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Photomultiplier tests - Requirements for SNO and standardized testing procedures

R.J.Boardman

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1 Abstract

There are many requirements that candidate photomultipliers must satisfy if they are to be used in the final detector. This report hopes to address two of these constraints :

1. The single photon counting efficiency, and
2. The transit time spread of single photon signals.

The importance of these parameters will be briefly discussed, and a standard procedure to determine them experimentally will be presented.

2 Photomultiplier requirements for SNO

Since the PMT's provide the sole means of detection in the experiment, their performance is quite crucial to the arduous procedure of *signal identification.* No amount of data analysis can recover information lost at this stage.

2.1 Signal Identification

It is most important that the neutrino interactions in the detector can be distinguished from signals due to radioactive background. In practice this is non-trivial, but the following techniques have been proposed :

- Minimize the radioactive background in the first instance, using low activity materials.
- Calculate the background. This can be done via ;
    1. A light water fill of the central vessel should provide some clue about background levels. In this case ν_e scattering can still occur, but this reaction will be strongly forward peaked.
    2. Monte Carlo simulations of the background will also be most useful.
- Shielding of both the heavy water and the PMT's will help reduce spurious signals.
- Event signatures will be used to distinguish interactions from background. For example, the (supernova) $\bar{\nu}_e$ interactions such as

  $$\bar{\nu}_e + d \rightarrow n + n + e^+$$

  produce a Čerenkov signal from the positron followed by two γ-rays from the neutron capture process.
- Vertex Reconstruction should identify where the event occurred. Thus we can accept or reject an event depending on its origin in the detector.

2.2 Vertex Reconstruction

It is the vertex reconstruction technique which requires the PMT's to have a low transit time spread (TTS) and good counting efficiency. However high counting efficiency also means that *more information* is obtained about each event, eg pulse heights give event energy information. A simple order of magnitude estimate of the spatial resolution of vertex reconstruction gives, for large n

$$r_{vertex} \simeq \frac{c\tau_{tts}}{\sqrt{n}}.$$

Where

r_{vertex} is the spatial resolution distance,

c is the speed of light in the (Čerenkov) medium,

τ_{tts} is the PMT transit time spread,

n is the number of PMT's detecting Čerenkov photons.

Since many events are strongly forward peaked. the spatial resolution is probably a factor of (say) 4 worse than this. This is because most of the timing information comes from the Čerenkov light emitted after the electron has been scattered. Current state of the art PMT's (with a TTS ≤ 3 ns FWHM) will give a spatial resolution of about 40 cm.

Realistic *Monte Carlo* simulations of the vertex reconstruction resolution have been performed by P.Skensved and B.C.Robertson [1, 2, 3].

3 Photomultiplier Tests

To ensure that SNO has the best PMT's for the job, candidates should be tested by the collaboration independently of the manufacturers. Each property of the PMT's should be verified by several groups within the collaboration, perhaps 3 or 4. Presented here are the testing procedures used for tests at Oxford University.

3.1 Standardized testing procedures

It is most desirable to test both absolute efficiency and TTS in conditions similar to those of the final detector. Specifically this means :

1. The PMT's should be optimized in an environment such that both counting efficiency *and* TTS can be measured simultaneously, with similar conditions.
2. The tests should be performed in the single photon regime, as in the SNO detector.
3. The response of the PMT's is strongly dependent on wavelength, so their properties should be measured using the same $1/\lambda^2$ spectrum as the Čerenkov light produced in the heavy water. A Čerenkov source is the obvious way to achieve this.
4. The PMT's should be tested in a known and variable magnetic field.
5. Where possible, the tests should be performed in water.
6. Where possible, the test equipment should be able to accommodate reflecting concentrators.

In addition to these six general principles there are the many details concerning PMT tests. These details are much less well defined than the general principles, so the approach here is to describe the apparatus and methodology of the Oxford group.

3.2 Tests at Oxford - the Mortar

The tests at Oxford satisfy the six general principles as described above, although we have found that it is more convenient to use separate apparatus to perform tests in water. The central piece of equipment is the 'Mortar' which is simply a piece of 'Tufnol' tube of length 2.3 m and radius 21 cm in which the PMT's are tested. It has the following features :

1. At one end there is a fast timing tube (FTT), a Hamamatsu 2 inch photomultiplier.
2. Attached to the front of the FTT is a source of Čerenkov radiation.
3. At the other end of the Mortar is the PMT under test. It is placed at a distance of 1.4 m from the Čerenkov source.
4. The inside of the Mortar is lined with black velvet to prevent stray light from being reflected by the insides of the Mortar.
5. A 'source blocker' is mounted next to the source so that the PMT under test can be shielded from the source when required. This provides calibration for counting efficiency measurements.
6. Around the outside of the Mortar are wound field coils to provide magnetic field compensation within the mortar.
7. Finally the Mortar is made light tight by a combination of matt black tape and matt black spray paint.

