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In Search of $\mu \rightarrow e\gamma$ - The MEG Experiment Status & Latest Results

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Abstract

Presented are the preliminary results of a search for the lepton-flavour violating decay $\mu \rightarrow e\gamma$ by the MEG experiment at the Paul Scherrer Institut in Switzerland. These results are based on data taken during a two months period in 2009 and amount to some $6 \cdot 10^{13}$ muon decays in the detector. Using a blind likelihood analysis technique a sensitivity of $6.1 \cdot 10^{-12}$ on the branching ratio is achieved with a preliminary upper limit on the branching ratio set at $1.5 \cdot 10^{-11}$ at a 90% confidence level.

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1. Introduction

Lepton-flavour is seen as conserved in the minimal Standard Model (SM) where massless neutrinos are assumed and hence the decay $\mu \rightarrow e\gamma$ is forbidden. With the now established fact of neutrino mixing in the neutral lepton sector and hence incorporation of finite but tiny masses into the SM this then allows such charged lepton-flavour violating (cLFV) processes as $\mu \rightarrow e\gamma$, though at a highly suppressed and immeasurably small level of $\oslash (10^{-54})$.

The SM is now believed to be an effective theory and a low-energy manifestation of a more fundamental theory at higher energies, in which mixing is naturally introduced by extra degrees of freedom given by the additional particles in the high-energy sector. This leads to predictions by several classes of models beyond the SM, such as supersymmetry, grand-unification, extra-dimensions or models with heavy right-handed neutrinos, for the branching ratio of cLFV decays such as $\mu \rightarrow e\gamma$ in the range of 10^{-11} to 10^{-15} [1-3] cf. Fig. 1. This range is just below one of the most stringent bounds on cLFV processes, obtained by the MEGA experiment [4] BR($\mu \rightarrow e\gamma$) $\leq 1.2 \cdot 10^{-11}$ (90% C.L.). The discovery potential for a more sensitive experiment such as MEG, which is aiming at a sensitivity of \bigcirc (10^{-13}), is then very favourable and even in the event of no signal, would pose stringent constraints on such models, thus validating the complementary method to that of high-energy TeV-scale accelerator searches for "New Physics".

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Fig. 1: Example of a MSSM prediction for the branching ratio of the $\mu \rightarrow e\gamma$ decay, (original plot taken from [2]) as a function of the righthanded selectron mass, for various *tan* β solutions. Also shown are the current MEGA limit and the expected MEG sensitivity.

1.1. $\mu \rightarrow e\gamma Chronology$

Mu --> e + gamma Chronology 1984 1994 2004 2014 1954 1964 1974 1.0E-04 - LAMPF 1.0E-05 early accelarator 1.0E-06measurements Ratio BR - TRIUMF 1.0E-07 ▲ Columbia **Pion Factories** 1.0E-08 - LRL Berkeley Chicago 1.0E-09 -O- MEG Sensitivity * * 1.0E-10 High-intensity muon 1.0E-11 beam era 1.0E-12 MEG Exp Sensitivity end 0 1.0E-13 Chronology Year

The quest for $\mu \rightarrow e\gamma$ dates back more than sixty years to the pioneering efforts of Hinks & Pontecorvo [5], who first searched for a signal in cosmic-ray decays. Many attempts since have still not revealed a signal even

Fig. 2: $\mu \rightarrow e\gamma$ decay search chronology showing three distinct accelerator-based eras of branching ratio results versus time, ranging from the early 50's to the present. Also shown is the expected MEG-sensitivity at around the end of 2012.

though there has been a constant improvement in the limit set by the first stopped pion beam experiments in the early 50's through to the early 60's, see Fig. 2. Two further advancements, seen as steps in the figure, show the increased experimental sensitivities derived from the significantly improved accelerator/beam intensity and quality achieved by the pion factories in the mid-70's and the following dedicated high intensity surface muon beams, as well as improvements to the detector technologies used.

2. Experimental signature and backgrounds

The $\mu \rightarrow e\gamma$ event signature for stopped muon decay comprises of a simple 2-body topology giving a backto-back positron, in the case of a positive muon and a photon, coincident in time and each aquiring half of the muon rest mass, i.e. each having an energy of 52.8 MeV. Positive muons are used since they can be both copiously produced in the form of a surface muon beam, see below, and unlike negative muons, they do not undergo muonicatom formation.

