The scintillation process produces photons in proportion to the primary ionization (or in some cases, the range) … we need to count the number of photons to obtain the energy deposited by the primary radiation in the detector.

- Photocathode / photoelectric effect
- Various coatings, low w & high quantum efficiency
- Electrons avalanche down a string of “dynodes” (8-14)
- Dynodes are also coated to enhance cascades
- HV can be positive or negative (schematics later)
- Vacuum tube – internal getter to maintain vacuum
- Low potassium glass ($^{40}\text{K}$)
- KE of electrons start out very low – some electron optics and external magnetic shields
PMTs – Photocathode

Photocathode material should be matched to the output spectrum of the scintillator and is characterized by a quantum efficiency \( \eta = \frac{N_e}{N_{hv}} \) or radiant sensitivity in mA/W or by luminous sensitivity in \( \mu A/\text{lm} \).

Insulators/semiconductors are better than metals, all electrons are bound. Free electrons in a conduction band tend to rescatter the Photoelectron and thermalize it before it can leave the metal.

“Bialkali” \( K_2CsSb \) \( \eta \sim 25\% \)
The layer is very thin (~30 nm) to allow the P.E to escape the layer – lowers absorption.

Fig. 9.2 Knoll, 3rd Ed.
PMTs – Secondary Emission

The electrons are accelerated between dynodes $\Delta V \sim 100$ V, penetrate into the material (recall $dE/dx$ …) and release secondary electrons. Secondary emission from the dynodes is characterized by a coefficient: $\delta = N_s / N_p$.

Typical dynode material is MgO, BeO, Cs$_3$Sb, recent materials are “negative electron affinity” GaP:Cs (see Fig. 9.4)

Secondary energy spectrum

From Burle’s Photomultiplier Handbook

Typical value $\delta \sim 5$, range $3 - 10$
Total gain in tube: $M = \delta^N$
Example: $\delta = 5$, $N=10$ gives $M = 5^{10} = 9.8 \times 10^6$
1% change, $\delta = 5.05$, $(5.05 / 5)^{10} \sim 10\%$
Electron optics between cathode and first dynode “focus” adjustment …

Nonrelativistic velocities: \( qV = \frac{1}{2} mv^2 \)

Transit time: \( t \sim N \frac{\Delta x}{v} \sim \left(\frac{N}{\sqrt{V}}\right) \)

Time Variance: \( \sigma_{\text{total}}^2 = \sigma_{\text{Cath}}^2 + \sigma_{\text{Dyn}}^2 \frac{\delta}{(\delta-1)^2} \)

Figs. 9.10, 11 Knoll, 3rd Ed.

Beware of cartoon, \( t \sim 50 \text{ ns}, \sigma \sim 1-2 \text{ ns} \)
PMTs – Single Photoelectron Spectrum

PMTs can be run in high-gain modes that are sensitive to single photoelectrons. In such cases the anode current must follow a Poisson distribution characterized by a mean and width of ‘one.’ Multiple photoelectrons can be easily distinguished.

Only single photoelectron events

Curve from many events made up from individual events with discrete numbers of photoelectrons.

(Related Fig. 9.6 in text shows separate peaks for n=1 – 4)
PMTs – Resolution

\[ Q = \alpha \quad M = \alpha \delta^N \quad \text{where} \quad \alpha = N_{\text{PhotoElectrons}} = N_{\text{Photons}} \eta \epsilon_{\text{collection}} = (N_{IP}S) \eta \epsilon_{\text{collection}} \]

\[
\left( \frac{\sigma_Q}{Q} \right)^2 = \left( \frac{\sigma_\alpha}{\alpha} \right)^2 + \left( \frac{\sigma_\delta}{\delta^N} \right)^2
\]

The cascade across one dynode:

\[
\bar{x} = \delta = \sigma_\delta^2
\]

\[
\left( \frac{\sigma_\delta}{\delta} \right)^2 = \left( \frac{\sqrt{\delta}}{\delta} \right)^2 = \frac{1}{\delta}
\]

If number of photoelectrons is Poisson:

\[
\left( \frac{\sigma_Q}{Q} \right)^2 = \left( \frac{1}{\alpha} \right) + \left( \frac{1}{\delta - 1} \right)
\]

Potential problems:
- Are photons monochromatic? \( \eta \)
- Are photoelectrons monoenergetic? \( \epsilon \)
- Is \( S \) a constant?

