Mu2e: coherent $\mu \to e$ conversion experiment at Fermilab

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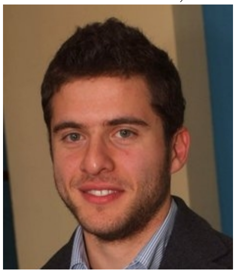

The Mu2e experiment at Fermilab will search for the charged lepton flavor violating process of neutrino-less $\mu \to e$ coherent conversion in the field of an aluminum nucleus. About $7 \cdot 10^{17}$ muons, provided by a dedicated muon beam line in construction at Fermilab, will be stopped in 3 years in the aluminum target. The corresponding single event sensitivity will be $2.5 \cdot 10^{-17}$. In this paper a brief overview of the physics explored by the $\mu \to e$ conversion is given, followed by a description of the Mu2e experimental apparatus and the expected detector performance.

1 Introduction

In the Standard Model (SM) version where only one Higgs doublet is included and massless neutrinos are assumed, lepton flavor conservation is an automatic consequence of gauge invariance and the renormalizability of the SM Lagrangian. However measurements of the neutrino mixing parameters during the last decades [2] showed that lepton flavor is not conserved. Including finite neutrino mass terms in the SM Lagrangian charged lepton flavor violation (CLFV) is also predicted. CLFV transitions are suppressed by sums over $\left(\Delta m^2_{ij}/M^2_W\right)^2$, where Δm^2_{ij} is mass-squared difference between the neutrino mass eigenstates $i,\ j$ and M_W is the W boson mass [3]. Because the neutrino mass difference is very small ($\Delta m^2_{ij} \leq 10^{-3}\mathrm{eV}^2$ [2]) with respect to the W boson mass, the expected branching ratios reach values below 10^{-50} [3,4], which are unmeasurable by the present facilities. As a consequence, an observation of CLFV process would represent a clear evidence of new physics beyond the SM. In general, CLFV can be studied via a large variety of processes: muon decays, such as $\mu^+ \to e^+\gamma$, $\mu^\pm \to e^\pm e^- e^+$, and muon conversion; tau decays: $\tau^\pm \to \mu^\pm\gamma$, $\tau^\pm \to \mu^\pm\mu^+\mu^-$, etc; meson decays: $\pi^0 \to \mu e$, $\mathrm{K}^0_\mathrm{L} \to \mu e$, $\mathrm{K}^+ \to \pi^+\mu^+e^-$, etc; Z^0 decays, such as $\mathrm{Z}^0 \to \mu e$, etc. The muon processes have been intensely studied in the CLFV for several reasons: low energy muon beams can be produced at high-intensity proton accelerator facilities; Final state of processes in the muon sector can be precisely measured. Search for CLFV with muons has been pursued looking for muon decays ($\mu^+ \to e^+\gamma$ and $\mu^\pm \to e^\pm e^- e^+$), and muon coherent conversion ($\mu^-\mathrm{N} \to e^-\mathrm{N}$). Even if LHC discovers new physics in the second run, precise measurements of CLFV processes can help discriminate among several theoretical

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models [4].

2 Experimental searches for $\mu^- \mathbf{N} \to e^- \mathbf{N}$

When negative muons are stopped in a target ("stopping target") they are quickly captured by the atoms ($\sim 10^{-10}$ s) and cascade down to 1S orbital. Then muons can undergo the following processes: decay in orbit (DIO) $\mu^- \to e^- \nu_\mu \bar{\nu}_e$; weak capture $\mu^- \mathrm{p} \to \nu_\mu \mathrm{n}$; coherent flavor changing conversion $\mu^- \mathrm{N} \to e^- \mathrm{N}$. The muon conversion represents a powerful channel to search for LFV, because it is characterized by a distinctive signal consisting in a mono-energetic electron with energy $\mathrm{E_{ce}} = \mathrm{m}_\mu - \mathrm{E}_b - \frac{\mathrm{E}_\mu^2}{2\mathrm{m_N}}$, where m_μ is the muon mass at rest, $\mathrm{E}_b \sim \mathrm{Z}^2\alpha^2\mathrm{m}_\mu/2$ is the muonic atom binding energy for a nucleus with atomic number Z, E_μ is the nuclear recoil energy, $\mathrm{E}_\mu = m_\mu - \mathrm{E}_b$, and $\mathrm{m_N}$ is the atomic mass [3]. In case of aluminum, which is the major candidate for upcoming experiments, $\mathrm{E}_{ce} = 104.973$ MeV [5]. In muon conversion experiments the quantity:

$$\mathrm{R}_{\mu e} = \frac{\Gamma\left(\mu^- + \mathrm{N} \to e^- + \mathrm{N}\right)}{\Gamma\left(\mu^- + \mathrm{N} \to \text{all captures}\right)}$$

is measured. The normalization to captures offers a calculation advantage since many details of the nuclear wavefunction cancel in the ratio [5].

