Summer student workshop 2024

Characterization of a simple particle detector using cosmic particles

Sune Jakobsen (some material from Christian Joram)

Additional material: AIDAinnova 2nd Annual meeting, 2 lectures on introduction to photo detectors

Program

Discussion of the detector parts

- Scintillators
- Wavelength shifters
- Photodetectors

Experimental Part

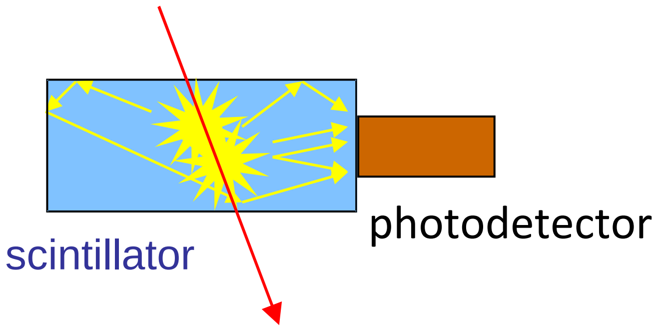
1. Determine the 1 photo-electron charge and calculate the gain of a photomultiplier.

2a. Measure the light yield of a MIP in a scintillator coupled to a photomultiplier using a light guide.

2b. Measure the light yield of a MIP in a scintillator coupled to a photomultiplier using a wavelength shifter.

3. Measure the Quantum Efficiency of a PMT in the wavelength interval 200 to 800 nm (optional)

Scintillators



Energy deposition by an ionizing particle or photon (γ)

$\rightarrow$ generation
$\rightarrow$ transmission
$\rightarrow$ detection

} of scintillation light

Two categories

Inorganic
(crystalline structure)

- Up to 70000 photons per MeV
- High Z (good for photoeffect Z^5)
- Large variety of Z and ρ
- Undoped and doped
- ns to μs decay times
- Expensive
- Fairly Rad. Hard (100 kGy/year)

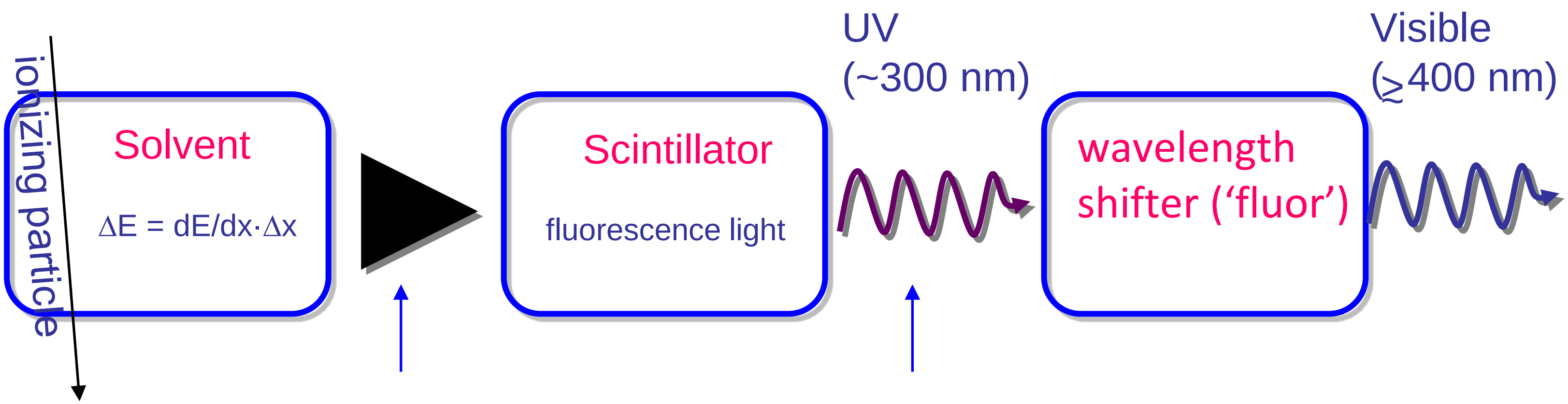
- E.m. calorimetry (e, γ)
- Medical imaging

Organic
(crystals, plastics or liquid solutions)

- Up to 10000 photons per MeV
- Low Z (not good for photoeffect)
- Low density ρ~1g/cm^3
- Doped, large choice of emission wavelength
- ns decay times
- Relatively inexpensive
- Medium Rad. Hard (10 kGy/year)

Plastic scintillators

Often they consist of a solvent + scintillator and a secondary fluor as wavelength shifter.



