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The MEG liquid xenon calorimeter

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Abstract. The MEG experiment at PSI, starting data taking this year, searches for the muon decay into one electron and one photon with a sensitivity to branching ratios around 10^{-13}, two orders of magnitude better then the present best experimental limit. To reach this goal a new kind of large acceptance, large mass (roughly 2.2 Tons) calorimeter based on liquid xenon scintillation light was developed. Several calibration techniques developed to monitor the calorimeter behavior during all the experiment data taking will be shown together with the experimental resolutions obtained.

1. The MEG experiment at PSI

1.1. Motivation

The MEG experiment [1] searches for the $\mu^+ \rightarrow e^+ + \gamma$ decay. In the Standard Model (SM) framework lepton flavor is preserved, therefore this decay is forbidden. If the present neutrino masses and mixing are considered, the probability of this transition is different from zero but negligible (BR$\sim 10^{-55}$). However all SM extensions enhance the rate through mixing in high energy sector of the theory and in particular, various supersymmetric grand-unified theories (SUSY-GUT) predict a branching ratio in the range $\sim 10^{-12} \div 10^{-14}$ [2]. The signature of a $\mu \rightarrow e + \gamma$ decay at rest is a simultaneous emission of the two daughter particles, having opposite directions and having the same energy equal to half of the muon mass $E_\gamma = E_e = m_\mu/2$ = 52.8 MeV. The main background is given by the accidental coincidence of a positron from the normal muon decay with a high energy photon coming either from radiative muon decay, 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, of 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:

$$BR_{Acc} \propto R_\mu \, \Delta E_e \, \Delta E_\gamma^2 \, \Delta t_{e\gamma} \, \Delta\theta_{e\gamma}^2 \tag{1}$$

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 present experimental limit is set to BR($\mu \rightarrow e + \gamma$) $< 1.2 \times 10^{-11}$ by the MEGA experiment [3]. The MEG experiment aims at reaching a sensitivity of 10^{-13} by using a novel liquid xenon scintillation calorimeter to measure the photon four-momentum.

[1] For the MEG Collaboration

1.2. Muon beam and sub-detectors

In the MEG setup, muons from the presently highest intensity muon beam, the $\pi E5$ beam line at Paul Scherrer Institut, are stopped in a thin target. Positron momentum and trajectory are measured by a magnetic spectrometer (COBRA) composed by a super-conducting non-uniform magnet and 16 drift chambers. The inhomogeneous field quickly sweeps positrons towards plastic scintillating bars that measure their timing. Photons reach the liquid xenon calorimeter where their energy, position and timing are measured (see Figure 1).

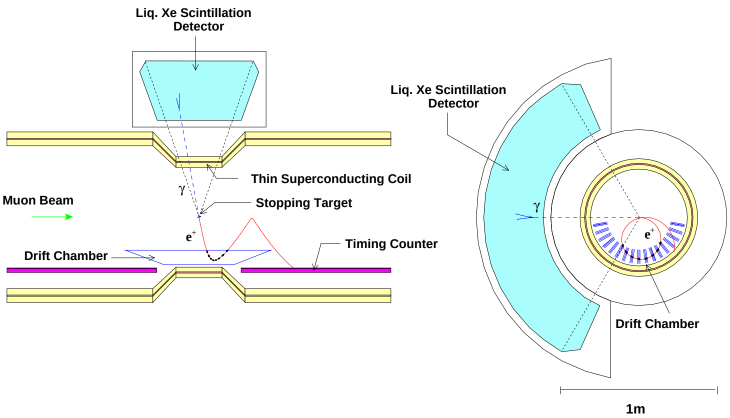

Figure 1. The set-up of the MEG experiment. The C-shaped liquid xenon calorimeter is visible on both views

