PURDUE UNIVERSITY DEPARTMENT OF PHYSICS

Physics 56400
Introduction to Elementary Particle Physics I

Now in PowerPoint!

Lecture 6

Fall 2018 Semester

Prof. Matthew Jones

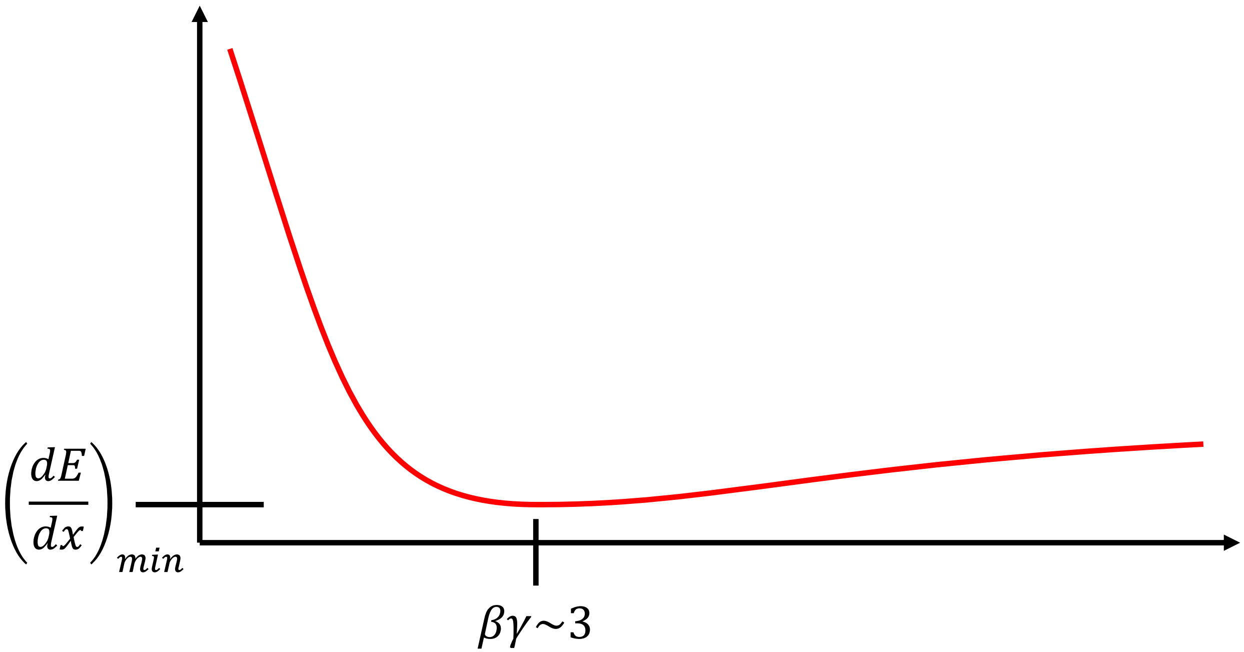
Particle Detectors

- Ultimately, we can really only detect ionizing charged particles.
  - We don’t detect photons directly. Instead we detect the associated electrons produced by Compton scattering or pair production.
  - We don’t detect neutrons directly. Instead we detect elastically scattered protons or nuclear fragments.
  - We don’t detect neutrinos directly. Instead we require that they convert to an electron or muon.
- Particle detector technology is built upon the foundation of charged particle detection.

Ionization Energy Loss

- Bethe equation:

$$\left\langle -\frac{dE}{dx} \right\rangle = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$



Ionization Energy Loss

Material	$\left(\frac{dE}{dx}\right)_{min}$ $[MeV \cdot g^{-1} \cdot cm^2]$	$\rho\ [g \cdot cm^{-3}]$	$\left(\frac{dE}{dx}\right)_{min}$ $[MeV \cdot cm^{-1}]$
H_2 (gas)	4.103	0.084 g/liter	0.000345
Ar (gas)	1.519	1.662 g/liter	0.00252
Xe (gas)	1.255	5.483 g/liter	0.00688
Be	1.595	1.848	2.948
C	1.725	2.210	3.812
Al	1.615	2.699	4.359
Fe	1.451	7.874	11.425
Cu	1.403	8.960	12.571
Pb	1.122	11.350	12.735
U	1.081	18.950	20.485
Polystyrene	1.936	1.06	2.052
PVT	1.956	1.03	2.015

Ionization Energy Loss

- Energy loss in a mixture of pure materials:

$$\frac{dE}{dx} = \sum w_j \left(\frac{dE}{dx}\right)_j$$

- Weight fractions of the components: w_j
- Example: air is 78% N_2 and 22% O_2 (by moles)

$$w_{N_2} = \frac{0.78 \times 28\ \mathrm{g \cdot mol^{-1}}}{(0.78 \times 28\ \mathrm{g \cdot mol^{-1}}) + (0.22 \times 32\ \mathrm{g \cdot mol^{-1}})}$$

$$w_{N_2} = 0.756$$

$$w_{O_2} = 0.244$$

$$\left(\frac{dE}{dx}\right)_{min} = \begin{cases} 1.825\ \mathrm{MeV \cdot g^{-1} \cdot cm^2} & N_2 \\ 1.801\ \mathrm{MeV \cdot g^{-1} \cdot cm^2} & O_2 \end{cases}$$

Ionization Energy Loss

$$\left(\frac{dE}{dx}\right)_{min} = 1.819\ \ \mathrm{MeV \cdot g^{-1} \cdot cm^2} \quad \text{(air)}$$

- Density of air (STP), $\rho = 1.205\ \mathrm{g/liter}$
- Minimum ionizing energy loss rate:

$$\left(\frac{dE}{dx}\right)_{min}^{air} \times\ \rho = 2.19\ \mathrm{keV/cm}$$

- Compare this with minimum ionizing energy loss in plastic:

$$\left(\frac{dE}{dx}\right)_{min}^{PVT} \times\ \rho = 2.015\ \mathrm{MeV/cm}$$

Ionization Energy Loss

- What happens to the ions that are created when a charged particle passes through some material?
  - Chemical reactions
  - Phase changes
  - Recombination
  - Ion drift (and subsequent detection)

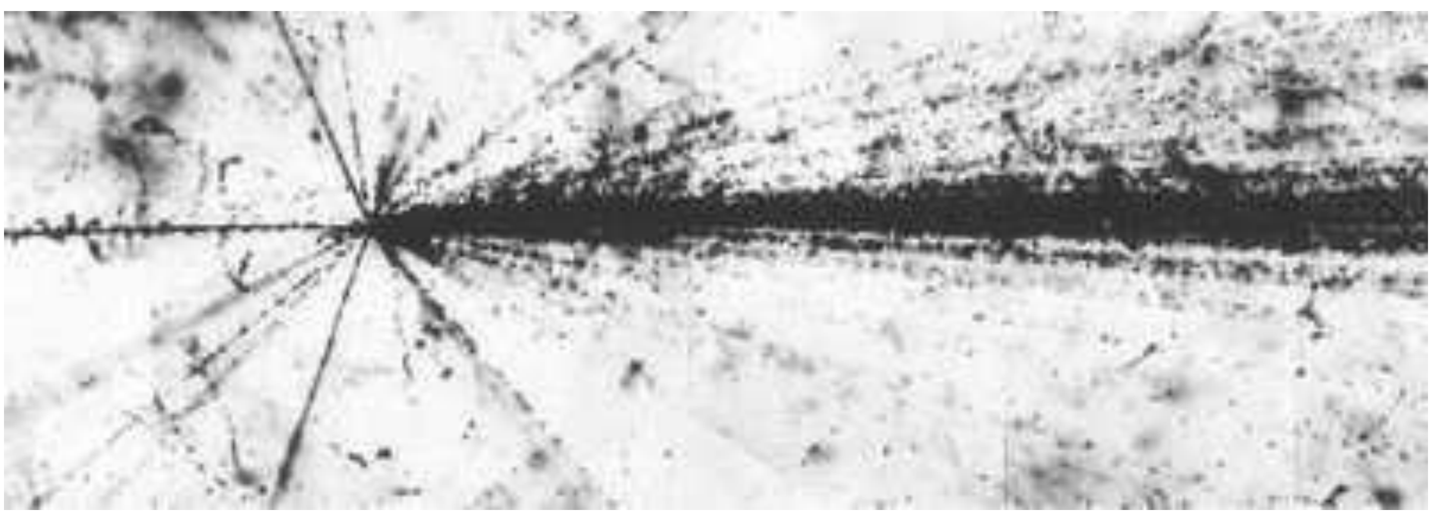
Slow

Can be very fast

Can be fast?

