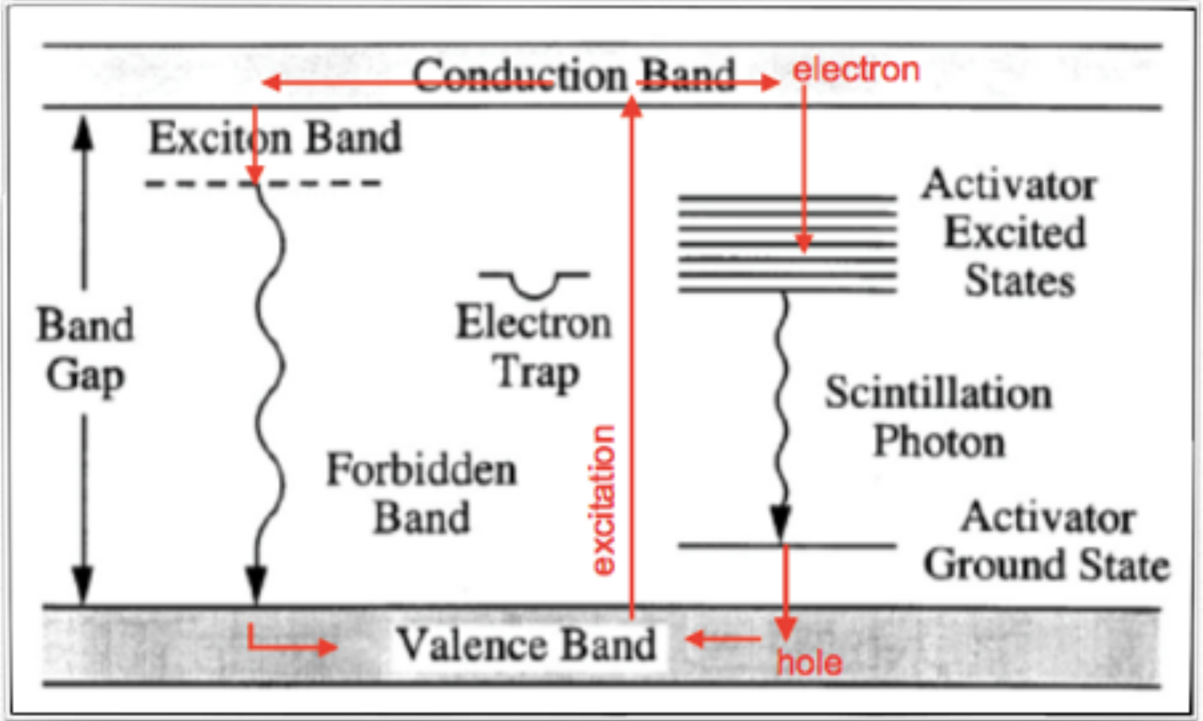


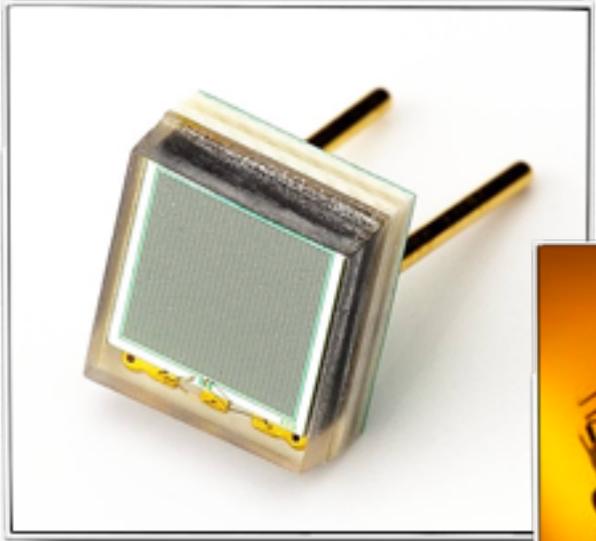
- Timing applications: Faster response, shorter decay time of the fluorescence.
- Large area coverage at relatively low cost.
- Coupled to a photomultiplier tube (PMT): Conversion of light into electric pulse through multiple multiplication stages (dynodes)

Crystal scintillators (Inorganic)



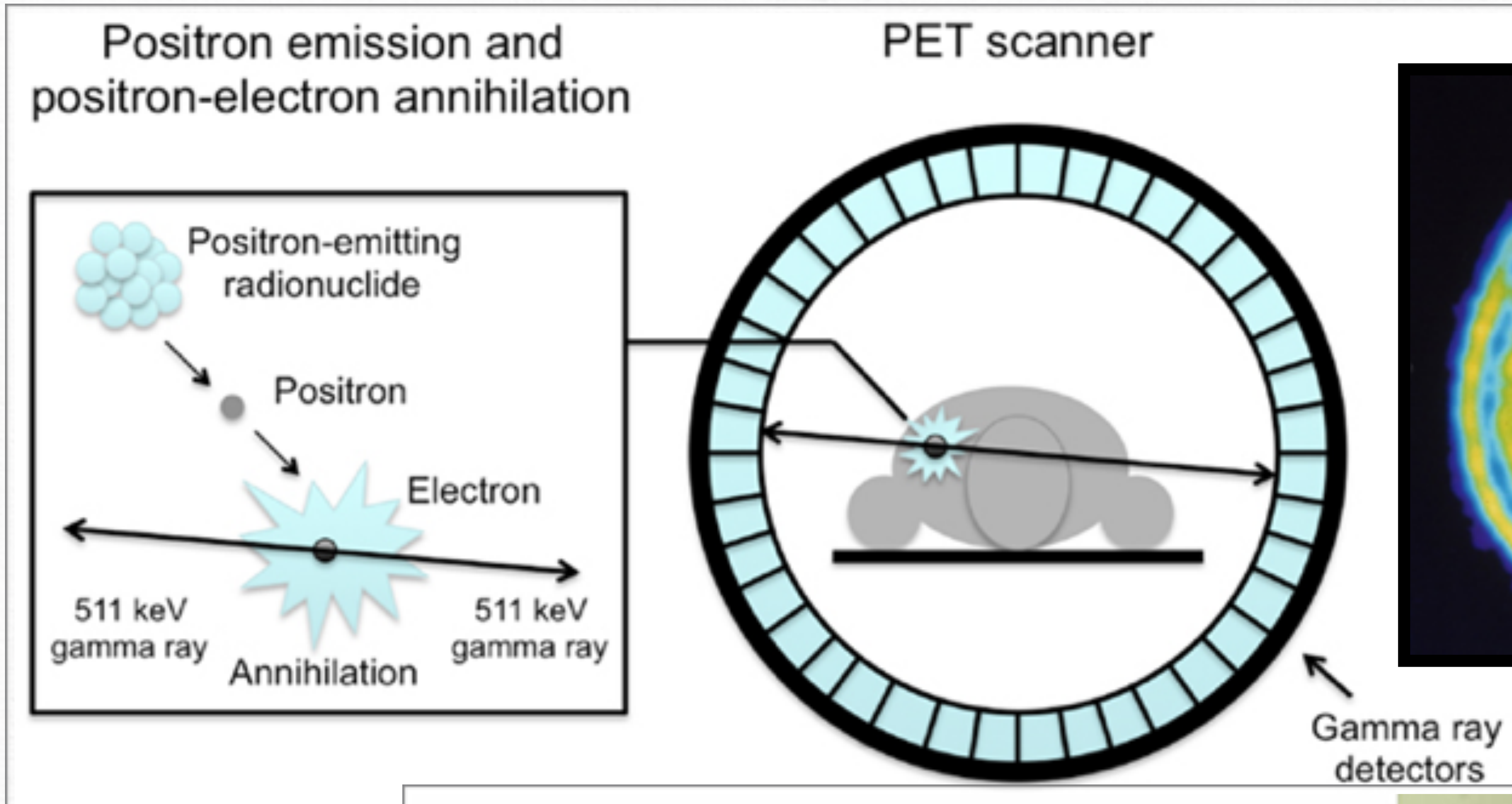
Electronic band structure: scintillation produced through impurities