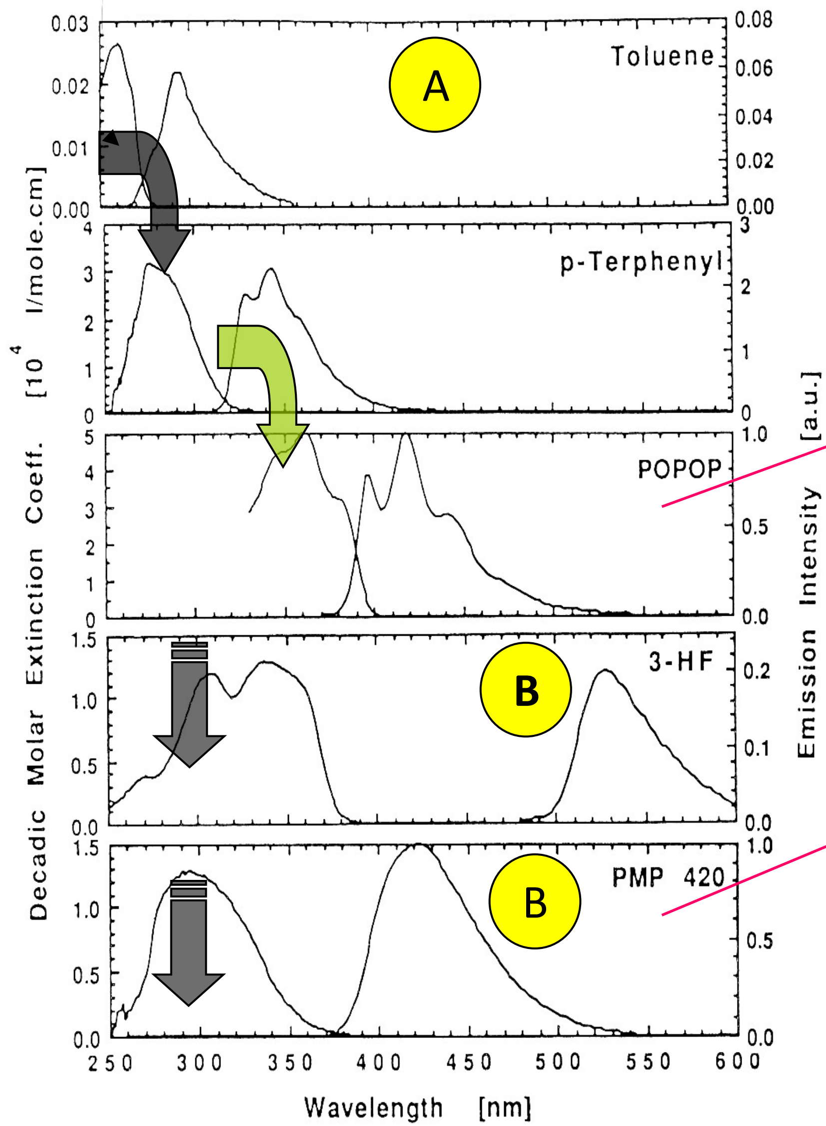
Fast and local energy transfer via non-radiative dipole-dipole interactions (Förster transfer).

radiative transfer

A fluor has its absorption and emission spectra shifted. The difference of the two peaks is called Stokes shift

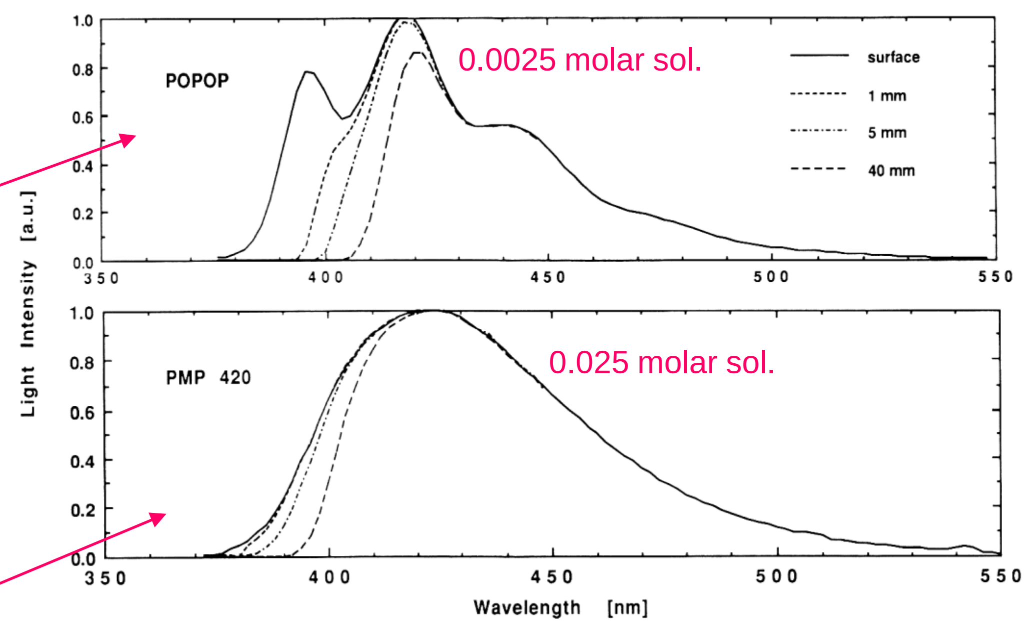
Wavelengh shifters - Two / One Dopant scheme

Abs. and emission spectra



A solvent + scintillator + wave shifter
↘ Förster ↗ ↘ Radiative ↗

B solvent + large stokes shift scintillator
↘ Förster ↗



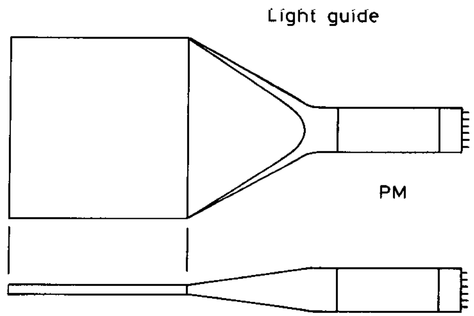
- Dopants in toluene: large Stokes shift dopants feature a much smaller self-absorption

