CENSORED INTRODUCTION OF MSC DISSERTATION

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In process plants, before the advent of computerised automation there would be trained engineers on-site maintaining equipment, monitoring equipment and taking measurements. Fluid levels may be measured by eye, often with the depth marked on the inside walls of fluid vessels. Fluid levels, densities and chemical compositions would be measured by manually obtaining samples and processing them in an on-site laboratory. As computers became more versatile and more available, machinery could be monitored and controlled by electronic systems thus reducing the operating costs of process plants. Full automation to enable unmanned process plants required new instrumentation technology, capable of obtaining all necessary measurements (flow, level, density, composition, etc) accurately whilst not requiring regular maintenance or calibration. As temperatures may vary rapidly and over wide ranges in a process environment, the instruments must be thermally stable – able to provide data with consistent precision over the range of temperatures that they will encounter. A robust way to measure densities and fluid levels is to use gamma radiation – such radiation will travel metres through gases (such as air) without significant absorption, but is absorbed more strongly in liquids and solids – the absorbance is determined by the density of such materials and the distance that the gamma rays travel through them.

When oil is extracted from beneath the sea, it is in a mixture with gases, water, rocks and sand. To separate the oil, it is put in a separation column and left to separate under gravity. The levels at which the different fractions exist, and how well they have separated can be obtained by manually extracting samples at various depths and analysing them, however this is time-consuming and requires extra staff. Due to the volatile nature of the gases and the oil, automating

the level and density measurements should ideally avoid introducing heat or electricity to the separation column. Nucleonic instrumentation provides a potential solution to this. Gamma sources may be located outside the separation column, as may the detectors (Figure 1.1-A). No new equipment or materials are introduced to the separation column. A column of collimated sources is installed externally on one side of the column, while a column of detectors with collimators is installed on the opposite side, or alternatively – one source and one detector are used, and are electro-mechanically scanned up and down the column. The density of the substance(s) between the sources and the detectors (including the walls of the separation column) determines the reduction in intensity of the gamma rays as they traverse the column.

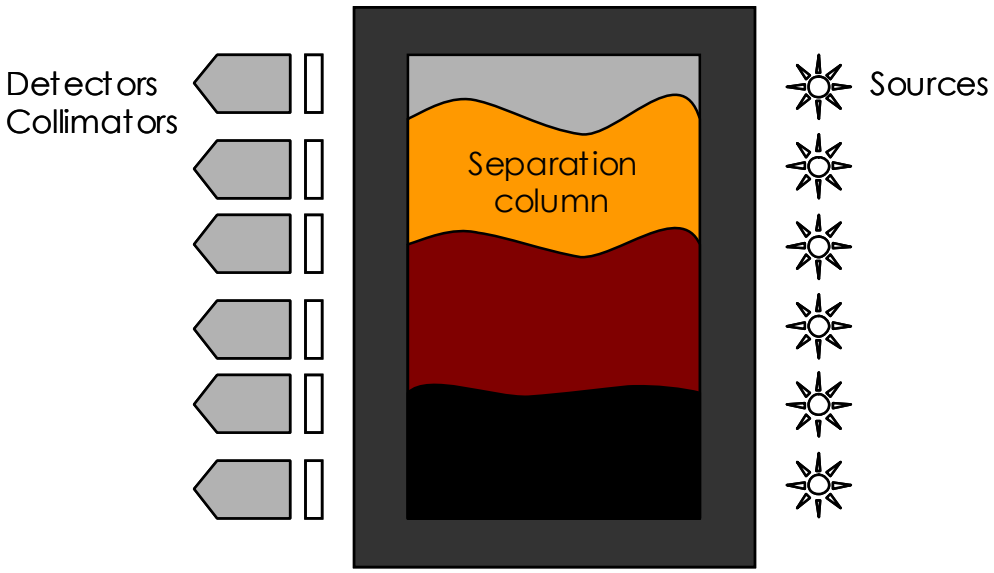

Figure 1.1-A: Using nucleonic instruments to measure fluid levels in a separation column.

Gamma sources are inherently stable; there is no known temperature dependence of the output (rate of gamma photon emission) of a gamma source – or indeed any dependence on the external environment. The decrease in intensity of a gamma source with time may be predicted with high precision, as it follows an exponential decay curve. Although the source is stable, the detectors require analogue electronics and are therefore unstable. Commonly, this is counteracted by using two gamma sources of different emission energies, one incorporated into the detector (reference source) and one on the other side of the column (object source). The detector measures a spectrum, obtaining the intensity of gamma photons over several different energy bands. The intensity of the reference source at the detector is known, as they are adjacent. The difference between the measured intensity and the expected intensity is used to correct the measured intensity of the object source, overcoming the instability of the detector. This introduces another source of error: the uncertainty in the energy values when spectra are obtained. If the reference source produces a peak with narrow spectral width, and of known energy then this source of error can be resolved by scanning a range of energy values. Assuming the most intense peak in the range is the reference peak, the spectral coordinate of the reference peak may be used to determine the position of the object peak. When the reference source does not provide a narrow peak, or there is no reference source, then other more complex methods are required. The detectors used in this investigation are assumed to have no measurable change in the proportion of gamma photons that they detect (their "quantum efficiency") at different temperatures, hence the instability manifests primarily on the energy axis of the obtained spectra rather than the intensity axis.

Measuring the depth of various fractions in a separation column requires multiple detectors or mechanically scanning the column, however measuring the level of a single fluid in a container may be achieved with just one detector (Figure 1.1-B). The intensity of the radiation at the detector falls off as the distance between the detector and the source increases, following an inverse square law.

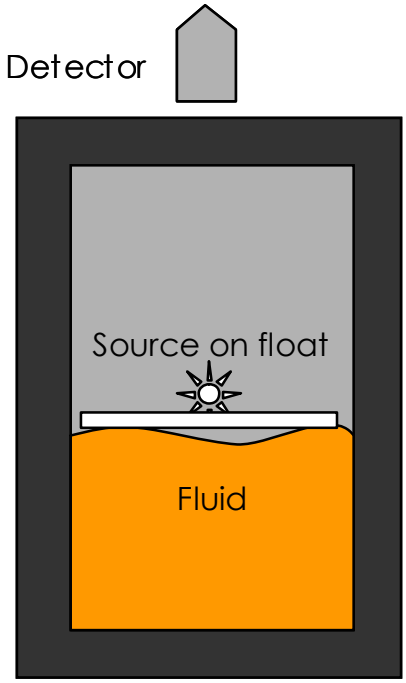

Figure 1.1-B: Measuring a fluid level with just one detector.

This document discusses the background to gamma spectroscopy, current stabilisation methods (including but not limited to detecting peaks and tracking them) and provides some novel stabilisation methods intended to overcome certain limitations that are encountered with cheaper detectors.

1.1. Gamma radiation

Since the discovery of X-rays (and implicitly, X-ray detection) by Hittorf[1] in the 19th century, then the subsequent study of them by Röentgen near the end of the century, high-energy radiation has been finding widespread use across the engineering and medical fields. The lack of ambient X-rays[2] and gamma rays at the Earth's surface (in comparison to visible light and infrared, see Figure 1.1-A) allows high-contrast images to be produced with high-energy photons. The ability of such photons to penetrate dense and opaque materials allows non-invasive imaging of parts within a machine or of materials/structures within a container.

