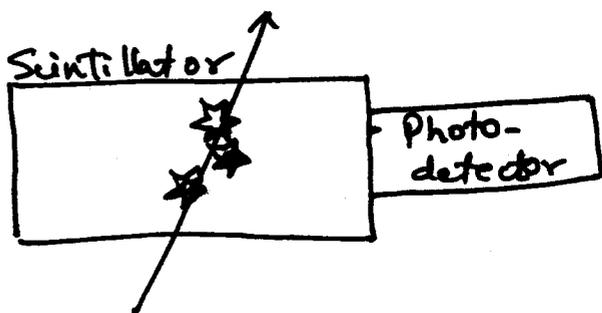


# Scintillation Detectors

- One of the oldest detection techniques  
(Recall ZnS screen from Rutherford's experiment,  
and Röntgen's fluorescent screen)
- One of the most widely used particle detection  
device to this date
- Multi-purpose detectors:
  - Trigger counter
  - Veto counter
  - Time of flight measurement
  - Tracking detectors (Fiber tracker)  
(Pixel trackers)
  - Calorimetry
  - Pre-shower detectors



Energy deposition by ionizing particle  
→ production of scintillation light  
→ photosensitive device + electronic read-out

# Scintillators

## Inorganic

- high light output  
~ 25 eV/ $\gamma$  in NaI(Tl)
- slow decay time/response  
~  $\mu$ s (CsI(Tl)) ; 0.62  $\mu$ s in BaF<sub>2</sub>
- Inorganic crystals

## Organic

- low light output  
~ 100 eV/ $\gamma$  required
- fast decay time/response  
~ 30 ns in BaF<sub>2</sub>
- Organic crystals
- Organic liquids
- Plastics

## + Gaseous Scintillators

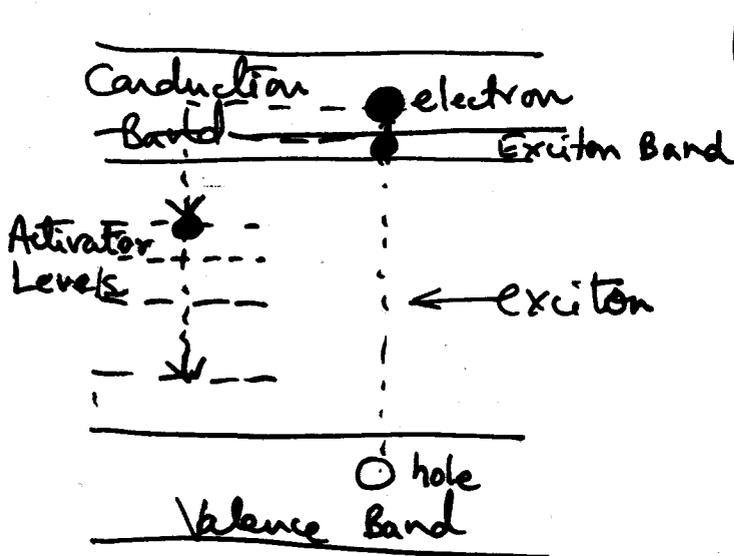
- Noble gases: Xe, Kr, Ar, He (also N<sub>2</sub>)
- Response extremely rapid (< 1 ns)
  - Light emitted in UV (where PMTs are inefficient)
  - Used in experiments with heavy charged particles or fission fragments.

## + Glasses

- Lithium or Boron silicates (Cerium activated)
- low light output (< 25-30% of anthracene)
- Used in  $\gamma$  detection, generally.

# Inorganic Scintillators

- The scintillation mechanism is an effect of the lattice. (Crystal structure of the material)
- Inorganic crystals, mainly alkali halides ( $\text{CsI}$ ,  $\text{NaI}$ ,  $\text{KI}$ , ...) with an activator impurity such as Tl



Most commonly used:  
 $\text{NaI (Tl)}$

non-alkali materials:  
 $\text{BGO (Bismuth Germanate)}$   
 $\text{Bi}_4\text{Ge}_3\text{O}_{12}$   
 $\text{BaF}_2$ ,  $\text{ZnS (Ag)}$

- Incident particles can transfer energy by:
  - exciting an electron from the valence band to the conduction band  
 → creates a free electron & a free hole
  - exciting an electron from the valence band to the exciton band  
 → creates a bound e-h pair (exciton)

- Free electrons, holes and the excitons can move freely through the lattice.
- Electrons combining with holes (or returning to the valence band) results in photon emission - frequency of the emitted radiation, response time depend on the band gap and the details of electron migration in the lattice.
- The dopants (or activator impurities) create additional activation centers (energy levels) in the forbidden gap.

These can be excited [by the excitons moving through the lattice], which then decay with photon emission.

The addition of the dopants thus increase the light yield, provide faster response and can also help match the radiation wavelength to the photocathode spectral sensitivity.

The decay time  $\propto e^{-E/kT}$

$E \equiv$  Energy of the excited impurity level.

- Sometimes the de-excitation can be radiationless (the impurity center becomes a trap).

Table 14. Properties of scintillating inorganic crystals

Scintillator	NaI(Tl)	LiI(Eu)	CsI(Tl)	Bi <sub>4</sub> Ge <sub>3</sub> O <sub>12</sub>	BaF <sub>2</sub> <sup>a</sup>	CeF <sub>3</sub>	PbWO <sub>4</sub>
Density (g/cm <sup>3</sup> )	3.67	4.06	4.51	7.13	4.9	6.16	8.3
Melting point (°C)	650	450	620			1443	
Decay time (μs)	0.23	1.3	1.0	0.35	0.62	0.03	0.01
λ <sub>max</sub> (emission) (nm)	410	470	550	480	310	310	470
Light yield (photons/MeV)	4 × 10 <sup>4</sup>	1.4 × 10 <sup>4</sup>	5.2 × 10 <sup>4</sup>	8200	6500	1000	100
Radiation length X <sub>0</sub> (cm)	2.59	2.2	1.86	1.12	2.05	1.7	0.89
Critical energy (MeV)	12.5		10.2	8.8	12	13.6	8.5
Molière radius (cm)	4.3		3.8	2.7	3.4	2.63	2.2
Refractive index n	1.85		1.8	2.15	1.56	1.68	2.16
(dE/dx) <sub>min</sub> (MeV/cm)	4.13		5.1	8.07	5.72	7.7	13.0
Temperature coefficient of light output (%K <sup>-1</sup> )	-(0.22-0.9)		<0.2	-1.7	-0.6		
Radiation damage	fair		fair	medium	very small	small	small
Hygroscopic	yes		weak	no	no	no	no

<sup>a</sup> BaF<sub>2</sub> has two scintillating components.

## Organic Scintillators

Scintillation is a molecular process  
Organic crystals (Anthracene  $C_{14}H_{10}$   
Naphthalene  $C_{10}H_8$ )

— Organic Liquids (Mixtures of one or more  
in a solvent

e.g., p-Terphenyl ( $C_{18}H_{14}$ )  
in Toluene)

— Plastics (most popular & most widely used)

polyvinyltoluene, polystyrene ← plastic solvents

Typical solutes:  $C_{18}H_{14}$

∴ Organic scintillators are typically 2 or 3 active  
Component mixtures in an organic base.

