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effect of radioactivity in photomultipliers for sensitive instrumentation

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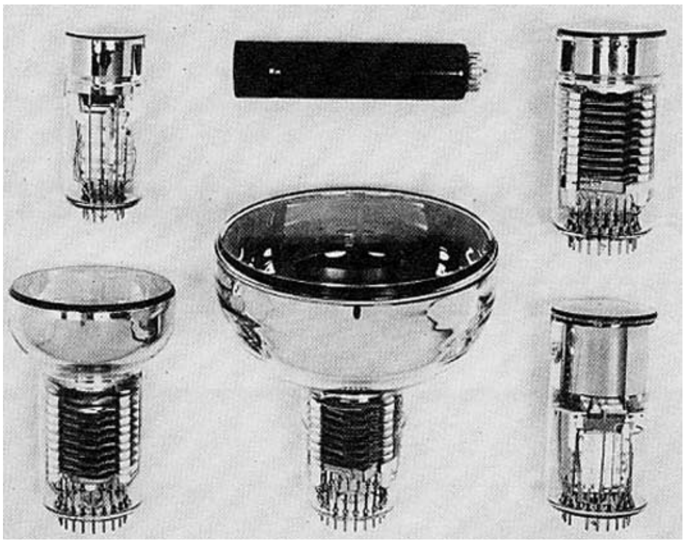


Examples of Electron Tubes’ range of photomultipliers with low radioactive content for applications such as radioactive tracers in modern medical diagnostic and investigative techniques.
Special types, with low radioactive window, envelope and stem, have been developed for the most extreme low background requirements in liquid scintillation counting.
In principle, the particular application determines the allowable degree of radioactive content in a photomultiplier and its associated components.

1 introduction

Traces of the naturally occuring radiosotopes ^{40}K, ^{238}U and ^{232}Th, and their daughter products, are present to varying degrees in all substances. We are concerned here with the levels of activity in the materials from which photomultipliers are manufactured. The decay schemes are complex, involving , β and γ emissions over a wide sprectrum of energies. A gamma ray spectrum of the natural background in the laboratory taken with an unshielded NaI(TI) crystal is shown in figure 1 .

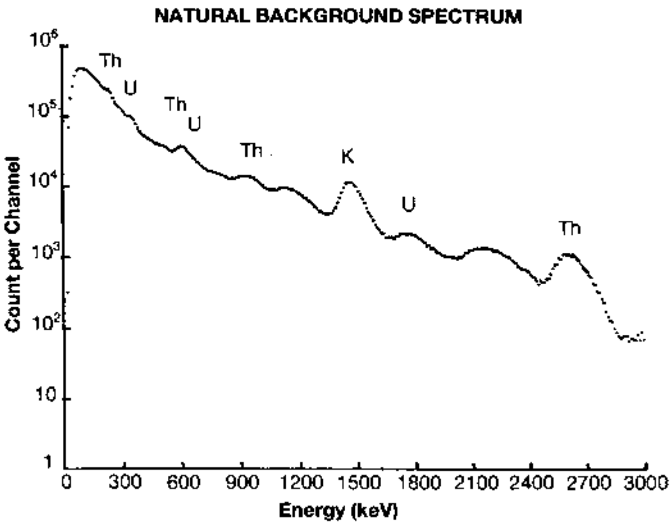


figure 1 the natural gamma ray spectrum measured with a 3” x 3” NaI(TI) crystal. Peaks due to the long-lived isotopes ^{40}K, ^{238}U and ^{232}Th and their daughter products are indicated.

In applications involving photomultipliers, it is principally the β and γ emissions from the constituent materials that are of concern. The most prevalent isotope in photomultipliers is ^{40}K with the decay scheme illustrated in figure 2 . Natural potassium contains 0.0117% ^{40}K, the remainder being non-radioactive ^{39}K. In practical terms, one gram of natural potassium emits 3.3 gamma rays per second of energy 1.46 MeV, together with beta particles at a rate of 27 per second.

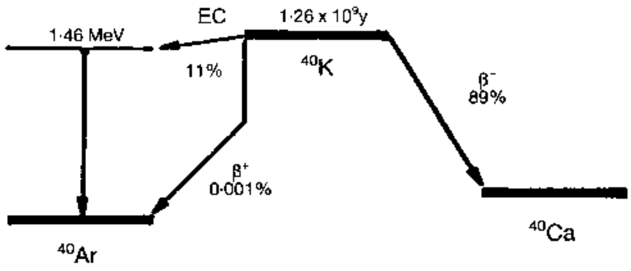


figure 2 the decay scheme of ^{40}K.

