

MSU Summer of 2001 REU Paper:

The Time Resolution of Scintillating Materials

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Abstract

Scintillators are a popular way in which physicists measure the presence of charged particles. Used in million dollar installations such as the CDF at Fermilab and what will be the Atlas detector at CERN, the physical characteristics of scintillating material has become vastly important. Aging effects of the material stresses the importance of optimal initial characteristics. One of these characteristics is a scintillator's time resolution. Improving the time resolution of scintillating material will ultimately lead to better counters.

I. Introduction

What is the universe made of? This question is a commonly asked by children in virtually any kindergarten. It is a simple and direct question. Yet, it is the complexities in answering this simple question that attracts the imagination of physicists, so around the world they too ask this child's question. In fact, physicists have been tackling this problem ever since the first days of Newton. Rephrased in a slightly different way, the question becomes-- what are the most elementary units of matter and what are their properties? The discovery of the atom ignited the search for tiny basic building blocks of matter. Today, physicists still struggle with finding the most elementary particles as they continue to look for such things as the Higgs boson, quarks, and vibrating strings.

In the early part of this century, scientists started to look at the microscopic level. Specifically, they looked at the atom and asked--are atoms the most fundamental units of matter? In 1897, J. J. Thompson discovered the electron after noticing a jet track left by a charged object as it traveled through a cathode ray tube. With this observation a new

sub-atomic realm was revealed to man, and, for the first time, it was known that there were indeed particles smaller than the atom. As the years followed, the other basic building blocks of ordinary matter (anything that is stable and listed on the periodic table of elements) the proton and the neutron came into our understanding. By 1932, the electron, proton, and neutron helped explain the structure of the periodic table and reduced the number of elementary units of matter from over a hundred to only three. This provided what was briefly thought to be a full understanding of primal units of matter.

Of course, nature had still many cards up her sleeve, and in the next couple of decades physicists discovered a wide range of sub-atomic particles. Particles called the kaon and pion were discovered in cosmic rays during the late 1940's giving birth to a new classification of particle known as mesons (meaning middleweights). These mesons were much heavier than the electron, but were lighter than the proton and neutron. So, the neutron and proton were classified as baryons (heavyweights). Even the anti-social electrons were put into a family of particles called leptons along with the discovered muon (1947) and the tau (much more recently) particle which both have the same charge as the electron, but each successively heavier. Uncharged, massless particles called neutrinos, born as a theoretical bookkeeping device, also entered the school of particles. There was found three neutrinos with each one being associated with a corresponding lepton. In other words, there is a tau neutrino, a muon neutrino, and an electron neutrino. It was also discovered that each particle had an anti-particle. An anti-particle has the same mass but opposite charge of its sister particle. So an anti-electron (positron) has the

same mass as the electron but a charge of +1. More and more particles were discovered, and the resulting mess lead to terrible confusion.

Adding to the confusion, scientists were not just interested in the particles themselves but also in the forces that interact with them. Known before 1900 was gravity and electromagnetism, but it wasn't long before two new forces were realized. Namely, the strong force which binds the nucleus of an atom together and the weak force that is responsible for decay. The photon, the first force carrier or boson, was theorized in 1905 by Albert Einstein but was not generally excepted until the mid 1920's since it seemed to contradict Maxwell's theory. Other force carriers were also discovered. The gluon, which has eight different types, mediates the strong force, and the W and Z bosons mediate weak interactions. These bosons act as messengers between particles giving them instructions on whether to be repealed or attracted.

After the dust settled, and theorists started putting the pieces together. The work of such physicists like Gell-Mann, Feynman, Rabi, Pauli, and many others created a set of laws between all these new types of particles, which was collectively called the standard model. It was discovered that mesons and baryons are in fact made up of small fractionally charged particles named quarks. A quark and an anti-quark make up a meson while three quarks (or three anti-quarks) make up a baryon. These quarks come in six flavors named up, down, strange, charm, top, and bottom.

Figure 1 shows the new periodic chart for particle physics. The top two rows are the quarks, the third row is the neutrinos, while the final row contains the electron, muon, and tau leptons. Each column is called a different generation. Much

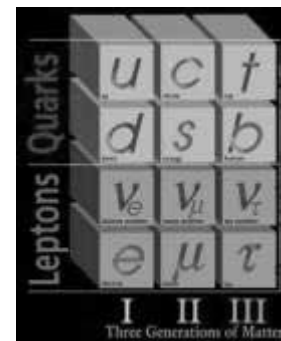


Fig. 1 The Standard Model

like the periodic table the chart is organized so that one decreases charge (+2/3, +1/3, 0, -1) as one moves down the rows and increases in mass as one moves to the right. There is also an anti-particle chart just like this figure 1 which is same in all respects except with opposite charges.