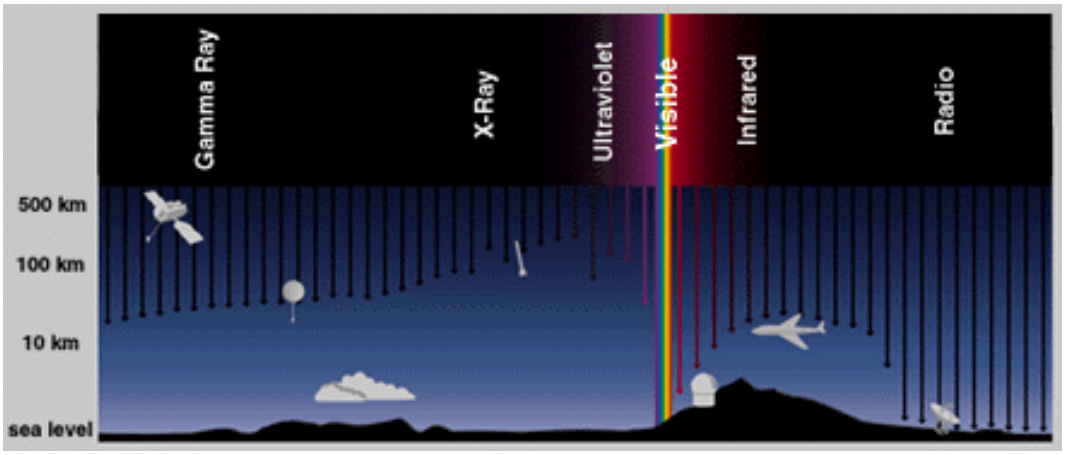

Figure 1.1-A: Penetration of gamma rays from space into the Earth's atmosphere[3] (Source: NASA)

While cameras* and detectors for analysing materials with visible light have existed for centuries[4] partly due to the availability of sources (e.g. the Sun) and detectors (e.g. the eye), analysis with X-rays required the development of new detector technologies†.

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* A brief history of cameras as optical systems may be found in my slides at http://www.battlesnake.co.uk/_uni/ultra-pres.pdf, which accompany the essay at http://www.battlesnake.co.uk/_uni/ultra.pdf

† Not strictly true, as Röentgen used standard photographic materials to produce his famous image of the bones of the hand. For instrumentation, new technologies were

Although X-rays are conventionally defined as: *"An electromagnetic wave of high energy and very short wavelength (between ultraviolet light and gamma rays)"*[5], there is a considerable overlap between the energy ranges considered to represent X-rays and those considered to represent gamma rays. A more practical way to differentiate between the two in this overlapping region of the spectrum is to consider the source of the radiation[6]:

- X-rays: high-energy (beyond ultraviolet) radiation emitted from *outside* the nucleus (commonly by electron transitions) – such as cathode rays.
- Gamma rays: high-energy (beyond ultraviolet) radiation emitted from *within* the nucleus (commonly by nuclear processes).

Due to the similarity between X-rays and gamma rays (with respect to the overlapping range of photon energies), much of the detector technology and processing techniques that were developed for X-ray instrumentation may also be applied to gamma ray instrumentation.

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required as photographic materials were generally single use and required slow developing processes after exposure.

1.2. Interactions between gamma rays and matter

There are many photon detection technologies* in use, but few are sensitive to gamma rays. Additionally, the ionising nature of gamma rays results in deterioration of common detectors when exposed to strong gamma sources. Gamma rays can interact with matter in three main[7,17:p93] ways:

- Photoelectric effect:

  The incident gamma ray photon has sufficient energy to liberate a bound (atomic or molecular) electron. This results in ionisation of the atom or molecule to which the electron was bound.

- Compton scattering

  Photons with energy sufficiently greater than the binding energy of the electrons that they are absorbed by, may only transfer part of their energy to the electron – resulting in both an ejected electron and also emission of a lower energy photon.[8]

- Pair-production

  Where the photon energy exceeds the energy of an electron-positron pair (i.e. $E_\gamma \gtrsim 1.022$ MeV), the photon may be absorbed by a nucleus and such a pair may consequently be emitted. The effects of pair production will not be considered in this document, as photon energies used will mostly be below the pair-production threshold. The positron may eventually annihilate an electron, resulting in the

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* To name a few: Coupled-charge device (CCD), CMOS sensors, avalanche photodiodes, Golay cells and thermopiles.

emission of two 511 keV photons (considered to be gamma rays, despite occurring outside the nucleus).

As gamma rays can ionise organic molecules, they are carcinogens.[9]

1.3. Detector types

There is a variety of different technologies* nowadays for detecting gamma radiation, via the interactions described in the previous section. Some are mostly historical, while others balance compromises between various detector criteria including:

- Spectral resolution: can the detector distinguish between photons of different energies, and to what energy resolution?
- Stability: how dependent is the response of the detector to temperature? Does the response change with time (drift)? Does the detector exhibit hysteresis after being exposed to high photon fluxes or pulse energies?
- Physical properties (size, mass, robustness): is the detector to be used in a portable device, or a large, fixed instrument? Will the detector be subject to strong shocks or vibrations?

1.3.1 Roentgen's screen

While Roentgen's famous image was obtained with x-rays rather than gamma rays, as the first image produced with high-energy radiation is it of historical significance. Roentgen was investigating the fluorescence that occurs when a high voltage is applied to a Crookes tube, when he noticed that a barium platinocyanide plate that was approximately 9ft from the tube (and blocked by a piece of opaque cardboard) flashed when he discharged a current into the tube.[10] Upon

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* Solid-state detectors (such as photodiodes) have been omitted, as TracerCo believe them to exhibit considerably more drift and ageing than photomultipliers.

further investigation, he found that "shadows" could be cast on the plate when certain materials were placed between the tube and the screen (Figure 1.3-A). In addition to this, he also demonstrated the medical potential of x-ray imaging by producing an image of the bones in his wife's hand.