Primary fluorescence agent is excited by  
the energy loss of particles. The primary  
scintillation light from the deexcitation is  
emitted in the UV range. However, the  
fluorescence agent is opaque to its own light  
(short absorption length). So, a second fluorescent  
agent which absorbs the UV light and re-emits  
at longer wavelengths is added. (Wavelength  
Shifter). The emission spectrum of the 2<sup>nd</sup> agent  
is matched to the spectral sensitivity of the  
light receiver.

We already talked about scintillators used as calorimeters

Some examples:

Pure CsI —  $\frac{k\text{TeV}}{\leftarrow}$  has a fast component, 6 ns  
So, desirable in high-rate experiments

CsI(Tl) — Babar  
When Tl is added, response is much slower, but, light yield increases significantly (needed to detect low energy signals).

PbWO<sub>4</sub> — dense, fast, radiation hard  
Used in CMS

Mainly used as EM calorimeters

High  $Z$  is good for shower production

Bremsstrahlung for electrons ( $\sigma \propto Z^2$ )

photoelectric effect ( $\sigma \propto Z^5$ )

and pair production ( $\sigma \propto Z^2$ ) for photons

Scintillation Sampling Calorimeters:

Use organic plastic scintillators in the form of fibres or plates

ZEUS, CDF

# Light Output

Average energy loss / photon for incident electrons

Scintillator  $E$  (eV/photon)

Anthracene 60

NaI 25

Plastic 100

BGO 300

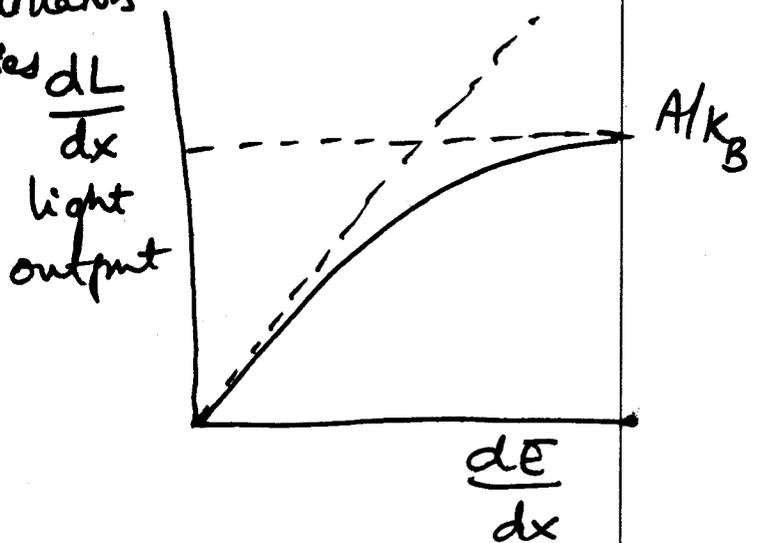
- \* Light output lower for heavier particles at same  $E$
  - \* efficiency of photodetection is also important.
- For photomultipliers, efficiency  $\sim 30\%$ .

## Linearity of Response

Particularly, for plastic scintillators  
 $L \propto E$ , at high energies  $\frac{dL}{dx}$

Semi-empirical model  
by Birks (1951)

$$\frac{dL}{dx} = \frac{A \cdot dE/dx}{1 + k_B \cdot dE/dx}$$



$A \equiv$  Absolute scintillation efficiency

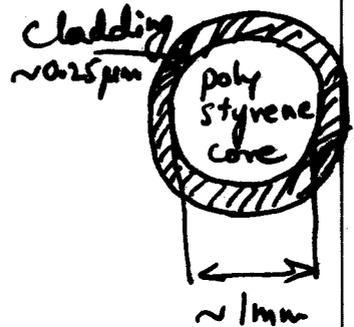
$k_B =$  Birks density parameter

$\rightarrow$  Higher the ionization density, higher the quenching interactions, lower the light.

For small  $\frac{dE}{dx}$ ,  $\frac{dL}{dx} \approx A \cdot \frac{dE}{dx}$ ; Large  $\frac{dE}{dx}$ ,  $\frac{dL}{dx} \approx A/k_B$

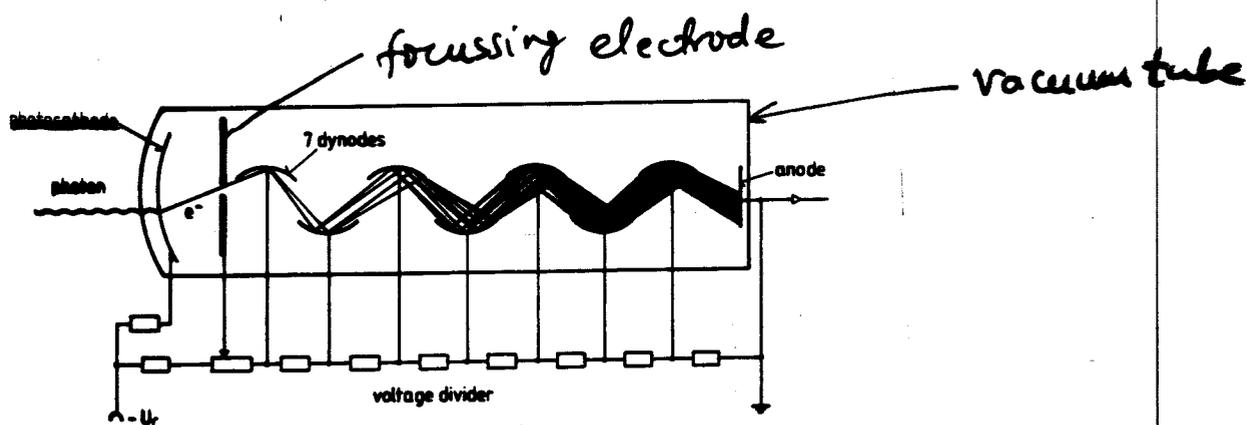
## Light Transfer to Photodetectors:

- Light Guides:  
transfer by total internal reflection
- Wavelength Shifter (WLS) bars  
Absorb and re-emit at longer wavelengths  
to match photodetector sensitivity.
- Fibers:
  - Clear fibers (Total internal reflection)
  - WLS fibers
  - Scintillating fibers  
(used in tracking)



# Photo Detectors

## • ~~Photo~~ Multiplier Tube (PMT)



- Photons from the scintillator impinge on the photocathode, electrons are emitted via photoelectric effect. [photocathode coated with a low-work function material]

$$Q.E. = N_{p.e.} / N_{photons} \quad \sim 25\% \text{ @ } 400\text{nm} \text{ in Cs-K with Sb}$$

- The emitted photoelectrons are accelerated and focused onto the first dynode of the tube. For every electron incident more secondary electrons are produced at the dynode (BeO, Mg-O-Cs)

dynode gain  $g = 3-5$

$$M = \prod_{i=1}^N g_i$$

For  $g=4, N=10$

$$M = 4^{10} \approx 10^6$$

- The amplified current is collected at the anode.

