Muon to Electron Conversion – How to Find an Electron in a Muon Haystack.

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The Standard Model of particle physics (SM) describes how the universe works at a fundamental level. Even though this theory has proven to be very successful over the past 50 years, we know it is incomplete. Many theories that go beyond the SM predict certain processes to occur that are forbidden by the SM, such as muon to electron conversion. This article will briefly review the history of muon to electron conversion and focus on the high–precision experiments currently being proposed, COMET and Mu2e, and a next–generation experiment, PRISM.

The PRISM experiment intends to use a novel type of accelerator called a fixed–field alternating–gradient (FFAG) accelerator. There has recently been renewed interest in FFAGs for the Neutrino Factory and Muon Collider and because they have applications in many areas outside of particle physics such as energy production and cancer therapy. The synergies between these particle physics experiments and other applications will also be discussed.

Keywords: Particle physics, muon to electron conversion, accelerator physics, FFAG.

1. INTRODUCTION

Particle physics aims to explain the behaviour of everything by understanding the fundamental building blocks of nature. The theory we have at the moment, known as the Standard Model of particle physics (SM), has two main groups of particles, leptons and quarks, and describes the way in which these particles interact by the exchange of a third set of particles known as gauge bosons. These particles are the fundamental building blocks with which we can construct all the things we observe in the universe, from atoms to galaxies. The SM is an incredibly successful theory, which was developed over 50 years, and almost all attempts to prove it wrong have failed. Figure 1 shows the quarks and leptons used in the SM. Every day matter is made of up quarks, down quarks and electrons. The other particles are only found at higher energies, for example in stars or particle colliders, with the exception of the neutrinos, which are all around. The figure also shows the direct transitions that are allowed in the SM. A quark in the top row can convert to any quark in the bottom row, whereas a lepton in the top row (a charged lepton) can only directly convert into a lepton in the bottom row (a neutrino) in the same column. Leptons within the same column are referred to as having the same flavour. Nevertheless the SM is at best incomplete, since it does not include gravity and theoretical predictions for certain interactions become unstable with increasing energy.
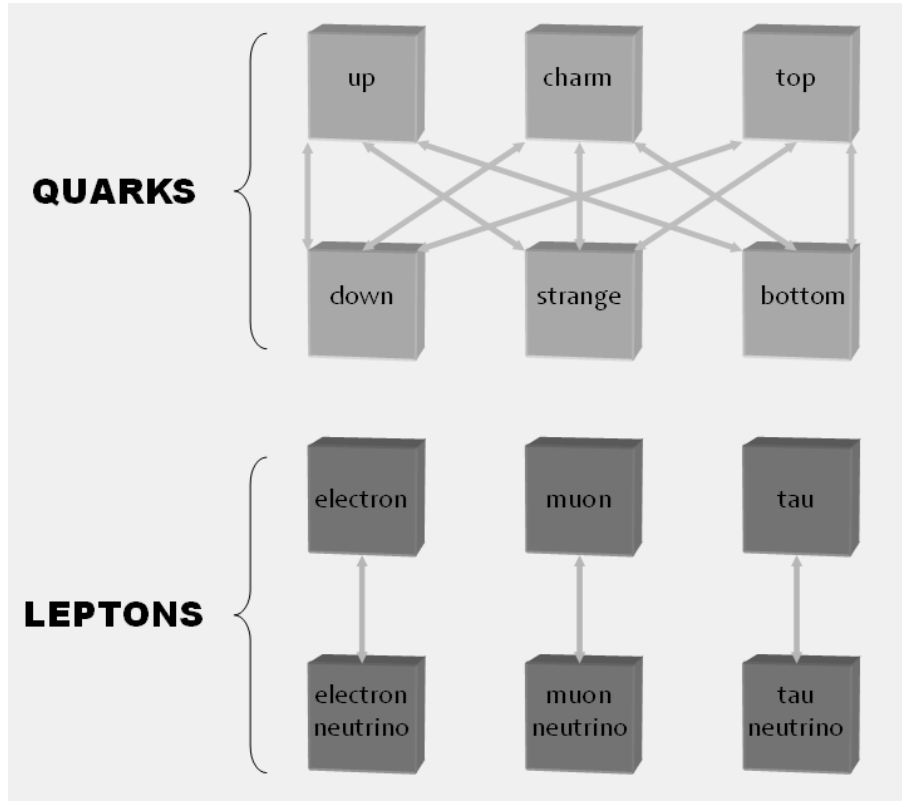
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Figure 1. The quarks and leptons that are the fundamental constituents of the Standard Model of particle physics. The arrows indicate the allowed direct transitions.