Scintillator readout

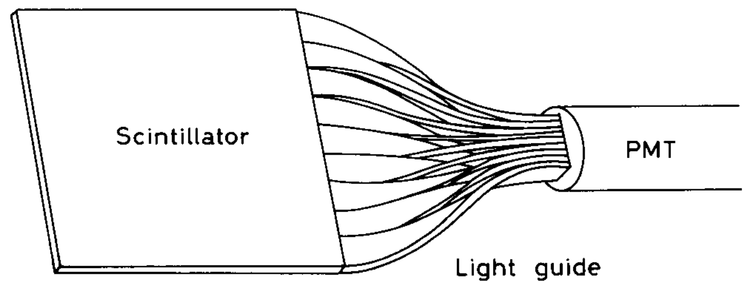
Readout has to be adapted to geometry, granularity and emission spectrum of scintillator.

Geometrical adaptation:

- Light guides: transfer by total internal reflection (+outer reflector)

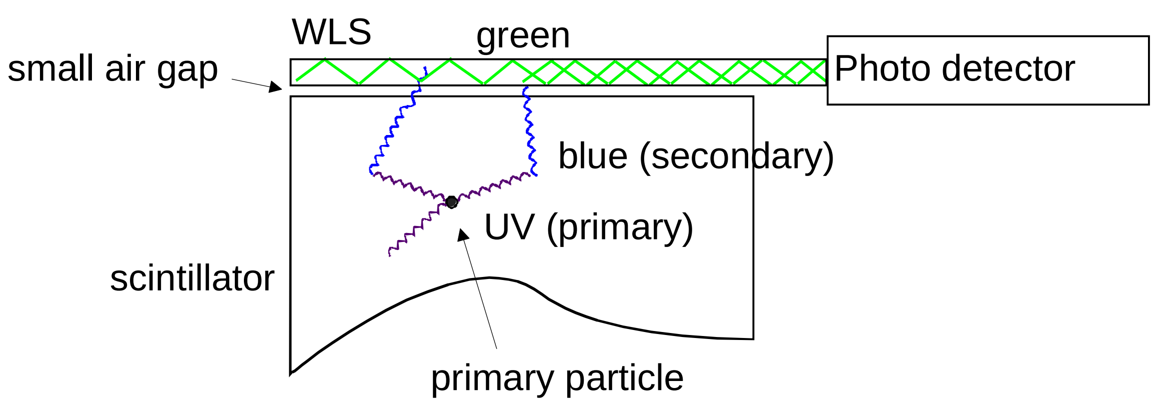


"fish tail"



