The IMB Nucleon Decay Detector Data Acquisition and Triggering System

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The data acquisition hardware and software for large deep underground nucleon stability detector will be described. Such hardware must process the information from an array of greater than 2000 photomultiplier tubes in real time, in the presence of a cosmic ray background of about three events per second. A hierachical scheme of processors and memory is used to perform real time pattern recognition and event identification with negligible impact on dead time. Fast, but crude, algorithms have been developed to reduce the offline analysis work load without endangering any of the alternate physics objectives, such as neutrino oscillations or neutrino burst detection.

Introduction

The Irvine-Michigan-Brookhaven (IMB) nucleon decay detector1) consists, basically, of 2000 photomultiplier tubes (PMT's) positioned on a 1m grid over the six faces of a 20m cube containing 8000 m^3 of water. The tubes face inward and are able to detect the Cerenkov light emitted when a proton or neutron in the water decays. A typical decay will light up 200 tubes; generally $\sim$ 100 each on opposite faces of the cube. This basic signal, two back-to-back Cerenkov cones emanating from a common point, must be distinguished from the general cosmic ray background going through the detector. The muonic background occurs at a rate of 3 Hz and consists of high energy (typically 200 GeV) muons going through the water. We hope to eliminate this background down to the level of $\lesssim 1$ event/year in order to be sensitive to nucleon decay at that level. The purpose of this paper is to describe a data acquisition and triggering system which allows us to selectively record data and compute event flags in real time in such an environment. In particular, we have developed algorithms which allow us to do on-line rejection of cosmic ray triggers by up to a factor of 500. These algorithms make use only of the binary (on-off) data from the PMT's along with their geometrical patterns. The full timing/pulse height/ geometrical data will then be used in off-line analyses on the remainder of events in order to attain the full rejection factor of $\sim 10^8$.

Basic Hardware

The phototube signals2) are fed into custom electronics through a single cable. This cable brings high voltage D.C. down to the tubes and the A.C. signal up to the electronics. 128 tubes are serviced by one crate, so 16 crates are sufficient for 2048 tubes. Two times of firing with respect to the hardware trigger and one integrated pulse height measurement for each tube are provided by each crate. The information is read into a CAMAC buffer memory to minimize deadtime. A fast trigger processor in the CAMAC crate then analyzes the event and decides whether the event is an uninteresting straight through muon that can be immediately rejected or a more complicated event that requires higher level processing. In the second case, the trigger processor informs the microprogrammable branch driver that a buffer is ready. The branch driver zero supresses the event and reads it into the PDP 11/34 for writing on tape and on-line monitoring of the apparatus.

For calibration purposes laser3) and LED light pulses can be sent into the detector.

The time of firing with respect to the main trigger can be electronically varied to continuously calibrate the time scales. The intensity of the laser light can be varied by moving different neutral density filters in front of the beam to calibrate the pulse height response.

Programmable high voltage supplies$^{4)}$ are used for all the photomultiplier tubes. With a low current (100 μA) base, 16 tubes are attached to a common H.V. channel with a maximum of 3 mA.

Basic Properties of the Events

The two classes of events expected in the detector are straight through cosmic rays and proton decay events. These can be distinguished by their topology, single track versus multiple track, by their range (cosmic ray muons have higher energy and illuminate more tubes), and by the pattern of tube hits characterizing entering tracks.

Entering muons are characterized by a very large path length, ∿ 20 m., producing much light and illuminating many tubes. Since the track enters and exits some of its path is very close to the tubes and will produce a relatively intense burst of light. Valid proton decay event candidates are constrained to lie within the fiducial region at least 2 meters from the walls. The maximum track length for a proton decay event is 2 meters for each of two tracks.

In principle, since decays have no net momentum, they should produce a back to back signature. Many factors, fermi motion and neutral particles obscure this. In addition, entering muons that come through the wall at an angle of less than 42° will also produce a back to back signature. The two cases can only be resolved by detailed consideration of timing. The time of firing of all tubes will be closer together for an event originating in the detector.

The total track length for an entering cosmic ray will be short and comparable to a signal event if the track enters and exits the detector near a corner or edge. Since the path is short the timing differences between the entering and exiting point may be very small, too. Special consideration must be given to these events.

Consider figure 1. The area illuminated by a track of length S ending a distance ℓ from the wall of P.M. tubes illuminates an area:

$$A = (2\ \ell s + s^2)\ f(\theta, \phi) \tag{1}$$

$f(\theta, \phi)$ is a function of the Cerenkov angle θ and the angle of incidence ϕ.