The above types of radiation are of direct relevance in scintillation spectroscopy, because they appear to the scintillator as a background source of radiation. In low light level and photon counting applications, radioactive contaminants produce background indirectly, principally by Cerenkov emission in the envelope. These separate manifestations of photomultiplier background are treated in section 3 in relation to specific applications.

2 the location of isotopes within the photomultiplier

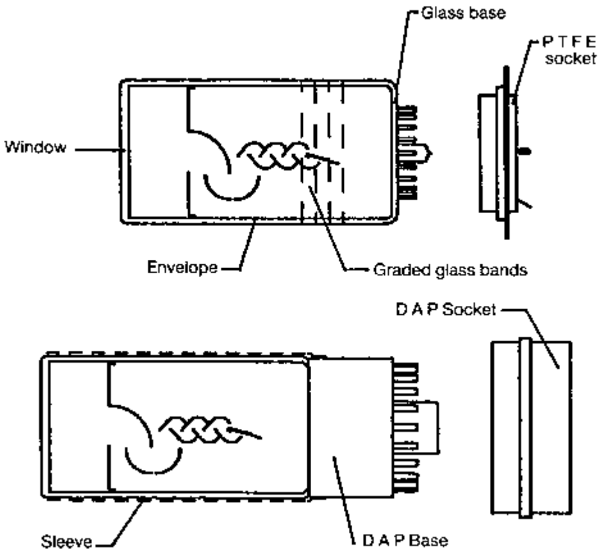


figure 3 illustrating different types of photomultiplier construction. Radioisotopes are located mainly in the window, envelope and base.

Outlines of typical photomulipliers are shown in figure 3 . A set of tubes was dissected and their component parts measured for activity. Results presented in table 1 were taken with a 3" x 3" NaI(Tl) well-crystal over the energy range 100 - 3000 keV.

table 1 relative activities of the constituents of a photomultiplier

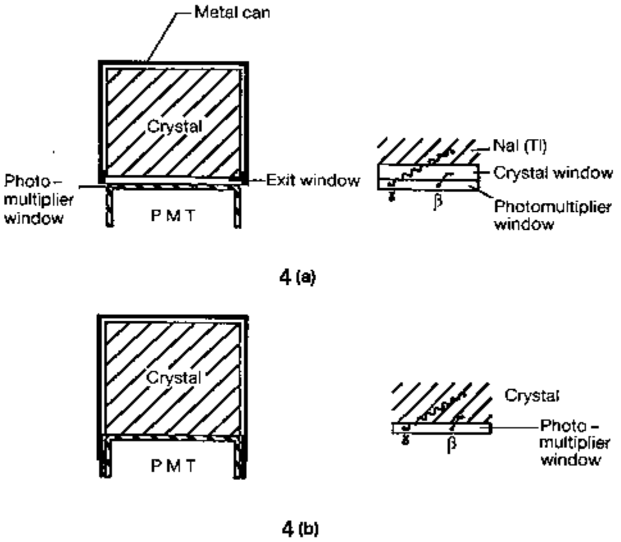
component	weight (g)	high K_2O glass	standard glass	low background glass	quartz window
a) window	10	30.0	3.0	1.0	< 0.2
b) envelope	60	180.0	18.0	6.0	13.0
c) metal strucure	70	0.5	0.5	0.5	0.5
d) glass base	15	30.0	5.0	1.5	5.0
e) DAP base	40	12.0	12.0	12.0	12.0
f) PTFE socket	28	0.2	0.2	0.2	0.2
g) DAP socket	84	24.0	24.0	24.0	24.0
h) PVC sleeve	7	0.1	0.1	0.1	0.1
i) min. activity	-	240.0	26.7	9.2	18.9

The last row in table 1 gives the minimum total activity, (i = a + b + c + d + f), achieved by using a photomultiplier with a glass base and a PTFE socket. A capped photomultiplier with a DAP base and socket is higher in activity. It should be stressed that the activities quoted above refer to the component activities. It is necessary to examine the requirements of each application to gauge the relative importance of the activity from a particular constituent.

3 applications

3.1 inorganic crystal assemblies

The standard crystal material for radiation detectors is NaI(Tl). The detector, consisting of a crystal and photomultiplier housing, can be made in two ways.



