Radiation Detectors – PAN 2oo7

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Radiation Detection --- Some Basics

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http://www.lbl.gov/abc/cosmic/

Classes of Radiation to Consider

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	zero mass	"low" mass	"high" mass
Neutral	Gamma rays		Neutrons
Charged		Electrons +/-	Nuclear Charged Particles

"Force"
Electromagnetic
Nuclear
Coulomb

Except neutrons, these particles interact *primarily* with the electrons in materials that they enter … they can ionize the materials. The coulomb interaction is long-ranged so charged particles interact with a large number of electrons and a moving charged-particle continuously slows down until it stops. On the other hand, a photon can only "collide" with one electron and the interaction creates a moving electron and a cation. Finally, neutrons only interact with nuclei and are detected through the secondary products of nuclear reactions.
The observation of this ionization is the fundamental operating basis for radiation detectors.

The amount of ionization is sometimes strongly, other times weakly related to the incident *kinetic energy* of the particle but depends critically on the stopping medium.

E.g, solid Silicon: ${}_{14}$Si atom, $r \sim 120$ pm, nucleus $r \sim 3.6$ fm

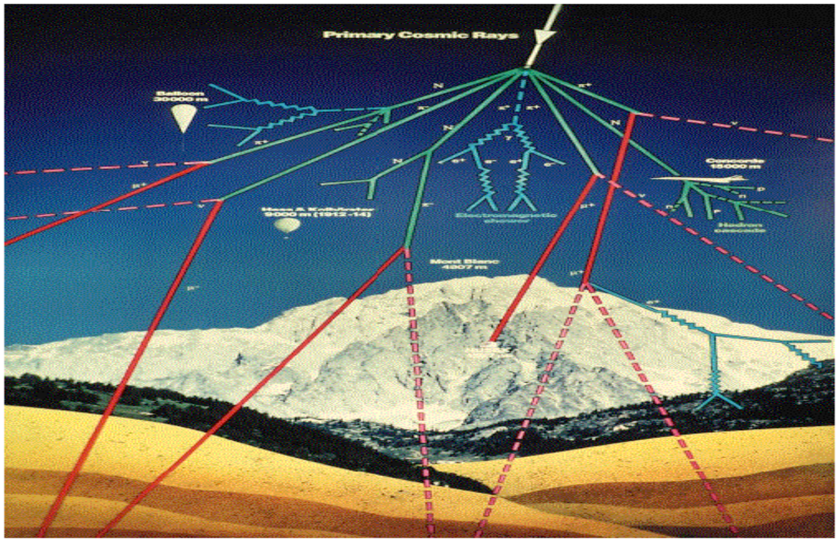
$\sigma_{Geo} = \pi r^2 \sim 4.5\text{x}10^{-20}\ \text{m}^2$ $\sim 4.1\text{x}10^{-29}\ \text{m}^2$

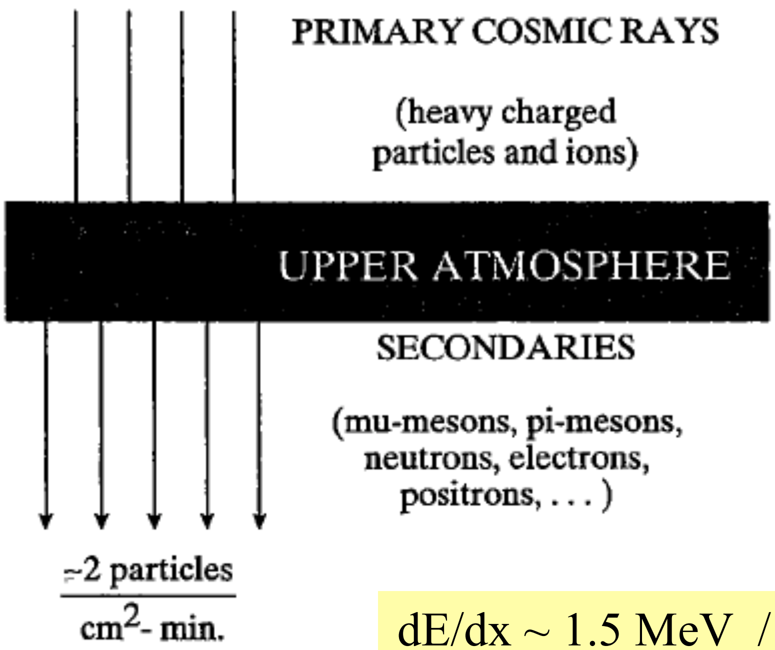
(and there are 14 electrons in that space)

