THE LIQUID XENON SCINTILLATION CALORIMETER OF THE MEG EXPERIMENT: OPERATION OF A LARGE PROTOTYPE

GIOVANNI SIGNORELLI*

Istituto Nazionale di Fisica Nucleare sezione di Pisa,
Via Filippo Buonarroti, 2
56127 Pisa, Italy.
E-mail: Giovanni.Signorelli@pi.infn.it

The MEG experiment at PSI will search for the $\mu \to e\gamma$ decay well below the present experimental limit ($BR < 1.2 \times 10^{-11}$). The detection of the 52.8 MeV photon in the experiment will be done by an innovative liquid Xenon calorimeter in which only the information provided by the scintillation light is used for the photon energy and position reconstruction. The major issues concerning this calorimeter, such as transparency to scintillation light and PMT behaviour at low temperature, will be reviewed. The calorimeter has been extensively tested with various particles: α-sources, cosmic ray muons and electrons. Recently a test with high energy photons from π^0 decays has been carried out at PSI: the calorimeter response to photons in an energy range very close to the final experimental conditions will be presented.

1. The MEG experiment at PSI

1.1. *Motivation*

The $\mu \to e\gamma$ decay is forbidden in the Standard Model (SM) because the vanishing of the neutrino masses imply the conservation of the Lepton Flavour. Even if the present neutrino masses and mixings are considered, the probability of this transition is negligible (BR $\sim 10^{-55}$). On the other hand all SM extensions enhance the rate through mixings in the high energy sector of the theory. Present predictions of various super-symmetric grand-unified theories are in the range $10^{-14} \div 10^{-11}$ for the branching ratio,[1] while the present experimental limit is set to $BR(\mu \to e\gamma) < 1.2 \times 10^{-11}$ by the MEGA experiment.[2]

*On behalf of the MEG collaboration

The signature of a $\mu \to e\gamma$ event is the occurrence of a space and time coincident positron-photon pair, carrying half of the muon mass of energy, each. The main background is given by the accidental coincidence of a positron from the normal muon decay with a high energy photon coming from radiative muon decay, or from positron brehmsstraalung or annihilation-in-flight.

Given the experimental resolutions on the measurement of the positron energy ΔE_e, of the photon energy ΔE_γ, on their relative timing and angle ($\Delta t_{e\gamma}$ and $\Delta\theta_{e\gamma}$ respectively) and the muon stopping rate R_μ the probability of misidentifying an accidental coincidence as a signal evidence is proportional to

$$BR_{\mathrm{Acc}} \propto R_\mu \Delta E_e \Delta E_\gamma^2 \Delta\theta_{e\gamma}^2 \Delta t_{e\gamma}. \qquad (1)$$

It is apparent from Equation (1) that superior energy, position and timing resolutions on both the electron and photon sides are essential in setting stringent limits for this decay.

The MEG experiment at PSI, proposed by an Italian-Japanese-Swiss-Russian collaboration, aims at reaching a sensitivity on $BR(\mu \to e\gamma)$ at a level of $10^{-13} \div 10^{-14}$,[3] by using a novel liquid xenon scintillation calorimeter to measure the photon four-momentum.

1.2. ***Set-up and Subdetectors***

In the MEG setup, muons from the presently highest intensity muon beam, the $\pi E5$ beam line at PSI, are stopped in a thin target (see Figure 1). Positrons are measured by 17 radial drift chambers and are quickly swept away, by an inhomogeneous magnetic field, towards a plastic scintillator timing counter. Photons cross the thin superconducting solenoid and reach the liquid xenon scintillation calorimeter where their energy, momentum and timing is measured.

2. The Liquid Xenon Calorimeter

The MEG photon detector is a 0.8 m^3 C-shaped volume of liquid xenon viewed by all sides by more than 800 UV-sensitive photo-multiplier tubes (PMTs) and kept liquid (T = 165 K) by a pulse-tube refrigerator. The internal and external radii of the active volume are 65 cm and 112 cm respectively, for a 17 X_0 thickness, and the angular extension is $\pm 60^\circ$ in ϕ and $|\cos\theta| < 0.35$ if the beam axis is taken to be the z-axis.

