Transducers and sensors

- All instruments based on measuring signals

  therefore need to understand

  the types of signals
  properties and characteristics of transducers
  applications which are appropriate
  impact on the instrument systems

- Transducer

  devices which produce an electrical signal proportional to a variable of interest

  why? *automation for speed, convenience (eg alarm) or objectivity*
  ease further manipulation of measurements
  extend range of processing beyond simple calculations

  digital processing now very cheap

- Big area - so which transducers should interest us most? Try to find:

  examples of components used for control or monitoring purposes

  sensors which exhibit properties of ***general interest***,
  even if employed for special purposes (like physics research...)

Major transducer types

- Control or measurement

  temperature, pressure, humidity, B-field, sound, strain, acceleration,...

  growing area of bio-chemical sensors

    beyond scope of these lectures but many common principles

    electrical output often desirable for reasons already cited

- ionisation sensors

  general purpose light detection (especially optical communication),

    radiation detection (α, β, γ, x-ray, charged particle,...)

  many examples of sensors developed for physics which now form components for general use

  and vice-versa

    specialised state of art instruments often exploit new technologies

Equivalent circuits

- To use any device, we need an effective model of it

  should characterise important properties

- Most common & simple picture

  Voltage source

  Current source

  } with associated impedance

  this defines how to connect it to a useful circuit

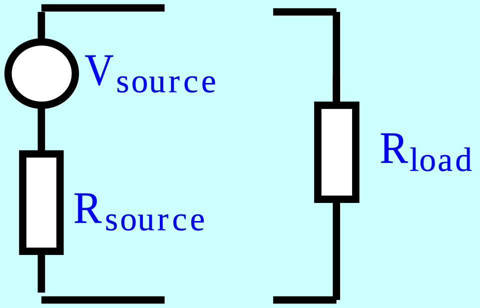
Voltage source

$i = V_{source}/(R_{source}+R_{load})$

$V_{load} = iR_{load} = V_{source}R_{load}/(R_{source}+R_{load})$

if $R_{source} >> R_{load}$ $\quad V_{load} << V_{source}$

if $R_{source} << R_{load}$ $\quad V_{load} \approx V_{source}$



we can only sometimes choose R_{source}

usually defined by transducer - may influence transducer selection
but often transducer chosen first

we do not always have complete freedom over R_{load}

eg if long cables are required

- To measure voltages, will often require a high load impedance

or low source impedance, if intervening circuit

- Matching

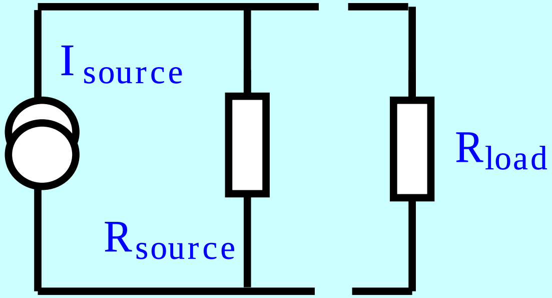
if $R_{load} = R_{source}$ obtain maximum power transfer from source to load

then $V_{load} = V_{source}/2$

Current source

$V_{load} = I_{source}(R_{source} \,||\, R_{load}) = I_{source}R_{source}\, R_{load}\,/(R_{source}+R_{load})$

$I_{load} = I_{source}R_{source}\,/(R_{source}+R_{load})$



$if\ R_{load} << R_{source} \quad I_{load} \approx I_{source}$

same comments as previous about ability to choose R_{source} and R_{load}

- To measure currents, will usually require a low load impedance

  or high (parallel) source impedance, if intervening circuit

- Matching

  $R_{load} = R_{source}$ to obtain maximum power transfer from source to load

  but this is not always done for practical reasons - discuss later

- Should note that neither source nor load impedance is always simple resistance

Temperature measurement

- Traditional - mercury thermometer
  - need long, accurately dimensioned tube
  - calibrated scale
    - *eg ice, steam*
- What limits precision? (problem sheet)
  - accuracy of tube bore
  - practical length of accurate tube
  - operating temperature (melting point of glass?)
  - change in metal dimensions & ability to observe them
  - change in dimensions of tube with temperature
- Although well developed technology, not very practical for many applications
  - especially those requiring automation & control
    - *cheap, accurate digital thermometers now seem to be widely used in hospitals & for home use - not all electronic*
- Similar discussion for bi-metallic thermostat
  - several electronic alternatives are available

Temperature sensor - characteristics required

- Specifications include

  Accuracy

  probably will depend on T, precision will depend on application, but should be known

  Linearity

  output (voltage or whatever..) should be α *T (K,°C,* $T\text{-}T_0$*,..)*

  Interchangeability

  would like to be able to replace the sensor and get similar results

  Signal size

  ease of measurement

  Remote sensing

  typically sensor can't be right at source, especially if hot or cold

  Temperature range

  specs are unlikely to be met from 0K to ∞

  Cost

- even if we think of a medical thermometer, these requirements do not change much

Thermocouple

- junction between two different metals can produce a small voltage

value typically very small (10-100µV/°C)

depends approximately on difference between two junction temperatures

- one should be reference

well known properties -

so can choose type appropriate to requirement and interchangeable

very convenient for quick, simple measurements

eg control applications

Caveats

relative measurements excellent but absolute measurements need care

define reference point (& maintain constant!)