There are two complementary approaches to furthering our understanding of particle physics. One is to directly produce new particles at high energies and study their behaviour. This is the method used by the Large Hadron Collider (LHC) which aims to directly observe new particles that only exist at energies that occurred within a billionth of a second after the big bang. Any observation of new fundamental particles that are not in the SM will be a ground–breaking discovery so the results from the LHC are eagerly awaited. The other approach is to make very precise measurements at relatively low energies. The probability for a particular process to occur is determined by contributions from all allowed processes. This means that there will be small contributions to this probability from processes that occur at all energies. Thus, by making very precise measurements it is possible to probe physics at energies far in excess of those that can be produced by any conceivable collider.

Precision measurements in the past have played an important role in particle physics, in particular kaon physics which gave the first realisation of the asymmetry between matter and antimatter and measurements of the anomalous magnetic moment of the muon which can be both measured and predicted to 0.5 parts per million and shows a tantalising discrepancy. Recently, most precision measurements have focused on quark processes such as the measurements done by the BaBar Collabo-

ration (2002) and the Belle Collaboration (2002) in the bottom–quark sector but no discrepancies with the SM have been established. On the other hand neutrino measurements have shown that the SM does not fully describe what we observe in nature. Experiments done by the Super–Kamiokande Collaboration (2002), the SNO Collaboration (2002) and the KamLAND Collaboration (2003) have demonstrated that neutrinos can change flavour, a phenomenon known as neutrino oscillation. This means, for example, an electron neutrino that was produced in the sun could change into a muon neutrino when it is finally detected on the Earth. This can only take place if the neutrinos have mass, whereas in the SM they are massless. Many theories that go beyond the SM incorporate neutrino oscillations and also predict other lepton processes that are forbidden by the SM. This is therefore a promising area for obtaining an insight into a new theory of particle physics.

One of the most promising areas is the measurement of muon processes because it is possible to build a dedicated facility to produce very large numbers of muons. Thus, making a measurement of very rare muon processes becomes possible. The idea for a dedicated muon facility for making precise measurements came from design studies currently taking place for the Neutrino Factory and the Muon Collider. These showed that it could be possible to build a facility that can deliver 10^{21} muons a year. There are a number of processes that could give us information about physics beyond the SM, such as a muon decaying to an electron and a photon; a muon decaying to two electrons and a positron; and a muon converting into an electron, in the presence of a nucleus, without any additional particles. All of these are referred to as charged lepton flavour violating (CLFV) processes. However, only the process where a muon converts into an electron can make best use of a dedicated facility. This is because only one particle (the conversion electron) needs to be measured, whereas the other processes require measuring more than one particle and so it is possible to wrongly combine the decay products of the muon.

If a small correction is made to the SM, to incorporate massive neutrinos, the probability for CLFV processes to occur would be about 10^{-52}. This is a lot smaller than any process we could hope to measure. However, many theories that go beyond the SM predict the probability for CLFV processes to occur to be greater than 10^{-15}. Even though this is still a very small probability (1 in a million billion), a measurement using a dedicated muon facility appears realisable with muon to electron conversions expected to provide the most stringent test of the SM.

2. AN ELECTRON IN A MUON HAYSTACK

The history of CLFV experiments goes back as far as the 1940's when muons in cosmic rays were being studied. Cosmic rays are produced by collisions of extra–terrestrial particles (mainly protons) with the upper atmosphere. It was believed that the muon was an excited state of the electron and therefore could become deexcited by emitting light (photons). Experimental searches by Hincks and Pontecorvo (1948) did not observe this process, thus setting an upper limit of 10% for its probability. Subsequently it was shown that the muon was not an excited electron and produced neutrinos, conserving lepton flavour, when it decayed.

Experimental searches for CLFV processes moved from using cosmic rays to using particle accelerators as these could provide muons with better defined characteristics and at much higher intensities. Even though the many experiments looking

for CLFV processes have significantly lowered the upper limit of the probability for these processes to occur, none of them were sensitive enough to make a positive observation.