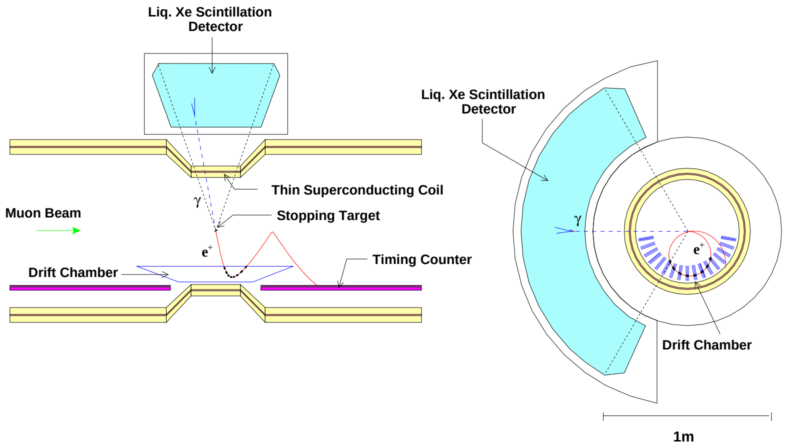


Figure 1. The set-up of the MEG experiment. The C-shaped liquid xenon scintillation calorimeter is visible on both views.

The scintillation light is read by 2" PMTs, specially developed by HAMAMATSU, immersed in the liquid. The PMTs have a fused silica window to match the spectral distribution of Xe scintillation light.

2.1. *Properties of Xe as a scintillation medium*

When charged particles traverse liquid xenon, they can ionize or excite Xe atoms. In either case the hit atom couples with another Xe atom to form an excimer, a Xe_2 molecule existing only in an electronic excited state, which eventually de-excites giving rise to a VUV photon ($\lambda_{\mathrm{peak}} =$ 178 nm, $\Delta\lambda = 14$ nm FWHM). The pairing and de-excitation mechanisms are different (and have different characteristic times) for ionized or excited atoms, and the ratio of excited to ionized atoms is different for different particles (*e.g.* electrons or α particles). This allows for particle ID from pulse shape discrimination. Liquid xenon light yield is comparable to that of NaI ($\sim$ 40000 phe/MeV) but with much shorter decay time (4 ns, 20 ns and 45 ns decay components) making it suitable in high-rate experiments.

2.2. *Calorimeter expected performances*

The calorimeter performances were estimated via Monte Carlo simulation and are presently being benchmarked using a large volume prototype (called "large prototype"). The most important parameter, the energy resolution at 52.8 MeV, depends heavily on Xe transparency, and is expected to be better than 4% for absorption lengths larger than one meter. A preliminary result on the energy resolution, obtained for the large prototype during a test at PSI using photons from π^0 decays, will be presented in the following.

2.3. *Test of the Large Prototype*

The large prototype is shaped as a portion of the full C-shaped calorimeter. It is a $40 \times 40 \times 50$ cm^3 active volume of liquid xenon viewed by 228 PMTs (Hamamatsu R6041Q). The PMTs are independently powered and set at a gain of 10^6. Four α-sources and eight blue LEDs are placed on the lateral faces to measure the PMTs quantum efficiencies and gain. The PMT gain is continuously monitored, and its uncertainty is at the percent level. The α-sources are also used to monitor the transparency of xenon. We developed a method to evaluate the xenon absorption length $\lambda_{\rm abs}$ which, although expected to be very large because of the lack of Xe self-absorption, can be heavily reduced if impurities such as water or oxygen are dissolved in the xenon even at a ppm level:[3] for each PMT we compare the ratio of the observed-to-expected α-source light taking into account the scintillation light propagation inside xenon. In this way a combined fit of the distribution gives a simultaneous determination of Xe scintillation light yield and absorption length. In figure 2 typical distributions and confidence region

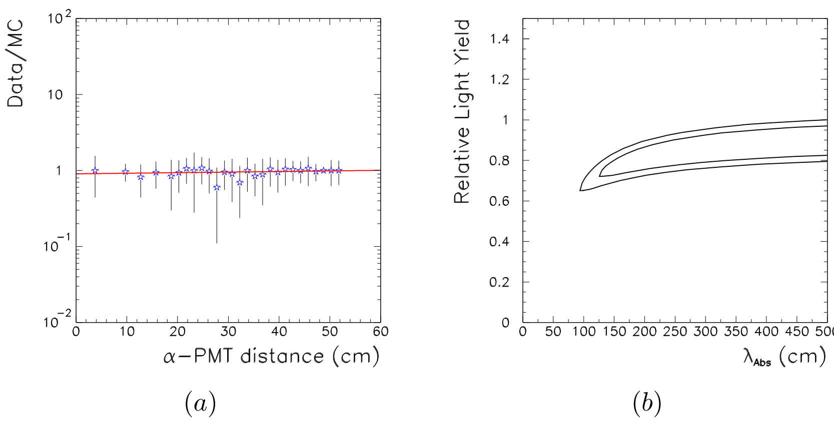
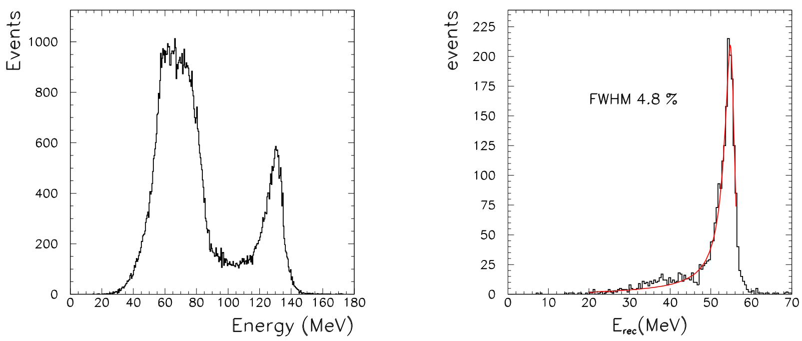