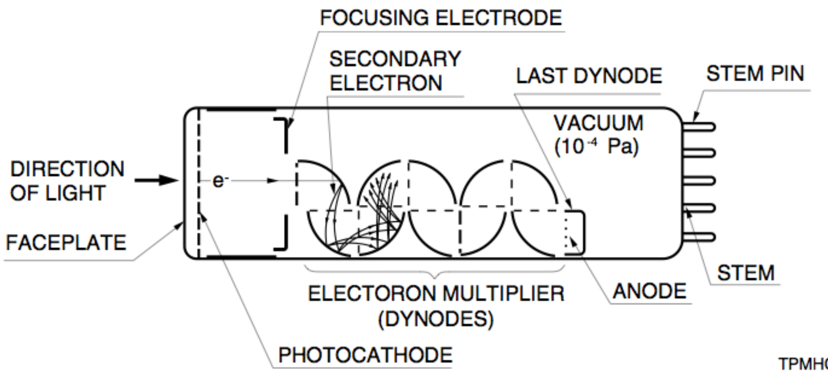
adiabatic

- Wavelength shifter (WLS) bars

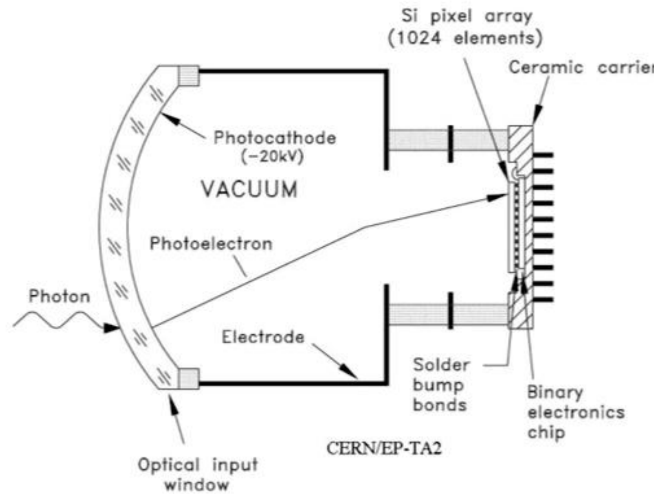


Photodetectors

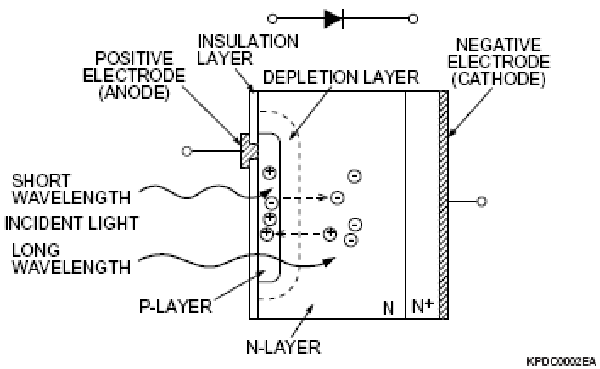
Photomultipliers



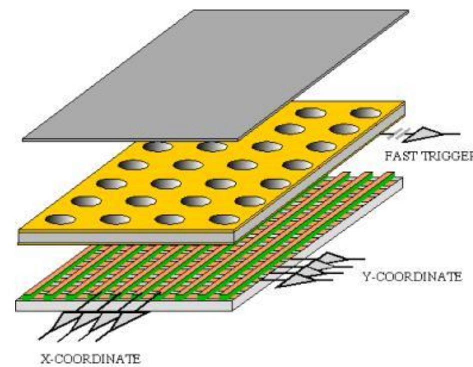
Hybrid Photon Detectors



Photodiodes



Gaseous Devices



Photodetectors

- Photodiode (PD)
  - No internal gain, direct conversion of optical photons to electron-hole pairs that are simply collected. External amplification is required.
- Avalanche PD (APD)
  - They incorporate internal gain through higher electric fields that increases the number of charge carriers that are collected.
- Geiger Mode APD (GM-APD = SiPM)
  - They are operated with a voltage above the voltage breakdown. Breakdown is triggered by a photoelectron or a thermal electron. It has to be quenched.
- Multipixel GM-APD
  - They are made of many small area GM-APD on the same substrate and electrically connected in parallel.

Cosmic Rays / Cosmic Radiation

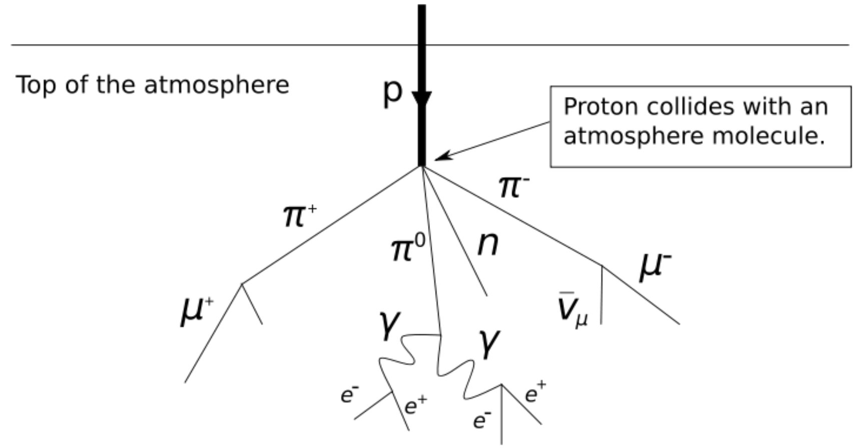
Cosmic rays are energetic charged subatomic particles, originating in outer space. Most primary cosmic rays are protons, atomic nuclei, or electrons.
When cosmic rays enter the Earth's atmosphere they collide with mainly oxygen and nitrogen molecules → cascades of lighter particles, called air showers. Photons and electrons form electromagnetic showers. Muons don't! In addition they have a long enough lifetime to reach the ground level. So, what we detect are mainly muons (and parts of e.m. showers).

The number of particles that hit the ground is dependent on several factors including location with respect to the earth's magnetic field, solar cycle, elevation, and the energy of the particles.

As a rule of thumb, the flux of muons above 1 GeV/c at sea level is :

$$\Phi = 70\ m^{-2}\ s^{-1}\ sr^{-1} \rightarrow 1\ cm^{-2}\ min^{-1}$$

→ "Cosmic muons" are very useful and cheap for testing particle detectors.



In 2012, it's just 100 years, that Victor Hess discovered the cosmic rays by means of electrometer (=ionization) measurements during balloon flights up to 5300m. He concluded "*The results of my observation are best explained by the assumption that a radiation of very great penetrating power enters our atmosphere from above.*" → Nobel prize 1936.

1 photo-electron

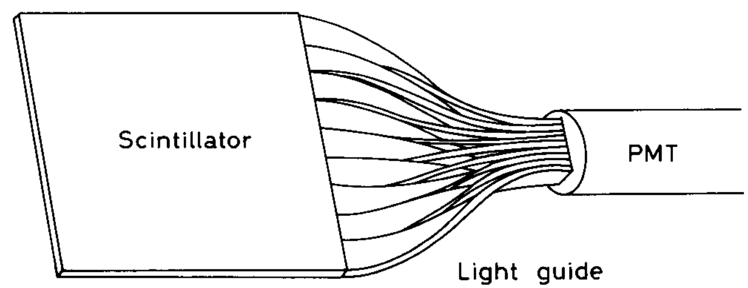
Task 1: Determine the 1 photo-electron charge and calculate the gain of a photomultiplier.