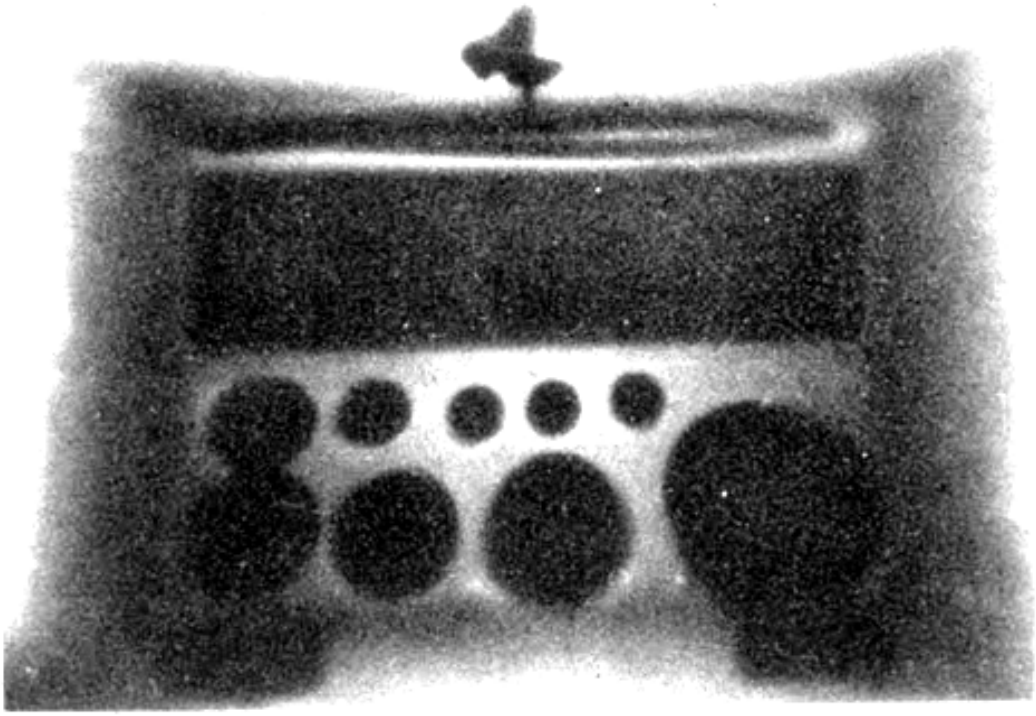

Figure 1.3-A: X-ray image of brass weights inside a wooden box[10]

1.3.2 Geiger-Müller tubes

The ionising nature of gamma radiation results in gamma ray-matter interactions producing free electrons. Consider a monatomic gas (commonly, a halogen or a noble gas such as Argon), contained between two electrodes with an applied voltage that is less than the breakdown voltage of the gas (creating an electric field but with no current flowing). When an atom in the gas is ionised by a gamma ray, it is attracted towards the cathode. Conversely, the liberated electron travels towards the anode. At sufficiently high voltages, the acceleration of the electron over the electric field gradient

may result in the electron becoming energetic enough to ionise more atoms, producing a cascade of electrons. This enables Geiger-Müller tubes ("GM tubes") to detect individual photons, in addition to charged particles (including alpha and beta particles).

For a potential difference of 2 kV across a 10 cm gap, an electron produced near the cathode will gain up to 2 keV of energy by the time it reaches the anode. For comparison, the first ionisation energy of Argon is[11] only 15.8 eV; such an electron could ionise a hundred more argon atoms before reaching the anode! Each of these liberated electrons may then in turn ionise more atoms as they are accelerated across the gradient (Figure 1.3-B), resulting in a measurable, momentary decrease in the voltage across the electrodes.

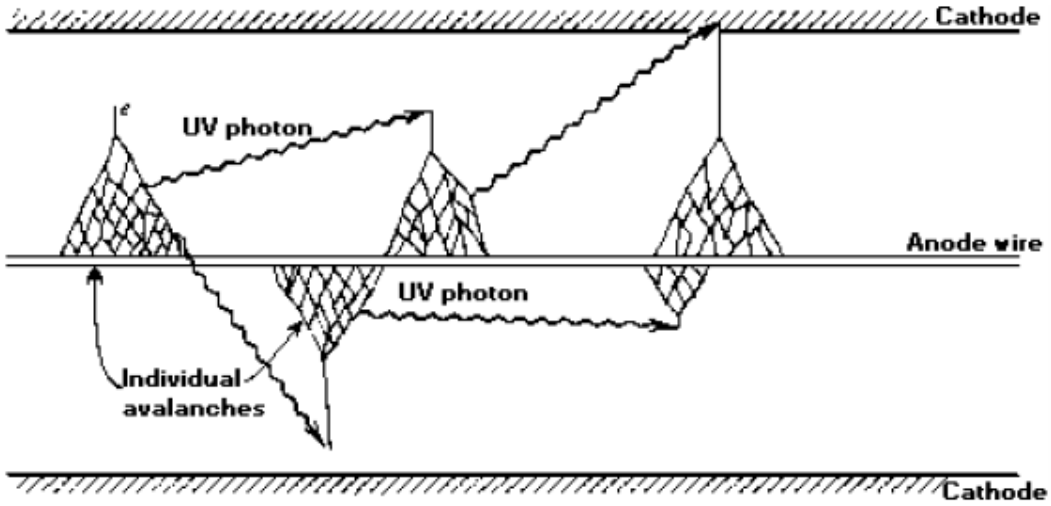

Figure 1.3-B: Cascade of electrons generated in a Geiger-Müller tube[12].

The ionised atoms are considerably heavier than the liberated electrons, and are accelerated at a lower rate by the electric field. These ions exhibit a shielding effect, reducing the electric field intensity in the tube and thus reducing the chance that future ionisations (by gamma rays) will cause cascades, until the ions eventually disperse. The "dead time" in which the tube cannot respond

to incident radiation is generally on the order of hundreds of microseconds[12,13]. As the number of liberated electrons depends on where in the electric field the initial ionisation occurred, Geiger-Müller tubes can only count photons, they cannot measure the photon energies.

In order to increase the probability of a gamma ray interacting with the gas within the tube, noble gases with heavier nuclei are often used in tubes designed specifically for gamma rays. This consequently results in longer dead-times, as heavier ions will take longer to disperse. Another solution is to use heavy metal (e.g. lead) cathodes. The greater absorbance of these in comparison to cathodes composed of lighter elements results in a greater probability of gamma rays interacting with the detector, while the lower ionisation energy of such materials results in the production of more highly energetic electrons. Increasing the relative amount of interactions that occur at the cathode forms the basis for the *photomultiplier tube*.

1.3.3 Photomultipliers

GM tubes can only detect radiation with sufficient energy to ionise atoms within the tube. In addition, they are unable to measure the energy of the detected particles. In a similar technology, the photomultiplier tube (PMT), the detector window is made of a material with a low work function (i.e. the energy required to remove an electron from the material surface is low). Between the photocathode and the anode are several "dynodes", also with low work functions. The dynodes are held at a voltage between those of the anode and the photocathode.

An incoming photon liberates an electron from the photocathode via the photoelectric effect. This is the accelerated towards the first dynode where it collides, releasing several more electrons from the

dynode. These are then accelerated towards the next dynode, where each electron liberates several more electrons (via secondary emission). The average number of electrons released via secondary emission depends on the voltage of the dynode. The dynodes thus provide controllable gain, increasing the number of electrons that are liberated when a single photon interacts with the photocathode (see Figure 1.3-C). Adding more dynodes increases the gain exponentially; a gain factor of over a million is possible in modern tubes[14].