Figure 2. (*a*) A typical distribution used to evaluate Xe purity (absorption length and light yield) during the large prototype normal operation; (*b*) The confidence regions at 68% and 95% confidence level for $\lambda_{\rm Abs}$ and for the light yield.

for the two parameters are shown after the successful implementation of a circulation and purification system described elsewhere.[4,5] A lower limit of $\lambda_{\rm abs} > 95$ cm at 95% confidence level has been obtained, together with a light yield $LY = 37500^{+4000}_{-10000}$ phe/MeV. The sensitivity on Xe absorption length is limited by the large prototype size.

2.3.1. *Measurements with photons*

A measurement of the large prototype energy resolution has been done using photons from the decay of neutral pions. Negative pions of ~ 110 MeV from the $\pi E1$ beam line at PSI where stopped in a liquid hydrogen target where they underwent radiative capture ($\pi^- p \rightarrow \gamma n$) or charge exchange reaction ($\pi^- p \rightarrow \pi^0 n$). The former process produces monoenergetic 129 MeV photons, while neutral pions from the latter process eventually decay in two photons whith a flat spectrum $54.9 < E_\gamma < 82.9$ MeV. There is a correlation between the two photon energies and their relative angle: photons of the two extremal energies are obtained in a back-to-back configuration were one photon goes in the direction of the parent π^0 momentum and the other is emitted opposite to it.



(*a*) (*b*)

Figure 3. (*a*) Raw spectrum of photons from π^0 decays measured by the large prototype; (*b*) the preliminary 54.9 MeV energy peak fitted with the restrictions explained in the text.

The photon spectrum measured by the liquid xenon calorimeter prototype, placed at 115 cm from the target, at 90° with respect to the incoming beam, is shown in figure 3*a*. A large array of 64 NaI crystals was placed on the other side of the liquid hydrogen target, at a distance of 115 cm and at 180° with respect to the “large prototype”. In this way back-to-back photons could be selected and the correlation between the energy of the photon measured in the liquid xenon detector and the energy of the photon measured in the NaI was exploited to select 54.9 MeV photons in the former. Two lead collimators were placed in front of the two detectors in order to define the two photon energies to better than 1%.

A preliminary analysis in which only deep events were considered, *i.e.* events in which the photon is reconstructed to have converted at least 2 cm after entering the xenon calorimeter active volume, gives the plot shown in figure 3*b*. The FWHM of the distribution is $\sim 4.8\%$, averaged on a 10×10 cm^2 incidence window.

3. Counclusion

A novel 0.8 m^3 liquid xenon scintillation calorimeter detector is being designed for the MEG experiment. A large scale prototype is presently under test in order to finalize this design. Promising measurement of xenon transparency over distance comparable to the calorimeter dimensions have been shown together with preliminary results of an energy resolution measurement in a region very close to that of real operation. The construction is expected to be carried on in 2005, for a data taking period starting in 2006.

References

1. R. Barbieri *et al.*, *Nucl. Phys.* **B445** (1995) 215.
   J. Hisano *et al.*, *Phys. Rev.* **B391** (1997) 341.
   R. Ciafaloni *et al.*, *Nucl. Phys.* **B458** (1996)
2. M. Ahmed *et al.*, [MEGA collaboration] *Phys. Rev.* **D65** (2002) 112002
3. A. Baldini, T. Mori *et al.*, “The MEG experiment: seearch for the $\mu \to e\gamma$ decay at PSI”, available at `http://meg.psi.ch/docs`
4. G. Signorelli, “The MEG experiment at PSI: status and prospects,” J. Phys. G **29**, 2027 (2003).
   S. Mihara, “R&D work on a liquid-xenon photon detector for the MEG experiment at PSI,” Nucl. Instrum. Meth. A **518** (2004) 45.
5. A Baldini, *et al.* [MEG collaboration] *in preparation.*