The coherent conversion leaves the nucleus intact, and there is only one detectable particle in the final state. The resulting electron energy stands out from the background (this will be more clear in the next paragraph), hence muon-electron conversion does not suffer from accidental background, and extremely high rates can be used.

2.1 Background sources

μ^- stopped in the stopping target can undergo a nuclear capture [6]. Particles generated in the muon capture (n, p and γ) may reach the detector system, and create extra activity that can either obscure a conversion electron (CE) track or create spurious hits. As a result, some specific shielding is required to reduce this background. Additional shielding is required against cosmic rays that can interact in the apparatus, producing electrons with an energy mimicking a CE.

Electrons from the high momentum tail of the muon DIO represent the largest background source for the $\mu^- \mathrm{N} \to e^- \mathrm{N}$ search. Figure 1 shows the energy spectrum of DIO electrons [7]. The

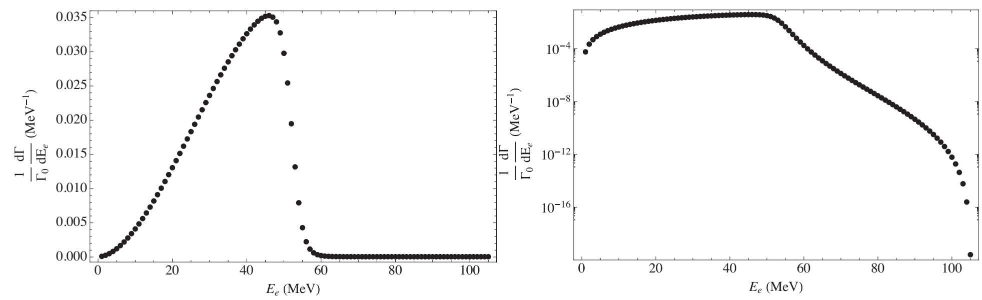

Figure 1 – DIO electron energy spectrum on linear (left) and log (right) scale, for muons bounded in aluminum nuclei.

main features of the DIO energy spectrum can be summarized as follows: (1) the endpoint of the spectrum corresponds to the energy of the electrons from $\mu^- \mathrm{N} \to e^- \mathrm{N}$ conversion (CE); (2) the overall spectrum is falling as $(E_{ce} - E_e)^5$, where E_{CE} is the CE energy, and E_e is the DIO energy; (3) about 10^{-17} of the spectrum is within the last MeV from the endpoint. Therefore, to reach a sensitivity at the level $O(10^{-17})$ the detector resolution is crucial.

Another relevant background comes from the radiative pion capture (RPC) process $\pi^- \mathrm{N} \to \gamma \mathrm{N}^*$, followed by the electron-positron pair conversion of the γ. Another source of background are pions; muon beam is generated from low energy protons (below 10 GeV of energy) interacting with a (production) target, so producing charged pions that then decay in a transport line. Unfortunately not all pions decay in the transport line, and, consequently, the muon beam is contaminated by pion. This source of background is reduced thanks to the difference between the pion and the bound muon life times. The pion has a $\tau <$ few tens of ns, while the bound muon has a mean lifetime of the order of several hundreds of ns (depending on the Z of the material [6]). Therefore using a pulsed beam structure, it is possible to define a live-gate delayed with respect to the beam arrival, and to reduce the $\pi^- N \rightarrow \gamma N^*$ contribution to the desired level. Other beam-related sources of background are: remnant electrons in the beam that scatter in the stopping target, muon decays in flight, and antiprotons annihilating in or near the stopping target.

3 Experimental technique

To get rid of forward neutral background, a number of twisted solenoids transport the muons from the Mu2e production target to the stopping target. This unusual field configuration is created by three coupled solenoids in a row (Figure 2): the Production Solenoid, the Transport Solenoid and the Detector Solenoid (DS). At the stopping aluminium target, the muon decay

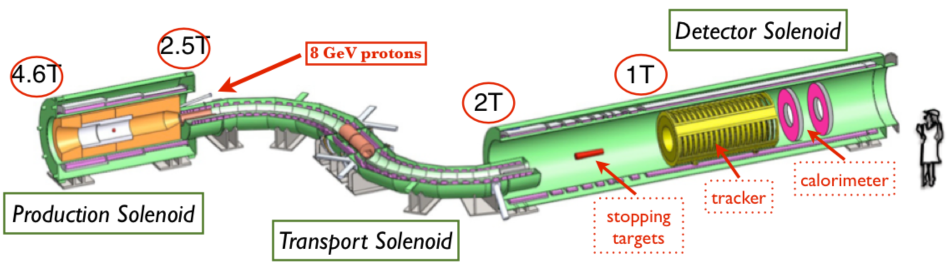

Figure 2 – Mu2e apparatus.