Materials:
Classic photomultiplier
Oscilloscope
Pulse generator
LED
High voltage power supply unit
Cables

Light yield using light guide

Task 2a: Measure the light yield of a MIP in a scintillator coupled to a photomultiplier using a light guide.

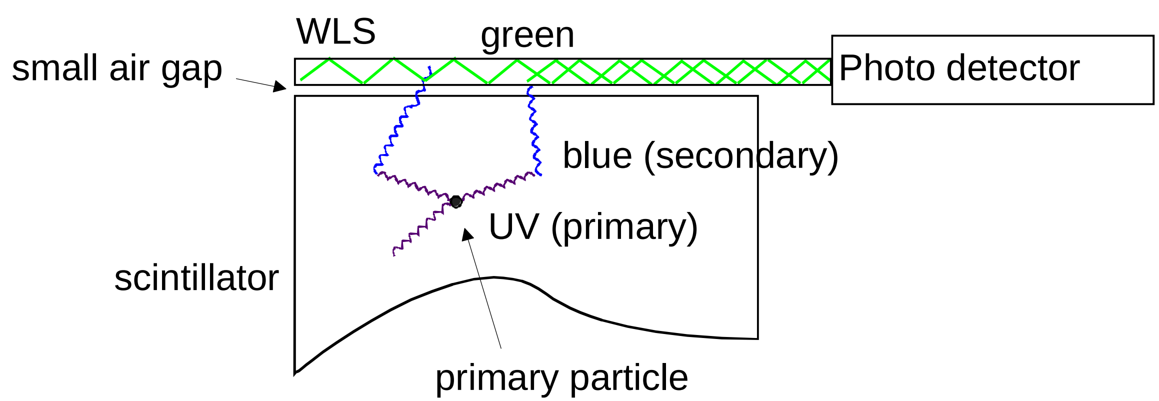
Materials:
Classic photomultiplier
Oscilloscope
Scintillator
Light guide
High voltage power supply unit
Cables



Light yield using wavelength shifter

Task 2b: Measure the light yield of a MIP in a scintillator coupled to a photomultiplier using a wavelength shifter.

Materials:
Classic photomultiplier
Oscilloscope
Scintillator
Wavelength shifter
High voltage power supply unit
Cables



Absolute Measurement of the Quantum Efficiency of a Classical PMT

Task 3: Measure the Quantum Efficiency of a PMT in the wavelength interval 200 to 800 nm. Discuss the result, its precision and possible error sources.

Set-up:

- PMT
- Xe-lamp
- monochromator
- reference photodiode
- Keithley picoampere meter
- PC (Labview)

Principle of the QE determination

$$\varepsilon_Q(\lambda) = \frac{N_e}{N_\gamma(\lambda)} = \frac{N_e \cdot e \cdot t}{N_\gamma(\lambda) \cdot e \cdot t} = e \cdot \frac{I_{photo}}{\Phi_\gamma(\lambda)}$$

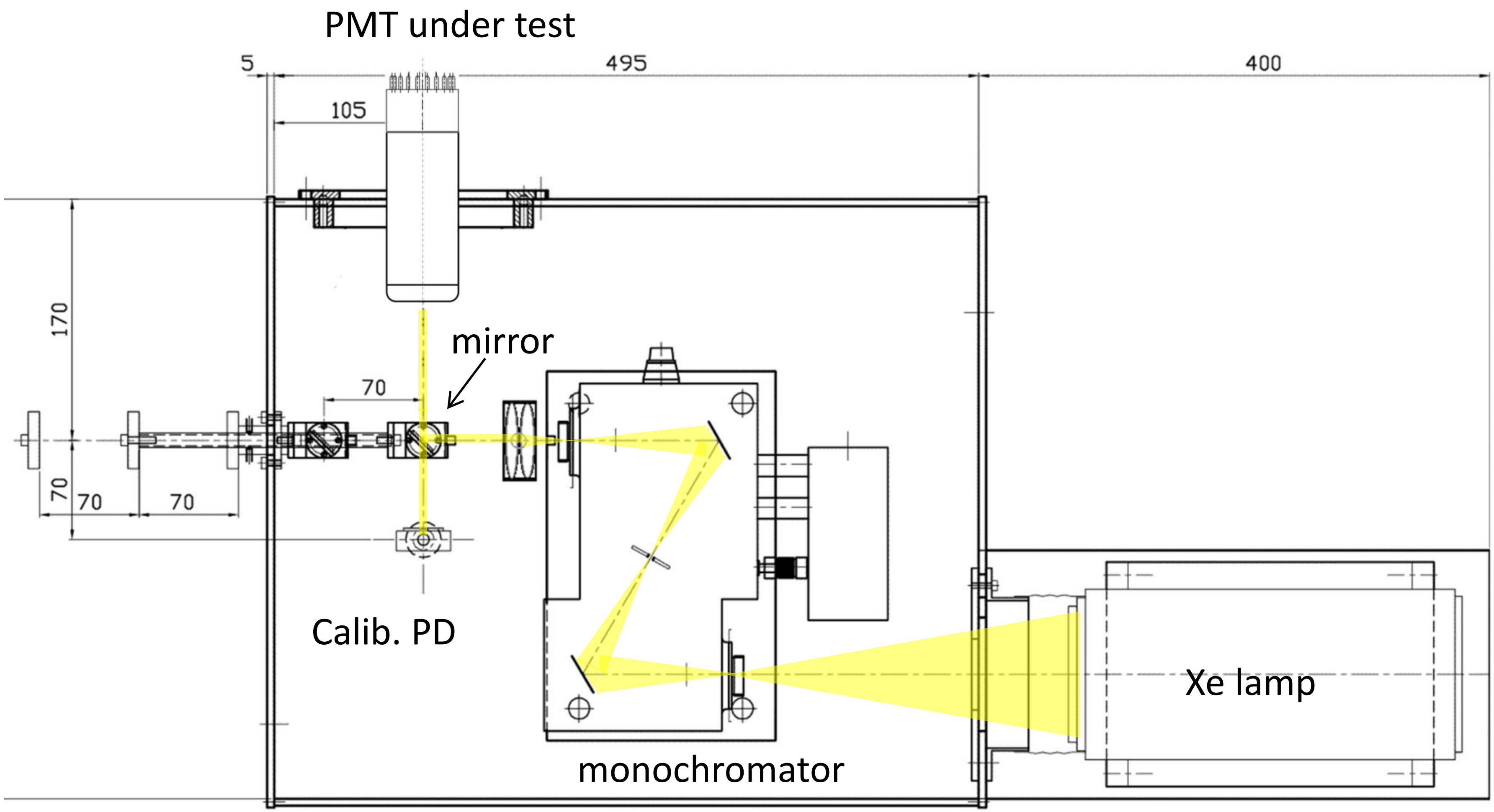
$\Phi_\gamma(\lambda)$ Photon flux, unknown !