In clear water, n = 1.33, about 335 photons per centimeter are emitted in the visible. Only about 67 of these survive the attentuation in the water (typical path length of 10 m) and the transmisivity of the phototube glass and the photocathode response.

Let, Q = Photons per unit track length, then:

$$P_A = Qs/A \tag{2}$$

are the number of photons per unit area, neglecting the distance dependence of the water attenuation. If we have T_A phototubes per unit area, then the number of tubes firing for a given track is:

$$\begin{aligned} T_F &= T_A \cdot A \cdot \text{Probability of firing} \\ &= T_A \cdot A \cdot (1 - \exp(-\langle n \rangle)) \end{aligned} \tag{3}$$

$$\langle n \rangle = EP_A \qquad \langle n \rangle \text{ is the mean number of photoelectrons} \tag{4}$$

E is a constant that depends on photocathode efficiency, electron collection efficiency, photocathode area, dynode gain and discriminator level. This yields:

$$T_F = T_A \cdot (2\,\ell s + s^2)\, f(\theta, \phi)\, (1 - \exp(-\, EP_A)) \tag{5}$$

At low light levels, $e^{-x} \sim 1 - x$ and we have:

$$\begin{aligned} T_F &\overset{\sim}{=} T_A \cdot (2\,\ell s + s^2)\, f(\theta, \phi) \cdot E \cdot P_A \\ &= T_A \cdot A \cdot E \cdot P_A \\ &= T_A \cdot A \cdot E \cdot Qs/A \\ &= T_A \cdot E \cdot Q \cdot s \quad \propto s \end{aligned} \tag{6}$$

The number of tubes firing, at low light levels, depends only on track length. The density of tube firing is a measure of the distance to the track.

$$\begin{aligned} D_F &= T_F/(T_A A) \\ &= 1 - \exp(-\, EP_A) \sim EP_A \end{aligned} \tag{7}$$

$$= \frac{EQ}{(2\,\ell + s)\, f(\theta, \phi)} \propto \frac{1}{2\,\ell + s} \tag{8}$$

The effect of water on the light is to attenuate it by a frequency dependent factor $\exp(-\, \ell/\Lambda(\nu))$. So it is difficult to include it in closed form calculations. Its effect is accounted for in the monte carlo. In general, except for very short distances it produces only a slight decrease in photons, Λ (450 nm) = 60 m. For short distances the near U.V. components may not get attenuated and yield a stronger signal.

At high light levels, typical of exiting cosmic rays or decay events outside of the fiducial volume we find:

$$\begin{aligned} T_F &= T_A \cdot A \cdot (1 - \exp(-\, EP_A)) \\ &\sim T_A \cdot A \\ &= T_A \cdot (2\,\ell s + s^2)\, f(\theta, \phi) \end{aligned} \tag{9}$$

and

$$\begin{aligned} D_F &= 1 - \exp(-EP_A) \\ &\sim 1 \end{aligned} \tag{10}$$

So for background events we have a large number of tubes firing for two reasons. The track is long and it is close to the wall. More noteably, the exiting track produces a high density of tube firing that distinguishes it from a contained event. These tubes will have a significantly higher pulse height than contained events. From equation 2 we have:

$$\begin{aligned} P_A &= Qs/A \\ &= Q/(2\,\ell + s)\, f(\theta, \phi) \quad \frac{1}{(2\,\ell + s)} \end{aligned} \tag{11}$$

Pulse height and tube density, equation 8, are both good measures of the location of tracks.

Monte carlo calculations indicate that for a typical, contained proton decay event of the type $P \to \pi^o e^+$ 50 to 100 phototubes fire for each track (2 tracks) and the average number of photoelectrons is 300. A mode like $n \to \pi^- \mu^+$ produces about half of that signal.

On the other hand, a straight through muon fires about 400 phototubes. Corner clipping muons do not fire a large number of tubes, 30-60, but this is because of the short track length. In all cases, the muons produce a distinct high density pattern.

Segmentation

The detector is triggered by charged particles passing through the water emitting

Cerenkov light that is detected by the photomultiplier tubes. The problem is to reduce the threshold as low as possible to be sensitive to low energy (10-100 MeV) neutrino interactions.