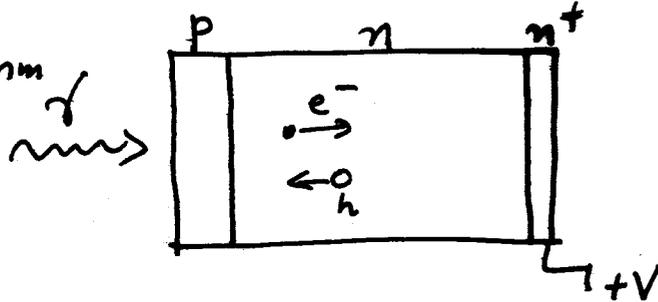
• PMTs are sensitive to B fields, even earth's field (30-60  $\mu\text{T}$ ). Mu-metal shielding used.

# Photo Diodes

• High Q = E.

~ 80% @  $\lambda \sim 700 \text{ nm}$

gain  $G = 1$



## Avalanche Photo Diodes (APD)

Add a high voltage (high electric field) region to effect avalanche multiplication.

High reverse bias  
Voltage  $\sim 100-200 \text{ V}$   
 $G \sim 100$

thin depletion region  
large field gradient

## Photo Triodes (vacuum tube Triode)

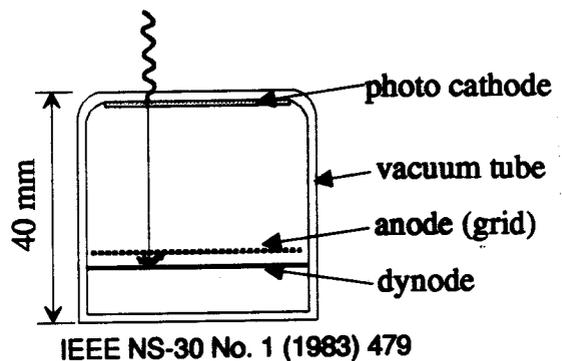
Single stage PMT  
not Silicon!

$G \sim 10$

works in axial B-fields  
of 1 T

Read-out of lead-glass  
end-cap calorimeter in

OPAL, DELPHI

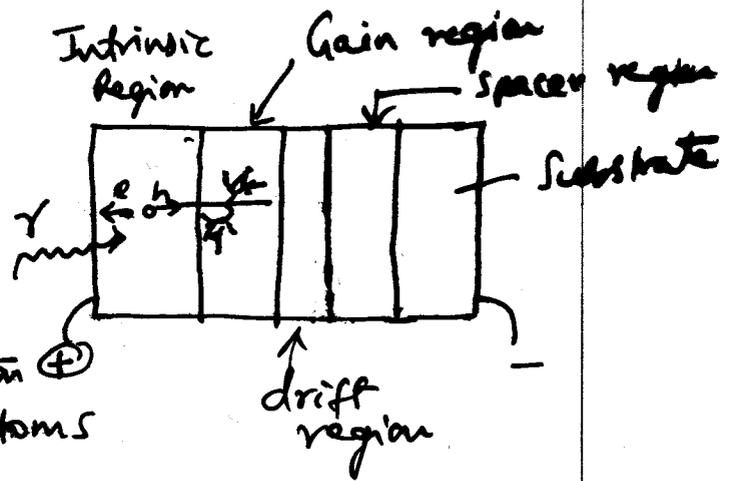


# Visible Light Photon Counter (VLPC)

A variant of the solid-state photomultiplier  
 S.S. Impurity Band Conduction Avalanche Diode

Electrons drifts towards highly doped region and ionizes a donor atom  $\gamma$   $\rightarrow$  free electron

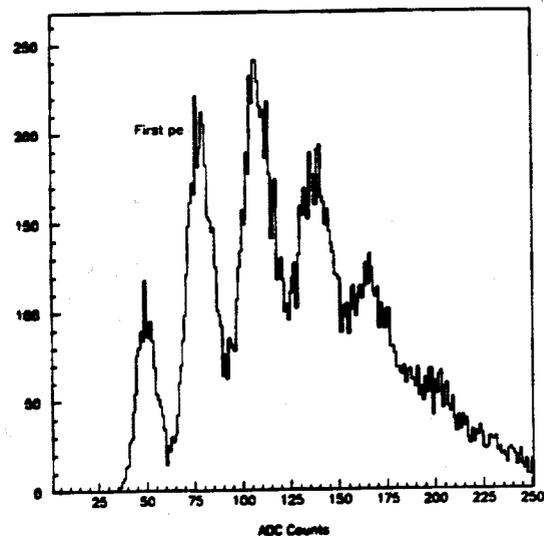
multiplication by ionization  $\oplus$  of more neutral donor atoms



Q.E.  $\sim 70\%$  ;  $G \sim 20,000$   
 Rate capability  $\sim 10 \text{ MHz}$

(D $\phi$  VLPC for the fiber tracker)

Bias voltage  $\sim 7\text{V}$   
 Operating Temperature  $\sim 7-14 \text{ K}$



# Scintillating Fiber Tracker

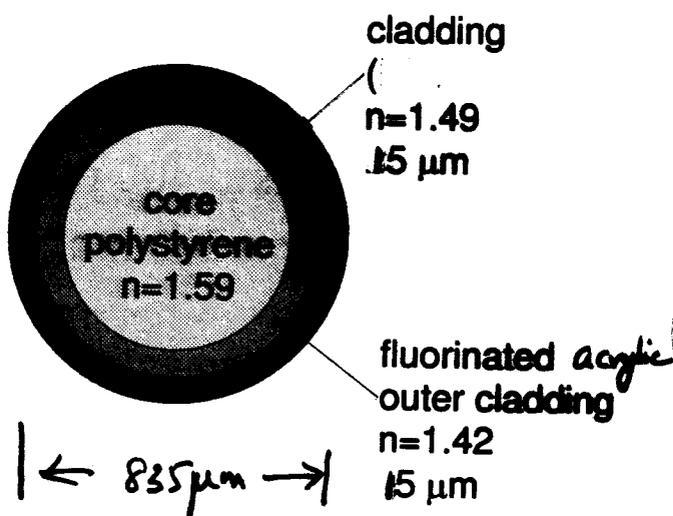
- Plastic fibers
- Capillary fibers filled with liquid scintillator

## Advantages

- High Geometrical flexibility
- Fine granularity
- low mass
- Fast response ( $\sim$  ns)  
→ first level trigger

