Measurement of the mean lifetime of cosmic ray muons in the A-level laboratory

Peter Dunne, David Costich and Sean O'Sullivan
Preston College, Fulwood, Preston PR2 8UR, UK

The Turning Points in Physics module from the NEAB A-level Modular Physics syllabus requires students to have an understanding of relativistic time dilation and offers the measurement of the mean lifetime of cosmic ray muons as an example of supporting experimental evidence. This article describes a direct measurement of muon lifetime carried out in the A-level laboratory.

Cosmic ray muons are created in the upper atmosphere when fast moving cosmic protons collide with nuclei of atoms such as oxygen or nitrogen. The collisions result in the creation of new particles from the energy of the interaction; the process is illustrated in figure 1. The particles arriving from space are known as primary cosmic rays whereas the particles created in the collisions are known as secondaries. Many of the new particles are very short-lived and do not survive to reach sea level, but positive and negative pions created in the process decay into muons that are detectable at ground level. The total secondary flux at sea level is about 1 $cm^{-2}\,min^{-1}$. Roughly 75% of the flux consists of positive and negative muons, and 25% of it consists of electrons and positrons.

If the negative muons stop in matter then they can be captured by atoms whereas the positive ones remain free. The mean lifetime of both positive and negative free muons is about 2.2 μs; captured muons have a shorter lifetime. According to classical physics, if the mean lifetime of the free muons is about 2.2 μs then they should only travel a few hundred metres when travelling at the speed of light after being created in the upper atmosphere, and many fewer than that indicated above would be expected to reach the ground. The only way to explain the high number of muons detected at sea level is through relativistic time dilation.

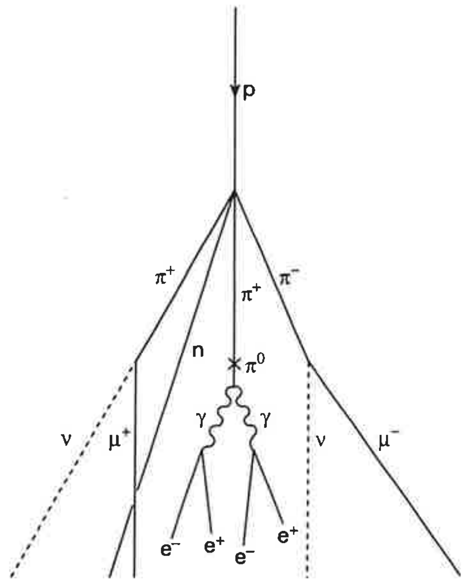

Figure 1. Typical interaction between a cosmic ray proton and an atmospheric nucleus.

A-level textbooks generally describe the theory and evidence well but students have to rely on faith when dealing with it. It is taken for granted that A-level laboratories are not equipped with the kind of apparatus to allow direct measurement of such phenomena. Coming to terms with special relativity is difficult if direct evidence is not immediately available so we decided to set up an A-level laboratory aimed at the study of cosmic rays and accumulate apparatus that would allow us to make the kinds of measurements carried out by cosmic ray particle physics pioneers in the 1930s and 40s.

We were helped by the Physics Departments at the University of Leeds and Lancaster University. They supplied us with the basic building blocks of scintillator materials, photomultiplier tubes, EHT supplies and discriminators. We then constructed the counters, built the processing electronics and developed the computer software to allow us to make our measurements.

Our original plan was to put together a counter telescope of four counter units in order to detect stopped muons using a coincidence/anticoincidence technique but we found that a good measurement of the mean lifetime of the muon could be made using a single scintillator. This suggests that the muon experiment could become within the reach of most A-level laboratories if a dedicated scintillator unit could be produced incorporating EHT power supply and signal processing electronics.

Mean lifetime and half-life

Contrary to what A-level textbooks and A-level exam questions would like us to believe, mean lifetime is *not* the same as the half-life of a radioactive sample. The mean lifetime associated with an elementary particle is simply the direct average lifetime of all measured lifetimes whereas the half-life of a sample of radioactive material is the time for the number of active nuclei to be reduced to half the original number. The half-life is a property of the sample, not a property of the individual members of that sample. If the decay constant associated with the sample is λ, then the mean lifetime of the members of that sample can be shown to be $1/\lambda$ whereas the half-life of the sample itself has the value $\ln 2/\lambda$.