The electronics supplies a prompt 50 ns pulse for each photomultiplier tube discriminator that fires. The pulse can be analog summed, so that the voltage is proportional to the number of PMT's that fire. The simplest, unbiased trigger is to take this pulse and discriminate at the n tube level, where n is large enough so that noise coincidences are infrequent. The average noise rate of the tubes is 3KHz. Since the longest diagonal dimension of the detector is $\sim$ 35 m, coincidence times of 150 ns are required. The probability of a tube firing in 150 ns is $NR\tau$, where $N = 2000$ tubes, $R = 3$ KHz, $\tau = 150$ ns, and $NR\tau = .9$. Thus the rate of a random 13 tube coincidence is $[e^{-NR\tau}(NR\tau)^{13}/13!] * 1/150\text{ns} \sim 10^{-4}\text{Hz}$.

Unfortunately, this corresponds to a 50 MeV threshold. To decrease the threshold, we segment the trigger. The detector is divided into 32 patches of 64 tubes, each of which is approximately a quadrant of a face. We sum the prompt discriminator pulses for each patch independently and discriminate at the 3 tube level. Now $\tau = 50$ ns, $NR\tau = (64) \times 3 \times 10^{3} \times 50 \times 10^{-9} \cong .01 \rightarrow$ patch rate $= e^{-.01}\frac{(.01)^{3}}{3!} * \frac{1}{50\text{ ns}} \sim 3$ Hz. Then we discriminate at 2 patches firing within a 150 ns window. The probability of a patch firing is $NR\tau = (32) \times 3\text{ Hz} \times 150 \times 10^{-9}\text{ ns} \sim 1.5 \times 10^{-5}$ so the random rate is $\sim \frac{10}{4}\frac{1}{150 \times 10^{-9}} \lesssim 10^{-3}$ Hz. This corresponds to a trigger at the 6 tube level $\sim$ 25 MeV, so we have reduced the threshold in half, although it is not as general--it requires the energy deposition to be somewhat concentrated.

The hardware trigger, which is a logical OR of the unbiased and segmented trigger, starts digitization of all 2000 PMT 2 times and a pulse height. The information is immediately transferred into a buffer memory in CAMAC.

Digitization

Analog time and pulseheight signals on each channel are fed directly to the inputs of a FET op-amp used as an A/D comparator. The signals are compared against a reference ramp which is shared between 128 tubes in a single crate, and the comparator outputs are scanned digitally over a 3 msec period to determine the time at which the comparator flips and thereby the voltage of the analog signal. This system of digitally scanning the individual comparator outputs is inherently immune to crosstalk and settling-time problems of analog multiplexing schemes, and the overhead necessary to digitize each of the 7000 input signals is reduced to 1/4 of a quad op-amp and 1/8 of an 8-input TTL multiplexor .

The scanning logic operates on a 70 nsec cycle time and digitizes each of the voltages into 64 x 9 RAM's, a procedure which avoids the complexity of individual counters or successive approximation registers on each digitization channel. In addition, the digitized data is immediately available for random or sequential access by the trigger processing hardware.

Buffering

The software trigger rejection algorithms currently implemented require approximately 40 msec to execute, whereas the digitization time is much less. For our expected trigger rate of $\sim$ 3 muons/second, the software generated dead time could be as much as 12% if the detector could not be made live until the event had been read out and processed. To permit this, the 7000 data words in the digitization RAM's must be transferred into a fast buffer memory, and the detector is immediately made live. In this way, dead time is reduced to (digitization time = 2.5 msec) + (event buffering time = 1 msec) = 3.5 msec per event, or ∿ 1% dead time.

To handle large bursts of triggers which may arise from either statistical fluctuations or physical sources (e.g., supernova neutrino bursts), a large number (∿ 8) of event buffers are planned. The buffer design is modular to provide for easy expansion. Each buffer memory is a dual port device, with one (write only) part connected to the flat cable buss used to read out the detector, and the other (read/write) port accessible via the CAMAC backplane.

Event Queuing

The queuing of buffer memories and the storage of event associated is handled by an LSI 11/23[5)] auxiliary crate controller[6)]. The 11/23 is resident in the same CAMAC crate as the supervisor, buffer memory and CAMAC modules which must be read out after each event trigger. The 11/23 has the following responsibilities:

1. Enabling buffer memories and turning the detector live after each event trigger . The queuing of buffers is done on a first in - first out basis.
2. Performing trigger rejection algorithms on data in buffer memory. It is equipped with a high speed auxiliary processor (2900) and floating point hardware to facilitate fast execution. The 11/23 produces a summary of the algorithm's results for rejection or acceptance up the line.
3. Informs the branch driver of the existence of buffers which have been processed by the 11/23 and are ready to be read out.
4. Reading out miscellaneous CAMAC modules such as pattern units and scalers. These modules contain data which must be saved for each event.
5. Creation of a queue-packet which contains information to be read by the branch driver including:
   a. A link to the next queue-packet.
   b. A real time clock readout at the time of the event interrupt.
   c. The number and CAMAC station number of the buffer memory.
   d. Miscellaneous CAMAC data.
   e. A summary of trigger algorithm results.