The current best limit for a muon decaying to an electron and a photon is 1.2×10^{-11} (which is about 10 billion times better than Hincks and Pontecorvo's experiment) and was set by the MEGA Collaboration (1999), which was based at the Los Alamos National Laboratory in the USA. The MEG experiment aims to push this further to 10^{-13}–10^{-14}. The MEG experiment is based at the Paul Scherrer Institute (PSI) in Switzerland and utilises the highest power proton accelerator in the world and has a state–of–the–art calorimeter (a device used to measure energy). Thus, it will be very difficult to push this limit much further than 10^{-14}.

The current best limit for muon to electron conversion with a gold target is 7×10^{-13} and was set by the SINDRUM II Collaboration (2006) based at PSI. Two experiments, Coherent Muon to Electron Transition (COMET) and Mu2e, have recently been proposed that aim to measure muon to electron conversion with an unprecedented sensitivity of 10^{-16}, which is an improvement on SINDRUM II's measurement by a factor of 10,000. That means being able to identify one electron of interest amongst a sea of 10,000,000,000,000,000 muons not of interest. This is like trying to find a pinhead buried in a beach 10km long! Such a dramatic increase in sensitivity is only possible by using a dedicated high–intensity muon facility. COMET has been proposed to be constructed at the Japan Proton Accelerator Research Complex and Mu2e would be sited at the Fermi National Accelerator Laboratory in the USA. Both experiments are currently at the stage of optimising their designs and aim to start building, given appropriate funding approval, within the next few years.

3. HOW WE PLAN TO DO THIS

The next–generation of muon to electron conversion experiments plan to use a high–intensity muon facility to make a measurement with an unprecedented sensitivity. In order to achieve this a very large number of muons need to be produced. This is done by using a pulsed proton beam to produce pions, which then decay into muons. Using this method gives the necessary quantity of muons but the momentum range of the muons will be large. If the beam contains high energy muons they can produce high energy electrons that can be confused with electrons produced by muon to electron conversion. It is therefore important that only muons with the correct momentum are selected.

Figure 2 shows the schematic layouts of the COMET (see COMET Collaboration 2009) and Mu2e (see Mu2e Collaboration 2008) experiments. Both experiments have similar components: a pion production target; a muon transport channel; a muon stopping target; a tracker; and a calorimeter. The pion production target is made of a heavy metal, for example tungsten. The pions produced are captured by a solenoidal magnetic field and travel down the muon transport channel towards the muon stopping target. The muon transport channel has to be long enough to ensure almost all of the pions have decayed and it is also used to remove muons with too high momentum. The muon stopping target consists of a series of 0.2mm thick aluminium disks. These disks are designed to slow the muons down and eventually stop them. When a muon stops in the aluminium disk it can either decay or be cap-
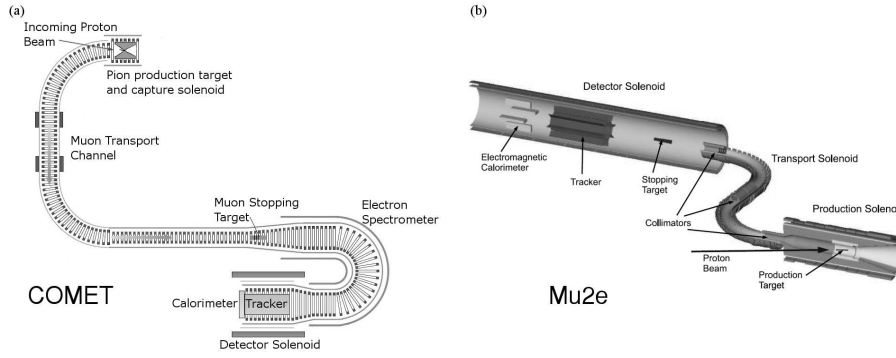
Figure 2. Schematic layout of (a) COMET and (b) Mu2e.

tured by an aluminium nucleus, both allowed in the SM, or convert to an electron, as predicted by many theories beyond the SM. Electrons from muon conversion will have a higher momentum than those from normal muon decay. So, by measuring the momentum of the electrons we can determine if a muon has converted into an electron. The tracker is designed to accurately measure the momentum of the electrons and the calorimeter is used to measure the energy and time–of–arrival.

One of the main differences between these two experiments is that COMET has a c–shaped muon transport channel whereas Mu2e's is s–shaped. This shape will affect how well the muon transport channel is able to select muons of the correct momentum and so will affect the sensitivity of the measurement. COMET also has an electron spectrometer, which is used to discard electrons that are not of interest. This relaxes the requirements of the detector systems (that is the tracker and calorimeter) as it will reduce the very high rate of uninteresting electrons.

