EARLY MUON-PHYSICS MEASUREMENTS WITH COSMIC RAYS

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In 1996 the American Institute of Physics, marking the centenary of the birth of elementary particle physics, published a book\(^1\) collecting together brief descriptions of experiments and theoretical papers that were pivotal in the development of the science. There were several entries about work done in Canada, four of which concerned the basic properties of muons\(^4\). The first two of the key muon papers concerned the measurement of the lifetime of stopped muons by Franco Rasetti at Laval University in 1941\[^2,3\]. The other two experiments\[^4,5\] concerned decay modes of the muon and were carried out by Ted Hincks and Bruno Pontecorvo at Chalk River later in the decade.

Although the muon experiments were well known to contemporary physicists they are now relatively obscure. It seems fitting, as we observe the centenary of the discovery of cosmic rays, to remember these seminal contributions to elementary particle physics. I will begin with a brief introduction to the muon and go through some of its early history. I will then describe the pioneering measurements of Rasetti, Hincks and Pontecorvo.

THE MUON

The muon is an important player in modern physics where it can be an object of study, a useful probe, and an annoying background. It is one of the three charged leptons found in the Standard Model of elementary particle physics; it has a negative electric charge and an associated neutrino ($\nu_\mu$), and is unstable, decaying in 2.2 microseconds to an electron and two neutrinos ($\mu^- \rightarrow e^- \nu_e \bar{\nu}_\mu$). With a mass of 105.7 MeV/c\(^2\) it has long been considered as a heavy electron although, as we shall see, it is not an excited electron, able to undergo the decay $\mu^- \rightarrow e^- \nu_\mu$ as well. As with all the Standard Model particles, the muon has an antiparticle with identical properties.

The muon participates in gravitational, weak, and electromagnetic interactions but, due to its non-negligible mass, it does not lose much energy to radiative processes like bremsstrahlung. This makes it highly penetrating, second only to neutrinos. Muons are commonly produced in the decays of mesons, primarily pions, and have been used extensively at accelerator laboratories, in intense high-energy beams, to probe the structure of the proton using the technique of deep inelastic scattering.

Muons are copiously produced in extensive air showers initiated when high energy cosmic rays (mostly protons and helium nuclei) impact the upper atmosphere. These showers are hadronic cascades containing large numbers of charged pions which decay (proper lifetime 26 ns) to muons and neutrinos. Due to time dilation, the high energy muons survive until they range out deep underground\(^2\). The net flux of muons at sea level is about one per second passing through one’s outstretched hand.

The muon was discovered by Carl Anderson and Seth Neddermeyer at Caltech in 1936-7\[^6\]. Anderson, who had discovered the positron in 1932 using a cloud chamber to image cosmic ray tracks, took the device to an altitude of 4300 m on Pike’s Peak for further studies. He and Neddermeyer identified a particle with mass intermediate between the electron and proton and named it the ‘mesotron’, from the Greek word for ‘mid’. This new particle was soon identified as that predicted in 1934 by Hideki Yukawa\[^7\] as mediator of the nuclear force. This was an error, only corrected a decade later following work by Conversi et al.\[^8\] which showed that Anderson’s mesotron did not participate in strong interactions. (Yukawa’s particle, the $\pi$-meson or pion, was discovered

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1. The others were about Ernest Rutherford’s study of radiation from uranium and his investigations into the nature of alpha rays, Bruno Pontecorvo’s proposal for the radiochemical method of detecting neutrinos and his paper about the universality of the Fermi weak interaction theory, and the first measurements of the neutron lifetime, by John Robson.
2. Hence the need for facilities like SNOLab.
in 1947, in nuclear emulsions exposed to cosmic-ray protons at high altitudes \cite{9}.

Although it was not anticipated at the time of the first measurements, the muon lifetime became a key experimental guide for early weak interaction theories since it was closely related to nuclear beta-decay rates.

**FRANCO RASETTI AND THE MUON LIFETIME**

Franco Rasetti was born in 1901 near the central Italian city of Perugia. He met Enrico Fermi while at the University of Pisa and the latter convinced him to switch from engineering to physics. They became close friends and collaborators, eventually becoming the leaders of the famous ‘ragazzi di via Panasperna’ (boys of Panasperna Street) Fermi’s group in Rome that established the science of neutron-induced radioactivity. Other members included Ettore Majorana, Emilio Segrè, Edoardo Amaldi, and a young Bruno Pontecorvo. Within the group, the infallible Fermi was nicknamed ‘the Pope’ while his deputy Rasetti was called ‘the Cardinal’. Rasetti had learned to make his own electronics and instruments while in Pisa and during various sojourns at labs in Europe and the US. Especially important was his expertise with Geiger-Müller (GM) counters, acquired while working with Lise Meitner and Otto Hahn in Berlin in 1931-32.

