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STATUS AND PERSPECTIVES IN $\mu \to e\gamma$ DECAY SEARCH

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ABSTRACT

The $\mu \to e\gamma$ decay, as well as other related Lepton Flavour Violation processes, is foreseen by a wide class of Supersymmetric Grand-Unified theories, with a branching ratio ranging between 10^{-14} and 10^{-12}. So it is considered as one of the most sensitive probe for the existence of Physics beyond the Standard Model. Past and present experiments will be rewied on the light of current theoretical models. Particular emphasis will be laid on the MEG experiment, to be operated at PSI, which will be able to improve the current sensitivity (10^{-11}) by two orders of magnitude so as to address the range of predictions.

1 Physics motivation

$\mu \to e\gamma$ decay, like other Lepton Flavour Violation (LFV) processes, is considered as one of the most interesting probe of Physics beyond the Standard

Model (SM). In the SM, Lepton Flavour is conserved as long as neutrino fields are massless. Also, LFV is allowed in extensions of the SM to include massive Dirac neutrinos, so as to give rise to neutrino oscillations, but the resulting branching ratios are so tiny ($10^{-45} \div 10^{-50}$) to be ever observed.

On the other hand, LFV is predicted with much higher branching ratios by a wide class of Grand-Unified, Supersymmetric theories (often referred to as Gravitation-mediated SUSY), as a result of a finite mixing in the slepton sector. LFV mainly arises through radiative corrections due the heavy top quark mass [1)] and these predictions depend on the symmetry group and on the parameters of the theory. However, according to evaluations based on minimal SUSY SU(5), $\mu \rightarrow e\gamma$ decay should occur, apart from accidental cancellations, with a branching ratio (BR) above 10^{-14}, as shown in Fig. 1[1].

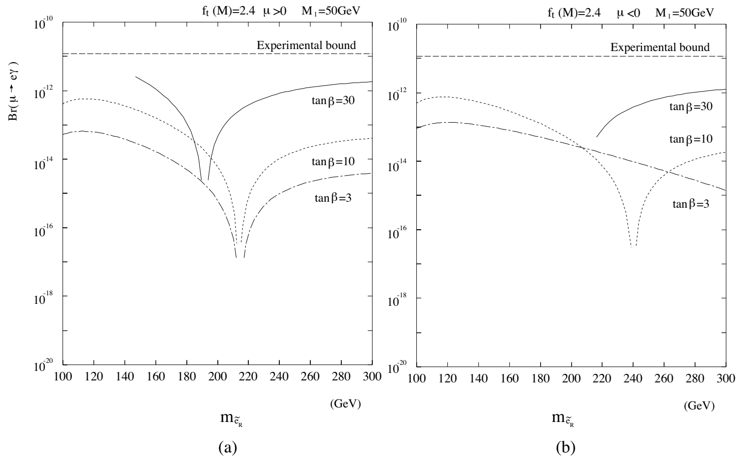

Figure 1: *Predictions for BR($\mu \rightarrow e\gamma$) in the minimal SU(5) SUSY model* [1)]. *Also shown is the current experimental limit set by the MEGA experiment* [2)]. *Values of* $\tan\beta < 3$ *have been recently excluded at 95% C.L. by recent analyses of LEP data* [3)].

It has been pointed out that an additional contribution to LFV is associated with neutrino oscillations via the see-saw mechanism induced by heavy

[1]Even larger rates are predicted by theories based on symmetry groups other than SU(5); in SO(10), for instance, BR($\mu \rightarrow e\gamma$) is enhanced by two orders of magnitude about, induced by loop diagrams whose amplitude is proportional to the τ mass.

right-handed Majorana neutrinos, which is invoked to explain the extremely small neutrino masses [4]. A possible contribution to the slepton mixing between $\widetilde{\mu}$ and $\widetilde{e}$ comes from V_{21}, the neutrino mixing matrix element to account for solar neutrino deficit. With this mixing parameter confined to the MSW large mixing angle (LMA) solution and right-handed neutrino mass scale above 10^{12} GeV, the BR for $\mu \to e\gamma$ is predicted to be larger than 10^{-13}.

