technical reprint

R/P068

sources of noise in photomultipliers

A.G. Wright

Introduction

It is essential to define at the outset what is meant by the term noise because of the many connotations of the word in current use. In what follows, the term *signal* will refer to the flow of current in the photomultiplier produced by the *intentional* or *controlled* application of optical power to the photocathode. By *dark noise* we refer to current (or pulses) produced when the photocathode is shielded from all external optical radiations. Noise may also be generated by the signal itself: This is termed *signal induced noise.* The sources responsible for dark noise and signal induced noise will be covered in the later sections.

The most significant contributory factor to the *noise-in-signal* is the photocathode quantum efficiency which is defined as the probability for photoelectron emission per incident photon. Quantum efficiencies seldom exceed 30%, even for the most efficient photocathodes. The information in a signal or a noise pulse is conveyed by a charge distribution, varying in time: in the photomultiplier, the charge carriers are electrons, (except in the special case of ion pulses). The fact that charge is quantised produces granularity in the current waveform. Obviously low-level signals suffer much more in this respect than do those signals containing many more electrons in the pulse, or time interval under consideration. This limitation on photomultiplier signal information is referred to as *shot noise* and may be regarded as a random modulation effect on any signal or noise pulse. It is not a *source* of noise in the same sense as, say, thermionic emission from the photocathode.

If the cathode current at any time t is I then the shot noise associated with this current is given by

$$\overline{i_s^2} = 2eI\Delta f \qquad \text{...... (1)}$$

Noting in equation (1) that I = Ne, where N is the number of photoelectrons in the pulse or time interval under consideration, emphasises that the root mean square fluctuation $\sqrt{\overline{i_s^2}}$ varies as $\sqrt{N}$ in accordance with Poisson statistics. However, the assumption that Poisson statistics apply at each gain stage in the multiplier is not always supported by experimental results. (A detailed account of this and noise-in-signal in general has been given by Oliver[1]).

Shot noise effects take place essentially at the front end of the photomultiplier where current levels are low but at the anode end the effect of Johnson noise must be considered. This is thermal noise associated with the output resistance at the anode, R. Its magnitude is given by

$$\overline{i_J^2} = \frac{4kT\Delta f}{R} \qquad \text{...... (2)}$$

Figure 1. Dark rate against supply voltage.
a) An example of a tube without plateau, 9783 #53584.
b) 'Good' tube with little 'excess' noise, 9813/D295.

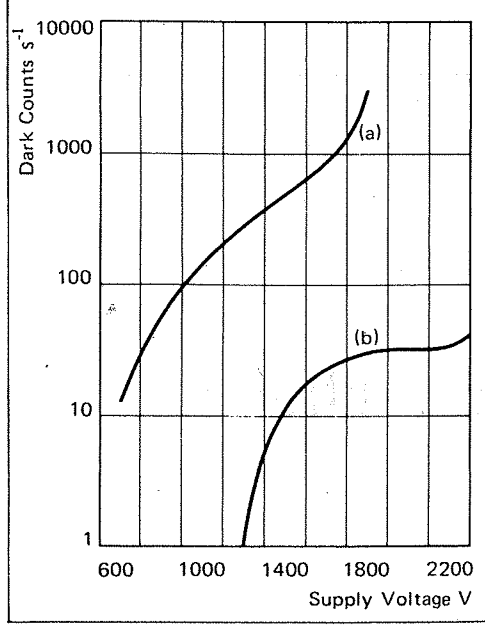


Figure 2. Single electron pulse hieght distributions in
a) side window tube, type 9783 #53584.
b) photon counting tube, type 9813/D295 with a high gain first dynode. K-D1 = 600 V. The single photoelectron resolution is typically 70%.