Two main sources of background ultimately limit the sensitivity of the experiment; they are the so-called "prompt" or correlated events stemming from radiative muon decay $\mu^+ \rightarrow e^+ v_e v_\mu \gamma$ (RMD) and "accidental" or "uncorrelated" events: in the second case, an overlap of a Michel decay, $\mu^+ \rightarrow e^+ v_e v_\mu$ with a high-energy photon from another process. The former RMD process has a branching fraction of approximately 1.4% for photon energies above 10 MeV, compared to the almost 100% of the Michel decay. However, the RMD decays become dangerous when the two neutrinos carry-off little energy such that the photon and positron are almost back-to-back, mimicking a $\mu \rightarrow e\gamma$ event signature. The redeeming factor is that the photon spectrum falls steeply at the end-point, close to the "signal" energy and that the rate of such RMD events in the signal region is only linearly proportional to the muon stopping rate R_µ. Conversely, the uncorrelated events consist of a Michel positron in accidental coincidence with an energetic photon from either RMD, positron annihilation-in-flight (AIF) or positron bremsstrahlung. Since both particles originate from the beam, the rate of such accidental events is proportional to the muon stopping rate squared R_µ². It can be shown [6] that in high-rate coincident experiments such as MEG, the accidental background is the dominating factor and that the effective accidental rate R_{acc} is proportional to both R_{μ}^2 and very importantly, to the detector resolutions:

$$R_{acc} \propto (R_{\mu})^2 \cdot \Delta E_e \cdot (\Delta E_{\gamma})^2 \cdot (\Delta \Theta_{e\gamma})^2 \cdot \Delta t_{e\gamma}$$
(1)

From Eq. 1 it becomes evident that the dominating factors limiting the sensitivity are the muon stopping rate and the angular, energy, in particular for the photon, and the timing resolutions of the detectors. Hence, it is of a real advantage to use a high-intensity DC muon because of the lower instantaneous rate and absolutely mandatory to require the highest possible energy, spatial and temporal resolutions for all detectors – thus defining the requirements for the novel solution of the MEG detector.

3. Experimental setup

The MEG experiment is located at the π E5 channel of the 590 MeV proton ring cyclotron facility of the Paul Scherrer Institut PSI in Switzerland. The 1.3 MW, 50 MHz proton beam produces one of the world's most intense surface muon beams, capable of producing more than 10⁸ muons per second. In order to produce an almost "pure" 28 MeV/c muon beam from one with an approximately 8-times higher beam positron contamination exiting the channel, a series of cleaning, focusing, degrading and coupling elements were added in form of the MEG beam line. This allows the beam with a final round spot-size of 11 mm (in σ) to be stopped in a thin 18 mg/cm² slanted CH₂-target, placed at the centre of the detector. For an optimal experimental sensitivity, matched to the detector resolutions, a beam rate of $3 \cdot 10^7$ muons per second is chosen.

Fig. 3 shows the MEG beam line as well as the detector and its main components, which cover a solid angle of about 10%: a detailed description is given in [7]. A Wien-filter and collimator system are used to rid the beam of its beam-related background, while a superconducting transport solenoid (BTS) and associated degrader system are used to stop the beam at the centre of the He-filled COBRA superconducting positron spectrometer.



Fig. 3: Schematic of the MEG experiment, showing the beam line with its Wien-filter, collimator system and BTS superconducting transport solenoid and central degrader system. This couples to the He-filled COBRA superconducting spectrometer, consisting of a gradient-field magnet and central target system, as well as a set of radial drift chambers (DC) for tracking purposes and two sets of fast scintillation counter arrays for timing and trigger purposes (TC). The 900 l "C-shaped" liquid xenon (LXe) photon detector is also shown and the downstream insertion system allowing the remote insertion of our Cockcroft-Walton beam pipe, for calibration purposes.