physics of thermocouple

hot wire end produces a temperature gradient

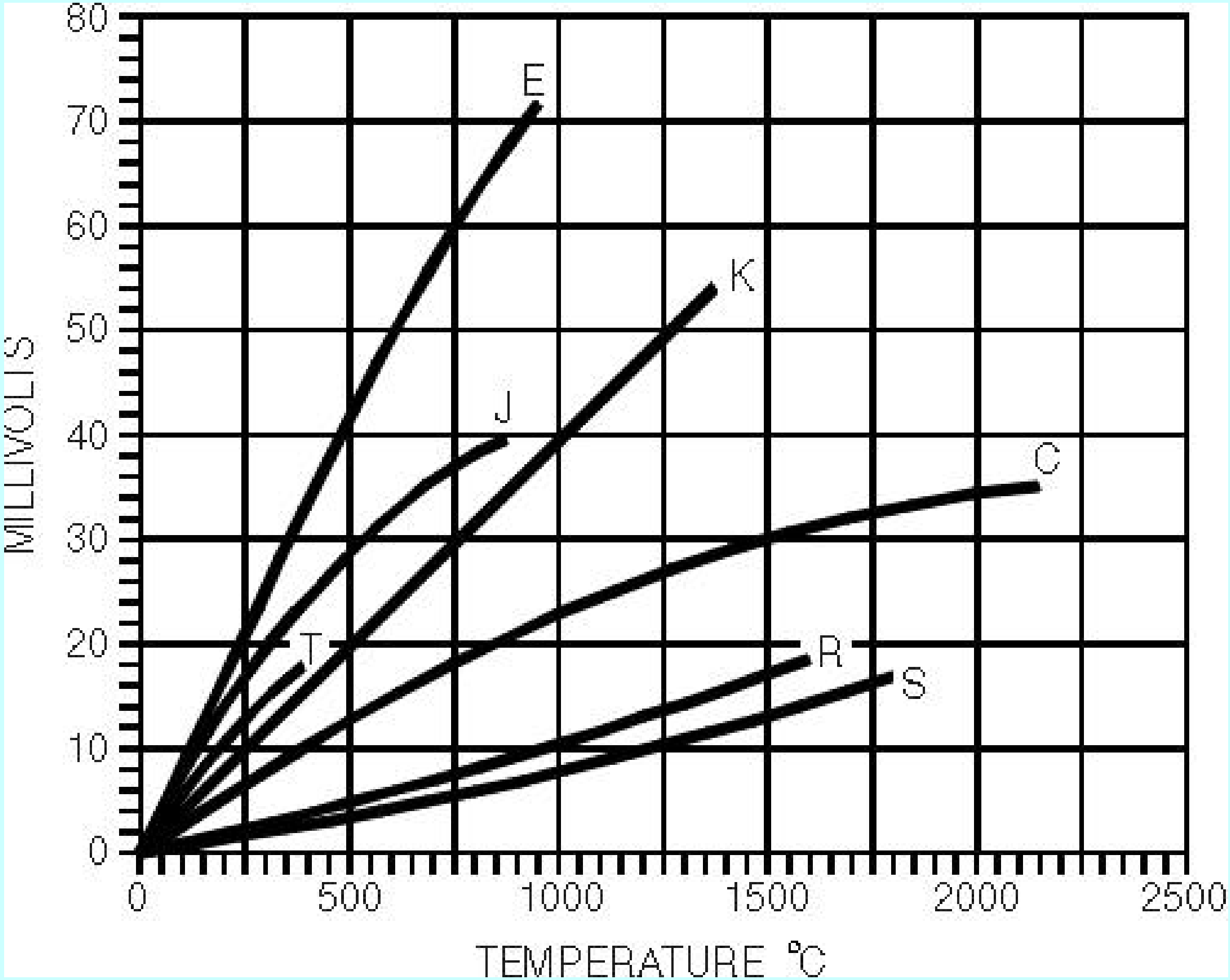
so a carrier density gradient

equilibrium is established when an electric field in the wire balances the carrier diffusion

not practical to put voltmeter across ends of wire - could be hot!

Types of thermocouple (ii)

- www.isi-seal.com/Technical_Info/ Tech_Thermocouple.htm



Types of thermocouple

Type	Metal-1	Metal-2	Tmax	Sensitivity	Vout (mV)	Vout (mV)	Vout (mV)	Rlead
			degC	µV/degC	mV	mV	mV	Ω/m
				at 20degC	reference junction at 0degC			typical
					(100 degC)	(400 degC)	(1000 degC)	
J	Iron	Constantan	760	51.5	5.27	21.85		12
K	Chromel	Alumel	1370	40.3	4.10	16.40	41.27	20
T	Copper	Constantan	400	40.3	4.28	20.87		10
E	Chromel	Constantan	1000	60.5	6.32	28.94	76.36	24
S	Platinum	90%Pt-10%Rh	1750	5.9	0.65	3.26	9.59	6
R	Platinum	87%Pt-13%Rh	1750	5.8	0.65	3.41	10.50	6
B	94%Pt-6%Rh	70%Pt-30%Rh	1800	0.0	0.03	0.79	4.83	6
C	95%W-6%Rh	74%W-26%Rh	2320	25.7	2.5	10.0	25.7	
	Constantan	**55%Cu-45%Ni**						
	Chromel	**90%Ni-10%Cr**						

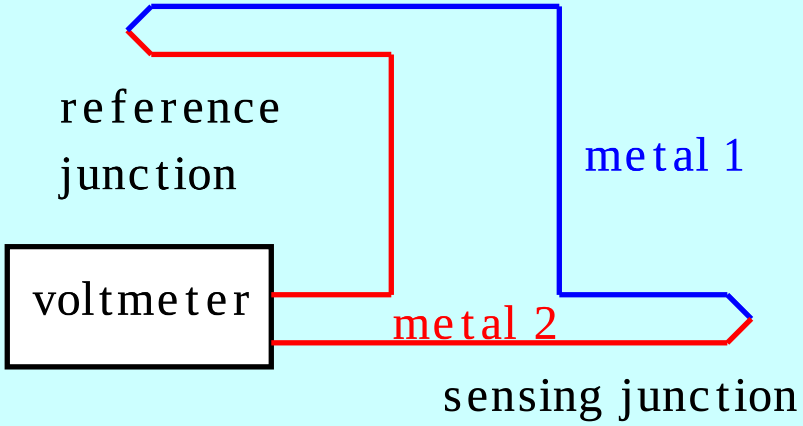
- Junctions are welded by manufacturer

Often equipped to plug into digital volt meter

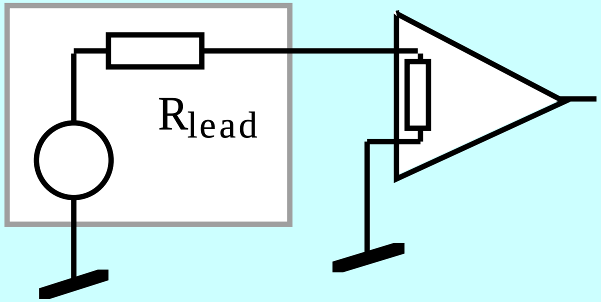
reference to room temperature with internal circuitry

"home-made" systems need care in adding wires -can add another junction

Thermocouple readout



- place reference junction at defined temperature
  - not practical for most situations
- use compensation circuit to correct for ambient conditions
  - principle of most temperature meters
  - = another temperature measuring device needed!
    - *however, not practical to place integrated circuit at hot node!*
- practical issues
  - low output voltage to be measured eg 20K x 50µV/K = 1mV
    - *measuring amplifier needs careful design to avoid noise*
  - amplifier input resistance should be reasonably high
    - *lead resistance not negligible if long*



