Measuring Particle Lifetimes

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Most subatomic particles are unstable, decaying into less massive particles after some random time interval. While it is impossible to predict when the decay will happen for any individual particle, the lifetimes of a large number of identical particles will fall on an exponential decay curve: $N(t) = Ne^{-\frac{t}{\tau}}$, and the lifetime of the particle is given by τ. It is possible to measure this lifetime if one can observe the decay of a large number of the particle in question.

The muon, heavy brother of the electron, is unstable, decaying into an electron and two neutrinos. Furthermore, cosmic rays provide us with an abundant source of muons to study. By stopping cosmic ray muons and measuring the time interval between arrival and decay for a large number of events, we can fit the data with an exponential function and thus evaluate the muon lifetime. Furthermore, this can be done inexpensively, within the budget of the high school physics laboratory, and provides an exciting introduction to many ideas and techniques of modern high energy physics. The entire experiment presents four challenges: stopping the muons, detecting their arrival and decay, measuring the time interval, and evaluating the data.

While high energy muons are very penetrating and difficult to stop, the cosmic ray muon spectrum includes enough particles of low energy that we can obtain sufficient data for our measurement in a reasonable amount of time if we provide a volume of a few gallons in which to catch muons. The material in which the muons stop also plays a role in the detection of the particles; any material that scintillates - emits light as charged particles pass through it - could be used. If cost is important, the material of choice will be a liquid scintillator such as Bicron BC517L, and a volume of five gallons will work well.

To detect the light produced in the scintillator when a muon enters or decays, we use a photomultiplier tube. Any general purpose ten stage two inch tube should work. I have used an RCA 6342, available used from OE Technologies (www.oetech.com). In addition to the tube, you need a high voltage power supply, also available from OE Technologies, or you could build your own.

The third task - measuring the time interval - is the most difficult to do on a tight budget. A computer will be necessary, but it need not be anything special; any computer with a PCI slot will do the job. Some sort of electronic timing device to measure the time intervals and communicate them to the computer is needed, and the commercially available units seemed to be priced beyond the typical high school budget. Here, the Fermilab Physics Section has come to the rescue with a custom built timing card. This circuit has a 10 MHz crystal clock and an eight bit counter. A pulse from the phototube starts the counter, which counts clock pulses. If a second pulse arrives before the counter reaches 255, it stops the counter and the count is passed to the computer via a serial line. If the counter reaches 255 without a stop pulse it simply resets and waits for another start pulse. Thus when a muon stops, it will start the counter, and the pulse from the decay electron will stop the counter if it occurs within 25.6 microseconds. Muons which do not stop will start the counter, but no stop pulse will occur before reset, as long as the volume of scintillator is small enough that the overall rate is low compared to the maximum measured time.

Since the timing circuit communicates via a serial line, any computer with a simple terminal program can collect the data. Start the program in open capture mode with no error checking, and save the data as plain ascii. A simple BASIC program can be used to read the file, convert the hexadecimal numbers to decimal, and keep track of the number of muons that decayed in each time interval. The same program could fit the exponential and calculate the lifetime, or if you prefer it could write an ASCII file to be used as input to a spreadsheet, or just print the tabulated data, which could then be processed on a graphing calculator.

If I were building this experiment today (summer 2000) I would seek out an inexpensive 8 bit counter/timer card for a PCI slot - prices have dropped considerably since 1995 when i built my setup. If you find a suitable card, send me the details and I will put them in this document!

Building the detector is simple. For my prototype I used a five gallon plastic jug with a screw cap big enough to accept the phototube, and after filling the jug with liquid scintillator to within a couple of centimeters of the opening, mounted the phototube using two inch wide black electricians' tape. The tube should not protrude into the scintillator - a small air gap between the oil and the tube presents no problem. The only absolutely critical thing is to make the whole assembly light tight. Aluminum foil, heavy paper, and electricians' tape will do the trick. Tiny light leaks will produce lots of spurious data, and any significant light leak can damage or destroy the phototube, so do not skimp here!

After mounting the tube, you can apply high voltage and look for signals. The voltage requirements will vary from tube to tube - follow the manufacturer's recommendation here. For the signal, use 50 ohm shielded cable such as RG58, and BNC or LEMO connectors. If you have an oscilloscope with a reasonably high sweep rate available, you can see pulses from the phototube as muons go through the scintillator. The typical pulse will have a negative amplitude of 50 millivolts or more, and a width of perhaps 20 nanoseconds. If you are lucky enough to have access to one, a digital storage 'scope is particularly nice for seeing these, as they arrive at random intervals. If you do not have access to any suitable ocilloscope, just connect the signal cable to the timing card, connect the card to a DC power supply and your computer, run your favorite terminal program, push the reset button on the card and watch the data come in!

With my five gallon detector we were stopping about 1500 muons in 24 hours, so with a week or so of running, enough data can be collected to make a good measurement. For the students in my senior (high school) physics class, I chose to have them use a spreadsheet for analysis, and I wrote a BASIC program to decode the hex data from the timing card, count the number of events in each time bin, and produce a file for input to the spreadsheet. The students can then add Time and Ln(count) columns to the sheet, and graph Ln(count) vs. Time. For you old timers (like me!) this is like using semilog graph paper. The slope of the best straight line through the data is the muon lifetime, or at least in an ideal world it would be! In reality there are two processes contributing to the data that are not muon decays.

The first problem is that occasionally two separate muons will pass through the detector within 25 microseconds, thus faking a decay. Fortunately this background is easily dealt with, since to a good approximation, it contributes events to each time bin with equal probability, while the decay process has a very low probability of occurring in the upper time bins. A plot of counts vs. time will therefore be seen to be asymptotic to some small constant, rather than zero. By subtracting this number from every bin before making the semilog plot, this background is effectively eliminated. If you are using a more sophisticated curve-fitting technique, you can fit the raw data to an exponential plus a constant.

The second process contributing fake decays is nuclear capture of muons. About half the cosmic ray muons are negative, the other half being positively charged antimuons. When a negative muon stops, it will end up orbiting a nucleus like an electron, but since the muon is 200 times more massive than an electron, its orbit can be very close to the nucleus and can often be captured by the nucleus. This can also happen with electrons and is sometimes called k-capture, since an electron from the k shell is most likely to be involved. This is a weak-force interaction; the resulting nucleus is unstable and quickly disintegrates, producing a pulse in the detector and thus faking a muon decay. While a more complete treatment of muon capture is beyond the scope of this article, I will say that for carbon nucleii, the probability of capture is high enough that the measured lifetime will be somewhat lower than the accepted value for muons.