Čerenkov Detectors

Detectable cerenkov 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 $n >> 1$ are good candidates for Cerenkov detectors.

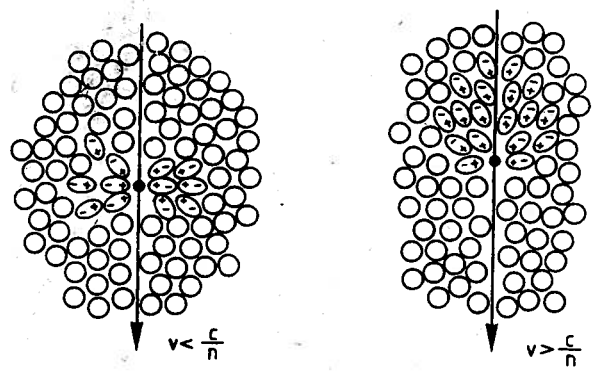
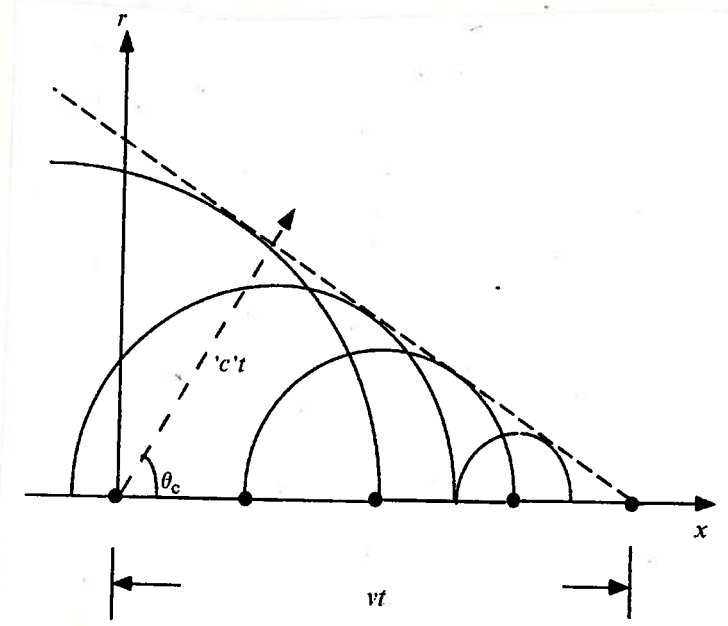


Fig. 6.7. Illustration of the Cherenkov effect [68].

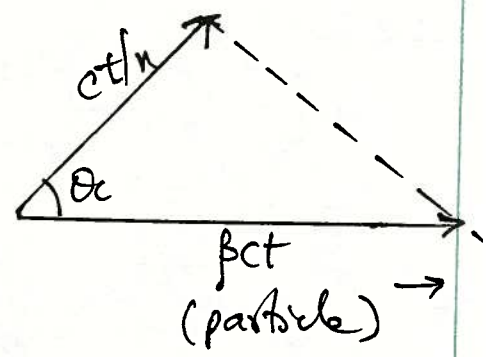
Charged particle polarizes atoms along its path
→ electric dipoles

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 ⇒ Cerenkov radiation



Cerenkov cone construction using Huygens' principle.



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

$\cos\theta_c = 1$ or $\theta_c = 0^\circ$ if $\beta = \frac{1}{n}$

As particle velocities increase, ie., for $\beta > \frac{1}{n}$, Cerenkov angle opens up into a cone.

And, $\theta_{max} = \cos^{-1}\left(\frac{1}{n}\right)$ ie., $\beta \to 1$.