Thermistor

- Semiconductor device with well defined R-T characteristic

coefficient of R vs T ~ -4%/°C ie. $\Delta R/R = \alpha\Delta T$

$R_{typical} \sim k\Omega$

precise conformity to standard from manufacturers

range ~ -50°C to +300°C

easy to use, with large change in value with temperature

Practical issues

provide current source to operate

accuracy depends on application

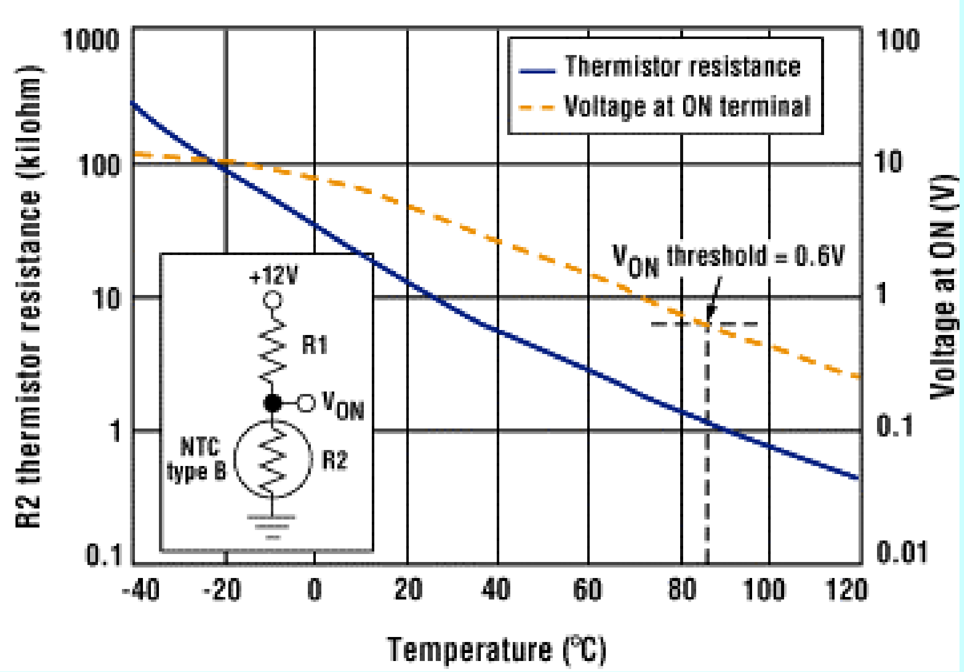
non-linear R-T behaviour

accurate applications => careful circuit choice (eg balancing bridge)

circuit self-heating can influence

small ΔT - thermal noise could be concern

need calibration



Temperature ICs

- Band-gap circuits

  Based on semiconductor junction diode I ~ exp(qV/kT)

- eg AD590 - discuss more later

  Manufacturer's specs (read them!!)

  Two terminal sensor (V_{supply}: +4V to +30V)

  Linear output current 1μA/K , ±0.3°C over range

  T range -55°C to +150°C

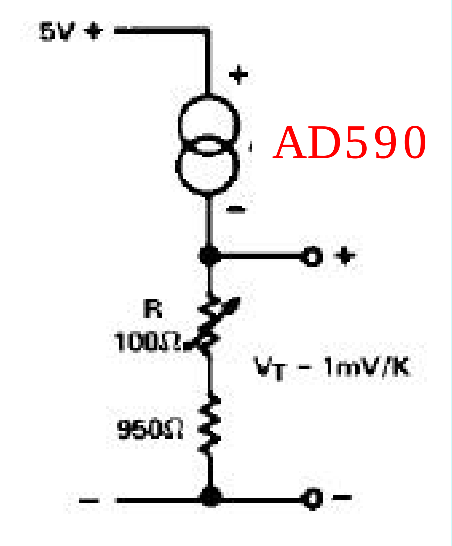
  Calibrated, with accuracy ±0.5°C

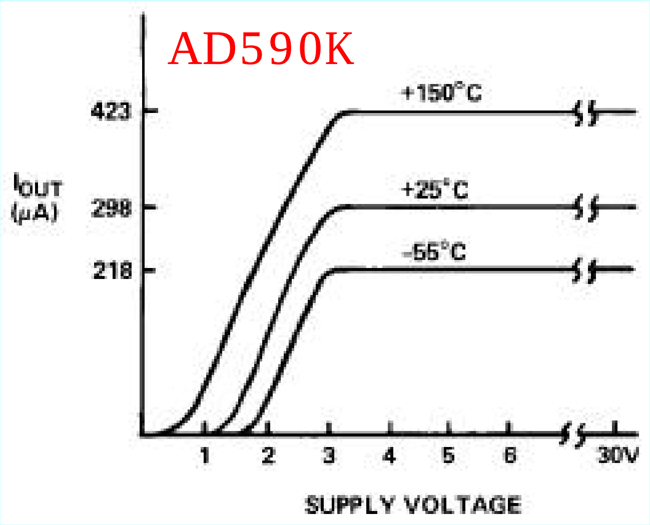
  Can be used remotely (x100 feet!), with long wires

  Low cost (≈£10 for <25)

  NB several versions

	Absolute error	Non-linearity
J	±5.0	±1.5
K	±2.5	±0.8
L	±1.0	±0.4
M	±0.5	±0.3





- Custom ICs -

  can design reference circuits,

  eg to save space or remote locations

Platinum resistance

- Platinum resistance

  Very stable and reproducible, wide T range (~ -200°C to 1000°C)

  T coefficient ~ +0.4%/°C

  Bulky and expensive for some applications (~ £2-3)