The positron kinematics and topology are reconstructed by means of a set central, radially placed drift chambers (DCs) while a set of scintillation counter arrays (TCs) located at either end of the magnet, are used to determine the positron timing as well as being used for trigger purposes. By use of a gradient magnetic field in the spectrometer, ranging from (1.27–0.5)T, a novel feature can be exploited, which gives the spectrometer its name COBRA (COnstant-Bending-RAdius). This allows, on the one hand, tracks emitted with the same momentum to have an almost constant projected bending radius, independent of emission angle at the target– so allowing a preferentially high momentum window to be set on the positrons. On the other hand, tracks are swept out of the fiducial volume more quickly than in a constant field solenoid, an important feature for a high-rate environment.

On the photon-side a 900 litre liquid xenon photon detector (LXe), exploiting the scintillation light produced by showering photons, is used to reconstruct the shower origin by means of 846 photomultipliers (PMTs) immersed in the liquid medium. The use of such a high density, homogeneous medium with no segmentation allows an excellent energy, spatial and temporal resolution for the detector to be achieved. However, particular care must be taken concerning the elimination of contaminants from the xenon, particularly water, oxygen and nitrogen, at the sub-ppm level. For this a sophisticated purification system is employed for both liquid and gaseous phases.

Moreover, achieving the planned sensitivity and proposed resolutions is one key aspect but monitoring and calibrating the detector and maintaining its optimal properties over long run periods is another. In order to achieve this goal MEG has implemented an arsenal of calibration and monitoring tools ranging from LEDs and α -sources, the latter, mounted on strings, strung inside the LXe detector's fiducial volume, for daily calibration of the PMTs, to various gamma-ray sources to measure the LXe detector's energy-scale and resolutions. The monoenergetic sources range from 4.4 MeV using an Am/Be neutron source to 55, 83 and 129 MeV from pion charge-exchange and radiative capture reactions on liquid hydrogen, the latter measurements being taken once per run period. Supplementary measurements using our dedicated Cockcroft-Walton (C-W) proton accelerator together with a mixed lithium and boron target allows gamma-rays of 17.6 MeV via Li(p, γ)Be and coincident gamma-rays of 4.4 and 11.6 MeV from B(p,2 γ)C as well as 16.1 MeV from B(p, γ)C to be taken on a weekly basis. The coincident

measurements and also RMD measurements taken during normal muon data-taking serve to intercalibrate the timing of the LXe and positron arms of the detector.

Finally, another novel and important aspect of the experiment is the fact that all approximately 3000 detector channels are digitized via two parallel arms. The one a multi-GHz custom built system (DRS), operating at 1.6 GHz for the PMTs and 0.8 GHz for the DC-signals, enabling the full resolution and pile-up rejection capabilities to be exploited – extremely important for high-rate environments. The other arm, belonging to the trigger system, is a 100 MHz FADC based system utilizing mainly the fast PMT signals from the TCs and LXe detector to kinematic ally select candidate muon-decay events with approximate signal photon energy in the calorimeter and a coincident positron event in the TCs with a rough collinear topology. The system allows a pre-scaled, multi-trigger event structure, with up to 29 event types, 12 of which form a MEG-event, reducing the instantaneous event rate of ~ $3 \cdot 10^7$ Hz to a data acquisition rate (DAQ) of ~ 6.5 Hz, currently with a live time of 84%.

4. 2009 Run and performance

Following an initial physics run in 2008, in which the DC-system encountered HV-stability problems which severely influenced the spectrometer performance and in which the expected light-yield in the calorimeter was lower than expected, 2009 saw both of these problems solved during the yearly accelerator shutdown period and the π E5 beam time allocation to another experiment. With a set of fully efficient chambers and after a period of LXe purification, resulting in an ~ 45% increased light-yield in the calorimeter, as well as a pion CEX calibration run, a stable physics data-taking period of 43 days during November and December was achieved with a total of 22 million triggers accumulated, corresponding to $6.5 \cdot 10^{13}$ muon decays.

The detector performance for the 2009 run was mainly assessed using data from the pion CEX run, calibration data from the C-W accelerator as well as RMD and Michel positron data. The five important parameters for measurement and which fully define the kinematics of a $\mu \rightarrow e\gamma$ decay are: the positron and photon energies (E_e and E_{γ}), their relative time ($t_{e\gamma}$) and their relative polar and azimuthal directions ($\theta_{e\gamma}, \phi_{e\gamma}$) with the positron direction "flipped" with respect to the photon.