## D $\phi$ Fiber Tracker

### Multi-clad fibers



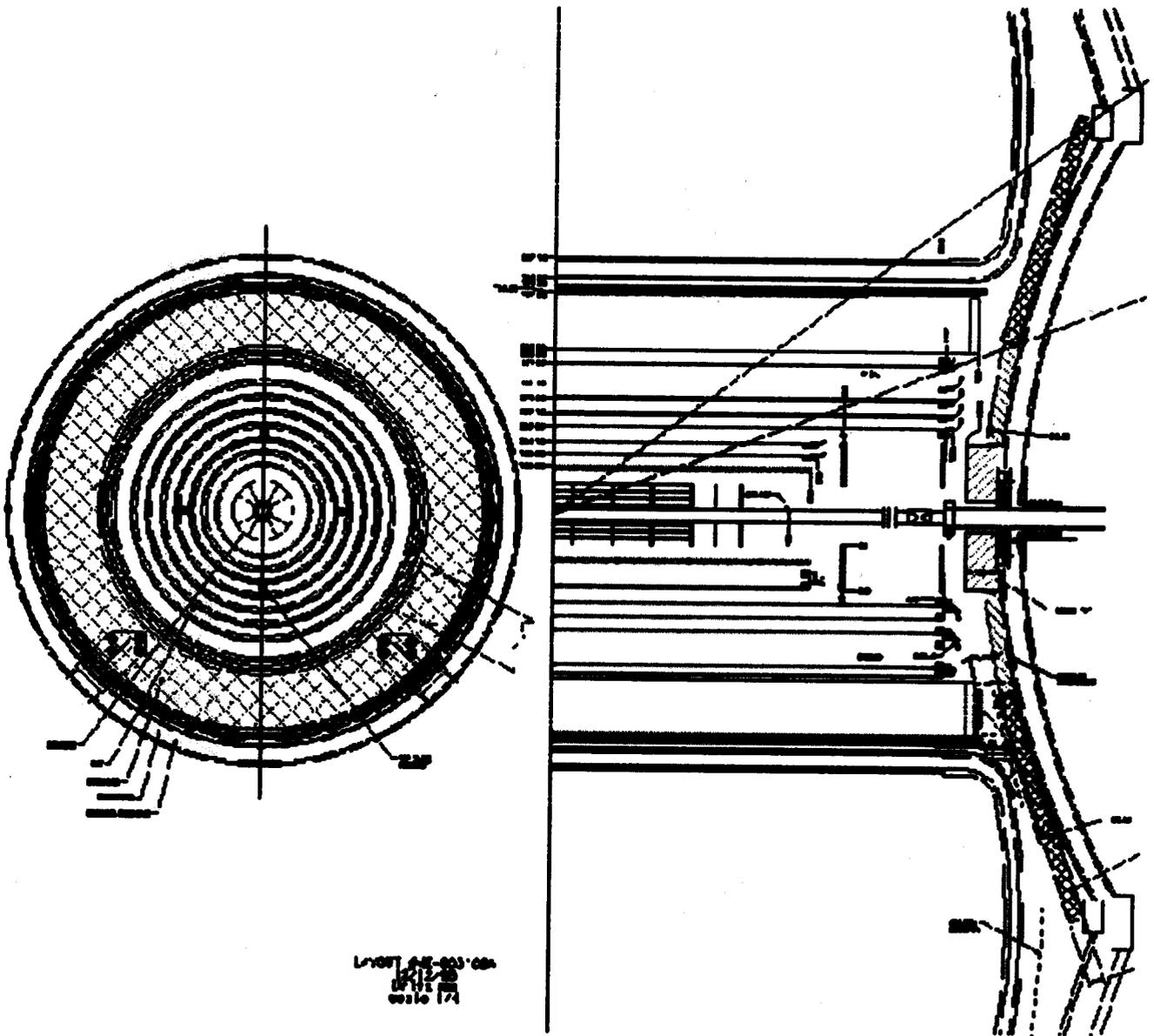
The addition of second cladding increases light trapping by 70%.

Also improved robustness of the fibers.

Core polystyrene doped with 1% p-terphenyl (PTP) and 1500 ppm 3-hydroxyflavone (3HF)

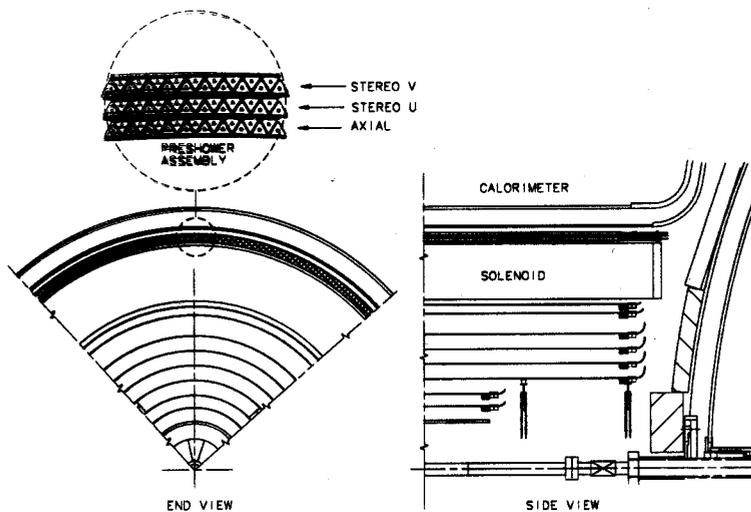
peak emission  $\lambda \sim 530 \text{ nm}$   
The scintillating fibers are mated to 11 m long multi clad fiber wave guides which conduct light to VLPCs on the platform

# DØ Upgrade Tracker



CFT: Scintillating fibers mounted on  
8 concentric cylinders.  
Constructed in ribbons each 128 fibres wide  
80 sectors in  $\phi$  71,680 channels





## Measures

energy and position  
Electron triggering and ID  
 $\gamma/\pi$  separation  
Covers  $|\eta| < 2.5$   
Level 1 trigger

## Consists of

Triangular scintillators  
WLS readout  
VLPC detection  
SVX-II readout

# Čerenkov Detectors

Detectable Čerenkov light is produced when a particle traverses a medium with a speed  $v > c/n$

$c/n$  = velocity of light in the medium

$n$  = refractive index of the medium.

Dielectric materials with  $n \gg 1$  are good candidates for Čerenkov detectors.

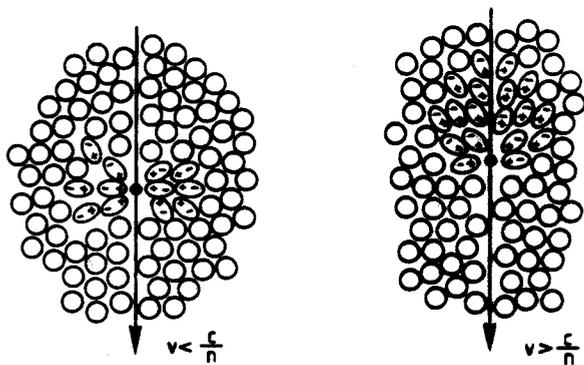
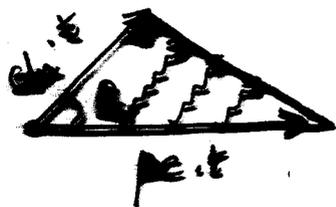


Fig. 6.7. Illustration of the Čerenkov effect [68].