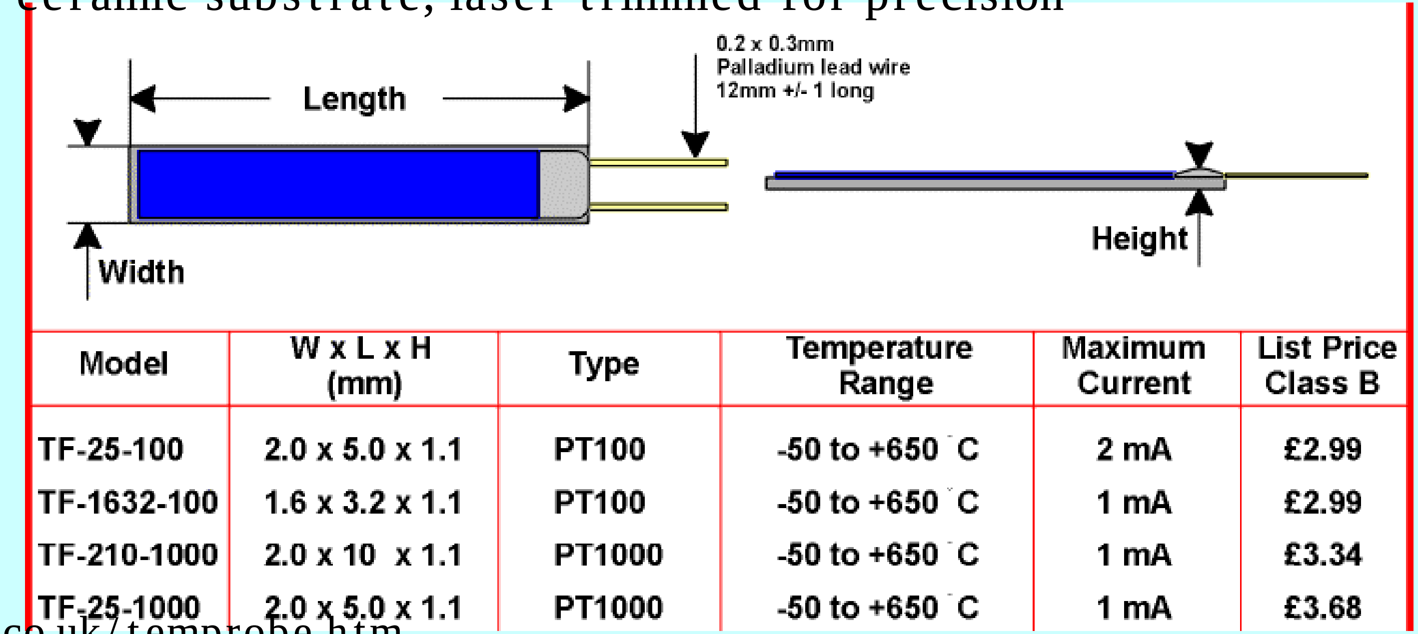
  need wires (R) or local I/V circuit

- Standard value R = 100Ω (PT100)

  eg Pt film deposited on ceramic substrate, laser trimmed for precision

  also

  wirewound versions



Model	W x L x H (mm)	Type	Temperature Range	Maximum Current	List Price Class B
TF-25-100	2.0 x 5.0 x 1.1	PT100	-50 to +650 °C	2 mA	£2.99
TF-1632-100	1.6 x 3.2 x 1.1	PT100	-50 to +650 °C	1 mA	£2.99
TF-210-1000	2.0 x 10 x 1.1	PT1000	-50 to +650 °C	1 mA	£3.34
TF-25-1000	2.0 x 5.0 x 1.1	PT1000	-50 to +650 °C	1 mA	£3.68

eg http://www.kalestead.co.uk/temprobe.htm

Other temperature transducers

- Exotics — each a specialised subject

Non-contact measurements	infra-red sensors based on, eg, CCDs
Ultra-low temperature	~ 0K

Ionisation sensors

- Indirect

  produce a signal which must be further converted to an electrical signal

  mostly light: scintillators, Cerenkov radiation, transition radiation (x-ray)

  acoustic

- Direct

  produce a directly measurable electrical signal

  may still require amplification

  gaseous and semiconductor devices dominate

Scintillators

- Light emitted following ionisation in a transparent material

Typical $I(t) \sim I_0 e^{-t/\tau}$ sometimes several components $I_1, I_2, \ldots \tau_1, \tau_2, \ldots$

Wavelength of emission determines requirement on photosensor type

along with signal speed requirement

eg. $\tau > \mu s$ => count rates << MHz

$\tau \sim ns$ => count rates >> MHz

- Two main material types - contrasting mechanisms

Inorganic scintillators

result of crystalline structure of material

large band gap => insulators

Organic scintillators

molecular property (independent of state - liquid or solid)

Inorganic scintillators

- ionisation excites electrons from valence to conduction band

  de-excitation via photon emission

  or radiationless transition

- Large band gap => slow process

  low transition probability

  short wavelength ($E_\gamma = E_{bandgap}$)

- Impurities add centres (traps) in band-gap

  increase transition rates

  suitable doping can also increase light output

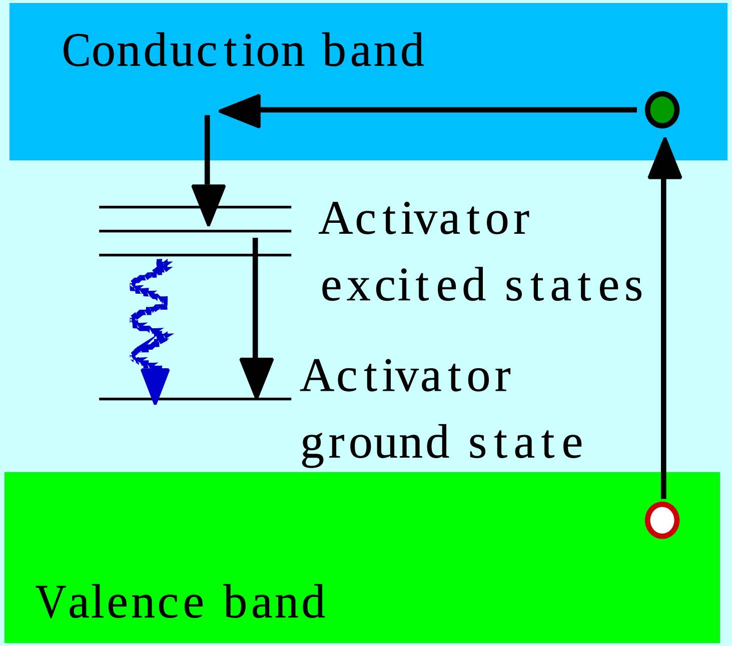
  eg thallium in NaI

  holes trapped at activator sites

  recombination with e^- *=> photon*

  smaller energy gap increases wavelength

  crystal also transparent to scintillation photons



Inorganic scintillator characteristics

- high light output but relatively slow (~µsec), good linearity

  dense, high atomic number (Z) material

  good for for e-/gamma ray detection

  expensive - very good crystals required, usually large.

  raw material, growing, cutting and polishing of large crystals

  many require specialised photosensor

  blue or UV emission

  some undoped materials offer advantages of speed and radiation hardness

  drawback of lower light yield

  care is needed in material preparation

  performance can be badly affected by (wrong!) impurities

  some crystals can be coated on photosensors

  convenient for efficient sensor systems but limits thickness

- applications

  medical imaging (eg. gamma camera, ~MeV photons from radio-isotopes)