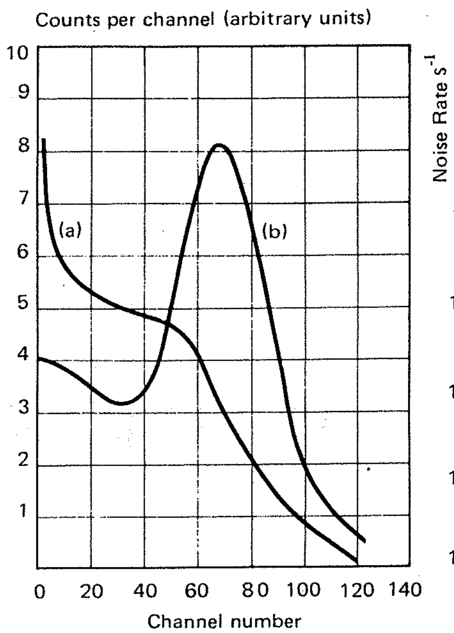
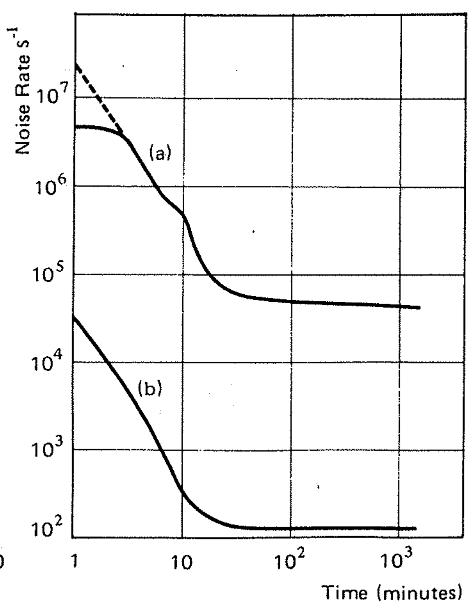


Figure 3. Time dependent noise in a 7" venetian blind photomultiplier.
a) >1 photoelectron equivalent.
b) >10 photoelectrons equivalent.



This source of noise is unlikely to be of any consequence in most photomultiplier-amplifier systems commonly used. Substitution into (2) shows that even under wide band conditions ($\Delta f \sim 10^8$ Hz), the contribution is negligible at photomultiplier gains in the range $10^6 - 10^9$. Indeed, freedom from Johnson noise limitations is one of the great virtues of the photomultiplier.

Dark current can be measured by a dc instrument connected at the anode while detailed information on the spectrum of dark current pulses is obtained by using the appropriate circuits for pulse analysis. A measurement of the dark current at a spot voltage may not be sufficient to classify a tube as 'good' or 'noisy'; a better indication is provided by recording the noise rate as a function of pulse size. If the level is set sufficiently low so that all single electron pulses are counted, then a good tube is one exhibiting a plateau as shown in figure 1(b). Photomultipliers that show a strong, non-thermal, voltage-dependent component of noise, as in figure 1(a), are said to suffer from *excess* noise. The importance of *excess* noise on the performance of the two photomultipliers of figure 1 may be assessed from their measured response to a single photon source, as shown in figure 2. The single electron peak is resolved more clearly in the 9813/D295 for two reasons: i) the uniformity in the secondary emission co-efficient across the dynode surface ii) the high gain provided by d1 reduces the statistical fluctuation in number of secondaries emitted.

Time Dependent Noise

It is well known that dark current is enhanced by exposing the photocathode to light and declines rapidly after applying the EHT. The time required for the noise rate to reach quasi-equilibrium is usually between one and ten hours but can be of the order of days. The settling time of a 7" venetian blind tube, after exposure to laboratory fluorescent lighting, is shown in figure 3. These results are for a tube which has been used continuously for several years; the settling time required for a new photomultiplier is often longer than this. It is probably true to say that the photomultiplier, even in a carefully controlled temperature environment, never reaches true equilibrium. Experimentally, of course, this would be very difficult to verify.