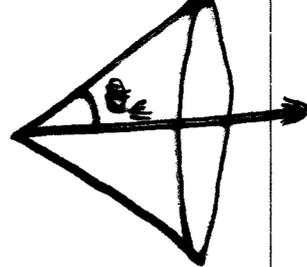
Charged particle polarizes atoms along its path  
→ electric dipoles

If  $v < c/n$ , the dipoles are symmetrically situated  
along particle's path  
⇒ integrated dipole field vanishes ⇒ no radiation

If  $v > c/n$ , symmetry is broken  
⇒ non-vanishing dipole field ⇒ Čerenkov radiation



$$\cos \theta_c = \frac{1}{n\beta}$$



In time  $t$ , particle travels a distance  $= \beta ct$   
 light travels a distance  $= \frac{c}{n} \cdot t$

$$\therefore \cos \theta_c = \frac{1}{n\beta}$$

In principle, the emission of a Cerenkov photon leads to a recoil of the charged particle, which changes its direction slightly.

Taking this into account gives,

$$\cos \theta_c = \frac{1}{n\beta} + \frac{\hbar k}{2p} \left(1 - \frac{1}{n^2}\right)$$

$\hbar k$  = momentum of the photon ;  $k = 2\pi/\lambda$

but,  $\hbar k \ll p$ ,  $\therefore$  2<sup>nd</sup> term can be neglected.

Emission of Cerenkov radiation is a threshold effect  
 Cerenkov radiation is emitted only if  $v > c/n$

or  $\beta > \frac{1}{n}$  i.e.,  $\beta_{th} \approx \frac{1}{n} \Rightarrow \theta_c \approx 0$  (forward)

$\theta_c$  increases and reaches a maximum for  $\beta = 1$

$$\theta_{max} = \cos^{-1} \frac{1}{n} \quad \text{'saturated' angle}$$

The threshold velocity for the emission of Čerenkov radiation corresponds to a threshold energy,

$$E_{th} = \gamma_{th} \cdot m_0 c^2$$

$$\text{where } \gamma_{th} = \frac{1}{\sqrt{1-\beta_{th}^2}} = \frac{1}{\sqrt{1-\frac{1}{n^2}}} = \frac{n}{\sqrt{n^2-1}}$$

Čerenkov detectors use one or more of the following properties

- The existence of a threshold for radiation
- The Čerenkov half-angle  $\theta_c$  depends on  $\beta$  of the particle
- Number of emitted photons depends on the  $\beta$  of the particle

$$\frac{d^2N}{d\epsilon d\epsilon_0} = \frac{\alpha z^2}{\pi c} \sin^2 \theta_c = \frac{\alpha^2 z^2}{r_e m_e c^2} \left(1 - \frac{1}{\beta^2 n^2(E)}\right)$$

$$\approx 370 \sin^2 \theta_c(E) \text{ /eV/cm}$$

Number of photoelectrons detected in a device,

$$N_{p.e} = L \cdot \frac{\alpha^2 z^2}{r_e m_e c^2} \int \epsilon_{coll}(E) \epsilon_q(E) \cdot \sin^2 \theta_c(E) dE$$

$\approx L \cdot N_0 \langle \sin^2 \theta_c \rangle$   
 Typical  $N_{p.e} \sim 15-20$  /cm

↑  
 photon collection efficiency

↑  
 Quantum efficiency (PMT)

medium	n	$\theta_{\max} (\beta=1)$	$N_{\text{ph}} (\text{eV}^{-1} \text{cm}^{-1})$
air	1.000283	1.36	0.208
isobutane	1.00127	2.89	0.941
water	1.33	41.2	160.8
quartz	1.46	46.7	196.4

- Contribution of Cerenkov radiation to energy loss is small compared to that of ionization and excitation

< 1% of ionization loss for MIPs  
 in gases with  $Z \geq 7$

- light yield is small compared to scintillation

$10^3 - 10^4$  times smaller  
 in a Cerenkov calorimeter

⇐ only tracks in the shower with

$v > c/n$  produce a detectable signal

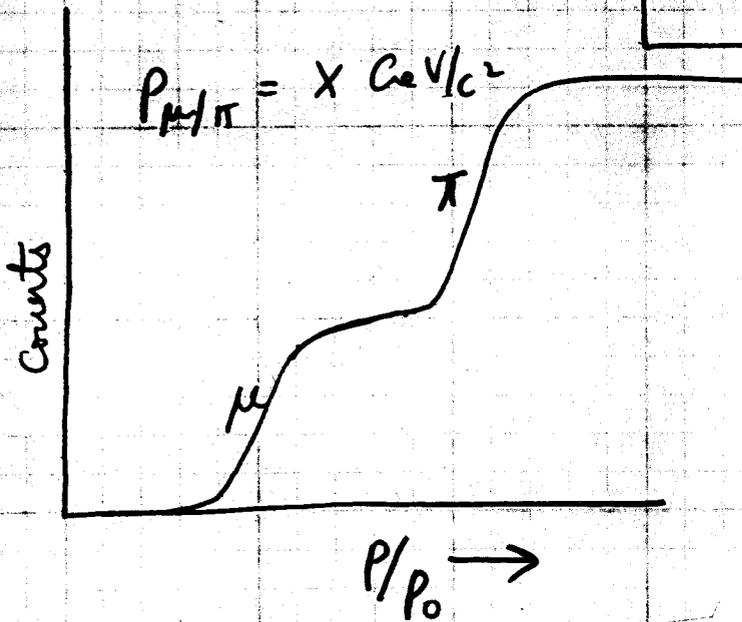
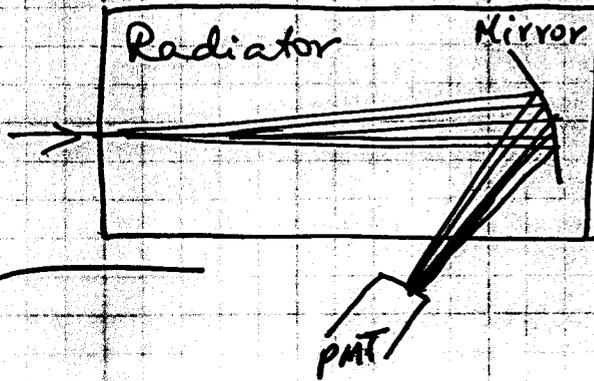
# Threshold Cerenkov Detectors

$$N_p \sim A \cdot \left[ 1 - \frac{1}{n^2 \beta^2} \right]$$

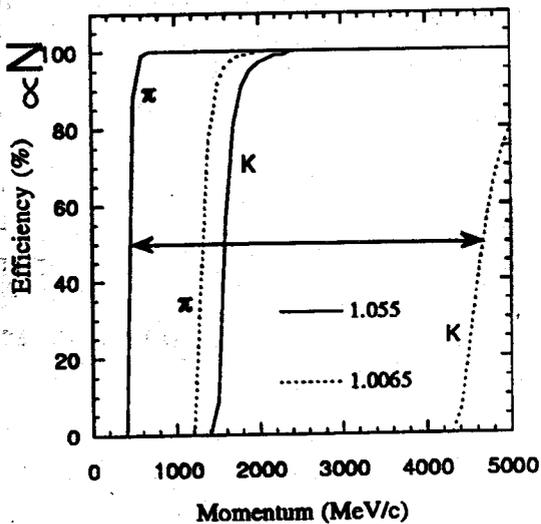
$$= A \cdot \left[ 1 - \frac{1}{n^2} \cdot \left( 1 + \frac{m^2}{p^2} \right) \right]$$