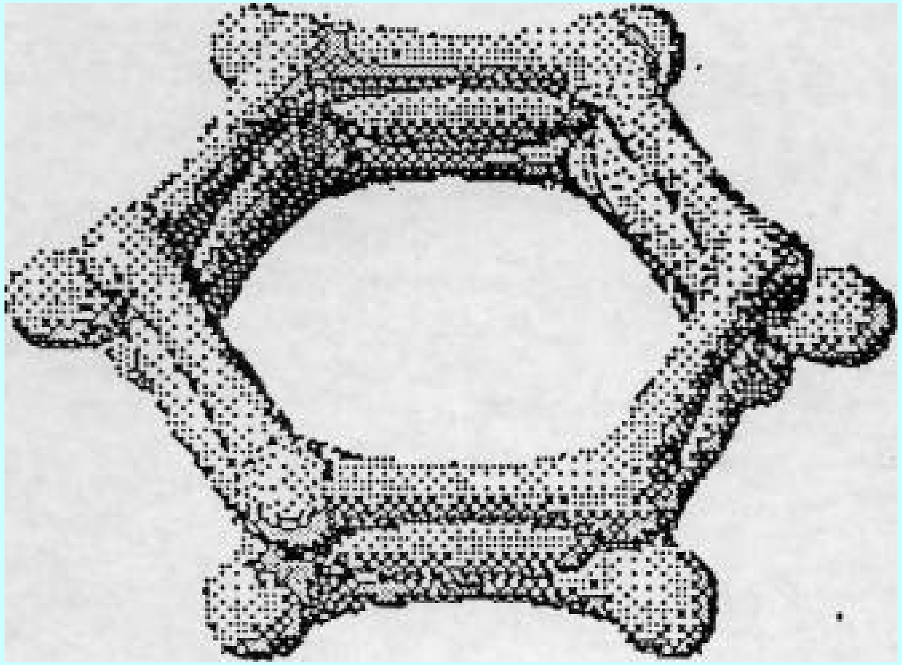
  astronomy and particle physics detectors

Examples of inorganic scintillators

		λ_{peak} (nm)	relative light output	time constant (µsec)	Density g.cm^{-3}	
Sodium iodide	NaI(Tl)	410	1	0.23	3.7	High light output, hygroscopic, large crystals fragile
Caesium iodide	CsI(Tl)	540	1.71	0.68 (64%) 3.34 (36%)	4.5	Non hygroscopic. wavelength match Si photodiodes
Bismuth germanate	BGO $Bi_4Ge_3O_{12}$	480	0.22	0.3	7.1	High Z, low light output
Barium fluoride	BaF_2 (fast) BaF_2 (slow)	220 310	0.05 0.16	0.0006 0.62	4.9	Fast, two components, in UV low light output, rad hard
Cerium fluoride	CeF_3	310 340	0.005 0.027	0.12	6.16	low light output, radiation hard
GSO	Gd_2SiO_5 (Ce doped)	440	0.24	0.056 (90%) 0.4 (10%)	6.71	Fast, rad tolerant
YAP	$YAlO_3$ (Ce doped)	440	0.47	0.027	5.37	Fast, good mechanical properties

Organic scintillators - hydrocarbon molecules

- Based on excited states of carbon atom, typically electron orbitals of benzene ring (C=C bonds)



imagine π orbitals as figures of eight binding two benzene rings

but free to move around ring

quasi-free electrons confined to molecular perimeter (length l)

1-d Schrodinger equation => $\psi(x) = \psi(x+l)$

$E_n = n^2h^2/2me^2l^2$ spectrum of energy levels

In practice more complex, vibrational states give fine structure

range of singlet & triplet states gives both long and short time constants

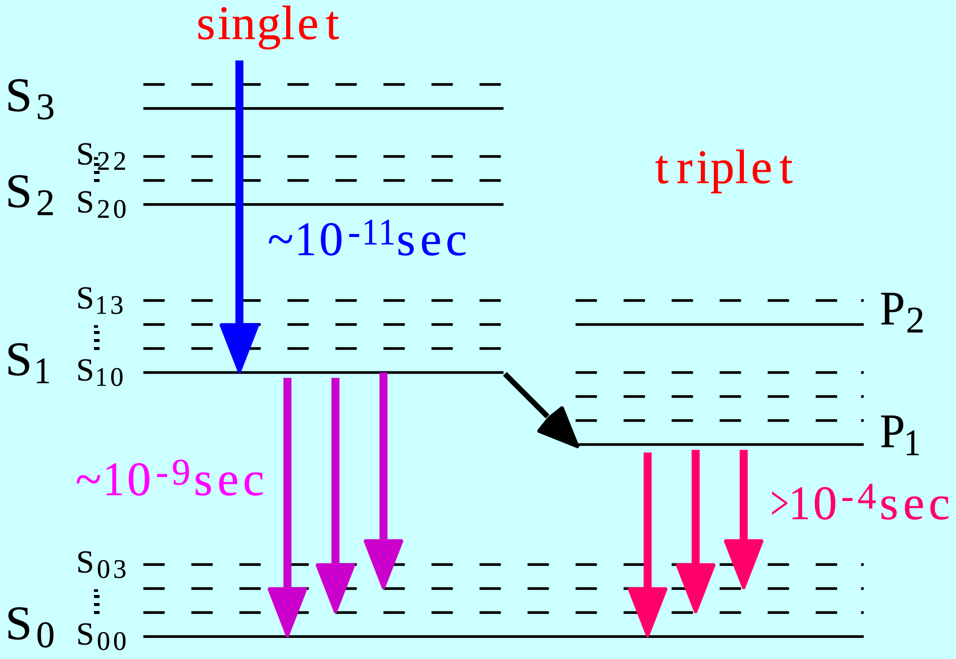
Organic scintillator spectra

- Complex spectrum of energy levels

major S & P states accompanied by vibrational sub-levels - $\Delta E \sim 0.16$eV

ionisation raises electron to excited state

fast decay to S_{00}



followed by

radiative decay to ground states

= fluorescence ~nsec

$\Delta E_{S1-S2} \sim$ few eV

or non-radiative decay S-P

slow and less likely

radiative decay P-S

phosphorescence ~msec

can also have "delayed fluorescence" from P state thermally excited to S_1

Organic scintillator characteristics

- Solid base material (plastic) doped with fluor - but can be liquid scintillator

