Forecast:
It's Raining
Muons
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The Relaxation Times

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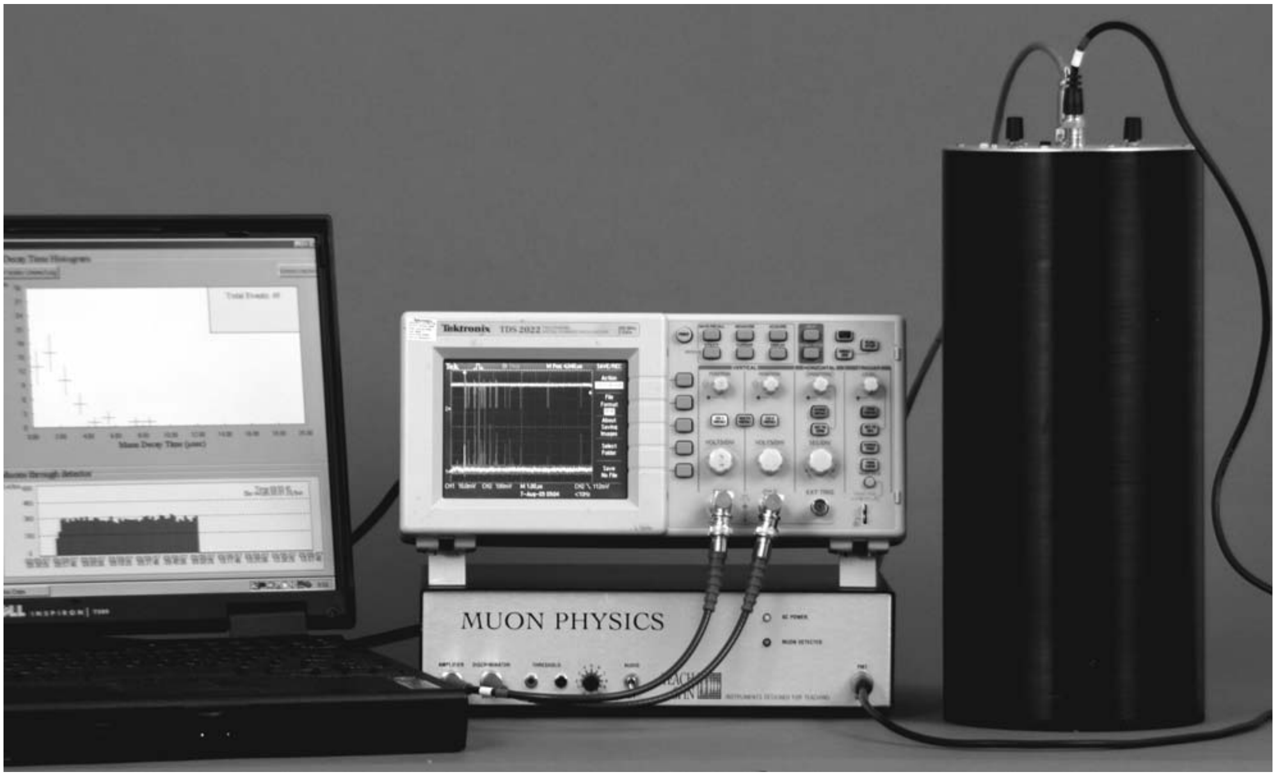
More About Muons



We enjoyed showing our Muon Physics apparatus in the 'workshop mode' at the Topical Conference on Advanced Labs held in July at Ann Arbor. While there, we devised a teaching method that we think you and your students will both enjoy and appreciate. It will show them the cause-and-effect relationships that lie between the muons and the computer screen in this experiment, and, along the way, it will teach them a lot about pulse electronics and event processing. All you need is a digital 'scope, and not even an expensive one.

