PROCEEDINGS OF SCIENCE

The MEG experiment result and the MEG II status

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The MEG experiment at the Paul Scherrer Institut is searching for the lepton-flavour violating decay $\mu^+ \to e^+\gamma$ with unprecedented sensitivity. MEG set the most stringent experimental bound to date, based on the analysis of 2009, 2010 and 2011 data, to be $\leq 5.7 \times 10^{-13}$ with an associated sensitivity of about 7.7×10^{-13}. Here we present the MEG final result which has an associated sensitivity of about 5.3×10^{-13}.

An experiment upgrade is conceived in order to further improve the sensitivity by one order of magnitude in three years of data taking. It will take benefit of the MEG infrastructures as the beam lines, the magnet and the calorimeter cryostat and technology, while the detectors and the TDAQ electronics were re-designed to cope with a doubled muon stopping rate in the target. The MEG II experiment is currently under construction, the commissioning is foreseen between the end of this year and the first months of 2017. I will overview the new detector and describe the most important improvements.

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1. Introduction

In the minimal standard model (SM) the lepton flavour violating (LFV) processes are not allowed at all; lepton flavour conservation is built in by hand assuming vanishing neutrino masses. Nevertheless, neutrino oscillations are now established facts (for a continuously updated review see [1]) and neutrino masses are definitely not vanishing as well as their mixing, while until now there are no corresponding indications in the charged sector. When massive neutrinos and neutrino oscillations are introduced in the SM, $\mu^+ \to e^+\gamma$ LFV decay is possible, but at an immeasurably small level (branching fractions $\sim 10^{-50}$ with respect to SM decays). However, many theories beyond SM, as for example grand unification supersymmetric theories, naturally accommodate finite neutrino masses and predict relatively large (and probably measurable) branching ratios (*BR*) for cLFV processes (see for example [2], [3], [4], [5], [6]). Therefore, sizable flavor violation processes in the charged sector would be strong indications in favor of new physics beyond the SM.

2. Signal and background

Positive muons coming from decays of π^+ produced by proton interactions on a fixed target, are brought to stop and decay at rest, emitting simultaneously a γ and a e^+ in opposite directions. Neglecting the e^+ mass, both particles carry away the same kinetic energy: $E_{e^+} = E_\gamma = m_\mu/2 =$ 52.83 MeV. The signature is very simple, but, because of the finite experimental resolutions, it can be mimicked by two types of background:

a) the *physical* or *correlated* background, due to radiative muon decay (RMD): $\mu^+ \to e^+\bar{\nu}_\mu\nu_e\gamma$. The *BR* of RMD process is (1.4 ± 0.2) % for $E_\gamma > 10$ MeV;

b) the *accidental* or *uncorrelated* background, due to the coincidence, within the analysis window, of a e^+ coming from the usual muon decay and a γ coming from RMD, $e^+ - e^-$ annihilation in flight, e^+ bremsstrahlung in a nuclear field and so on. This is the dominant background.

3. Detector and calibration systems

The MEG experiment [9] (Fig. 1 (b)) uses the secondary $\pi E5$ muon beam line extracted from the PSI (Paul Scherrer Institute) proton cyclotron. A 3×10^7 μ^+/s beam is stopped in a 205 μm slanted polyethylene target. The e^+ momentum is measured by a magnetic spectrometer, composed by an almost solenoidal magnet (COBRA) with an axial gradient field and by a system of sixteen ultra-thin drift chambers (DC). The e^+ timing is measured by two arrays of plastic scintillators (Timing Counter, TC): it is equipped with two sections of 15 scintillating bars each. The γ energy, direction and timing are measured in a ≈ 800 l volume liquid xenon (LXe) scintillation detector. The LXe as scintillating medium was chosen because of its large light yield (comparable with that of NaI) in the vacuum ultraviolet region ($\lambda \approx 178$ nm), its homogeneity and the fast decay time of its scintillation light (≈ 45 ns for γ's and ≈ 22 ns for α's) [14]. The LXe volume is viewed by 846

Hamamatsu 2″ PMTs, specially produced to be sensitive to UV light and to operate at cryogenic temperatures.

Several calibration tools (LEDs, point-like α sources deposited on wires [15], Am-Be sources, Michel decays, through going cosmic μ's, a neutron generator, 55 MeV and 83 MeV γ's from charge exchange reaction $\pi^- \mathrm{p} \to \pi^0 \mathrm{n}$, γ-lines from nuclear reactions induced by a Cockcroft-Walton accelerator [16] and so on) are frequently used to measure and optimize the detector performances and to monitor their time stability.

4. Data analysis and result

The data are analysed with a combination of blind and likelihood strategy. Events are preselected on the basis of loose cuts, requiring the presence of a track and the relative time $|\Delta T_{\mathrm{e}\gamma}| <$ 4 ns between the two daughter particles. Preselected data are processed several times with improving calibrations and algorithms and events falling within a tight window ("blinding box", BB) in the γ energy and relative time plane $(E_\gamma, \Delta T_{\mathrm{e}\gamma})$ are hidden. The remaining pre-selected events fall in "sideband" regions and are used to optimise the analysis parameters, study the background and evaluate the experimental sensitivity under the zero signal hypothesis. When the optimisation procedure is completed, the BB is opened and a maximum likelihood fit is performed on the distributions of five kinematical variables (positron and gamma energies, relative time and angles: E_{e^+}, E_γ, $\Delta T_{\mathrm{e}\gamma}$, $\theta_{\mathrm{e}\gamma}$ and $\phi_{\mathrm{e}\gamma}$), in order to extract the number of Signal (S), RMD (R) and Accidental Background (B) events. Probability Distribution Functions (PDFs) are determined by using calibration measurements and MC simulations for S, theoretical formulae folded with experimental resolution for R[1] and sideband events for B. Michel positrons are used to calculate the normalisation factor needed to convert an upper limit on S into an upper limit on $BR(\mu^+ \to \mathrm{e}^+\gamma)$. For the final result the target alignment procedure has been revised and improved to correctly handle the associated uncertainty.

