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Single-Photoelectron Noise Reduction in Scintillation Detectors*

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Abstract

The 1994–95 search at SLAC for millicharged particles used four $21 \times 21 \times 130\text{-cm}^3$ Bicron 408 scintillation counters to detect a signal at the single-photoelectron level. The competing noise requiring minimization was due to a combination of PM tube (8-inch Thorne EMI 9353KA) afterpulsing and ambient radiation-induced scintillator luminescence. A very slow decay (> 30 µs) component was observed and received particular attention. Efforts to reduce the SPE noise included photomultiplier tube base modifications, detector shielding and cooling, signal amplification, and veto procedures.

INTRODUCTION

A recent search[3] at the Stanford Linear Accelerator Center for the possible existence of millicharged particles utilized a large plastic scintillation detector. The plan involved detecting the passage of any charged particles not filtered by 85 meters of rock. The mQ experiment was particularly interested in particles with charge in the range 10^{-3}–10^{-5} of the electron charge.

The interesting signals from the photomultiplier tubes for this radiation are at the single-photoelectron (SPE) level. However, at the photomultiplier tube (PMT) gain needed to observe the SPE signals, the background noise rate was 2–3 orders of magnitude higher than the ambient radiation rates. Furthermore, the noise was observed in distinct clusters and was found to originate in both the photomultiplier tubes and in the scintillation materials. A major effort was mounted to understand and reduce the noise, from both sources. The results of the effort are presented here.

THE DETECTOR

The mQ beam in this experiment is several meters underground, and horizontally directed. Four Bicron 408 detectors measuring $21 \times 21 \times 130\text{-cm}^3$ each were placed in a square configuration (Fig. 1). Its longest dimension was aligned with the beam, 110 meters from the particle source. Each segment was viewed with an 8-inch hemispherical

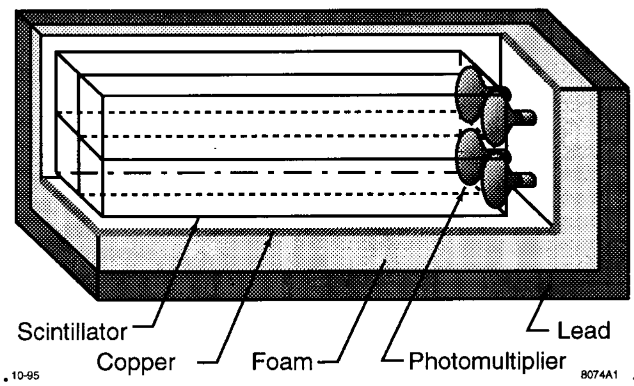

Fig. 1. Four-counter mQ scintillator array.

Thorne EMI 9353KA PMT mounted in optical contact with its hollow-cut scintillator.

Each counter was wrapped with aluminum foil, encased in copper sheeting to assist uniform cooling, and placed in a 0.5-inch Lucite enclosure for mechanical support. The PMTs were magnetically shielded with Netic, and all conductive layers were grounded. The four-counter array was then encased in an insulated copper vault whose temperature, with all components, could be controlled between −30° C and +25° C. The detector was installed 5.5 meters underground, without overburden.

Another smaller counter, the prototype[2] for the large detector, was maintained to permit off-line tests.

NOISE SOURCES

The SPE noise rate in the prototype counter was roughly proportional to the energy deposition rate. The noise

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originating in the photomultiplier tubes can be intrinsic or directly induced. Intrinsic PMT noise includes thermionic emission and internal radioactive decays[2]. Induced noise is caused mostly by positive ion feedback, and results in afterpulses.

Scintillator noise results from the production of metastable states by radiation depositions in the organic material[3]. Part of the deposited energy is stored and then released later by different mechanisms, at SPE strengths. We observed luminescence with both long (~days) and short (<10 μs) time constants.

SPE NOISE MEASUREMENTS

SPE signals were examined by direct oscilloscope viewing during testing, and by CAMAC ADC histogramming in the data run mode. Count rates that were 2 to 3 orders of magnitude higher than any ambient radiation levels revealed the presence of the noise. SPE noise clustering was observed directly by setting an oscilloscope trigger on a specific pulse height and then observing the combs of trailing pulses—which lasted tens of microseconds and longer.

Noise rates were measured by scaling discriminated pulses with a threshold of ~1/3 SPE and output widths of both 30 ns and 30 μs. The rate in the 30-ns window was a measure of the total noise rate, while the rate of the 30-μs window represented the cluster rate.

Typically, the SPE signals were easily distinguished in the spectra (Fig. 2). These were produced using ×40 external amplification. Noise rates were studied in coincidence with cosmic muons; with induced gamma radiation including ^{241}Am and ^{137}Cs; by observing the effects of ambient radiation; and by the use of embedded LEDs (RGB). We examined noise rates as a function of gate widths, pulse size, and detector temperature. All transparent constituent materials, such as light guides and optical grease, were tested with uv exposure and radiation for their luminescence characteristics.

