A Low Cost Detector for μ-e Decay Events

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Abstract

Low-cost ground-level detectors for μ-e decay events count events due to a narrow band of the differential muon spectrum, unlike most cosmic-ray particle detectors, which respond to all events above a threshold energy. Mu-e detectors of modest size (0.2 cubic meters) and mass (200 kg) near sea level have high counting rates (3 events/sec), increasing by a factor 3 at mountain altitudes. An economical design is presented employing mineral-oil-based scintillator, two 127 mm dia PMTs and standard building-construction materials for the μ-e detector, and CMOS integrated circuits for the special delayed-coincidence electronics which provides NIM- level μ and electron pulses and an analog pulse with height proportional to decay time. Applications include search experiments for the Cowan Effect, ground-level monitoring of solar modulation effects, and perhaps as a novel detector element for air-shower arrays.

1 Motivation:

In connection with earlier cosmic ray experiments by the group in 1992, expected diurnal variations of intensity for galactic dark matter were calculated as a function of sidereal time. Noticing that the time of peak intensity coincided with peaks in μ-e decay rates reported by a group from Catholic University led by Clyde Cowan [Cowan & Ryan, 1965; Buckwalter, Cowan & Ryan, 1966; Ryan et al, 1966], we hoped to reproduce the effect in Arizona [Bowen, 1999; Young, McGuire & Bowen, 1999], and perhaps explain the results by the existence of a strongly interacting component of dark matter. Cowan's group employed μ-e decay targets ranging from 227 kg to 650 kg of plastic or liquid scintillators. At Arizona we still possessed a large supply of mineral oil-based liquid scintillator from an experiment 30 years ago.

2 Experimental Design:

2.1 Detector: We have built a large volume liquid scintillator detector on Mt Lemmon at 2700 m, or ~ 747 g/cm^2. The main detector is comprised of over 820 kg of 90% mineral oil, 10% Naptha, and a solute of 2.5 g/l 2,5-Diphenyloxazole (PPO) and 0.5 g/l 1,4-Bis-[2-(5-Phenyloxazolyl)]Benzene (POPOP) equally divided into 4 separate cells. Each liquid cell is 0.58 m square and 0.69 m deep, with two downward looking 127 mm RCA 8854 photomultipliers mounted inside on the lid. The total scintillation target mass is then 205 kg. When closed light tight, the spherical PMT faces dip into the liquid surface, with the photocathode being mostly immersed in liquid.

The total detector is composed of four such cells, arranged in a square with each side facing roughly in cardinal directions. The entire unit is raised four feet from the concrete floor to lessen the likelihood of detecting μ-e decays in the floor. Counter T2, a 0.82 m square, 2 cm thick plastic scintillator, is located at the center of the target array, 1.15 m above the liquid surface. Counter T1, a 0.60 m square, 2 cm thick plastic scintillator, is 0.71 m further above. Each scintillator is mounted inside a white box viewed by one 127 mm RCA 4522 PMT.

The main structural support consists of four 4 by 4 in wood posts, with three 2 by 10 in rafters supporting the detector weight. Each detector cell is constructed of 1/2in CDX plywood, with two 0.15 mm sheets of polypropylene folded into the corners to form (without any cuts) a liquid-tight lining inside the cell. The plywood interiors of all cells are painted with a white elastomeric roofing paint designed to reflect sun light. Extra rigidity is given to the structure with metal angle supports at the tops, middle, and bottom of the outside corners.

2.2 Trigger and Data Acquisition Electronics: PMT signals are conducted into a separate counting room via 50Ω cables. Each of the eight target scintillator PMTs is terminated at its threshold discriminator in a 50Ω resistance which also serves as a $\times 10$ resistance divider. The 1/10 amplitude PMT signals are split in resistive dividers and sent to individual inputs of two CAMAC ADCs, one gated by the muon signal and the other by the electron signal. Signals from counters T1 and T2 are sent directly to the muon-gated ADC.

Standard width NIM pulses are sent from the 8 discriminators to a specially built NIM module (the μ-e module), where separate delay-gating circuitry is provided for each cell and trigger selection is done. A trigger is possible from the sequence of a muon pulse in one cell of the main detector, and a decay electron present in the same detector 0.6- 6.6 μs later. First, the NIM discriminator pulses from the two PMTs in a single cell are ANDed. The output of the AND passes through a 0.5 μs delay line and a 0.10 μs univibrator delay before triggering a 6 μs delayed gate. The stability of these delays was found to be critical for a stable triggering rate. The gate opening unclamps an integrator, and begins the charging of a mica capacitor to measure time delay. A muon-gating pulse is always sent to the muon ADC when the gating circuit is quiescent (i.e., gate closed). If a second AND output pulse occurs within the 6 μs open-gate interval, (a) it is routed to the electron ADC gate and to the CAMAC trigger, (b) it stops the charging of the integrator, and (c) it initiates an early reset of the gate and it discharges the capacitor. Stable univibrator delays are obtained using mica timing capacitors and CMOS Harris CD74HC4538E univibrators.