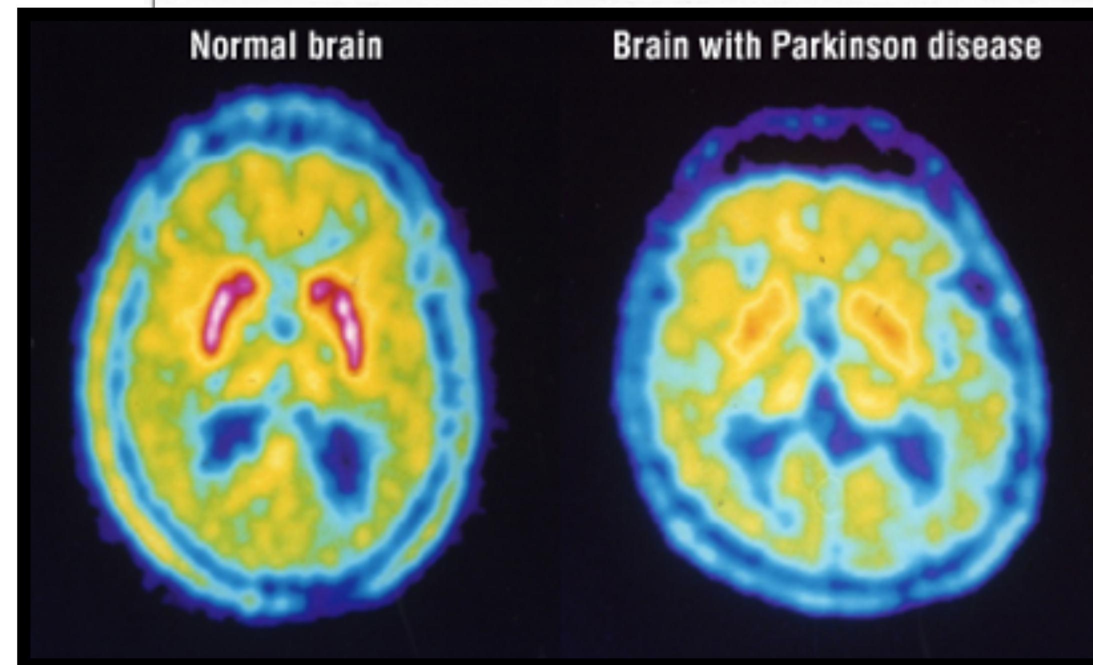


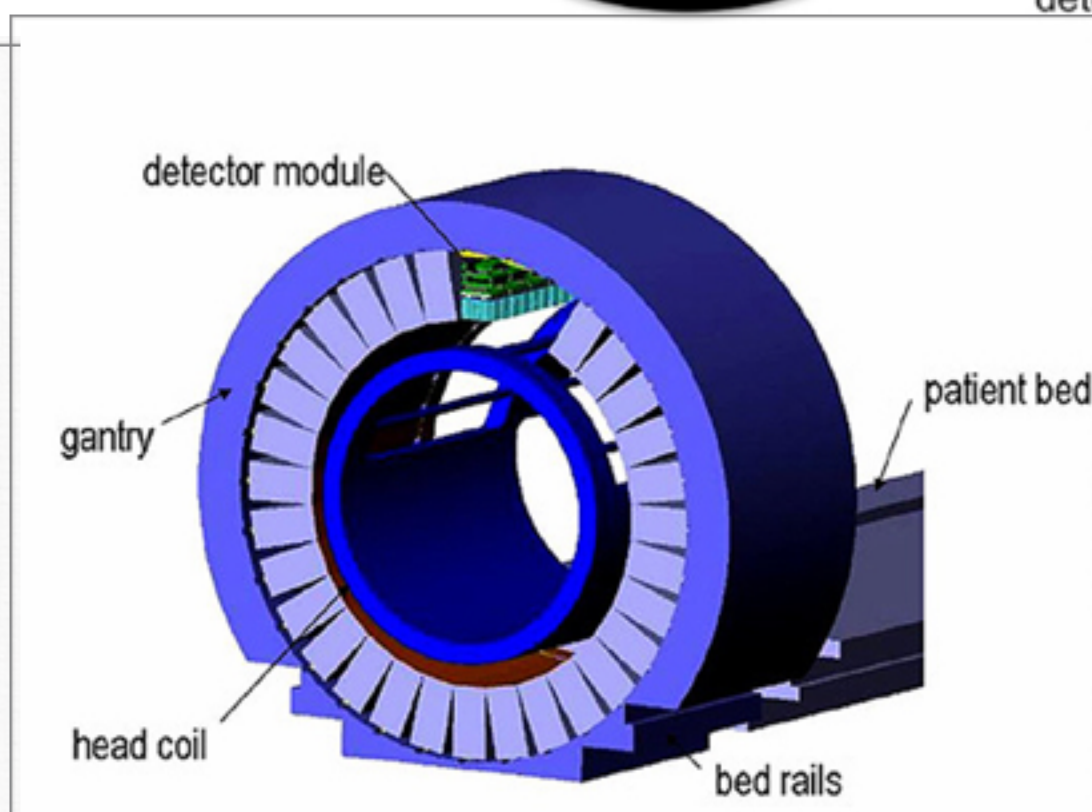


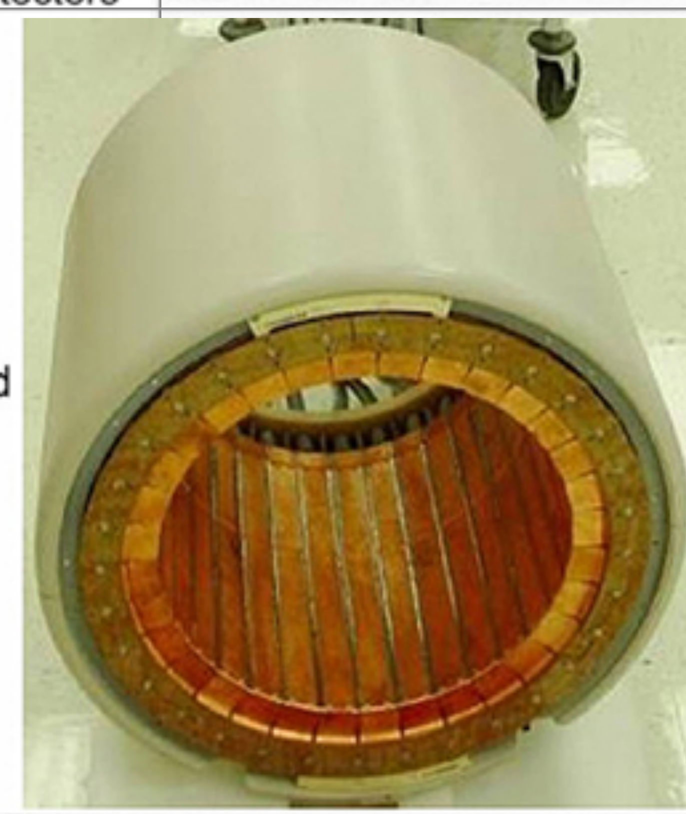
- Spectroscopy: Larger density means higher resolution and efficiency.
- For better performance are normally used together with **solid state detectors** (we will see this later in this talk!)

Applications in medical physics



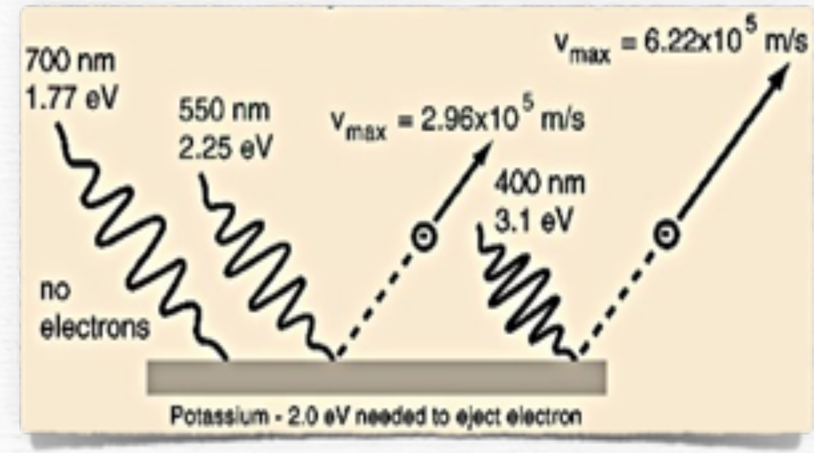




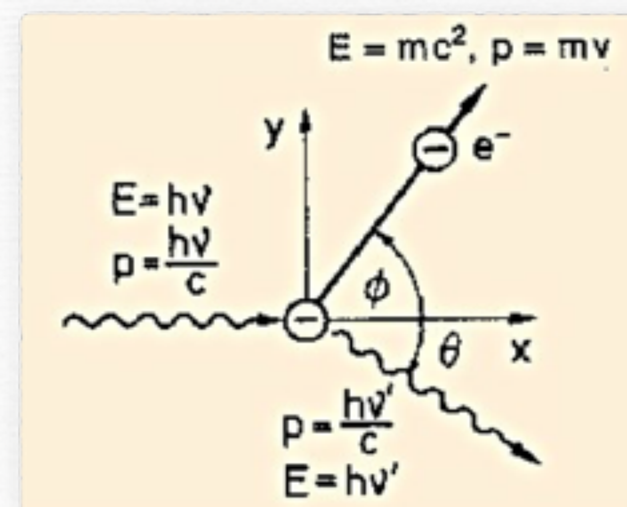


Remember!

I- Photoelectric effect

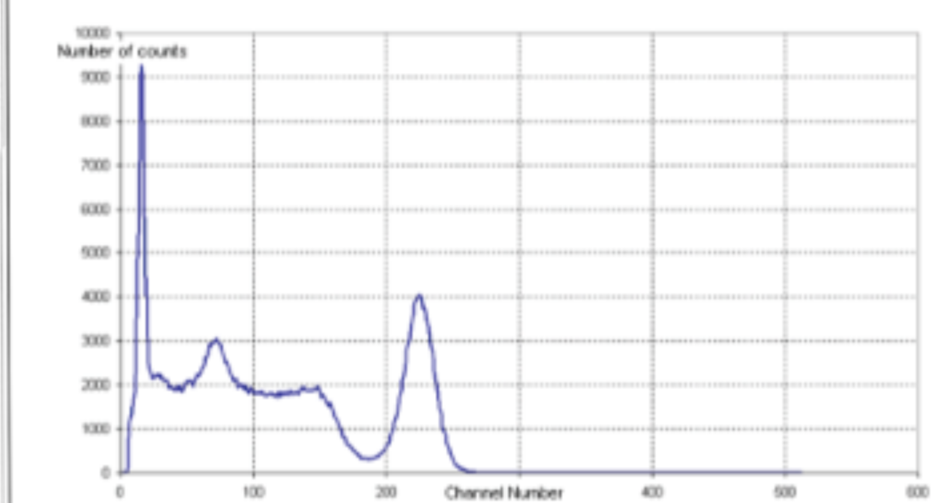


II- Compton effect

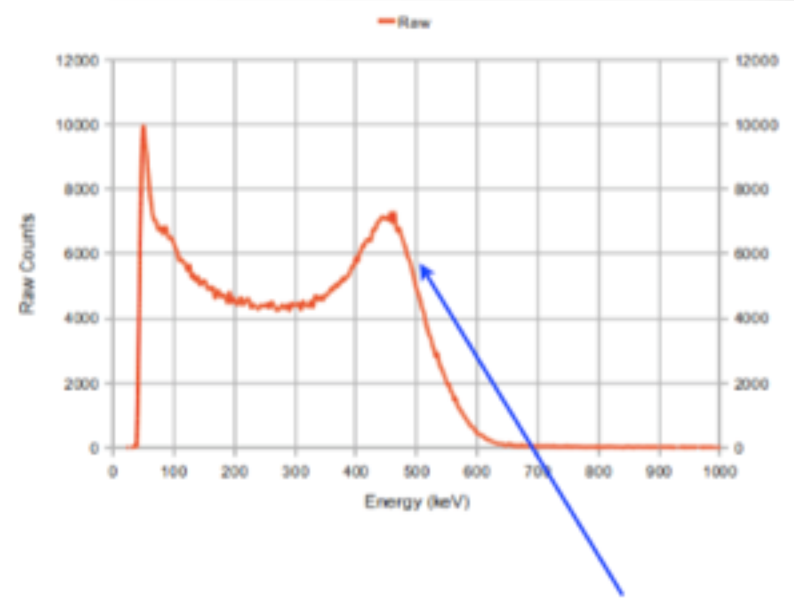


^{137}Cs source: 662 keV

Crystal scintillators (Inorganic)



Plastic scintillators (Organic)



Organic scintillators for gamma-neutron discrimination

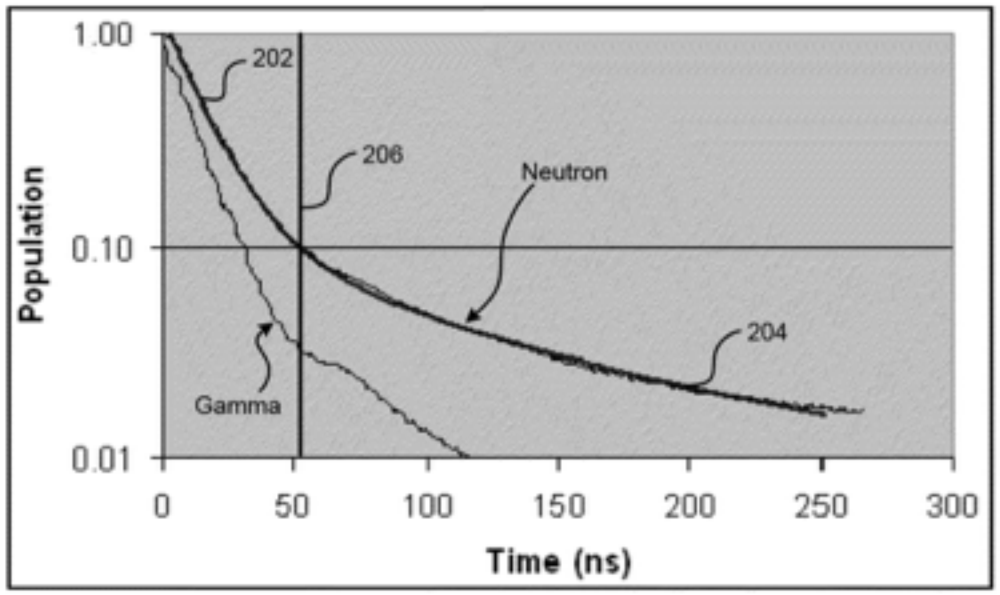


FIG. 2A
(prior art)