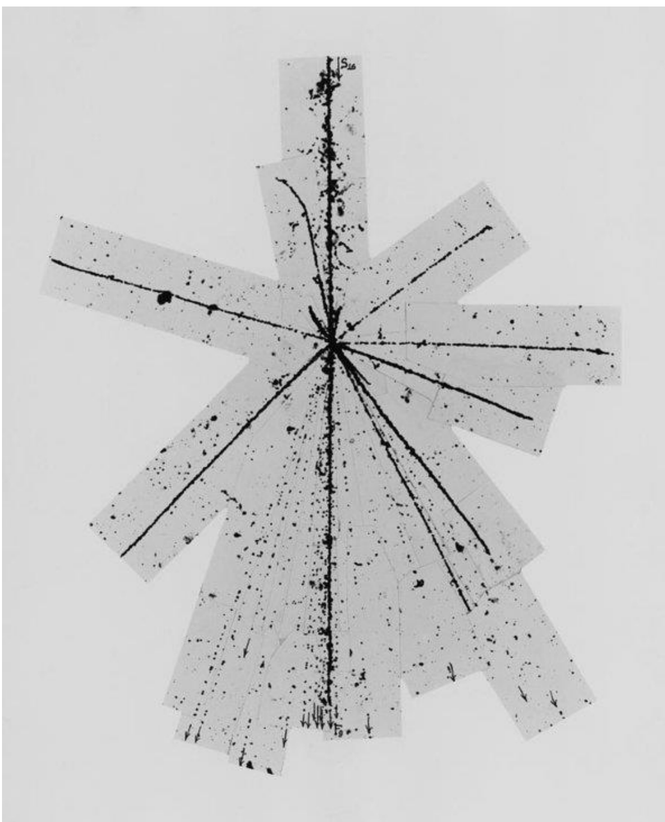
Ionization Energy Loss

- Electrons liberated by ionization can reduce a chemical compound (eg, AgBr) to produce a metal.
  - Density of metallic Ag atoms is proportional to dE/dx
- Development of the material causes more metal to crystalize around the nucleation sites.
- Fixation of the material inactivates any unreacted AgBr.



Photographic Emulsions

- Photographic emulsions provided some of the first "images" of cosmic ray interactions.

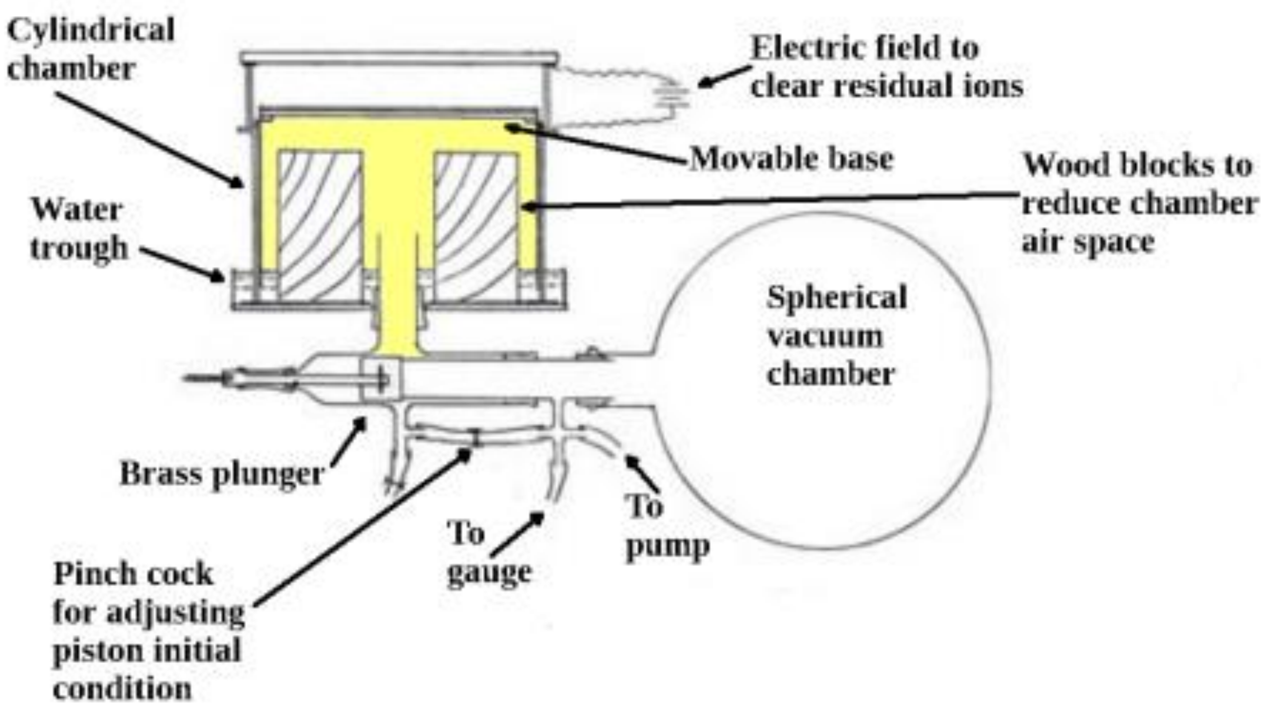


- Particle identification is possible by measuring the thickness of the tracks.
- Slow, heavy particles (eg, protons) leave thick tracks.
- Faster, light particles (pions) leave thicker tracks.
- Electrons leave thin tracks.
- Particle ID is possible and can be done precisely.

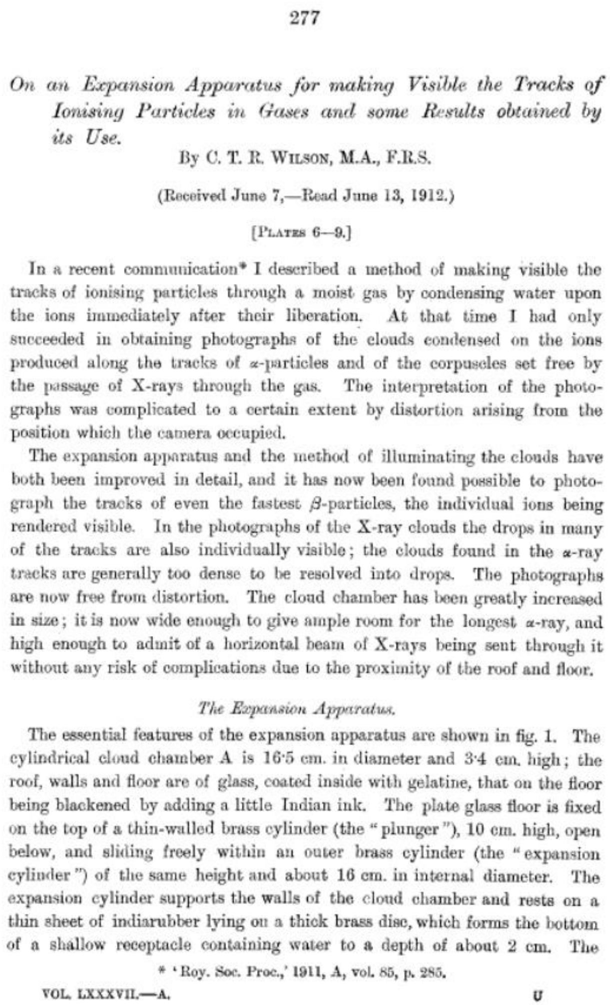
Cloud Chambers

- Ionization can induce a phase change in supercritical gas (eg, water vapor)

Wilson's cloud chamber design



Cloud Chambers



On an Expansion Apparatus for making Visible the Tracks of Ionising Particles in Gases and some Results obtained by its Use.

By C. T. R. Wilson, M.A., F.R.S.

(Received June 7,—Read June 13, 1912.)

[Plates 6—9.]

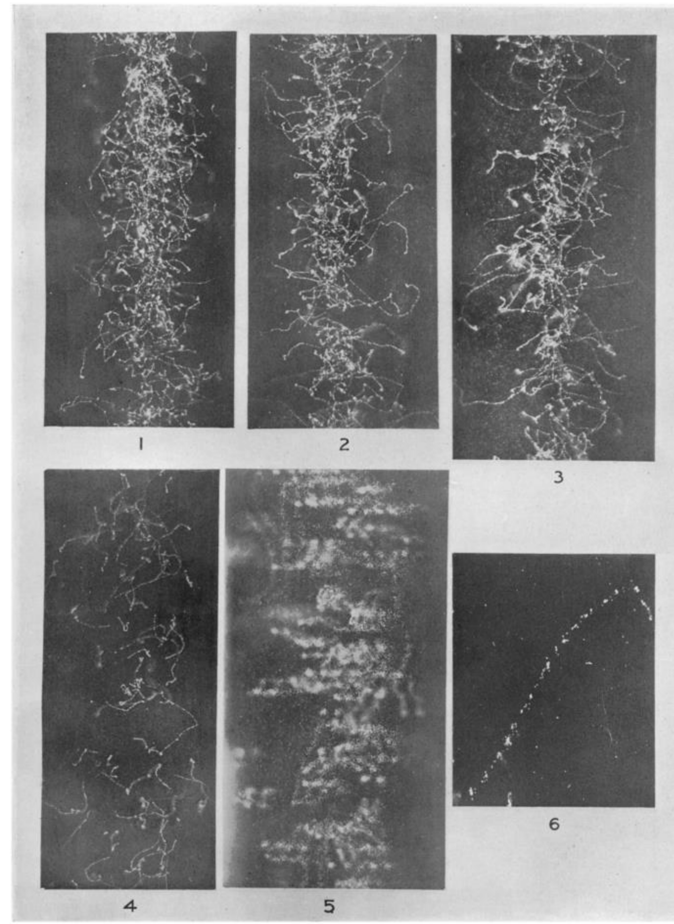
In a recent communication* I described a method of making visible the tracks of ionising particles through a moist gas by condensing water upon the ions immediately after their liberation. At that time I had only succeeded in obtaining photographs of the clouds condensed on the ions produced along the tracks of α-particles and of the corpuscles set free by the passage of X-rays through the gas. The interpretation of the photographs was complicated to a certain extent by distortion arising from the position which the camera occupied.

