Searching for the $\mu \to e\gamma$ decay with MEG and MEG-II

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The MEG collaboration searches for the $\mu \to e\gamma$ decay at the muon beam line $\pi E5$ of the Paul Scherrer Institut in Switzerland. The world best upper limit has been set to be $B(\mu \to e\gamma) < 5.7 \times 10^{-13}$ at 90% C.L. analyzing a data set of $3.6 \times 10^{14}$ stopped muons on target.

An upgrade program of the detector (MEG-II) should lead to a sensitivity at a level of few $10^{-14}$ within the next five years.

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1 Introduction

Lepton Flavour Violation in the decay of charged leptons (cLFV) is of the utmost importance to find evidence of New Physics (NP) beyond the Standard Model (SM) of fundamental interactions. The $\mu \rightarrow e\gamma$ decay in SM is predicted to have a tiny branching fraction ($B$) of the order of $10^{-55}$, that is basically explained by the neutrino flavour oscillation and by the very small ratio of the neutrino over the $W$ mass [1].

At the same time in almost every extension of the SM predicting NP effects [2, 3, 4, 5], a $B(\mu \rightarrow e\gamma)$ at the level of $10^{-12}$ is well possible, calling for an experimental effort to search for this decay. The $\mu \rightarrow e\gamma$ process has a clear two body decay topology and advances in this search have been obtained in the last 60 years with more and more precise detectors and with higher and higher intensity muon beams.

2 The MEG experiment

The MEG experiment has been operated at the πE5 beam line of the Paul Scherrer Institut (PSI) at Villigen (CH) since 2007 until 2013. A continuous positive muon beam is available with a maximal rate of about $10^8$ muon per second. MEG took data with an optimal muon stopping rate on a thin target of $3 \times 10^7$ muon/s.

The MEG detector includes a spectrometer made of a special gradient magnetic field and low mass drift chamber planes to track the positrons emerging from the target. The magnetic field sweeps out of the tracking volume the lower momentum positrons and direct the higher momentum positrons on two fast scintillator arrays readout by PMT to measure the positron emission time. Photons produce showers in a 900 liter liquid Xe calorimeter where scintillating light is produced and detected by PMTs with a photon detection efficiency of about 60% [6].

2.1 MEG datasets and analysis

MEG collected data until 2013 for a total number of about $7 \times 10^{14}$ muon stopped on target. The results presented here are based on half of this data-set (collected in the 2009-2011 period) [7].

The signature of the signal event is given by a back-to-back, monoenergetic, time coincident photon-positron pair from the two body $\mu^+ \rightarrow e^+\gamma$ decay. In each event, positron and photon candidates are described by five observables: the photon and positron energies ($E_\gamma$, $E_e$), their relative directions ($\theta_{e\gamma}$, $\phi_{e\gamma}$) [9] and emission time ($t_{e\gamma}$). The analysis is based on a maximum likelihood technique applied in the analysis region defined by $48 < E_\gamma < 58\,\text{MeV}$, $50 < E_e < 56\,\text{MeV}$, $|t_{e\gamma}| < 0.7\,\text{ns}$, $|\theta_{e\gamma}| < 50\,\text{mrad}$ and $|\phi_{e\gamma}| < 50\,\text{mrad}$, which is described in detail in [8].
The background has two components, one coming from the Radiative Muon Decay \( \mu^+ \rightarrow e^+ \nu \bar{\nu} \gamma \) (RMD) and another from the accidental superposition of energetic positrons from the standard muon Michel decay with photons from RMD, positron-electron annihilation-in-flight or bremsstrahlung. At the MEG data taking rate, 93% of events with \( E_\gamma > 48 \) MeV are from the ACCidental background (ACC).

2.2 MEG results

A blind analysis procedure is applied by masking a region of \( 48 < E_\gamma < 58 \) MeV and \( |t_{e\gamma}| < 1 \) ns until the Probability Density Functions (PDFs) for the likelihood function are finalized. The background studies and the extraction of the PDFs are carried out in data sidebands close to the signal region. Signal PDF are obtained from various sources: monochromatic 55 MeV photons from \( \pi^0 \) decays for \( E_\gamma \), a fit to the Michel positron \( E_e \) spectrum edge for \( E_e \), \( t_{e\gamma} \) in RMD events with \( E_\gamma < 48 \) MeV for \( t_{e\gamma} \) and special samples of tracks to validate the \( \theta_{e\gamma} \) and \( \phi_{e\gamma} \) PDFs. The performances obtained with the MEG detector are summarized by the observables resolution reported in the first column of Table 1.