4 (a)

4 (b)

figure 4 two methods for coupling a NaI(Tl) crystal to a photomultiplier. In (a) the crystal is a separate unit. All β emission from the photomultiplier window is shielded from the crystal by its exit window. In (b) the crystal is attached directly to the photomultiplier, making the arrangement sensitive to β emission from the window

a) The crystal is encapsulated in a metal can with a low background, optical window, as shown in figure 4(a) . If this window is thicker than 1 mm, then beta particles emanating from the window of the photomultiplier will not reach the crystal. The only significant background contribution is from those gamma rays originating in the photomultiplier window which penetrate and interact in the crystal. It is obvious, because of the geometrical factors, that the effects of radiation from the cylindrical part of the envelope and base will be significantly reduced.

b) Crystal manufacturers offer assemblies in which the photomultiplier and crystal form an integral unit within a light-tight housing (figure 4(b)). This configuration offers better resolution than a), but will exhibit higher background because of the beta contribution.

Table 2 gives the contribution to background counts for a range of Electron Tubes' photomultipliers when coupled to a NaI(Tl) crystal of the same diameter. For an integral assembly the background counts will be about double these figures. The results were obtained by noting the increase in counts following the imposition of window material between the crystal and a photomultiplier with a quartz window.

table 2 contribution to background (100 - 3000 keV) in NaI(TI) crystals coupled to the photomultipliers listed

Tube Type	Diameter	Window Material	Background min^{-1}
9924	30 mm (1.18 in)	standard glass	1 ± 1
9766X	30 mm (1.18 in)	low background	< 0.5
9902	38 mm (1.50 in)	standard glass	2.0 ± 1
9902X	38 mm (1.50 in)	low background	< 0.5
9256	52 mm (2.05 in)	standard glass	4.0 ± 0.5
9256X	52 mm (2.05 in)	low background	0.8 ± 0.5
9256Q	52 mm (2.05 in)	quartz	< 0.5
9758	75 mm (2.95 in)	high K	15 ± 0.5
9765	75 mm (2.95 in)	low background	1.5 ± 0.5
9791	130 mm (5.12 in)	standard	42.0 ± 1
9792	130 mm (5.12 in)	low background	8.0 ± 1

3.2 low background anti-coincidence systems

Very low level β and γ ray spectrometry can be achieved with active anti-coincidence shielding, such as CsI. In these applications the ultimate detectivity of the system is determined by the level of background within the active shield. For a system incoproating a massive NaI(TI) crystal viewed by several photomultiplires, the choice of low background glass is recommended in preference to quartz. This might seem surprising, but the reason lies in the fabrication method of a quartz window photomultiplier. A photomultiplier made entirely from quartz is not feasible because of the large difference in linear expansion coefficients between quartz and the base pins. In the manufacture of a quartz window photomultiplier, the expansion differences are taken up by a graded glass seal in the tubular part of the envelope. The graded seal consists of a series of glass bands that increase in expansion coefficient from the fused quartz to the higher metal seal glass of the base. Certain of the graded bands have unavoidably high potassium content.

3.3 photon counting

In low count rate applications, with signals at the single photon level, such as low level ^{3}H counting with liquid scintillators, the use of low background or quartz photomultipliers ensures improved performance. In photon counting, we need to be concerned with background light generation by relativistic beta particles in the window. An electron of energy ≥ 0.5 MeV radiates light by the Cerenkov effect; ^{40}K has an end-point of 1.33 MeV and therefore most emissions over the spectrum of energies will result in the generation of light. A photomultiplier with a well-resolved single electron peak, which serves to calibrate the energy scale, has been used to quantify the background from radioactive contaminants in terms of photoelectrons. In figure 5 , the spectrum b) was obtained by placing a window of high potassium content glass in optical contact with the window of the photomultiplier with the spectrum a). Results for other types of glass measured in a similar way are listed in table 3 .

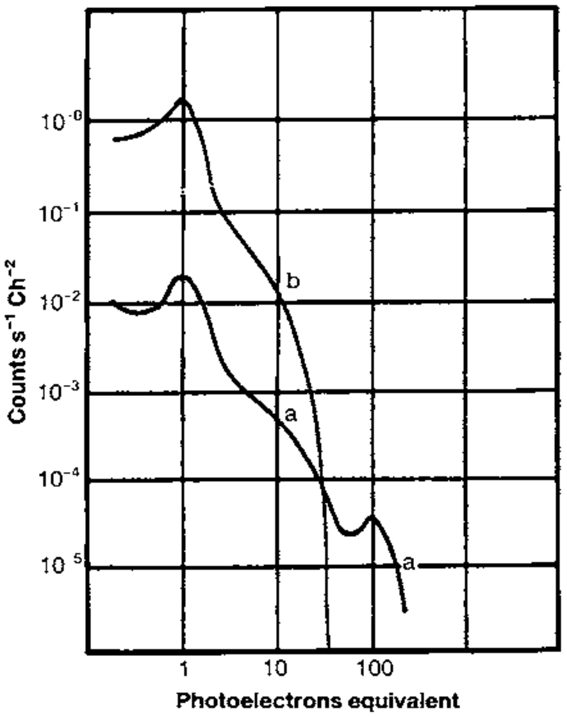


figure 5 (a) is a differential pulse height spectrum for a cooled photomultiplier with a quartz window. Note the cosmic ray peak at 100 p.e. (b) represents the contribution to the background from a window with high potassium content; the spectrum was obtained from (a) after optically coupling the sample window to the photomultiplier.

table 3 contributions to photomultiplier background in counts per second over the energy ranges indicated in photoelectrons equivalent, (p.e).