The mathematically inclined might like to start with the exponential equation $N(t) = N(0)e^{-\lambda t}$ and show that the mean lifetime has the value $1/\lambda$ by considering the direct average, i.e.

$$\text{mean lifetime} = \frac{\int_0^\infty N(t)t\,dt}{\int_0^\infty N(t)\,dt}.$$

In the case of muons, the mean lifetime has the value 2.2 μs but the half-life of a sample of muons would have a value of 1.52 μs.

Measuring the mean lifetime

Measuring the mean lifetime of the muon involves working with an exponential curve in a way similar to that of measuring the half-life of a radioactive sample, but the way that the curve is developed is different. An easy way to see the differences is to consider the standard dice throw analogy for radioactive decay. In this analogy a large number of dice are thrown and those that land with a six face uppermost are removed at each throw. A graph of number of dice left versus number of throws is plotted. The decay constant for the situation is $1/6$ and hence the half-life of the sample would be expected to be $6 \ln 2$ throws, i.e. about four throws. To model the muon lifetime measurement we would have to take the dice one at a time and continue throwing each individual die until a six occurred. The number of throws before a six occurs represents the lifetime. The die would then be removed from the sample. A graph of number of dice having a given lifetime versus lifetime would then be plotted. The mean lifetime should be six throws.

The shape of the graphs produced by the two different methods would be exactly the same. The first graph is produced by measuring the number of dice per throw whereas the second is produced by considering the number of throws per die.

For cosmic ray muons, the lifetimes of individual particles can be measured by looking for pairs of pulses from the detector that are a few microseconds apart. We associate these pairs of pulses with muon decay events, the first pulse being due to the arrival and capture of the muon in the apparatus and the second associated with the emission of the decay electron. The first pulse starts a timer and the second one stops it. The 'ticks' of the timer are analogous to the throws of the die.

Whilst this is not a measurement of the true time between the creation and subsequent decay of the muon, the distribution of the measured time intervals has the same characteristics as the true lifetime curve. It is comparable to moving the origin of the graph to a new position; it doesn't matter where the origin is, the exponential has the same shape.

Experimental detail

We based our experiment on a standard PC digital input/output card that we had originally bought to explore the possibilities of transferring our BBC computer interfacing work to a PC platform. The input/output card carries an 8255 input/output port and an 8254 timer chip driven by a 10 MHz clock, hence giving us the facility to measure time intervals of 0.1 μs upwards.

The 8254 has a facility that allows the user to load a down-counter with a number and then count down at the clock frequency when its gate pin is held at logic HIGH. We arranged for the first pulse of the muon–electron pair to switch a bistable from one state to the other and the second pulse to switch it back. The output from the bistable was then used as the gate pulse for the counter. The counter was loaded with the number 255, hence giving a maximum measurement interval of 25.5 μs.

We developed computer software that enabled us to accumulate a record of time intervals between muon capture and the subsequent electron emission and plot a histogram of time interval frequency versus time interval. A typical histogram is shown in figure 2. A plot of ln(frequency) versus time was also produced (figure 3) and the gradient of the line was determined by a least-squares analysis of the data. The gradient of the log graph has a value $-\lambda$, hence the mean lifetime of the muon could then be determined from 1/gradient.

Apparatus

The counter unit consisted of a cylindrical block of plastic scintillator with a collection volume of about 0.02 m^3. A photomultiplier tube with a 12 cm diameter collecting face was placed in contact with the surface of the plastic. The assembly of PM tube and scintillator was housed in a lightproof box. The output pulses from the photomultiplier were negative-going with a typical width of about 10 ns. In order to see the pulses from the PM tube it was necessary for us to view an oscilloscope in a darkened room. After about 10 minutes, when our eyes had become accustomed to the dark, it was possible to see the pulses clearly with second pulses associated with the emission of decay elecrons occurring about once every 30 seconds. A typical muon–electron pair of pulses is shown in figure 4.