The maximum likelihood fit is performed in order to estimate the number of signal, RMD and ACC events in the analysis region. The definition of the likelihood function is described in detail in [8].

![Figure 1: Distribution of the \( B \) upper limits at 90% C.L. for a pseudo-experiments ensemble.](image)

The distribution of the \( B \) upper limits at 90% C.L. is obtained over an ensemble
of pseudo-experiments, randomly generated according to the PDFs based on a null signal hypothesis, with the rates of ACC and RMD evaluated from the sidebands. The sensitivity is estimated as the median of such distribution (Fig.1) to be $7.7 \times 10^{-13}$.

No signal events are found in the signal region while obtaining $N_{\text{RMD}} = 163 \pm 32$ and $N_{\text{ACC}} = 2411 \pm 57$.

![Confidence level curve for the $B$ for the 2009-2011 data-set (and separately for the 2009-2010 and 2011 subsets).](image)

The confidence interval for the number of signal events is calculated by a frequen
tist method with a profile likelihood-ratio ordering [8, 10, 11], where the numbers of RMD and ACC events are treated as nuisance parameters.

To translate the estimated number of signal events into a signal branching ratio two methods are used, either counting the number of Michel positrons selected with a dedicated trigger or the number of RMD events observed in the muon data leading to a 4% uncertainty in the branching ratio estimate (Fig.2).

The upper limit on $B(\mu^+ \rightarrow e^+\gamma)$ is $B < 5.7 \times 10^{-13}$ at 90% C.L. which improves the previous best upper limit [8] by a factor of four.

### 2.3 MEG outlook

The final MEG results will use a data set that will be twice larger than the currently analyzed sample, with a corresponding predicted sensitivity of $5.0 \times 10^{-13}$. Given the detector performances the sensitivity does not significantly improves adding more data (Fig.3).
The dominant accidental background (proportional to the square of the muon stopping rate and to the various observables resolutions) can be reduced only with a better detector. This then allows to use a higher muon stopping rate. Moreover, several models of NP still leave room for $B$ in the $10^{-14}$-$10^{-13}$ range \cite{12}. Given the availability of a higher muon flux at PSI, an upgrade program for the MEG detector in the next coming years is very desirable.

3 MEG upgrade, MEG-II

The MEG collaboration has recently proposed an upgrade program (MEG-II) for its detector \cite{13} that has been approved by PSI and by its funding agencies.

3.1 MEG-II proposal and sensitivity

The MEG-II relies on the following improvements compared with the present MEG experiment, shown schematically in Figure 4 and here enumerated:

1. Increasing the number of stopping muons on target;

2. Reducing the target thickness to minimize the material traversed by photons and positrons on their trajectories towards the detector;
3. Replacing the positron tracker, reducing its radiation length and improving its granularity and resolutions;

4. Improving the positron tracking and timing integration, by measuring the $e^+$ trajectory to the positron timing counter interface;

5. Improving the positron timing counter granularity for better timing and reconstruction;

6. Extending the calorimeter acceptance;

7. Improving the photon energy, position and timing resolution for shallow events;

8. Integrating splitter, trigger and DAQ while maintaining a high bandwidth.

This would lead to better resolutions as outlined in Table I. In particular a higher efficiency positron spectrometer with $E_e$, $\theta_e$ and $\phi_e$ smaller resolutions would considerably improve the performance of the detector. With sizeable improvements in the other sub-detectors and with a muon stopping rate $7 \times 10^7$ muons per second MEG-II will have a predicted sensitivity of $5 \times 10^{-14}$ after 3 years of nominal data-taking.
Table 1: Resolution (Gaussian $\sigma$) and efficiencies for MEG-II