There is a significant variation in behaviour between photomultipliers: Gadsden[2] found a drop in rate of about 5 after 3½ hours; while Robben[3] detected a diminution in rate by a factor of 2, after 1 year. In an attempt to explain, at least part of this time dependence, Krall[4] exposed a dummy faceplate to 1.5 J of ultra violet radiation (λ = 365nm). (In effect not very different from exposing the tube to commercial fluorescent lighting) and then placed the dummy on the window of a dark adapted low noise photomultiplier with the results shown in Table 1 (a). In a second experiment, the photocathode was exposed to 0.1 J of the same radiation and then placed in a dark chamber; the subsequent emission rate is shown in Table 1 (b). Krall[4] takes this to indicate that phosphorescence of the faceplate is not the major contributor to the initial high rate observed immediately after switch on. The high rate observed in 1 (b) is used to support the explanation that some metastable excitation mechanism of the photocathode is rosponsible. Young[5], however, has an alternative explanation for the time dependence of the dark noise. He argues that ions within the photomultiplier are largely responsible and that a "progressive gettering action, like an ion pump, when the voltage is applied takes place. The number of free ions available is greatly enhanced on exposing the interior of the tube to the UV radiation source (through the semitransparent photocathode)".

Whatever the true explanation might be, the fact is that most photomultipliers after exposure to light require several hours of continuous operation to ensure a stable noise count.

Temperature Dependent Noise

If a tube has been allowed sufficient time to stabilize, then the temperature variation of the noise at a fixed gain may be investigated by cooling the tube. Two examples, one for venetian blind tubes[6], and the other for a photomultiplier with a GaP first dynode[7], are shown in figure 4.

In both instances the noise is accounted for by Richardson's equation for thermionic emission.

$$N = A\,T^n \exp(-\phi/kT)\ \mathrm{cm^{-2}\ s^{-1}} \qquad \text{...... (3)}$$

Barton[6] deduces a low effective work function of ϕ = 1.25 ± .05 eV which he says may be accounted for by the appropriate semi-conductor theory. Coates[7] uses a figure of ϕ = 1.5 eV and he notes an apparent change in ϕ with temperature. Young[5], however, attributes most of the thermal dark current to ions, claiming that the thermionic emission is negligible. The strong temperature dependence is explained by the adsorption of the gas on to the metallic surfaces at low temperatures and the release at high temperatures; the work function of about 1eV represents the binding energy of the ions to the surfaces within the photomultiplier. In support of his thesis Young[5] quotes the results of an experiment[6] in which just the stem of the tube was cooled. The single electron rate does indeed change but only by a factor of ~2, whereas on cooling the cathode the rate changes by a factor of 100 or so.

What is to be concluded from these conflicting explanations for the temperature dependent noise sources?

1. Coates[7] takes $A = 7.5 \times 10^{20}$ and n = 2 which are the appropriate values for a metal. For a semi-conductor[8], such as the photocathode, A is generally less than the above value and n = 5/4.
2. The contribution to the temperature dependent noise is therefore not entirely explained by thermionic emission but perhaps by a combination of thermionic plus ionic.

Temperature Independent Noise Sources

It is clear from figure 4 that below 0°C, the noise is substantially independent of temperature for S11 and bialkali photocathodes, for S20 photocathodes the corresponding temperature is −20°C.

Cerenkov Radiation from Cosmic Rays

The relative proportions of the constituents of the cosmic radiation, at sea level, are: 70% due to muons, 30% from electrons and less than 1% contributed from protons and pions, and the intensity of all constituents increases rapidly with altitude. Very roughly the flux at sea level is 1-2 particles $\mathrm{min^{-1}\ cm^{-2}}$ with an angular distribution of the form

$$I = I_v \cos^n\phi \quad \text{with } n \simeq 2 \qquad \text{...... (4)}$$

Since a high proportion of these particles are relativistic, they will emit Cerenkov radiation on passing through the photomultiplier faceplate.

The total number of photons produced per cm of path length in quartz, by relativistic particles of unit charge, is about 10^3 in the wavelength range 200 – 550 nm; the figure for glass is about half this because of the strong absorption below 300 nm. For a mean quantum efficiency of 15%, one can expect ~150 photoelectrons cm^{-1} of path. The orientation of the cathode bears on the result because the light is emitted in a cone of vertex semi-angle 48° as illustrated in figure 5. Young[9] has investigated the effect in considerable detail and confirms what one might expect in practice: larger but fewer pulses when the tube axis is horizontal and most pulses with the face uppermost.