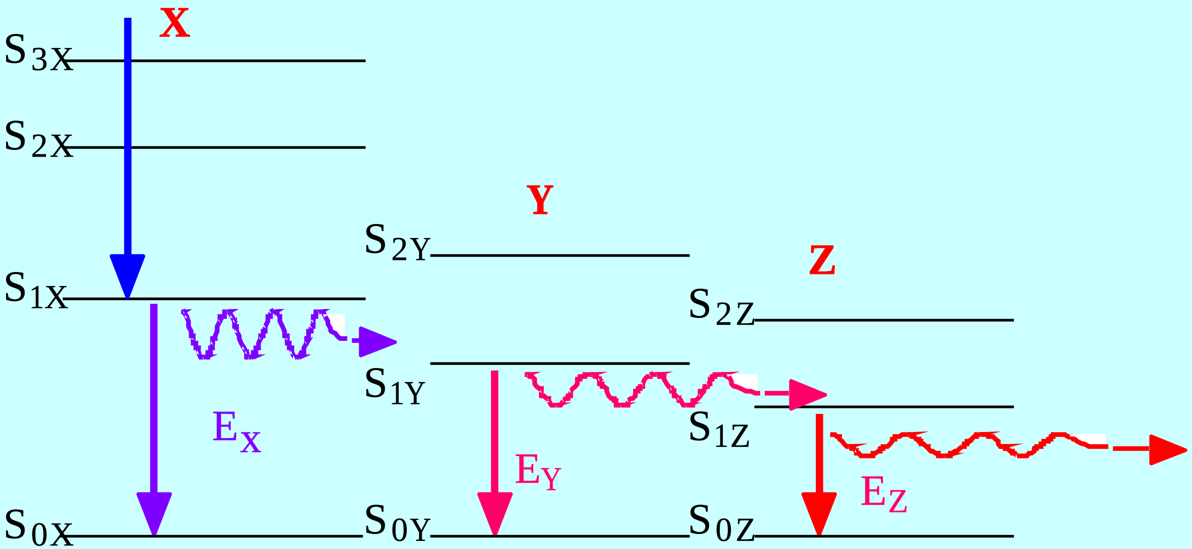
  inexpensive, low Z (primarily C, H, O)

- Primary fluor likely to be very short wavelength

  not usually matched to available sensors

  re-absorption by secondary fluor shifts light to longer, detectable wavelength

  overlapping spectra required



Initial photon is absorbed within a few mm, then re-emitted

plastic doped with wavelength shifters converts far-UV light emission to convenient part of spectrum

can be also used to transport light - eg in fibre or plastic light guide

- multi-step process, including efficiency & attenuation

  low light output cf inorganic scintillators, and non-linear

Examples of organic scintillators

Primary fluor	peak wavelength	time constant	relative light output
	nm	ns	cf NaI
Napthalene	348	96	0.12
Anthracene	440	30	0.5
p-terphenyl	440	5	0.25
PBD	360	1.2	

Wavelength shifter			
POPOP	420	1.6	
bis-MSB	420	1.2	
BBQ	500		

Originally discovered in pure natural materials like anthracene but chemists have produced a wide range of binary and tertiary systems

Chemistry of fluors determines λ and time constants

Typical commercial products (Nuclear Enterprises)

	peak wavelength	trise	tdecay	Attenuation length
		ns	ns	cm
NE110	434	1.0	3.0	400
NE104	406	0.6	1.8	120
NE108	535		~15	

Applications

fast detection but without energy measurement, Time of Flight

astro-particle physics, environmental monitoring, nuclear detection

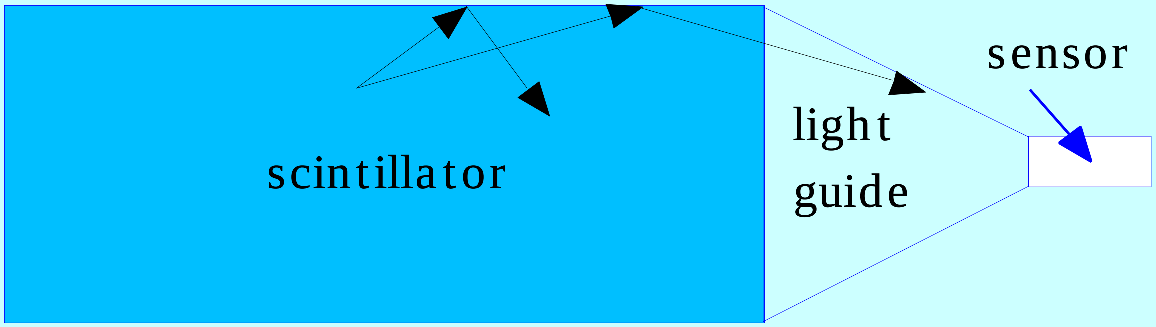
Light collection from scintillators

- Primary and subsequent emission will be isotropic

  very often require light to be collected on a area much smaller than scintillator

