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Lepton Flavour Violation with the MEG-II Experiment

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Lepton flavour conservation, being an accidental symmetry in the Standard Model (SM) of particle physics, is prone to be violated in most of the models of new physics. Although lepton flavour violation (LFV) has been already observed in the form of neutrino oscillations, the consequent effect in the charged lepton sector is unobservably small. Hence, charged LFV is both a very sensitive probe for physics beyond the SM and a phenomenon whose observation would provide an unambiguous evidence for such new physics. The goal of the MEG II experiment is the search for the LFV decay $\mu \to e\gamma$, with a sensitivity below 10^{-13}, a factor 10 better than the phase-1 MEG experiment. The construction and commissioning of MEG II have been recently completed and the first physics data are expected to be collected at the end of year 2021. In this contribution I will present the current status of the experiment and its expected performances. A recent result for the search of the $\mu \to eX$ with $X \to \gamma\gamma$ $\mu \to eX$ with $X \to \gamma\gamma$ decay in the dataset of MEG will be also reviewed.

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1. Introduction

The search for rare muon decays contributed to shape the Standard Model (SM) of particle physics since the very early days, starting from the pioneering work of Hincks and Pontecorvo [1]. Nowadays, the quest for charged lepton flavour violation (LFV) in muon decays is one of the frontlines in the search for New Physics (NP) beyond the SM. Indeed, in the SM the conservation of lepton flavour is an accidental symmetry, not deriving from the gauge structure of the theory but a mere consequence of its particle content, namely the absence of right-handed neutrinos. Consequently, this conservation law is easily violated in NP models, and the present limits already strongly constrain the construction of such theories. Indeed, LFV has been already observed in the form of neutrino oscillations, but the effect induced in charged lepton transitions is expected to be negligibly small. Thanks to these features, the search for processes like $\mu \to e\gamma$ is extremely promising, and any observation would provide an unambiguous evidence of NP, free of theoretical uncertainties.

Along with $\mu \to e\gamma$, other processes like $\mu \to eee$ and the muon to electron conversion in the Coulomb field of a nucleus, $\mu + N \to e + N$, can be also considered. Based on naive assumptions in effective field theories, $\mu \to e\gamma$ is usually believed to be the golden channel if the NP enters through dipole-like interactions, while 4-fermion interactions should be better probed by the other processes. Indeed, more recent studies [2] showed that $\mu \to e\gamma$ is also sensitive to 4-fermion interactions through loops, and the real sensitivity to the different kind of operators depend on the specific model, so that the processes should be regarded as truly complementary for maximizing the discovery potential and discriminating among models if an observation is made.

2. The search for $\mu \to e\gamma$

The search for $\mu \to e\gamma$ is performed by stopping positive muons in a thin target and looking for a photon-positron pair having the kinematics of a two-body decay at rest. Positive muons are preferred over negative muons, to avoid capture by nuclei, which would screw up the kinematics of the decay. Positron and photons should equally share the center-of-mass energy, carrying out $m_\mu/2 \sim 52.8$ MeV each, and be emitted with a relative angle of 180 degrees. When this search is performed with very high rates of stopped muons, the dominant background comes from the accidental coincidence of positrons and photons coming from different SM muon decays, so that a precise measurement of the relative time, along with the aforementioned kinematical observables, allows to strongly suppress the contamination. A subleading contribution to the background comes from the radiative muon decay $\mu^+ \to e^+\overline{\nu}_\mu \nu_e \gamma$, which will elude a selection based on the relative time, but will still be discriminated by the kinematics.

The best limit on the branching ratio (BR) of $\mu \to e\gamma$ was set by the MEG experiment [3], $BR(\mu \to e\gamma) < 4.2 \times 10^{-13}$ at 90% confidence level. The experiment was performed at the Paul Scherrer Institut (Villigen, Switzerland), where beam lines delivering up to 10^8 μ/s are available. Due to its accidental nature, the dominant background scales with the square of the beam intensity. Hence, an increase of the beam rate is beneficial for the sensitivity of the experiment (going with $S/\sqrt{B}$, being S and B the signal and background yields over the lifetime of the experiment) only if

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the experiment is run under zero-background conditions. Given the resolutions achieved in MEG, the optimal beam rate was 3.3×10^7 μ/s.

