catch the light

technical reprint R/P092

photomultipliers for low background applications

electron tubes

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Photomultipliers are unequalled for performance in large area, low light level detection. Dark matter and neutrino detectors can call for large numbers of photomultipliers. In order to detect rare Cosmic and man-made events in such studies, special photomultipliers are manufactured with high purity materials. The measurement and purity of these materials are discussed.

1 introduction

Photomultipliers are extremely sensitive light detectors which give a current output proportional to light input. They are sensitive to single photon events and yet detect over a large active area, up to 500 cm^2 in some types. They have high dynamic range up to 10^{12} photons per second, combined with a wide band-width from dc to 100 MHz. They are widely applied throughout the industrial, medical and scientific communities.

The photomultipliers referred to in this article are produced by Electron Tubes Limited in the UK where around 200 staff manufacture photomultipliers, silicon devices, detector packages and detector modules.

2 radioisotopes

Alpha, beta and gamma decays within the materials of the detector can produce interactions with scintillators that have time and energy signatures similar to by-products of the rare events being investigated. While alphas and betas within a photomultiplier will be stopped in the envelope those near the surface of the envelope will not be. All gammas above a few hundred keV will also pass through the envelope and will produce background events that set a limit to low event rate detectivity at energies up to a few MeV.

High purity materials with a minimum of natural potassium, thorium and uranium are essential in the manufacture of photomultipliers for such applications. The concentration of these elements can be determined by measuring the rates of their characteristic gamma decays.

2.1 potassium

Natural potassium contains 0.0117% of ^{40}K which decays by beta emission[1]. The decay is direct to ^{40}Ca with a probability of 0.89 and alternatively to ^{40}Ar following electron capture. A positron and 1.46 MeV gamma (probability 0.107 per ^{40}K decay) are emitted after electron capture.

The calculation below gives the relationship between concentration in ppm and gammas emitted per day per kg i.e. between mass in mg and gammas emitted per day.

1 gram of natural potassium contains A_v/Z atoms where A_v is Avagadro's number (6×10^{23}) and Z is the atomic weight of natural potassium (39). The radioactive isotope ^{40}K has a natural abundance of 0.0117% and so 1 mg of natural potassium contains 1.8×10^{15} atoms of ^{40}K.

The decay rate λ is given by $\ln(2)/T_{½}$ where $T_{½}$ is the half-life of ^{40}K (1.28×10^9 years). Therefore λ is 1.48×10^{-12} decays per day. With a 0.107 probability of a gamma being produced per decay, 1 mg of natural potassium produces $1.8 \times 10^{15} \times 1.48 \times 10^{-12} \times 0.107 = 285$ gammas per day, i.e.

Gammas from natural potassium: $\boxed{\mathbf{1\ ppm = 285\ d^{-1}\ kg^{-1}}}$

2.2 thorium

A similar calculation can be made for thorium. The ^{232}Th decay series (4n) found in **table 1** gives a summary of gammas arising from ^{232}Th and daughter products[3], with 2.74 gammas > 0.1 MeV per chain from a single ^{232}Th decay. The half-life of the decay chain depends on that of ^{232}Th since it is so much longer than any of its daughters.

Calculating as before, 1 g of thorium contains A_V/Z atoms where Z is 232 and so 1 µg of thorium contains 2.59 x10^{15} atoms. Then with $T_{½}$ of 1.41 x 10^{10} years, the decay rate is 1.35 x 10^{-13} d^{-1}.

With 2.74 gammas > 0.1 MeV per chain, 1 g of thorium produces 2.59 x10^{15} x 1.35 x 10^{-13} x 2.74 = 958 gammas per day, i.e.

Gammas > 0.1 MeV from thorium: **1 ppb = 958 d^{-1} kg^{-1}**

2.3 uranium

The ^{238}U decay series (4n + 2) can also be found in many texts[2]. **Table 2** gives a summary of gammas arising from ^{238}U and daughter products[3], with 2.16 gammas > 0.1 MeV per chain from a single ^{238}U decay. The half-life of the decay chain depends on that of ^{238}U since it is so much longer than any of its daughters.

Calculating as before, 1 gram of uranium contains Av/Z atoms where Z is 238 and so 1 µg of uranium contains 2.52 x10^{15} atoms. Then with $T_{½}$ of 4.47 x 10^{9} years, the decay rate λ is 4.25 x 10^{-13} d^{-1}. With a 2.16 gammas > 0.1 MeV per chain, 1 µg of uranium produces 2.52 x10^{15} x 4.25 x 10^{-13} x 2.16 = 2.31 x 10^{3} gammas per day, i.e.