The 11/23 and the branch driver have two methods of communication. The first method consists of the LSI 11/23 generating a LAM on the CAMAC dataway. This signal can be monitored by the branch driver. The second method of communication involves the use of a Dataway Access Port[7)] (DAP). The DAP is a DMA device which interfaces between the CAMAC dataway and the 11/23's computer bus. This device allows the branch driver to read and write in the 11/23's RAM. Hence, the two processors can talk to each other by setting and clearing flags in memory.

Algorithms

The full offline reconstruction program must be able to extract length, direction and relative orientation of the tracks. Online the objective is to use simple characteristics to classify the event and not necessarily to extract any additional information.

The primary purpose of any online trigger algorithm is to unambiguously identify cosmic rays. Speed is more important than efficiency since later analysis can refine the cut. In actual fact, the objective is to quickly reduce the data sample to a level that is easily handled offline, without reducing the detection efficiency for real events. The algorithm should be relatively insensitive to extensive and detailed calibrations.

We have studied an algorithm based on the density of tubes firing. The algorithm is enhanced on the edges where muons and proton decay events are most ambiguous. We define a statistic NN_{wall} which is the total number of adjacent tubes firing. One calculates NN_{wall} by counting every tube in which the next tube has also fired. This is done in two dimensions on all of the six faces. This is augmented by NN_{edge}, the number of contiguous tubes along the twelve edges of the cube.

The statistics:

$NN = NN_{wall} + 5 \cdot NN_{edge}$

NPT = number of tubes firing

are computed. Muons have a greater rate for NN/NPT. In figure 2 a plot of NN versus NPT is shown for 500 cosmics (370 are off scale above). It is clear that a cut as indicated, reduces the background by a factor of $\frac{2}{500} = 0.4\%$. Simulated decay events are illustrated in figure 3. The open circles are from the fiducial region, the crosses come from the edges, a meter more on each side. Eight percent of true events are lost from the fiducial region but these can be offset by gains from the additional volume.

The algorithm is fast, easily implemented, and insensitive to calibrations since it uses only the on-off status of the tube and not the detailed timing or pulse height.

We have considered an algorithm that computes the mean pulse height per phototube firing in a region. This gives good background rejection and in fact allows classification of events. One can, for example, keep multiple muons. But the algorithm is sensitive to the detailed pulse height calibration. At low light levels the pulse height has proved not to be a reliable estimate of the light intensity on the photocathode. As we have seen in equation 8, the density of tubes firing has essentially the same information as present in the ideal mean pulse height, equation 11.

In principle, one can run a hierarchy of algorithms. If an event can clearly be rejected, then the process stops; but if an ambiguity exists, a more powerful program can run. Since the sample to be processed decreases at each step one can implement sophisticated χ^2 fits at the upper levels. We are considering subsets of the offline programs for this purpose.

Monitoring and Readout

The conclusions of the trigger algorithms are communicated via a queue-packet to a programmable branch driver8). The driver extracts the summary information from the table and accepts or rejects the events under command of the main experimental computer. In this way at any time the rejection algorithm can be overidden without need to reload, but the system is not burdened with transmitting useless data upline. If the event is accepted the branch driver packs it, adds addresses and suppresses zeros and transfers it to the main computer. Zero suppression is done at this level since most trigger algorithms run faster with the data unpacked.

The primary job of the main computer, a PDP-11, is to write data tapes, monitor the detector for problems, schedule diagnostics and communicate to the experimenter.

Operational Experience

The detector is not yet fully implemented but all subsystems are operational and have been tested. The density, or nearest neighbor algorithm has been implemented and benchmarked. Using a sequence of shift and AND instructions to test for contiguous tubes and a table lookup scheme to calculate the number of tubes on in any region, a speed of about 30 msec per event for a full 2048 tube detector has been measured. We expect only 3 cosmic ray muons per second, so this would imply a dead time of 10%. In fact, since we have buffered the event, the detector is live in 3.5 msec yielding a dead time of 1.1%. A virtue of the buffering scheme is that the algorithm has the mean time between events to execute since fluctuations in event rate can be stacked.