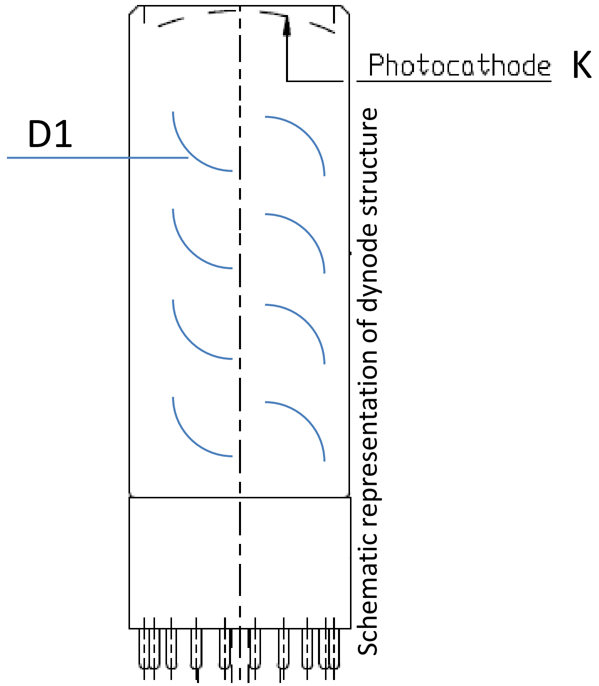
Use a reference detector with known (calibrated) ε_Q to determine the photon flux

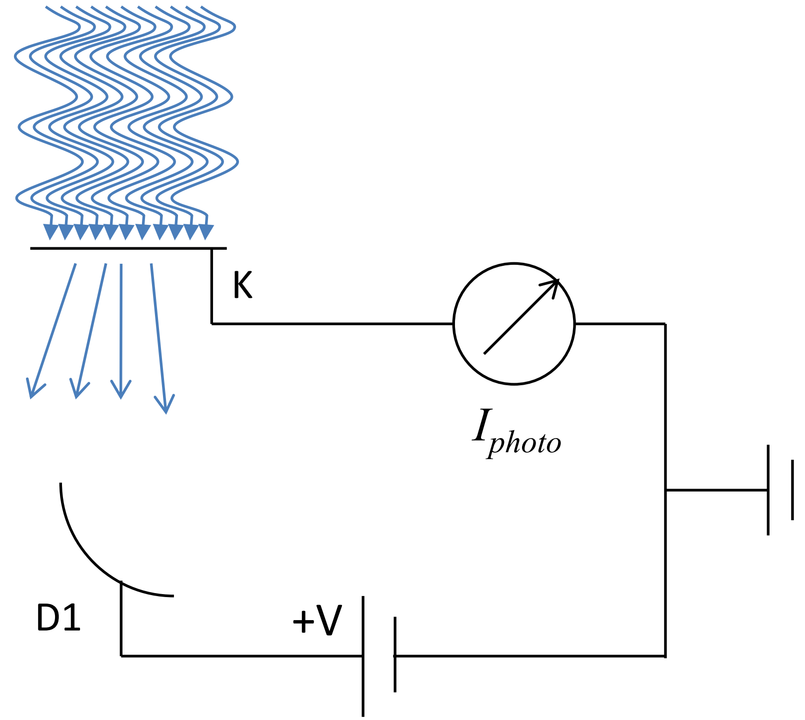
$$\varepsilon_Q(\lambda)\Big|^{REF} = e \cdot \frac{I_{photo}^{REF}}{\Phi_\gamma(\lambda)} \quad \Rightarrow \quad \Phi_\gamma(\lambda) = e \cdot \frac{I_{photo}^{REF}}{\varepsilon_Q(\lambda)\Big|^{REF}}$$