The expansion apparatus and the method of illuminating the clouds have both been improved in detail, and it has now been found possible to photograph the tracks of even the fastest β-particles, the individual ions being rendered visible. In the photographs of the X-ray clouds the drops in many of the tracks are also individually visible; the clouds found in the α-ray tracks are generally too dense to be resolved into drops. The photographs are now free from distortion. The cloud chamber has been greatly increased in size; it is now wide enough to give ample room for the longest α-ray, and high enough to admit of a horizontal beam of X-rays being sent through it without any risk of complications due to the proximity of the roof and floor.

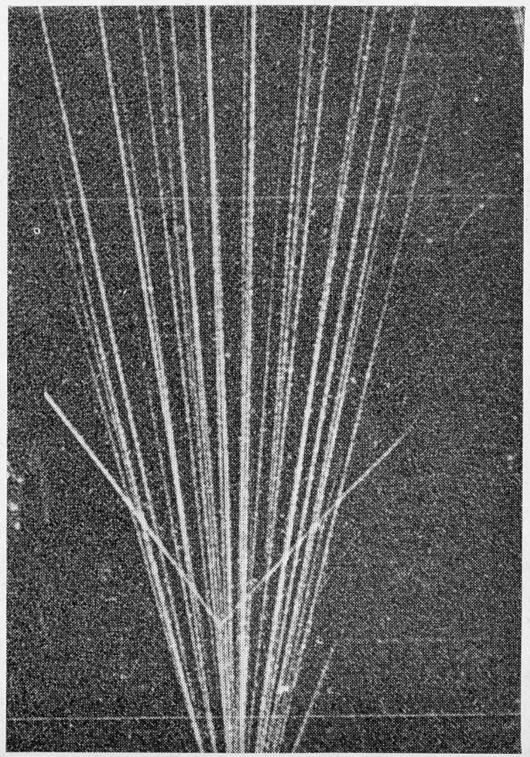
The Expansion Apparatus.

The essential features of the expansion apparatus are shown in fig. 1. The cylindrical cloud chamber A is 16·5 cm. in diameter and 3·4 cm. high; the roof, walls and floor are of glass, coated inside with gelatine, that on the floor being blackened by adding a little Indian ink. The plate glass floor is fixed on the top of a thin-walled brass cylinder (the "plunger"), 10 cm. high, open below, and sliding freely within an outer brass cylinder (the "expansion cylinder") of the same height and about 16 cm. in internal diameter. The expansion cylinder supports the walls of the cloud chamber and rests on a thin sheet of indiarubber lying on a thick brass disc, which forms the bottom of a shallow receptacle containing water to a depth of about 2 cm. The

* 'Roy. Soc. Proc.,' 1911, A, vol. 85, p. 285.

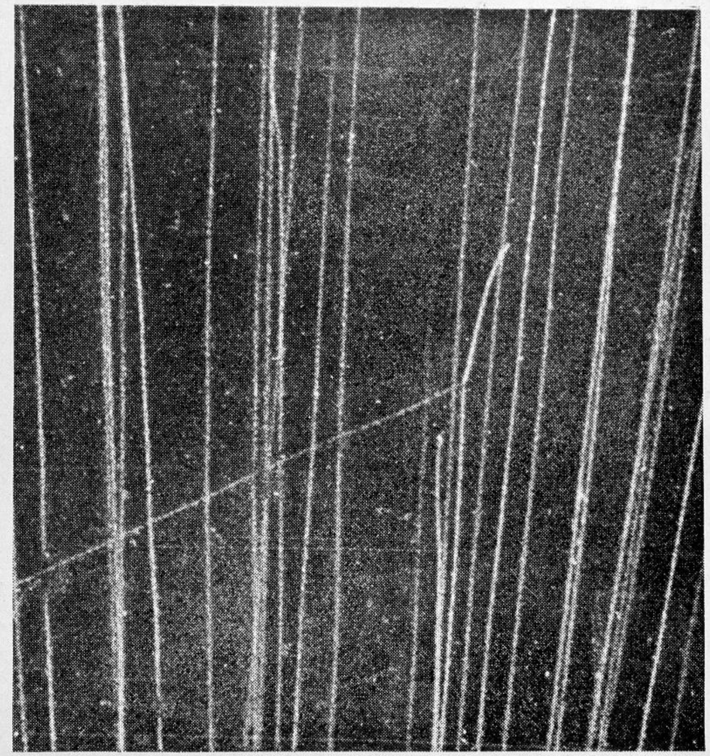


Cloud Chambers



Alpha particle strikes helium nucleus and they part at right angles (Blackett)

See p. 293



Alpha particle enters nitrogen which ejects proton and becomes oxygen (Blackett)

See p. 306

Experiments by Patrick Blackett (1925)

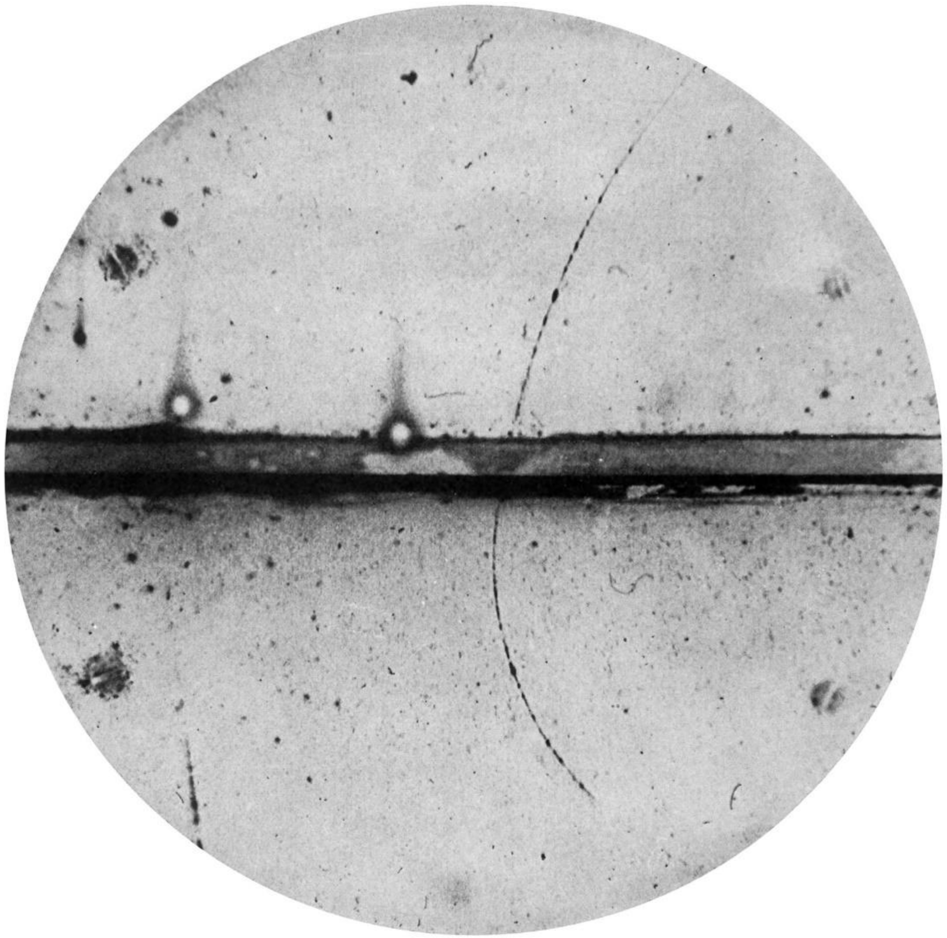
Cloud Chambers

- Momentum can be measured from curvature in a magnetic field:

$$p\ [\mathrm{MeV/c}] = 0.2998\ \frac{q\ [\mathrm{e}] B\ [\mathrm{kG}]}{R\ [\mathrm{cm}]}$$

- Charged particles lose energy as they move through material.