    on average, equal light intensity per face

  make use of total internal reflection at surface to enhance collection at sensor

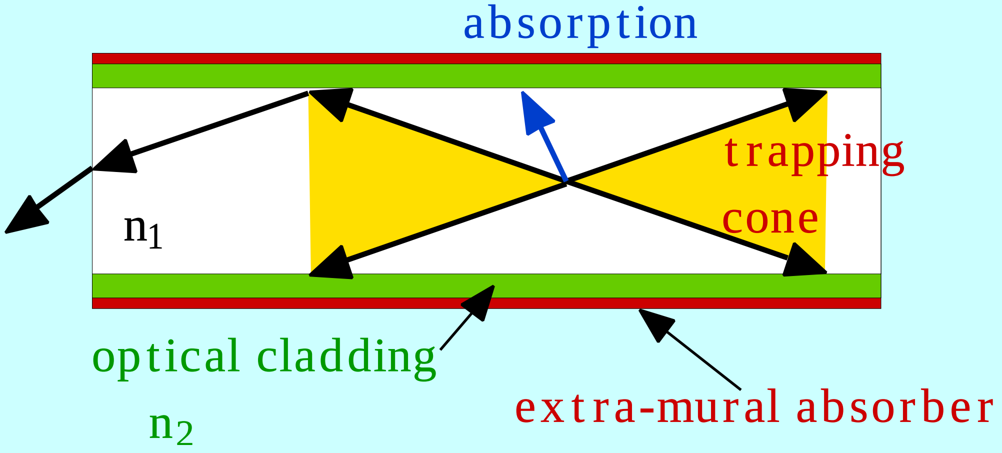


eg. loosely wrap scintillator so it has an air-scintillator boundary

for critical applications trace rays to optimise geometry

also used in scintillating optical fibres

  same principle for all optical fibre light transmission



Scintillators - summary

- Inorganic

  based on crystals

  important for accurate energy measurement and stopping power

- Organic

  molecular property of hydrocarbons

  important for speed and low cost

- Long term behaviour

  Both types of scintillator are damaged slowly by radiation

  inorganic - atomic displacement creates new band gap energy levels

  giving attenuation of light

  organic - breaking of chemical bonds alters chemistry

  reduction of light output and attenuation

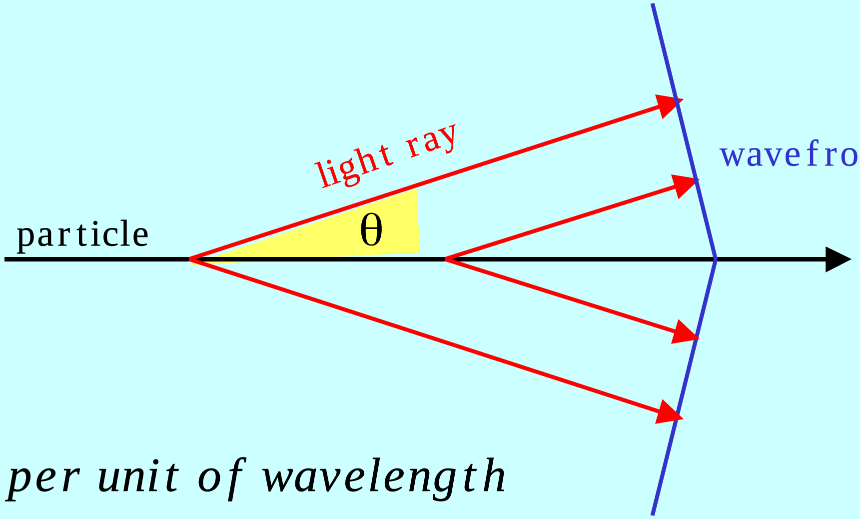
Cerenkov radiation

- when a **charged** particle travels faster than $c_{material}$ in a transparent medium

light emitted on surface of a cone, angle θ

$\cos\theta = 1/\beta n$

$\beta = v/c$ n = *refractive index*



- Characteristics

much of light in visible region of spectrum

No of Cerenkov photons per unit thickness per unit of wavelength

$d^2N/dxd\lambda \sim \sin^2\theta/\lambda^2$

significant sensitivity gain if extend photon observation to shorter wavelengths

since light output = f(β) possible to distinguish particles of different mass

suitable sensor required

any photon detector with sufficient sensitivity in visible-UV

- Applications

identification of particles in accelerator beams and experiments

ultra-high energy particle detection in atmospheric air showers

Examples of Cerenkov radiators

Radiator		**n**	θ_{max} $\beta = 1$	**N_0 (cm^{-1})** $200 < \lambda < 750$nm
He	gas	1.000035	0.48°	0.11
Air	gas	1.000283	1.36°	0.94
Isobutane	gas	1.001270	2.89°	4.3
Aerogel	solid	1.025-1.075	12.7-21.5°	81-226
Freon	liquid	1.233	35.8°	575
Water	liquid	1.33	41.2°	729
Quartz	solid	1.46	46.7°	892
BGO	solid	2.15	62.3°	1319

Exotics

- Transition radiation
  - radiation emitted when charged particle crosses dielectric boundary
    - *signals in x-ray region (~ few keV)*
    - *very weak radiation - multiple boundaries required to generate measurable signal*
      - *but amplitude* $\sim \gamma = 1/(1-\beta^2)^{1/2}$ *particle ID at very high energy*
- Bolometers
  - large fraction of ionisation energy does not appear as electrical signal
    - *in crystals, eg silicon, excites phonons in crystal = heat*
  - quantum of measurement = energy per phonon ~ meV (10^{-3}eV!)
    - *potential for very high energy resolution*
  - measure change in T $\Delta T = E_{deposit}/C$ C = heat capacity of sensor
    - *C ~ mass so need small sensor and low T (near 0K)*
  - nevertheless, some good results $\Delta E_{FWHM} = 17$eV at 0.05K for 6keV x-ray
- Superconducting sensors - several types
  - two metal superconductors separated by thin insulator layer
    - *under bias, QM tunneling of ionised excited states through insulator*
      - $\varepsilon \sim$ *meV gives potential for high resolution*

Application: particle identification

- A common requirement in nuclear and particle physics is to identify which type of particle is being observed
- stable **neutral** particles - γ, n

  very different types of interaction so easy to distinguish- discuss later

- stable or long-lived **charged** particles: e^-, p^+, $\pi^\pm$, $K^\pm$, d, He^+, other ions

  typically momentum measurement is made by bending charged particle in B field

  Force = $q\mathbf{v}\mathrm{x}\mathbf{B} = mv^2/r$ => $r = qB/p$ if motion in plane perpendicular to **B**

  direction of bend indicates if charge is + or -

- p and charge are not enough to identify particle, need measurement of m or E

  $E^2 = m^2 + p^2$ (c = 1 units , m = MeV/c^2, E = MeV, p = MeV/c)

  Two common methods : Time of Flight & Cerenkov

Time of Flight

- Simply measure time taken between two measurement points, separation L

$t_1 = L/v_1$ $\quad t_2 = L/v_2$ $\quad 1/\beta = E/p \approx 1+m^2/2p^2$ for $p \gg m$

$\Delta t = t_1 - t_2 = (L/c)(1/\beta_1 - 1/\beta_2) \approx 3.3\text{ns}(1/\beta_1 - 1/\beta_2)$ for L = 1m