NOISE REDUCTION TECHNIQUES AND RESULTS

Afterpulse Veto

The mQ experiment used an induced deadtime method to reduce the shorter components of the noise. Pulses following any signal surpassing thresholds (30 mV) were blocked by the long discriminator output (30 μs), as described above. This eliminated some PMT afterpulses and delayed luminescence signals appearing during the gate. Since afterpulsing is related to energy deposition, multi-tiered discriminator thresholds with proportional width gates were tried and found unwieldy. A single 30-μs gate was finally selected as optimal.

Shielding

The ambient radiation level in the mQ experiment vault led to the need for detector shielding; four inches of lead was used. Encasing the prototype in 2 inches of lead resulted in a decrease of a factor of ~3 in the singles count rate. Cluster, or

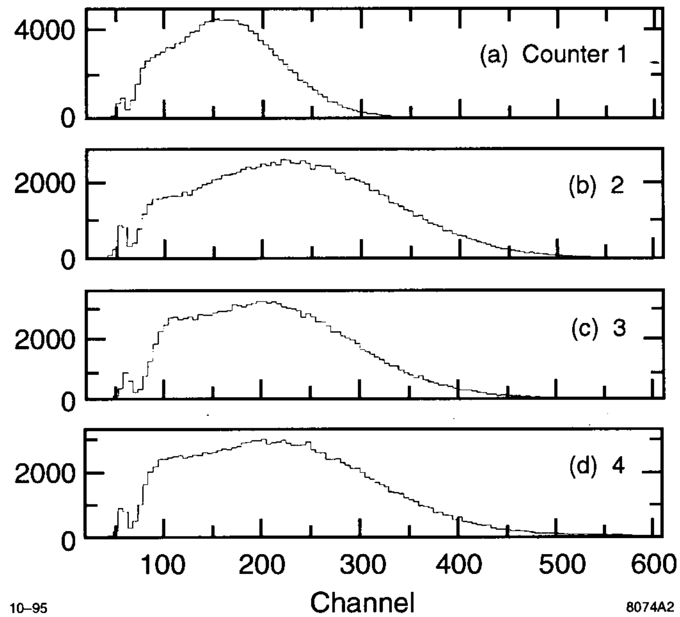

Fig. 2. LeCroy 2249W ADC spectrum with SPE peak.

veto, rates (using the 30-μs gate width) were also smaller by a similar factor (Fig. 4a).

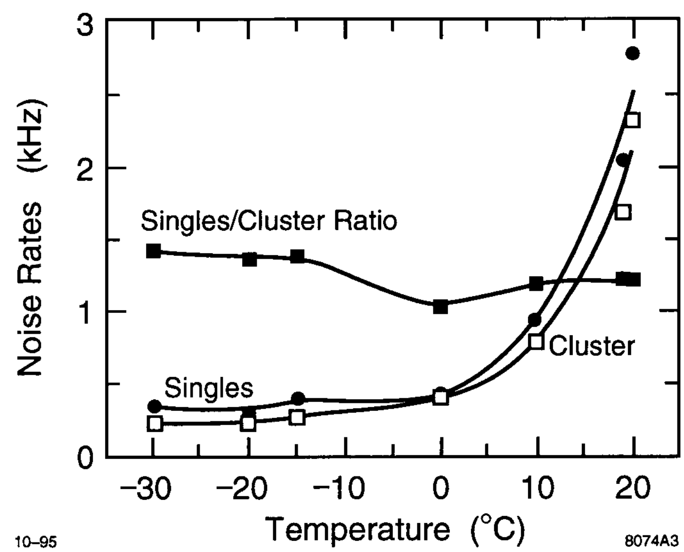

Fig. 3. Singles and veto-noise rates from a Thorne EMI 9353KA photomultiplier alone, plotted versus temperature.

Cables (signal, LED, HV) into the detector were found to affect the SPE measurements; strap grounding and multiple sheathe cables became important. The magnetic shields were grounded.

Intrinsic Photomultiplier Noise

A positive HV system (grounded cathode) was selected to avoid electroluminescence in the PMT glass. Intrinsic activity in the PMT was minimized by the selection of the Thorne EMI 9353KA tubes. Thermionic emission from the photocathodes was reduced by cooling (Fig. 3). It is also reduced somewhat by lowering the tube voltage (see below).

Induced Photomultiplier Noise

Afterpulses (1 to 100-μs delay) result from positive ion feedback, derived from residual or seeped tube gas[2]. We sought to minimize this effect by lowering the PMT gain for large pulses but without affecting the gain for small pulses. This was done by removing the dynode capacitors. Reducing the dynamic range in this fashion led to a 50% decrease in the count rate.

We found we could also reduce afterpulsing by decreasing the energy with which electrons (and ions) struck the dynodes. The idea is to lower the HV, and restore the gain by external (x40) amplification. We found the high voltage could be reduced from ~1400 volts to ~1100 volts; after more reduction than this, amplifier noise began to compromise the benefits. This procedure reduced the count rates by approximately 30%.

Very Long-Time Constant Luminescence

Various modes of luminescence and phosphorescence are discussed in the literature[3,4,5,6,7]. The mQ project started with a Plexiglas PMT light guide coupled to the Bicron 408 scintillator in the small prototype counter. An analysis of the high noise rates led to the discovery that the Plexiglas itself exhibited marked, very long-lived luminescence. The Plexiglas noise-count rate decreased markedly with temperature. We replaced the light guide with one cut from Bicron 408, and used only scintillator material in the main detector.