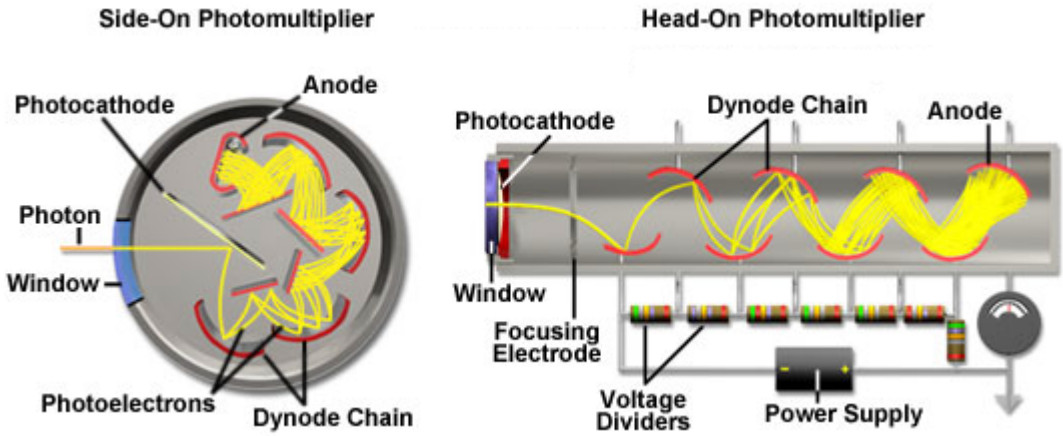

Figure 1.3-C: Anatomy of a photomultiplier tube[15]

When an electron cascade reaches the anode, it creates a momentary current. This current may be measured by observing a momentary dip in the voltage across the tube (see Figure 1.3-D). The height of a pulse corresponds to the number of photons in the pulse.

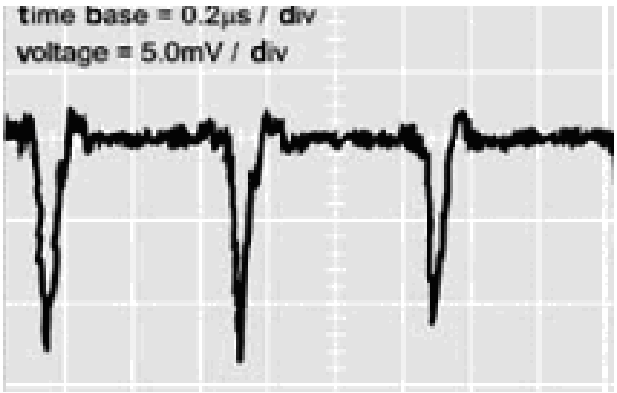

Figure 1.3-D: Voltage response of a photomultiplier to photon pulses[16]

As the number of electrons released by secondary emission depends on the voltage of the dynode, the gain of the tube can be controlled via the voltage applied to it. Because no heavy ions are produced within the tube, there is no "dead time" – the ability to temporally resolve two pulses is instead dependent on the width of the output pulses (which is typically on the order of nanoseconds) and the processing electronics/algorithms. Consequently, fluctuations and instabilities in the voltage source will manifest as unwanted fluctuations in the PMT output.

Unlike GM tubes, photomultipliers are able to respond to a wide band of photon energies, extending through the visible part of the spectrum and infrared region. As photomultipliers rely on electron emission from materials with low work functions, individual electrons will occasionally be released by the photocathode and dynodes via thermal excitation resulting in false "counts" occurring occasionally. False counts arising from electrons released thermally from dynodes may be rejected, as the measured voltage dip across the tube will not be as high as that for an electron released from the photocathode. This is because less dynodes are involved in the cascade – resulting in less gain. The current arising from thermionic emission is known as "dark current", as it remains when no light is actually incident on the tube.

If two photons are incident in quick succession (so the electronic peaks generated by them would overlap considerably), a single large peak may instead be produced. This occurs as the electron cascades from each photon reach the anode within the pulse rise time, so are counted as one (photon) event.

Various photocathode materials are available, exhibiting different spectral responses (Figure 1.3-E) and quantum efficiencies in addition to varying dark currents. The choice of photocathode depends on the

intended application. A more detailed overview of photomultiplier design parameters and photomultiplier implementations may be found via online at ET Enterprises[16].

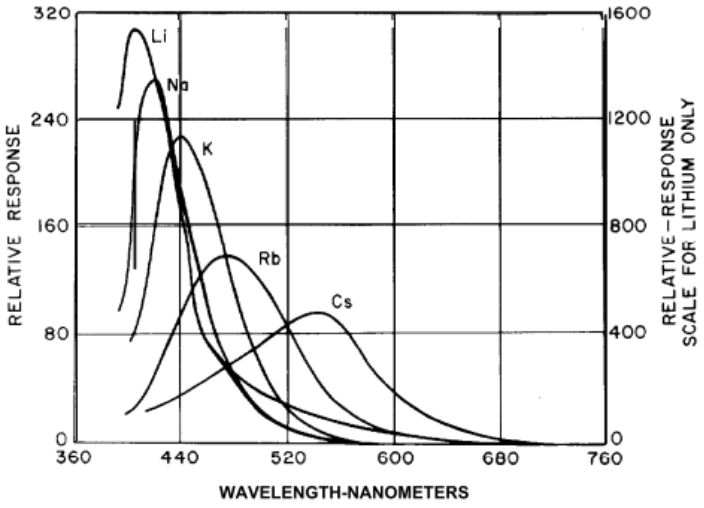

Figure 1.3-E: Spectral responses of photocathodes composed of various group I elements.[17]

Photomultiplier tubes are available in a variety of sizes, and while not as small as a photodiode, they may be as compact as a typical whiteboard marker (Figure 1.3-F).

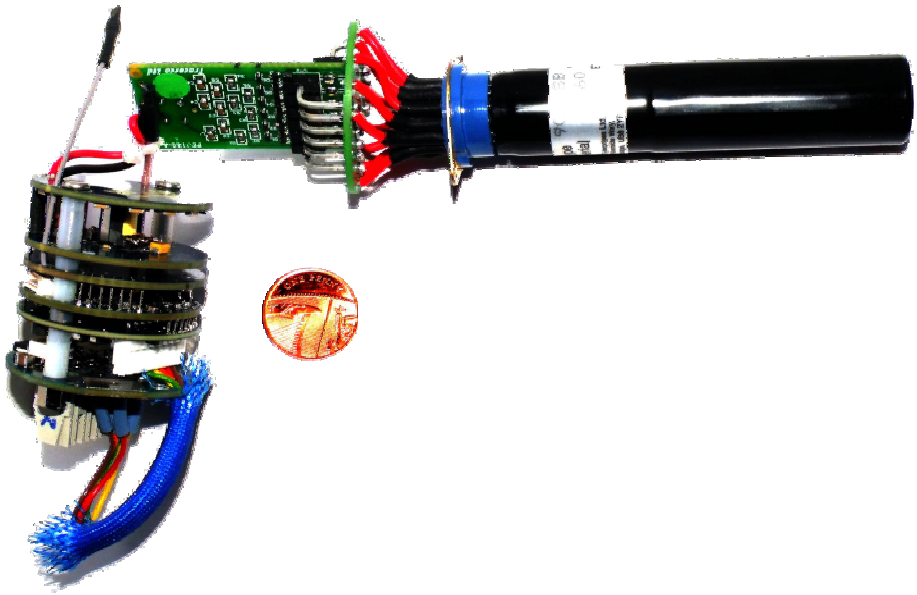

Figure 1.3-F: A typical photomultiplier tube, with some processing circuitry and a high-voltage generator.