Example, water has $n = 1.33$

$\therefore \beta_{th} = 0.752$

$E_{th}^{e} = 0.34$ MeV

$E_{th}^{\mu} = 69$ MeV

$\beta = \frac{p}{E}$

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

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

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

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

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 cerenkov half-angle θ_c depends on β of the particle
- Number of emitted photons depends on the β of the particle

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

$$\simeq 370 \sin^2\theta_c(E) \ /eV/cm$$

Number of photoelectrons detected in a device,

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

$\simeq L \cdot N_0 \langle \sin^2\theta_c \rangle$

Typical $N_{p.e} \sim 15-20$ /cm

photon collection efficiency

Quantum efficiency (PMT)

medium	n	θ_{max} (β=1)	N_{ph} (eV^{-1} 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

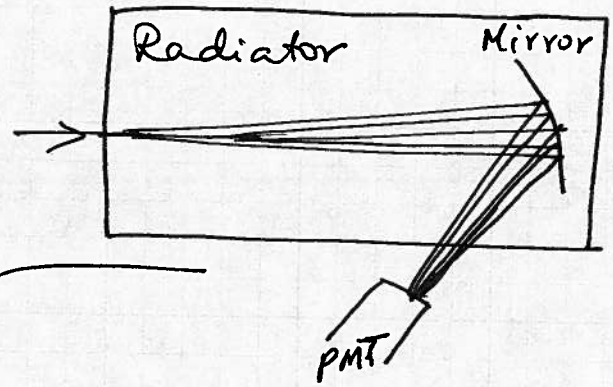
Threshold Cerenkov Detectors

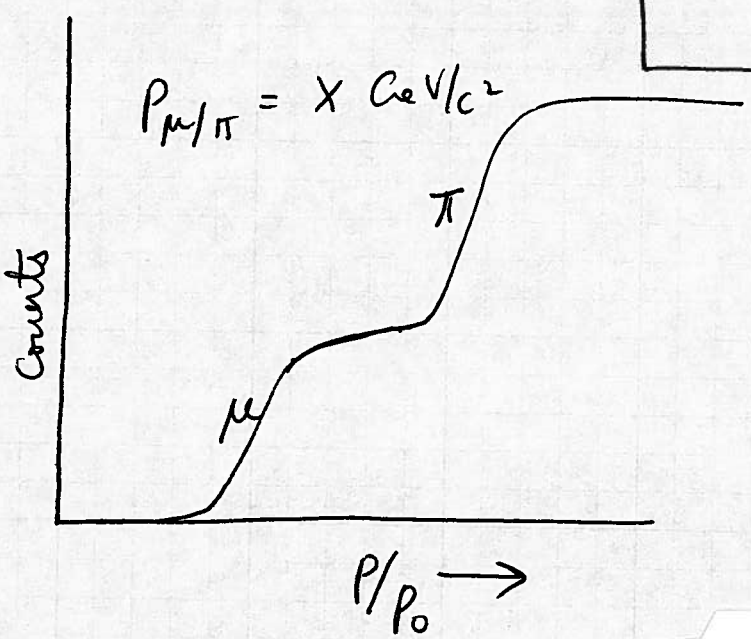
$$N_p \sim A \cdot \left[1 - \frac{1}{n^2 \beta^2} \right]$$

