4 Scintillation Detectors

4.1 Photomultipliers

See W. R. Leo, Chapt. 8; also Knoll, Ch. 9

The essential elements of a photomultiplier tube (PM) are:

(a) Front window, usually borosilicate glass but sometimes quartz

(b) Light sensitive cathode, which for the better tubes is now a bialkali (K-Cs-Sb), coated on the inside of the front window. Photoelectrons are emitted by the cathode and collected at the first dynode.

(c) Focusing electrodes

(d) Secondary emitting dynodes usually made of copper-beryllium; most tubes have 10 to 14 stages with each dynode more positive than the previous one by about 150 volts. An external resistive divider chain located in the base to which the tube is connected sets these voltages.

(e) Anode on which the electrons are finally collected and a signal developed. It is often built into a 50-ohm transmission line structure.

Some important tube parameters are:

(a) Spectral response. This depends on front window and cathode material; it is usually given in ma/watt; peak sensitivity is usually at about 400 nm.

(b) Quantum efficiency. The ratio of the number of emitted photoelectrons to the number of incident photons. This is an important tube parameter for counting applications; it reaches a peak of about 30% for tubes with bialkali cathodes but is only about 20% for tubes with standard cathodes (Cs-Sb).

(c) Secondary electron yield. The number of secondary electrons emitted by each dynode depends on the energy of the incident electron and hence on the voltage between dynodes. A typical yield might be about 5 secondary electrons varying as a power (less than one) of the applied voltage. The overall gain of the tube is then $d^N$ where $d$ is the secondary yield and $N$ is the number of stages. For a ten stage tube this might be $5^{10}$.
or $10^7$. The variation of gain with the voltage goes as a high power of the (but less than N) of $V$.

(d) Dark current, noise. The cathode emits thermionic electrons at a low rate even in the absence of illumination. This rate depends, of course, on the cathode area and increases with temperature. The dark current may be very high if the tube has recently been exposed to light even with the high voltage off; it usually recovers. Tubes with bialkali cathodes have unusually low noise rates. There is a large variation in noise rate from tube to tube. Of course the noise rate above some voltage threshold will increase with high voltage.

(e) Linearity. For very high voltages or for high light levels the gain of the phototube will begin to saturate due to space charge buildup near the anode and the response will no longer be linear with input pulse height. This should be avoided if linearity is required. Increasing the voltage between stages at the anode end of the tube helps. Capacitors are always placed across the resistors of the divider chain for the last few dynodes. These capacitors supply charge for pulses that draw more current than is instantaneously available through the resistive divider. The capacitor then recharges between pulses or between accelerator spills if the events arrive in bursts during a spill. The capacitors must be chosen so that the charge drawn off during a pulse or burst of pulses will not significantly change the voltage at a dynode.

(f) Single photoelectron spectrum. Noise pulses are due to a single photoelectron emitted from the cathode. Variations in the gain of the stages of the tube and statistical fluctuations at the first dynode result in a continuous distribution of output anode current. Normally it is almost impossible to distinguish a one-photoelectron pulse from a two photoelectron pulse, etc. Some recent tubes, however, are made with a high gain first dynode (negative electron affinity materials such as GaP) where the secondary emission ratio can be as high as 50. In this case the resolution is much better and one can easily distinguish one photoelectron from two.

(g) Transit time and transit time spread. The transit time is the time between the arrival of a photon at the cathode and the output pulse at the anode. This time is of the order of 40 nsec and a big contribution to it comes from the relatively large space between the cathode and first dynode. The variations in transit time result in a degradation of the time resolution that one can achieve and are mainly due to differences in the trajectories that an electron can take between the cathode and first
dynode. These differences are due to different points of origin on the cathode and different initial velocities and angles. The velocity of the photoelectron depends on the wavelength of the light.

(h) Rise time. The intrinsic rise time depends on the dynode structure. It is often measured using single photoelectron pulses. This eliminates the contribution of the transit time spread due to the cathode-to-first dynode region. The actual rise time of a pulse depends on the transit time spread and also on the spread of arrival time of photons on the face of the tube. The rise time of tubes designed for fast pulse applications is typically 2-3 ns. The transit time and rise time are reduced with increased voltage across the tube, the voltage between the cathode and first dynode being most important.

Phototubes coupled to scintillation counters are used either for energy measurements where the number of photons is the significant parameter or for time determination or as part of a coincidence arrangement.

4.2 Energy Measurement

In many applications the principal limitation on energy resolution is due to fluctuations in the number of photoelectrons that are collected. This number is much smaller than the number of photons originally emitted, losses occur from geometrical effects in the scintillator, absorption, and the quantum efficiency of the phototube.

