The MEG II experiment and its future developments

The MEG II collaboration*

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Abstract

This letter of interest describes the goal of the MEG II experiment and the possibility for future experiments after MEG II. The MEG II experiment is currently under preparation for starting physics run in 2021 to look for new physics beyond the SM using charged lepton flavor violating muon decay, $\mu^+ \to e^+\gamma$. This experiment utilizes the world most intense continuous (DC) muon beam at PSI. PSI has a project to improve the muon beam intensity up to $10^{10}\mu^+$/s called HiMB (high intensity muon beam). Future developments to make maximum use of the HiMB will also be mentioned.

1 Introduction

The search for the charged lepton flavor violating (CLFV) processes is sensitive to new physics models such as SUSY, Extra Dimensions, an extended Higgs sector, leptoquarks, and GUT. Many experiments therefore have been conducted using muons and taus in Europe, the US, and Asia. In particular, experiments which utilize high-intensity muon beams provide the most sensitive exploration for CLFV [1][2][3]. Since different CLFV modes such as $\mu^+ \to e^+\gamma$, $\mu^+ \to e^+e^-e^+$, $\mu^- N \to e^- N$, have different transition rates depending on the new physics models, these channels are complementary to discover new physics and to identify the underlying physics models[4][5]. The $\mu^+ \to e^+\gamma$ process is sensitive to new particles through LFV loop diagrams (dipole couplings) and to new physics mass scales above 10^3 TeV/c^2, which is well beyond the direct search at collider experiments. The most stringent limit was set by the MEG experiment in 2016 using data from 2009-2013, Br($\mu^+ \to e^+\gamma$) < 4.2$\times 10^{-13}$ at 90% CL[6].

The signal of the $\mu^+ \to e^+\gamma$ decay at rest can be distinguished from the background by measuring the photon energy E_γ, the positron momentum p_{e^+}, their relative angle $\Theta_{e^+\gamma}$, and timing $t_{e^+\gamma}$ with the best possible resolutions. The background comes either from radiative muon decays (RMD) $\mu^+ \to e^+\nu\overline{\nu}\gamma$ in which neutrinos carry away a small amount of energy or from an accidental coincidence of an energetic positron from Michel decay $\mu^+ \to e^+\nu\overline{\nu}$ with a photon coming from RMD, bremsstrahlung or positron annihilation-in-flight (AIF). The number of accidental coincidences N_{acc} depends on the experimental resolutions and the beam rate (R_{μ^+}) as shown below,

$$N_{\rm acc} \propto R_{\mu^+}^2 \times \Delta E_\gamma^2 \times \Delta p_{\rm e^+} \times \Delta\Theta^2_{\rm e^+\gamma} \times \Delta t_{\rm e^+\gamma} \times T,$$

where resolutions of different parameters are indicated as Δ, and T is the measurement time. In the MEG experiment, which used $R_\mu \sim 3 \times 10^7 \mu^+/s$, the accidental background was more than 90% of events near the signal region (E_γ >48 MeV). In order to improve the sensitivity, not only increasing the muon beam intensity, but also improving its detector resolutions are required.

2 The MEG II experiment

The main goal of the MEG II experiment is to look for new physics via a charged lepton flavor violating process, $\mu \to e\gamma$ decay. The MEG II experiment plans to continue the search for the $\mu^+ \to e^+\gamma$ decay with a sensitivity improvement by one order of magnitude compared to MEG[7].

The PSI high intensity proton accelerator delivers the most intense DC muon beam in the world with its 590 MeV kinetic energy proton beam and presently 1.4 MW average beam power[8]. Protons hit the so called target E and muons are produced from the pion decay and can be selected by dedicated beam lines.

The πE5 beam line is used by the MEG II experiment. It is a 165° backwards-oriented, windowless, high-acceptance (150 msr), low-momentum (< 120 MeV/c), dual-port π, μ or e channel. For the MEG II experiment the muon beam line is tuned at 28 MeV/c with a momentum bite of 5-7 % FWHM, depending on the opening of the momentum selecting slits placed in the front-part of the channel. The so called surface muons are in fact selected and used, coming from the pion decaying in proximity of the target E surface. A clean muon

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beam is transported to the center of the MEG II apparatus. A Wien-filter in combination with a quadrupole triplet and a collimator system determines a separation quality between muon and positron beams of 8.1 σ_μ, corresponding to a 12 cm physical separation at the collimator system[7]. The beam is then transported inside the superconducting solenoid COBRA (COnstant Bending RAdius) magnet, where the MEG II stopping target is placed, via a superconducting magnet, the BTS magnet. At the center of the MEG II apparatus a beam of 1.19×10^8 μ^+/s at 2.2 mA (Proton current) is delivered with a gaussian shape with a spatial sigma of ≈ 10 mm.