Gammas > 0.1 MeV from uranium: **1 ppb = 2310 d^{-1} kg**

table 1 gamma summary table for Thorium from reference[3]

Isotope	Split	MeV Low	MeV High	% Total	% > 0.1 MeV	Most Abundant MeV	%	Next most Abundant MeV	%
232Th		0.012	0.125	9	0	0.012	8		
228Ra		0.007	-	-	0				
228Ac		0.013	1.887	166	119	0.013	39	0.911	28
^{228}Th		0.012	0.216	11	0	0.012	10		
224Ra		0.012	0.465	5	4	0.241	4		
220Rn		0.549	-	-	0				
216Po		0.805	-	-	0				
212Pb		0.011	0.300	108	49	0.839	45	0.077	18
212Bi		0.010	1.806	29	20	0.727	12	0.010	8
212Po	64%	-	-	-	0				
208Tl	36%	0.011	2.615	239x0.36	228x0.36	2.614	99x0.36	0.583	84x 0.36
Total				**414**	**274**				
Conclusion: 4.14 gammas per 232Th decay with 2.74 gammas > 0.1 MeV									

table 2 gamma summary table for Uranium from reference[3]

Isotope	Split	MeV Low	MeV High	% Total	% > 0.1 MeV	Most Abundant MeV	%	Next most Abundant MeV	%
238U		0.013	0.066	9	0	0.013	9		
234^{Th}		0.013	0.133	19	0	0.013	10	0.063	4
234Pa		0.013	1.001	2	1				
234U		0.013	0.121	11	0	0.013	11		
230Th		0.012	0.168	9	0	0.012	8		
226Ra		0.012	0.310	5	3	0.186	3		
222Rn		0.512	-	-	0				
218Po		-	-	-	0				
214Pb		0.011	0.839	104	78	0.352	37	0.295	19
214Bi		0.011	2.448	136	134	0.609	46	1.765	16
214Po		0.797							
210Bi									
210Po		0.803	-	-	0				
Total				**323**	**216**				
Conclusion: 3.23 gammas per 232Th decay with 2.16 gammas > 0.1 MeV									

table 3 analyses of special glass for SNO/Borexino at various laboratories

Special Melt Schott 8246 Concentration	Natural Potassium ppm	Error +/- ppm	Thorium ppb	Error +/- ppb	Uranium ppb	Error +/- ppb
California	33	3	18	4	18	2
CENBG	30	1	25	8	23	5
Guelph			15	5	21	2
Holborn	33	8	10	8	34	3
INFN	30		20		25	
Southampton	19	2	9	1	16	1

table 4 weight of materials in Electron Tubes Limited Photomultipliers

PMT Type	Diameter mm	Glass Weight g	Metal Weight g	Ceramic Weight g	Total Weight g
9078	19	10	9	1	20
9111	25	11	7	2	20
9125	30	24	16	10	50
9102	38	29	24	7	60
9266	52	70	20	10	100
9265	75	105	20	10	135

table 5 material purity used in Electron Tubes Limited Photomultipliers

Material	Natural Potassium ppm	Error +/- ppm	Thorium ppb	Error +/- ppb	Uranium ppb	Error +/- ppb
glasses						
Schott 8245	1390	20	860	30	1090	20
ETL X	300	10	246	20	101	38
ETL B53	60	15	30	10	30	20
metals						
ETL Parts	0	15	30	10	0	10
ceramics						
96% Pure	200	70	130	30	50	20
99.6% Pure	20	20	60	20	50	10

Taking the 52 mm diameter type 9266B as an example, **table 6** shows the gammas > 0.1 MeV emitted for the
different materials. It is readily apparent that the glass dominates. Various glass options are available to suit requirements; the general purpose 9266B uses the Electron Tubes Ltd. low background glass (x) throughout while the variant 9208B has the ultra low background glass (U) throughout Other types in **table 4** use the glasses listed in **table 6** and can be calculated similarly.

table 6 gammas per day from a type 9266 photomultiplier with various materials.

Source	Units	Metals	Ceramics		Glass		
		ETL Parts	96% Pure	99.6% Pure	Schott 8245	ETL X	ETL U
Natural Potassium	mg	0	2	0.2	97	21	4
Thorium	µg	0.6	1.3	0.6	60	18	2
Uranium	µg	0	0.5	0.5	6	7	2
Natural Potassium	dpm	0	0.4	0.04	19	4.2	0.8
Thorium	dpm	0.4	0.9	0.4	40	12	1.3
Uranium	dpm	0	0.8	0.8	121	11	3.2
Total	**dpm**	**0.4**	**2.1**	**1.24**	**180**	**27.2**	**5.3**

dpm = decays per minute

3 comparative analyses

In any practical counter the efficiency is less than 100% and measurements are made by comparison to known standards. Nevertheless the above calculations are useful in estimating the maximum number of background events which arise from the material in a detector. One special melt of glass for photomultipliers has been measured at a number of laboratories around the world using radio-assay techniques and also at Southampton University in the UK using inductively coupled mass spectrometry. The concentrations are summarised in **table 3**.

4 photomultipliers

Photomultipliers are constructed from glass, metals and ceramics. **Table 4** gives weights of these materials in the most common ElectronTubes Limited photomultipliers used for scintillation applications. The potassium, thorium and uranium contents of the most frequently used materials are given in **table 5**.

5 conclusions

The gamma decay rate of potassium, thorium and uranium can be used to determine their concentrations in materials used in detectors for scientific research. These rates can also be used to determine the gamma background in the detector due to these same materials.

6 acknowledgements

Thanks are due to Dr. A G Wright, Marketing Director of Electron Tubes Limited, who developed the decay rate calculations and advised throughout.

7 references

[1] Lederer, Hollander and Perlman, *Table of Isotopes 6th Edition.*

[2] *The Radiochemical manual 2nd Edition*, editor B. J. Wilson.

[3] Grove Engineering, *RADDECAY.EXE freeware* (Data source RSIC).

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