The quest for $\mu \rightarrow e\gamma$: present and future

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Abstract The quest for $\mu \rightarrow e\gamma$ is one of the most important endeavors to search for New Physics beyond the Standard Model. In this talk I will review the current status of the experimental searches by the MEG Collaboration at PSI. I will also present a study of the experimental limiting factors that will define the ultimate performances, and hence the sensitivity, in the search for $\mu \rightarrow e\gamma$ with continuous muon beams of extremely high rate (one or even two orders of magnitude larger than the present beams), whose construction is under consideration for the next decade.

Keywords Lepton Flavor Violation · Muon decays · Muon beams · New Physics searches

1 Introduction

Lepton flavor conservation is an accidental symmetry in the Standard Model (SM), not related to the gauge structure of the model but merely arising from its particle content, namely the absence of right-handed neutrinos. As a consequence, most of New Physics (NP) models predict some Lepton Flavor Violation (LFV) effects and, indeed, they are already strongly constrained by the present limits, like $BR(\mu \rightarrow e\gamma) < 4.2 \times 10^{-13}$ from the MEG experiment [1]. The search for charged LFV is hence a clean and effective way to search for NP.

The $\mu^+ \rightarrow e^+\gamma$ decay is searched for in the decay at rest of stopped muons from a high-intensity continuous beam. Both the electron and the positron will have an energy of 52.8 MeV and will be emitted collinearly and back-to-back. A prompt background comes from the radiative muon decay $\mu^+ \rightarrow e^+\nu_e\gamma$,
when the neutrinos carry a very small fraction of the available energy. Nonetheless, the dominant background at very high intensities is the accidental coincidence of a positron from a normal muon decay and a photon from the radiative decay of another muon or the annihilation in flight of another positron. The observables which can be used to discriminate signal and background are hence the positron and photon energies, the relative angle of their directions and their relative time.

A $\mu \rightarrow e\gamma$ experiment is composed of a thin target to stop muons, a positron section able to reconstruct the positron momentum and trajectory and give a precise timing, and a photon section with very good energy, time and position resolutions.

According to [3], the accidental background rate depends on the beam intensity and resolution according to:

$$\Gamma_{\text{acc}} \propto \Gamma^2_{\mu} \cdot \delta E_e \cdot \delta E_\gamma \cdot \delta T_{e\gamma} \cdot (\delta \Theta_{e\gamma})^2$$

(1)

where $\Gamma_{\mu}$ is the muon stopping rate and $\delta E_e$, $\delta E_\gamma$, $\delta T_{e\gamma}$ and $\delta \Theta_{e\gamma}$ are the energy, time and angular resolutions. The dependence on the square of $\Gamma_{\mu}$ makes useless a beam intensity increase if the total background yield over the experiment lifetime is not negligible. Under these conditions, it can be advantageous to loose some efficiency if it allows to improve the resolution, and recover the efficiency loss by increasing the beam rate, which is otherwise not possible.

The search for $\mu \rightarrow e\gamma$ relies on the availability of high-intensity muon beams like the ones delivered at the Paul Scherrer Institut (PSI) in Switzerland, with up to $10^8$ muons per second. It could be possible with the present technologies to increase this intensity by one or two orders of magnitudes. A study have been performed [2] to identify the experimental factors which would limit the sensitivity of future searches for $\mu \rightarrow e\gamma$ with beams of such a high intensity.

2 The status of the MEG-II experiment

The MEG collaboration is currently finalizing an upgrade of all sub-detectors, with the goal of improving by one order of magnitude the sensitivity reached in the first phase of the experiment. Figure 1 shows a scheme of the new experiment, MEG II [4]. Like MEG, it is composed of a positron spectrometer in a non-uniform magnetic field, a positron timing detector (Timing Counter) and a LXe calorimeter for the photon detection.