These are very challenging experiments because the process being measured is very very rare. There are many ways that a background process can mimic the signal of a muon that has converted into an electron such as: high energy muon decays; electrons produced by cosmic rays; and electrons produced from other physics processes. Thus, the experiment needs to be designed in a way to ensure that these background processes are not misidentified as muon to electron conversion. In order to understand all possible sources of backgrounds accurate computer simulations of the experiments are required. This is a critical component of the experiment and one for which my collaborators and I will take responsibility for the COMET experiment.

4. THE ULTIMATE MEASUREMENT?

The Phase Rotated Intense Slow Muon (PRISM) experiment aims to improve on COMET and Mu2e by a further factor of 100 by using a special type of accelerator called a fixed–field, alternating–gradient (FFAG) accelerator. Figure 3 shows the layout of the PRISM experiment. Most of the components are similar to the COMET experiment, the main difference being the addition of an FFAG ring in the muon transport channel. The advantage of using the FFAG ring is that it can reduce the momentum spread of the muon beam, which improves the efficacy of the
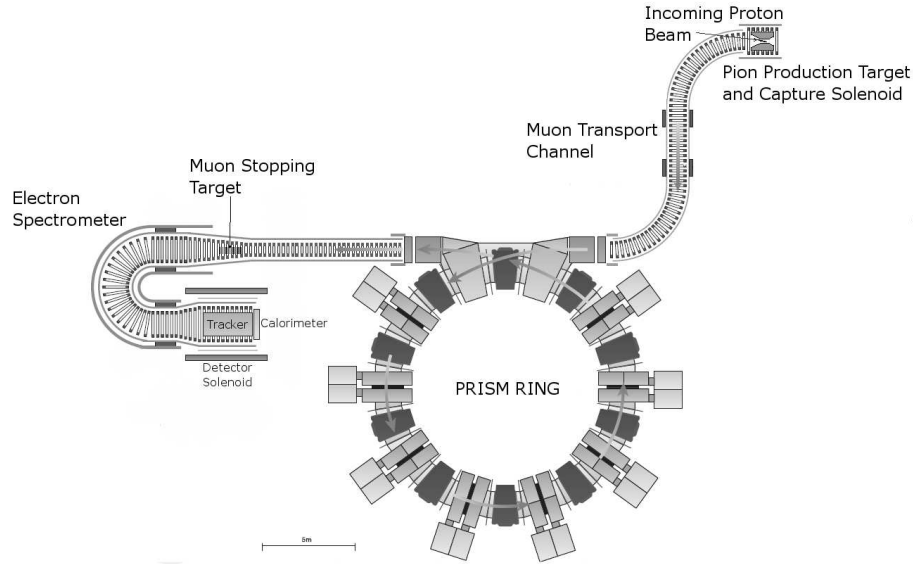
Figure 3. Schematic layout of the PRISM experiment.

stopping target. The momentum spread of the signal electrons can thus be reduced, allowing a more accurate measurement to be made.

PRISM aims for a measurement sensitivity of 10^{-18}. By making a measurement with this sensitivity it will be possible to see how the probability for a muon to convert into an electron depends on the material used for the stopping target. This is important because different theoretical models give different predictions for this behaviour. PRISM therefore has the potential to give an unprecedented insight into the fundamental processes of the universe. So you may ask the question, why do COMET or Mu2e before PRISM? The answer is that there are many technological challenges that need to be overcome before we can confidently say it is possible to build the PRISM experiment. One of the main challenges arises from the fact that the muon beam is much larger than most conventional accelerator beams and so a very specialised technology needs to be developed in order to inject the muon beam into the FFAG ring without losing a significant fraction of it.

A demonstration experiment of the PRISM FFAG ring was built and tested in 2008 at Osaka University, see Figure 4. The magnets used for PRISM are much larger and more complex than standard accelerator magnets. The aim of this test ring was to study the characteristics of the magnets and other properties of the ring and to see how they compared with computer simulations. I was fortunate enough to be able to contribute to the commissioning of this ring.

Some of the technological challenges facing PRISM are common to other projects that use FFAGs. A PRISM task force, led from the UK, was set up in July 2009 that aims to address these issues and utilise synergies with other FFAG projects in the UK and other countries.

Figure 4. Picture of the PRISM test ring experiment at Osaka University.