In gases,

$$n - 1 = (n_0 - 1) p/p_0$$



Study of Aerogel detectors for Babar



Two aerogel radiators

A1:  $n = 1.055$

A2:  $n = 1.0065$

$p > 0.4 \text{ GeV}/c$ :  $\pi$  in A1

$p > 1.2 \text{ GeV}/c$ :  $\pi$  in A1 and A2

$p > 1.4 \text{ GeV}/c$ : K in A1

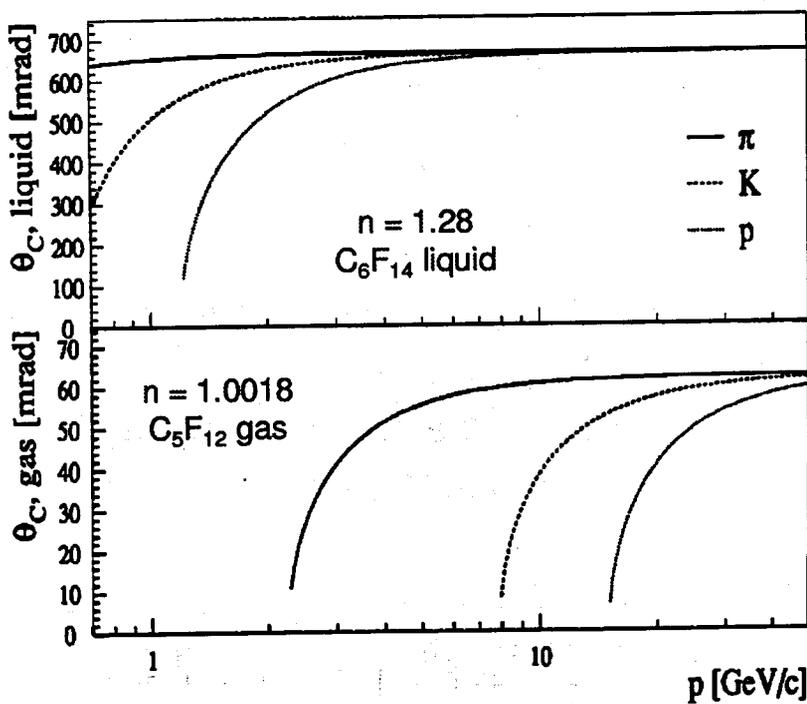
$p > 4.2 \text{ GeV}/c$ : K in A1 and A2

$\pi/K$  separation between .4 and 4.2 GeV/c

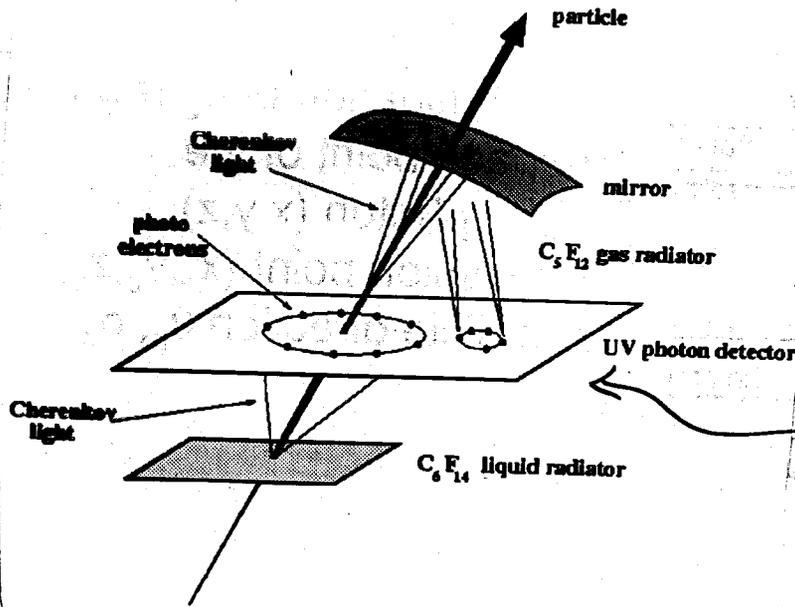
# RICH DETECTORS

$$\theta_c = \cos^{-1} \left( \frac{1}{n\beta} \right) = \cos^{-1} \left( \frac{1}{n} \cdot \frac{E}{p} \right)$$
$$= \cos^{-1} \left( \frac{1}{n} \cdot \frac{\sqrt{p^2 + m^2}}{p} \right)$$

$\therefore \theta_c$  can be used to discriminate particles of different masses, if the momentum,  $p$ , is known/measured using, say, a tracking chamber.



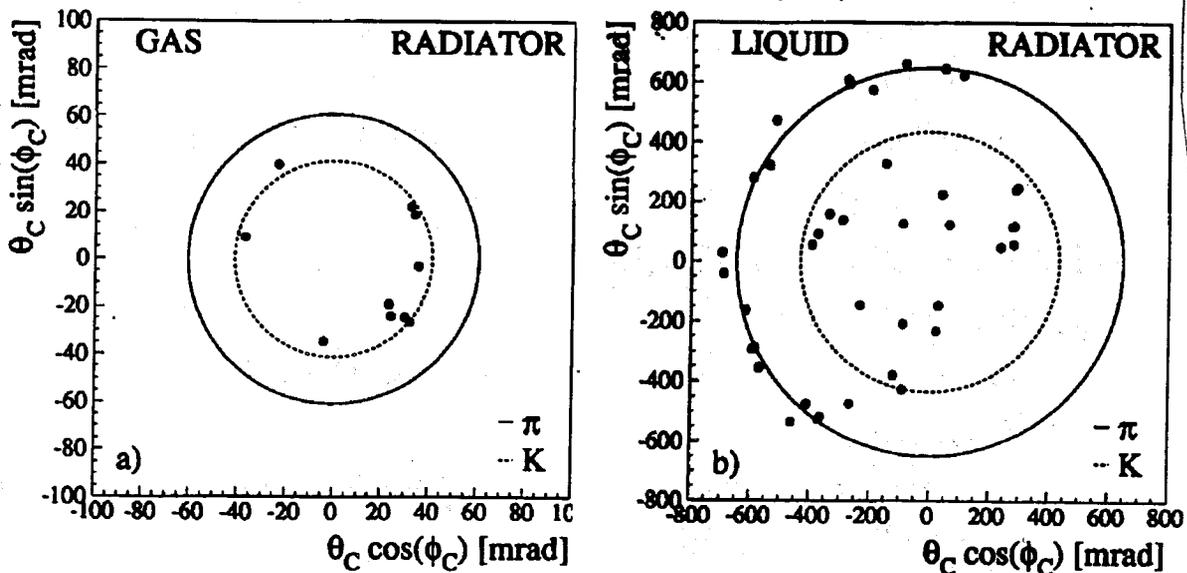
A RICH detector with two radiators to cover a large momentum range.



DELPHI and SLD:  
 $\pi/K/p$  separation  
 0.7-45 GeV/c.  
 photo sensitive chamber.