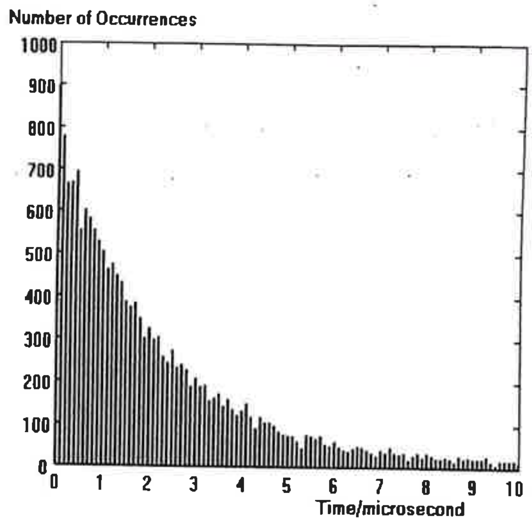

Figure 2. Frequency distribution of muon lifetimes.

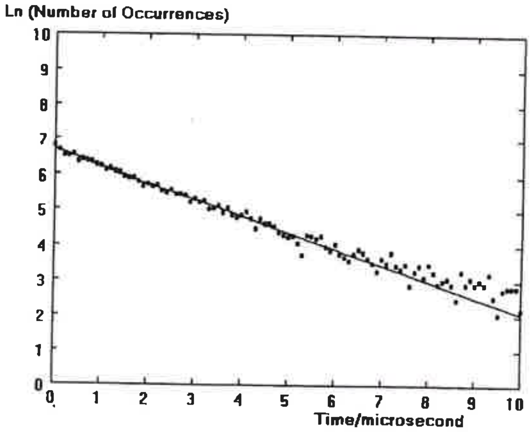

Figure 3. Logarithmic plot of frequency distribution of muon lifetimes.

A block diagram of the processing electronics is shown in figure 5. The pulses from the PM tube are passed through a fast amplifier based upon a standard video op-amp (figure 6). They are

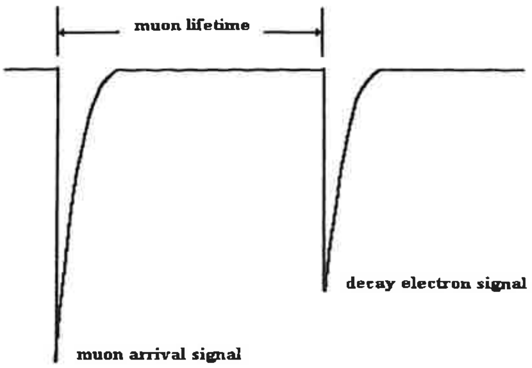

Figure 4. Typical muon–electron pulses from the photomultiplier tube.

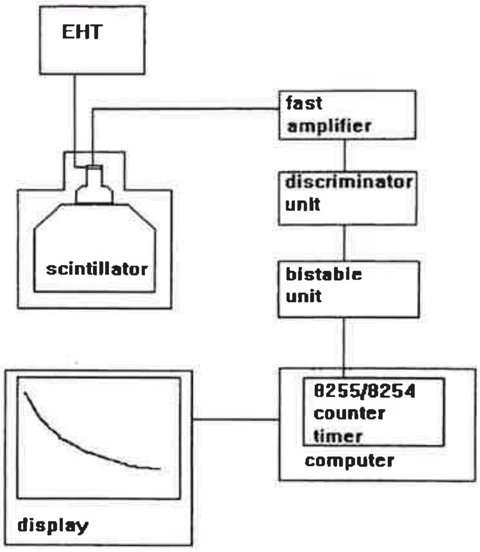

Figure 5. Block diagram of the muon lifetime experiment.

then fed into a discriminator unit set to respond to pulses greater than 100 mV. The output pulses from the discriminator are positive-going with a height of 2 V and a width of 35 ns. These pulses are fed directly into the bistable unit (figure 7). The complete apparatus can be seen in figure 8.