As a result of fascist policies, the Rome group began to disintegrate during the late 1930s; the coup-de-grace was Fermi’s departure at the end of 1938. Meanwhile, at Laval University a decision to create a department of physics had been taken. Chemistry was well established but Physics was taught as a set of service courses by Cyrias Ouëllet, a physical chemist. It was Ouëllet who eventually recruited Rasetti to establish the Laval Physics Department, overcoming many obstacles presented by the deteriorating political situation in Europe and difficulties with Canadian immigration authorities. Rasetti’s scientific stature and his credentials as a member of the Pontifical Academy of Sciences helped smooth the way on both sides of the Atlantic \cite{10,11}.

When Rasetti arrived at Laval he was starting from zero but he had the advantage of self-reliance and expertise with instrumentation. He carried out his measurements on the lifetime of the muon with electronic circuits and GM counters constructed by himself and his students, even selling surplus units to universities and laboratories throughout North America. In this he was aided for a time by Paolo Pontecorvo, Bruno’s older brother who was an electrical engineer. Recruited in September 1939, he stayed for just under a year, leaving after Italy entered the war as an ally of Germany, and anti-Italian policies of the Canadian government (from which Rasetti was protected) made life very difficult.

Rasetti’s setup is shown schematically in Figure 1. A set of GM counters, labelled A, B, C, D in the Figure identified an incoming muon. The layers of lead were to filter out electrons and products of local showers and also served to slow the muons down, to increase the number stopping in an absorber (iron or aluminum depending on the run). The bank of counters labelled F were used in anticoincidence to signal events where the muon stopped. The G counters were added in anticoincidence to ensure that the muons were unaccompanied by shower components not stopped by the lead. The E counters detected the emerging decay electrons.

Such a setup is found in many upper-year physics laboratory courses but the counters are pieces of plastic scintillator read out by photomultiplier tubes (PMTs). In Rasetti’s day, the modern electrostatic PMT had only just been developed (at RCA in 1937) and plastic scintillators, first demonstrated in 1950 \cite{14}, were years away. Similarly, a simple time-to-digital converter (TDC) would now be used to measure the time between the arrival of the muon and the appearance of the decay electron. However the response times of the GM counters, coupled with the slow vacuum-tube electronics of the day, resulted in resolving times on the order of the muon lifetime. A different strategy was needed.
Events satisfying ABCDEFG with a coincidence time of 36 μs were counted in a register. A subset of those events, where a 1.2 μs coincidence between D and E also occurred were counted in a different register. These latter events included those where the muon simply scattered from the absorber into the E counters but not those events where the muon stopped and the decay electron emerged after more than 1.2 μs. The difference in rates from the two registers was used as evidence for the first detection of the decay of muons at rest and a lower limit of 1.2 μs was given for the lifetime [13]. An earlier attempt by others [15] to do make the same measurement had failed, owing to the use of lead as absorber. The decay electrons did not have enough energy to escape.

Rasetti went on to improve the electronics and was able to use the same apparatus to count coincidences with three coincidence times: 15 μs, 1.95 μs, and 0.95 μs. (The last interval was used with the iron absorber; when aluminum was used 0.76 μs was employed since the resolving times for the GM counters had changed.) Data were acquired over three months of almost continuous running and the muon lifetime was determined by fitting the rates from the different coincidence times to an exponential decay hypothesis. A value of $1.4 \pm 0.3$ μs using the iron absorber was obtained. With aluminum the result was $1.6 \pm 0.4$ μs. These values are lower than, but statistically consistent with, the currently accepted value. A year and a half later, Rossi and Nereson used a similar setup to make a more precise measurement: $2.15 \pm 0.07$ μs [16,17]. They used an early form of TDC and were able to make the characteristic decay plot with 0.2 μs bins.

Rasetti went on to do a few more measurements with muons and continued with a parallel line of research in slow-neutron physics. His graduate student, Paul Koenig, wrote an MSc thesis on cosmic-ray muon showers and a PhD thesis on absorption of slow muons in various materials. Over time Rasetti’s focus switched to paleontology which was well-suited to his love of the outdoors. Field trips to the Burgess Shales in the Canadian Rockies allowed him to indulge his passion for mountaineering; a high-standard alpinist, Rasetti had once rolled into France and found refuge in the US, where he worked for an oil exploration firm in Oklahoma using his experiences with the via Panasperna group to develop the first neutron-based well-logging techniques. He joined the British team at the Montreal Laboratory in 1943 and followed the action to Chalk River in early 1946. Like Fermi, Pontecorvo was equally gifted as an experimentalist and theorist. He was one of the four physicists in the crowded control room when the NRX reactor went critical in July 1947, his presence among the operators tolerated because he and a student (David Kirkwood, also present) had provided the diagnostic instrumentation.