Recall how the Muon Physics apparatus works. There's a big plastic scintillator inside the black aluminum cylinder, through which muons are passing frequently. The muons passing through (or the lower-energy muons that come to rest inside the plastic) all deposit some energy in the plastic. And, of course, the scintillator material is optimized to convert some of that energy into a very brief pulse of light. A fraction of that light reaches the photocathode of a photomultiplier tube (PMT) attached to the scintillator, where it ejects photoelectrons. Inside the PMT, those initial photoelectrons are multiplied, via a cascade process, to yield a macroscopic charge pulse delivered to the PMT's anode. That charge pulse emerges from the scintillator unit via a BNC cable, and is conveyed over to the electronics unit.

Inside the electronics box, there is a linear amplifier which shapes that charge pulse into a brief, positive-going, analog voltage pulse. This is the first place along the cause-and-effect chain where the pulse is easy to see with an oscilloscope. Using a 50-Ω termination on a BNC tee at the output labeled 'AMPLIFIER', a short cable to a 'scope's input, and setting the 'scope for a five second persistence, we see pulses like those in Fig. 1.

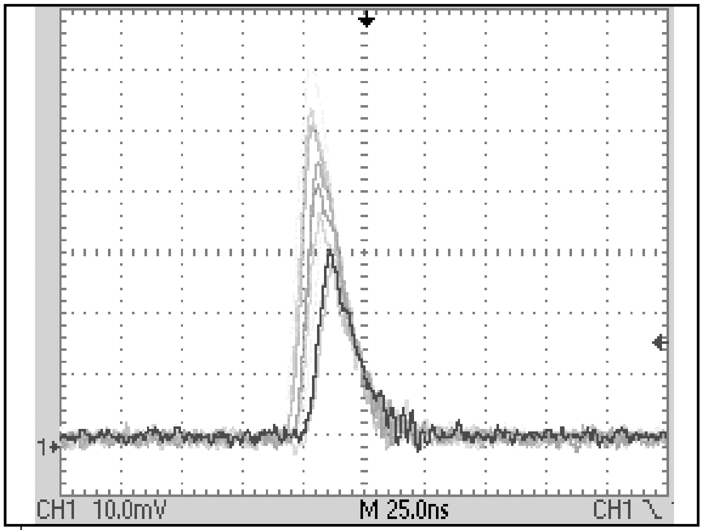


Fig. 1: Amplifier output pulses, viewed using 10 mV/div vertically, 25 ns/div horizontally, triggering on upward slopes at a level of +15 mV, and using 5 seconds persistence time. (The high voltage monitor on the PMT reads –11.068 V.)

Notice that multiple pulses have occurred during that five seconds of persistence, and note also that the pulses differ in amplitude. Why so? Mostly, because muons aren't aimed at the scintillator, so some of them pass through its center, and others just catch a corner of it. As a result, the amount of energy deposition naturally varies accordingly.

Notice too that these pulses we're attributing to the passage of muons lie atop a voltage baseline which itself is 'noisy'. Some of that is noise generated in the electronics box, and some is due to genuine scintillation events. Those scintillations, however, are produced by the (relatively) low-energy events associated with ambient radioactivity. The presence of that 'noise' brings up an important question -- what shall we 'count' as a real muon event, and what signals do we want to reject?

This is an issue in ***all*** pulse-processing experiments, and here too we'll deal with it using an 'electronic pulse-height discriminator'. The electronics of our pulse-height discriminator are set to 'fire', to give an output pulse, whenever there is an incoming pulse from the PMT amplifier that is larger than a given voltage pre-selected by the experimenter. This pre-selected value is called the threshold voltage. There is a knob on the front panel that sets the threshold voltage (CONTROL) and a set of pin jacks (THRESHOLD) that can be used with a voltmeter to read a DC voltage proportional to the threshold.

To see the results of that discrimination criterion, it's time to use the additional output labeled 'DISCRIMINATOR' on the electronics box. With Channel 1 still devoted to the amplifier output pulse, we now trigger the 'scope on the falling edge of the discriminator's output. To accomplish this, we put another 50-Ω termination on a BNC tee at the discriminator's output, and convey its signal via a second short BNC cable to the oscilloscope's Channel 2 input. The results are shown in Fig. 2a & 2b.