Since the number of electrons grows rapidly as they move down the dynode chain, fluctuations in the secondary emission processes are not important (except, in some, cases for the first dynode). Spatial non-uniformity of the cathode may be a factor also. There are, however, other factors having to do with the scintillation material itself or the nature of the primary particle interactions which may degrade the energy resolution of the system; some effects include non-uniformity of response of the scintillator, geometry- dependent light collection efficiency, attenuation length for light in the scintillator, fluctuations in the number of charged particles produced in the interaction. In the case of NaI used to detect gamma rays there is known to be a small nonlinearity in response to electrons of different energies. In a typical event in which a several MeV gamma ray is detected, a sequence of interactions take place: Compton scattering, photoelectric effect, etc. The specific type and sequence of these interactions fluctuate.
The number of photoelectrons collected, \( n \), will be distributed according to a Poisson distribution:

\[
P(n) = e^{-N} \frac{N^n}{n!},
\]

where \( N \) is the average number of photoelectrons. Notice that if the average is small there may be significant probability to collect zero photoelectrons and miss the event entirely. Thus if the electronic system is sensitive to pulse heights corresponding to one or more photoelectrons the inefficiency will be \( P(0) = e^{-N} \). If the threshold were higher the inefficiency would be even greater.

For larger average numbers of photoelectrons the distribution approaches a Gaussian with mean, \( N \), and \( \sigma \) given by \( \sqrt{N} \). The mean number of photoelectrons, \( N \), can be determined by measuring the relative width of the pulse height spectrum, assuming that there is no significant contribution to the width other than photoelectron statistics. If the peak position of the Gaussian is measured as well as \( \sigma \) then the number of photoelectrons is given by \( N = (\text{peak} - \bar{t})^2 \). It is usually very easy to measure directly the full width at half maximum, (FWHM); it is related to \( \sigma \) according to FWHM = \( 2.35 \sigma \). You can derive this.

### 4.3 Time Measurement

The output pulse from the photomultiplier has a shape that depends on the light emission characteristics of the scintillator folded with the time response of the tube itself due to transit time spread and other effects. The scintillator output pulse can be represented by a function with a fast rise and slow decay for example:

\[
f(t) = N_o (e^{-t/\tau_1} - e^{-t/\tau_2})
\]

For many purposes it is sufficient to approximate this by a simple exponential decay \( N_o e^{t/\tau} \).

The decay time for plastic (organic) scintillator is of order nanoseconds while for NaI it is about 230 nanoseconds. The output pulse may be represented by a folding of the exponential decay with a Gaussian or by a shape similar to the input shape given above. What happens to an exponentially falling pulse if it goes through low pass RC circuit? The main issue is how to derive a time from this output pulse. The time associated with the pulse can be defined in several ways: the time of the centroid; the time when a certain voltage or charge level is reached; the time when a particular fraction of the pulse height has been attained.
The simplest method of deriving a time from a pulse is to set a discriminator to trigger at a fixed low voltage on the leading edge of the pulse. This method of detecting the "first photoelectron" leads to a minimum resolving time that depends on the total number of photoelectrons and on the decay time of the scintillator. The results of a calculation of the mean arrival time of the first photoelectron are given in Siegbahn page 510. This method is commonly used but will in addition result in a "time walk" effect since for a fixed rise time the time that a particular voltage is reached depends on the pulse height. Good timing is possible for fast scintillators provided the dynamic range of pulse heights is not too large and the average number of photoelectrons is large enough. Given the rise time and the range of pulse heights the effect of time walk can be estimated. However there are often complications since discriminators may fire at a point that depends on the charge collected rather than at a fixed voltage.

Another method of deriving a time involves differentiating the pulse and triggering on the "zero-crossing". A very good method if the dynamic range is large is to trigger on a "constant fraction" of the pulse height. Even better time resolution can be obtained if one keeps track of the pulse height for each event and corrects the time with an appropriate algorithm, this usually requires computer processing of the data. The quality of the time measurement can be improved if a large number of photoelectrons are available, otherwise fluctuation in arrival time will degrade the time measurement. Similarly, provided the origin of the event is known, one may correct for travel time of the photons in large detectors.

4.4 Coincidence Counting

See W. R. Leo Chapt. 15.4; also Knoll, Ch. 17

A coincidence unit will usually give an output whenever the input pulses overlap in time. Let us assume that we have a dual coincidence circuit whose inputs come from two discriminators with output pulse widths, \( T \). We will get an output from the coincidence circuit if the second pulse is displaced from the first one by a time ranging from \( -T \) to \( T \).

The lower limit on the resolving time depends on the time jitter of the pulses from the detector and discriminator and on their rise time. A direct measurement of the resolving time is done with a "delay curve". You vary the delay of the one of the two inputs and count coincidences per unit time or coincidences normalized to "singles" (one of the inputs). To count efficiently the delay curve should have a plateau and the delay should be set to the middle of it.
If you have two independent, random sources of pulses going to the two inputs of the coincidence unit there will be a chance or "accidental" coincidence rate. This rate is $2N_1N_2$. 