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

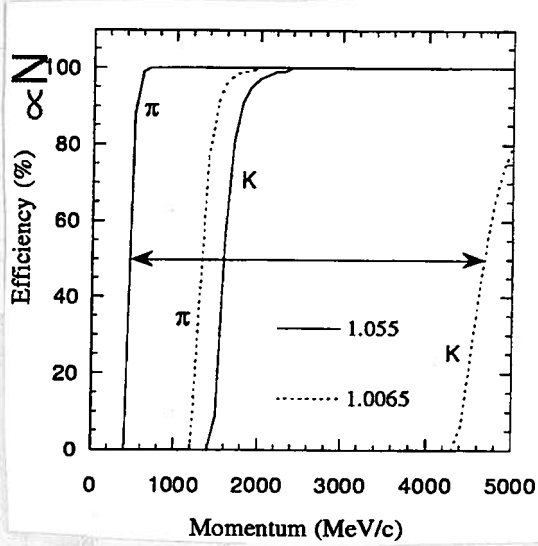
In gases,

$$n - 1 = (n_0 - 1)\, P/P_0$$





Study of Aerogel detectors for Babar



Two aerogel radiators
A1: n = 1.055
A2: n=1.0065

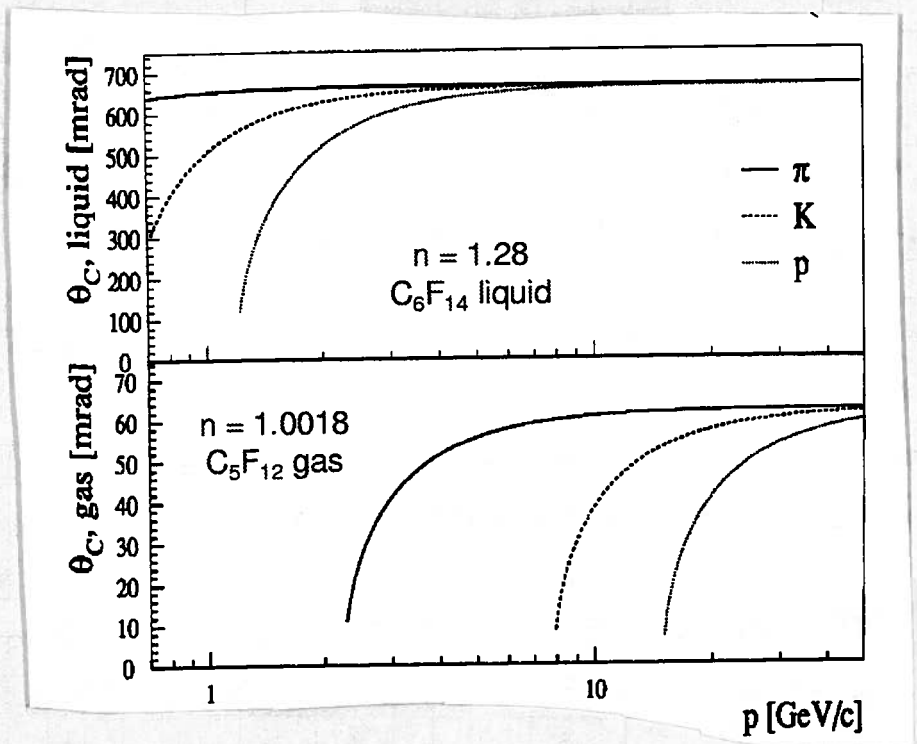
p > 0.4 GeV/c: π in A1
p > 1.2 GeV/c: π in A1 and A2
p > 1.4 GeV/c: K in A1
p > 4.2 GeV/c: K in A1 and A2
π/K separation between .4 and 4.2 GeV/c

RICH DETECTORS

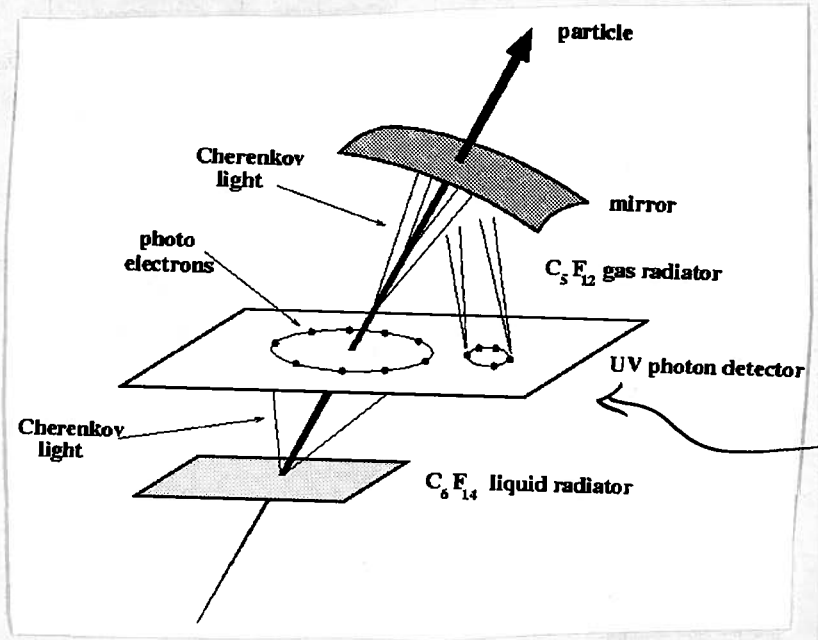
$$\theta_c = \cos^{-1}\left(\frac{1}{n\beta}\right) = \cos^{-1}\left(\frac{1}{n}\cdot\frac{E}{p}\right)$$