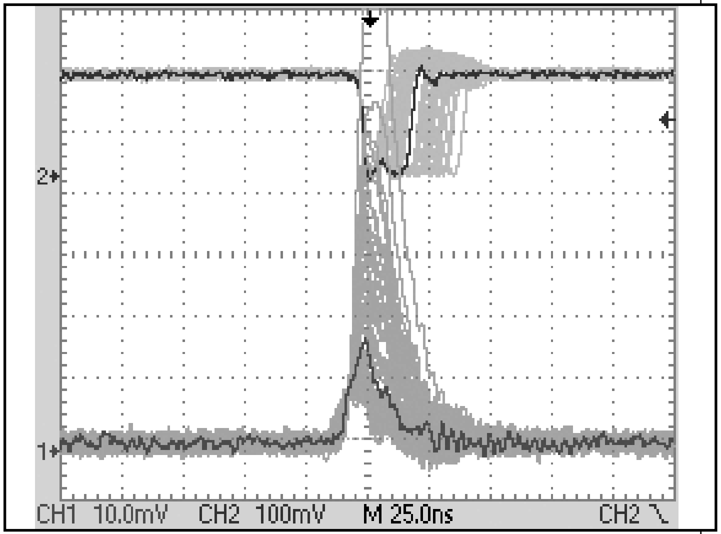


Fig. 2a: Lower trace, Channel 1, the amplifier output; upper trace, Channel 2, the discriminator output. Discriminator control is set at 2 on its 0 – 10 scale.

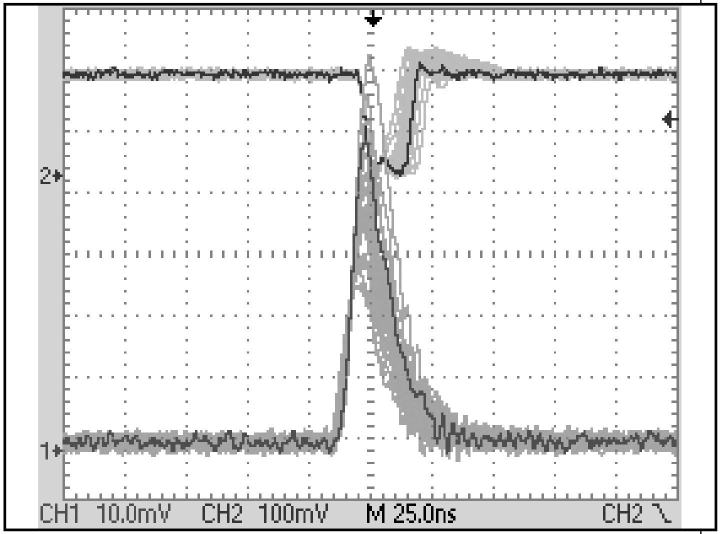


Fig. 2b: Same as 2a, except discriminator set at 8.

Notice that the discriminator's output sits quiescently at +160 mV, and drops briefly to zero, for a standardized duration, if and only if the discriminator 'fires'. The fact that the discriminator pulse occurs after the amplifier pulse reflects the fact that the amplifier-output pulse is the cause, and the discriminator-output pulse is the effect.

The only amplifier pulses that appear on the 'scope screen are those that fire the discriminator and thus, subsequently, trigger the 'scope. In particular, one can see in Fig. 2a that the smallest amplitude pulse is about 15 mV high for the discriminator setting of 2, whereas Fig. 2b shows that the smallest amplitude pulse is 30 mV high for a setting of 8. Instead of reading the dial on the discriminator, students can measure the DC voltage provided at the test points. It turns out the voltage at the test points is **not** the threshold voltage, but is proportional to it. It is a useful exercise for the students to measure the proportionality constant. (It turns out to be 50 mV threshold/1Volt at test points.) With this understanding of the role of the discriminator, students can now choose a proper setting for accumulating data.