2 Experimental status

2.1 Event signature and background

The signature of $\mu^+ \to e^+\gamma$ at rest is a coincidence of a e^+ and a γ, moving back-to-back and both with energy equal to 52.8 MeV, *i.e.* half the mass of muon. Past searches were carried out by using μ^+-decay at rest to benefit from the simple kinematics of two-body decays. Nuclear capture on materials prevents from using negative muons.

This signature can be mimicked by radiative muon decays, $\mu^+ \to e^+\gamma\nu_e\overline{\nu}_\mu$, with e^+ and γ emitted back-to-back and the two neutrinos sharing almost no energy ("correlated" background), or by accidental coincidences of a e^+ from "normal" Michel decays and a high-energy γ due to positron interaction (annihilation or brehmsstrahlung) with surrounding materials ("accidental" background). The background rate crucially depends on detector performances; in particular, the accidental component, which is the most dangerous, approximately depends on the detector resolution on positron and photon energy, on the relative timing and on the angle between them according to the expression

$$\delta E_e \cdot (\delta E_\gamma)^2 \cdot \delta t_{e\gamma} \cdot (\delta\theta_{e\gamma})^2 \tag{1}$$

2.2 The first attempt

Searches for $\mu \to e\gamma$ have a long history reaching back 1947, when a first attempt was operated by Pontecorvo without a muon beam available yet [5]. So he was forced to use cosmic rays as a muon source, lead blocks as muon moderator and γ-converter at the same time, and Geiger-Muller counters to detect both γ and e tracks. The number of events collected turned out to be compatible with the background; the resulting upper limit ($BR < 10\%$) was too loose if compared with more recent searches, but it used to be low enough to safely exclude $\mu \to e\gamma$ as the dominant branch in muon decay[2].

2.3 Last results

During the last 25 years, the sensitivity to was raised by two order of magnitudes about. This was possible thanks to improved detection resolution of the four variables appearing on the right side of Eq.1. In tab.1, the 90% C.L. upper limits of $\mu^+ \to e^+\gamma$ decay in past experiments are listed along with their detector performances.

Table 1: *Progress of $\mu \to e\gamma$ search during the era of meson factories. The upper limits are at 90% C.L., while the resolution is quoted as full width at half maximum (FWHM).*

Place	Year	$\Delta E_e/E_e$	$\Delta E_\gamma/E_\gamma$	$\Delta t_{e\gamma}$	$\Delta\theta_{e\gamma}$	Upper limit
TRIUMF 7)	1977	10%	8.7%	6.7 ns	—	$< 3.6 \times 10^{-9}$
SIN 8)	1980	8.7%	9.3%	1.4 ns	—	$< 1.0 \times 10^{-9}$
LANL 9)	1982	8.8%	8%	1.9 ns	37 mrad	$< 1.7 \times 10^{-10}$
LANL 10)	1988	8%	8%	1.8 ns	87 mrad	$< 4.9 \times 10^{-11}$
LANL 2)	1999	1.2%	4.5%	1.6 ns	17 mrad	$< 1.2 \times 10^{-11}$
MEG	2005	0.8%	4%	0.15 ns	19 mrad	10^{-13}

3 The future: the MEG experiment

The MEG experiment will be conducted at PSI, where the most intense DC muon beam in the world is currently available, by a joint italian-japanese-russian-swiss collaboration 11). This search for $\mu^+ \to e^+\gamma$ aims at reaching a sensitivity of 5×10^{-14}, an improvement of about to orders of magnitude with respect to the current limit set by the MEGA experiment 2). This is possible thanks to unprecedented detector performances at these energies (see last row in tab.1); in particular, the resolution on photon energy and direction plays a key role in background suppression (see eq.1) and requires research and

[2]Just one year after, Steinberger 6) measured the continuous electron spectrum, which lead to formulate the hypothesis of two neutrinos in the final state.