Cloud Chambers – Positron Discvoery



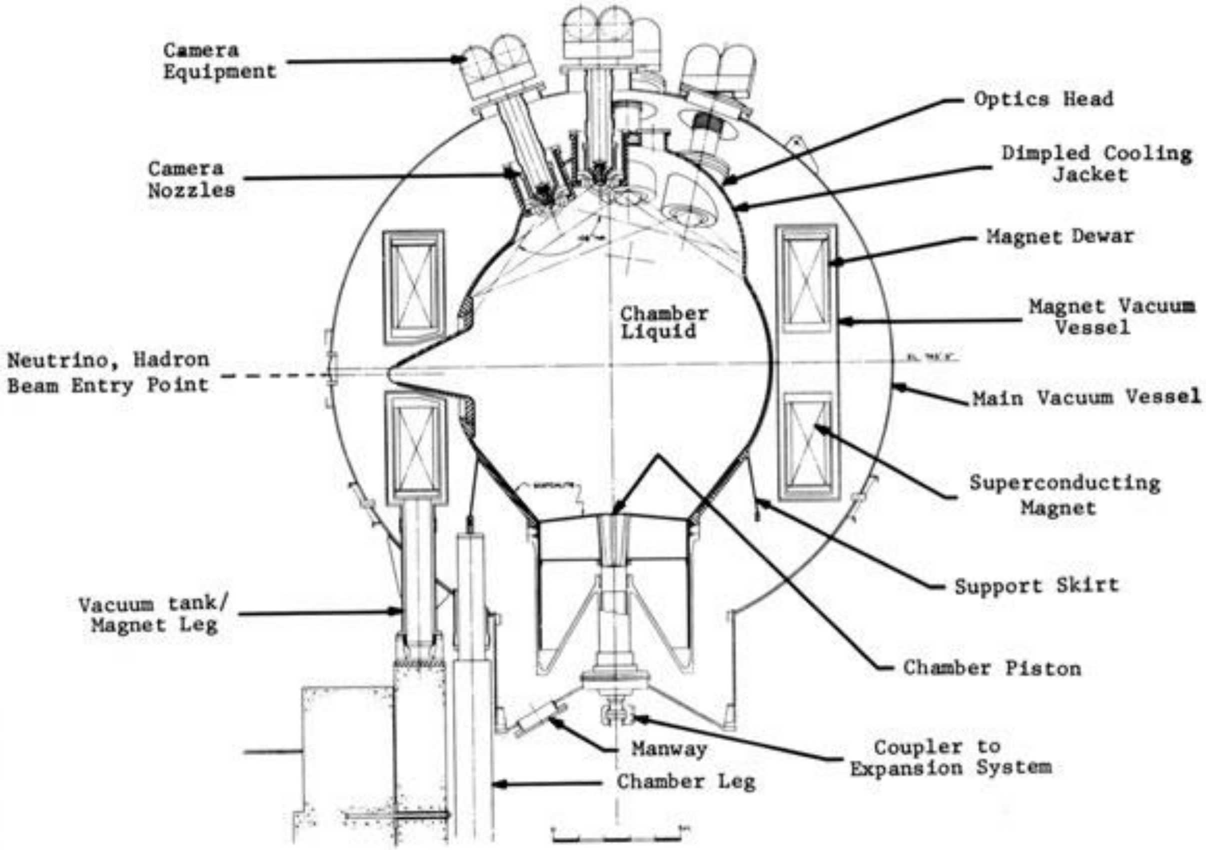
Anderson, 1933

- Particle enters from above
- From the direction of curvature in the magnetic field, its charge is determined to be positive
- Its momentum is determined from the magnitude of curvature
- Its velocity is determined from the density of the vapor trail
- The mass is consistent with that of an electron
- The particle loses energy after passing through a lead plate, confirming that it entered from above.
- This is consistent with being an electron with positive charge.

Bubble Chambers

- When the pressure is suddenly reduced in a liquefied gas, bubbles form around nucleation sites.
- The density of bubbles is correlated to dE/dx
- Particularly important for proton beam experiments
- The liquefied gas serves as both the target and the detector.
- Used throughout the 1960's-1980's.