The construction of the new Timing Counter has been completed in 2017. The detector is made of 512 scintillator tiles read out by SiPM. Positrons go through several tiles whose time measurements are combined. It requires an accurate calibration of the time offsets between the different tiles, performed by means of a dedicated laser system and using positron tracks from muon decays. Both techniques have been tested in an engineering run in 2017 and the detector already reached the goal resolution of $\sim 35$ ps.
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Figure 1: The MEG II experiment

The MEG II experiment

The 16 planar drift chamber that composed the MEG positron spectrometer will be replaced by a single cylindrical drift chamber with 9 layers of stereo wires. The single hit resolution of the new chamber is expected to be $\sim 100$ $\mu$m. The resulting positron momentum resolution will be improved by a factor of 3 with respect to MEG, going below 100 keV/c, while the positron reconstruction efficiency will be improved by a factor of 2, mainly thanks to the longer extent of the chamber. The wiring and sealing of the drift chamber has been completed in Summer 2018 and the chamber will be tested on beam at PSI at the end of the year.

The LXe calorimeter of the MEG experiment has been upgraded by replacing the photomultiplier tubes in the in the inner face of the detector with MPPCs customarily designed in collaboration with Hamamatsu in order to improve their sensitivity to the UV light emitted by LXe. The MPPCs allow a better coverage of the inner surface of the calorimeter, with a significative improvement of the energy and position resolution, in particular for photons converting just at the entrance of the calorimeter. An average energy resolution of 1% at 52.8 MeV is expected. The first photons in the upgraded calorimeter have been detected in the 2017 engineering run.

A radiative muon decay veto, composed of LYSO crystals and plastic scintillators, will be added in MEG II to identify events with a low energy positron in coincidence with a high energy photon making background in the calorimeter.

The largely increased number of readout channels of the new experiment stimulated the development of a new data acquisition scheme, which integrates trigger and data acquisition capabilities in a single system. Prototypes of the acquisition electronics have been successfully tested in the 2016 and 2017 engineering runs.

The MEG detector is expected to be tested on beam, for the first time with all sub-detectors, in the second half of 2018, and to start taking physics
data in 2019, for a 3-year run. The improved resolutions will allow to increase the muon beam rate up to $7 \times 10^7$ muons per second, compared to $3 \times 10^7$ in MEG. The MEG II experiment is foreseen to reach an expected upper limit of $6 \times 10^{-14}$ on the BR of $\mu \rightarrow e\gamma$.

3 Future high-intensity muon beams

Experiments searching for $\mu \rightarrow e\gamma$ with muon beams exploit the production of muons by a proton beam impinging on a target. Protons produce pions that decay and give muons. The most intense continuous muon beams are delivered at PSI, with intensities up to $10^8$ muons per second. The laboratory is considering the possibility of building a new beam line with an increased muon collection efficiency at the production target and an increased transport efficiency toward the experimental areas. It should be possible to reach a rate of $10^{10}$ muons per second [5].

This rate is limited by the thickness of the production target. At PSI it stops 12-18% of the protons in the beam, which needs to be preserved to serve a neutron spallation source downstream of the muon production target. An alternative approach is being explored at RCNP in Osaka, Japan, with the MuSIC project [6]. A thicker target is used in this case, allowing to increase by two orders of magnitude the muon yield per unit of proton beam power. Although the projected muon beam rate is lower than what can be obtained at PSI, it is a good demonstration of an alternative approach which can be used to reach unprecedented intensities.

The construction of a continuous muon beam line is also under consideration in the context of the PIP-II project [7] at Fermilab, USA. The goal is to reach intensities similar to what could be obtained at PSI.

4 Experimental techniques, limiting factors and sensitivity for $\mu \rightarrow e\gamma$ at future muon beams

Due to the $F_\mu^2$ dependence of the accidental background rate, an increased muon beam intensity can be exploited in the search for $\mu \rightarrow e\gamma$ only if the detector resolutions can be improved so that the background yield is kept at a negligible level. Hence, it is important to identify the factors which will limit the resolutions of the next generation of $\mu \rightarrow e\gamma$ experiments.