The details of the Mortar design features are noted below.

3.2.1 The Fast Timing Tube

The FTT is a Hamamatsu H1949 2 inch diameter, 12 stage, head-on type photomultiplier tube with a bi-alkali photocathode and borosilicate glass. It is used with a metallic case which provides magnetic shielding. The operating voltage is about 2.5 kV, at which the TTS is (quoted at) 0.55 ns full width at half maximum (FWHM) and the pulse rise time is typically 1.3 ns. This FTT enables measurements of the TTS of the candidate PMT's to be made.

3.2.2 The Čerenkov radiation source

The Čerenkov source is a 160.1 KBq source of ${}^{90}_{38}Sr$ sealed in a perspex sphere of radius 15 mm. The strontium-90 has a half-life of 28.6 years and β decays via ${}^{90}_{39}Y$ yielding a β^- with an end point energy of 2.274 MeV. The threshold for the production of Čerenkov light in this medium is an electron kinetic energy of about 170 KeV.

3.2.3 Single photon counting

The strontium source is quite 'bright' in the sense that each decay produces many ($\sim 10^2$) photons.This means that the test PMT should be located far enough from the source so that single photons are counted, i.e. the solid angle Ω subtended by the PMT should be such that

$$\frac{\Omega}{4\pi} \leq 10^{-2}.$$

At 1.4 m from the source. a 8 inch PMT has

$$\frac{\Omega}{4\pi} \simeq 10^{-3},$$

so that one can be sure of counting only single photons. Note that the activity of the source does *not* affect single photon counting, assuming the source to be less than about 50 MBq !

3.2.4 The Mortar internal lining

In order to extract *absolute* values of total counting efficiency, we must be certain that no stray light is reflected off the sides of the Mortar into the PMT. Any material to coat the inside of the Mortar must not only have the lowest possible reflectivity, but must also have no *specular* reflectivity.

It has been found that Liberty's black velvet (LBV) is one such material, which has a coefficient of specular reflectivity $R_s \leq 10^{-4}$ when used correctly. LBV is made with a nap, i.e. the fibres of the cloth naturally point in one direction. Empirically, one can achieve the lowest values of specular reflectivity with the nap pointing *towards* the light source. Thus the insides of the Mortar are lined with LBV, such that the nap points towards the Čerenkov source.

3.2.5 The source blocker

In order to estimate background levels in counting efficiency experiments it is necessary to have a source which can be blocked by a shutter. (The alternative is to remove the source, but this is both tedious and can allow outside light to hit the PMT's). Hence the Mortar is fitted with a simple source blocker which can be operated from outside the Mortar.

The source blocker is piece of matt black card lined with LBV, and is located adjacent to the Čerenkov source. The source blocker can be moved into place by a handle operated from outside the Mortar. When in place it completely blocks all direct (non-scattered) Čerenkov light that would otherwise hit the PMT under test. Note that it is unnecessary and even *undesirable* to block scattered Čerenkov light, as that is a legitimate component of the 'background'.

3.2.6 Magnetic field compensation

Since several properties of the PMT's (such as counting efficiency) depend strongly on local magnetic field, the Mortar is equipped with solenoid-type coils wound axially on the outside. The coils are wound at a density of 100 turns per unit length (metre), which means a current of about $I \simeq 500$ mA is needed to cancel the earth's magnetic field.

For simplicity, the Mortar is designed to study the effects of axial fields only; non-axial fields can be investigated using other apparatus at Oxford. Thus the Mortar is aligned along the earth's magnetic field, and the current in the coils is adjusted to achieve field cancellation inside the Mortar. A Hall probe is used to check field cancellation, so that residual fields are only $B_r \simeq 10^{-7}$ Tesla.

3.2.7 Light proofing

The Mortar is made light tight by ensuring that all holes and inlet are well sealed by first sealing with matt black tape, and finally sprayed matt black with spray paint. The most difficult places to seal are the inlets for the electrical cables and the plates which cover the ends of the Mortar. With some effort, the PMT's difference in rate of counting with the Mortar in daylight to that in darkness is less than 10^{-2} Hz .

3.3 Electronics and Signal Processing

The raw signals from both PMT anodes are processed by the following stages:

1. The signal are filtered to remove any d.c offset potential; this is only necessary for the test PMT, as the FTT has a grounded anode.
2. The a.c signal is then amplified using a LeCroy 612A photomultiplier amplifier with a gain of 10.
3. The a.c signals from both pmt's are then fed into Constant Fraction Discriminators; we still use the Ortec 583.
4. The signals then activates an afterpulse filter which veto's further signal from both tubes for 100 μs.
5. A LeCroy qVt multichannel analyser is then used to determine the TTS of the test PMT, in conjunction with the FTT signal.
6. The count rates are determined by a scalar (vetoed by the afterpulse filter), which starts and stops a quartz timer.
7. The scalar can also count the coincidence rate using a LeCroy 466 coincidence unit

The details of the signal processing techniques are noted below.

