Time-of-Flight Technique to Search for Non-Weakly-Interacting Massive Particles

Patrick McGuire and Theodore Bowen
Dept. of Physics, University of Arizona,Tucson, AZ 85721

ABSTRACT

We discuss the application of the time-of-flight (TOF) technique to a search for non-relativistic supermassive electrically or strongly interacting particles. Accidental coincidences are the primary background in such a search at balloon altitude. If we employ four scintillation counters, and measure 10 μs time delays to a precision better than 10 ns, then the TOF method can reject accidental coincidences for particles depositing more than 0.4 MeV cm^2/g in a typical balloon detector configuration.

1. INTRODUCTION

Strongly or electrically *interacting massive particle* (IMP) search experiments need[1] a sensitivity many orders-of-magnitude lower than the previously expected flux above the atmosphere of $J_{IMP} \sim 1$ cm^{-2}s^{-1}sr^{-1} (for $M_{IMP} \sim 1$ PeV). Due to the high interaction cross-section of IMPs, and the non-relativistic nature ($\beta_{CDM} \sim 0.001$, $v_{CDM} \sim 300$ km/s) of any cold dark matter (CDM) candidate, a high-altitude time-of-flight search for very slow IMPs is a plausible method to search for such low fluxes.

2. FLIGHT OPPORTUNITY

A Goddard/Caltech/Siegen nuclear astrophysics collaboration had an upcoming balloon flight called IMAX, with a payload that included four widely separated 1-2 cm thick plastic scintillator detectors. The IMAX collaboration agreed to install a low-power, lightweight, low readout-rate electronics module in their payload for an IMP search at high-altitude, with only a 5 g/cm^2 overburden. Due to the above constraints, the Arizona group chose to construct a special-purpose detector module (D-module) to discriminate the PMT pulses, to provide a delayed coincidence, and to measure the time delays between hits in successive counters and the pulse heights in each counter. An Ortec ADC811 module transferred the analog time delay and pulse height outputs of the D-Module to an onboard VAX for processing and telemetry.

From each scintillation detector's group of PMTs, IMAX provided a charge of ~10 pC per minimum ionizing particle to the D-module. In order to avoid possible interchannel crosstalk in our D-module, we chose to set our discriminator thresholds at ~2 pC. Therefore, for the 1 cm thick counters, the D-module's light detection threshold was $\Delta E_{thr} \sim 0.4$ MeV. The resolution of the input charge measurements was better than 1 pC. The resolution of the time delay measurements for each channel was typically 5-10 ns, over a 0.4-15 μs range.

3. TIME-OF-FLIGHT (TOF) TECHNIQUE

The time-of-flight method would easily detect slowly moving IMPs, as long as their collision cross-section is sufficient to produce scintillation signals. Accidental coincidences are the principal background to slow moving IMPs. No known particle is massive enough to simulate the passage of a slow IMP through a stack of several sufficiently thick scintillation counters.

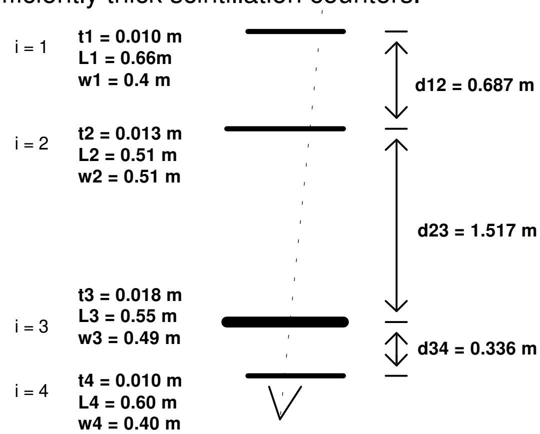

Fig. 1: Diagram of IMAX scintillator positions and dimensions. We indicate the inter-counter separations, d(i,j), the counter widths, w(i), the counter thicknesses, t(i), and the counter lengths, L(i). The length dimension is *into* the page.