1.3.4 Scintillators

A scintillator responds to incident radiation by emission of some other type of radiation. For example, thin sheets of zinc sulphide will produce flashes of light when impacted by alpha particles, but will only interact with a small proportion of incident gamma or x-ray photons, allowing selective detection of alpha particles. Common scintillation mechanisms used in gamma ray detectors are fluorescence and phosphorescence. Via these mechanisms, a high-energy gamma ray (100 keV to several MeV) may excite several electrons/atoms/molecules in the scintillator, resulting in many photons being emitted by the scintillator (for comparison, deep-blue light at 400 nm has a photon energy of around 3 eV; red is approximately 1.5 eV). The more energetic the incident photon, the larger the quantity of photons will be emitted by the scintillator. Many different scintillator materials exist for detection of different types of particle (including ions, neutrons and electrons) or different energy ranges of x-rays/gamma rays.

When combined with a photomultiplier, the energy of an x-ray or gamma ray photon incident on the scintillator may be measured indirectly by the photomultiplier. A high-energy photon excites one or more electrons in the scintillator. These electrons eventually relax, some radiatively. The radiative relaxation produces lower-energy photons in the visible/UV region. A higher-energy incident photon will liberate more electrons – therefore producing more low-energy photons. These photons are then detected by the photomultiplier. As they are all produced in a short interval*, they create one large electron shower in the photomultiplier, rather than separate pulses. The resulting electronic signal from the photomultiplier encodes the number of detected photons – which allows the energy of the original high-energy photon to be estimated.

The photoelectric effect is not the only interaction occurring within the scintillator; a high-energy incident photon may also undergo many Compton scattering interactions, reducing its energy before it is finally absorbed via the photoelectric interaction. This results in a wide band of low-energy noise in the spectrum (Figure 1.3-G). When the photon energy is greater than 1.022 MeV, the photon may interact with nuclei, producing electron-positron pairs. When one or both of the 511 keV photons released† escape the scintillator, the detected photon energy will be reduced by 511 keV or 1.022 MeV. This results in the addition of two spectral peaks to the observed spectrum. These are referred to as the "escape peak" and the "double-escape peak" respectively and are observed at energies 511 keV and 1.022 MeV below the energy of the photopeak.

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* Dependent on the fluorescent lifetime of the scintillator

† By annihilation of the positron with an electron

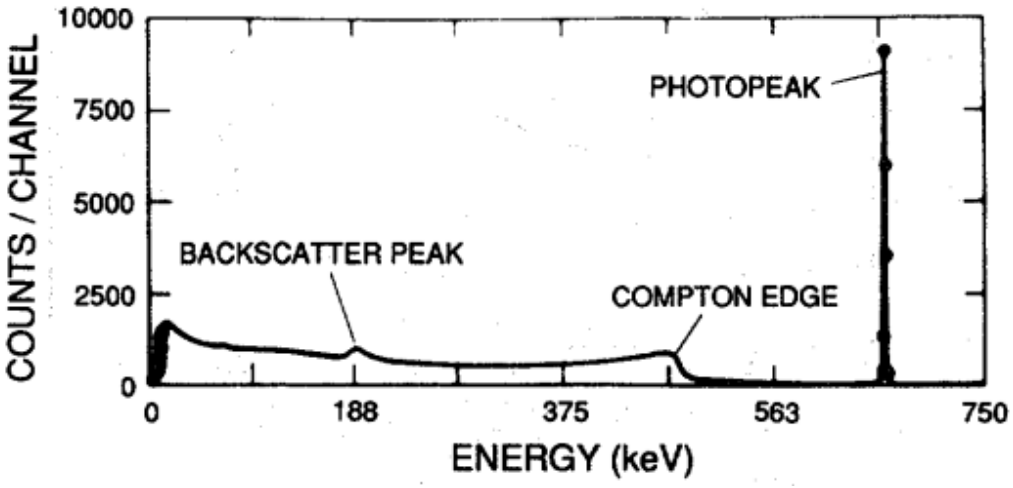

Figure 1.3-G: Gamma spectrum, illustrating Compton noise[18]

Crystal scintillators

The most common[17,p93] scintillator used in gamma ray and x-ray detection is crystalline sodium iodide, doped with thallium. These scintillators have high light output[19] and are often compact in size (Figure 1.3-H).

Figure 1.3-H: Sodium iodide scintillator, next to an English one-pence coin for comparison.

Incoming gamma rays excite electrons in the sodium iodide into the conduction band. These electrons may then move through the lattice until they reach a thallium atom, which provides states within the otherwise forbidden region of the energy landscape. The electron then makes a radiative transition as it energetically relaxes through these states. As the concentration of thallium atoms is very low (less than 1%, typically around 0.1%)[20], the scintillator is mostly transparent to the produced photons. If the scintillator were partially opaque to its own emissions, flashes originating further from the detector would be attenuated as they travel further through the scintillator, resulting in "blurring" of the spectral response of the scintillator. Sodium iodide scintillators have a decay time-constant of around 250 nanoseconds[17,p93] at room temperature, although this may reduce to 100 ns at higher temperatures[21]. The decay time of a scintillator limits its ability to resolve two separate photons that are incident to it in close succession.

Plastic scintillators

The quantum efficiency of a crystal scintillator may be impaired by defects within the crystal. Additionally, production of large crystal scintillators is typically expensive*. Plastic scintillators offer a (usually) cheaper alternative, as they can be grown (often more easily[22] than crystals) to any size and shape†[23], and are often less brittle than crystal scintillators. By utilising a mixture or material containing several different fluorescent functional groups, it is possible to create a

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* NaI is also hydroscopic so must be encased in waterproof material. Commonly, the scintillator is encased in a reflective metal shell, with one end open and coated with waterproof grease.

† With lengths in excess of a metre, strands of such scintillators enable fibre-based detection

scintillator that allows conversion of the initial photons (in response to external radiation) to a specific wavelength (for optimum response from the photomultiplier), via a chain of different wavelength-conversions provided by the different functional groups.[22] Another considerably more efficient mechanism to alter the emission spectrum of the scintillator utilises resonance energy transfer (RET), which does not require an intermediate photon (energy is transferred between groups via dipole interactions).[24,p13] Ikezaki[25] has presented an in-depth discussion of energy transfer in anthracene-doped polyvinyltoluene scintillators.

Anthracene absorbs strongly[26] beyond blue (Figure 1.3-I) and re-emits in the range from the green to ultraviolet[26] regions of the spectrum (Figure 1.3-J), via fluorescence.

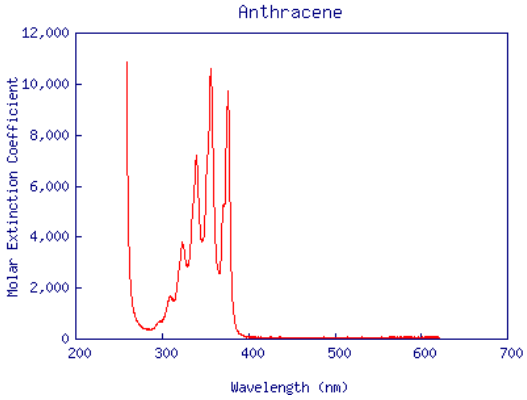

Figure 1.3-I: Absorption spectrum of anthracene[26]

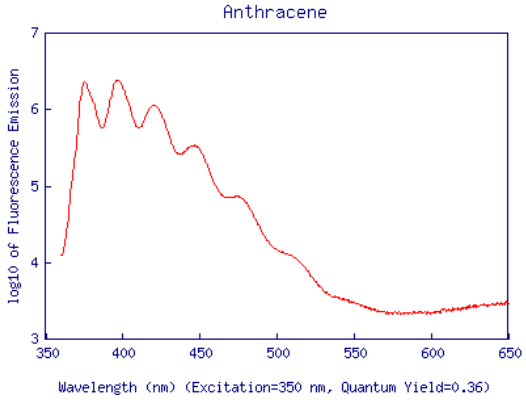

Figure 1.3-J: Fluorescence spectrum of anthracene[26]

A consequence of this is that anthracene will absorb some of its own emissions. In a long scintillator, flashes originating from the far-end (relative to the detector) of the scintillator will be attenuated considerably more than flashes originating from the near-end by the

time they reach the PMT*. Gamma rays that are absorbed at the far-end of the scintillator will be measured to have lower energies than gamma rays (of the same actual energy) that are absorbed at the near-end of it, resulting in a decrease in the overall spectral resolution of the device.