3. The MEG II experiment

The MEG II experiment [4] is the result of a complete upgrade of the MEG detector [5]. It is composed of a liquid Xenon calorimeter (XEC) for the detection of the photon, a magnetic spectrometer with a cylindrical drift chamber (CDCH) for positron tracking and a set of scintillator tiles (Timing Counter, TC) for positron timing. The experiment is sketched in Fig. 1

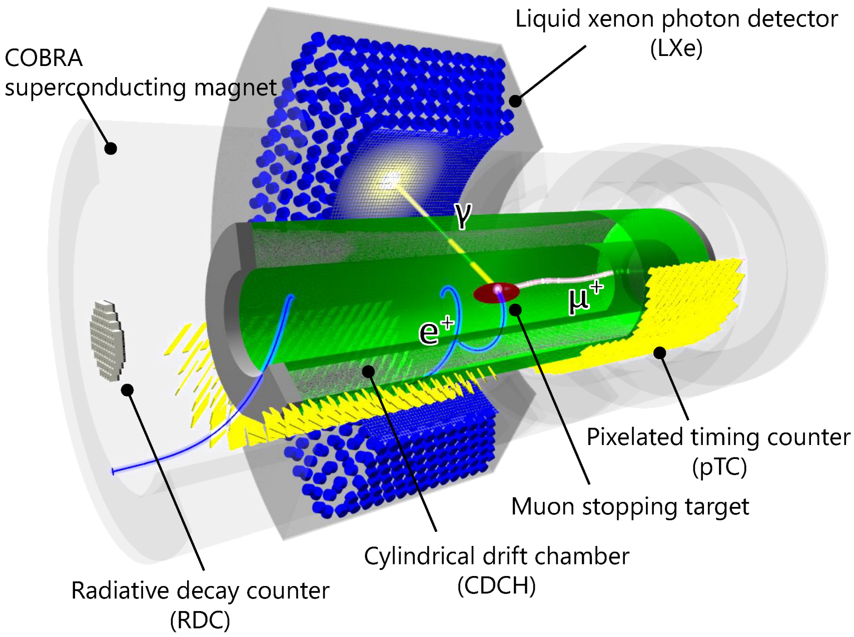

Figure 1: A schematic view of the MEG II experiment

The XEC is a complete photon detector, measuring not just the energy but also the position and time of the photon conversion. It contains 800-liter of Xenon in liquid phase, whose scintillator light is collected by PMTs and silicon photon detectors (MPPC). The UV-sensitive MPPCs [6] have been introduced in MEG II to replace the PMTs in the entrance face of the calorimeter. The consequently higher granularity is beneficial in improving the detector resolutions, in particular for photons converting right after entering the detector, and helps rejecting events where more than one photon enter the calorimeter within a short time interval. The energy resolution of the XEC is expected to approach 1.7% at 52.8 MeV. A position resolution of 2.4/5 mm in the direction parallel/orthogonal to the inner surface is expected. Along with the measurement of the positron formation point at the target, provided by the spectrometer, it allows to determine the photon angles with a resolution of a few mrad for signal events. The design time resolution is 84 ps.

The CDCH is a 9-layer drift chamber with full-stereo geometry, made of 20 μm gold-plated tungsten anodes and $40/50$ μm silver-plated aluminum cathodes [7]. The chamber is installed inside a superconducting solenoid of variable section, producing a graded magnetic field (from 1.3 T at the center of the magnet to 1 T at 1 m from the center). The gradient prevents positrons emitted almost orthogonal to the beam axis to recurl several times inside the detectors, to suppress the pileup in the CDCH, and makes positrons of the same momentum to experience the same curvature irrespective of the emission angle, to maximise the acceptance of the spectrometer to signal positrons while keeping a reduced radial extension. A momentum resolution of 100 keV is expected on signal positrons. The position of the muon decay, determined as the intersection of the positron track with the plane of the target, is expected to be determined with 1.6/0.7 mm resolution along z/y, being z the beam axis and y the vertical coordinate. The angles at the production point are expected to be measured with a resolution of 6.7/3.7 mrad in θ/ϕ.