The bistable can be reset either from a control pulse from the computer via the 8255 I/O port or from the 8254 counter itself. The reset pulse from the 8254 occurs when a countdown sequence has passed through zero. This means that if the counter is loaded with a value of 255 then time intervals greater than 25.5 μs would be ignored by the system.

The first pulse of the pair from the muon–electron decay also sets a second bistable. This second bistable is continuously read by the computer software. When the output of this bistable goes high the computer recognizes that an event has occurred and that the timer will have been enabled by the gating pulse. This is the signal to the computer to read the timer, work out the time interval and plot its value on the graph. After the timer has been read a pulse is sent out from the 8255 to reset both bistables and the counter is reloaded with the number 255 ready for the next pulse pair.

The system can be left running for days in order to build up a large record of events. The exponential character of the graph emerges very quickly. The software carries out a least-squares analysis of the data once the total number of events has exceeded 500 and then recalculates for each subsequent event. The value of the mean lifetime derived from the data is displayed and continually updated.

Results

The graph of $\ln N(t)$ versus t is clearly linear in the range 0–6 μs. Beyond 6 μs the background events associated with random pairs of pulses become dominant. Whilst the slope of the best-fit line produced by considering values of lifetime less than 6 μs gives a value of the mean lifetime of about 2.2 μs, the value of the first decimal place is really determined by an arbitrary cut-off point in the calculation. If values of lifetimes in the dominantly background region of greater than 6 μs are included then the lifetime value rises above 2.2 μs. From our measurements and investigations we feel confident that we can quote the result that the mean muon lifetime has the value 2.2 ± 0.1 μs.

We could compensate for the background events by carrying out a least-squares fit on lifetime values greater than about 10 μs to find the corresponding equation of the curve associated with those events. This would allow us to make corrections to the frequency values at the lower end of the curve and hence produce a mean lifetime with a 'background' count correction.

Alternatively we could use other detectors in a counter telescope arrangement and use coincidence circuitry to ensure that we are definitely dealing with muons stopped in the target counter and

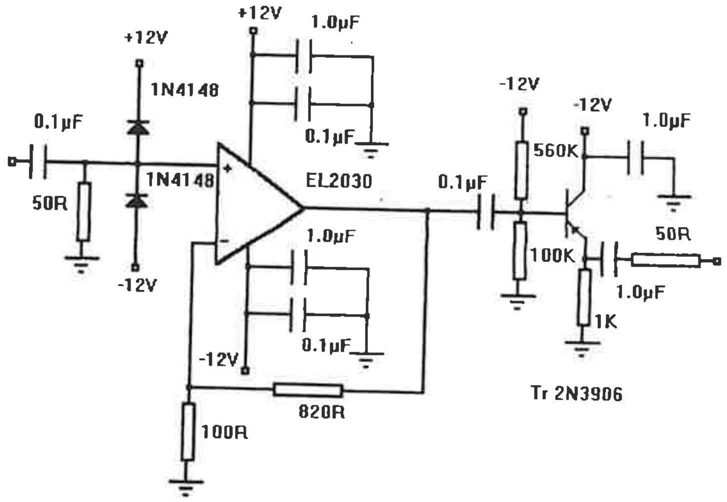

Figure 6. Fast amplifier based on the EL2030 video amplifier.

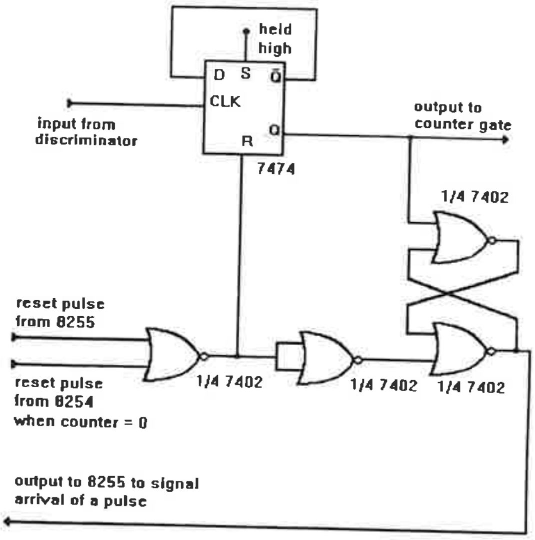

Figure 7. Bistable unit for controlling the timer.