Substances containing aromatic rings fluoresce, allowing some to be used as scintillators. Benzene has a negative electron affinity (it attracts electrons), while its pi-system† creates regions of high electron density. When an electron is photoexcited by a high-energy photon, it may excite other electrons before relaxing. Anthracene is composed of three fused benzene rings (Figure 1.3-K). The high electron density within the rings is illustrated in Figure 1.3-N. The structure of styrene is shown in Figure 1.3-L, to provide a comparison with vinyl toluene (Figure 1.3-M). The addition of a methyl group to styrene (to form vinyl toluene) increases the electron density of the ring.

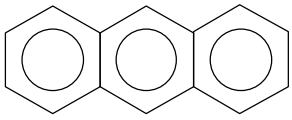

Figure 1.3-K: Anthracene

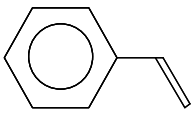

Figure 1.3-L: Styrene

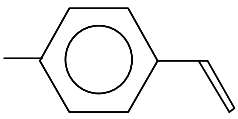

Figure 1.3-M: Vinyl toluene

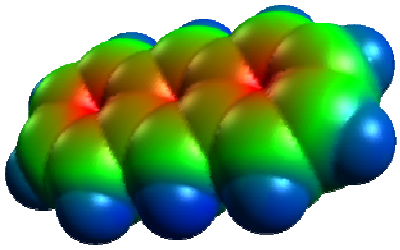

Figure 1.3-N: Electrostatic potential at the Van der Waals surface of anthracene (rendered on Avogadro 1.0.3)

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* Assume that the scintillator is coated with reflective paint, so photons originating from the scintillator can only escape via the end that is interfaced with the PMT.

† Overlapping pi-orbitals, oriented normal to the plane of the ring create dense regions of delocalised electrons above and below the ring.

1.4. Stabilisation

The responses of both the scintillator and the detector (PMT or photodiode) vary with temperature. Increased thermal quenching results in a decrease of light output from the scintillator as the temperature increases[21,27], while thermal excitation of electrons in the photocathode and dynodes results in an increase of gain with photomultipliers at higher temperatures. The increased probability of thermionic emission in the photomultiplier also results in an increase in dark current.

As the energy of a photon is calculated from the number of electrons that impact the anode in a single pulse, the effect of an increase in gain is a stretching of the measured spectrum (Figure 1.4-A). [redacted]

(Figure 1.4-B).

Figure 1.4-A: [redacted]

- x-axis: apparent photon energy (arbitrary units)
- y-axis: count rate (s^{-1})

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* TracerCo T251 using 125mm PVT scintillator

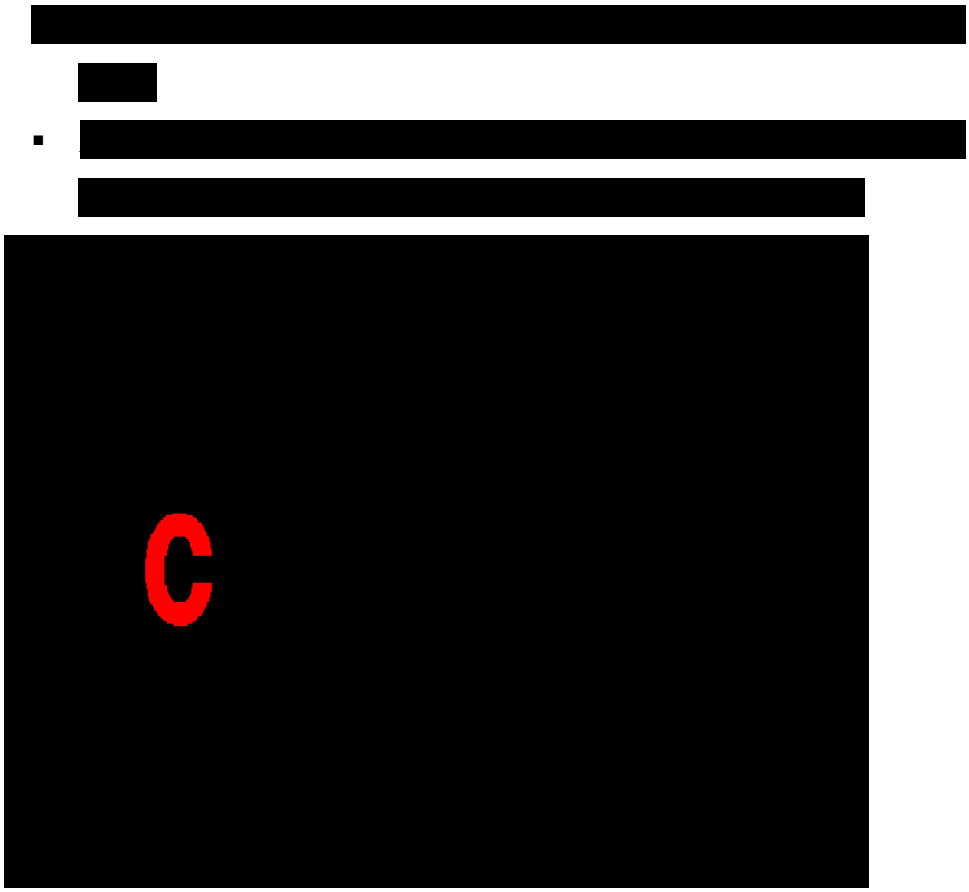

Figure 1.4-B: Low-energy counts at different temperatures (see caption of previous image for legend)

This thermal drift may be compensated for by adjusting the gain of the PMT (via the voltage applied to it), however a simple lookup table will not suffice to provide the voltage values as the thermal responses of separate photomultipliers (from the same manufacturer) vary considerably (Figure 1.4-C).