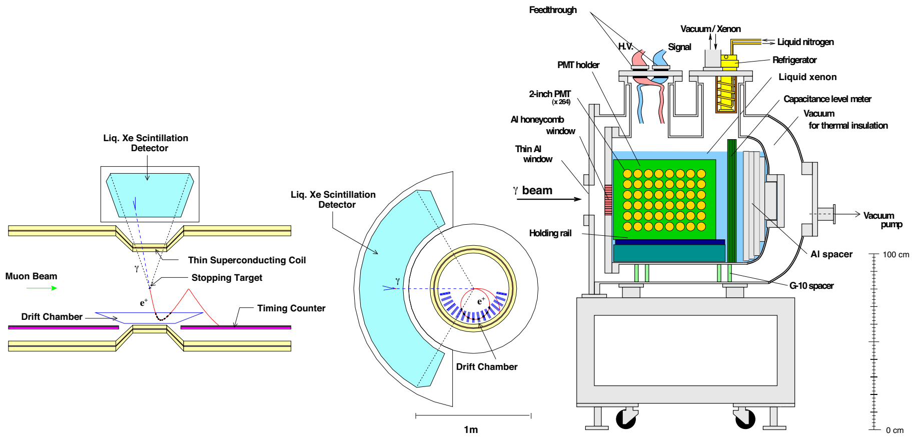

Figure 2: *Left: the MEG detector layout (front and side views). Right: the liquid Xenon calorimeter prototype.*

development of a new challenging detection technique, based on liquid Xenon calorimetry.

3.1 Detector layout

The detector set-up is shown in fig.2. The design obeys the need of minimizing the amount of material being traversed by the positron and the photon, so as to reduce their interaction with matter which might deteriorate both resolution and detection efficiencies.

Beam and target

The beam mainly consists of 28 MeV muons ("surface" muons) coming from decays at rest of charged pions produced by 590 MeV protons colliding on a Be target. The beam can reach an intensity up to $10^{-8}\mu^{+}\ \mathrm{s}^{-1}$ and is focussed on a $\sim 5mm$-wide spot and stopped on 150 μm-thick polyethilene target. The positron contamination of the beam is of the order of 1% about.

The spectrometer

Positrons are detected by a spectrometer, combining position measurements of 17 drift chambers (DC) and timing information provided by scintillation timing counters (TC). The magnet of the spectrometer (named COBRA, from COnstant Bending RAdius) provides a quasi-solenoidal field, with a gradient in the target region such that the bending radius is almost independent of the emission angle over a wide angular range. That gradient is also needed to sweep out high-$p_\perp$ positrons, which else might turn and hit the DCs many times, thereby increasing their occupancy.

The positron momentum resolution is 0.8% FWHM, provided that DC hits are reconstructed with a precision of 200 μm for the radial coordinate and 300 μm for the axial one. The timing resolution of TCs is $\sim$ 100 ps.

The Liquid Xenon calorimeter

A 800 l liquid Xenon calorimeter (LXe) is used to detect photons and provide precise energy, direction and timing information. The main properties of liquid Xenon are listed in tab.2. LXe has a high light yield (comparable to

Table 2: *Properties of liquid Xenon.*

Density	2.95 g/cm^3
Energy deposition per scintillation photon	24 eV
Radiation length	2.77 cm
Decay-time	4.2 ns, 22 ns, 45 ns
Peak emission wavelength	175 nm
Scintillation absorption length	$>$ 100 cm
Attenuation length (Rayleigh scattering)	$\sim$ 40 cm
Refractive index	1.56

a NaI) and a fast decay time (one order of magnitude shorter than inorganic crystals), which are necessary ingredients for energy and timing resolution as tiny as required for this experiment. Moreover, LXe is transparent to its own scintillation light, which makes detector response more homogeneous than in scintillating crystals. However, the optical properties might be affected by contaminants, mostly water, able to absorb UV light in the Xe emission band. Therefore, the liquid Xenon batch needs to be purified by circulation through molecular sieves and water content must be continuously monitored during detector operation. The scintillation is collected by about 800 photomultipliers (PMT coverage $\sim$ 35%), whose output provides a detailed image of the scintillation light needed to reconstruct the vertex of photon interaction as well as to identify pile-up γ-rays.