3.3.1 The Constant Fraction Discriminator

To get the best performance from the Ortec 583 one must optimize both the delay and walk parameters. The walk adjust is set to ground potential. The delay is provided by an external cable of time delay $t_{d(ext)}$ and an internal delay of approximately $t_{d(int)} \simeq 0.7$ ns. A useful empirical formula for the external shaping delay is

$$t_{d(ext)} \simeq 1.1\, t_r - t_{d(int)},$$

where t_r is the 10% to 90% risetime of the anode pulses. The final values of $t_{d(ext)}$ where 1 ns for the FTT and 2.5 ns for the test PMT.

3.3.2 Afterpulse filtration

It is common for large PMT's to afterpulse for times up to 100 μs after any signal. These rogue pulses are often caused by ionized gas molecules in the PMT, which are accelerated toward the photocathode and liberate electrons on impact. Since we have no way of distinguishing a photon signal from a afterpulse signal,the electronics counts the signals in such a way that it is not dependant on the afterpulse rate.

When a signal is received (from either tube) a pulse generator is triggered which vetos *all* further signals for a preset time, usually set at 100 μs. This veto also stops the timing signals so that the real time clock is stopped for this period. When this veto time is large compared with a typical afterpulse time the observed count rate becomes independent of the veto time. To reduce the effective 'deadtime' of the counting, the veto time should be as low as possible, whilst being longer than any afterpulse time. The suggested time is 100 μs.

3.3.3 The qVt Multichannel Analyser

The LeCroy 3001 qVt multichannel analyser is used to measure the TTS of the test PMT. In 't' mode, the signal from the FTT starts the qVt and the test PMT stops the QVT. The qVt must be used in the External Trigger mode when used in this way. It has a maximum resolution of 0.1 ns and the full scale time is approximately 100 ns. The results can be displayed on a oscilloscope for a quick check, but an interface to a P.C is preferable.

Note that the qVt can also produce a charge spectrum of signals from a PMT, in coincidence if necessary.

3.4 Measurments and analysis

The Mortar can investigate the following properties of a test PMT :

1. The relative counting efficiency of the PMT.
2. The absolute counting efficiency of the PMT.
3. The TTS of a PMT.
4. The effect of axial magnetic fields.
5. The charge spectrum of a test PMT.
6. The Afterpulse rates of PMT's.

3.4.1 Relative counting efficiency

This is by far the easier of the two counting efficiency measurements. It can be done by a bare count of the PMT or counting in coincidence with the FTT. For each measurement the background is estimated by repeating the count with the source blocker and then subtracting this background.

A bare count has a background which can be 10 times the signal, but counting for long enough ensures that statistics play no part, and 0.25% statistical accuracy can be achieved. In coincidence the signal to noise ratio is about 50:1, and 0.05% statistical accuracy is easily achieved.

Note that we can check these results for consistency by noting that FTT records a signal for a known fraction of the events recorded at the test PMT. Thus the ratio of these measurements should be a known constant.

3.4.2 Absolute counting efficiency

To make absolute measurements we need to know more about the Čerenkov photons emitted by the source. Their energy, spatial distribution, and number per decay are vital parameters. To calculate these parameters we propose to simulate the source and its geometry using a Monte Carlo program using the Electron Gamma Shower (EGS4) routines. This should enable absolute measurements to be achieved.

3.4.3 The TTS measurements

The TTS results are usually analysed by looking at the FWHM of the coincidence peak, correcting for the non-zero TTS of the FTT (0.55 ns). Since TTS's add in quadrature this represents a correction at about the 1 percent level.

Since most PMT do not have a gaussian distribution of TTS's, we are in favour of quoting results in terms of the standard deviation of the TTS distribution. This also has the advantage of showing up small 'satellite' peaks.

3.4.4 Magnetic field effects

By varying the current in the solenoid we can investigate the effects of axial magnetic fields on the above properties.

3.4.5 Charge spectrum measurements

Using the qVt in 'q' mode one can measure the charge spectrum of the PMT. These data are usually presented pictorially.

3.4.6 Afterpulse measurements

One can estimate the afterpulse rate in any PMT by estimating the difference in count rate when the afterpulse filter is turned off. Another instructive measurement is the afterpulsing in the range 0.4 μs to 10 μs, which is related to the muon lifetime.

References

[1] P.Skensved and B.C.Robertson. *Monte Carlo Simulations for Spherical SNO Detector with and without Reflectors*. SNO-STR-88-126.

[2] P.Skensved and B.C.Robertson. *Miscellaneous effects*. SNO-STR-90-28.

[3] P.Skensved and B.C.Robertson. *Summary of Monte Carlo Calculations Presented at LANL Meeting*. SNO-STR-90-27.