5. BENEFITS FOR SOCIETY

Much of the cutting–edge technology needed for particle physics experiments has applications outside of particle physics. Some of the issues for PRISM are the same for other FFAG based projects such as accelerator driven sub–critical reactors (ADSR), cancer therapy machines and accelerators for studying chemistry, biology and materials science.

It is a fact that the world's oil and natural gas supplies are limited and so it is vital for the survival of society as we know it to have an alternative to these resources. There is also the suggested link between the burning of fossil fuels and global warming. Nuclear energy has been used in the past but issues with nuclear waste have made it unpopular in most countries. ADSR systems provide an alternative nuclear energy resource that has the benefits of nuclear power but with less of the problems. ADSR systems take advantage of a nuclear reaction that is not self–sustaining and use an accelerator to drive the fission process. This means that when the accelerator is switched off the production of energy stops, unlike conventional nuclear reactors, which makes it inherently safe. The other main advantage of ADSR systems is that the fuel it uses is more abundant and the radioactive waste produced is not as long–lived. However, in order to realise an ADSR machine accelerator technology needs to be developed. ADSR systems require a 10MW proton accelerator. The most powerful proton accelerator that exists is the PSI Cyclotron, which is only 1.2MW. There are other issues with ensuring the reliability of the accelerator beam that also requires the development of accelerator technology. To address some of these issues FFAGs have been proposed as a cost–effective solution. A demonstration experiment of an FFAG–based ADSR system has been built and

commissioned at the Kyoto University Research Reactor Institute in Japan (see Pyon *et al.* 2009).

Most conventional cancer therapy machines use x–rays (high–energy photons) to destroy cancerous cells. This treatment is appropriate for cancers located near the surface of the skin. For tumours located deeper in the body x–rays are not suitable as they deposit most of their energy near the surface of the skin. Irradiating a deep tumour will therefore cause damage to healthy cells. A different technique using protons or carbon ions can be used to specifically target deep tumours. This is because they deposit their energy over a small area and the depth at which they penetrate is given by their energy. Thus, deep tumours can be treated by using an accelerator to deliver a variable energy proton or carbon ion beam. The idea of using ions for cancer therapy has been around since 1946, when R. Wilson proposed it (see Wilson 1946), though it did not become widely available due to the cost and relatively complex operation of the accelerator. One of the most expensive components of the accelerator complex is the gantry system which delivers the beam to the patient. Most of the patients are held in a fixed horizontal position, so the gantry system needs to rotate around the patient's body to deliver the beam to where it is required. Mounting a hundred tonnes of magnets in a mechanical support structure that can rotate and accurately deliver the beam is very complicated and costly. The technology used for the COMET and PRISM transport channels has the potential to provide a more cost effective gantry system.

Two types of conventional accelerators are used for cancer therapy, synchrotrons and cyclotrons. Synchrotrons are able to deliver a variable energy beam but are complex to operate and have a relatively low throughput of patients. Cyclotrons on the other hand are simpler to operate and can treat patients quicker but have a fixed output energy. This means the energy of the beam needs to be degraded using an absorber which leads to problems with the activation of the absorber and increasing the energy spread of the beam. FFAGs have the potential to treat patients quickly and deliver a variable energy beam. They also have the advantage of being relatively simple to operate and are more compact than a cyclotron.

The UK is involved in several FFAG–based projects related to ADSR (see ThorEA) and the development of cancer therapy machines (see CONFORM). It is important to realise that pushing the boundaries of fundamental science will have beneficial by–products for society and these should be fully exploited.

6. SUMMARY

The observation of muon to electron conversion will be a ground–breaking discovery and will lead to a new understanding of how the universe works at a fundamental level. Making a measurement with a sensitivity of 10^{-16} will be very challenging and requires careful computer simulation of the whole experiment. Both COMET and Mu2e believe that this is possible and aim to have a technical design ready within the next couple of years.

The second phase of COMET, PRISM, will aim to make a more sensitive measurement by a factor of 100. However, his requires the development of technology before a working design can be realised. Some of the challenges for PRISM are common to other FFAG projects and the PRISM task force aims to utilise these

synergies to address these issues. This will have applicability to other FFAG–based projects that aim to solve the world's energy problem and help cure cancer.

The next few years will be a very exciting time for particle physics. Results from the LHC together with high precision measurements of lepton processes, like muon to electron conversion, will lead us towards the ultimate goal of particle physics that is the theory of everything.

7. ACKNOWLEDGEMENTS

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