eliminate random pairs of pulses. Whilst this approach would be closer to that used by working particle physicists it would cut our count rate significantly due to the narrower solid angle of collection of a counter telescope compared to the full 2π steradian solid angle of collection of a single unit. Our arrangement gives a good result in a single day; a counter telescope would extend the time required to a week or so and reduce the impact of the experiment as a demonstration.

Outcomes and next steps

We have moved into a field of measurement that is normally associated with undergraduate laboratories in those university physics departments where there is an active interest in particle physics and cosmic ray studies. Our direct measurement of the muon lifetime gives us a value comparable to that measured in professional laboratories and demonstrates that real particle physics can be carried out in the A-level laboratory.

The main difficulties in the work were associated not with the basic physics but with getting our hands on the building blocks of apparatus to enable us to do the job. In addition, progress was slow due to the limited amount time per week that could be devoted to the work because of other curriculum pressures.

The positive support of individuals in the universities of Leeds and Lancaster saw us through. The experiment itself demanded the application of much basic physics. We felt a need to be totally familiar with the operation of the scintillator material and the photomultiplier tubes to be sure that we really were measuring what we were aiming for. On the experimental side we had to consider the effects of poor optical coupling between the scintillator and the photomultiplier, multiple internal reflections in the scintillator, the construction of the photomultiplier tube dynode chains, the structure and operation

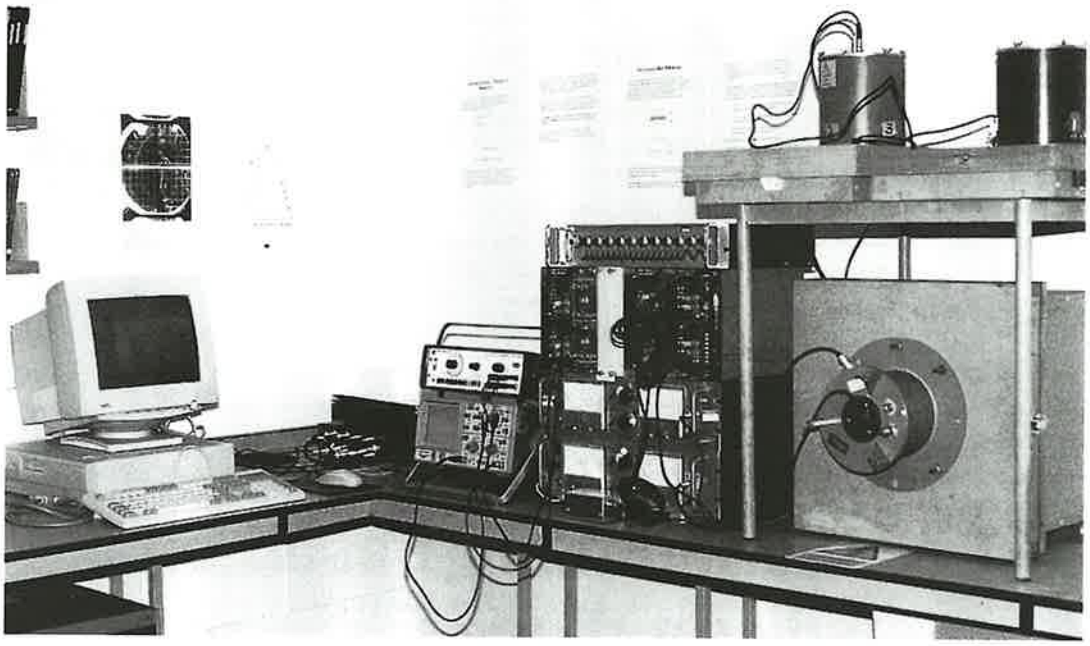

Figure 8. Photograph of the apparatus.

of the photomultiplier, the statistics of interpulse times and random events, the relationship between half-life and mean lifetime, capacitance effects in high speed electronics, the importance of correct termination of interconnecting cables etc. On the theoretical side we found ourselves learning about primary and secondary cosmic rays, particle creation and decay etc. Like all extracurricular science, the work was rich in its outcomes.