II. CDF and Atlas

All sub-atomic particles are incredibly small, less than 10^{-18} meters across (in fact they might not even have any size at all!). This is much smaller than resolution of an electron microscope. So how do we know about them? Usually, physicists use large particle accelerators. These accelerators accelerate electrons or protons to speeds fractions of the speed of light. Typically, beams of these particles are sent through a circular track with large permanent magnets stationed throughout. These magnets accelerate the charges to their high speeds. Since accelerating charges radiate energy it becomes harder to reach high speeds as the rings get smaller. Or mathematically, $R = pc/(qB)$, where R is the radius of the ring, p is the momentum of the particle, c is the speed of light, q is the charge of the particle, and B is the strength of the magnetic field. That means these circular tracks are usually quite big, km in radius. These beams of highly energetic particles collide with either a stationary target or other highly energetic particles. The resulting collision spews out the inner most components of the beam's particles. Physicists measure what comes out, and try to reconstruct what was there originally.



Fig. 2 A Colliding Beam

At accelerators particle speeds are measured in electron volts, eV, instead of meters per sec. This is because at high energy the particles asymptotically approach the speed of light.

Energy of a Proton	Fraction of the Speed of Light
1 eV	0.00005
1 MeV (10^6 eV)	0.046
1 GeV (10^9 eV)	0.875
1 TeV (10^{12} eV)	0.99999956
7 TeV	0.999999991

Table 1 Energy of a Proton

Table 1 shows the energy of a proton with the corresponding speed. As one can see, after a GeV we are only adding 9's after the decimal point. So it becomes easier to talk in terms of eV's.

Currently the largest running particle accelerator is located near Chicago at Fermilab. It has a four-mile long ring in which the protons and anti-protons collide at 4



Fig. 3 A look at FermiLab

TeV. Fermilab has two different detectors CDF, Collider Detector at Fermilab, and DZero which both search the outer limits of our understanding.

The next generation of atom smashers will be at the Large Hadron Collider located at CERN in Geneva

Switzerland. To be completed in the year 2006, the Atlas detector at the LHC will be the biggest and highest energy accelerator to date. It will be able to reach 14 TeV collisions! Much higher than what is produced at Fermilab.

III. Setup

Cosmic rays was one of the mediums in which many of the early particles were discovered. Basically, cosmic rays are made by collisions of high-energy “stuff” (mostly protons) that travel through outer space, and collide with earth’s atmosphere. The shower of particles that results is also high-energy, short-lived particles. Kaons, pions, and especially muons are what we see here at the surface of the earth. Cosmic rays are quite common and therefore there is a semi-steady flow of muons to detectors here on the earth’s surface. This gives us a cheap source of high-energy muons.

To proceed one must know a little about how a scintillator works. A scintillator is sheet of plastic that tracks charged particles. When a charged particle enters the scintillator some of material’s atoms are ionized. These excited electrons then release light, and it is that light that we look for.

To test the time resolution of a piece of scintillator we used a simple design that incorporated the steady flow of cosmic muons and parts from older experiments. From one of these previous experiments, there were trapezoidal aluminum cases enclosing scintillator sheets of the same size and shape. These cases and scintillator came in two different sizes: one approximately three feet long while the other size was approximately half of foot smaller. We placed the smaller two and a half feet long sheet of scintillator into the larger three foot aluminum case. This gave enough space at one end of the case to place two small two-inch phototubes into the case.

Along each side of the scintillator was placed a set of wavelength shifting fibers that were bent at one end to focus them into a phototube. The light from the scintillator would be trapped inside the fibers and carried along the side of the case. One phototube was used for each side. The wiring from each of the phototubes was then lead out through a small square hole in the smaller top edge of the case. The case was sealed with black electrical tape to prevent any light pollution. To further prevent unwanted light from reaching the phototubes, the square opening was also stuffed with foam and wrapped with tape.