The mineral-oil-based scintillator has a relatively slow scintillator decay time of $\sim 50\mu$s, which is quite adequate for the 2.2 μs decay time of μ-e decay. However, the PMTs provide pulses only a few nanoseconds in width for each photoelectron when the PMT output is fed directly into a 50Ω cable. Therefore, an integrating R-L-C network or amplifier must be inserted between the PMT and 50Ω cable. We found a simple, passive series-parallel circuit quite satisfactory [Harnwell, G.P., 1938]. If, in the circuit of Figure 1, $RC = \frac{L}{R} = \tau$, the desired time constant and $R = 50\Omega$, the PMT cable will be perfectly terminated in 50Ω resistance, yet an L/R integrated signal will appear at the output. Analysis shows that an identical integrated signal appears at the RC junction, so the two junctions may be connected, if desired, depending upon the source impedance desired for the discriminator output load.

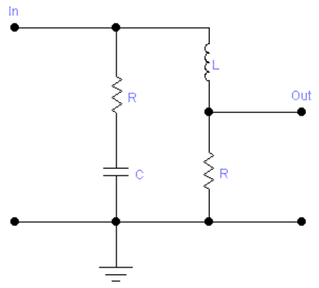

Figure 1: L-R-C integrator

As mentioned above, the μ-e strobe outputs for muon and electron events are sent to two separate LeCroy ADCs. When the muon ADC is strobed, the computer is notified and the muon pulse heights are read. The computer, a Pentium 166Mhz running Linux 2.0.21, waits 6μs for notification of the electron ADC being strobed. If this occurs, electron pulse heights are read and the event is stored. At this time, an Ortec AD811 ADC is read to give information on which cell contained the event, and the decay time of the muon. If no electron is reported, the data acquisition program starts again, clears the muon ADC registers and waits for another muon.

2.3 Detector Backgrounds: Two effects are the principal causes of background counts: PMT afterpulsing and accidental coincidences. To reduce the response to PMT afterpulsing, two PMTs were installed in each cell, and a coincidence was required (resolving time $\approx 100ns$) for both the muon signal and the electron decay signal. As the afterpulsing decreased in frequency with increasing time following a true scintillation pulse, a delay (0.6 μs in this case) further reduced the frequency of afterpulses, which was evident by several successive peaks on the exponential μ-e decay curve. It is also possible to program the computer to remove time slices where afterpulsing appears.

The accidental pulse-pair rate, A, in counts / s, the second pulse being in the 6 μs gate, is given by $A = R^2T$, where $R =$ counts / s of the cell (after the AND between its PMTs) and $T =$ gate length in seconds. For the conditions of Mt. Lemmon, $R \approx 320$ counts / s and $T = 6 \times 10^{-6}$ sec, so $A \approx$ 0.6 counts / s. The μ-e decay trigger rate is $\sim$ 10 events / s, so $\sim$ 6 % of the triggers are accidentals. In Tucson, $R \approx 100$ counts

/ s, and the μ-e decay rate ≈ 3 events / s, so $A = 0.06$ events / s, giving a 2 % background. Since the range of a decay electron with maximum energy is ≈ 0.3 m in liquid scintillator, the second pulse of an accidental pulse pair will often have a pulse height exceeding the upper limit for decay electrons. As a result, many of the accidentals can be removed by the computer program. On the mountain, the two-fold rate was, on average, 91 % of the singles rate, so if PMTs with very little afterpulsing were available, a singe PMT would suffice for each cell.

2.4 Detector Tuning Results: The detector was tuned to set PMT output levels approximately equal as well as each cell triggering on an equal, major share of decay electrons. Two-fold rates for PMT pairs were set at about 320 counts / s, a 3-fold increase over what was satisfactory in a prototype detector at 720 m altitude.

3 Conclusions:

A 200 kg μ-e detector is close to an optimal size for operation in a natural CR background, as the accidental rate increases with the square of the singles rate, placing an upper size limit, and the decay electron should be well-contained for most events, placing a lower size limit.

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