Energy Scales: atomic eV, nuclear MeV

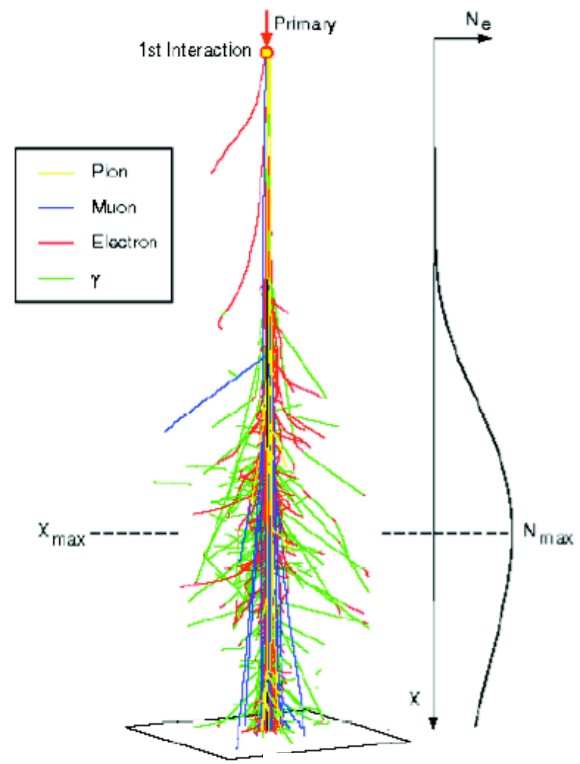
Object of Experiment: Cosmic Rays

Cartoon of a "shower" event





Calculation of a "shower" event



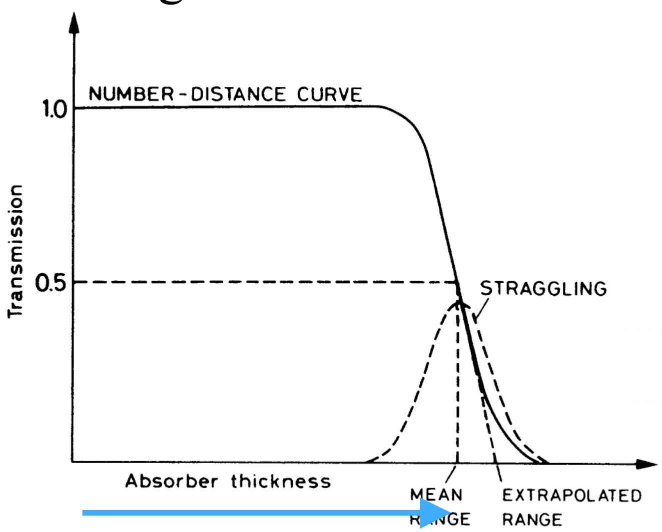
R. Chartrand, et al. LANL

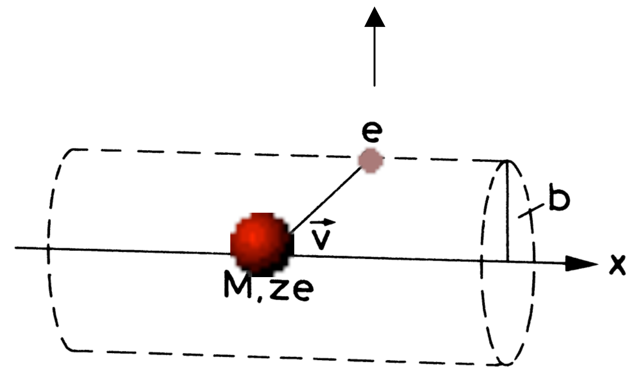
~cos^2 Θ angular distribution

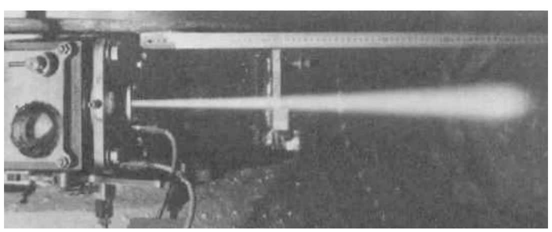
dE/dx ~ 1.5 MeV / cm [for material with density ~ 1 g/cm^3]

Interaction of massive C.P. with Matter

Massive charged particles (cosmic ray muons fall into this category) interact with the electrons in the bulk material but the very large ratio of masses (e.g., the smallest ratio is $m_p/m_e \sim 1800$) means that the ions will travel on straight lines, continuously slow down by kicking out electrons, and finally stop at some point after a huge number of interactions.