The analysis procedure was applied combining the statistics accumulated from 2009 to 2013. The sensitivity of the experiment with a null signal hypothesis is evaluated by taking the median of the distribution of the upper limit on the branching ratio obtained over an ensemble of toy MC experiments. The rates of RMD and BG events, as measured in the sidebands, are assumed in the simulated experiments. The branching ratio sensitivity at 90% C.L. is found to be 5.3×10^{-13} consistent with the upper limits obtained in several comparable analysis regions of the $\mathrm{T}_{\mathrm{e}\gamma}$ sidebands.

The observed profile likelihood ratios as a function of the branching ratio independently for 2009-2011 and 2012-2013 runs together with the combined data sample are shown in Fig. 1(a). The analysis of the combined data sample gives a 90% C.L. upper limit of 4.2×10^{-13}[17], which constitutes the most stringent limit on the existence of the $\mu^+ \to \mathrm{e}^+\gamma$ decay, superseding the previous limit by a factor of 30.

5. MEG II status

The interest in this topic has grown so much in the LHC era that the high energy physics

[1] In RMD events, the kinematical boundaries introduce a correlation between E_{e^+}, E_γ and positron-gamma relative angle which must be taken into account in the PDF.

Variable	Foreseen	Obtained	Upgrade Scenario
ΔE_γ (%)	1.2	1.7	1.0
Δt_γ (ps)	43	67	≤ 67
γ position (mm)	4-6	4-6	~ 2
γ efficiency (%)	> 40	63	70
ΔP_e (keV)	200	306	≤ 130
e^+ angle (mrad)	$5(\varphi), 5(\theta)$	$8.7(\varphi), 9.4(\theta)$	$\leq 4(\varphi), \leq 5(\theta)$
Δt_{e^+} (ps)	50	107	30
e^+ efficiency (%)	90	40	≥ 85
$\Delta t_{e\gamma}$ (ps)	65	122	80

Table 1: Comparison between MEG design and obtained resolution with the upgrade expected ones.

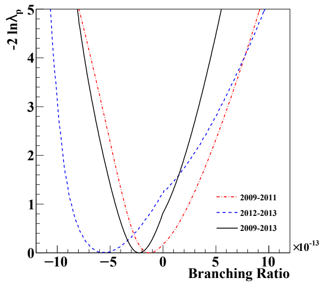
community looking forward to further improving the sensitivity on this measurement by at least one order of magnitude. This is the reason why the MEG collaboration has proposed a significant detector upgrade [18], which has been approved by the scientific committee of PSI, which is hosting also the upgraded experiment, as well as the national funding agencies. As reported in Table 1 the resolution and efficiencies of the MEG experiment are not at the level of the proposal; the new experiment will solve most of the problems in particular on the positron side.

The upgraded experiment will reuse use some of the infrastructures provided by the MEG experiment, such as the beam line and the magnet, and will profit of the collaboration expertise gained with the first phase of the experiment. A graphical comparison between the MEG and the upgraded detectors is reported in Fig. 1 (b). The upgraded experiment, relies on the following improvements:

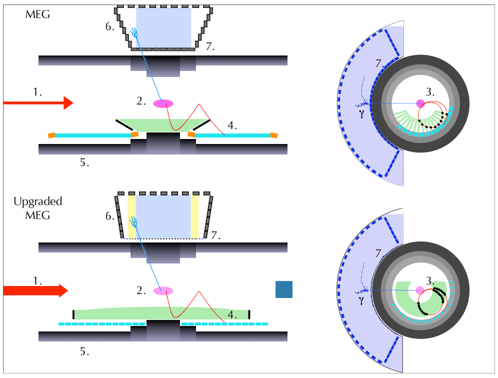
1. Increasing the number of stopping muons on target;
2. Reducing the target thickness to minimise the material traversed by photons and positrons on their trajectories towards the detector;
3. Replacing the positron tracker, reducing its radiation length and improving its granularity and resolutions;
4. Improving the positron tracking and timing integration, by measuring the e^+ trajectory to the TC interface;
5. Improving the timing counter granularity for better timing and reconstruction;
6. Improving the γ-ray energy resolution near the acceptance edge;
7. Improving the $\gamma-$ray energy and position resolution for shallow events;
8. Use a new Radiative Decay Counter (RDC) device to measure low energy positron associated with high energy photons on the LXe calorimeter to further reduce RMD background and improve the sensitivity by a further 10%;

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

The MEGII experiment is currently under construction. A medium size prototype of the new Timing Counter and the RDC detector were tested at PSI with the μ-beam at the MEG II intensity together with the first module of the new TDAQ last summer. The results, being in agreement with the design values, are very promising for both devices. The detector will be assembled within June 2017 to be ready for a first engineering run next year. The physics data taking will start in 2018 and will last 3 years.



(a)



(b)

Figure 1: (a) Profile likelihood ratios as a function of the $\mu^+ \to e^+\gamma$ branching ratio for 2009-2010, 2011 and the combined 2009-2011 data sample; (b) an overview of the MEG upgraded experiment versus the present one. The MEG upgrade will rely on a higher intensity beam rate (1.) stopped in a thinner target to reduce the multiple scattering (2.), a new unique volume drift chamber with higher granularity and transparency (3. and 4.) to the the new pixelated TC (5.); the LXe detector will have a larger acceptance and the inner face PMTs will be replaced with SiPM (6.,7.); the RDC counter (blue box) is a placed downstream along the beam axis.

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