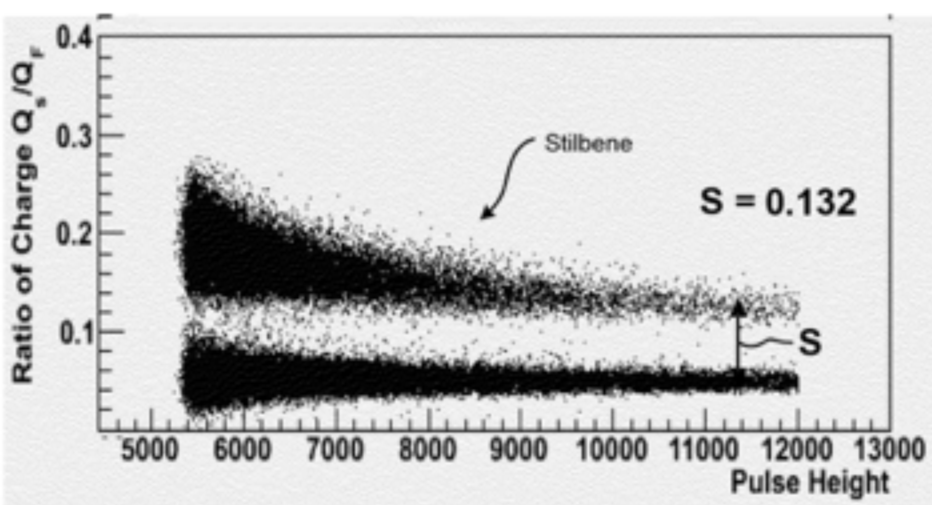
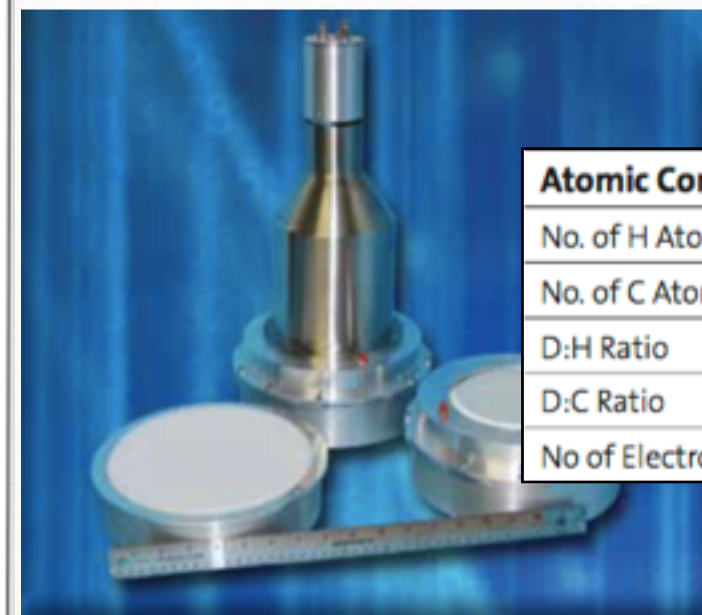
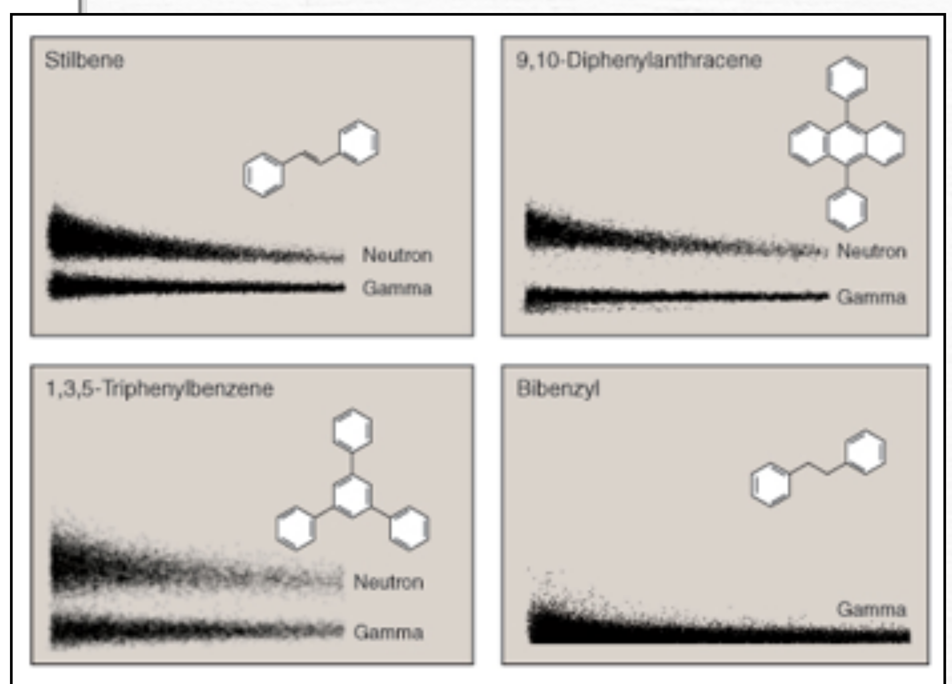


FIG. 2B
(prior art)

Remember!
Neutron moderates with water and carbon

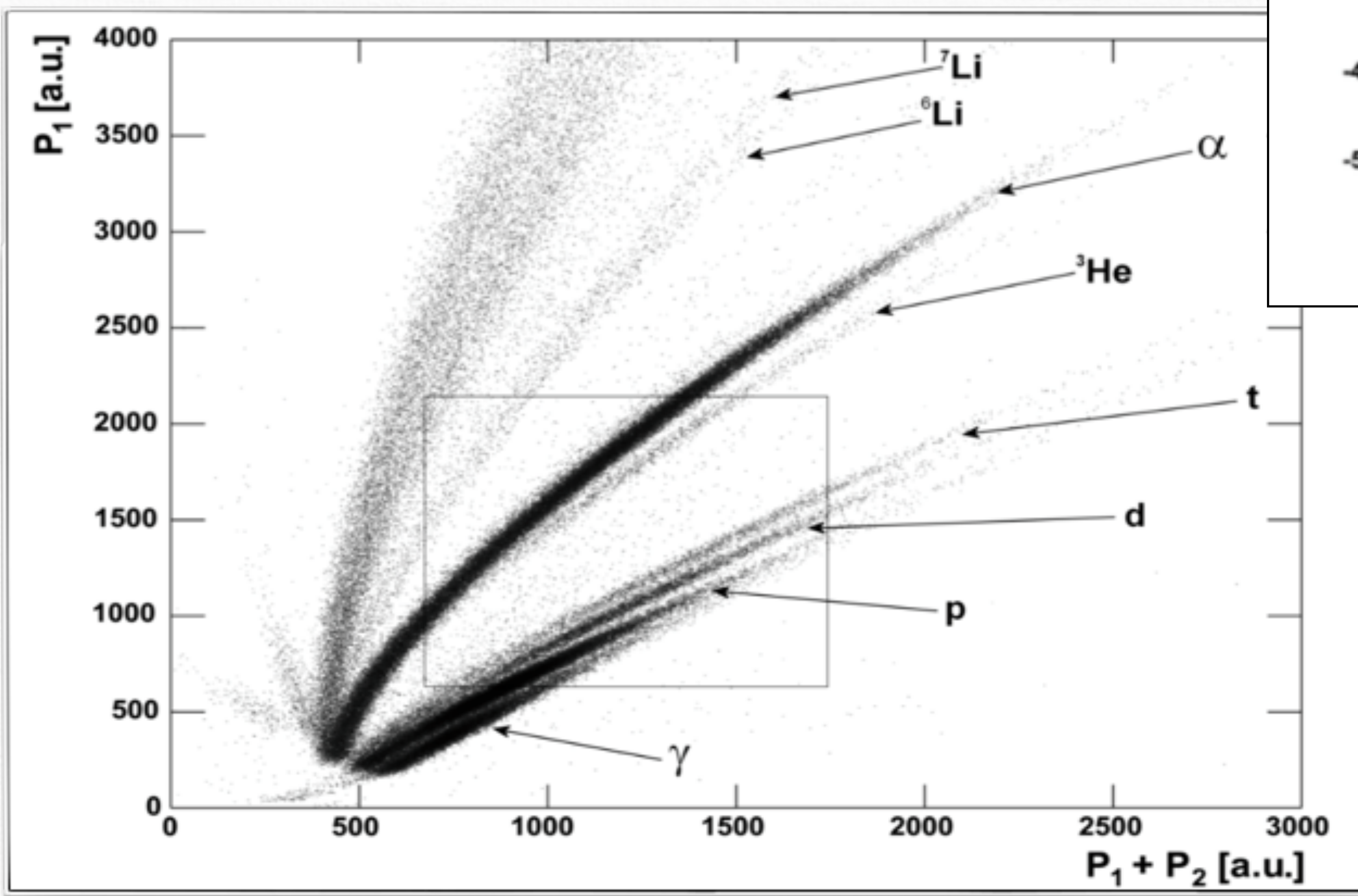


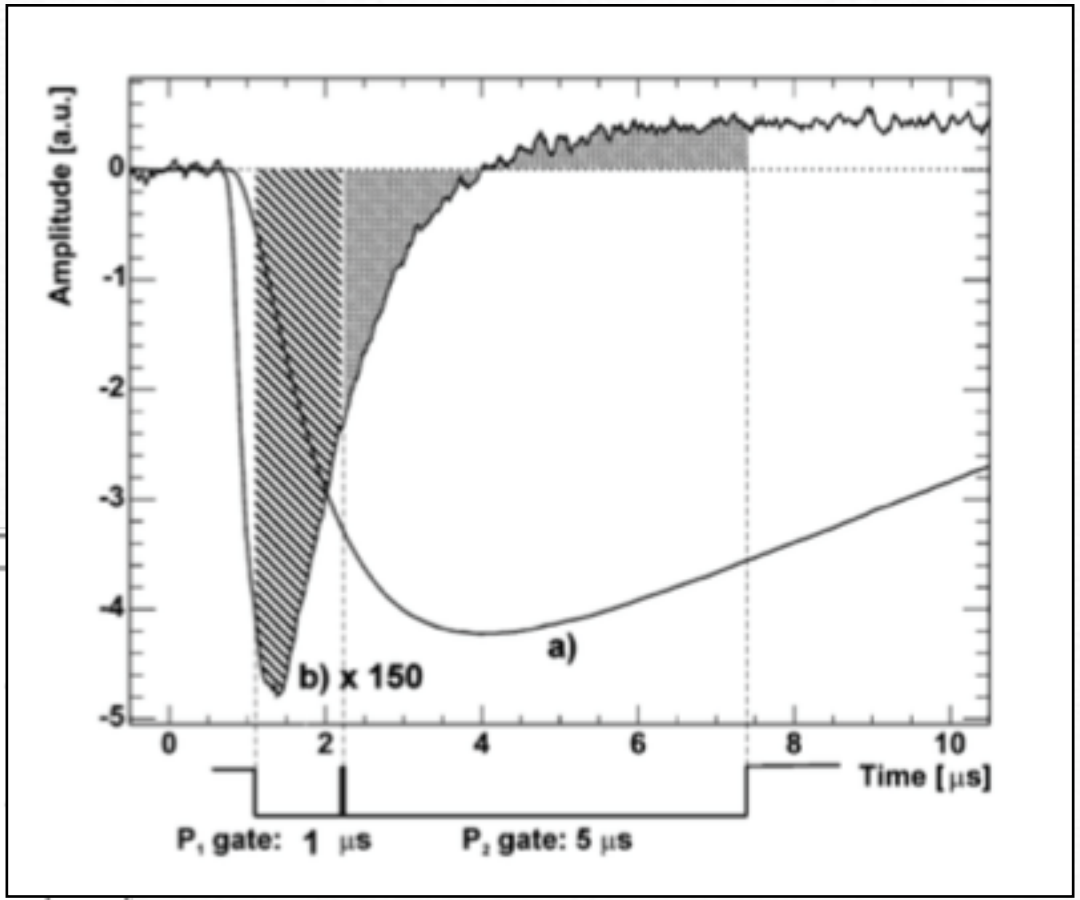
Atomic Composition	
No. of H Atoms per cc (x10^{22})	3.55
No. of C Atoms per cc (x10^{22})	4.10
D:H Ratio	114:1
D:C Ratio	0.99
No of Electrons per cc (x10^{23})	2.87