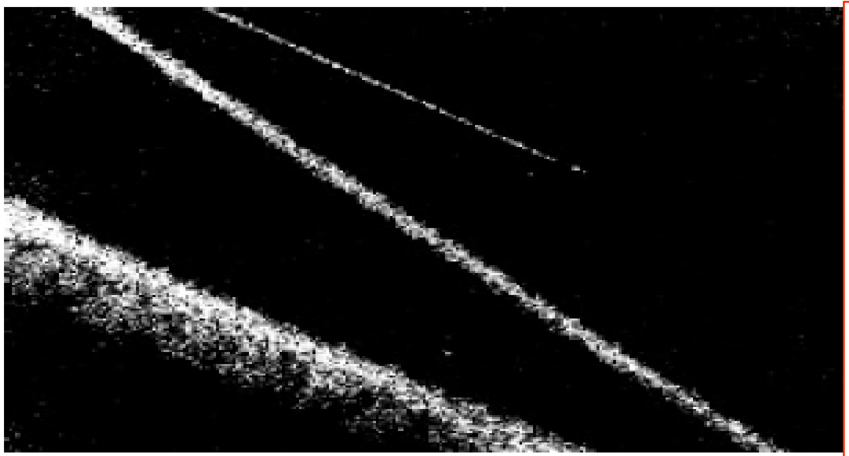


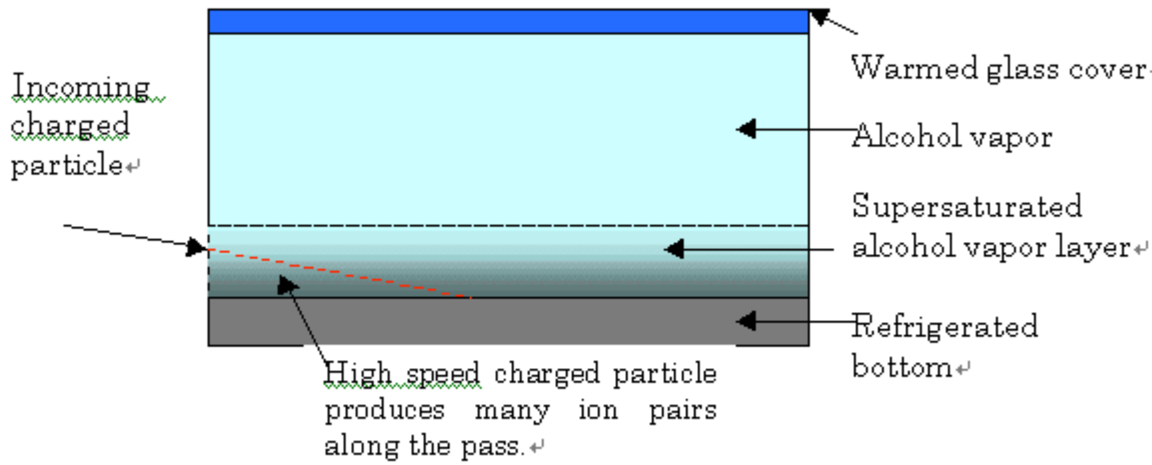


Deuterons in air from:
A.K. Solomon, "Why Smash Atoms?" (1959)

We expect that the ion intensity remains essentially constant with depth until the end of the range when the ions come to rest.
On the other hand the kinetic energy of the ion will drop continuously in tiny increments until rest.
The energy change is small in any single collision.

Cloud Chamber





2 **Schematic view**

http://www.invisiblemoose.org/site_material/WALTA/Cosmic_Rays_CD/ support_material/detectors/bubble_chamber/www.lalanet.gr.jp/nsm/E-radiation.html

Cloud Chamber Images of particles from ^{252}Cf

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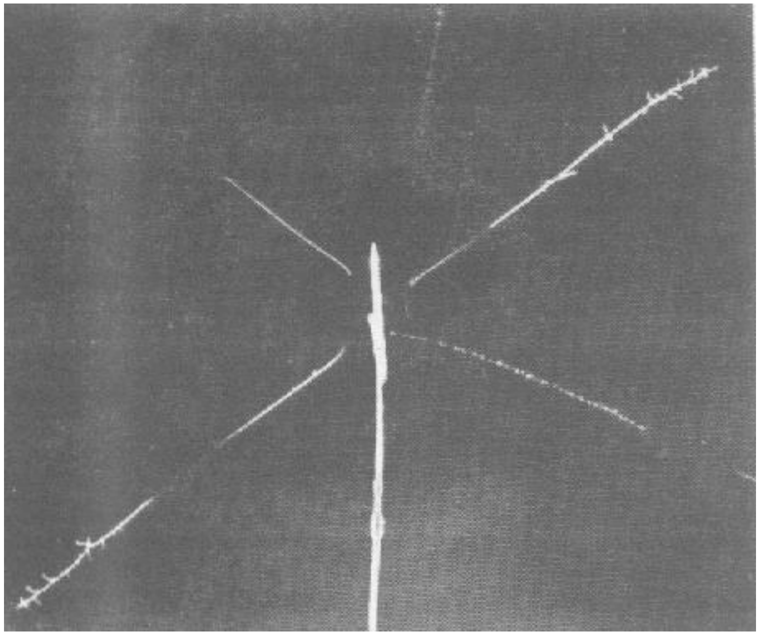