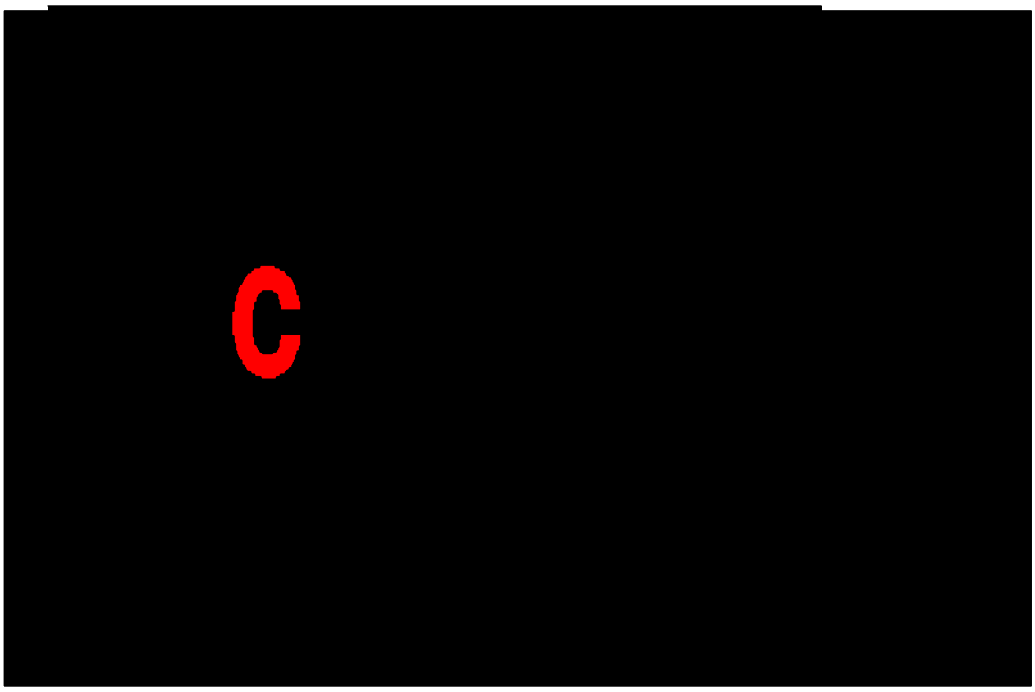

Figure 1.4-C: Thermal drift of a gamma-ray peak on different detectors of the same design.[28] X-axis is temperature and Y-axis is peak position.

Photomultiplier tubes also experience "ageing", where their response permanently changes with usage. Both the photomultiplier and the scintillator will exhibit hysteresis in response to intense radiation.

The gain of the photomultiplier can be adjusted in order to compensate for these various sources of drift. As the photon energy of a nuclear gamma-ray source does not vary with age or temperature, [redacted]

1.5. Fate and legacy of a gamma photon: a typical signal path for a photomultiplier-base scintillation counter

For this example, a Cs-137 (caesium) source will be used with a PVT scintillator, a simplified photomultiplier and typical processing circuitry. A system flowchart illustrating the following processes may be found at (p.28).

A Cs-137 atom decays to Ba-137 (barium), via beta emission. Ninety-five percent of Cs-137 decays result in a metastable nuclear isomer of barium, Ba-137m, which decays to the ground state by emission of a 662 keV gamma photon. A 662 keV photon enters the PVT scintillator, experiencing multiple Compton interactions (reducing the energy of the photon), before being completely absorbed via the photoelectric interaction, resulting in an excited electron. This electron collides with others, transferring energy to them and exciting them. A proportion of these electrons relax fluorescently, emitting photons in the visible to ultraviolet region. While most of these photons are absorbed by the scintillator or escape the detector, some will be absorbed by the photocathode of the photomultiplier. A fraction of these (typically up to ~30%) will liberate an electron from the photocathode via the photoelectric effect, which will be accelerated by the electric field gradient within the tube (and often, guided by focusing fields). These accelerated electrons then impact upon a dynode, releasing many more electrons via secondary emission. After several dynode interactions, the original current will have been multiplied (via secondary emissions) to create a considerably larger current (up to or over a million times stronger). This transient current

causes a measurable, but small* transient decrease in the voltage between the anode and cathode†, shown in Figure 1.5-A.

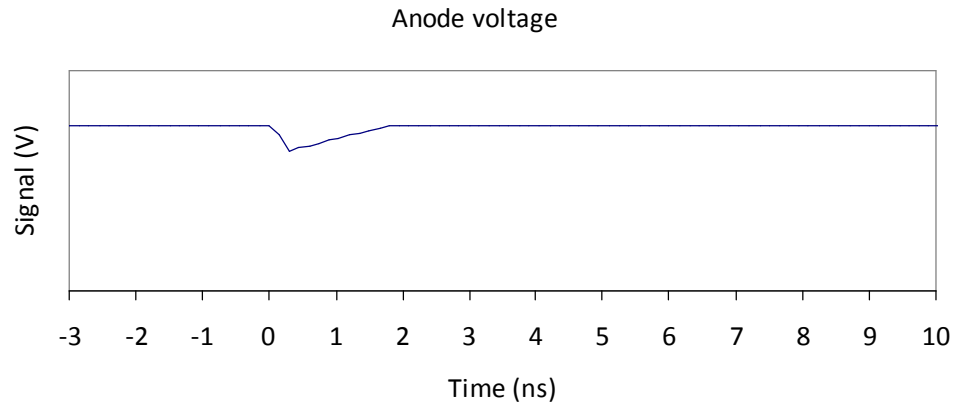

Figure 1.5-A: Typical response of photomultiplier anode voltage to a photon burst from the scintillator

A resistor-capacitor (RC) network at the anode filters the offset from this‡ signal (Figure 1.5-B), which is then amplified by a class-B amplifier (Figure 1.5-C).

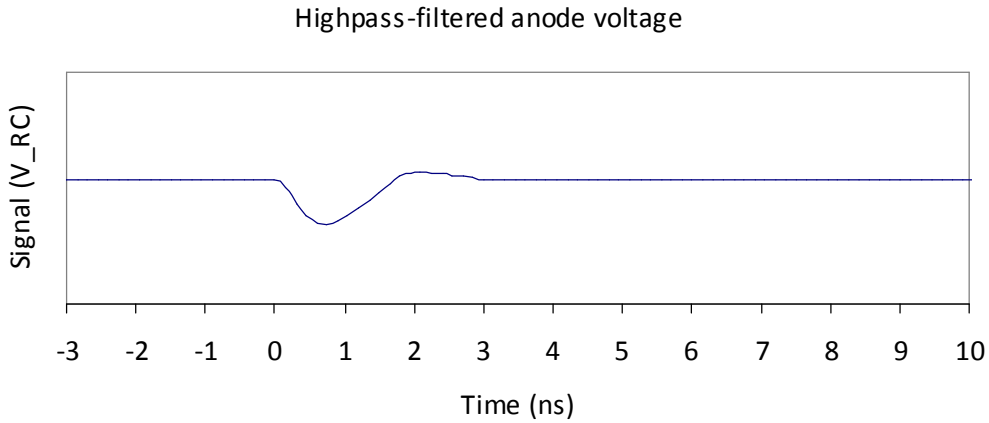

Figure 1.5-B: RC-filtered anode response (high voltage offset removed, small dip in voltage is now easier to measure)

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* Small, relative to the DC offset applied across the tube

† The following graphs of anode voltages take the cathode as a zero volt reference

‡ Low-frequency signals in a capacitive circuit experience a higher "resistance" than higher frequencies. In this case, the capacitor filters out the DC offset of the anode voltage, while passing the sharp transient pulse created by the electron cascade.