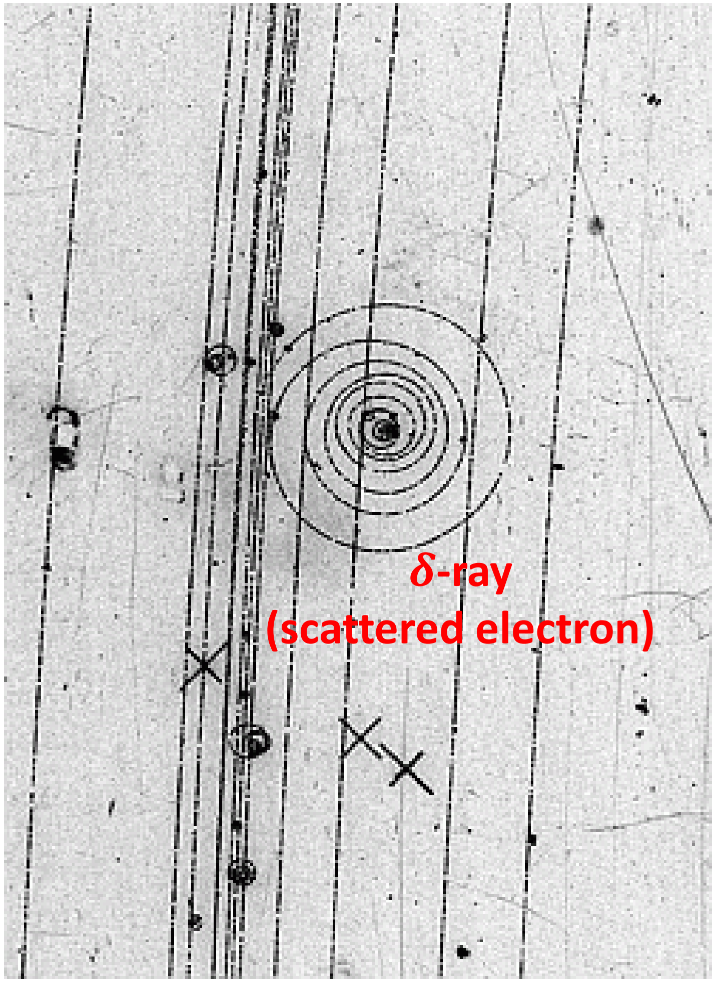
Bubble Chambers



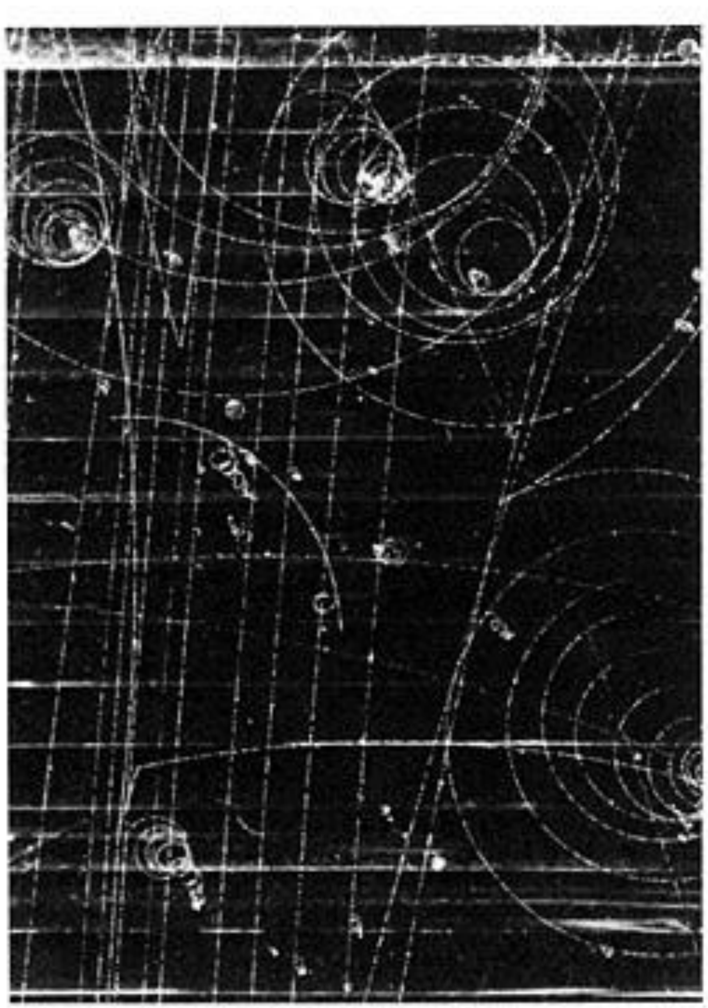
Bubble Chambers

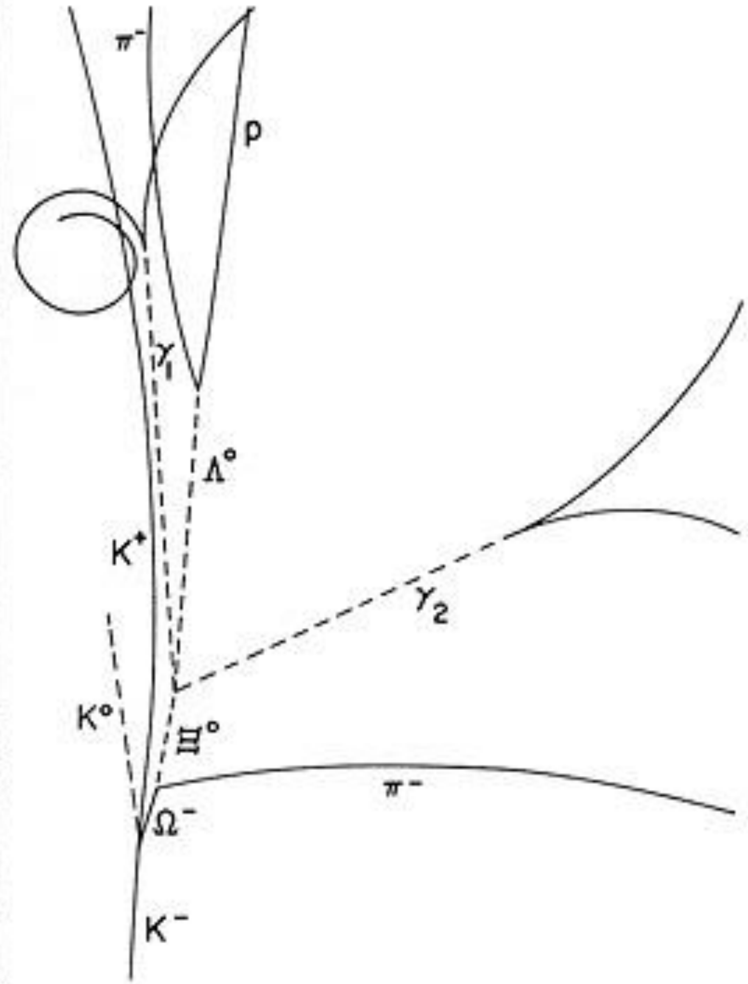
- The pressure can be reduced and pictures taken immediately after passage of a beam pulse through the chamber.
- Taking pictures from multiple angles allows stereoscopic reconstruction of 3-d images.
- The pressure is then increased to re-liquefy the bubbles of gas that form.
- Repetition rate is of order 1 second, but can be as high as a few cycles per second.
- Film is subsequently developed and scanned for interesting events.
- Momentum determined from curvature of tracks in a magnetic field.

Bubble Chambers



Bubble Chambers





Disadvantages of Bubble Chambers

- Slow: the fastest chambers cycled at 30 s^{-1}.
- Non-selective: pictures were taken of every event. Most events are not interesting.
- Size scales with beam energy to contain all decay products.
- Image quality affected by variation in index of refraction throughout the liquid.
- Not easily automated…

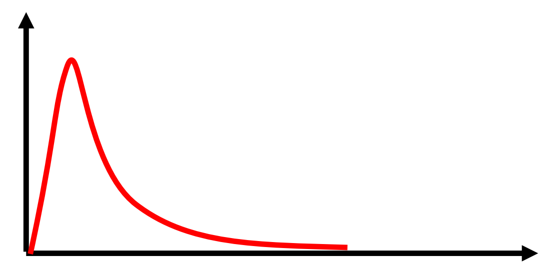
Scintillation Detectors

- Consider ionization in a transparent material.
  - Create vacancies in atomic electron orbitals
  - Liberates free electrons
- Electrons migrate through the material until they recombine with a vacancy
  - Light is emitted as the vacancy is filled
  - Light is often in the visible region
- Problem: medium will not be transparent at the wavelength of primary emission.
  - Photons emitted as vacancy is filled have the right energy to create a new vacancy
  - Very short optical attenuation length

Scintillation Detectors

- Transparent crystals can be doped with a low concentration of atoms that emit light.
- Alternatively, atoms must rapidly decay to a meta-stable state that cannot be excited directly from the ground state.
- Light yield is proportional to the deposited energy
- Time response:

$$y(t) = e^{-t/\tau_f}(1 - e^{-t/\tau_r})$$



- Generally classified as inorganic (crystals) or organic (plastic) scintillators
- Light mostly propagates by total internal reflection.

Inorganic Scintillators

	NaI(Tl)	CsI(Tl)	BaF_2	BGO	LSO:Ce	GSO:Ce	YAP:Ce	LuAP:Ce
Emission peak (nm)	410	565/420	310/220	480	420	440	360	365
Light yield (ph/keV)	38	65	11/1.5	8.2	25	9	18	12
Decay time								
Slow (ns)	230	680/3000	600	300		400		
Fast (ns)			0.8		40	60	27	17
Density (g/cm^3)	3.7	4.5	4.9	7.1	7.4	6.7	5.4	8.4
Chemical composition				$Bi_4Ge_3O_{12}$	Lu_2SiO_5	Gd_2SiO_5	$YAlO_3$	$LuAlO_3$
$1/\mu$ (cm) at 140 keV	0.41	0.28	0.29	0.086	0.11	0.16	0.7	0.1
$1/\mu$ (cm) at 511 keV	3.1	2.4	2.3	1.1	1.2	1.5	2.2	1.1
μ_{ph}/μ (%) at 511 keV	18	22	19	44	34	26	4.4	32

The total attenuation and absorption coefficients, μ and μ_{ph}, respectively, were calculated with XCOM (Berger et al., 1999) without including the coherent scattering. The detector materials are: NaI(Tl) and CsI(Tl)—thallium-doped sodium/caesium iodide, respectively; BGO—bismuth germinate; LSO:Ce and GSO:Ce—cerium-doped lutetium/gadolinium oxyorthosilicate, respectively; YAP:Ce and LuAP:Ce—yttrium/lutetium aluminium perovskite, respectively.

A MIP through NaI(Tl) would have $\left(\frac{dE}{dx}\right)_{min} = 1.305\ \mathrm{MeV \cdot g^{-1} \cdot cm^2}$

Light yield: $n_{ph} = (38{,}000\ \mathrm{ph \cdot MeV^{-1}}) \cdot (1.305\ \mathrm{MeV \cdot g^{-1} \cdot cm^2}) \cdot (3.7\ \mathrm{g \cdot cm^{-3}})$

$= 1.83 \times 10^5\ \mathrm{cm^{-1}}$

Inorganic Scintillators

Table A6.2 Properties of some inorganic scintillators

scintillator composition	density (g/cm^3)	index of refraction	wavelength of maximum emission (nm)	decay time constant (μs)	scintillation pulse height[1)]	notes
NaI	3.67	1.78	303	0.06	190	2)
NaI(Tl)	3.67	1.85	410	0.25	100	3)
CsI	4.51	1.80	310	0.01	6	3)
CsI(Tl)	4.51	1.80	565	1.0	45	3)
CaI(Na)	4.51	1.84	420	0.63	85	3)
KI(Tl)	3.13	1.71	410	0.24/2.5	24	3)
^{6}LiI(Eu)	4.06	1.96	470-485	1.4	35	3)
CaF_2(Eu)	3.19	1.44	435	0.9	50	
BaF_2	4.88	1.49	190/220 310	0.0006 0.63	5 15	
$Bi_4Ge_3O_{12}$	7.13	2.15	480	0.30	10	
$CaWO_4$	6.12	1.92	430	0.5/20	50	
$ZnWO_4$	7.87	2.2	480	5.0	26	
$CdWO_4$	7.90	2.3	540	5.0	40	
CsF	4.65	1.48	390	0.005	5	3)
CeF_3	6.16	1.68	300 340	0.005 0.020	5	
ZnS(Ag)	4.09	2.35	450	0.2	150	4)
GSO	6.71	1.9	440	0.060	20	
ZnO(Ga)	5.61	2.02	385	0.0004	40	4)
YSO	4.45	1.8	420	0.035	50	
YAP	5.50	1.9	370	0.030	40	

1) relative to NaI(Tl) 2) at 80 K 3) hygroscopic 4) polycrystalline

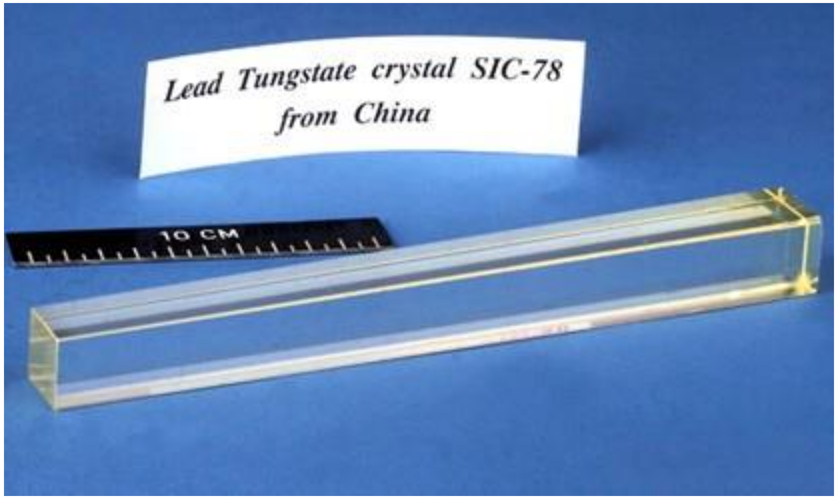
$PbWO_4$	8.28	1.82	440, 530	0.01			100

LAr	1.4	1.29 5)	120-170	0.005 / 0.860			
LKr	2.41	1.40 5)	120-170	0.002 / 0.085			
LXe	3.06	1.60 5)	120-170	0.003 / 0.022			4×10^4