With a stack of four ~1 cm thick scintillators (Fig.1), by measuring the time delay between hits in successive counters, $\Delta t_{i,i+1}$, we can compute the velocity, $v_i = d_{i,i+1}/\Delta t_{i,i+1}$ between each successive pair of counters. If the velocity change, $\Delta v_{i+1,i} = v_{i+1}-v_i$, while traversing each interior counter is nearly zero, then a particle must have passed through the counter and deposited more than the minimal detectable energy, ΔE_{thr}, with very small change in momentum. This is the obvious signature for an IMP passing through all four counters. For a particle of mass, M ~ 1 PeV, and velocity, β ~ 0.001, the kinetic energy is T ~ 1 GeV, and the momentum is p ~ 1 TeV/c. Therefore, for an energy loss of $\Delta E \sim \Delta E_{thr} \sim 0.4$ MeV, the change in velocity is:

$$\frac{\Delta v}{v} \approx \frac{\Delta E}{2E} \sim 10^{-4}. \tag{1}$$

For lower masses or higher energy losses, the change in velocity would be larger. If the particle time-of-flight between a pair of counters is 5 μs, then in order to have a measurable change in velocity, we need to be able to resolve time-of-flight differences smaller than 1 ns.

A time-of-flight experiment requires a sequence of delayed coincidence logic gates. Each successive pair of counters needs to be able to sample the same range of velocity. For the unevenly spaced IMAX counters, we show in figure 2 the delayed gate arrangement designed to measure a velocity range of v ~ [100,1000] km/s, using the counter spacings from figure 1. Due to the small counter spacing between counters 3&4, and the anti-coincidence gate time for prompt pulses of 300 ns, we chose 1000 km/s as the upper limit of the range for velocity measurement. We only include 3 counters in the coincidence, but we do measure the time delay Δt_{34}.

The D-module registers overload pulses for $\Delta E > \Delta E_{max}$, where ΔE_{max} is typically twice the minimum ionizing signal. Since the time delay resolution of $\sigma_{\Delta t23}$ ~ 10 ns, the D-module can measure a maximum mass of:

$$M_{IMP,\max} \sim \frac{(\Delta E_{\max,2}+\Delta E_{\max,3})}{\left[\frac{\sigma_{\Delta t_{23}}}{\Delta t_{23,\max}}\right]\left[\frac{v_{23,\min}}{c}\right]}$$
$$\sim 60\,TeV. \qquad (2)$$

The D-module can detect particles with masses above 60 TeV, but it cannot resolve their masses.

Disregarding propagation through the atmosphere and requiring a 4-counter coincidence, the D-module can detect a particle mass no less than:

$$M_{IMP,\min} \sim \frac{2(\Delta E_{thr,2}+\Delta E_{thr,3})}{(v_{12,\max})^2-(v_{34,\min})^2}$$
$$\sim 300\,GeV, \qquad (3)$$

making the D-module's measurable mass range, $M_{IMP} \in [0.3,60]$ TeV.

We did not account for possible light saturation effects in the above calculation, so the actual measurable mass range might be more restricted. Also, if the IMP interacts in the additional material between the scintillator detectors, amounting to ~3 g/cm^2, the actual minimum measurable mass will be ~700 GeV.

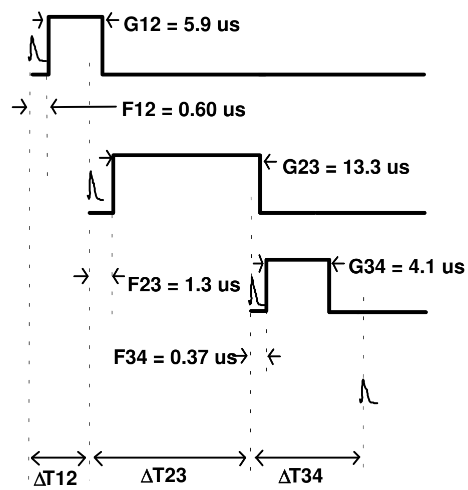

Fig. 2: Delayed-coincidence timing diagram for 3 counters. For each successive gate, we indicate the gate-delay, F(i,j), and the gate-width, G(i,j). We also indicate the time delays, ΔT(i,j), between intercounter pulses. The fourth counter is not included in the coincidence, but as long as there is a hit in the fourth counter during the G34 gate, T34 is measured.