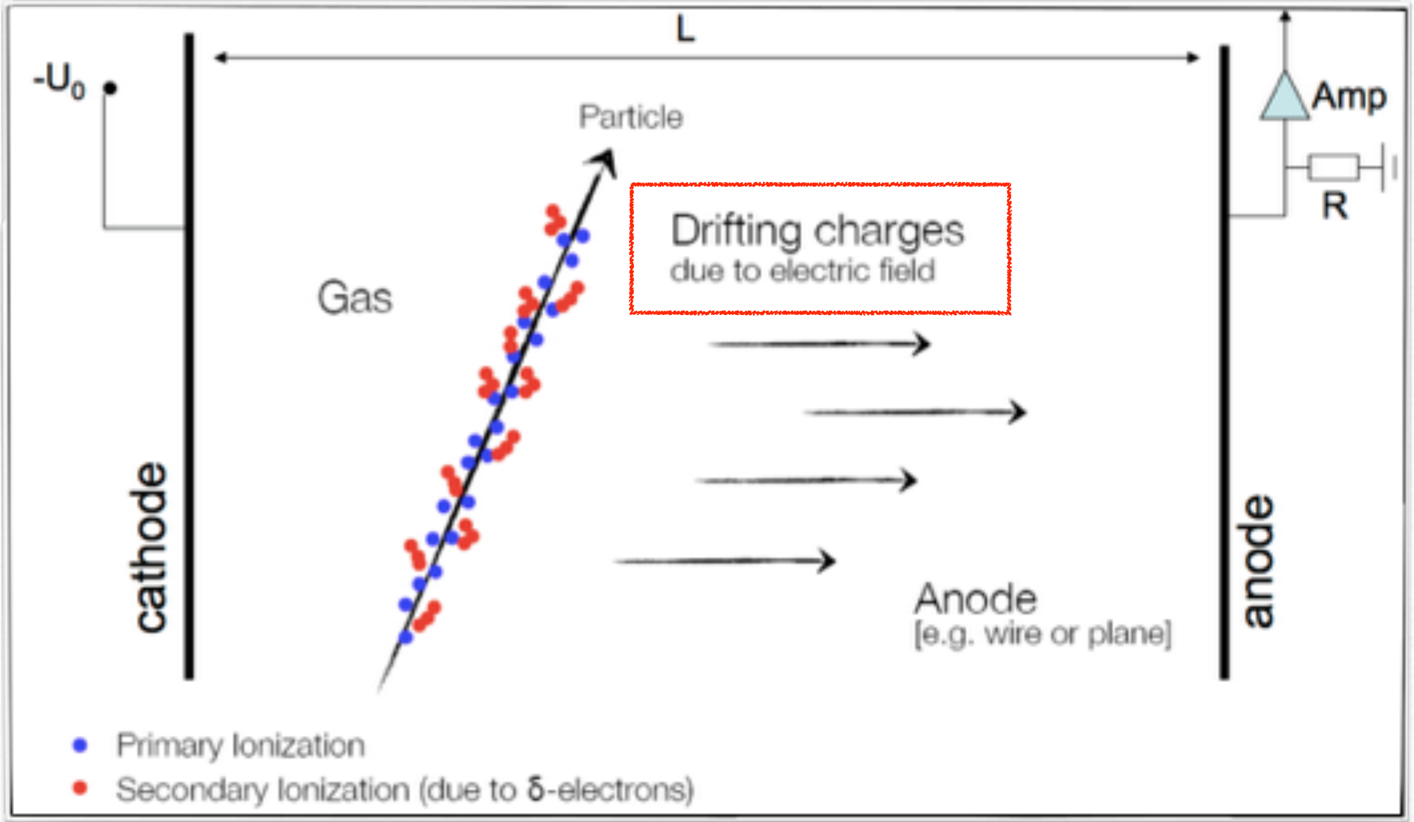


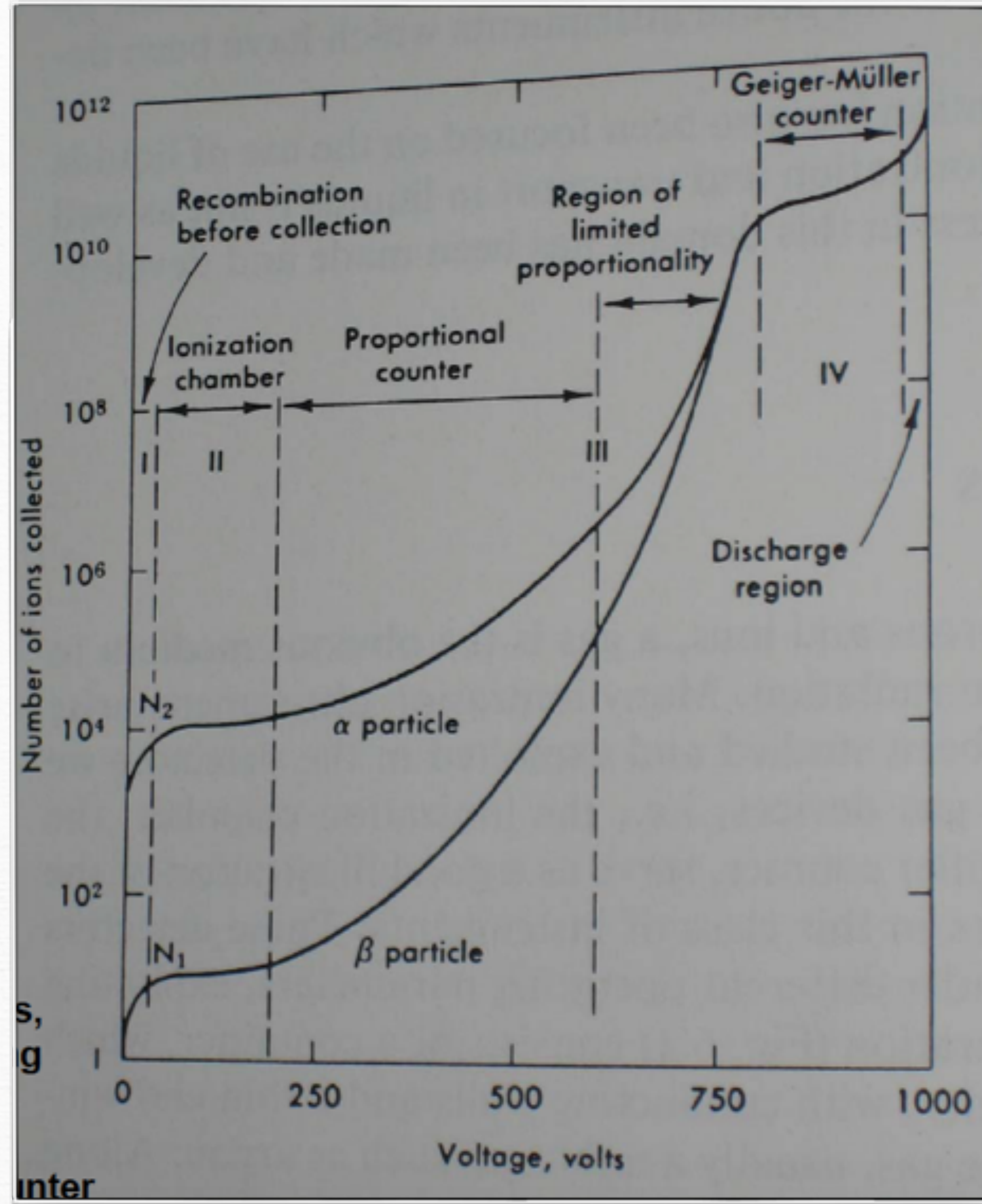
Particles of different ionization powers produce longer or shorter pulses in the detector, resulting in different pulse shapes

Inorganic scintillators for particle discrimination







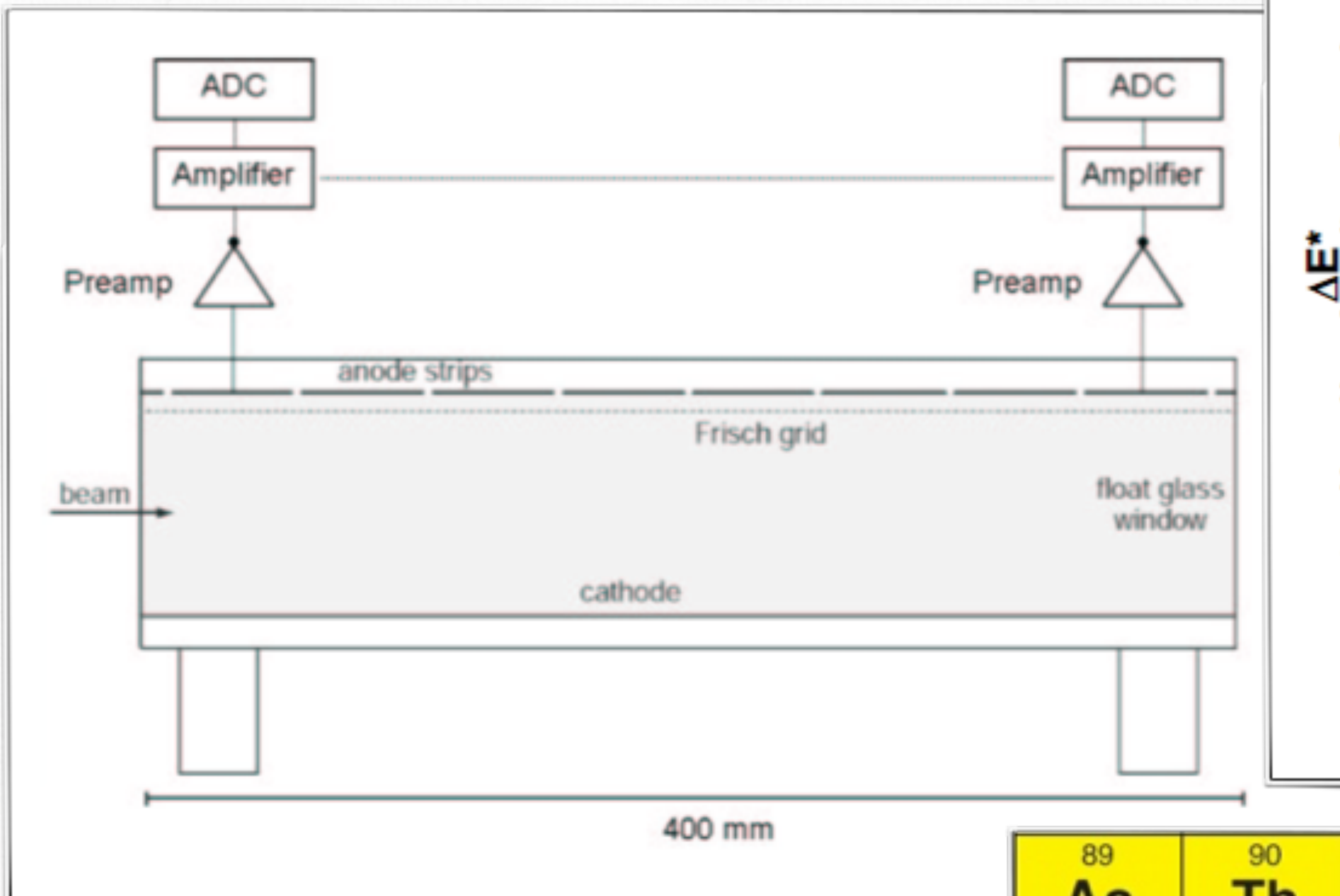


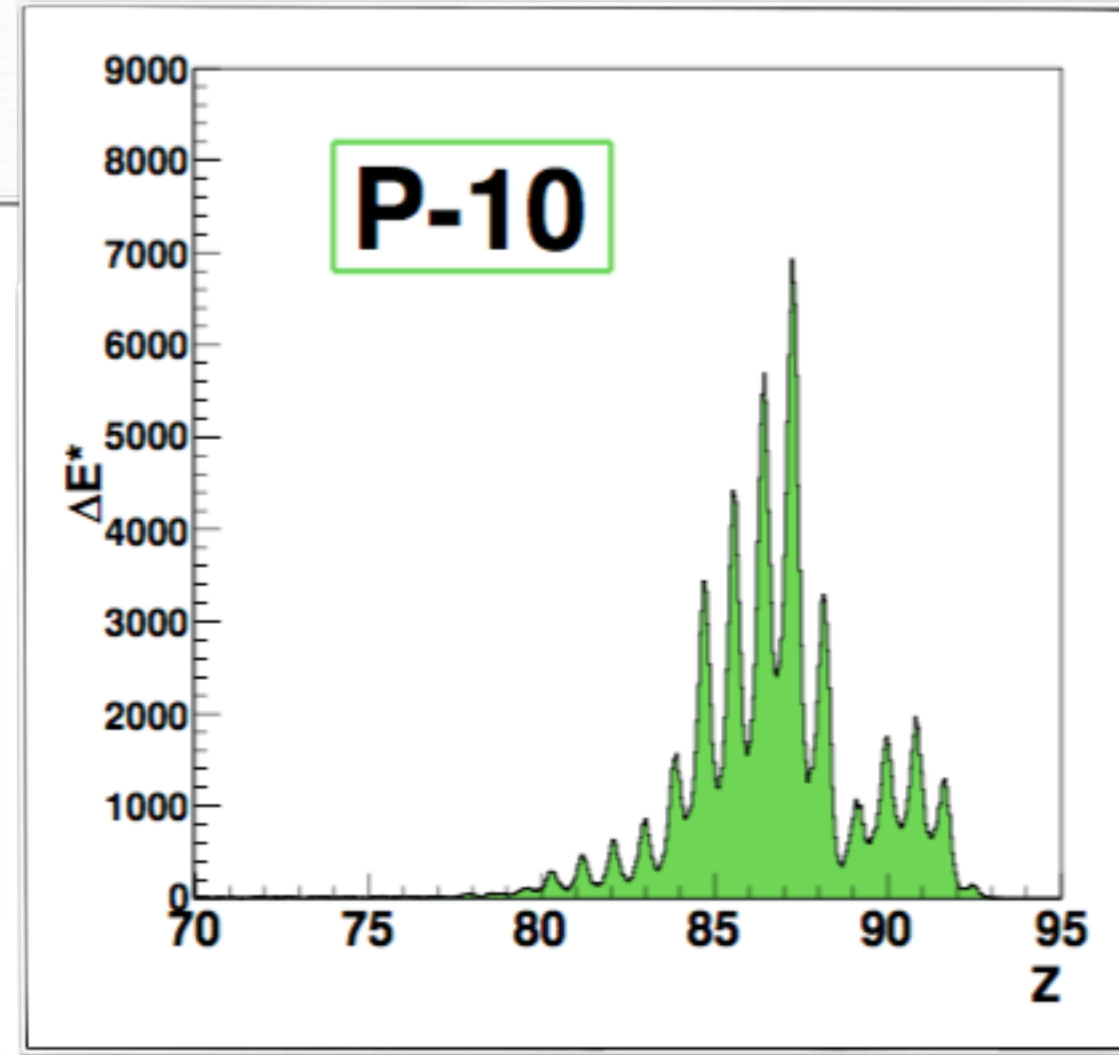
II.- Ion Chamber: Measurement of the dose. Collection of charges

III.- Proportional counter: Proportionality between energy and charge collected.