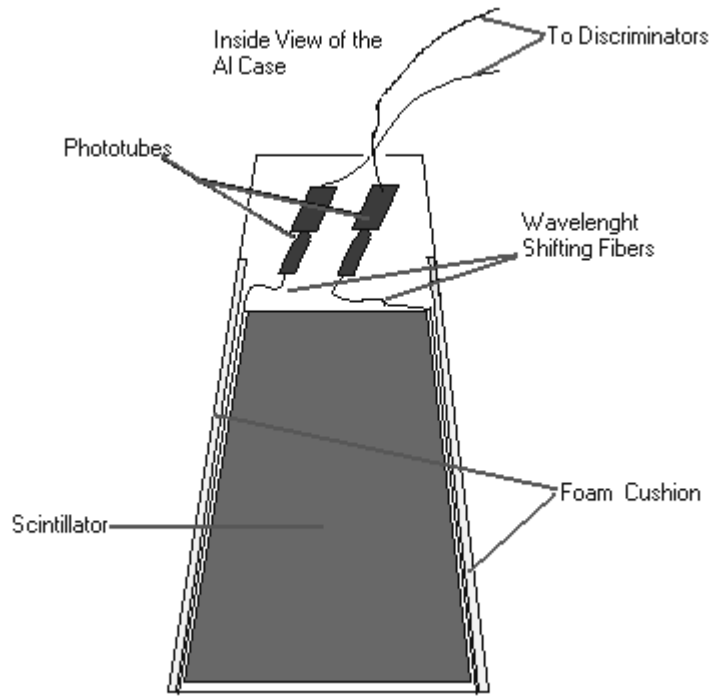
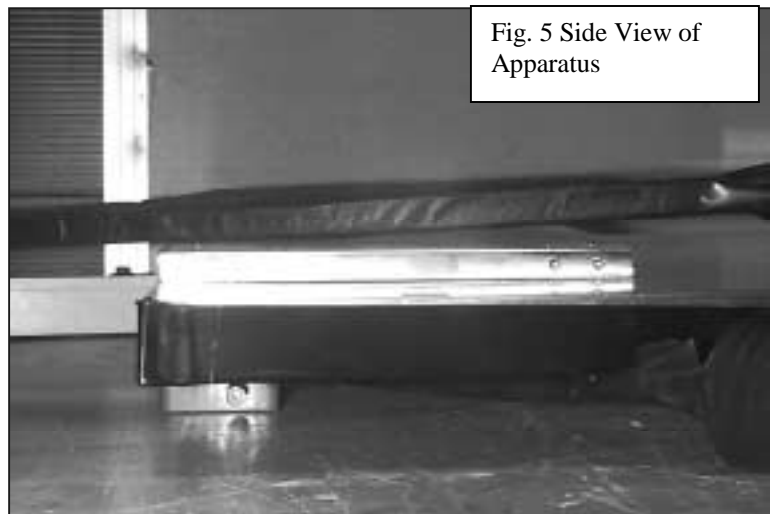


Fig. 4 Inside look into the Apparatus

The information from the phototubes was immediately feed into a discriminator and the resulting standard NIM pulses were routed into a TDC, or Time-to-Digital converter, in order to measure the time differences between the two pulses.

Since we were only interested high-energy muons a six-inch squared tungsten plate was placed on top of the case to filter out low energy photons



and other particles found in cosmic showers. Two large scintillators attached to high voltage phototubes, one above the tungsten plate and one below the case, served as trigger counters helping to establish when a muon traveled through the system.

IV. Results

Typically, we ran for a thousand events per data table. Table 2 shows a set of data.

Delta (S1-S2)	TDC (S1)	TDC (S2)	ADC (T1)	ADC (T2)	% of good hits
2	53	51	747	494	96.4
3	1042	1039	260	348	
-18	46	64	204	290	Average delta
-28	43	71	351	72	-1.987
8	48	40	81	1018	
19	82	63	126	412	Var
-23	57	80	252	325	373.01
-10	52	62	362	180	
11	59	48	315	389	Sqrt((Var)/2)
14	69	55	244	194	13.65668335
43	88	45	242	354	
-9	48	57	316	1122	Error in NanoSec
18	76	58	229	234	3.414170836

Table 2 Data Collected During a Run

Column two and three, labeled S1 and S2, is the time each pulse from the wavelength shifting fibers reached the computer. Places where the pulse is above thousand occur when, for whatever reason, the pulses are late or don't show up at all. The TDC card then cuts off their times at a maxim. That maxim, which is just above a thousand, is what comes out. These points, called junk points, are removed from any calculation since they are considered an anomaly.

The difference between the two columns, called delta and calculated in column one, is the primary interest. It is with delta that we calculate the time resolution of the

scintillator. Column four and five, labeled T1 and T2 are each trigger counter's peak in millivolts. The final column contains the calculated results.