For the positron spectrometer arm a technique of "double-turn" tracks was predominantly used to determine the resolutions, this involves treating the two segments or turns of the same track as independent tracks and comparing their differences at a common point of closest approach to the beam-axis. The positron energy resolution so obtained can be well described by a double Gaussian function with a core resolution of 390 keV comprising of 79% of events, while the remaining 21% belongs to a tail component with a resolution of 1170 keV. An independent check was made by fitting the kinematic edge of the Michel spectrum, shown in Fig. 4c, the absolute energy-scale of E_e is also derived from this fit. Furthermore, the positron angular resolutions determined as, $\sigma \theta_e = 11.2$ mrad and $\sigma \phi_e = 7.1$ mrad and the vertex position resolutions of 2.3 mm transverse to the beam direction and 2,8 mm along the beam were also evaluated via the "double-turn" method. A cross-check of the vertex resolution was made by looking at the reconstructed edges of a set of holes placed in the target for this purpose.

On the photon-side, the E_{γ} response function and energy-scale, as well as the resolutions are determined by measured spectra taken during the CEX calibration run (c.f Figs. 4a,b) and checked for consistency by comparing with a Monte-Carlo (MC) generated spectrum, folded with the measured response functions and fitted to measured accidental photon spectra in so-called "side-band" data (see below). The energy resolution achieved, averaged from a 3-D resolution map over the calorimeter, was $\sigma E_{\gamma} = 2.1\%$ for depths greater than 2 cm, 2.8% for depths between 1 cm and 2 cm and 3.3% for depths less than 1 cm. The photon position resolutions were determined by MC simulation to be 5 mm transverse to the impacting photon direction and 6 mm along the depth direction. These were checked by independent measurements, using a series of lead collimators placed in front of the calorimeter.



Figs 4 (a –d): Photon and positron signal and background distributions used to determine the energy-scale and resolution for the two arms of the detector and the combined timing resolution a) Shows the E_{γ} photon response function, as measured during the pion CEX run. b) Accidental photon background spectrum measured outside the signal region (side-bands). c) The measured Michel spectrum (crosses) together with a fit (red line) including the convolution of the response function (blue dotted line). d) Measured relative timing distribution, showing the radiative decay (RMD) peak on top of a flat accidental background, the data were taken as part of the mixed MEG-trigger at full rate

The combined detector resolutions are obtained by combining the relative quantities. In the case of the two angles, they are obtained from the positron angular resolutions, the vertex resolution and the photon positional resolution and give $\theta_{e\gamma} = 14.7$ mrad and $\phi_{e\gamma} = 12.7$ mrad. The relative timing resolution between the positron and photon is obtained from a fit to the measured RMD timing spectrum, measured in the E_{γ} side-band (40 MeV $\leq E_{\gamma} \leq 45$ MeV), and then extrapolating to the signal energy from measured CEX-data, which results in $t_{e\gamma} = 142$ ps as shown in Fig.4d.

4.1. Normalization

In order to convert the number of "signal events" N_{Sig} into a branching ratio, a normalization factor which takes the total number of muon decay into account must be formulated. Since the Michel decay accounts for almost 100% of muon decays, it is used for normalization purposes in the experiment. The corresponding number of Michel decays is found by selecting events from the highly pre-scaled Michel trigger, part of the multi-trigger MEG-event structure, and imposing the same cuts as on MEG candidate events. Various corrections are made for the difference between Michel and signal event efficiencies and acceptances, as shown below:

$$\frac{BR(\mu \to e\gamma)}{BR(\mu \to ev\bar{\nu})} = \frac{N_{Sig}}{k} \equiv \frac{N_{Sig}}{N_{Michel}} \cdot \frac{f_{Michel}^E}{P_{Michel}} \cdot \varepsilon_{trig} \cdot \varepsilon_{rec} \cdot \frac{1}{\varepsilon_{\gamma}} \cdot \frac{1}{A_{\gamma}} = N_{Sig} \cdot (1.0 \pm 0.1) \cdot 10^{-12}$$

In total $N_{Michel} = 18096$ events were found in the 2009 data-set. The other main factors were $f^{E}_{Michel} = 0.114$, the accepted fraction of the Michel spectrum, the pre-scale factor $P_{Michel} = 1.2 \cdot 10^7$ and the conditional photon detection

efficiency $\varepsilon_{\gamma} = 0.58$. The remaining Michel to signal ratios for trigger and reconstruction efficiency as well as the conditional photon geometrical acceptance have values close to unity.