IV.- Geiger-Muller: Counting with high efficiency gamma radiation, X-rays, and alpha and beta particles.

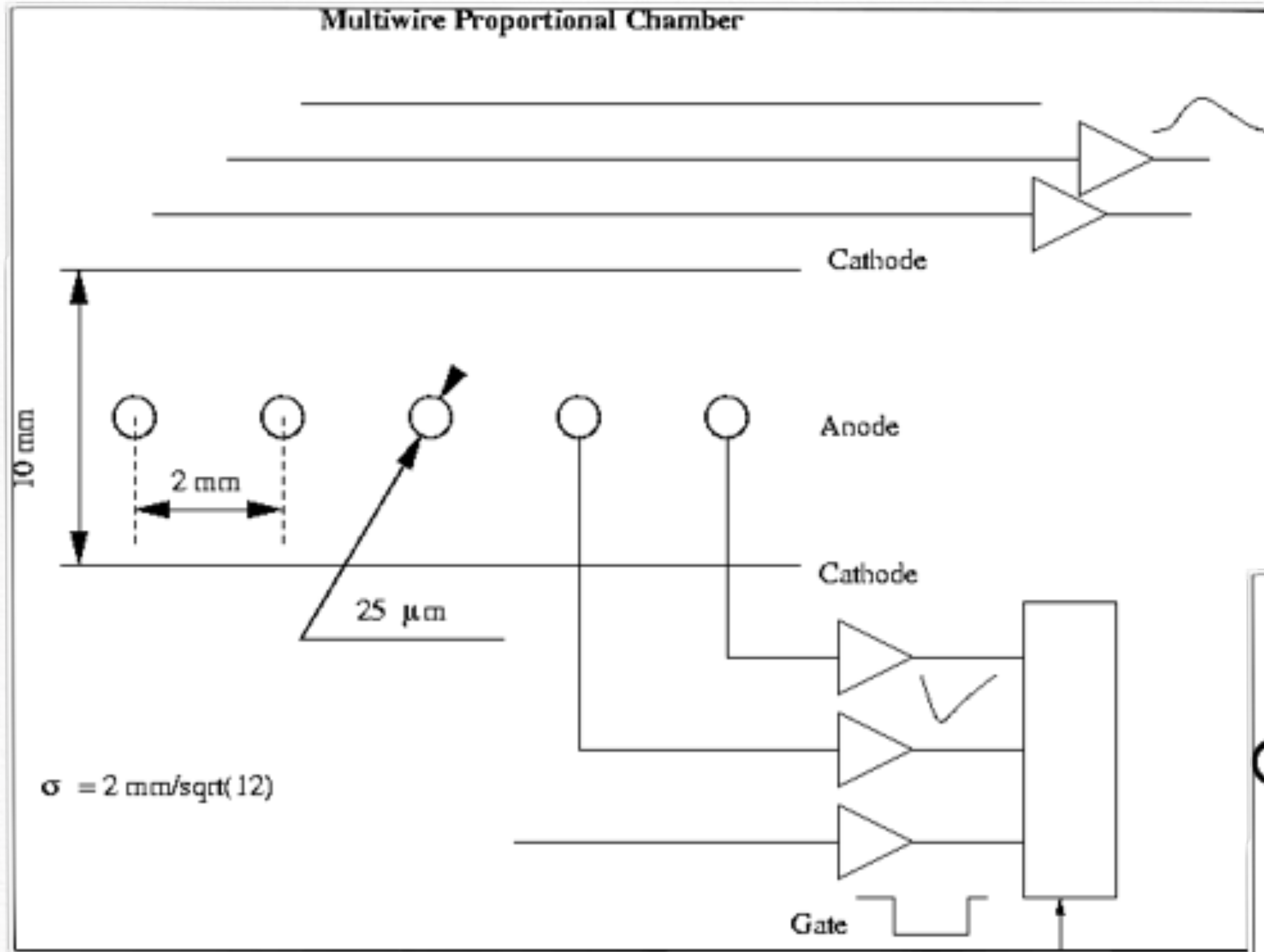
Multisampling ionization chambers

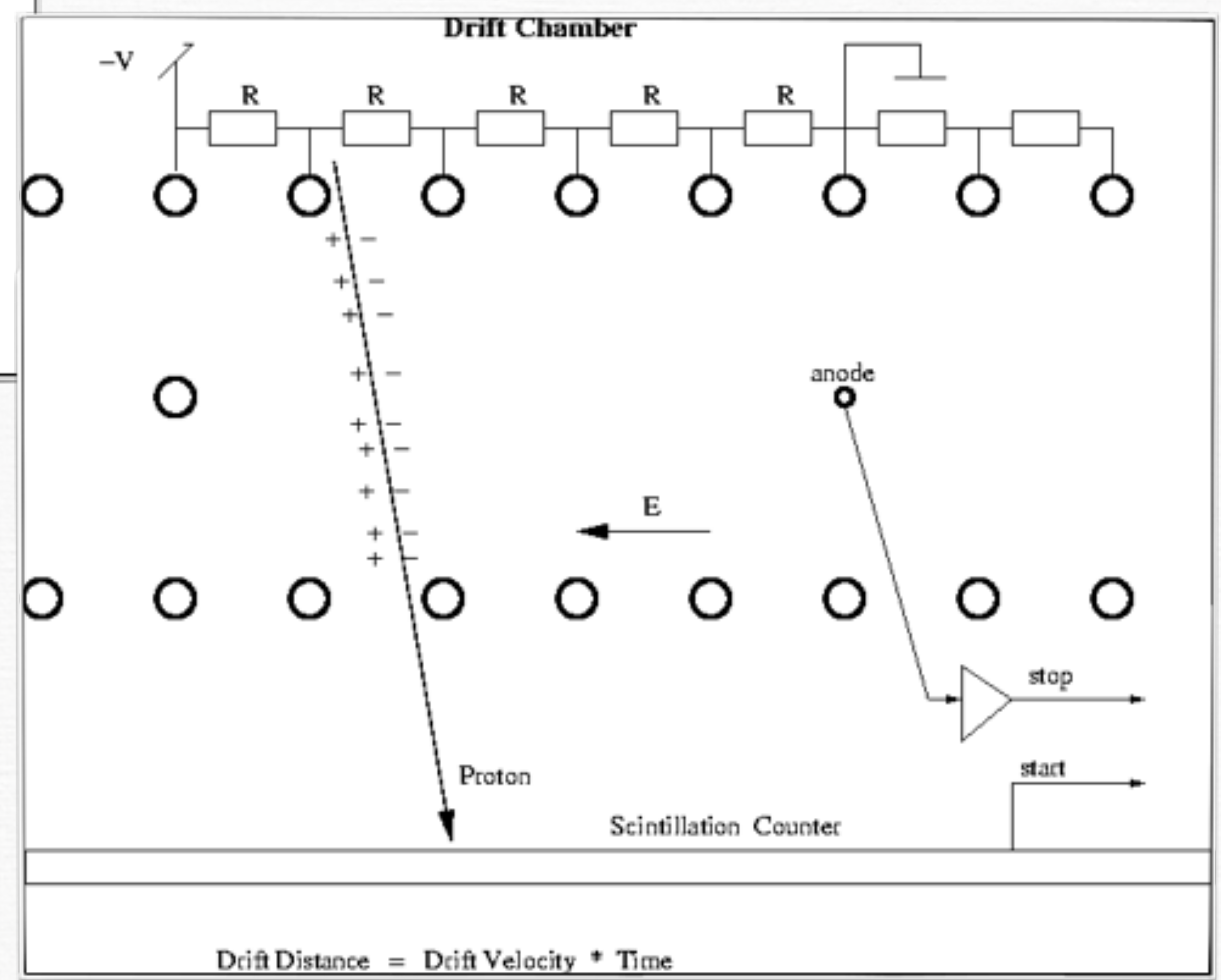




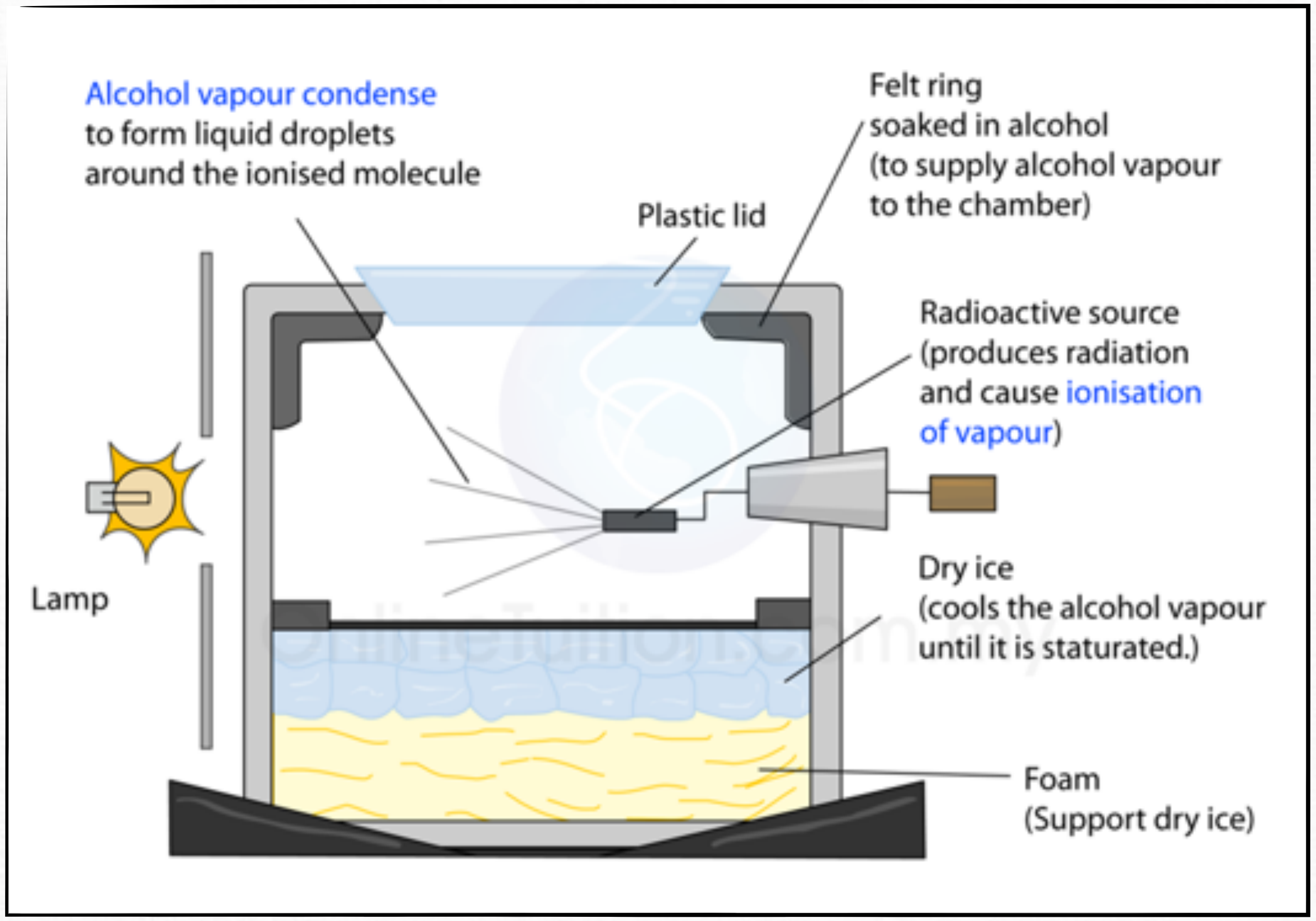
89 Ac actinium [227]	90 Th thorium 232.038 06(2)	91 Pa protactinium 231.035 88(2)	92 U uranium 238.028 91(3)	93 Np neptunium [237]	94 Pu plutonium [244]	95 Am americum [243]	
96 Cm curium [247]	97 Bk berkelium [247]	98 Cf californium [251]	99 Es einsteinium [252]	100 Fm fermium [257]	101 Md mendelevium [258]	102 No nobelium [259]	103 Lr lawrencium [262]