| PDF parameters | MEG  | MEG-II |
|----------------|------|--------|
| $e^+$ energy (keV) | 306 (core) | 130 |
| $e^+ \theta$ (mrad) | 9.4 | 5.3 |
| $e^+ \phi$ (mrad) | 8.7 | 3.7 |
| $e^+$ vertex (mm) $Z/Y$ (core) | 2.4 / 1.2 | 1.6 / 0.7 |
| $\gamma$ energy (%) ($w < 2\,\text{cm})/(w > 2\,\text{cm})$ | 2.4 / 1.7 | 1.1 / 1.0 |
| $\gamma$ position (mm) $u/v/w$ | 5 / 5 / 6 | 2.6 / 2.2 / 5 |
| $\gamma$-$e^+$ timing (ps) | 122 | 84 |

**Efficiency (%)**

|              | MEG | MEG-II |
|--------------|-----|--------|
| trigger      | $\approx 99$ | $\approx 99$ |
| $\gamma$     | 63  | 69    |
| $e^+$        | 40  | 88    |

3.2 MEG-II status

The design of a single volume drift chamber with full azimuthal coverage has been finalized in a 2 m long, stereo wires only, low mass chamber. Such a longer chamber will also have a higher transparency for positrons to a system of scintillating tiles than the current MEG detector. This will allow a more precise determination of the positron path length that is crucial to improve the timing of the positron track.

Such detector has to sustain a hit rate larger than 30 kHz/cm$^2$ on its innermost layer at the nominal muon stopping rate of $7 \times 10^7$ muon/s. At the same time it has to provide a point (R) resolution of the order of 100 $\mu$m. To sustain such rate 1200 almost square 7x7 mm$^2$ cells organized in layers with a 8° stereo angle are foreseen. A signal $\mu \to e\gamma$ positron will therefore cross on average $1.7 \times 10^{-3}$ radiation lengths along its path in the chamber volume.

The current R&D program has demonstrated on small scale prototypes that the required resolution can be obtained and that integrating a charge of 0.5C/cm on a sense wire would not lead to severe ageing problems.

The procedure for the wiring of the new MEG-II drift chamber is currently optimized along with all its mechanical details. The construction should start at the end of 2014.

A new positron timing detector is in the construction phase, with the aim of having 600 scintillator tiles read out by SiPM. Beam tests have demonstrated that a 40 ps resolution can be obtained. The tiles configuration would allow several time measurement along the positron path, a reduction of the pile-up and a better geometrical reconstruction of the positron hits.
For the liquid Xenon detector an increase of the active area of the photo-detectors on the front face is foreseen. Large area SiPM (10x10 mm\(^2\)) with an extended sensitivity in the ultra-violet range (where the Xenon scintillating light spectrum peaks) will replace the current PMTs.

A new readout electronics to cope with four times more channels in the whole apparatus and to preserve the full waveform recording for each channel is under study. It will be made of a multi-functional digitization boards with both digitization and trigger capabilities.

Ancillary devices (that are not yet part of the MEG-II layout) are under study. A radiative decay counter able to veto the very low momentum positron from RMD and an active target made of 250 \(\mu\)m square scintillating fibers \([14, 15]\) are considered.

4 Conclusions

The MEG experiment has set the world best upper limit on the \(\mathcal{B}(\mu \rightarrow e\gamma)\) to be \(5.7 \times 10^{-13}\) at 90 \% C.L. analyzing a data set of \(3.6 \times 10^{14}\) stopped muons on target. More data are going to be analyzed rather soon to reach a sensitivity of \(5.0 \times 10^{-13}\).

The MEG-II program is well advanced in the development of new sub-detectors, planning to build the new devices in 2015 and to start data-taking in 2016. MEG-II will reach in three years nominal data-taking a sensitivity of \(5.0 \times 10^{-14}\) with the aim of challenging a larger and larger number of models of NP.

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\[ \theta_{e\gamma} = (\pi - \theta_e) - \theta_\gamma \text{ and } \phi_{e\gamma} = (\pi + \phi_e) - \phi_\gamma, \theta \text{ and } \phi \text{ being the polar angle and the azimuthal angle, respectively, taking the z-axis as the beam-axis.} \]