Background from Radio-isotopes

These sources of radiation are located in the glass of the tube and in the immediate environment; sources external to the photomultiplier may be naturally occurring or they may be derived from radioactive material in the vicinity of the apparatus.

The most abundant sources of environmental radiation are well known: ^{40}K, ^{238}U and ^{232}Th. The decay schemes for the latter two consist of long chains of daughter products, linked by emissions of α, β and γ rays. The universal abundance of these three isotopes stems from their extremely long half lives of 10^9 – 10^{10} years. Naturally occurring potassium contains ~ 0.01% of the radioactive isotope ^{40}K. The measured potassium content [10,11] for various window materials is shown in Table 2 but it should be stressed that batches of the same glass show some variation.

The number of disintegrations per second for glass containing 0.06% potassium is readily estimated from these figures to be 0.4 disintegrations s^{-1} (for a 2" photocathode). Potassium at the level of 0.06% is regarded as a low figure in photomultipliers intended for low background counting applications and the performance of commercial tritium counters, for example, is not significantly degraded even though the scintillations provide signals containing only a few photoelectrons[10]. The decay scheme for ^{40}K indicates that 89% of decays go via β decay with end point energy 1.33 MeV: an electron with $E > 0.51$ MeV produces about 400 photons/cm in the visible region by Cerenkov radiation in glass[12].
Over a path length of 2 mm we can expect a maximum of

$$400 \times 0.2 \times 20\% = 16 \text{ photoelectrons}$$

Contributions to dark noise from sources of ^{60}Co, ^{241}Am and ^{90}Sr have been investigated[13] with the results shown in figure 6. The equivalent end point signal of 20 photoelectrons for ^{90}Sr (end point energy 2.27 MeV) agrees well with the figure of 16 calculated above for ^{40}K.

The importance of the results of figure 6 lies not in the rate of events obtained, since this is simply proportional to the source strength used, but indicates quite clearly that α, β and γ sources in the naturally occurring background are likely to produce between 1 – 30 photoelectrons per interaction. The natural radioactive background varies greatly from place to place so actual measurements on photomultipliers apply only to a particular location. May and Marinelli[14] found uranium contributions of 0.5 – 2 s^{-1} and ~40 s^{-1} for potassium in 3" and 5" tubes. Delaney and McGovern[15] obtained equivalent rates for 2" tubes.

Noise Due to Leakage

Interelectrode potentials lie in the range 100 – 1000 V and since dc currents as low as 10^{-12}A may be important, leakage resistances less than $10^{15}\Omega$ could be a source of noise[5]. Fingerprints left on the base of a tube and dust which over long periods of time settles preferentially on the high potentials of the dynode chain are obvious sources of leakage. In certain critical experiments, the tube base should be carefully cleaned with an appropriate solvent and shielded from contact with dust or moisture. Phenolic base material has been found to be more leaky than glass and Teflon, and overcapped tubes may possibly be more noisy than their pressed glass counterparts. Noise can be created by potential gradients in the tube envelope; Krall[4] found that a potential of only 50 volts applied to a dummy faceplate produced sufficient electroluminescence to affect a neighbouring photomultiplier.

Ion Noise

Small amplitude noise pulses in the distribution have been attributed to: thermal emission from the dynodes, ohmic leakage and electron emission from the dynodes as a result of ion bombardment. A fraction of the large amplitude pulses is attributed to ionic bombardment of the cathode, but this will be discussed later in greater detail.

Generation of Light in the Photomultiplier

There are at least three possible mechanisms:

(i) ionisation of the residual gas molecules – likely in the regions nearest to the anode where the electron density (in the current) is highest. Optical feedback along the envelope to the cathode is possible, and in certain tubes a deliberate restriction is introduced during the manufacture of the envelope.

(ii) electrode glow[4] – the upper limit to gain in photomultipliers is of the order of 10^9; above this value breakdown occurs principally by light emission from the last few dynodes in consequence of the excessive electron bombardment. The intensity of the light emission was sufficient to enable the effect to be photographed. This source is not usually important in most applications, except perhaps in low level coincidence counting where the light may activate an adjacent photomultiplier.