The percentage of good hits is the percentage of times that neither TDC reached its maxim. A higher percentage relates to the quality of the data. The average delta is the mean of all the thousand events that were recorded. To find the variance of delta one uses the equation:

$$\sigma(\Delta)^2 = \Sigma(\Delta - \text{Average}(\Delta))^2 / (n-1)$$

Here σ^2 is the variance, Δ is delta, and n is the number of events. We also have that:

$$\sigma(\Delta)^2 = \sigma(S1)^2 + \sigma(S2)^2$$

Making the assumption that:

$$\sigma(S1)^2 = \sigma(S2)^2$$

gives us:

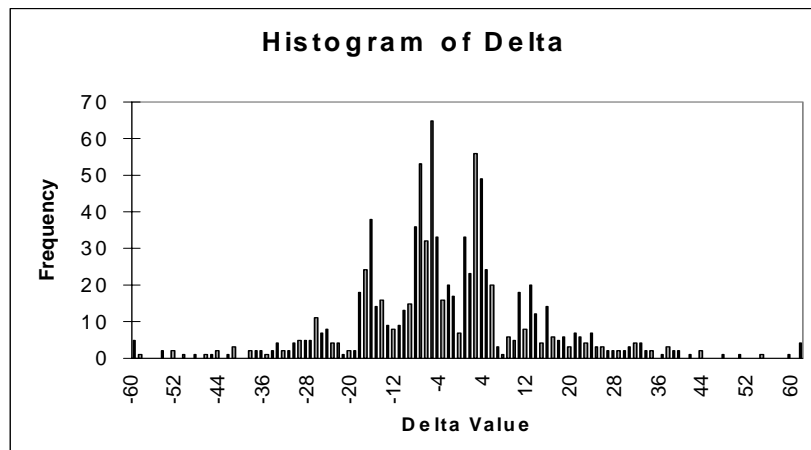
$$\sigma(\Delta)^2 = 2 * \sigma(S1)^2$$

$$\text{sqrt}(\sigma(\Delta)/2) = \sigma(S1)$$

This is what is found third item in the last column. Since the TDC is set up to read each count as 250 psec, dividing this $\text{sqrt}(\sigma(\Delta)/2)$ by four gives the resolution in nsec.

Figure 6 shows a histogram of delta one run. One can see the basic bell curve

Fig. 6
Histogram of
Delta



shape centered around -3 . Figure 7 (located on page 12) shows a histogram depicting the peaks of the trigger counters.

To see if the time resolution was position dependent three positions were marked on the scintillator's aluminum case. Position A was at the small edge, position C was located on the opposite side along the larger edge, and position B overlapped the two. Each position was ran and a summary of the results is in table 3.

Test Number	% of good	mean	Var (NanoSec)
0801a	93.7	-1.54	3.656
0802a	94.4	-2.69	3.411
0803a1	92.9	-1.44	3.578
0803a2	95.4	-3.88	3.786
0801b	94.8	-3.12	3.507
0802b	92.6	-3.55	3.009
0803b1	96.4	-1.98	3.415
0803b2	93.5	-2.54	3.301
0801c	93	-3.85	3.16
0802c	93.4	-1.69	3.105
0803c1	93	-2.46	3.198
0803c2	92.9	-2.47	3.298

Table 3
Summary of
Results

The letter contained in the test number is the position that the counters were in at the time of data collection. One can see that the resolutions do vary with position. As the scintillator gets wilder the resolution becomes better.

V. Conclusions

You may have noticed that figure 6 does have three distinct peaks, a non-statistical effect. Also it is slightly asymmetrical. This histogram is not atypical for this setup. All the data runs produced this same basic shape. In fact, all the other runs produced these triple peaks. What causes these strange effects? Figure 8 gives us little insight into what is happening. One possibility is that the TDC card, which measures the times, has tendencies built in to it. Perhaps brought on by bit errors.