5) at 170 nm

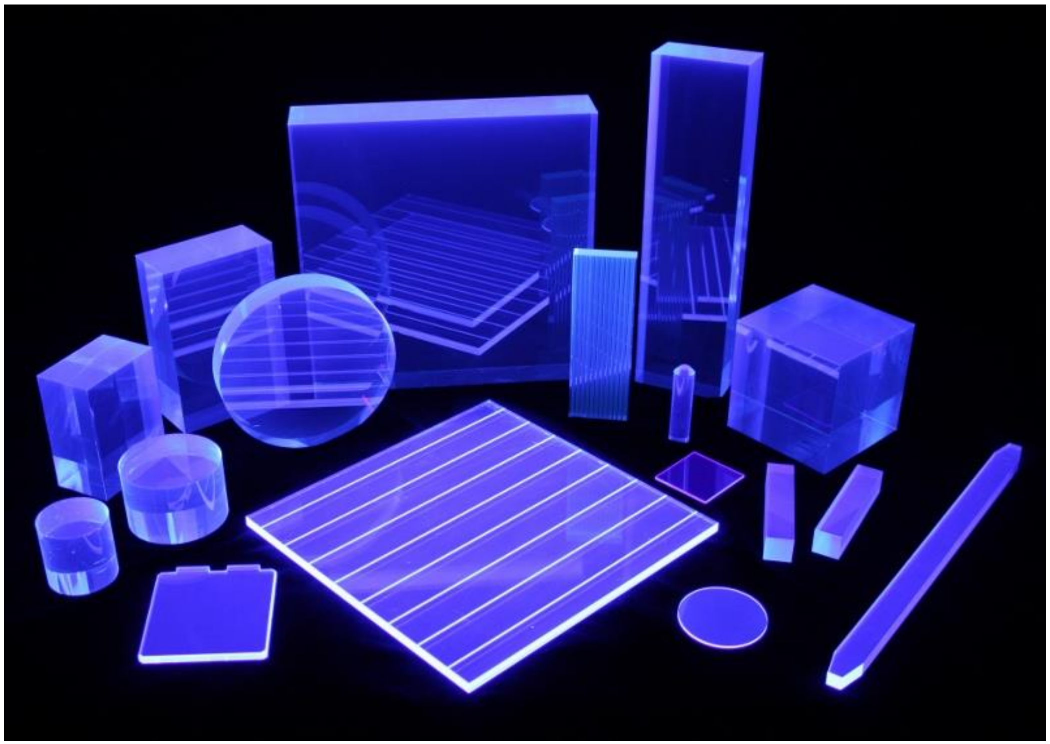
Inorganic Scintillators

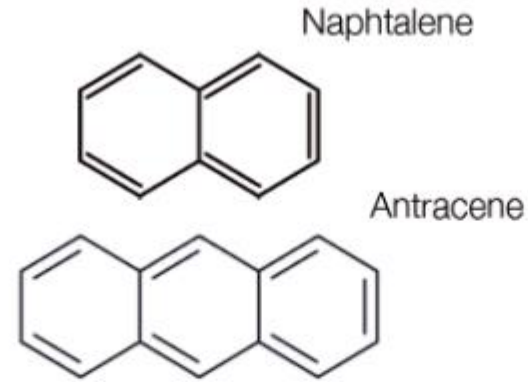
- Can have high light yields
  - Good energy resolution
- Some are quite fast
- Some are rad-hard



- Difficult and expensive to make them very large.
- Some are hygroscopic
- Limited geometries.

Plastic Scintillators





- Transparent plastic (eg, polyvinyltoluene – PVT) is easily cast, bent, cut and polished.
- Very fast time response
- Generally lower light yield compared with organic scintillators
- Generally not rad-hard

Plastic Scintillators

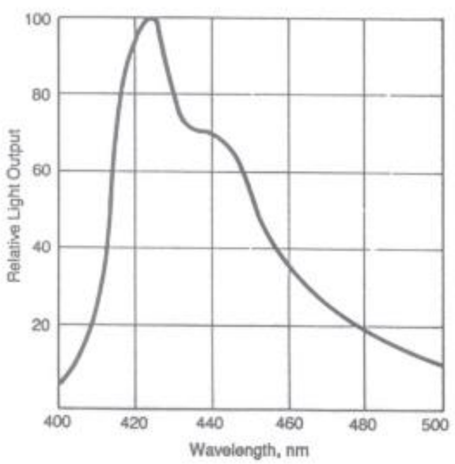
- Elgin Technologies:

  https://eljentechnology.com/products/plastic-scintillators
- Saint-Gobain:

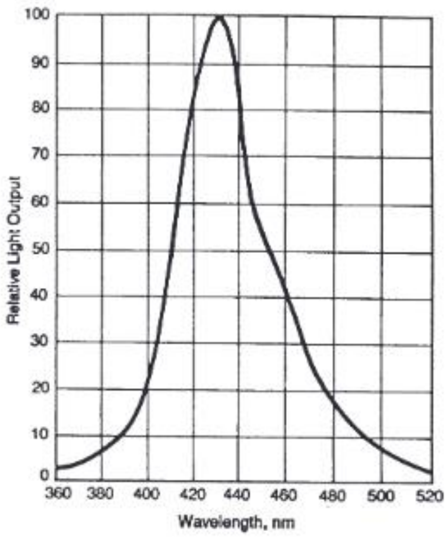
  https://www.crystals.saint-gobain.com/products/plastic-scintillators
- Light output is often measured as the percentage of Anthracene, which is 40-50% the light output of NaI(Tl)

Emission Spectra

BC-400



BC-408



Plastic Scintillators

Scintillator	Light Output % Anthracene[1]	Wavelength of Maximum Emission, nm	Decay Constant, ns	Bulk Light Attenuation Length, cm	Refractive Index	H:C Ratio	Loading Element % by weight	Density	Softening Point °C
BC-400	65	423	2.4	250	1.58	1.103		1.023	70
BC-404	68	408	1.8	160	1.58	1.107		1.023	70
BC-408	64	425	2.1	380	1.58	1.104		1.023	70
BC-412	60	434	3.3	400	1.58	1.104		1.023	70
BC-416	38	434	4.0	400	1.58	1.110		1.023	70
BC-418	67	391	1.4	100	1.58	1.100		1.023	70
BC-420	64	391	1.5	110	1.58	1.102		1.023	70
BC-422	55	370	1.6	8	1.58	1.102		1.023	70
BC-422Q	11	370	0.7	< 8	1.58	1.102	Benzephenone,0.5%*	1.023	70
BC-428	36	480	12.5	150	1.58	1.103		1.023	70
BC-430	45	580	16.8	NA	1.58	1.108		1.023	70
BC-440	60	434	3.3	400	1.58	1.104		1.032	99
BC-440M	60	434	3.3	380	1.58	1.104		1.039	100
BC-444	41	428	285	180	1.58	1.109		1.023	70
BC-452	48	424	2.1	150	1.58	1.134	Lead, 2%	1.050	60
BC-480	**	425	-	400	1.58	1.100		1.023	70
BC-482A	QE=.86	494	12.0	300	1.58	1.110		1.023	70
BC-490	55	425	2.3	NA	1.58	1.107		1.023	70
BC-498	65	423	2.4	NA	1.58	1.103		1.023	70

Plastic Scintillator

- Example: a MIP travels through 4 cm of BC-408. How many photons are produced?

$$\left(\frac{dE}{dx}\right)_{min}^{PVT} = 1.956\ \mathrm{MeV \cdot g^{-1} \cdot cm^{2}}$$

$$\rho = 1.023\ \mathrm{g \cdot cm^{-3}}$$

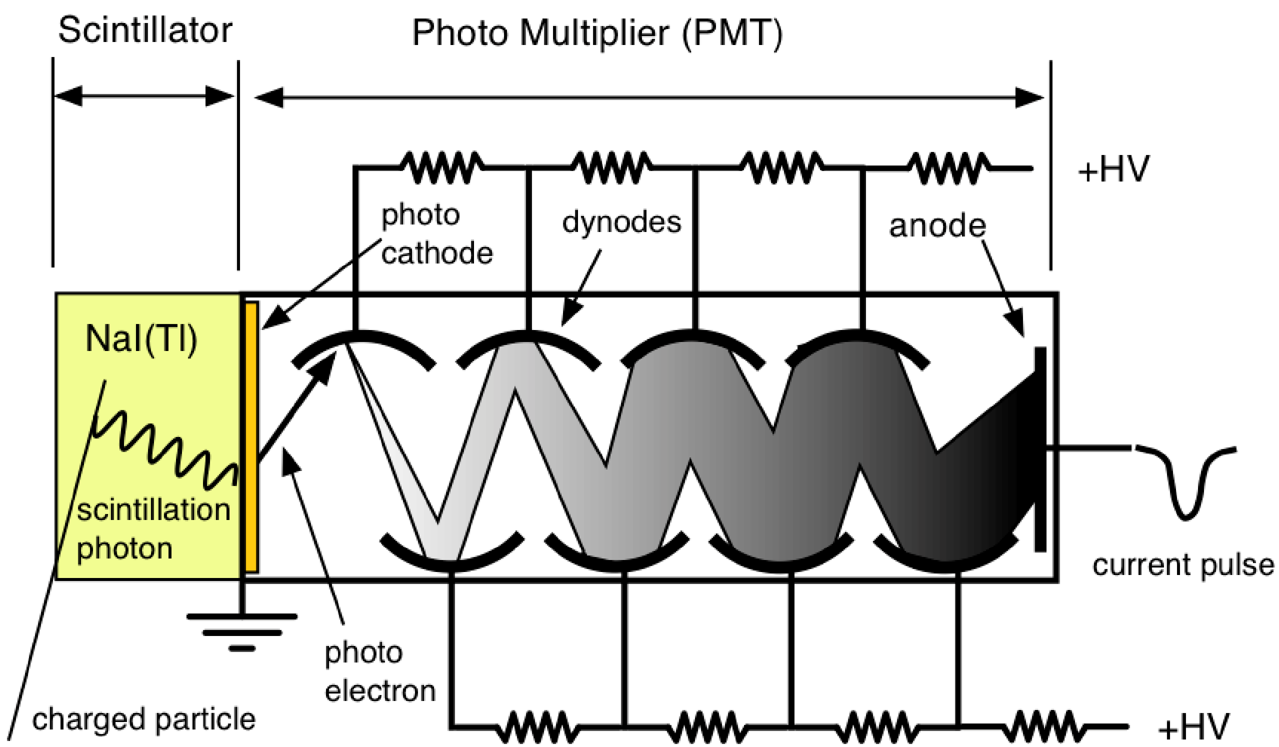
$$n_{ph} = (4\ cm) \cdot (1.956\ \mathrm{MeV \cdot g^{-1} \cdot cm^{2}}) \cdot (1.023\ \mathrm{g \cdot cm^{-3}}) \cdot (0.64 \times 0.5) \cdot (38{,}000\ \mathrm{ph \cdot MeV^{-1}})$$