The result of a good choice for threshold level is the successful transformation of analog information (the 'muon pulses' of varying heights) to digital information (the standardized shape, giving a yes/no indication of a 'muon event'). It's these 'event pulses' that are used, inside the electronics box, to start and stop the electronic stopwatch. And that 'stopwatch' is the source of all the muon timing information sent on to the computer.

There's still more you can do, learn, and teach, using the 'scope. The next opportunity is to use the 'scope to see what happens soon *after* a typical triggering event. For this purpose, we widen the time base, say to 1µs/div, move the trigger point to the left (to give a view of 9 µs of time after each triggering event), and use the *peak detect mode*. Here, we can get a bit quantitative: muon events happen at a rate of about 5 per second, so there's a typical waiting time of 1/5th of a second until the next one. That's 200 ms, or 200,000 µs, so, typically, the successor muon event will *not* appear in the 'scope's 9 µs field of view.

But, if you set up this display, and wait a minute or two, you'll see the first occurrence of a 'successor event' – one is shown in Fig. 3.

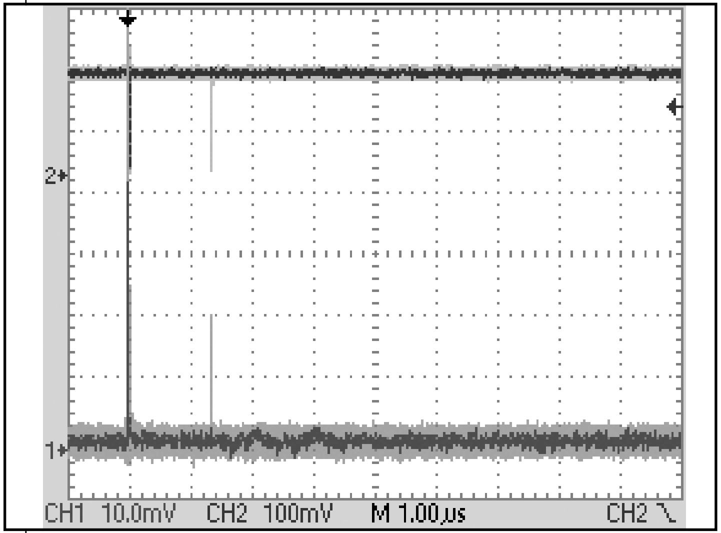


Fig. 3: Traces as in Fig. 2, of amplifier pulses (below) and discriminator pulses (above), but with time-base set to 1 µs/div, and persistence time set to infinite.

Here you see, at the 'scope's trigger point, the overlapping record of hundreds of trigger events; and you can also see, at 1.4 µs after the trigger point, that one of these many overlaid traces included a second 'muon event'. We can offer two possible hypotheses for this successor event:

A: the 'scope was triggered by one muon's passage through the scintillator, and the successor pulse was due to the passage of another, separate, unrelated, muon;

B: on one of the many traces, the 'scope was triggered by a muon coming to rest in the scintillator, and the visible successor pulse was due to the decay *of this very muon, producing either a positron or an electron* in the scintillator.

Now, if the computer was connected to the electronics box, and it was executing the Muon program with a Start that coincided with the beginning of the persistence interval shown in Fig. 3, you'd get to learn another valuable conceptual connection. After perhaps a minute's wait, just as you saw the first 'successor event' appear at 1.4 µs on the 'scope's face, you would *also* see one event, one count, one occurrence, appear for the first time in the main histogram in the computer's display window. That's because the electronic stopwatch in the electronics unit starts its clock at every muon event, and (in this 'pioneer' case) has stopped that stopwatch at a successor event only 1.4 µs later. This pair of events of 1.4 µs spacing corresponds to one occurrence of an 'interpulse' spacing lying between 1 and 2 µs. This is just what the computer tabulates. It adds of one instance, or one unit, to the column lying between the 1 and 2 labels of the histogram.