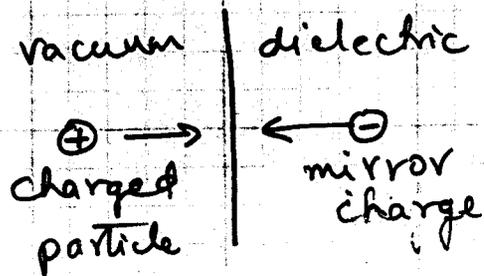
$\pi, K$  from  $Z$  decay in DELPHI

(W. Adam et al. NIM A 371 (1996) 240)



## Transition Radiation Detectors (TRD)

Even below Cerenkov threshold, charged particles may emit electromagnetic radiation. This happens when a charged particle traverses a medium with a discontinuous refractive index or boundary between media with different dielectric properties.



Charged particle moving towards a boundary forms an electric dipole along with its mirror charge.

The electric dipole field strength varies in time as the particle moves and vanishes as it crosses the boundary.

The time-dependent dipole electric field causes the emission of EM radiation.

The number of TR photons can be increased by having a periodic arrangement of foils and air-gaps.

The radiation intensity  $\sim$  and energy increases with Lorentz factor  $\gamma$ .

## TRD (Contd.)

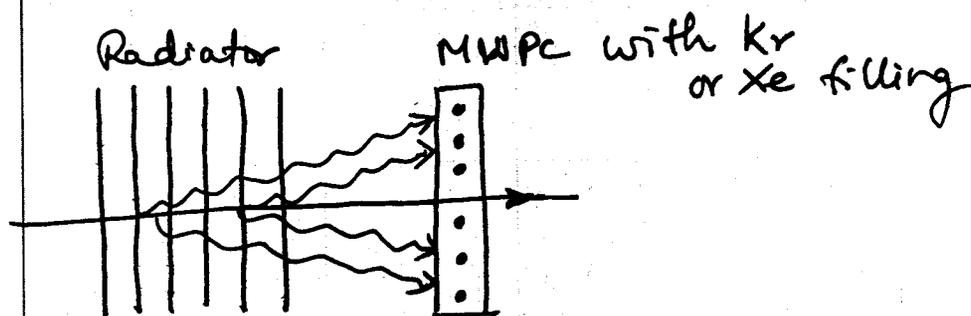
The angle of TR photon emission is,

$$\theta = \frac{1}{\gamma}$$

and the emitted photons are in the X-ray range.

The periodic arrangement of foils and gaps produce a threshold behaviour.

For particles with  $\gamma < 1000$ , no TR emission.



low  $Z$ , e.g. Li foils

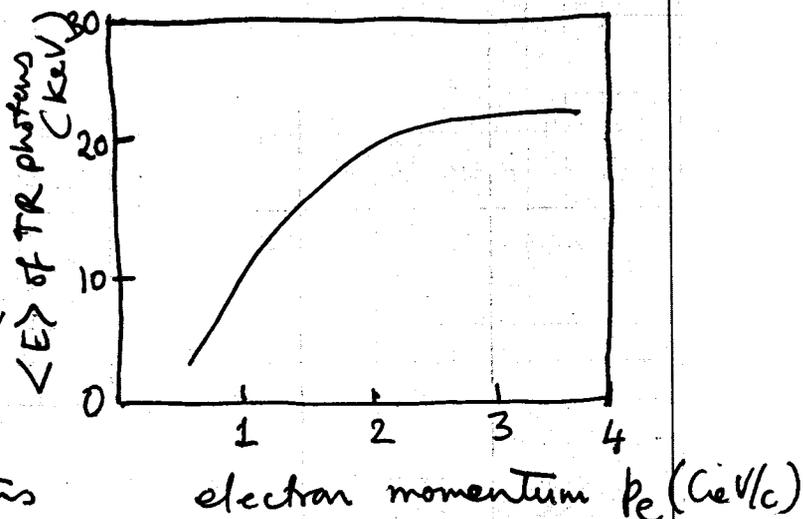
$$\therefore \sigma_{\text{photo}} \propto Z^5$$

For pions,

$$\gamma \approx 1000 \Rightarrow E = 140 \text{ GeV}$$

So, pions do not produce any TR photons below 140 GeV

$\Rightarrow e/\pi$  separation



# Schematic view of the BooNE Detector

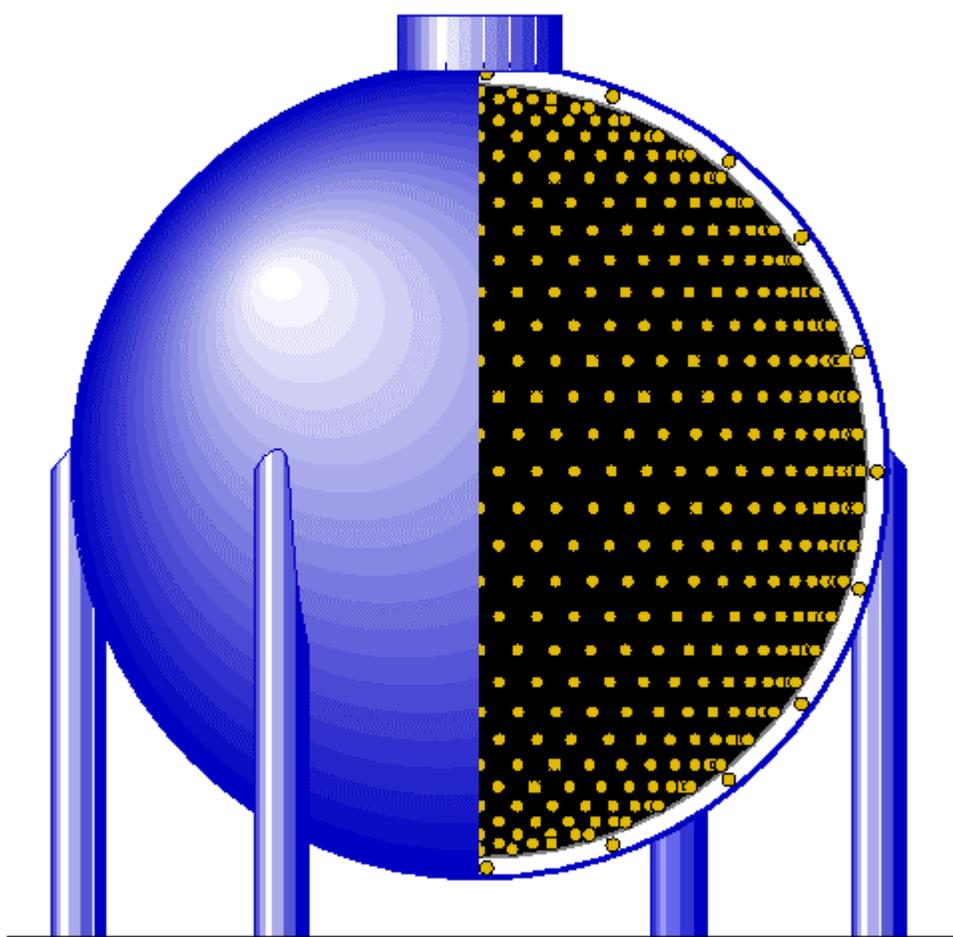


Figure 1.3: A schematic drawing of the MiniBooNE detector.