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References

1. The I.M.B. detector is a collaborative effort of: R. Bionta, C. Bratton, B. Cortez, C. Cory, S. Errede, W. Foster, W. Gajewski, M. Goldhaber, T. Jones, W. Kropp, J. Learned, J. LoSecco, F. Reines, J. Schultz, E. Shumard, D. Sinclair, D. Smith, H. Sobel, J. Stone, L. Sulak, J. van der Velde, and C. Wuest.
2. EMI 9870, 5" hemispherical phototube.
3. PRA nitromite laser; Photochemical Research Associates.
4. Bertan B-HIVE, programmable high voltage supply.
5. Digital Equipment Corporation, Maynard, MA, U.S.A.
6. Bi Ra 1123, 1116, 1133, 1150, auxiliary crate controller.
7. Bi Ra 1151, dataway access port.
8. Bi Ra MBD-11, programmable branch driver.

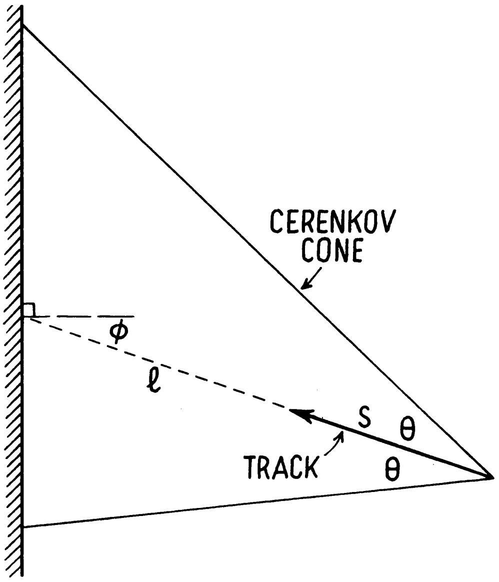

Fig. 1 The relative orientation of the Cerenkov cone from a track of length s, ℓ distance from the wall

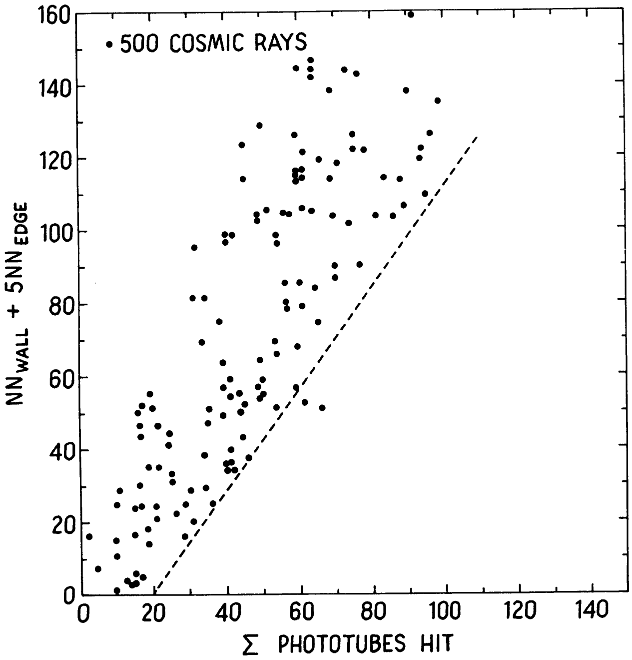

Fig. 2 A plot of the nearest neighbor statistic versus total phototubes firing for cosmic ray background. The dashed line gives a 99.6% rejection of these events.

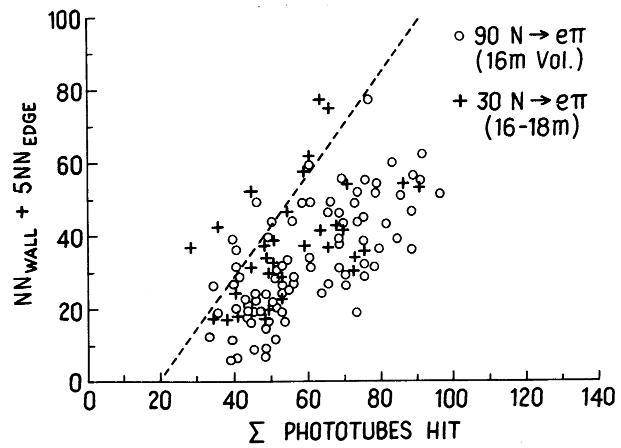

Fig. 3 Similar to figure 2 for contained and uncontained nucleon decays. Only 10% are lost.