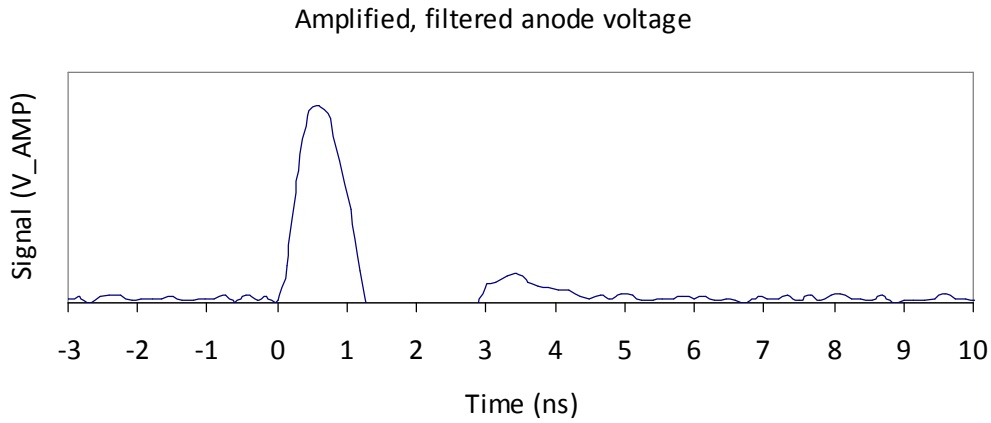

Figure 1.5-C: Amplified (via an inverting amplifier), RC-filtered anode response

There are various different methods to process the resulting amplified signal. In the devices that will be developed and used in this project, a sample/hold circuit measures peak heights. The held values are compared electronically against two reference values, referred to as the window threshold and window threshold plus the window width (see Figure 1.5-D). If the held peak height is between these values, an accumulator is incremented. Note that several windows may be present on one device, each set to count photons in a different energy range. A system flowchart documenting the complete journey from gamma photon to accumulator value is shown in Figure 1.5-E.

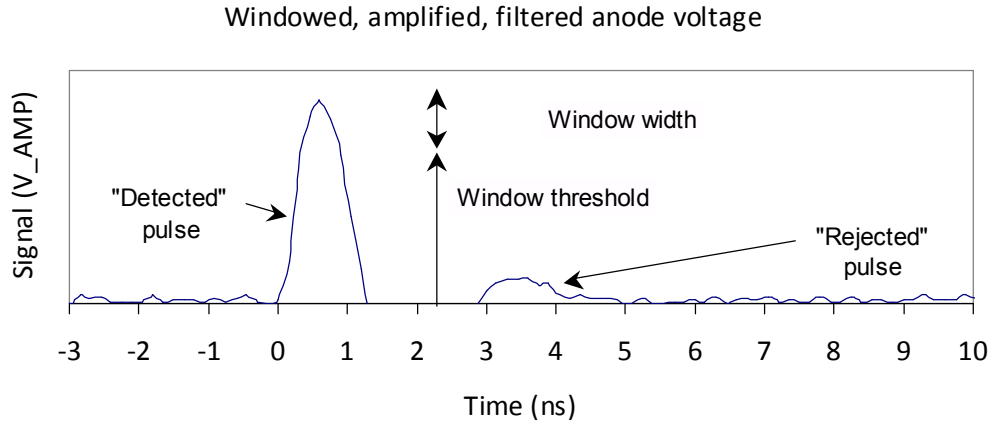

Figure 1.5-D: Using electronic "windows" to focus on a particular region of the spectrum.

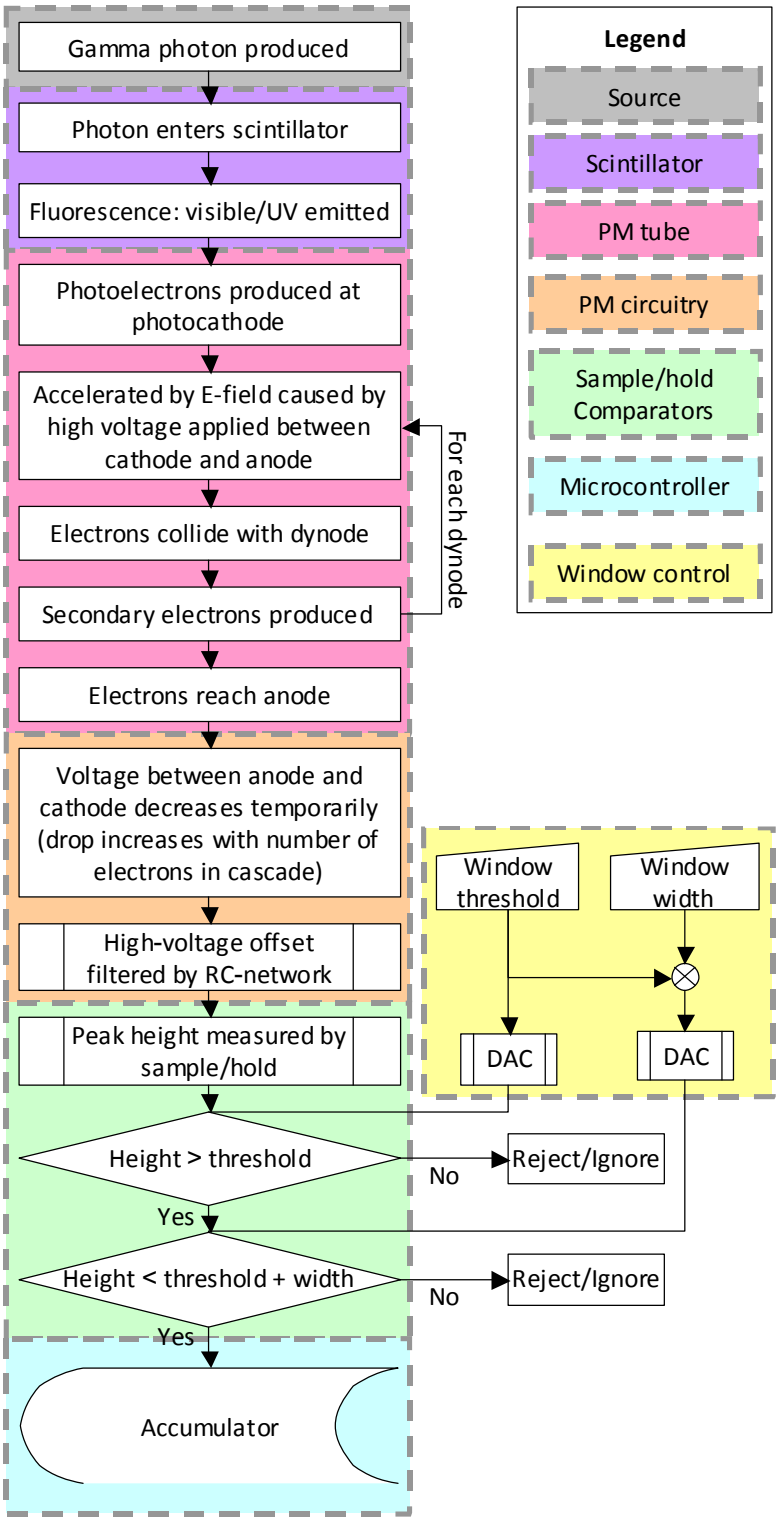

Figure 1.5-E: Information path in the device, from a gamma photon to the count rate in a computer-controlled window.

** DAC = Digital to analogue converter*