5. 2009 Analysis

The analysis principle is based on a "blind" maximum likelihood approach, with the data sample selected using the previously mentioned five observables (E_e , E_{γ} , $t_{e\gamma}$, $\theta_{e\gamma}$, $\phi_{e\gamma}$). The full analysis region is comprised of the "analysis-box" or signal region, approximately a 10-sigma region around the central values of the five observables, and three "side-band" regions. The latter are a lower energy region the " E_{γ} side-band" used to study the RMD timing peak and RMD-background contribution to the signal region and the "left" and "right" side-bands used to study the accidental background around the signal energy in the analysis-box region.



Fig. 5: Analysis region shown in the $(E_{\gamma} - t_{e\gamma})$ -plane, showing the analysis-box or signal region in the plane of these two observables, which is initially "blinded" until all analysis algorithms have been optimized. Also shown are the three side-band regions used to study the accidental background.

This approach is valid since our background is dominated by accidentals which are also expected to be present in the signal region. Events falling in the $(E_{\gamma}-t_{e\gamma})$ -plane of the signal region are initially hidden or "blinded" until all cuts and background optimization algorithms applied to the side-band data are optimized. A schematic of the different regions is shown in Fig. 5. The analysis-box region is defined as: 48 MeV $\leq E_{\gamma} \leq$ 58 MeV, 50 MeV $\leq E_e \leq$ 56 MeV, $|t_e| \leq 0.7$ ns and $|\theta_e| \leq 50$ mrad.

A maximum likelihood fit is made to the data sample in order to determine the best values for the number of signal, RMD and background events, N_{Sig} , N_{RMD} , N_{BG} respectively. The fit is made over an extended region, so as to better constrain the background. The extended likelihood function is defined as:

$$\mathcal{L}(N_{Sig}, N_{RMD}, N_{BG}) = \frac{N^{N_{obs}} \cdot e^{-N_{exp}}}{N_{obs}!} \prod_{i=1}^{N_{obs}} \left[\frac{N_{Sig}}{N_{exp}} \cdot S(\vec{x}_i) + \frac{N_{RMD}}{N_{exp}} \cdot R(\vec{x}_i) + \frac{N_{BG}}{N_{exp}} \cdot B(\vec{x}_i) \right]$$

where $x_i = (E_e, E_{\gamma}, t_{e\gamma}, \theta_{e\gamma}, \phi_{e\gamma})$ is the vector of observables for the ith-event. The probability density functions (PDFs) corresponding to the respective event categories are $S(x_i)$, $R(x_i)$ and $B(x_i)$. The total number of expected events is given by $N_{exp} = N_{Sig} + N_{RMD} + N_{BG}$ while N_{obs} equals the total number of observed events in the analysisbox. The signal PDF $S(x_i)$ is the product of the measured detector response functions corresponding to the five observables defined by x. The PDF for the RMD $R(x_i)$, is the product of the same $t_{e\gamma}$ resolution function as used for the signal PDF, together with the four remaining, but correlated, observables response functions obtained by

convoluting the theoretical RMD-spectrum with the respective measured response functions. Finally, $B(x_i)$ the background PDF is the product of the response functions of the five observables obtained from the measured background spectra in the side-bands. The position dependence of the LXE detectors response, as well as positron tracking quality, were taken into account by using event-by-event PDFs.