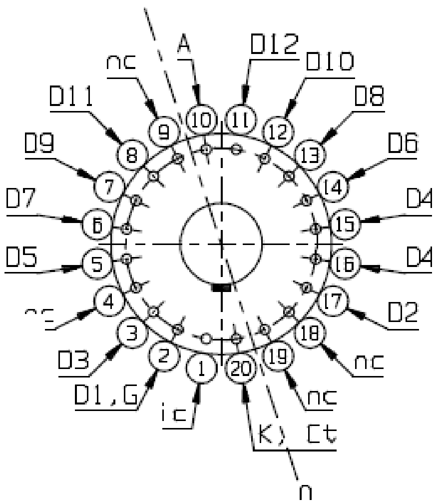
(DUT = Detector Under Test
REF = Reference Detector)

$$\varepsilon_Q(\lambda)\Big|^{DUT} = e \cdot \frac{I_{photo}^{DUT}}{\Phi_\gamma(\lambda)} = \frac{I_{photo}^{DUT}}{I_{photo}^{REF}} \varepsilon_Q(\lambda)\Big|^{REF}$$


PMT under test
5
495
400
105
170
70
70
70
70
mirror
Calib. PD
monochromator
Xe lamp


Photocathode K
D1
Schematic representation of dynode structure


K
I_{photo}
D1
+V


A
D12
D10
D8
D6
D4
D4
D2
nc
nc
K, Ct
ic
D1, G
D3
D5
D7
D9
D11
nc

The 818-UV Low-Power UV Enhanced Silicon (Si) Photodetector is supplied with a NIST traced calibration report that details individual detector responsivity measured with and without attenuator over the 200 to 1100 nm wavelength range.

Model	818-UV
Detector Type	Semiconductor
Spectral Range	200 to 1100 nm
Active Diameter	1.13 cm
Detector Active Area	1 cm^2
Material	Silicon-UV Enhanced
Power Density, Average Max w/ Attenuator	0,2 W/cm^2
Power Density, Average Maximum w/o Attenuator	0,2 W/cm^2
Pulse Energy, Maximum - w/ Attenuator	0,1 $\mu J/cm^2$
Pulse Energy, Maximum - w/o Attenuator	0.1 nJ/cm^2
Uniformity	±2 %
Shunt Resistance	≥10 MΩ
Calibration Uncertainty	4% @ 200-219nm 2% @ 220-349nm 1% @ 350-949nm 4% @ 950-1100 nm
Calibration Uncertainty, w/ Attenuator	8% @ 200-219nm 2% @ 220-349nm 1% @ 350-949nm 4% @ 950-1100nm
NEP	0.45 pW/√Hz
Reverse Bias, Maximum	5 V
Linearity	±0.5 %
Connector Type	BNC

51 mm (2") photomultiplier
9813B series data sheet

ET Enterprises electron tubes

1 description

The 9813B is a 51mm (2″) diameter, end window photomultiplier with blue-green sensitive bialkali photocathode and 14 BeCu dynodes of linear focused design. The 9813QB is a variant for applications requiring uv sensitivity.

2 applications

- high energy physics studies
- low light level detection

3 features

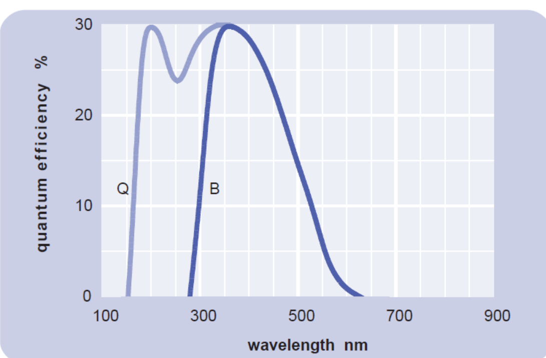
- high gain
- good SER
- high pulsed linearity

4 window characteristics

	9813B borosilicate	9813QB* fused silica
spectral range**(nm)	290 - 630	160 - 630
refractive index (n_d)	1.49	1.46
K (ppm)	300	<10
Th (ppb)	250	<10
U (ppb)	100	<10

* note that the sidewall of the envelope contains graded seals of high K content
** wavelength range over which quantum efficiency exceeds 1 % of peak