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

$\therefore$ θ_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.



DELHI and SLD:

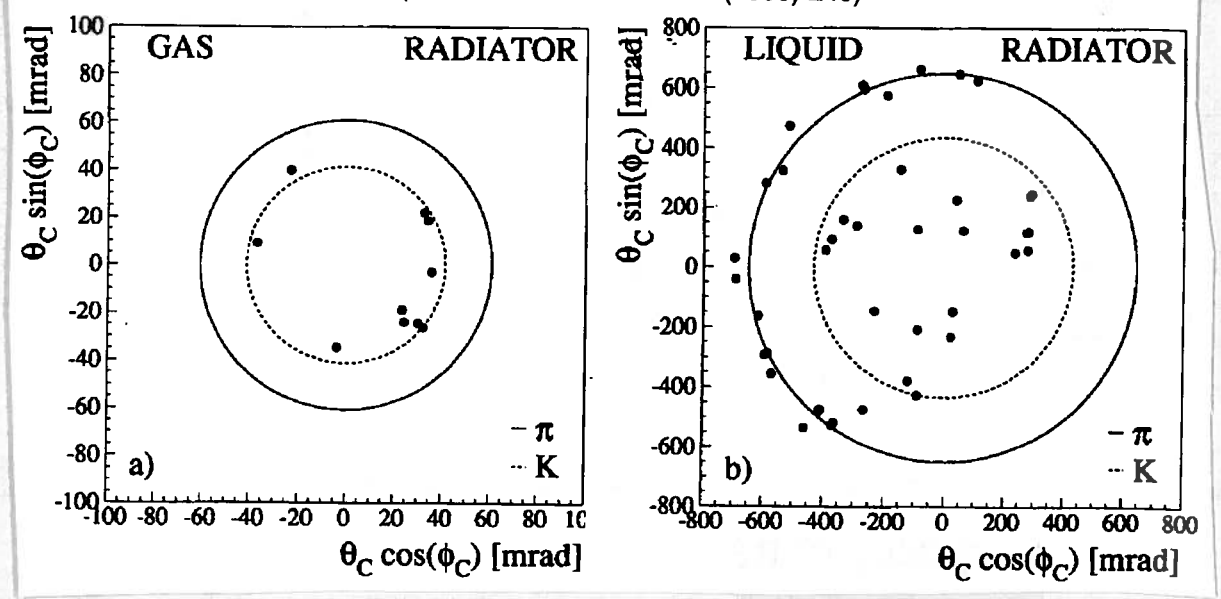
$\pi/K/p$ separation

0.7 – 45 GeV/c.

photosensitive chamber.

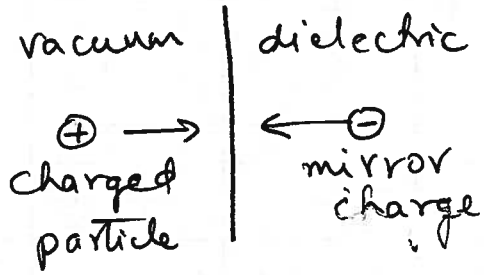
π, K from Z decay in DELPHI

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



Transition Radiation Detectors (TRD)

Even below Čerenkov 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 and energy increases with Lorentz factor γ.

TRD (Contd.)