$$n_{ph} = 97{,}000$$

- Energy loss is 8 MeV.

Photomultiplier Tubes

- The light from inorganic or plastic scintillator is almost always coupled to a light-sensitive detector.
- Typically, a photomultiplier tube serves this purpose:

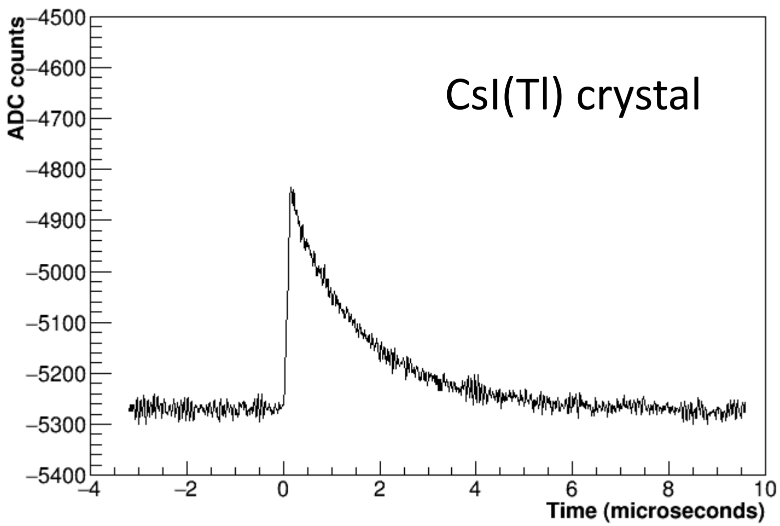


Hamamatsu Photonics

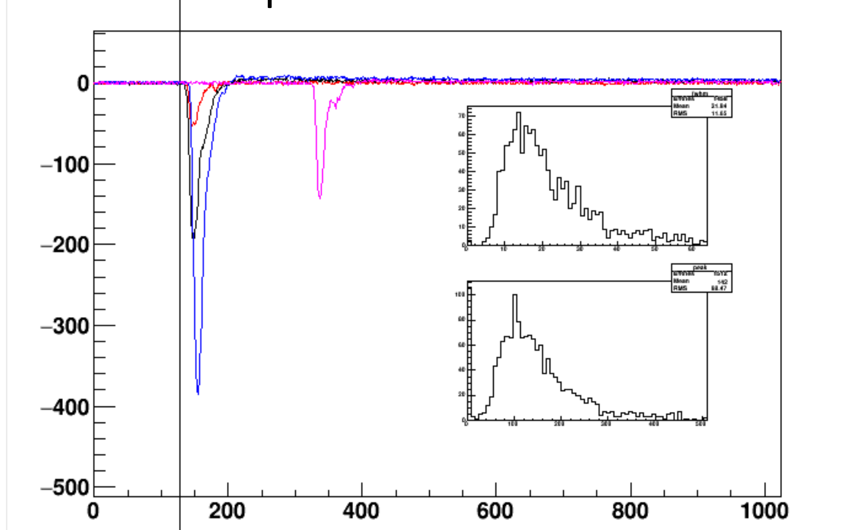
- https://www.hamamatsu.com/

Photomultiplier Tubes

- PMT's can drive signals long distances on 50 ohm coaxial cable with minimal signal degradation
- Signals are large enough to be processed without the need for preamplifiers



Stack of plastic scintillator sheets



Time (nanoseconds)

- Fast scintillator makes it possible to detect coincidences in multiple channels

Photomultiplier Tubes

- The glass envelope must be transparent to the scintillation light
  - Borosilicate glass (transmits blue light)
  - Quartz glass (also transmits UV light)
- The photocathode must have high quantum efficiency but must be thin enough to allow electrons to emerge from the far side.
  - Frequently a bi-alkali metal like cesium-potassium
- Dynodes are coated with secondary electron emissive materials, such as Be-Cu-O
- The number of stages influences the gain, but also the timing response.
- Good reference:

Photomultiplier Tubes

- Spectral response can be optimized to cover the emission spectrum of scintillator

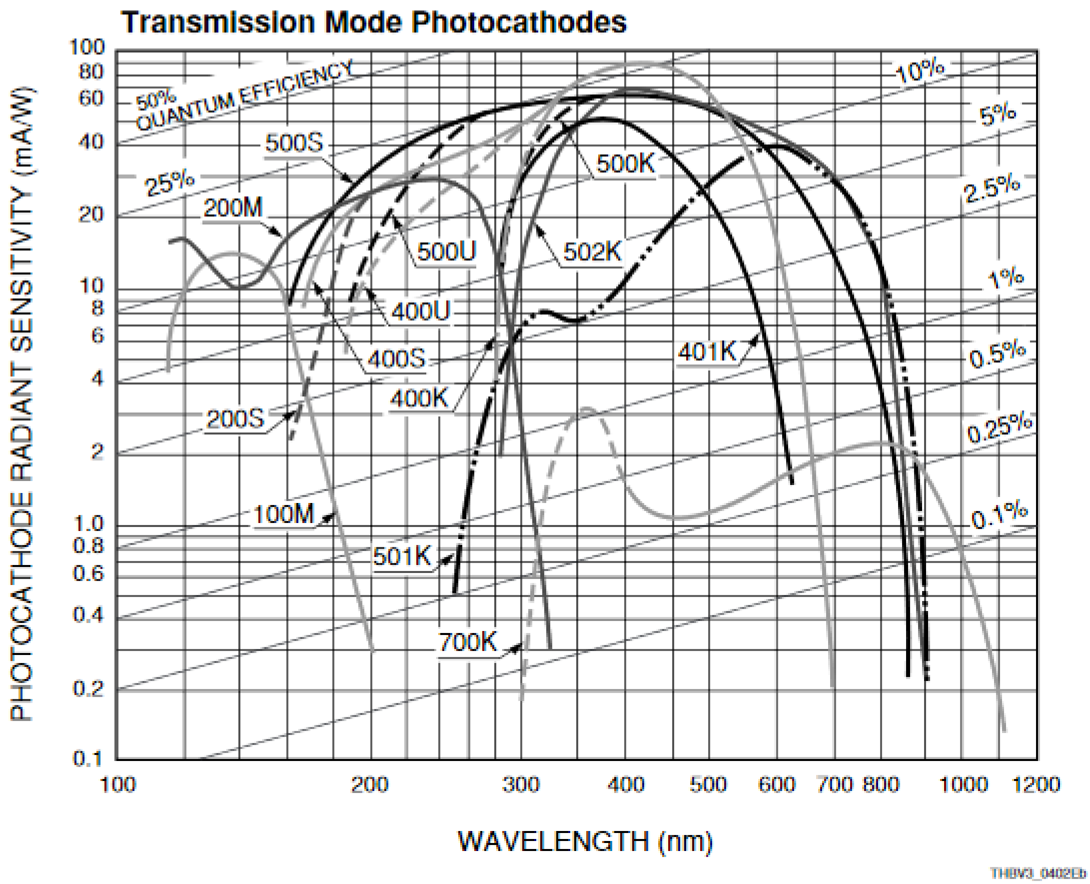
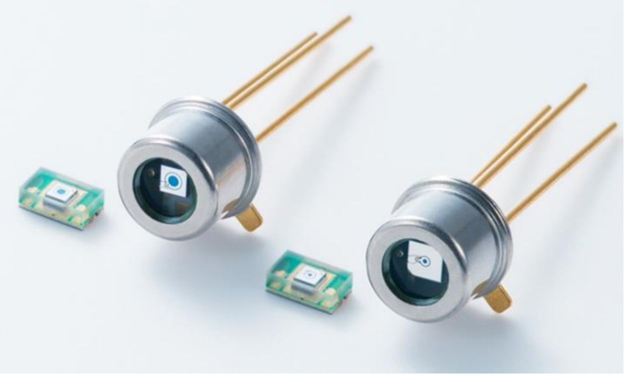