\( \eta < 1 \) so the number of photoelectrons essentially determines the resolution.

i-th sequential, identical dynode:

\[
\left( \frac{\sigma_\delta_i}{\delta_i} \right)^2 = \frac{1}{\delta_1} + \left( \frac{1}{\delta_1} \right) \left( \frac{1}{\delta_2} \right) + \cdots + \left( \frac{1}{\delta_1} \right) \left( \frac{1}{\delta_2} \right) \cdots \left( \frac{1}{\delta_i} \right)
\]

\[
\left( \frac{\sigma_\delta_i}{\delta_i} \right)^2 = \frac{1}{\delta} + \left( \frac{1}{\delta} \right)^2 + \cdots \left( \frac{1}{\delta} \right)^i
\]

\[ \text{if} \ \delta > 1 \ \& \ i \ \text{large then} \ \left( \frac{\sigma_\delta_i}{\delta_i} \right)^2 = \frac{1}{\delta - 1} \]
PMTs – other resolution issues

Stray B-fields – use so-called mu-metal or iron shields

Differential sensitivity of photocathode surface – diffuse light over surface

Dark current – thermal photoelectrons, electronic noise, cosmic rays

High voltage stability … $Q \sim V^n$ where $n \sim$ (number stages minus a few)

Gassy tubes … electrons ionize residual gas and give afterglow.

Photocathode glass … transparent to uv or not?

http://www.scionixusa.com/

http://www.scionixusa.com/

Fig. 4.2 Quantum efficiency curve of a standard bialkali photocathode together with the scintillation emission spectrum of NaI(Tl).
PMT Bases – Voltage Distribution

ORTEC 266 (minimal) base
HV can be positive or negative
If (+) then anode is +HV, “AC-coupled”
If (–) then anode is Gnd, “DC-coupled”
cathode is –HV … glass becomes charged

Example: Estimate the anode current in a typical PMT for a NaI(Tl) scintillator.

NaI(Tl) ~40k photons/MeV, \( \tau = 230\text{ns} \),
PMT: \( \eta = 0.25 \), \( M = 10^6 \)
rough Photoelectron Rate \( \sim \frac{N(e^-)}{\tau} \sim 43 \text{ /ns} \)
\( I = \frac{dQ}{dt} \sim (43 \text{ e}^-/1 \times 10^{-9} \text{s}) 10^6 (1.602 \times 10^{-19} \text{ coul/e}^-) \)
\( I \sim 7 \times 10^{-3} \text{ A} = \text{7 mA} !! \) for one pulse
Crude approach: set current in Resistor chain “10x I”
but this leads to high power dissipation \( P = V I \sim 100\text{W} \)
PMTs – DC Pulse shape

Model of the connection to the anode of a DC-coupled PMT

\[ i(t) = i_0 e^{-\lambda t} \] with \( \lambda \) from scintillator,

with boundary condition:

\[ Q = \int_0^\infty i_0 e^{-\lambda t} dt = \frac{i_0}{\lambda} \]

\[ i(t) = \lambda Q e^{-\lambda t} \]

\[ i(t) = \lambda Q e^{-\lambda t} = i_C + i_R \quad \leftrightarrow \quad i(t) = \frac{dq}{dt} + \frac{V(t)}{R} \]

\[ i(t) = \lambda Q e^{-\lambda t} = C \frac{dV}{dt} + \frac{V}{R} \]

\[ \frac{dV}{dt} = \frac{\lambda Q}{C} e^{-\lambda t} - \frac{V}{RC} \]

\[ V(t) = \frac{1}{\lambda - \Theta} \left( \frac{\lambda Q}{C} \right) \left[ e^{-\Theta t} - e^{-\lambda t} \right] \quad \Theta = \frac{1}{RC} \]

Pulse maximum, set \( dV(t)/dt = 0 \)

\[ t_{\text{max}} = \frac{1}{\Theta - \lambda} \ln \left( \frac{\Theta}{\lambda} \right) = \ln \left( \frac{\Theta}{\lambda} \right)^{1/\Theta - \lambda} \quad V(t_{\text{max}}) = \left( \frac{\lambda Q}{C[\lambda - \Theta]} \right) \left[ \left( \frac{\Theta}{\lambda} \right)^{\Theta-\lambda} - \left( \frac{\Theta}{\lambda} \right)^{-\lambda} \right] \]

If “slow” electronics: \( RC \gg \tau \) then \( \Theta \ll \lambda \) and \( V(t_{\text{max}}) = \frac{Q}{C} \)

If “fast” electronics: \( RC \ll \tau \) then \( \Theta \gg \lambda \) and \( V(t_{\text{max}}) = \frac{Q\lambda}{\Theta C} \ll \frac{Q}{C} \)

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Electron multipliers – other devices

Channeltron: essentially a continuous dynode in a curved tube.


Typical Phillips device $12.5 \, \mu m \, \phi \, 15 \, \mu m$ apart $\rightarrow \varepsilon_{geo} \sim 0.55$

GEM gaseous electron multiplier: derivative of gas-filled proportional counter

Typical device $70 \, \mu m \, \phi \, 140 \, \mu m$ apart, $M \sim 10^3$