With only one example of a 'successor event' in hand, it is impossible to decide between hypotheses A and B above for its origin. If, however, we continue watching for perhaps 20 to 30 minutes, with the 'scope set as in Fig. 3, we'll get a lot more instances of these successor events, all of them lying on the same 'scope-face display. It's the *distribution in time* of a *sample* of such events across the 'scope's face that differs according to the two hypotheses as follows:

A: successor events due to a separate, unrelated muons, are as likely to fall near the 1 µs mark as they are to land at any other time (say 8 µs) -- since the muons involved under this hypothesis are independent and uncorrelated;

B: successor events due to the decay of stopped muons will **<u>not</u>** be uniformly distributed in time across the 'scope's face. Instead, they will be more concentrated at short times, and exponentially fewer at long times, because of the exponential decay of muons in the scintillator.

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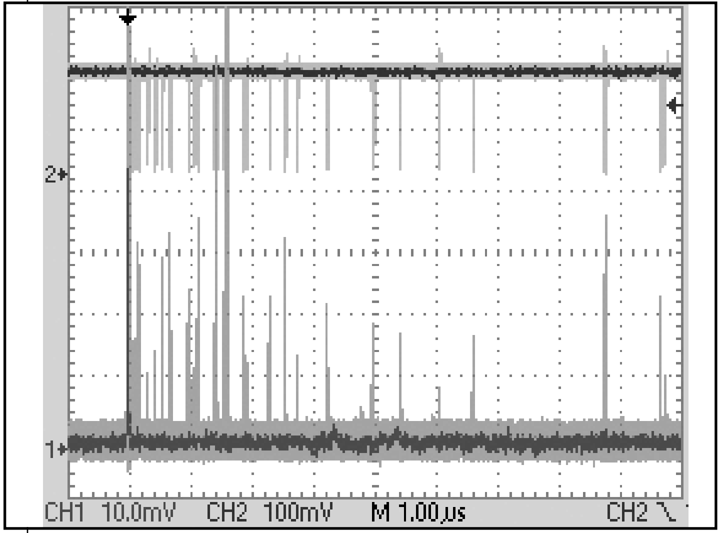

Fig. 4: Another infinite-persistence view as in Fig. 3, but this one showing 20 minutes' worth of accumulation of events occurring in the 9 µs after triggering events.

Fig. 4 clearly shows that hypothesis B is the one strongly supported by the data. Of the 24 events visible, 15 fall within the first 2 µs, while only 5 fall in the next block of 2 µs width, and only 3 fall in the next bin of time of 2 µs width.

Now once the idea of accumulating evidence of successor events on a 'scope's face has been attached to the emergence of instances of addition to the histogram, it should be clear that the histogram is the method of choice for accumulating, and viewing, lots of data. And with a few hours, or a few days, of data accumulation, students will see the emergence of a fine exponential decay curve due to type-B processes.

The sharper students will also see, underlying that exponential and continuing for the full 20 µs width of the histogram, a flat background called 'accidental coincidences', attributable to type-A) processes. In fact, the best of your students will even be able to predict how *many* such events ought to appear in each time-bin of the histogram. They'll need only some careful reasoning, and numbers for the muon event rate r (say, 5/second), the histogram's bin width τ (typically 1 µs), and the duration T of data accumulation (say 1 day = 86,400s). The mean number of accidental coincidences per bin for this case is predicted to be:

$$N = (r\,T)(r\,\tau) = r^2\,T\,\tau = (5\ /\ s)^2\ (86{,}400\ s)(1 \text{ x } 10^{-6}\ s) \approx 2$$

Think of all that a student can learn in this investigation, including all these electronic, instrumental, statistical, and reasoning skills that extend far beyond the particular (though interesting) case of muons -- and you'll see why we think there's a lot to learn in, and from, our Muon Physics apparatus.