4. POSSIBLE BACKGROUND SIGNALS

Slow non-supermassive particles are not a background in our search. In a single 1 cm scintillator, slow non-supermassive charged particles will lose enough energy to stop. With discriminator thresholds set at approximately one-fifth the minimum-ionizing signal for a 1 cm scintillator, the nuclear recoils from slow neutrons deposit too little energy (for $\beta_n = 0.003$, $\Delta E \leq 20$ keV) to be detected. If the slow neutrons do not interact elastically, but get absorbed in one counter (which often gives a signal above the discriminator threshold), then the neutrons will not be able to satisfy a 4-counter coincidence. Hence, with sufficiently thick counters and sufficiently high discriminator thresholds, both charged and neutral non-supermassive particles cannot be an IMP background.

If each counter has the same separation from its neighbors, electronic noise might be a background in a time-of-flight search. A stray radiofrequency signal might give a signal at the same time delay for all three time delay measurements. Fortunately, in our search, all counters have different separations from their neighbors so that electronic noise probably does not cause false signals, as long as we compare velocities between counters, and not time delays.

Accidental coincidences are the main background that will consistently diminish the sensitivity of a time-of-flight search for slow supermassive particles in cosmic rays. The time-ordered accidental coincidence rate A(n) for n counters is proportional to each counter's singles rate, R_i, and to the gate width, $\tau_{j-1,j}$, for each of the delayed coincidence gates:

$$A(n) = \prod_{i=1}^{n} R_i \prod_{j=2}^{n} \tau_{j-1,j} \quad \text{for } n \geq 2$$
$$= R^n \tau^{n-1} \quad \text{if } \forall \text{ i\& j, } R_i = R, \text{ and } \tau_{j-1,j} = \tau, \tag{4}$$

where the customary factor of n has been suppressed due to the time-ordering requirement. Near the top of the atmosphere, the total particle vertical flux at solar minimum at Saskatoon[2] is near 0.25 $cm^{-2}s^{-1}sr^{-1}$. For a single scintillator size of 2500 cm^2, this corresponds to a count rate of nearly 2000 Hz. Since we set the discriminator thresholds rather low, the singles rates at float might be ~4000 Hz, due to additional PMT noise. If R = 4000 Hz and τ = 10 μs, for all counters, then the accidental delayed coincidence rate is $A(n) \approx 4000*(0.04)^{n-1}$ Hz, which gives $A(4) \approx$ 0.26 Hz. With a total 4-counter solid angle of $\Delta\Omega$ ~ 100 cm^2sr, a delayed-coincidence experiment would therefore be sensitive to fluxes $J_{IMP} \geq 10^{-3}$ $cm^{-2}s^{-1}sr^{-1}$. If TDCs measure the actual time-delays between hits in successive counters with a timing resolution of ~10 ns, then $A_{timing}(4) \sim A(4)\times(10\text{ ns}/10\text{ μs})^2 \sim 10^{-7}$ Hz, which corresponds to ~0.1 accidentals in a 24 hour balloon flight. Thus, the time-of-flight method would be able to identify *individual* supermassive particle events, with a minimum detectable flux of $J_{IMP,min} = 10^{-7}$ $cm^{-2}s^{-1}sr^{-1}$ ($J_{IMP,min}$ corresponds to detecting a single event in a 24 hour flight).

The TOF method does not need x-y spatial information to reject accidentals, so we do not need to analyze the volumes of data that might result from multi-wire proportional chambers or drift chambers. Not only can the 4-counter time-of-flight method detect highly ionizing slow supermassive particles with high flux sensitivity, but the TOF method can also detect such particles that deposit energy at the minimum-ionizing level or lower, with a sensitivity that might rival other methods.

ACKNOWLEDGEMENTS

We would like to thank the IMAX collaboration for providing the timely flight opportunity for this experiment. We would also like to thank A. Pifer, K. Kendall, D. Barker, P. Halverson, J. Pando, and T. Metcalfe for their assistance both in our mountain-top IMP search, and in preparing for the balloon experiment. This work is supported by NSF Grant 91-21427.

REFERENCES

[1] P.McGuire, T.Bowen, et al., these proceedings

[2] Komori(1962)