The TC is made of 512 BC-422 scintillator tiles with dimensions of $L \times W \times T = 120 \times (40 \text{ or } 50) \times 5 \text{ mm}^3$ [8]. Each tile is readout by 6 parallel-connected silicon photomultipliers (SiPM) at each end. A system of optical fibres distributes synchronous laser pulses through the detector to align the time offsets of the single detectors [9]. The TC was tested with positrons from muons on target since 2019 and already reached the design resolution of 35 ns.

Analog signals from all subdetectors in MEG II are digitized with 12-bit resolution with the high-speed chip DRS4, installed on the WaveDREAM board [10], which also provides trigger capabilities and biasing for the silicon detectors of the XEC and TC. It allowed to integrate a fully-digital FPGA-based trigger and the acquisition of digitized waveforms for offline analysis into a single system, a solution that was necessary to handle the increased number of readout channels with respect to MEG.

The design performances would allow to reach an upper limit of $\sim 6 \times 10^{-14}$ in a three-year run of the experiment.

4. Current status

In 2020 the experiment was run for the first time with all the detectors installed. In 2021 the full readout electronics was also available and the first physics data were collected.

Already in 2019 the photon detection efficiency (PDE) of the MPPCs in the calorimeter was observed to decrease continuously while running the detector on the muon beam, a deterioration ascribed to the large amount of UV scintillation light from LXe. Fortunately, the resolutions of the XEC are not expected to be dominated by the photoelectron statistics, as far as the PDE stays above 4%. Moreover, a recovery procedure was experimented, consisting in increasing the temperature of the MPPCs up to 70 °C for several hours, a procedure that can only be done during a long shutdown of the detector, due to the necessity of warming it up from the LXe temperature and then cool it down to restore the operative conditions. Consequently, an optimal beam rate of 5×10^5 μ/s was defined, allowing to run the experiment for 120 days per year without a significative deterioration of the performances, while the recovery procedure will be performed during the long winter shutdown of the PSI proton beam facility.

The main challenges in the construction of the chamber came from the necessity of combining small cells, to tolerate the expected, high particle flows, and a very low material budget, to restrain the multiple scattering suffered by positrons. The extreme thinness of the wires that was necessary to fulfil these requirements resulted into severe fragility issues for the aluminum wires in humid

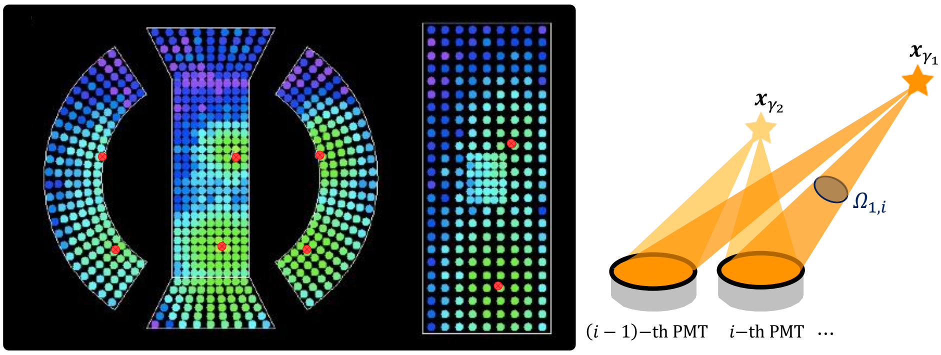

Figure 2: The reconstruction of two photons in the LXE calorimeter of MEG.

environments [11], and the CDCH could be finally completed and installed only in 2020 after having adopted strict procedures to always keep the wires in a dry atmosphere. The detector is also operated with an extremely light mixture based on helium and isobutane in 90/10 concentrations. In past experiments, such mixture was usually complemented with a small amount of water vapours to improve the stability on beam. The necessity of avoiding any level of humidity during the operations prevented the implementation of such a solution, and finally a working mixture was found, by modifying the custom gas distribution system [12] to add oxygen and isopropyl alcohol at 0.5% and 1.5% concentrations, respectively. According to measurements performed during the 2020 engineering run, such concentrations are not expected to compromise the detector performances. At the end, in 2021 the detector could be finally operated for a few months without any significative discharge rate.