Figure 5. The Cerenkov effect due to cosmic ray muons (μ) and electrons (e) shown for different photomultiplier orientations.

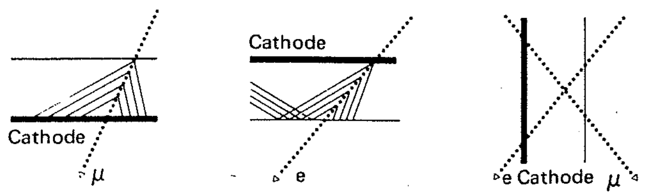


Figure 4. Variation of single electron noise rate with temperature from
a) 31000D, 2" bialkali[7].
b) Various S11, venetian blind, tubes[6].

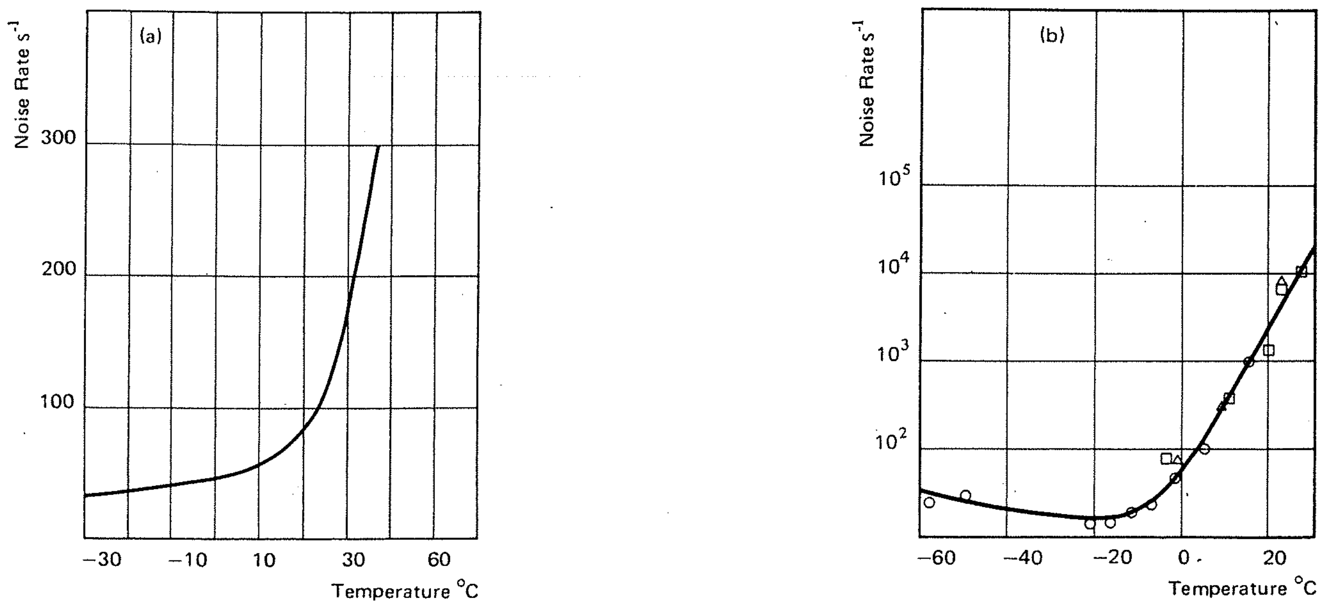


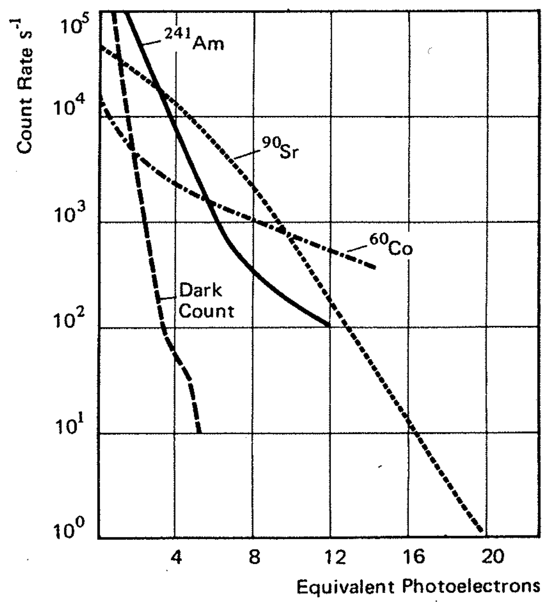
Table 1. Time varying dark noise, Krall[4].
1(a) dummy only exposed to UV radiation and
1(b) photocathode exposed to UV.