Soon after Pontecorvo’s arrival in Chalk River, he and Hincks built the apparatus which was to provide the data for their investigations into the nature of the muon. A photograph of the key components is shown in Figure 2. As with Rasetti’s experiment, GM tubes were the detecting elements and the basic logic was to demand the upper two trays (A and B) to produce a signal but for the lower tray (C) to be silent, thus signalling that a muon had stopped in the graphite absorber between B and C. In contrast to Rasetti’s strategy of orienting the absorber material with the long edge in the vertical plane, thus trading area for stopping depth, Hincks and Pontecorvo opted for the alternate choice. They reasoned that ‘thin but wide’ had more rate than ‘thick but narrow’ due to the angular divergence of the incident muon flux.

Their first important publication [4] concerned a search for gamma rays among the decay products of the muon. When the muon had been mis-classified as Yukawa’s meson, it had been
natural to assume that it would decay into an electron and a neutrino. However with the results of Conversi et al. [8] casting doubts on the classification, alternative decay hypotheses were considered and needed to be tested experimentally. One of the most obvious possibilities was the decay $\mu \to e\gamma$ and it was this decay that the Chalk River team looked for.

To enhance the detection efficiency for gamma rays, they placed 2.1 mm sheets of lead above and below the graphite so that a gamma ray emerging from the absorber would convert to an $e^+e^-$ pair which could, being charged, be detected by one of the GM counters. To select $\mu \to e\gamma$ candidates, they required AB followed by a delayed B or C or BC. (Note that in this experiment C was not used in anti-coincidence for the first part of the trigger.) The delayed signal was required to come between 0.6 and 5.3 $\mu$s after the initial AB signal. A single delayed signal from B or C would arise from a decay electron but a delayed BC coincidence would be strong evidence for the putative decay scheme.

After many runs, with various combinations of absorber and thicknesses of lead to check on systematics, the team was able to rule out $\mu \to e\gamma$ as an important channel for muon decay. Although not phrased in the language of 99% confidence limits on a branching ratio, this result was the first of a long series which continues to this day at laboratories like TRIUMF and PSI. The non-existence of this decay shows that, although the muon seems to be very similar to the electron, it is not an excited version (an $e^*$). In modern parlance, it is from a different family and has a distinct lepton number.

The second key paper from Hincks and Pontecorvo [5] explored the nature of the decay products. It had been established that two components were present: ‘hard’ – able to penetrate 38 g/cm$^2$ of absorber and ‘soft’ – easily absorbed by 20 g/cm$^2$ of material. In this paper the authors included two extra trays of GM counters (D and E) below tray C. Above each new tray was a layer of lead or carbon to be used for decay-product absorption studies. The basic trigger for the observations was ABC, indicating a stopping muon. Logic pulses from delayed C, D, and E and various coincidences and anticoincidence combinations were recorded with a ten-pen recorder. The conclusion from this study was that the ‘hard’ component was bremsstrahlung and the ‘soft’ component was the decay electron which was its source. From the range-energy relations for charged particles they were able to conclude that the average energy of decay electrons was above 25 MeV.

Bremsstrahlung was a complication on the path to determining the energy spectrum of the decay electrons. It is now known that the muon decays via $\mu^- \to e^-\nu\bar{\nu}$, a classic three-body decay where the electron has a continuous distribution of energies, but in the late 1940’s a two-body decay, with a consequent monoenergetic electron had not been ruled out. Hincks and Pontecorvo had shown that the use of absorption measurements would require more care and statistics to get a reliable primary energy spectrum for the decay electron. Again, research in this general area has continued ever since; one important example is the recent TWIST experiment at TRIUMF [20].

Still a member of the British contingent at Chalk River, Pontecorvo left for Britain in 1948 and continued his research at the Atomic Energy Research Establishment, Harwell. In the summer of 1950 he disappeared while on vacation, surfacing much later in the USSR where he remained for the rest of his life, working at the Joint Institute for Nuclear Research in Dubna. His contributions to nuclear and particle physics, especially neutrino physics, are many and profound.

Ted Hincks remained at Chalk River until 1961, at which time he moved to the National Research Council in Ottawa. His group, in collaboration with researchers at the University of Chicago which had a cyclotron capable of producing muons, did pioneering experiments in muonic-atom physics. In 1965 he became Chairman of the Department of Physics at Carleton University, while retaining his duties as head of particle physics at NRC. While at Carleton he was one of the founders of the Institute of Particle Physics.
CONCLUSIONS

In 1953, a 3 GeV proton synchrotron became operational at Brookhaven National Laboratory in the US. This was the first accelerator to have beam (kinetic) energy above 1 GeV and it was named the ‘Cosmotron’ since it could produce particles so far only observed in products of cosmic-ray interactions. Although research in cosmic-ray physics continues today, it is focused on the nature of the radiation itself, where it comes from and how it is accelerated. The advent of the Cosmotron marked the end of the use of cosmic rays as a source of high energy particles and it ended an era where small groups, working in labs without large machines, could make important measurements in elementary particle physics.

REFERENCES

1. V.V. Ezhela (ed), Particle Physics: One Hundred Years of Discoveries (An Annotated Chronological Bibliography), American Institute of Physics, 1996.