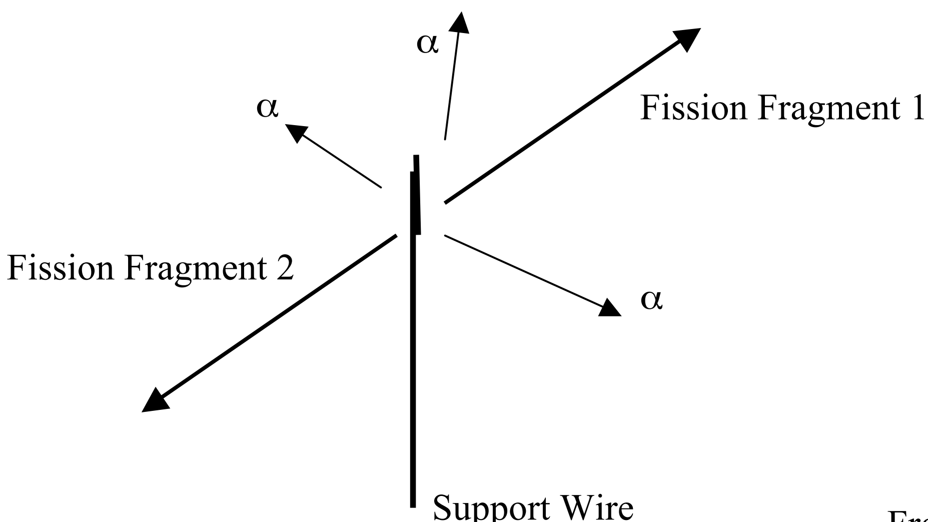

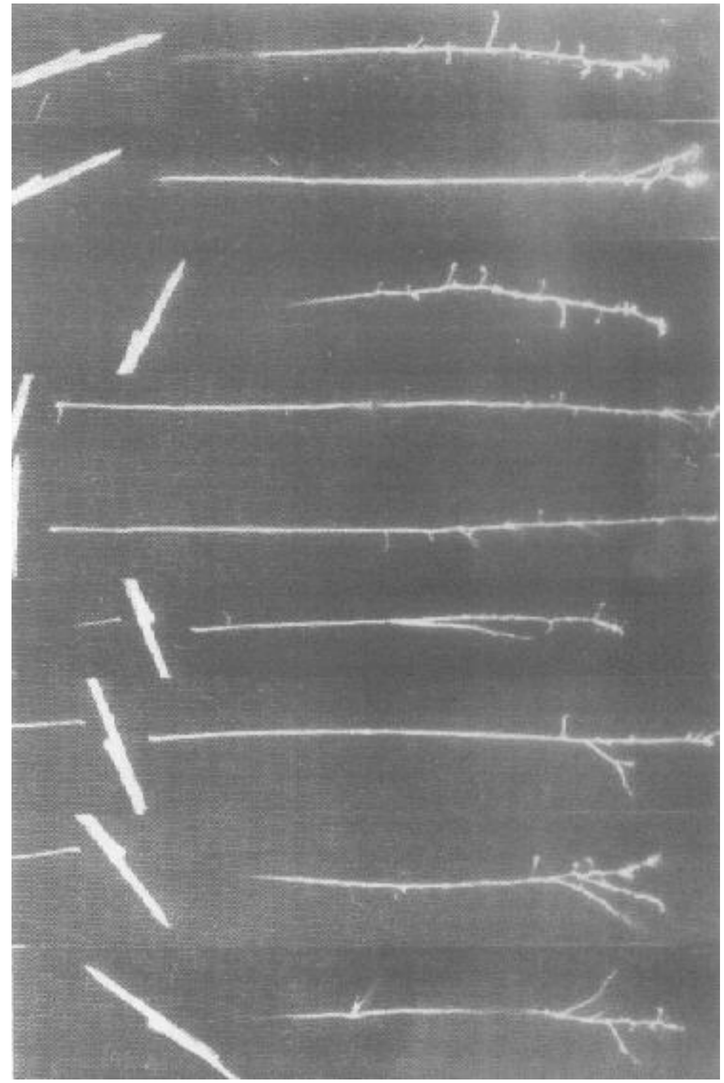

From: http://www.lateralscience.co.uk/cloud/diff.html

General Features of Detectors

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Primary Ionization is created by the interaction of the radiation in the bulk material of the 'detector' – then what?