	Elapsed time (min) after UV exposure	Cathode emission rate $s^{-1}cm^{-2}$
1 (a)	2	14
	3	11
	10	9
	30	8
1 (b)	10	1400
	20	750
	50	310
	1 day	30
		5

Table 2. Potassium content of various window materials.

Material	% Potassium
Corning 9741[10]	0.06
Jobling Pyrex[10]	0.055
Borosilicate[10]	0.07
Quartz[11]	0.008
Pyrex[11]	0.05

Figure 6. Noise spectra obtained from various radioactive sources[13]



(iii) discharges from sharp corners and points in the internal metallic structure of the tube are likely, particularly in new tubes which probably benefit from a running in period at an elevated EHT.

1/f Noise

It would seem that there is little evidence that 1/f noise occurs in the photocurrent but it has been shown to be present in the dark current in the frequency range 0.001 – 0.3 Hz. Coates[16] gives a comprehensive summary of the work to date; apparently those tubes which exhibit excess noise are likely to suffer from 1/f noise as well.

Burst Noise

Some tubes, even after several weeks of continuous operation, suddenly increase their dark current from an assumed equilibrium value and then back again after a time interval of several hours. Similar behaviour results from capacitor breakdown or small fluctuations in EHT of about 1% but if these sources can be definitely eliminated, there is possibly no explanation available.

Cathode-like Behaviour of Dynodes

Photocathode material is deposited on the dynodes during the course of manufacture of certain tubes. The dynode will not only act as a noise source but also, as an inefficient cathode. High intensity light levels on the semi-transparent photocathode can give rise to a prepulse originating on the first dynode.

Afterpulses Due to Positive Ions

The mechanism of afterpulse formation described by Morton[17] is the generally accepted description of the phenomenon in most photomultipliers: afterpulses are produced as a result of the ionization of residual gaseous impurities between the cathode and the first dynode. Allen[18], on the other hand, proposed that ions originate from adsorbed layers on the dynodes. The positive ions formed are accelerated towards the cathode by the non linear focusing electric field, V(s); on impact these ions liberate up to five electrons which constitute the secondary signal or afterpulse. It can be shown that for a wide range of functions V(s), the transit time τ of an ion is nearly independent of the point of creation, s, of the ion[19]. This accounts for the distinct peaks which occur in afterpulse distributions as shown for example in figure 7(a). Also, the transit time of an ion of mass m and charge z is proportional to $(m/z)^{1/2}$ and in theory it should be possible to identify the residual gaseous constituents within a particular photomultiplier.

The afterpulse rate and size distribution is of direct relevance to the user of photomultipliers. Investigations (to be reported later) performed on a number of 2", 5" and 7", ungettered, venetian blind tubes with S11 photocathodes established the afterpulse rate to be of the order of 1% per photoelectron. (The use of a getter in the 9813 photomultiplier reduces the afterpulse rate to only ~0.03% per photoelectron). These experiments also revealed that the pulse height distribution is a function of both the accelerating voltage between K and d1 and τ. Raising K – d1 voltage increases the mean size of the

Figure 7. Afterpulse spectra in a 7" venetian blind photomultiplier, type 9623, excited by
a) LED signal of 100 photoelectrons equivalent.
b) Cosmic ray muon, or electron, Cerenkov event of 100 photoelectrons equivalent.