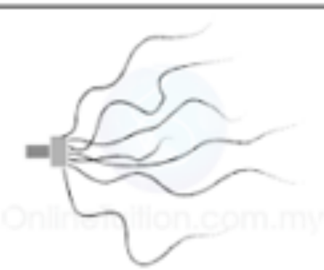
Tracking with gas detectors



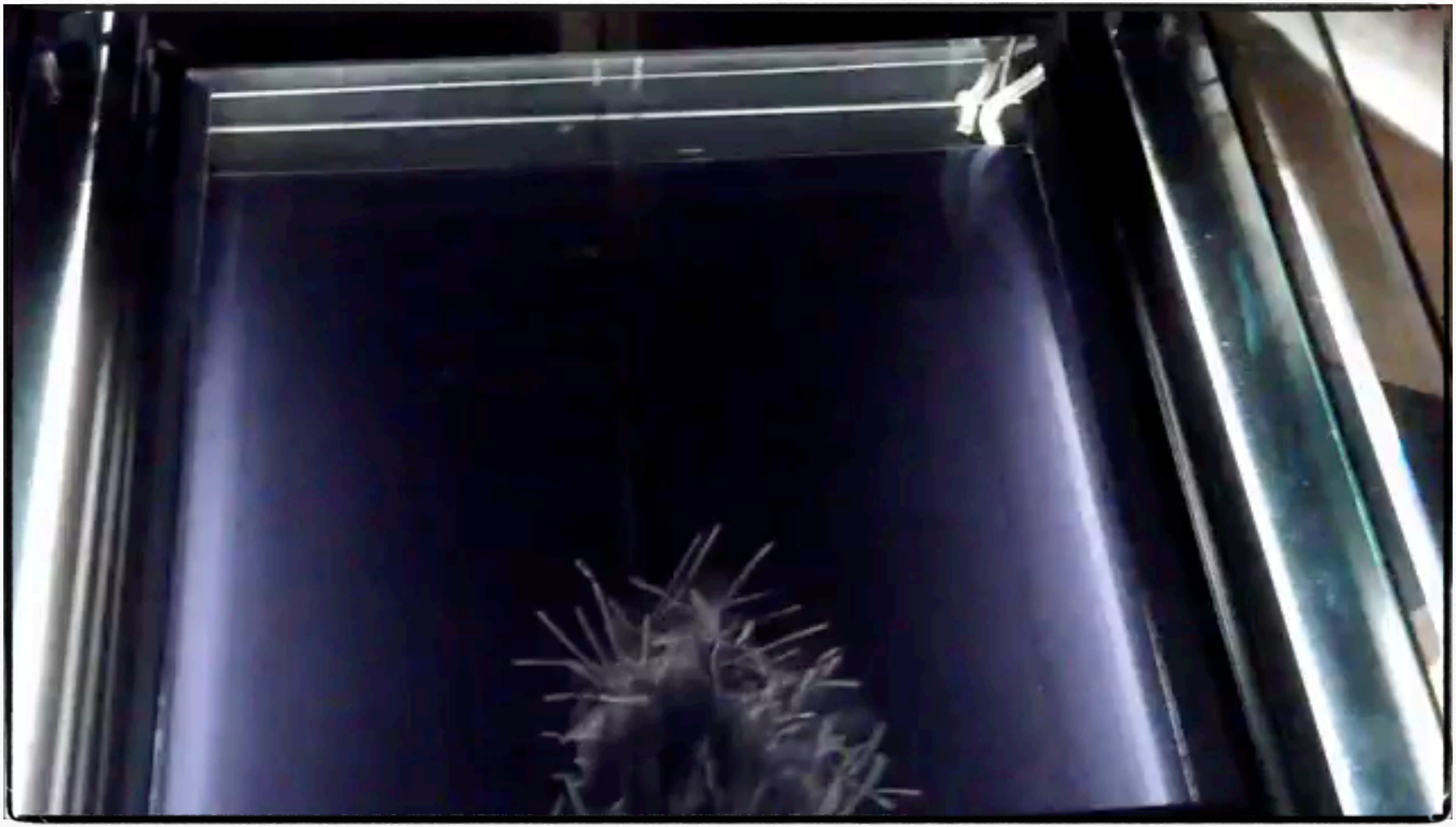


Cloud chamber

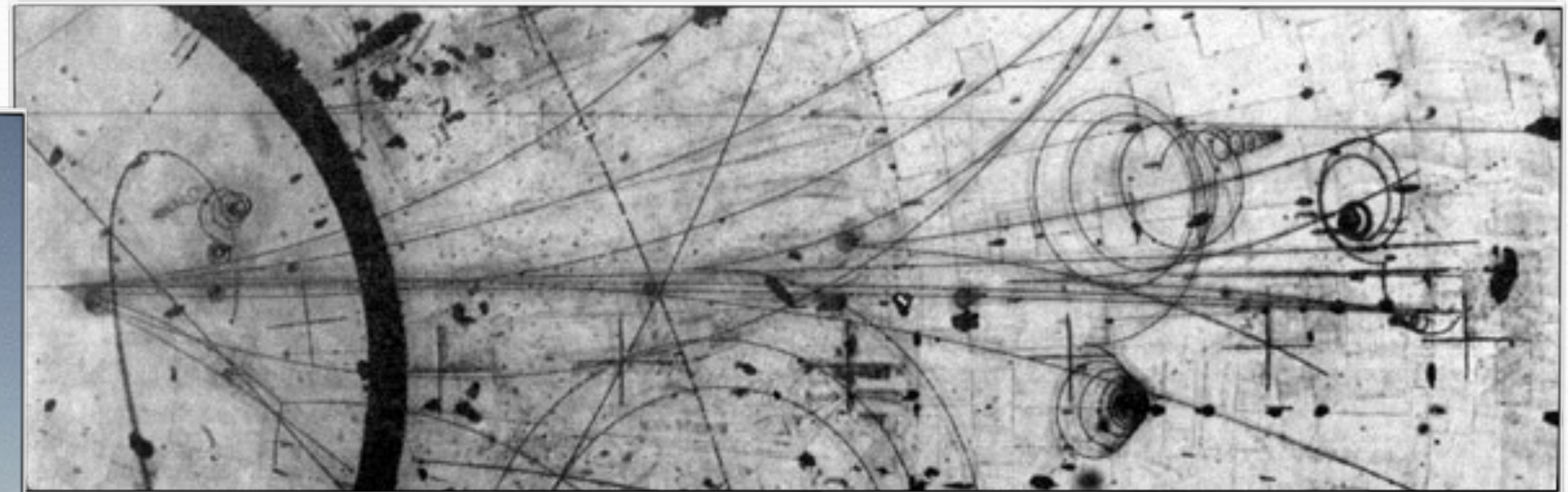


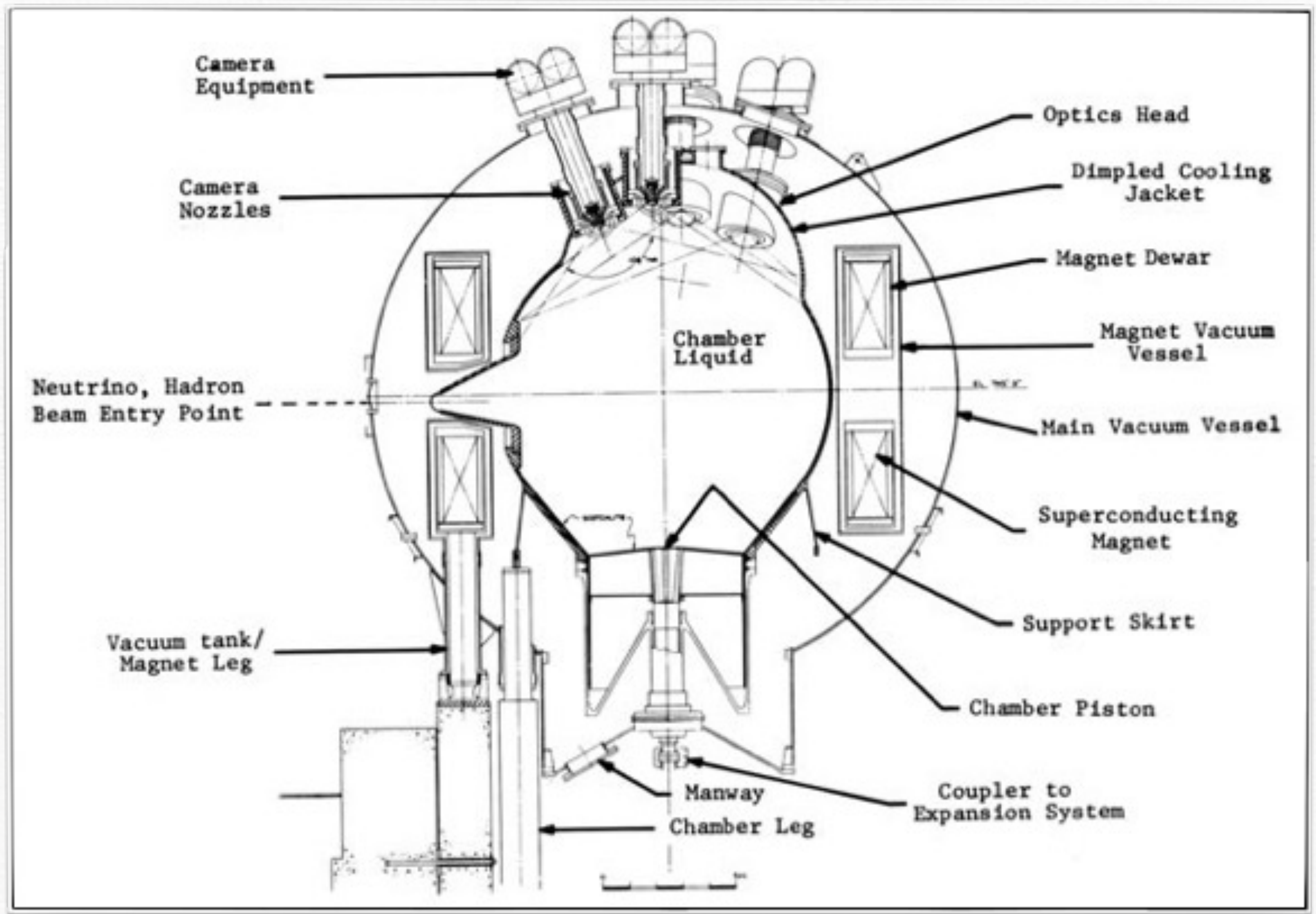
Alpha-particle tracks:	Beta-particle tracks:	Gamma-ray:
		
Thick and straight, with the occasional deflection if an alpha particle collides with an air molecule.	Thin and crooked. The particles cause much less ionization and, being light, are continually being pushed off; caused by air molecules nearby.	Don't produce tracks as such. The tracks seen are those caused by electrons which have absorbed energy from photons and have escaped from atoms.