Trigger and electronics

The trigger scheme utilizes the fast signals provided by LXe and TC. These are sampled by 100 Mhz FADC and processed by FPGAs to obtain a fast event reconstruction. The expected acquisition rate is expected to be $\sim 20\ \mathrm{s}^{-1}$ for a nominal muon stop rate of $10^{-8}\ \mathrm{s}^{-1}$. Every photomultiplier in both LXe and TC and each DC cell is readout by a fast (2 Ghz sampling speed) waveform digitizer based on a custom-made chip (DOMINO), which is needed to achieve excellent timing, energy and position resolutions.

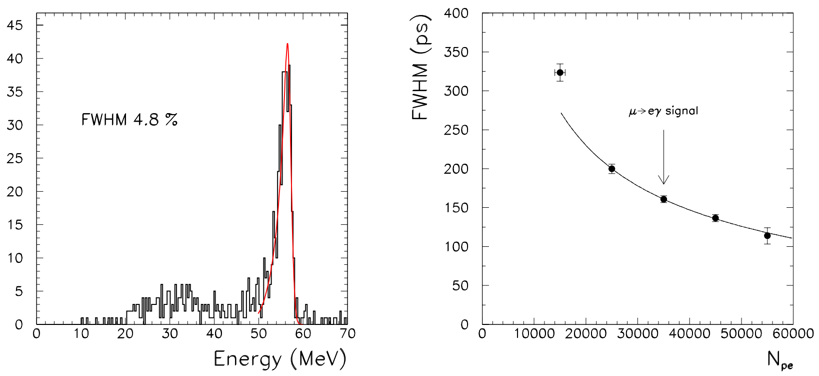

Figure 3: *Performance of LXe. Left: energy resolution for 55 MeV γ from π^0-decay. Right: intrinsic timing resolution as a function of the number of collected photoelectrons. The arrow in the plot points towards the bin corresponding to the 52.8 MeV energy window.*

3.2 The e.m. calorimeter prototype

R&D work on the photon detector has been accomplished by using a 100 l prototype, deep enough ($\sim 18X_0$) to fully contain the photon e.m. shower (see fig.2). It was first used for PMT calibration and to study the main optical properties of LXe. More recently (fall 2003) it was exposed to a 55 MeV γs, from decays of π^0 from charge exchange reaction ($\pi^- \mathrm{p} \to \pi^0 \mathrm{n}$) on a liquid Hydrogen target, to test the detector behaviour under conditions similar to

$\mu \to e\gamma$ decay. The photon tagging was performed by using a NaI detector on the opposite side with respect to the π^- target.

The results obtained for energy and timing resolution are shown in fig.3. The energy distribution was obtained by applying simple topological cuts (distance from the photon spot centre < 1.5 cm and depth > 3 cm) to exclude photons interacting respectively with the sidewalls of a Lead collimator and with the front wall of the LXe prototype. The resolution turned out to 4.8% FWHM, dominated by escape effects on the low-energy tail (the right edge, which does not depend on these effects, is 1.8% wide), which is close to the experimental goal. The timing resolution was studied as a function of the energy deposit in the calorimeter and found to improve with photostatistics, as expected. The value obtained for 55 MeV photons is 160 ps, which is still higher than needed. However, the use of PMTs with higher quantum efficiency (from current 5% to 20%) will improve the timing resolution by a factor two, so as to match the experimental goal.

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