Since $\beta \sim 1$, good measurement accuracy required

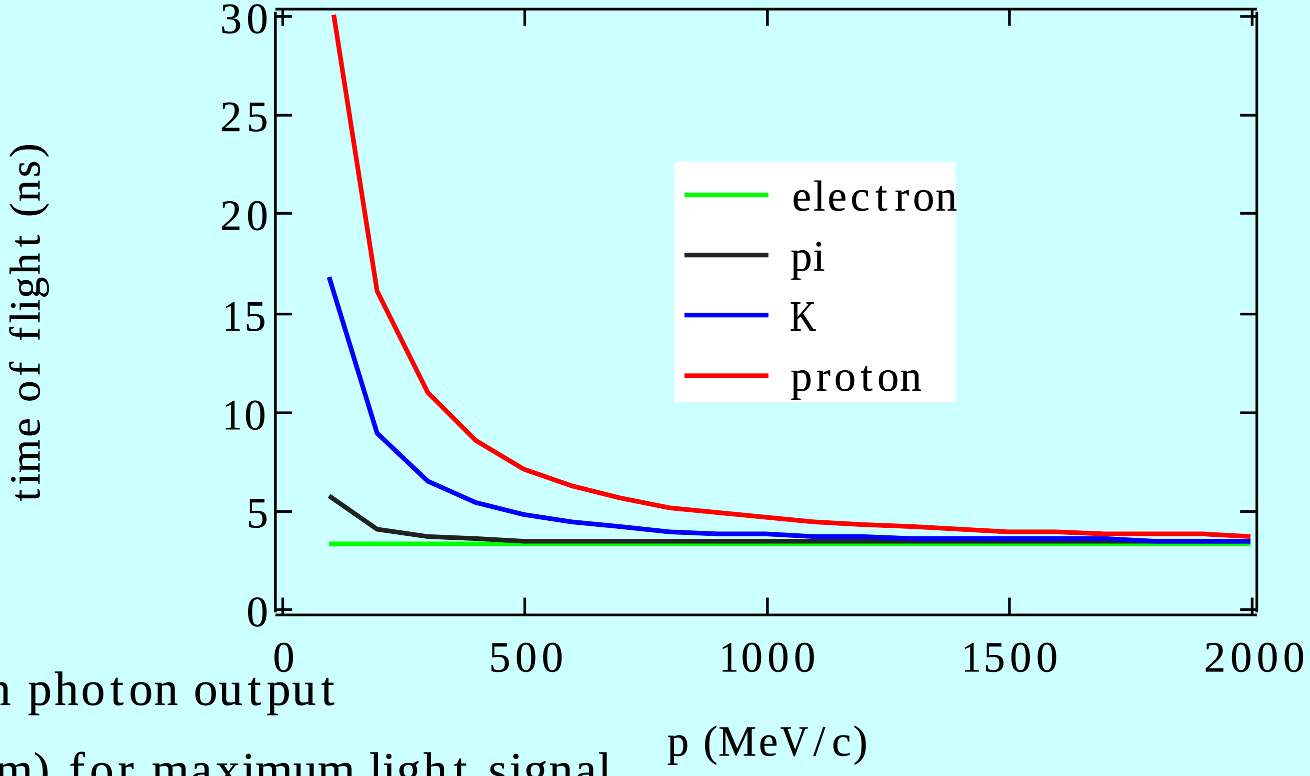
$\Delta t = (L/2p^2c)(m_1^2 - m_2^2)$

$m_e = 0.511$ MeV/c^2

$m_\pi = 140$ MeV/c^2

$m_K = 494$ MeV/c^2

$m_p = 938$ MeV/c^2



- Requirements

fast scintillator with high photon output

thick scintillator (~few cm) for maximum light signal

fast response photodetector

Cerenkov identification

- cosθ = 1/βn   so β > 1/n for light emission

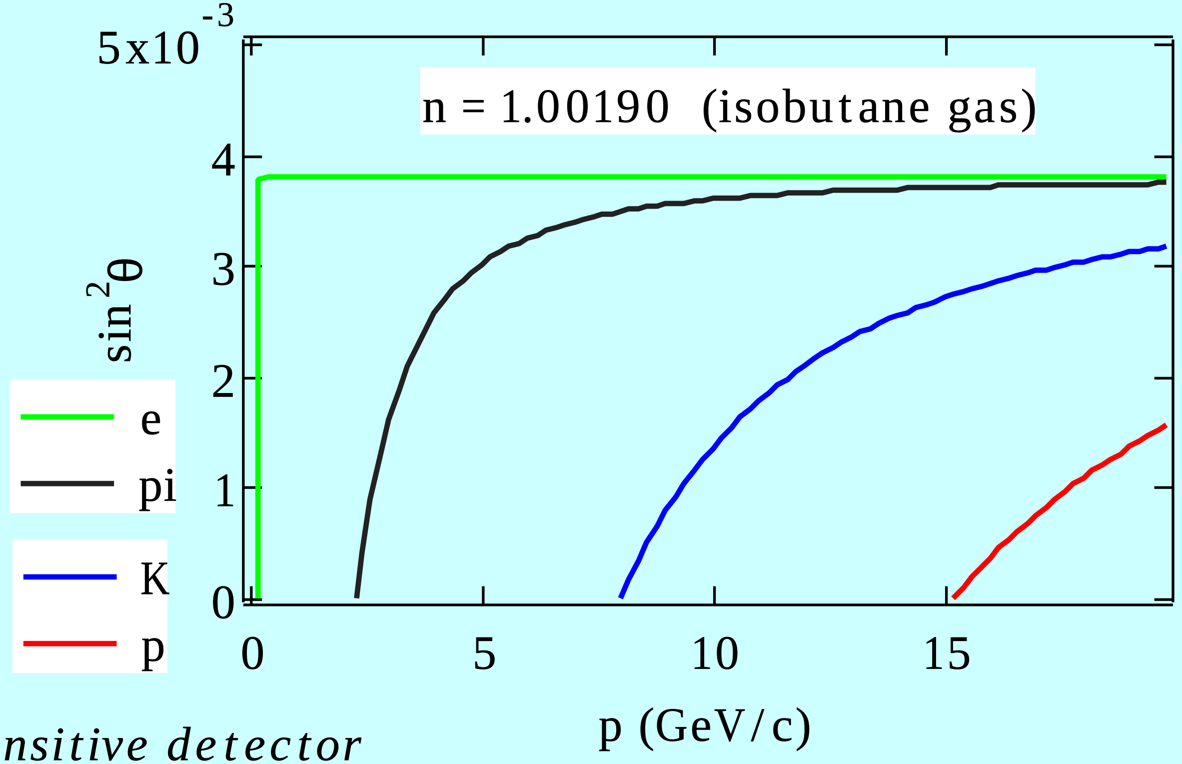
- light output $N_\gamma = N_0 L \sin^2\theta = N_0 L(1-1/\beta^2 n^2)$

  a good figure of merit $N_0 \approx 100\text{cm}^{-1}$

  depends on details of construction and photosensors

  for gaseous radiator L > 1m

  still expect small Nγ



- threshold counters

  binary 0/1 signal

- ring imaging detectors

  focussing mirror

  cone -> ring

  count photons with position sensitive detector