Rate	Technique	Device	Energy Proportionality?	Temporal Information?	Position Information?
Low	Collect ions	Ion Chamber	Excellent	Poor	Average
	Multiply & Collect ions	Proportional counter	Very good	Average	Good
	Convert into photons	Scintillation counter	Acceptable	Good	Varies
	Create discharge	Geiger-Mueller Ctr. Spark chamber	No	Good	Varies
High	Collect current	Ion Chamber	Radiation Field	None	None

Scintillation Counters

A few photons are produced in de-excitation of primary ionization, scintillation devices rely on enhancing and detecting these photons. The primary ion pairs are essentially ignored and these materials are generally insulators.

General requirements:

•Linear conversion of ΔE into photons

•Efficient conversion into (near) visible light

(e.g., Plastics: 20k/MeV or NaI: 38k/MeV)

•Transparent to scintillation photons, good optical medium

•Short decay time for fluorescence (ns OK, ps good)

•Good mechanical properties (n~1.5 for glass)

Scintillator classes:

Organic molecules – molecular transitions in fluor

Inorganic materials – transitions in atomic dopants

Photomultiplier Devices: Light to Current

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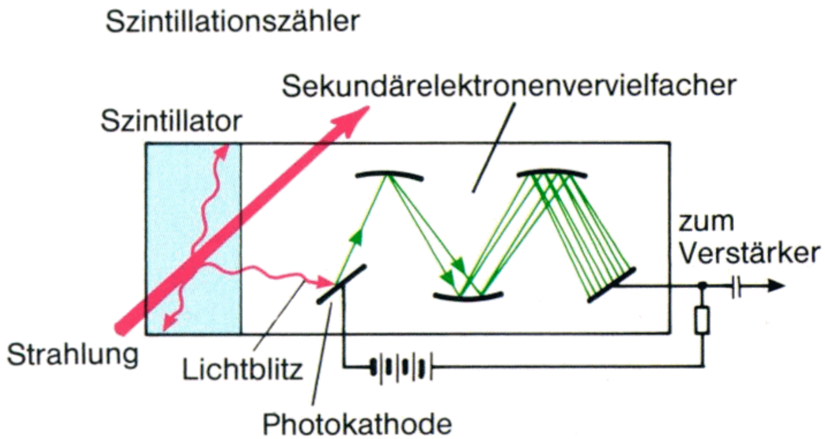
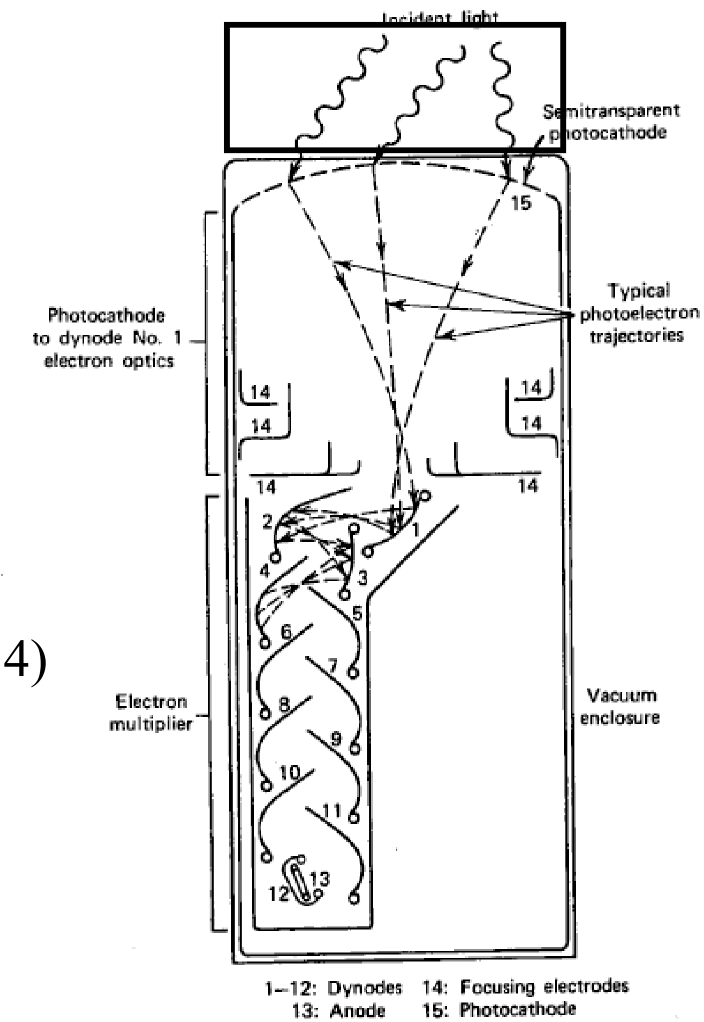
The scintillation process produces photons in proportion to the primary ionization … we need to count the number of photons to obtain the energy deposited by the primary radiation in the detector.