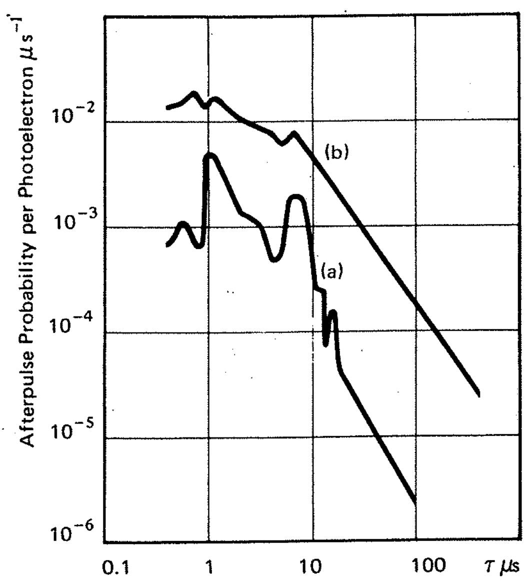
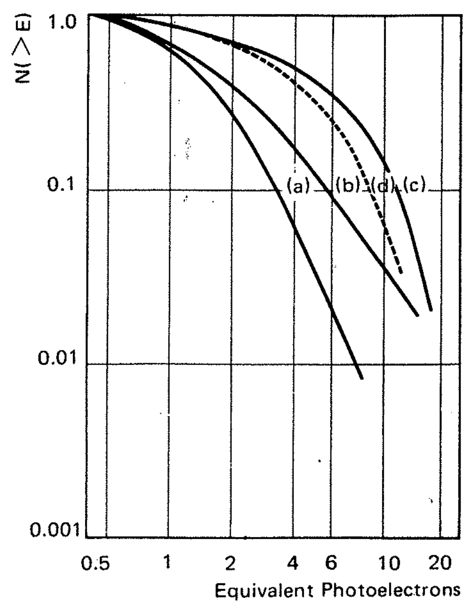


Figure 8. Afterpulse size distributions (integral) for a 7" photomultiplier type 9623. (a) single electron response, (b) $6 < \tau < 8\ \mu s$, K – d1 = 750 V; (c) $0.9 < \tau < 1.4\ \mu s$, K – d1 = 750 V; (d) $0.9 < \tau < 1.4\ \mu s$, K – d1 = 400 V.



afterpulses; afterpulses observed for $0.5 < \tau < 1.5\ \mu s$ are significantly bigger than those for $5 < \tau < 10 \mu s$. This information is shown in figure 8. Afterpulses also originate from ionization in the interdynode regions of the photomultiplier but unless the ions are able to make their way back to the cathode, which is unlikely in a venetian blind structure, the afterpulses they produce will be of a size generally less than one photoelectron equivalent. Unless carefully aligned, the dynode structure in fast, linear tubes appears open to the passage of ions back to the cathode[20].

Afterpulses Subsequent to Large Cerenkov Pulses

This source of afterpulses is ascribed to the passage of charged particles through the faceplate of the photomultiplier[5,7,13,21]. The exact mechanism responsible for this type of afterpulse is not firmly established: it is possibly caused by fluorescence in the glass or by the excitation of metastable levels in the photocathode, or both. The number of afterpulses per initiating event depends on the type of photocathode and on the material of the faceplate: trialkalis produce significantly more secondaries than do bialkalis or SbCs photocathodes, particularly when the photocathodes are laid down on sapphire as opposed to glass[21]. The afterpulse signature of these events is very different from the ion afterpulse time distributions, as can be seen in figure 7(b). A typical event from a cosmic ray muon or electron passing through a 1 cm faceplate of an S11 photomultiplier is an initiating pulse, due to the Cerenkov light, of ~100 photoelectrons; this is followed by 10 – 15 afterpulses extending over a time interval of 100μs (exceptional events show ~50 afterpulses). The time distribution is a composite one: in the interval 0 – 10μs, the distribution shows the ion afterpulse time structure superimposed on an elevated background level; at times greater than 10μs, the distribution falls off as $\sim \tau^{-3/2}$. The size distribution, in contrast with that for ion afterpulses, indicates that the majority of these signals are at the single photoelectron level.