Material	Signal Level cps	
	0-2 p.e.	2-20 p.e
high K glass	20.0	15.0
standard glass (2.5 mm)	2.0	1.5
low background (2.5 mm)	0.7	0.5
low background (0.7 mm)	0.2	0.2
quartz	< 0.1	< 0.1

3.4 coincidence systems

The distribution in figure 5, spectrum b), shows the presence of signals in the size range 0 to 20 photoelectrons. This background is derived from light impulses containing between 0 and 100 photons per event. A proportion of the light signal from each background event is directed away from the photomultipiler window in which it was generated. In a system where two or more photomultipliers are in physical proximity, there is therefore a finitie probability of registering a coinicident event. A ^{3}H liquid scintillation counter is an example of an equipment where this mechanism causes unwanted background counts. In such systems, two photomultipliers are arranged with their windows facing each other at a separation of 2-3 cm. To show the magnitude of the effect, a simple coincidence experiment was carried out with two 30 mm photomultipliers operated in coincidence with a window separation of 8 mm. The results are shown in figure 6 in terms of the plateau characteristics. This is a widely used method for the presentation of low light level measurements. The curves are derived by counting the signals which exceed a fixed threshold as the gain of the photomultipier is increased. A curve is presented for each photomultiplier using a random source of single photons as the source. The curve (c) is the coincident background for the pair of tubes (a) and (b) using the same counting thresholds. A similar experiment with two high potassium content tubes gave the results in (d), which shows ten times the activity of the low background pair of photomultipliers.

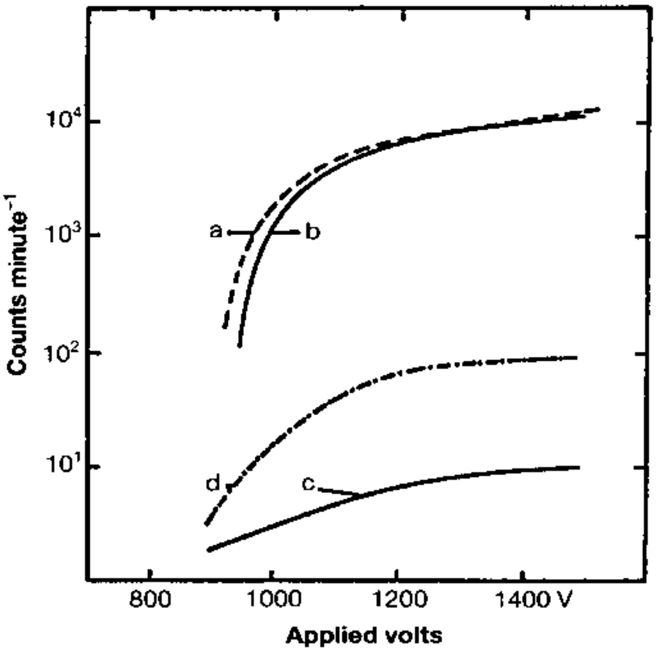


figure 6 illustrating crosstalk in a pair of photomultipliers operated in the photon counting mode. (a) and (b) are the plateau cruves for the tubes operated singly. (c) is the coincidence background characteristic for the pair of low background glass photomultipliers, (a) and (b). (d) is the coincidence background curve for a pair of photomultipliers with high potassium content windows.

4 conclusions

The ultimate detectivity of any system involving photomultipliers is influenced by the levels of radioactivity in the materials from which they are fabricated, principally it is the envelope and window materials that are the major source of activity. In scintllation counters it is the direct interaction of the radiation from residual isotopes that leads to unwanted signals. In photon counting and similar low light level applications it is mainly light produced by Cerenkov radiation that leads to enhanced background. A photomultiplier with a capped DAP base is not recommended for low level work because of the activity of the base and matching socket. Current practice is to use PES - a very low activity material. Although quartz exhibits very low levels of radioactivity, a photomultiplier with such a window may not be the best choice in certain whole body systems because of the activity of the glasses in the graded seal.

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