•Photocathode / photoelectric effect
•Various coatings, low w & high quantum efficiency
•Electrons avalanche down a string of "dynodes" (8-14)
•Dynodes are also coated to enhance cascades
•HV can be positive or negative (~1ooo V)
•Vacuum tube – internal getter to maintain vacuum
•Low potassium glass (^{40}K)
•KE of electrons start out very low – some electron optics and external magnetic shields

Fig. 9.1 Knoll, 3rd Ed.

PMTs – Other Resolution Issues

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Stray magnetic fields – use so-called mu-metal or iron shields

Differential sensitivity of photocathode surface – diffuse light over surface

Dark current – thermal photoelectrons, electronic noise, cosmic rays!

High voltage stability … Q ~ V^n where n ~ (number of stages minus a few)

Photocathode glass … transparent to uv or not?

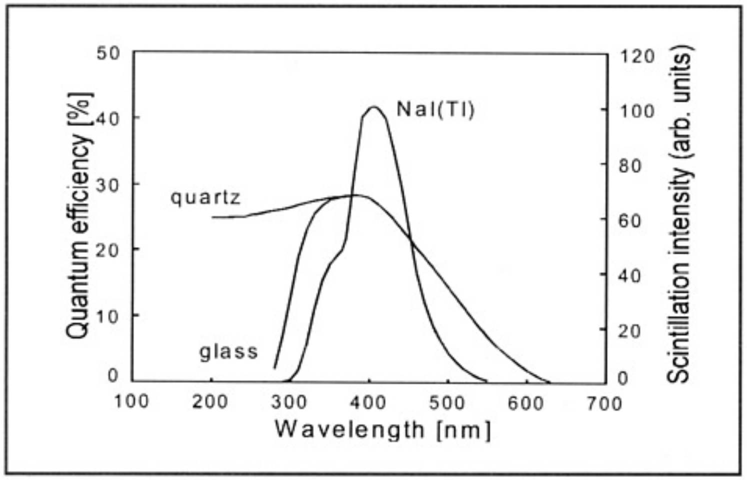
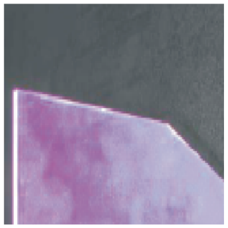


Fig. 4.2 ***Quantum efficiency curve of a standard bialkali photocathode together with the scintillation emission spectrum of NaI(Tl).***

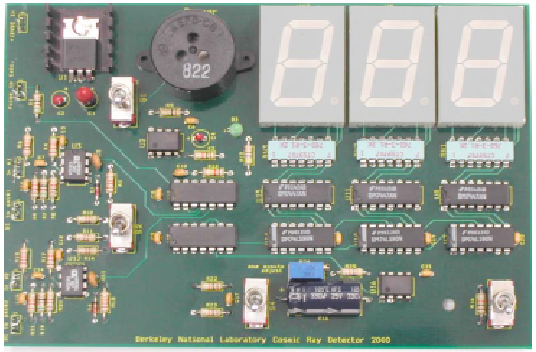
http://www.scionixusa.com/

The Berkeley Cosmic Ray Detector

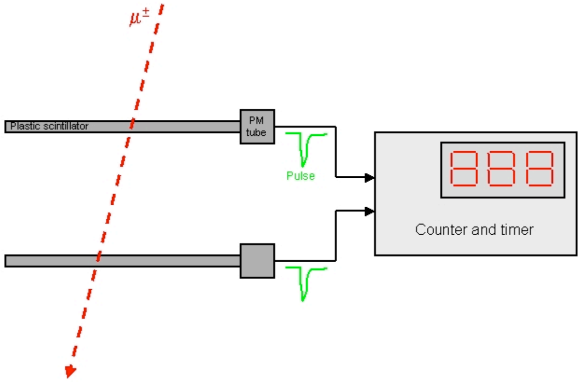


Plastic scintillator, active material, creates ~ 30k photons per CosmicRayMuon, must be polished so that light is internally reflected to one end for collection

PMT converts photons to electrical pulse, good optical connection, wrapped to keep stray light (photons) out