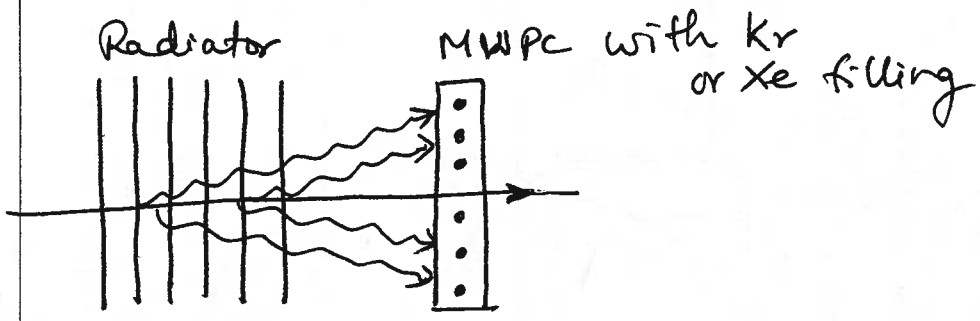
The angle of TR photon emission is,

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

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

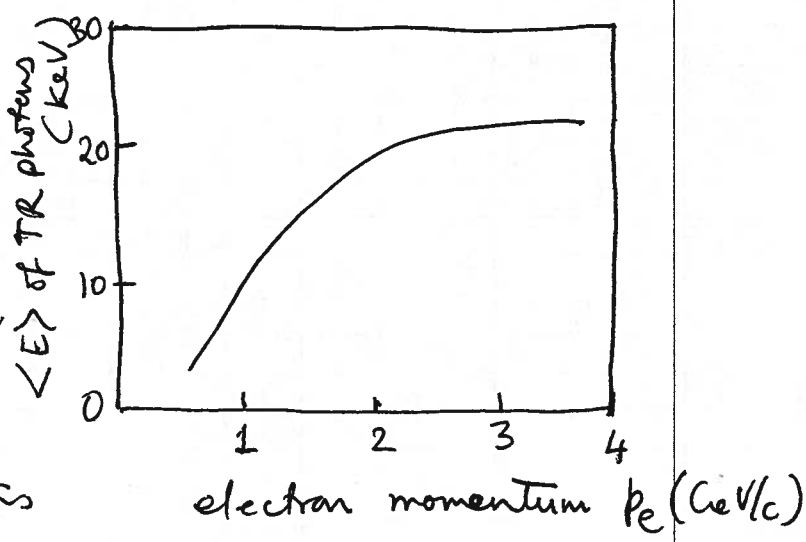
The periodic arrangement of foils and gaps produce a threshold behaviour.

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



low Z, e.g. Li foils

$\because \sigma_{photo} \propto Z^5$



For pions,

$\gamma \approx 1000 \Rightarrow E = 140$ GeV

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

$\Rightarrow e/\pi$ separation

Some Historical Track Detectors

Cloud Chamber : "Wilson Chamber"

- One of the oldest : 1911
- In 1932, Anderson discovered the Positron in cosmic rays. In 1937, he and Neddermeyer discovered the muon in cosmic rays, using the cloud chamber.

- Principle:
  The chamber contains a gas-vapor mixture (air-water vapor, Argon-alcohol, etc.) at the vapor saturation pressure. When a charged particle travelling through produces an ionization trail, a fast adiabatic expansion is triggered (using signals from Scintillation counters). The temperature drops, the vapor gets supersaturated and condenses along the positive ion trail. The droplets can be illuminated and photographed revealing particle trajectories

In contrast to the Expansion cloud chamber, one can have Diffusion cloud chamber ← permanently sensitive

Multiplate cloud chamber is much like a calorimeter with absorber plates and photographic readout.