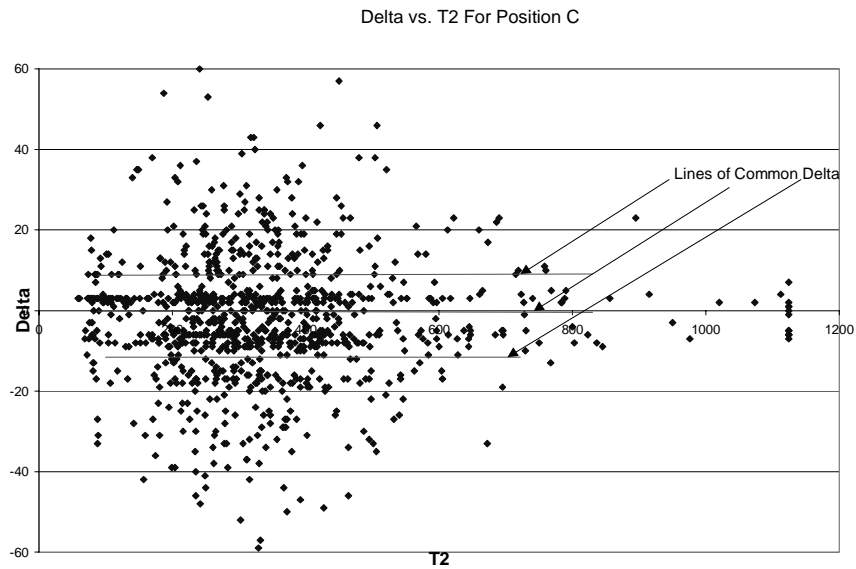


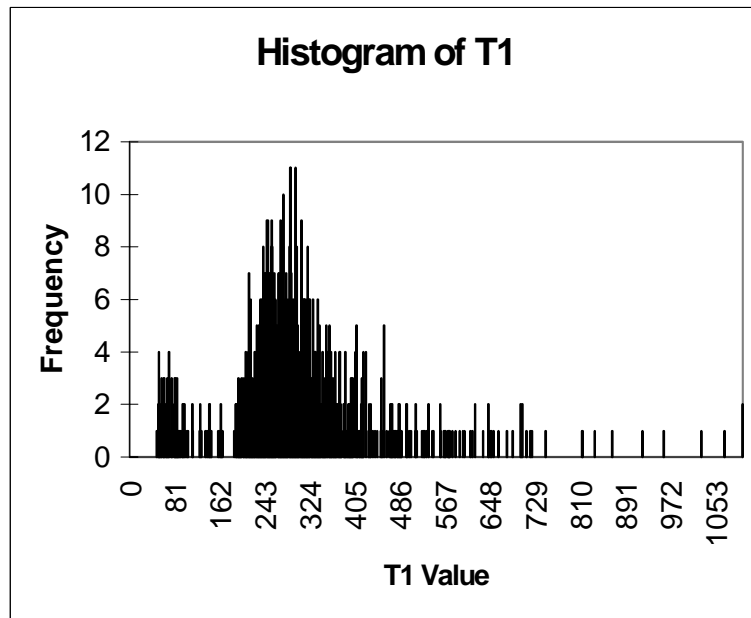
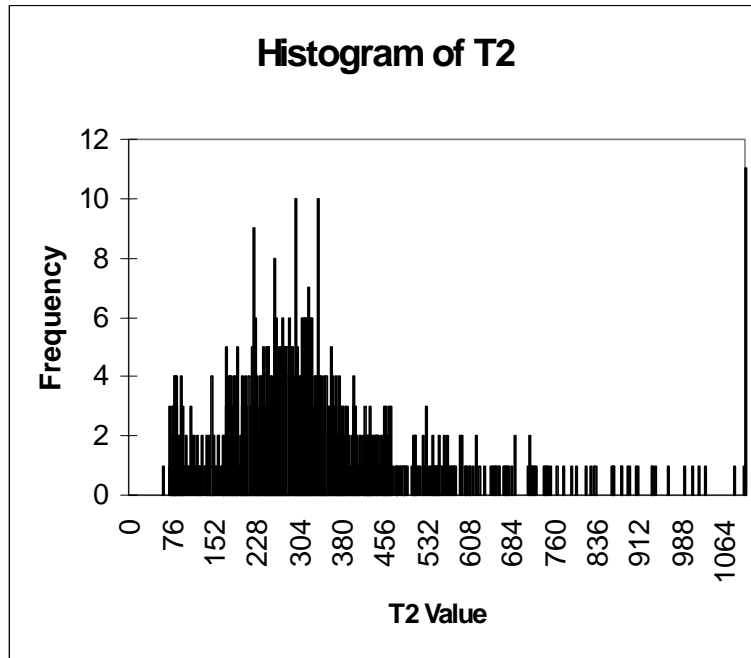
Fig. 8 Delta vs. a Trigger Counter

This puts doubt in most of the calculated results. The resolution was anywhere between 3.1 and 3.6, but those numbers might not mean much if part of the data is discarded by the TDC. Modifications are needed to correct this in order to be confident in our results.

VI. What's Next

There are several things that can be done to improve what we can learn about the time resolution of scintillating material. Most obvious is to increase the light yield by increasing the size of the scintillator. Also, by lengthening the piece of material we will better understand the effects of position on time resolution. Since small pieces of scintillator are often glued together in order to make larger sheets, it would be interesting to note whether these glue joints effects the material's resolution.

Fig. 7 Histograms of the Trigger Counters for Run



VII. Acknowledgments

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VIII. References

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1987