Circuit board, supplies voltages to PMT's, records pulses and coincidence pulses



Two paddles – coincidences are sensitive to direction

Radiation Sources .. Charged Particles –1–
Radiation Sources .. Electrons –2–
Radiation Sources .. γ Rays – 3 –

Radiation Sources .. Charged Particles –1–

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Alpha Decay:

$^{A}Z \rightarrow {}^{A-4}(Z\text{-}2)^{2-} + {}^{4}He^{2+} + Q_{\alpha}$ e.g., $^{238}U \rightarrow {}^{234}Th^{2-} + {}^{4}He^{2+} + Q_{\alpha}$

$$Q_{\alpha} = M[{}^{A-4}(Z\text{-}2)^{0}] + M[{}^{4}He^{0}] - M[{}^{A}Z]$$

Nuclei heavier than A ~ 150 are theoretically unstable against alpha decay but because it is a quantum mechanical tunneling process that is extremely sensitive to the Q-value of the process. Thus, alpha decay is only important for the heaviest nuclei and it rarely feeds excited states.

The particles are quite energetic 4 - 9 MeV but interact very efficiently with electrons in materials and stop within ~100 microns in solids.

Two-body final state gives a discrete energy distribution – must subtract recoil energy.

E.g., the "A=4N" natural decay chain:

$$^{232}Th \xrightarrow[\alpha,10^{10}\,yr]{} {}^{228}Ra \xrightarrow[\beta]{} {}^{228}Ac \xrightarrow[\beta]{} {}^{228}Th$$

$$^{228}Th \xrightarrow[\alpha,1.9\,yr]{} {}^{224}Ra \xrightarrow[\alpha,4d]{} {}^{220}Rn \xrightarrow[\alpha,56s]{} {}^{216}Po \xrightarrow[\alpha,0.2s]{} \boxed{{}^{212}Pb}$$

$$\boxed{{}^{212}Pb} \xrightarrow[\beta,11hr]{} {}^{212}Bi \xrightarrow[\beta,61m]{} {}^{212}Po \xrightarrow[\alpha,0.3\mu s]{} {}^{208}Pb \qquad E_{\alpha}=8.78\text{ MeV}$$

$$^{212}Bi \xrightarrow[\alpha]{} {}^{208}Tl \xrightarrow[\beta,3m]{} {}^{208}Pb^{*} \qquad E_{\gamma}=2.61\text{ MeV}$$

E_{α}=6.05, 6.09 MeV

Beta Decay: $n \rightarrow p^+ + e^- + \underline{\nu} + Q$ e.g., $^{14}C \rightarrow {}^{14}N^+ + e^- + \underline{\nu} + Q$

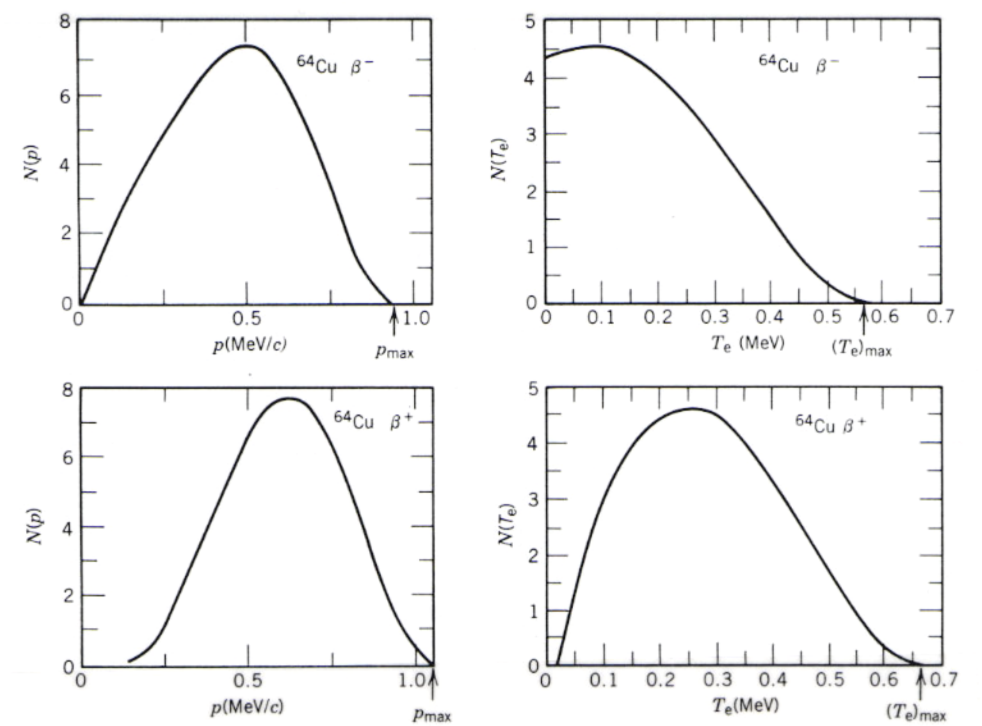
$Q = M(^{14}N^0) - M(^{14}C)$

and $(p^+ \rightarrow n + e^+ + \nu + Q')_A$ e.g., $^{13}N \rightarrow {}^{13}C^- + e^+ + \nu + Q'$