5 typical spectral response curves

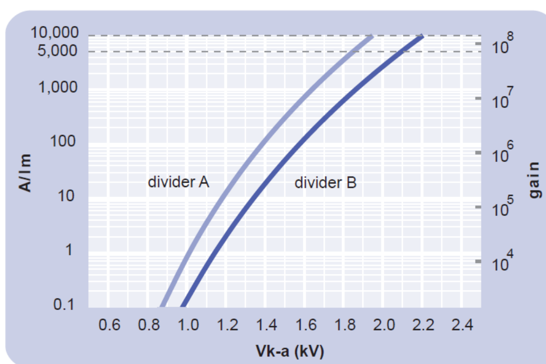


6 characteristics

	unit	min	typ	max
photocathode: bialkali				
active diameter	mm		46	
quantum efficiency at peak	%		30	
luminous sensitivity	µA/lm		70	
with CB filter		8	11.5	
with CR filter			2	
dynodes: 14LFBeCu				
anode sensitivity in divider B:				
nominal anode sensitivity	A/lm		5000	
max. rated anode sensitivity	A/lm		10000	
overall V for nominal A/lm	V		2100	2500
overall V for max. rated A/lm	V		2200	
gain at nominal A/lm	x 10^6		70	
dark current at 20 °C:				
dc at nominal A/lm	nA		10	200
dc at max. rated A/lm	nA		20	
dark count	s^{-1}		300	
pulsed linearity (-5% deviation):				
divider A	mA		50	
divider B	mA		150	
pulse height resolution:				
single electron peak to valley	ratio		2	
rate effect (I_a for $\Delta g/g$=1%):	µA		1	
magnetic field sensitivity:				
the field for which the output decreases by 50 %				
most sensitive direction	T x 10^{-4}		2	
temperature coefficient:	% °C^{-1}		± 0.5	
timing:				
single electron rise time	ns		2	
single electron fwhm	ns		3	
single electron jitter (fwhm)	ns		2.2	
transit time	ns		46	
weight:	g		180	
maximum ratings:				
anode current	µA			100
cathode current	nA			100
gain	x 10^6			140
sensitivity	A/lm			10000
temperature	°C	-30		60
V (k-a) [1]	V			3000
V (k-d1)	V			500
V (d-d) [2]	V			450
ambient pressure (absolute)	kPa			202

[1] subject to not exceeding max. rated sensitivity [2] subject to not exceeding max rated V(k-a)

7 typical voltage gain characteristics



CERN

8 voltage divider distribution

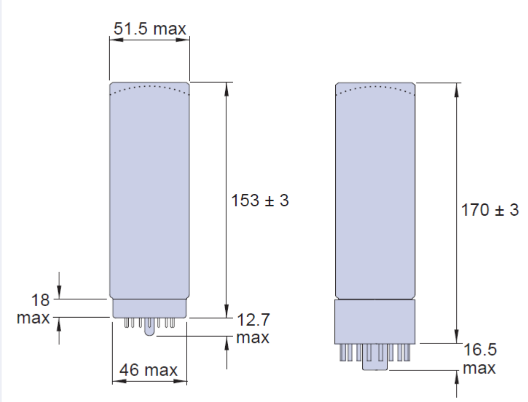
	k	d_1	d_2	d_{11}	d_{12}	d_{13}	d_{14}	a	
A	300V	R	....	R	R	R	R	R	Standard
B	300V	R	....	R	1.25R	1.5R	2R	3R	High Pulsed linearity

note: focus connected to d_1

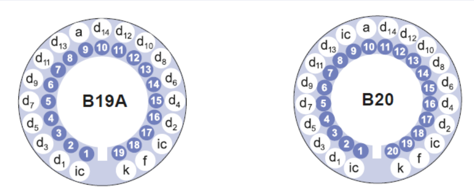
Characteristics contained in this data sheet refer to divider B unless stated otherwise.

9 external dimensions mm

The drawings below show the 9813B in hardpin format and the 9813KB with the B20 cap fitted.



10 base configuration (viewed from below)



B19A hardpin base
(for 9813B)
'ic' indicates an internal connection

note: connect f to d_1

B20 cap
(for 9813KB)
'ic' indicates an internal connection

note: connect f to d_1

Our range of B19A sockets is available to suit the hardpin base. Our range of B20 sockets is available to suit the B20 cap. Both socket ranges include versions with or without a mounting flange, and versions with contacts for mounting directly onto printed circuit boards.

11 ordering information

The 9813B meets the specification given in this data sheet. You may order **variants** by adding a suffix to the type number. You may also order **options** by adding a suffix to the type number. You may order product with **specification options** by discussing your requirements with us. If your selection option is for one-off order, then the product will be referred to as 9813A. For a repeat order, ET Enterprises will give the product a two digit suffix after the letter B, for example B21. This identifies your specific requirement.

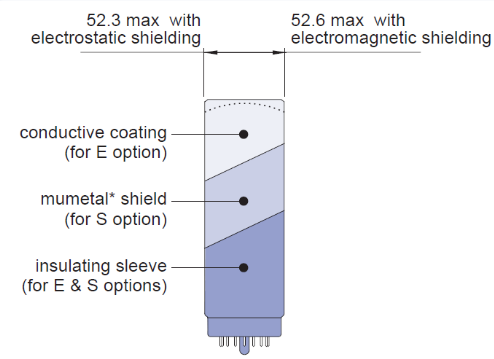
9813 ☐ ☐ ☐ ☐

window variants
Q fused silica

base options
K capped

options
E electrostatic shielding see drawing below
S electromagnetic shielding see drawing below
M supplied with spectral response calibration

specification options
B as given in data sheet
A single order to selected specification
Bnn repeat order to selected specification



12 voltage dividers

The standard voltage dividers available for these pmts are tabulated below:

9813B	9813KB	k	d_1	d_2	d_{10}	d_{11}	d_{12}	d_{13}	d_{14}	a
C638A	C643A	3R	R	....	R	R	R	R	R	
C638B	C643B	3R	R	....	R	1.25R	1.5R	2R	3R	
C638C	C643C	300 V	R	....	R	R	R	R	R	
C638D	C643D	300 V	R	....	R	1.25R	1.5R	2R	3R	

R = 330 kΩ note: focus connected to d_1

*mumetal is a registered trademark of Magnetic Shield Corporation

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