General Conclusions

The noise rate of a photomultiplier depends on: the type; the area of the photocathode and the individual properties of the photocathode, eg the work function. Bialkali photocathodes are considerably less noisy compared with the trialkalis. Typical noise rates for photomultipliers operated at room temperature are as follows: 400, 100 and 30 $s^{-1}\ cm^{-2}$ for trialkali, S11, and bialkali photocathodes, respectively. The source responsible for the wide range in noise rates in tubes of the same type may also account for the range in photocathode sensitivities.

If tubes with low noise are to be selected from a batch, then it is advisable to make the selection after several weeks of continuous operation because in some instances tubes which initially give high dark rates settle down to comparatively low levels of dark noise. In certain applications the shape of the noise distribution may be important, and this is very variable.

It is possible to reduce the noise of a selected tube by cooling: a reduction by as much as a factor of 10^4 for a large area photocathode can be gained by cooling the tube. The noise can be further reduced where the background radiation level is high: one inch of lead is an effective shield for low energy radioactive sources, occurring either in the natural background or elsewhere.

The normal helium content of the atmosphere is only 5.2 ppm but sufficient to cause a noticeable increase in the afterpulse rate over a period of years. This is because helium diffuses readily through glass (in particular quartz) and consequently photomultipliers operated in the vicinity of a helium dewar show a marked increase in their afterpulse noise rate[19]. This process is, of course, irreversible.

References

1) C.J. Oliver (1968), *Noise in electron/photomultipliers in physical aspects of noise in electronic devices. Institute of Physics, London, 1968, 207.*
2) M. Gadsden (1965), *App Optics, 4, 1446.*
3) F. Robben (1971), *App Optics, 10, 776.*
4) H.R. Krall (1967), *IEEE Trans NS, 14, 455.*
5) A.T. Young (1969), *App Optics, 8, 2431.*
6) J.C. Barton *et al* (1964), *J Sci Inst, 41, 599.*
7) P.B. Coates (1971), *J Phys E, 4, 201.*
8) A. Venema (1966), *Thermionic Emission in Handbook of Vacuum Physics, Ed. A.H. Beck, 2, Physical Electronics, Pergamon Press.*
9) A.T. Young (1966), *Rev Sci Inst, 37, 1472.*
10) H.B. Jepson (1977), *private communication.*
11) J. Sharpe and V.A. Stanley (1962), *Tritium in the physical and biological sciences, 1, IAEA, 211.*
12) J.V. Jelley (1959), *Cerenkov radiation and its applications. Pergamon Press.*
13) R.L. Jerde, L.E. Peterson and W. Stein (1967), *Rev Sci Inst, 38, 1387.*
14) H.H. May and L.D. Marinelli (1962), *Symposium on whole body counting, Vienna IAEA.*
15) C.F.G. Delaney and A.J. McGovern (1965), *IEEE Trans NS, 12, 343.*
16) P.B. Coates (1972), *J. Phys D, 5, 915.*
17) G.A. Morton, H.M. Smith and R. Wasserman (1967), *Trans IEEE NS, 14, 443.*
18) J.S. Allen (1952), *Los Alamos Report LA 1459.*
19) P.B. Coates (1973), *J Phys D, 6, 1159.*
20) H.A.W. Tothill, *private communication to Coates*[19].
21) K. Dressler and L. Spitzer (1967), *Rev Sci Inst, 38, 436.*

talk to us about your application or choose a product from our literature:

photomultipliers, voltage dividers, signal processing modules, housings and power supplies

ET Enterprises Limited
45 Riverside Way
Uxbridge UB8 2YF
United Kingdom
tel: +44 (0) 1895 200880
fax: +44 (0) 1895 270873
e-mail: sales@et-enterprises.com
web site: www.et-enterprises.com

ADIT Electron Tubes
300 Crane Street
Sweetwater TX 79556 USA
tel: (325) 235 1418
toll free: (800) 521 8382
fax: (325) 235 2872
e-mail: sales@electrontubes.com
web site: www.electrontubes.com

choose accessories for this pmt on our website

an ISO 9001 registered company

DS_ R/P068 Issue 3 (18/01/11)