A magnetic spectrometer complemented with fast detectors is almost an obliged choice for the positron detection. In the MEG-II drift chamber, the multiple scattering will already give a significative contribution to the resolutions. Hence, gaseous detectors are the preferred choice for the spectrometer, owing to their low material budget. The unavoidable material in the muon stopping target and in front of the detector will finally limit the angular resolutions to about 4 mrad. Also, the momentum resolution expected in MEG-II is likely to be irreducible even with the best compromises of resolutions and
low material budget. When high intensity muon beams are considered, the detector aging also plays a crucial role. One of the main technological issues for future experiments will be to face this issue, and replacing gaseous detectors with solid state detectors could be unavoidable, with a consequent deterioration of the performances.

For the photon, two options can be considered: the calorimetric and the photon-conversion approach. A calorimeter provides very high efficiency, mostly limited by the interaction of the photon with the material in front of the calorimeter, with good energy, position and time resolutions. The photon-conversion approach exploits $e^+e^-$ pair creation in a thin conversion layer, followed by tracking of the pair in a spectrometer. It can give extremely good resolutions but a very poor efficiency. At very high beam intensity, anyway, this approach can still be competitive, as discussed above.

For calorimetry, the choice of the scintillating material determines the performances of the detector. A very good candidate could be LaBr$_3$(Ce), which could allow to reach an energy resolution of 800 keV at 52.8 MeV with an extremely good time resolution (30 ps). This material is very expensive but it could allow nonetheless to significantly increase the acceptance of the photon detector with respect to the one of MEG and MEG-II ($\sim 10\%$), which has to cope with the extremely high cost of Xenon.

For the conversion technique, the performances are determined by the pair production probability and the fluctuations of the energy loss of the $e^+e^-$ pair in the conversion material. The best compromise is obtained for high-$Z$ materials, like Lead and Tungsten. A resolution of 800 keV and an efficiency of 3% is obtained for a converter thickness of 0.1 radiation lengths. It is important to notice that the photon conversion technique also allows to get a rough estimate of the photon direction, that helps to reject the accidental background. On the other hand, this technique needs to be complemented with fast detectors for timing. If one wants to stack multiple conversion layers, they need to be interleaved with fast detectors of lower $Z$ and it deteriorates the performances of the system. An alternative could be the implementation of an active conversion layer using fast and thin silicon detectors [8].

There is also some room for an optimization of the target. In particular, the possibility of using multiple targets can be considered because, if the conversion technique allows to determine the target where the photon has been produced, it allows to reduce the accidental background.

We imagined a conceptual experiment to search for $\mu \rightarrow e\gamma$ assuming reasonable incremental improvements in the detector technologies, taking into account the limiting factors discussed above. Expected upper limits on the BR of $\mu \rightarrow e\gamma$ have been evaluated assuming a counting experiment and making use of the Feldman-Cousins algorithm [9] under different scenarios. The results are shown in Fig. 2 as a function of the muon beam intensity.
The search for LFV is one of the most promising fields in the quest for NP. The present limit on $\mu \rightarrow e\gamma$ by the MEG collaboration already strongly constrains the NP models and an improvement of one order of magnitude is expected with MEG-II. We investigated some long term prospects for the $\mu \rightarrow e\gamma$ search. Our estimates show that a 3-year run with an accelerator delivering around $10^9$ muons per second could allow to reach a sensitivity of a few $10^{-15}$ (expected 90% upper limit on the $\mu \rightarrow e\gamma$ BR), with poor perspectives of going below $10^{-16}$ even with $10^{10}$ muons per second. Below $5 \times 10^8$ muons per second, the calorimetric approach needs to be used in order to reach this target. If a muon beam rate exceeding $10^9$ muons per second is available, the much cheaper photon conversion option would be recommended and would provide similar sensitivities.

The sensitivity would be eventually limited by the fluctuations of the interaction of the particles with the detector materials: this indicates that a further step forward in the search for $\mu \rightarrow e\gamma$ would require a radical rethinking of the experimental concept.

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