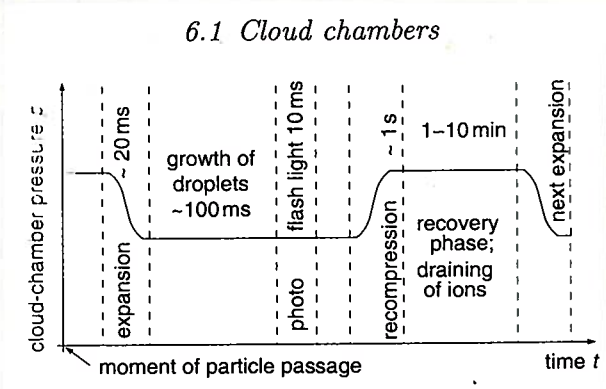
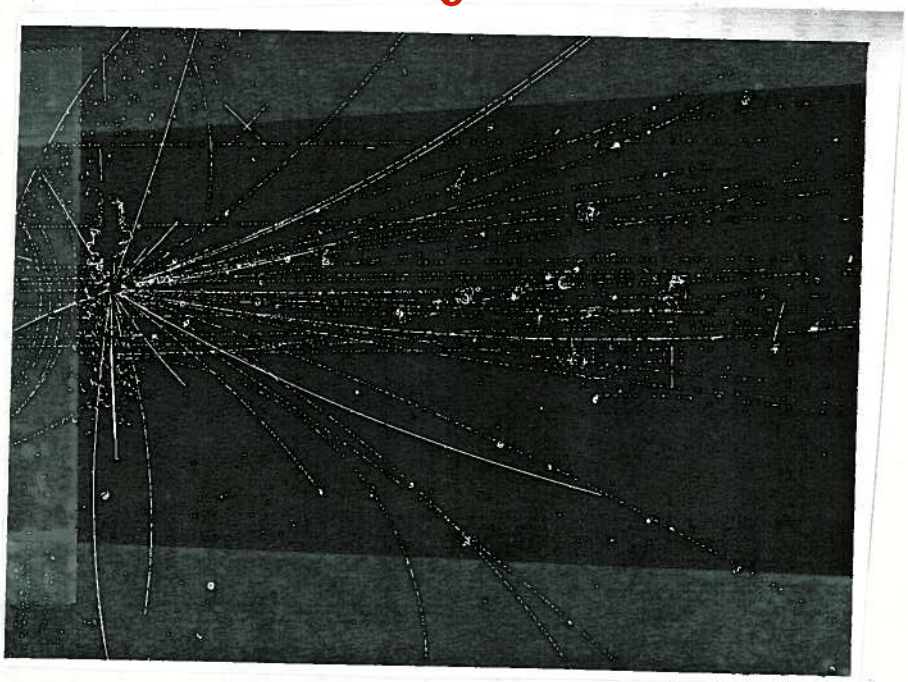


Fig. 6.1. Expansion cycle in a cloud chamber [5].

Bubble chamber

- Like the cloud chamber requires optical or photographic recording.
- The liquid (H_2, D_2, Ne, C_3H_8, Frean, ..) is held in a pressure container close to the boiling point. When the chamber volume is expanded by retracting a piston, the reduction in pressure causes the boiling temperature of the liquid to go down. So the liquid is in super-heated state and bubbles form along the path of a charged particle. Again, as in the cloud chamber, the positive ions produced by the incident particle act as nuclei/seeds for bubble formation.

π^- Ar Interactions in a 30" hydrogen bubble chamber
↓ Fermilab



From W. D. Walker & P. C. Bhat 1988

Bubble chambers have much better spatial resolution than cloud chambers

Have been used extensively until late 1980's in many discovery experiments including

Discovery of neutral currents at CERN

$\nu_\mu e^- \to \nu_\mu e^-$

8a

There are many more that were used.

Nuclear Emulsions:

Fine-grained silver halide crystals (AgBr, AgC
embedded in a Gelatin sub-strate.
After exposure, the plates are developed and fixed as in the photographic processing.
Evaluation done under a microscope.
Lately CCD's and semi-automatic pattern-recognition systems.
Used by Powel in 1947 on high mountains to finding the Pion in cosmic rays.

Recently used by DONUT project to discover ν_τ.

Spark Chambers

Predecessor of MWPC and Drift chambers.
Operated in the discharge region of the ionization chamber.