The analysis of the data collected in 2021 is currently on-going. An updated estimate of the detector performances that we can expect to reach show that the MEG limit could be already approached with 2021 data, corresponding to 25% of the statistics we plan to collect in one nominal year (with shutdown periods taken into account). A complete 120-day run in 2022 would allow to improve the limit by a factor up to 3, and the possibility of reaching the design sensitivity of 6×10^{-14} around 2024 is currently confirmed.

5. A search for $\mu \to eX$ with $X \to \gamma\gamma$ on MEG data

The MEG detector is specifically designed for the search of the two-body decay $\mu \to e\gamma$, with acceptance and trigger that tends to discard any other kind of events. Nonetheless, there is some room to search for some specific, alternative decay channels. While the sensitivity to a generic $\mu \to e\gamma\gamma$ decay is found to be poor, due to the lack of geometrical acceptance, a competitive search could be performed for the $\mu \to eX$ decay, where an exotic particle X of mass in the range 20-45 MeV/c^2 is produced and decays into a photon pair. Such a particle is assumed to be a scalar or pseudo-scalar, as predicted in many models with pseudo Goldstone bosons from broken symmetries (see [13] and references therein).

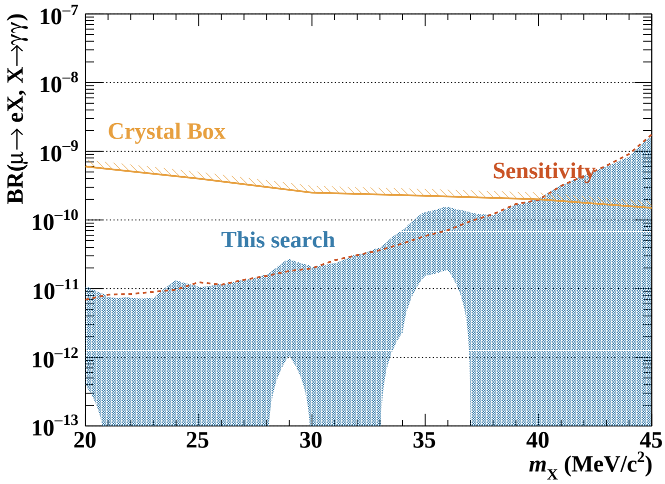

Figure 3: 90% confidence intervals from the search of $\mu \to eX$ with $X \to \gamma\gamma$ under different X mass hypotheses.

The capability of the XEC in discriminating and measuring multiple photons inside the calorimeter is exploited, as shown in a typical event in Fig. 2. After selecting events where two photons and at least one positron are reconstructed, a blinding procedure is followed by removing from the data set events in a signal region defined by the relative time of the two photons and the relative time of the first photon and the positron. Then a selection is performed by exploiting the two body kinematics of the prompt decay. Finally, the events in the blind region are included in the analysis, counted and compared to the number of expected events, extrapolated from the sidebands of the signal region. No significant excess was observed under the different mass hypotheses, and the limits in Fig. 3 were extracted.

The improved granularity in the inner face of the MEG II calorimeter, along with the increased statistics, will allow to improve significantly these limits in the next years. The possibility of exploring other exotic decays, like $\mu \to eX$ and $\mu \to eX\gamma$ with an invisible X, is also under consideration and feasibility studies are on going.

6. Conclusions

I reported the current status of the MEG II experiment for the search of the LFV decay $\mu \to e\gamma$. The experiment, a complete upgrade of the MEG detector, collected its first physics data in 2019. The expected upper limit from a 3-year run at 5×10^7 μ/s is about 6×10^{-14}. Searches for other exotic muon decays are also possible, as already done in MEG with the recently published search for $\mu \to eX$ with $X \to \gamma\gamma$. MEG II is the first running experiment in the current generation of muon LFV searches, and options for the next generation are already under study [14].

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