Figure 4-2 (b): Typical spectral response characteristics of transmission mode photocathodes

Photo-detectors

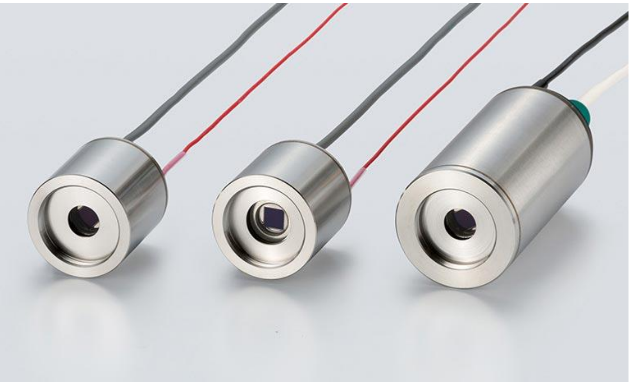
- Photomultiplier tubes have many advantages:
  - Fast
  - High gain
  - Low noise
  - Large active area
  - Relatively robust
  - Anode can be pixelated
- Some disadvantages:
  - Generally can’t operate in magnetic fields
  - Can become contaminated (especially by He)
  - Large
  - Expensive

Alternatives to PMT's



Avalanche photodiodes

Silicon photomultipliers

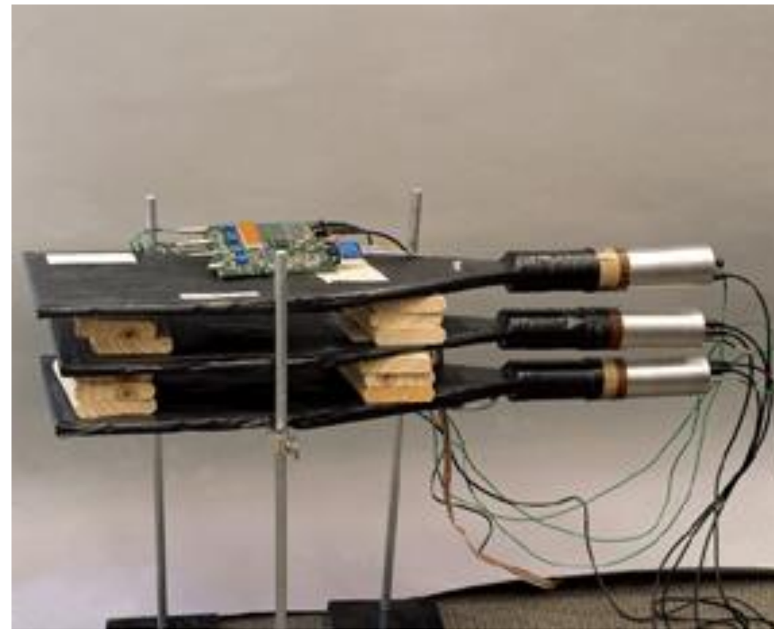


Hybrid photomultipliers

The active area of these sensors is usually much smaller than the dimensions of (large) scintillators

Interfacing with Light Sensors

- Optical interfaces can be joined using optical grease or epoxy
- Light should propagate mostly be internal reflection
- White paper/aluminum foil wrapping mainly prevents the wrapping material from whetting the surfaces
- Black plastic/electrical tape blocks all exterior light.



Interfacing with Light Sensors

- Frequently, the geometry of scintillator does not quite match the geometry of a photomultiplier tube…
- Light guides are an example of non-imaging optics

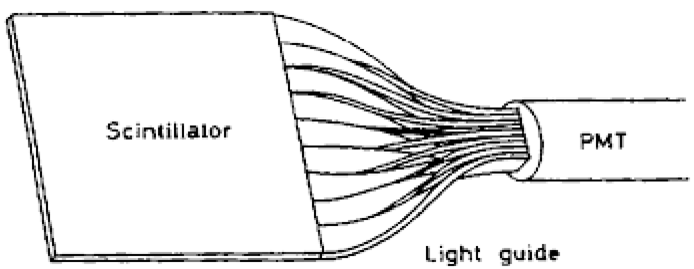
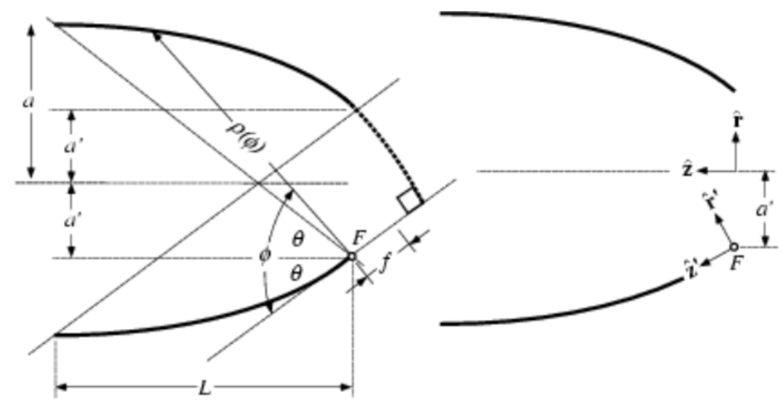


Figure B.1: Schematic diagram of a Winston cone light concentrator. The entrance and exit apertures are of radius a and a', respectively. F is the focus of the upper parabola segments, and f is its focal length. The length of the cone is L. The diagram on the right shows the origins and orientations of the focus-centered and symmetry axis-centered coordinate systems discussed in the main text.



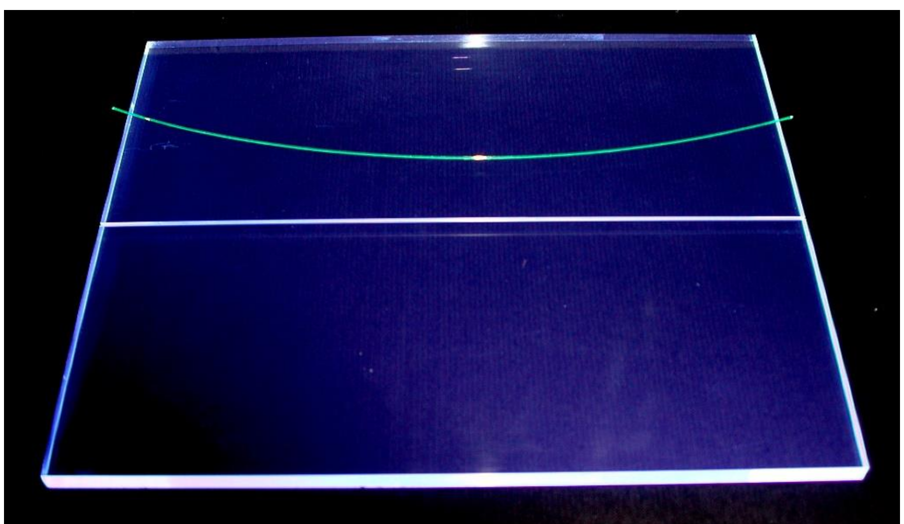
Limits of optical concentration are subject to Liouville's theorem.

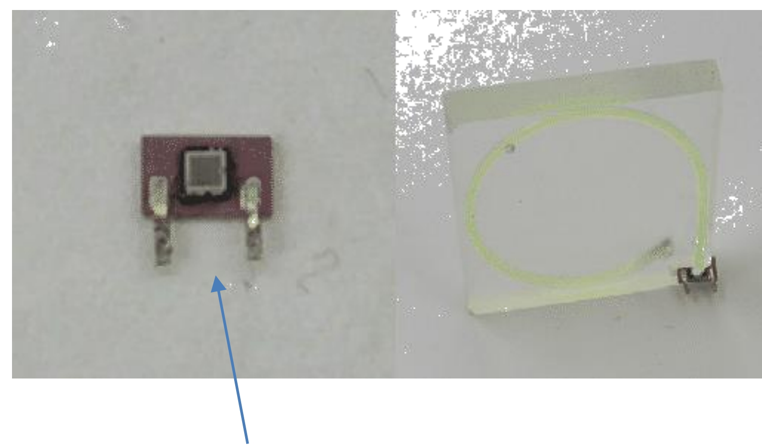
Liouville's Theorem

- Light rays can be moved closer to the optical axis at the expense of increasing their angle with respect to the optical axis.
- Large angle light will be reflected backwards by the concentrating optics.
- This is a problem when interfacing large area scintillators with small area photosensors.

Wavelength Shifting Fiber

- Wavelength shifters provide a way to “defeat” Liouville’s theorem.
- Wavelength shifting fibers may be embedded in plastic scintillator.
- Blue light is absorbed and green light is emitted isotropically – a significant fraction is captured by total internal reflection within the fiber.





Silicon Photomultiplier