$^{13}N \rightarrow {}^{13}C^0 + e^- + e^+ + \nu + Q'$

Three-bodies in final state gives continuous energy distribution but there are thousands of radioactivities to choose from.
Note limits: 0 < Kinetic Energy < Q

$Q' = M(^{13}C^0) + 2\, m_o c^2 - M(^{14}C)$



Phase space or Fermi Functions have Coulomb shifts … Interesting example of a radioactivity that can "decay two ways"

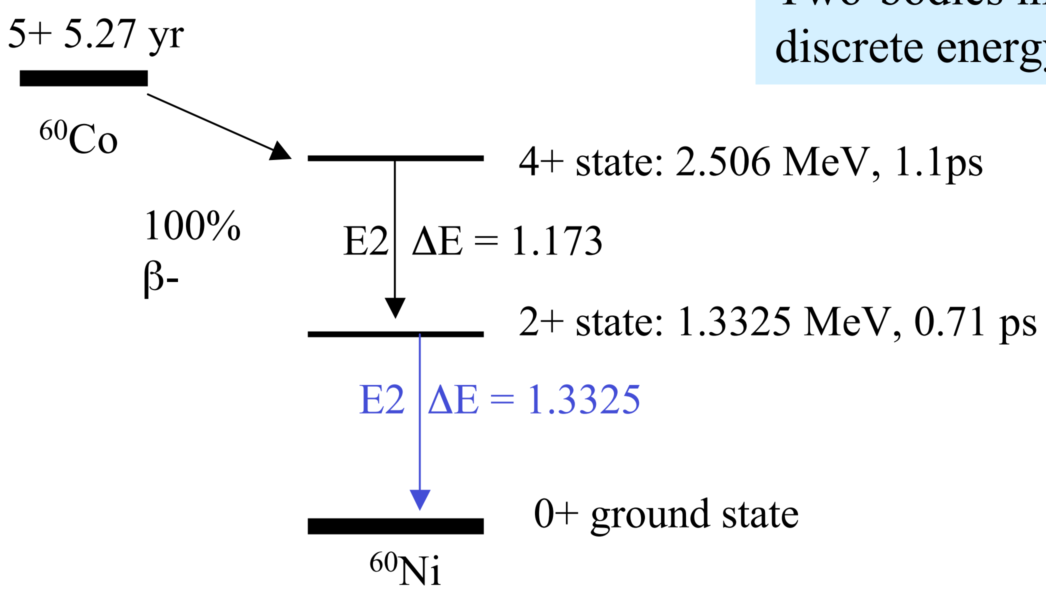
$^{64}Cu \rightarrow {}^{64}Ni^- + e^+ + \nu + Q_{\beta+} = 0.6529$ MeV
$^{64}Cu \rightarrow {}^{64}Zn^+ + e^- + \underline{\nu} + Q_{\beta-} = 0.5782$ MeV

Radiation Sources .. γ Rays – 3 –

Gamma rays are emitted by nuclear excited states, their lifetimes are generally too short to provide useful sources (except for some special cases called “isomeric” states).

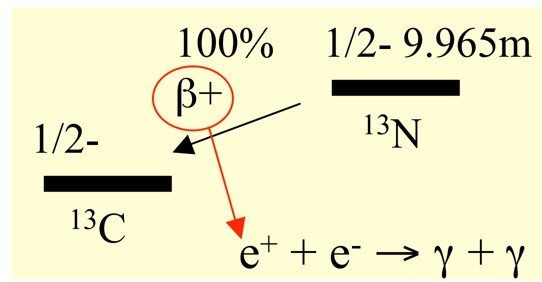
<u>Beta-delayed</u>: $^{A}(Z+/-1) \rightarrow {}^{A}Z^{*} \rightarrow {}^{A}Z + \gamma$ the gamma decay is for many purposes prompt, but often the lifetimes of the excited states can be significant and their exponential decay can be measured.

Two-bodies in final state gives a discrete energy distribution …



There will be an angular correlation among the beta and two gammas ..

Annihilation Radiation:



<u>Bremsstrahlung:</u> from electron beams, continuous energy spectrum primarily used for irradiations