We examined several common transparent materials found in scintillation environments, and found they all exhibit very long-time constant luminescence ($T \geq 1$ min.). These tests were made with 30-s exposures to long-wavelength uv light. The results, in order of decreasing noise rates, are: glass (Pyrex), UVA Plexiglas, polyethylene, UVT Plexiglas, various scintillators, other acrylics, and polycarbonates. A liquid scintillator (NE236) showed no phosphorescence in this test.

TEMPERATURE DEPENDENCE

In this work, the scintillators could be cooled along with the PMTs, and we were able to investigate the temperature dependence of the SPE count rate. The singles and cluster rates vs. temperature for one of the 8-inch PMTs by itself are seen in Fig. 3. The noise rates dropped smoothly but flattened out near −15° C, with the cluster rates almost equal to the singles rates at 20° C but dropping to 75% less than the singles at the low temperature asymptote. Most clusters, in this case, are comprised of single pulses of SPE amplitude.

Figure 4a shows the noise rates versus temperature when two inches of lead was added to the prototype. The flat cluster rates contrast with the singles rates, which rise as T decreases (there is indeed a shallow minimum in the veto rate, at 7° C). Interestingly, the ratio of singles per cluster rises sharply (Fig. 4b) with the shielding in place whereas it is flat without the lead. The reduction of gamma (MeV level) radiation seems to make clustering effects more prominent, implying that cosmic muon events lead to relatively more clustering (the tube-alone data cannot account for the sharp rise).

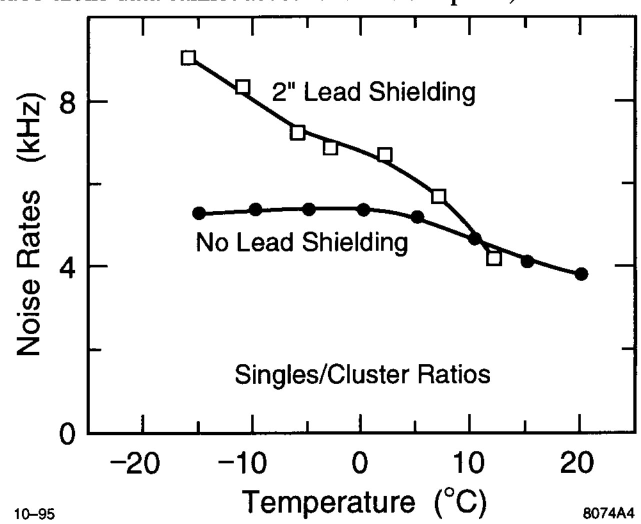

Fig. 4a. Prototype counter singles and veto-noise rates with and without two-inch lead shielding, versus temperature.

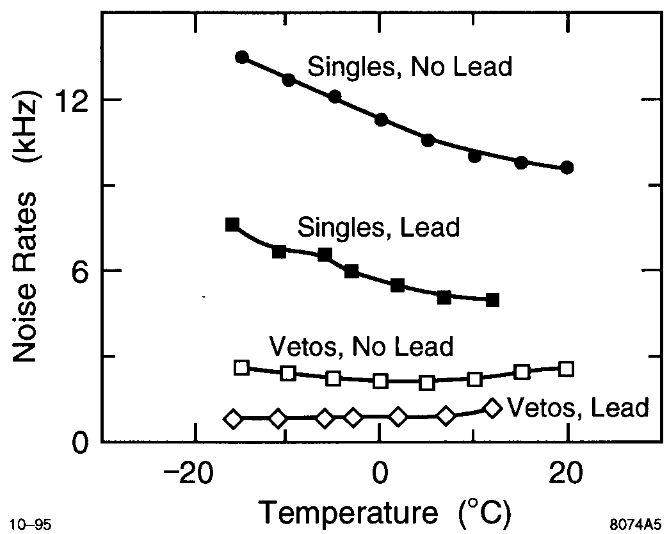

Fig. 4b. Comparison of the singles/veto ratios with and without two-inch lead shielding, plotted versus temperature.

The mQ experiment studied the noise rates for the main detector throughout a –20° C to +20° C range. A minimum was found in the cluster rates near 7° C, similar to that seen (in an expanded scale) in Fig. 4a for the prototype counter. It is assumed the minima result from the increasing noise in the scintillators and the decreasing noise in the PMTs. The 7° C temperature was considered optimal for the detector operation.

RESULTS OF NOISE REDUCTION

Each of the four counters in the main detector had initial SPE noise rates exceeding 100 kHz. These rates were observed with the use of the low-activity tubes, the Bicron 408 light guides, and the enhanced grounding techniques. The combined effects of cooling, lead shielding, tube base modification, HV gain and/or amplification optimization, and induced deadtime techniques gave a final noise rate of ~4 kHz.

REFERENCES

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[2] The protoype differed only in its length (30 cm), although it was made up of four two-inch slabs of Bicron 408 and had a separable Bicron 408 coupling to its PMT.