The positron spectrometer uses the gradient magnetic field to sweep away the low-momentum e^+. The COBRA magnet is retained from MEG, while the positron detectors inside are replaced with new ones. Positron tracks are measured by a single-volume low mass cylindrical drift chamber, more transparent towards the new pixelated timing counter. The resolution for the e^+ momentum is improved with more hits per track obtained by a high density number of drift cells[9]. The positron timing is measured with improved accuracy by a new pixelated timing counter based on scintillator tiles read out by SiPMs[10]. The photon energy, interaction position and timing are measured by an upgraded LXe photon detector. The energy and position resolutions are improved with a more uniform collection of scintillation light achieved by replacing PMTs on the photon entrance face with newly developed VUV-sensitive MPPCs[11]. A radiative decay counter for an active background suppression is newly introduced in order to identify a low-momentum e^+ associated to a high-energy RMD photon[12]. The trigger and data-acquisition system are also upgraded to meet the stringent requirements of the increased number of read-out channels from different detectors[13].

Detector construction is completed and commissioning is in progress. Physics data taking is expected to begin in 2021 and to last for a few years. The upgraded detector is expected to provide resolutions roughly a factor of two better than MEG, allowing MEG II to utilize a muon beam intensity of 7×10^7 μ^+/s, resulting in a factor of ten improvement in the expected sensitivity.

3 Future developments

PSI currently delivers the most intense continuous muon beam in the world up to few $10^8 \mu^+/s$. The High Intensity Muon Beam (HiMB) project at PSI aims at developing new muon beam lines able to deliver up to $10^{10} \mu^+/s$, with a huge impact for low energy muon based searches [14]. While the next generation of proton drivers with beam powers in excess of the current limit of 1.4 MW still requires significant research, the focus of HiMB is the optimisation of existing target stations and beam lines. Detailed Monte Carlo simulations show that geometrical target optimisations would result in beam intensity gains in the range of $30-60\%$, that could be further increased by using novel target materials such as boron carbide. Higher muon capture and transmission beam line efficiencies can be obtained with the design of beam line optics based on pure solenoid elements. The expectation is an increase of the total fraction of captured and transmitted muons by more than one order of magnitude with respect to the current hybrid beam lines. A new production target with optimized geometry has been installed in 2019 and tested along the primary beam line at PSI, proving that the expected increase of muon yield associated with the new target can be achieved, consistently with the Monte Carlo simulation prediction. It corresponds to effectively raising the proton beam power at PSI by 650 kW, equivalent to a proton beam power of almost 2 MW without additional complications such as increased energy and radiation deposition into the target and its surroundings.

The HiMB project together with other ongoing activities at PSI, as the muCool project [15, 16] aiming at delivering tertiary beam line with high brightness, would represent a great opportunity for all searches based on low energy muons, as the next generation of CLFV searches including a more sensitive search of $\mu^+ \to e^+\gamma$. HiMB will already be crucial for the second phase of the Mu3e experiment in preparation at PSI, allowing to reach a sensitivity of 10^{-16} on the $\mu^+ \to e^+e^+e^-$ decay search with the Mu3e apparatus [17]. Improvements in sensitivity to $\mu^+ \to e^+\gamma$ process beyond the MEG II would require to reduce the accidental background significantly in order to fully make use of the maximum beam rate of the increased muon beam intensities by HiMB, and to maximize the potential of the new physics discovery. Several ideas to improve the detector performance are already discussed[18][19][20]; additional studies are required to verify that these ideas are feasible.

4 Summary

The MEG II experiment uses an intense muon beam at PSI to explore BSM parameter spaces to new physics mass scale of more than 10^3 TeV/c^2 well beyond colliders. Within the next few years, the sensitivity of the $\mu^+ \to e^+\gamma$ search will be improved by an order of magnitude by the MEG II experiment. Further improvements after the MEG II experiment using the HiMB project are being considered.

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