# Detector Containment Plant

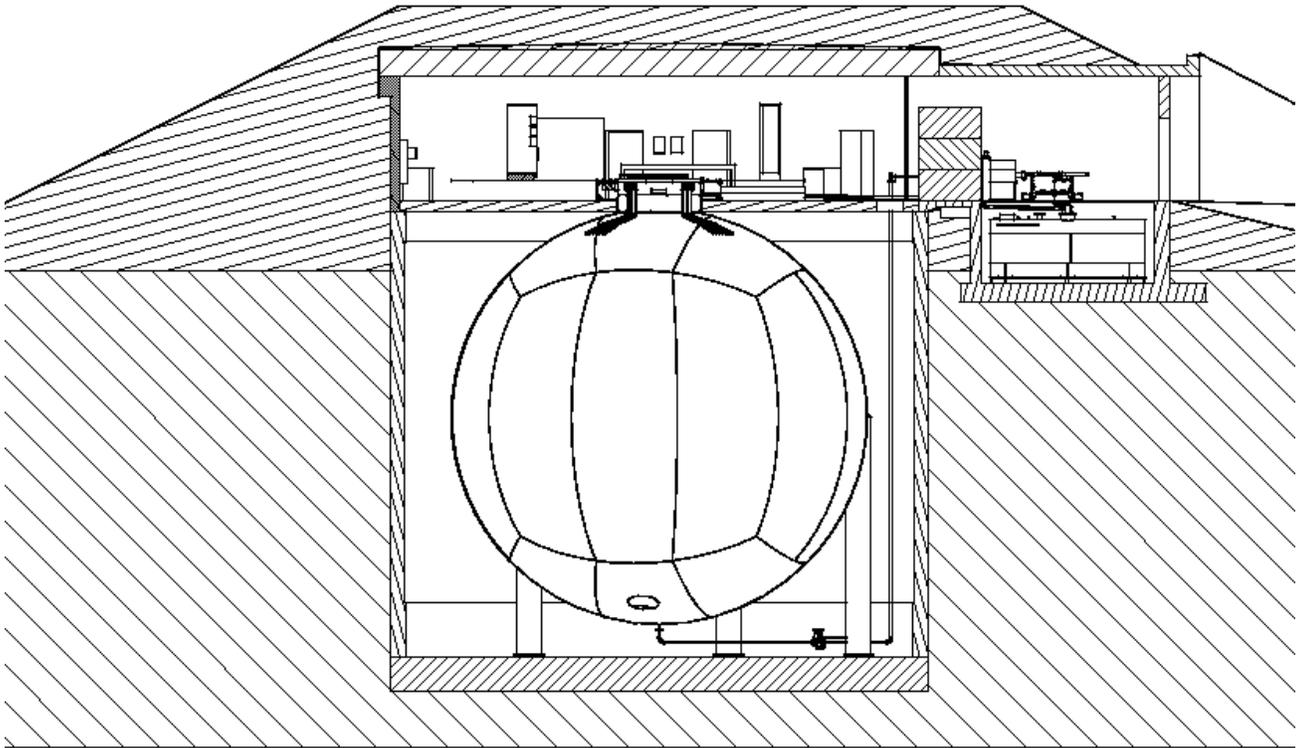


Figure 3.3: The Detector Containment Plant.



Figure 6.1: Photograph of the Hamamatsu R1408(modified) 8 inch diameter, 9-dynode stage photomultiplier tube to be used in the MiniBooNE detector. It is shown in its wire-frame mounting fixture.

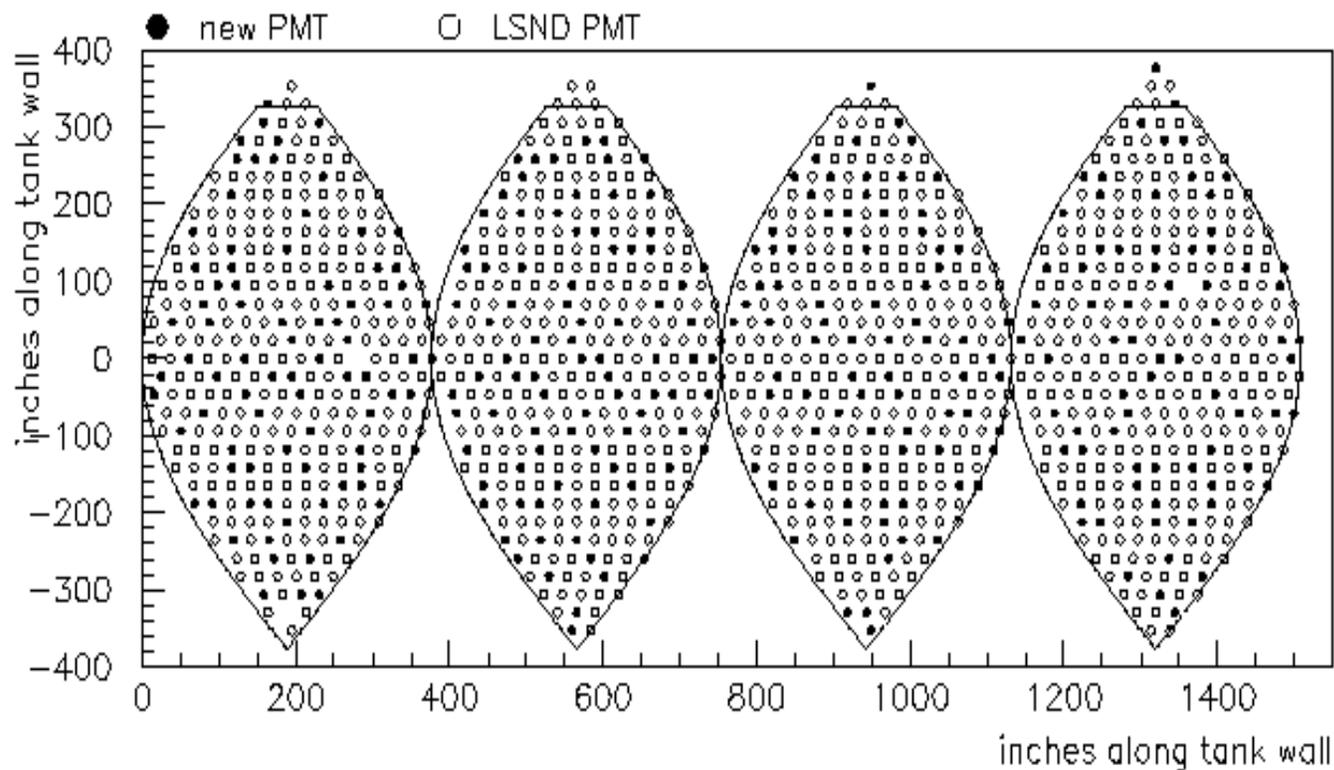


Figure 4.1: Main phototube layout. PMT's are not drawn to scale. There are a few gaps in this map where tubes had not yet been assigned.

# Cerenkov Light...