5.1. Experimental sensitivity & fit results

The background spectra of the large data sample in the side-bands are initially studied prior to opening the blinding-box in order to estimate the background level in the signal region. The sensitivity of the experiment under a "null" signal hypothesis i.e. $N_{Sig}=0$ and N_{RMD} , N_{BG} both equal to their expected values, is evaluated by means of a toy MC simulation used to generate the outcome of many such experiments, according to the measured PDFs and by fitting each outcome to determine the 90% C.L. upper limit. The mean of this distribution together with the previously mentioned normalization factor then gives the branching ratio upper limit at 90% C.L as $6.1 \cdot 10^{-12}$. This value is in good agreement with the values obtained from the $t_{e\gamma}$ "right" and "left side-bands which give a 90% C.L. upper limit of $(4-6) \cdot 10^{-12}$.



Figs. 6a,b: Event distribution in the signal region shown for a) $(E_{\gamma} - E_e)$ -plane and b) $(t_{e\gamma} - \Theta_{e\gamma})$ -plane. For each region, cuts were applied to the other two observables which gave a 90% selection efficiency. Also shown are the 1-, 1.64- and 2σ signal PDF contours, as well as the event ranking according to their relative signal likelihood (see text).

Finally the analysis-box was "unblinded" revealing the event distributions shown in Figs. 6 a, b, which show the signal region projected onto the $(E_{\gamma} - E_e)$ - and $(t_{e\gamma} - \Theta_{e\gamma})$ -planes, where $\Theta_{e\gamma}$ corresponds to the opening angle between the photon and positron. Events located close to the signal region were checked for any strange behavior concerning detector, beam or hit-map response, no irregular behaviour was found. Also shown in the figures are the contours of the signal PDFs for 1-, 1.64- and 2σ as well as the events numbered according to their relative signal likelihood, defined as (S/R+B).

The maximum likelihood fit to the 370 events observed in the analysis-box region (shown in Fig. 7), yielded a best-fit value of $N_{Sig} = 3.0$ events and $N_{RMD} = 35 \pm_{22}^{24}$ the number of RMD-events is consistent with the expectation of (32±2), calculated by scaling the observed number of events in the E_{γ} side-band. One also expects on average, one to two background events to fall within the signal region. The 90% confidence intervals for N_{Sig} are constructed by means of a toy MC simulation using the likelihood ratio ordering principle [8]. The systematic uncertainties and the normalization factor are taken into account by allowing the likelihood functions to fluctuate

according to their uncertainties. The resultant 90% C.L. upper limit on the number of signal events is $N_{Sig} = 14.5$, with $N_{Sig} = 0$ still within the confidence interval. This translates into an upper limit on the branching ratio of:

$$\frac{BR(\mu \to e^+ \gamma)}{BR(\mu \to e^+ \nu \overline{\nu})} \le 1.5 \cdot 10^{-11} \text{ at } 90\% \text{ C.L}$$



Fig. 7: shows the Likelihood fit results for the 370 observed events in the analysis-box. The solid and dashed lines show respectively the best fit event distributions, projected onto each observable and the upper limit of the number of signal events at 90% C.L. The green (lower), red, magenta and blue (upper) curves correspond to signal, RMD, accidental background and the sum distributions respectively.

Three independent analyses using different statistical approaches, PDF parameterizations and background treatment, gave consistent results.

6. Conclusion

A blind likelihood analysis performed on our 2009 data-set, accumulated over a 43 day period of data-taking and comprising of 22 million trigger originating from some $6.5 \cdot 10^{13}$ muon decays, yielded a preliminary sensitivity on the branching ratio of $6.1 \cdot 10^{-12}$. This is a factor of two better than the current limit. Our preliminary upper limit on the branching ratio for the decay ($\mu \rightarrow e \gamma$), normalized the Michel decay is BR($\mu^+ \rightarrow e^+ \gamma$) $\leq 1.5 \cdot 10^{-11}$ at 90% confidence level. The null event hypothesis $N_{Sig} = 0$ is still within the 90% C.L. interval, though the probability of our best fit value corresponding to the null hypothesis is of the order of 3%. The consistency of the results was cross-checked by three independent analyses, using different statistical approaches as well as different forms of parameterizing the PDFs and different ways of treating the background.

MEG is expected to continue to accumulate statistics at least until the end of 2012, with further improvements

to both the hardware and the analysis techniques of the experiment planned, such that the sensitivity goal of \bigcirc (10⁻¹³) can be achieved.

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