Cloud chamber



NAL 15-Foot Bubble Chamber @ Fermilab

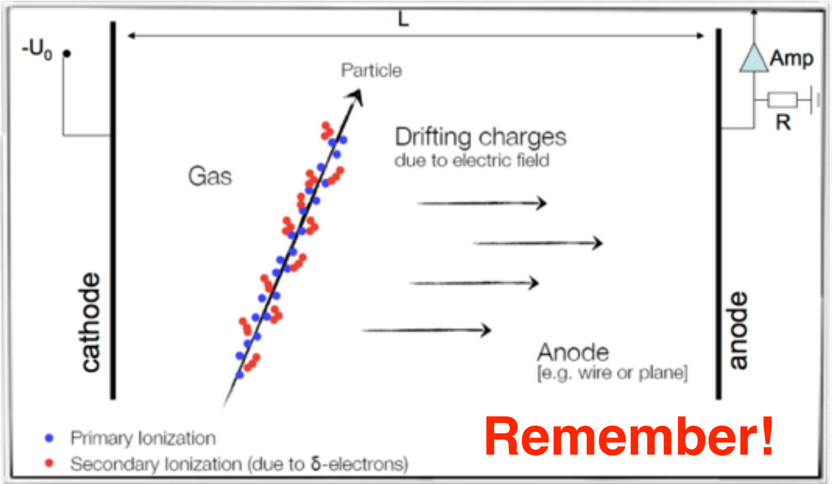


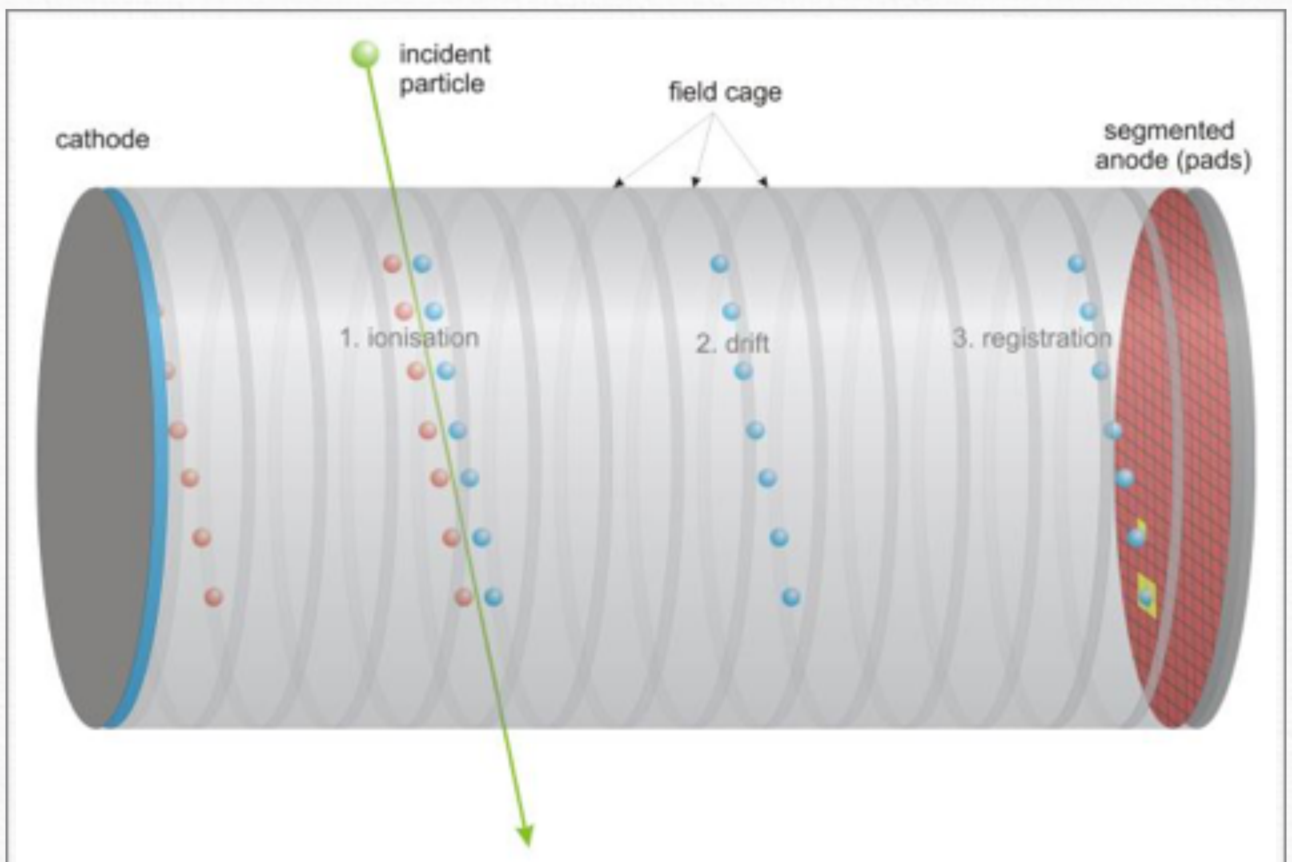


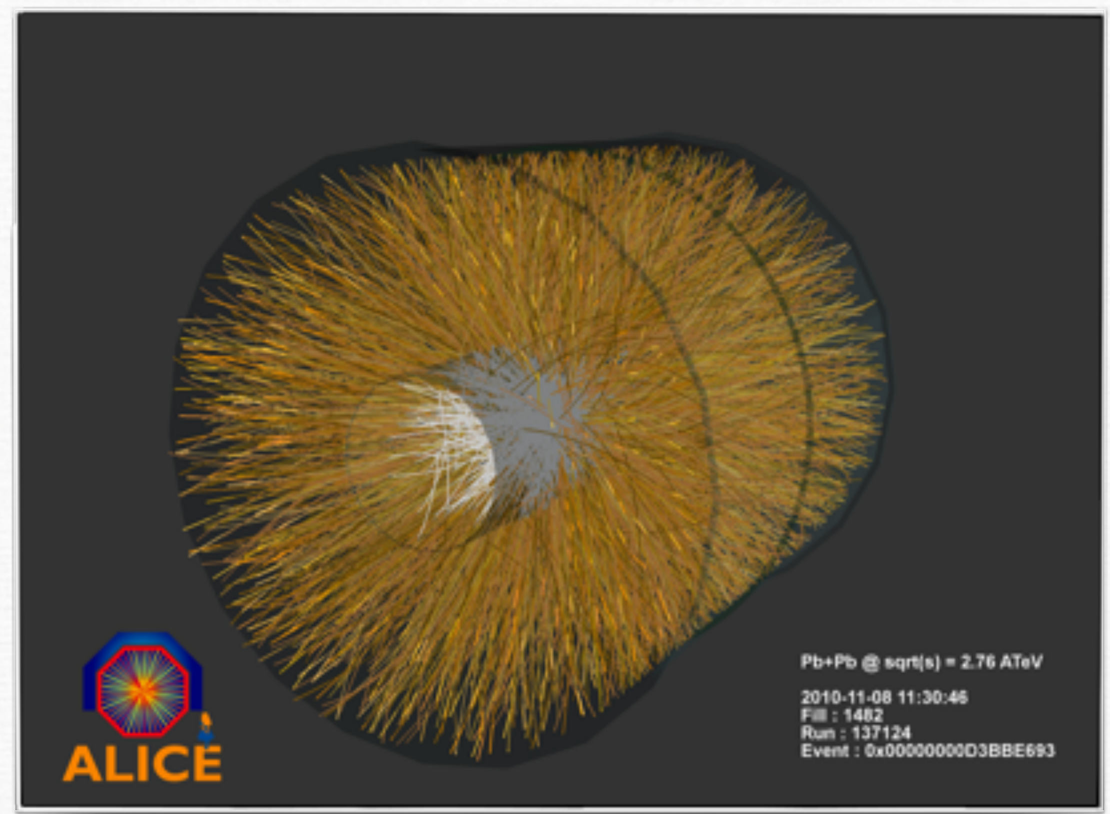
Time Projection Chambers

A microscope for nuclear reactions

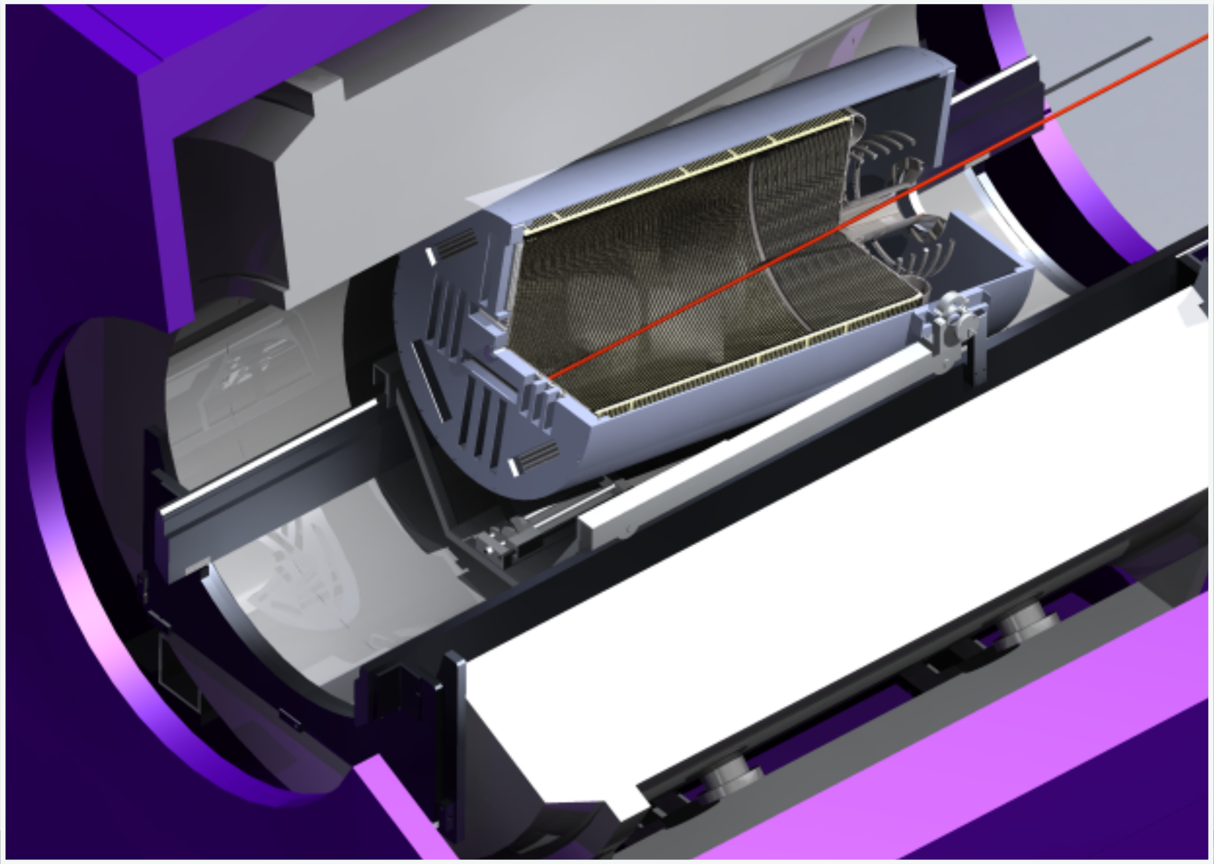
ALICE TPC @ CERN

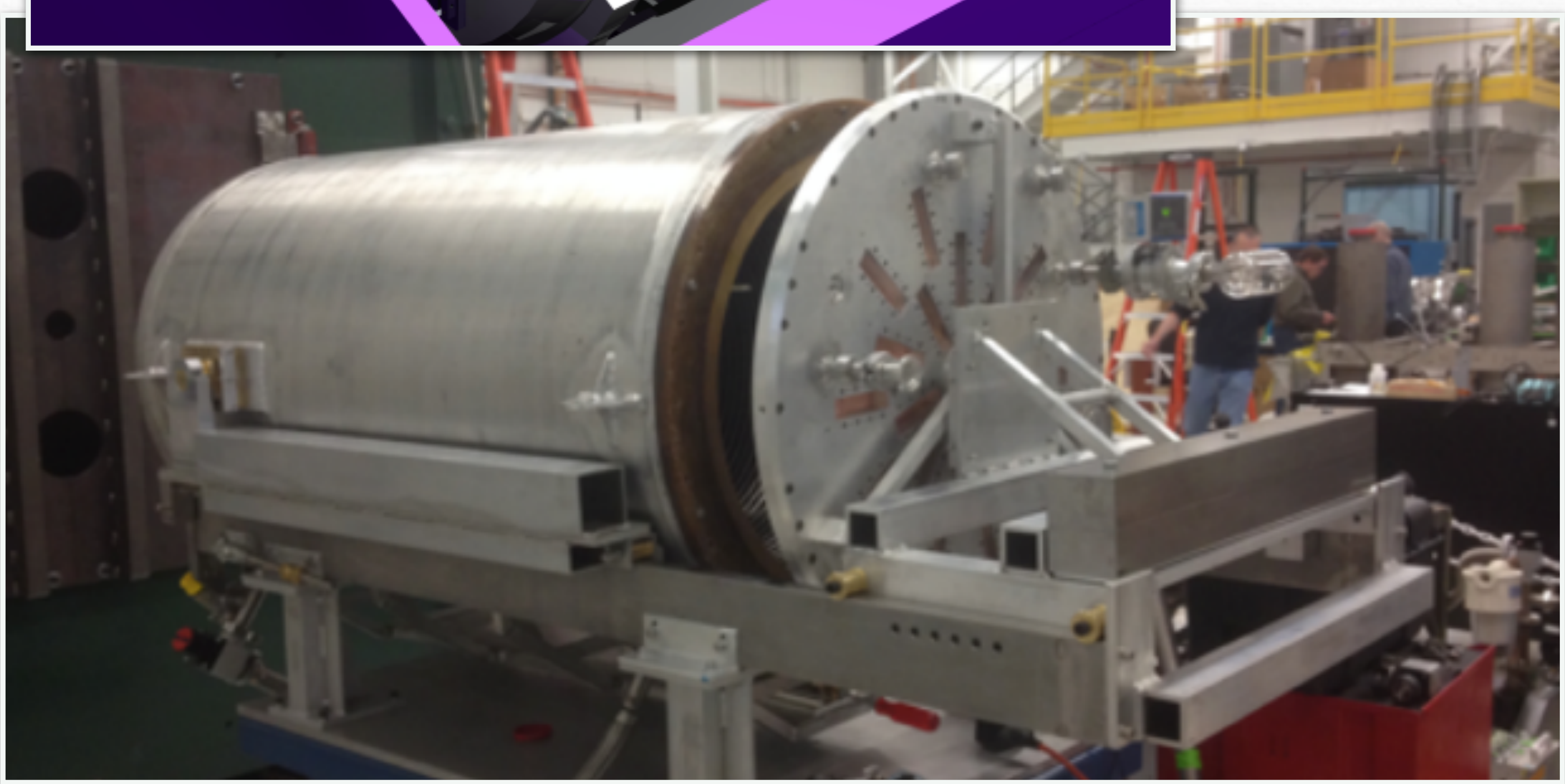


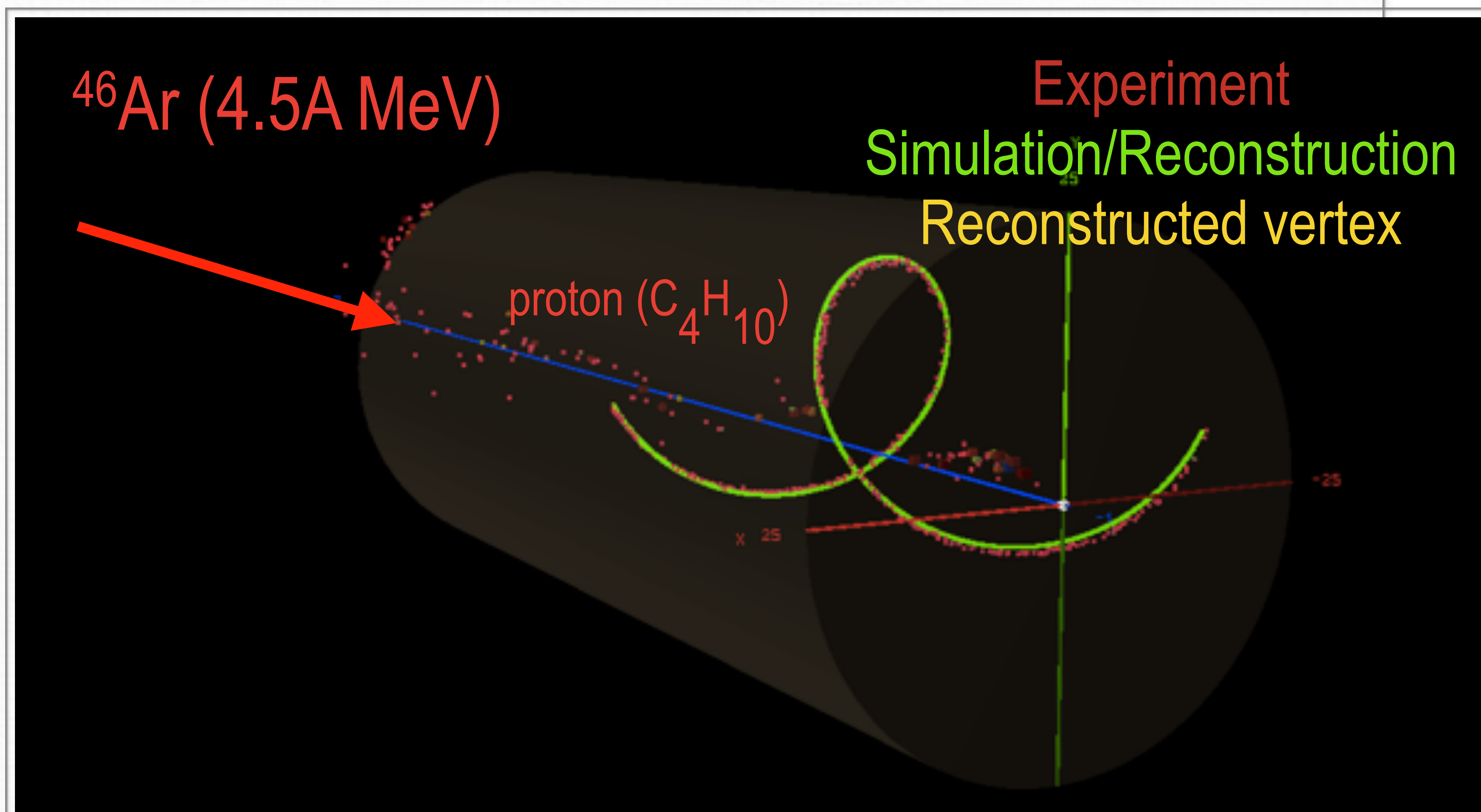


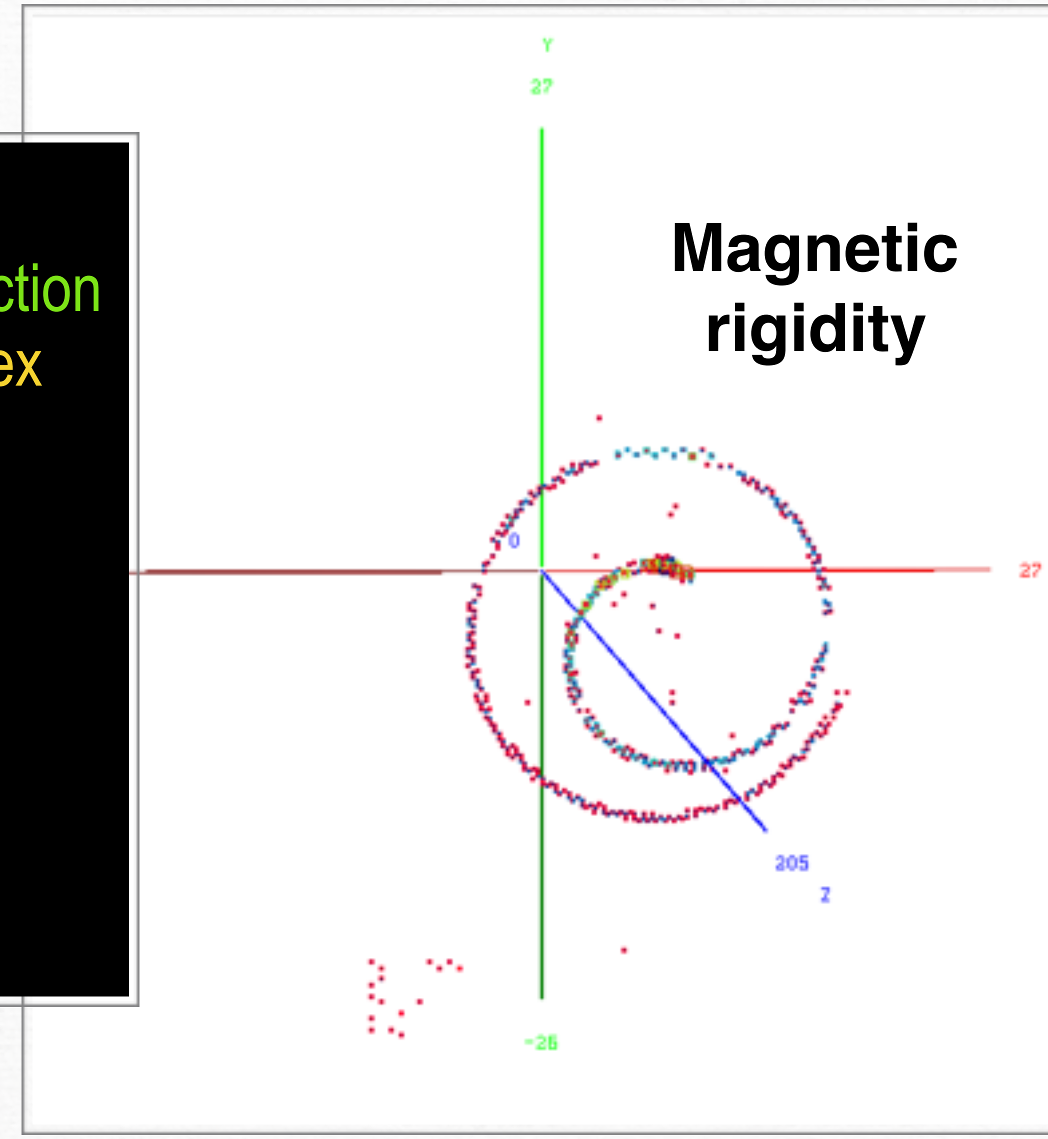


Active Target Time Projection Chamber (AT-TPC)







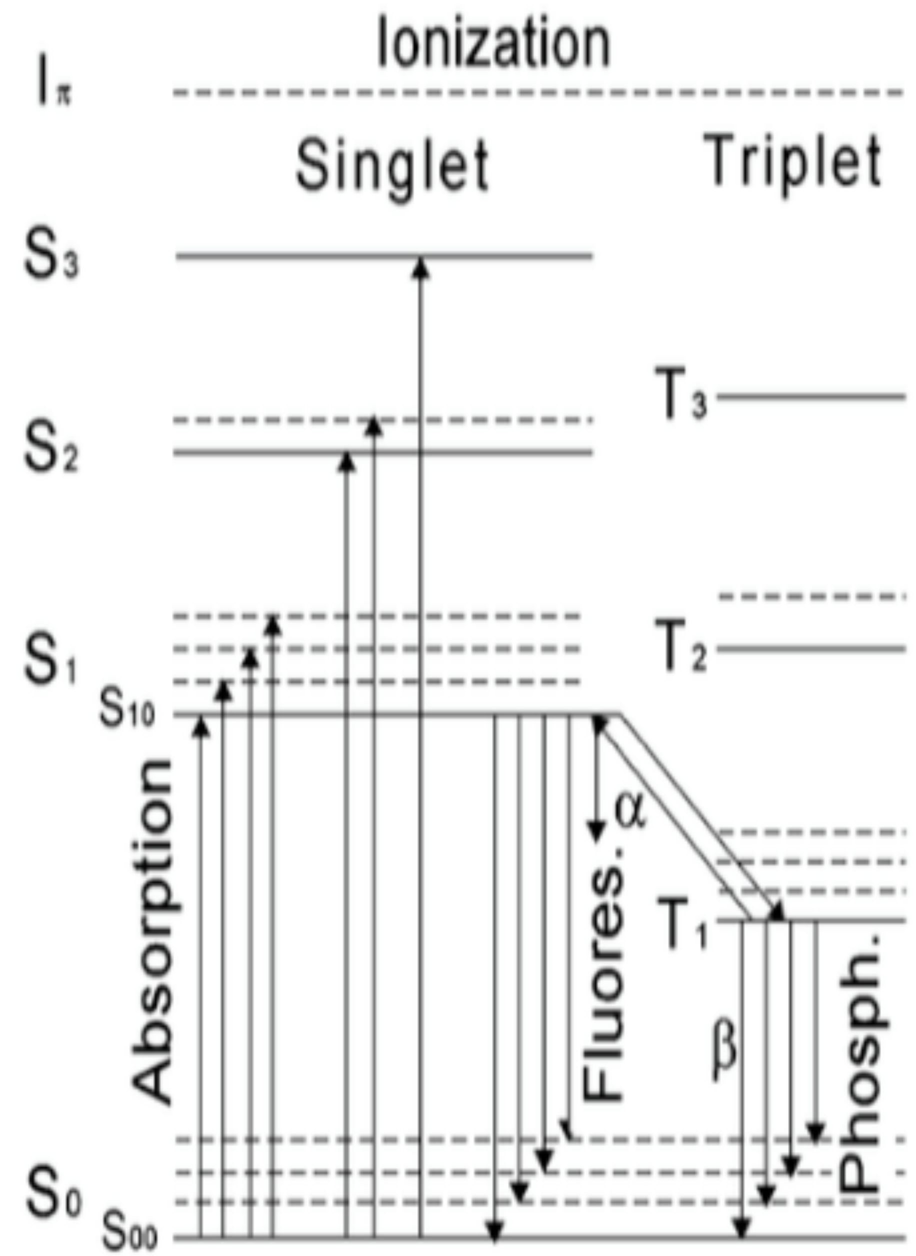


Tracks of the particles in 3D

Backup

Scintillation in Organic Molecules

- after absorption of a photon or excitation by ionization, the molecule undergoes vibrational relaxation to S_{10}
- the excited S_{10} state decays radiatively to vibrational sub-levels of the ground state; the S_{10} lifetime is ~ns
- thus the fluorescence emission spectrum is roughly a "mirror image" of the absorption spectrum (same spacing)
- emitted photons have less energy than S_{00}-S_{10} – that's the important Stokes shift
- no S_2-S_0 emission; internally de-excite in picoseconds (non-radiatively)



excited triplet state can't decay to ground state (angular momentum selection rules) → results in delayed fluorescence and phosphorescence