electrons are momentum analysed in the DS field from the target to the detector elements. 39% of the stopped muons decay in orbit (DIO), while 61% are captured in the aluminium nuclei. A high- precision apparatus made of a straw tube tracker and a crystal calorimeter placed inside the DS separates CE and DIO events. Figure 3 shows the signal and the DIO background yield, normalized to 3 years of data taking. Same Figure shows that if we define a narrow momentum window (signal window) around the signal peak, the mean expected background from the DIO electrons is about 0.2 events, while assuming $R_{\mu e} = 10^{-16}$ the signal yield is expected to be about 3.5 events. It has also been shown in reference [8] that the contribution from the other background sources adds 0.3 events in the signal window.

4 Summary

The Mu2e experiment will search for the $\mu \rightarrow e$ conversion in the field of an aluminum nucleus with a single event sensitivity of $2.9 \cdot 10^{-17}$. This will improve the current best limit by 4 orders of magnitude, probing new physics at scales up to 10,000 TeV. The detector system consists of a low-mass straw tube tracker that will measure the signal momentum with an expected resolution better than 200 keV/c, and a crystal calorimeter made of pure CsI that will measure the energy (time) of the signal particle with a resolution of about 5% (100 ps). The design of the apparatus is mature and the construction of several components is underway to start data taking in the end of 2020.

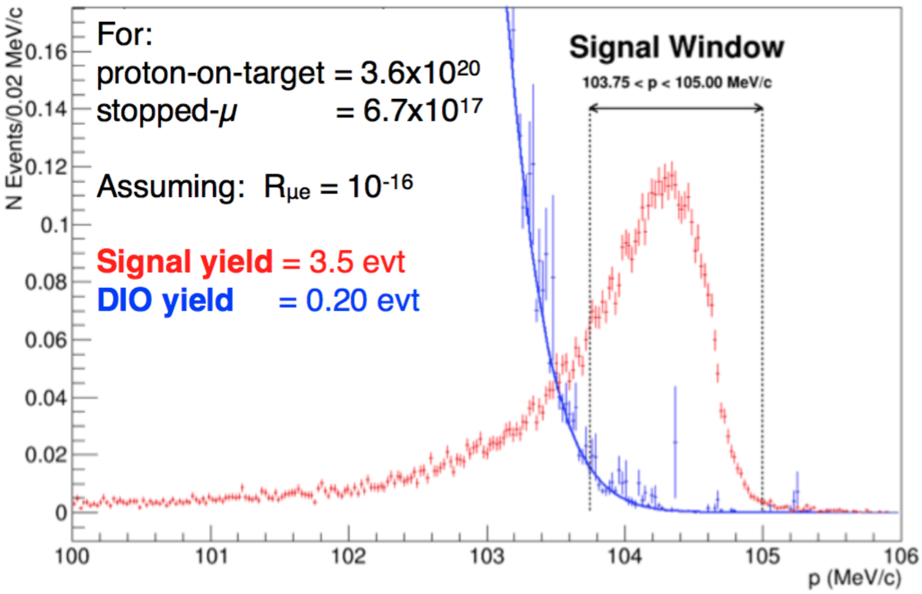

Figure 3 – Signal and DIO background yield normalized to 3 years of Mu2e data taking.

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References

1. Mu2e Collaboration, http://mu2e.fnal.gov/collaboration.shtml
2. Olive, K. and others, *Review of Particle Physics*, Chin. Phys., C38, 2014
3. Marciano, W. J. and others, *Charged Lepton Flavor Violation Experiments*, Annual Review of Nuclear and Particle Science, 58, 1, 315-341, 2008
4. Cei, F. and Nicolo, D., *Lepton Flavour Violation Experiments*, Adv. High Energy Phys., 2014, 2014
5. Kitano, R. and Koike, M. and Okada, Y., *Detailed calculation of lepton flavor violating muon electron conversion rate for various nuclei*, Phys. Rev., D66, 2002
6. Measday, D. F., *The nuclear physics of muon capture*, Phys. Rept., 354, 2001
7. Czarnecki, A. and Garcia i Tormo, X. and Marciano, W.J., *Muon decay in orbit: Spectrum of high-energy electrons*, Phys. Rev., D84, 1, 8, 2011
8. Bartoszek, L. and others, *Mu2e Technical Design Report*, arXiv:1501.05241, [physics.ins-det], 2014