We have developed a greater appreciation of the central role of cosmic ray studies in the emergence of the science of particle physics. We intend to mine this rich vein of recent physics history a little further and try to reproduce a range of other standard cosmic ray explorations. We have accumulated a substantial amount of lead from the college's Department of Construction and intend to explore the energy spectrum and composition of the sea level flux. We will use our other counters to look at the polarization of the muon and the asymmetric electron emission in a magnetic field. We would like to build our own high quality expansion cloud chamber to be coupled to a digital camera and computer so that we can make mass measurements, arrange for collisions to be observed and seek Rochester and Butler's strange particles. We are also particularly keen to stop a muon in a cloud chamber and record the electron/positron emission event directly. We aim to have a fully operational spark chamber—we want to see the particles in addition to counting them.

Those who are working hard to bring particle physics into the mainstream curriculum have produced some excellent materials and need to be congratulated for their efforts. Much of what has been produced has been based, quite rightly, on accelerator physics and data. But a good flux of high energy particles comes through the ceiling for free and the physics involved in investigating that flux covers a significant proportion of the traditional A-level syllabus.

We intend to investigate the development of a dedicated scintillator/photomultiplier unit which would incorporate its own EHT supply and processing electronics. Such a unit would deliver TTL signals to the user for direct interfacing to a computer. We believe that a dedicated scintillator unit could be developed for a fraction of the cost of the supporting apparatus that we have been using, and the use of several such units could open up a wide range of cosmic ray-based particle physics studies at A-level.

Acknowledgments

We would like acknowledge the contributions of the many individuals whose direct support opened up this field of activity to us. In particular we thank Professor Sir Arnold Wolfendale for the initial encouragement, Jeremy Lloyd-Evans and Paul Ogden of the University of Leeds for the loan of equipment and extensive guidance, John Windsor of Lancaster University for the loan of equipment and technical support, Tony Hincks and Peter Wright of Preston College for the construction of the lightproof housings, and Jonathan Mitchell, Marc Sutton and Jim Wrathall of Preston College for their involvement in the early stages.

Received 10 June 1998
PII: S0031-9120(98)94972-3

A direct reading thermometer based on a silicon diode

L Kirkup and C Tonthat
University of Technology, Sydney, Australia

Commercially available silicon diodes are suitable as temperature sensors over a wide range of temperature. Despite their robustness, abundance and very low cost, they are seldom used in high school or junior undergraduate laboratories as temperature sensors. Here we describe a simple circuit based on an inexpensive quad operational amplifier that permits a direct reading temperature instrument to be constructed using silicon diodes, thereby encouraging their use in introductory thermal experiments.

Silicon diodes have long been used as temperature sensors, particularly at cryogenic temperatures where their linearity, high sensitivity and low noise are attractive characteristics (McDonald 1995). Due to their low thermal mass they are ideal for use in situations requiring the tracking of rapidly changing temperatures. Despite their robustness and the fact that they are inexpensive relative to other temperature-measuring devices such as mercury-in-glass or thermocouple thermometers, diodes are not widely used for the measurement of temperatures between 0 and 100 °C. It is possible that the primary reason for this is that, unlike thermocouples and platinum resistance temperature sensors, there exists no readily available signal conditioning module that can transform the voltage across a diode into a direct reading of temperature.

Here we describe a simple 'single chip' circuit that provides the necessary signal conditioning to permit direct temperature reading using a silicon diode. For applications where low accuracy is acceptable (say within ±2 °C of the true temperature), low-cost components may be used so that signal conditioning for a diode can be constructed for under £5 (excluding power supply and voltmeter). This allows silicon diodes to be conveniently applied to temperature sensing in standard experiments found in senior school or first-year university physics laboratories, such as the determination of cooling curves for bodies with different emissivities or the melting point