2. The liquid xenon calorimeter

2.1. Structure

The MEG electromagnetic calorimeter was operated for two months at the end of 2007. It is a 0.8 m^3 C-shaped volume filled with about 800 liters of liquid xenon cooled (T = 165 K) by a pulse-tube refrigerator and by auxiliary liquid nitrogen lines mounted on the internal part of the cryostat. The cryostat structure is made of steel. Its front part is made of a thin steel window (0.5 mm) supported by an aluminum honeycomb and carbon fibers, to reduce the photon interaction probability between the production target and the liquid xenon (see Figure 2). The internal and external radii of the active volume are 65 cm and 112 cm respectively, for a 17 X_0 thickness, and angular extension $\pm 60°$. Inside, mounted on an aluminum and plastic (peek, only inner face) structure, there are about 846 2" UV-sensitive photomultiplier tubes (HAMAMATSU Photonics Inc.) immersed in the liquid xenon. They have a compact structure with twelve amplification stages in order to operate also in a moderate magnetic field ($\approx$ 50 gaus).

2.2. Proprieties of Xenon as a scintillation medium

There are two different ways to produce scintillation light in xenon: ionization and excitation of the atoms. Both ways lead 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 (λ_{peak} = 178 nm, $\Delta\lambda$ = 14 nm FWHM). The two mechanisms are different and lead to different characteristic times. Further, the ratio between ionization and excitation is different for different particles. Liquid xenon light yield is very high ($\approx$ 40000 phe/MeV, $\approx$ 80% of NaI) and it has a very fast response time (4 ns, 20 ns, 45 ns decay components). The high density (2.95 g/cm^3) and atomic number (Z = 54) of liquid xenon allow to make a compact detector. Thanks to the

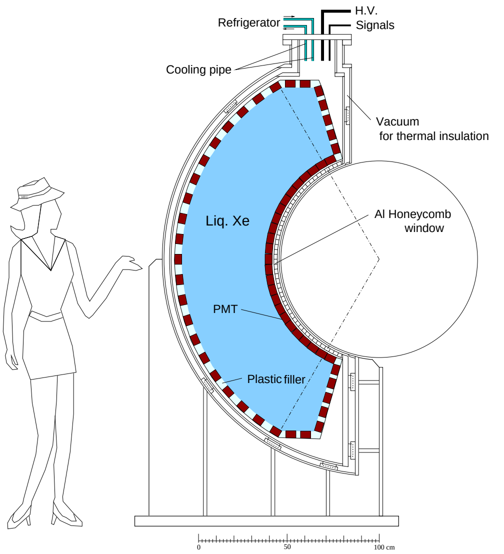

Figure 2. View of liquid xenon calorimeter

above mentioned scintillation mechanism (excimer production) self-absorption should be small and light attenuation is dominated by Rayleigh scattering and absorption processes due to impurities in the liquefied gas; in particular water vapor and molecular oxygen have absorption lines in the range of interest (VUV). In order to purify xenon, a gas-phase purification system with water, oxygen and particle filters runs in parallel to a similar liquid-phase purification system with a fluid pump to increase purification efficiency and speed.

2.3. Data Acquisition system
The signals from all photomultipliers are read from two different digitizer types. The first is a 100 MHz digitizer for triggering purposes. The second one is a 2 GHz digitizer called Domino Ring Sampler [4] which consists of a circular pipeline of 1024 capacitors sequentially cleared and opened to sample the incoming signals. This is necessary to obtain a timing resolution of 100 ps by bin interpolation. In figure 3 we can see alpha and gamma waveforms for the two different types of digitizer.

2.4. Calibrations
In order to ensure that the required performances are reached and maintained during the MEG run, we developed several complementary and redundant methods to calibrate and monitor the behavior of the calorimeter.

2.4.1. LED and alpha sources
36 LEDs are mounted on the calorimeter lateral faces in twelve different positions, able to lighten all photomultipliers. Assuming a linear response of PMTs and a Poisson distribution for photoelectrons, the charge distribution variance is proportional to the photomultiplier gain according to following expression:

$$\sigma^2 = g\,(q - q_0) + \sigma_0^2 \tag{2}$$

where σ is the variance, g is the gain, q is the charge and q_0 and σ_0 are the charge and the variance of the pedestal respectively. By impulsating the LEDs at different voltages and using

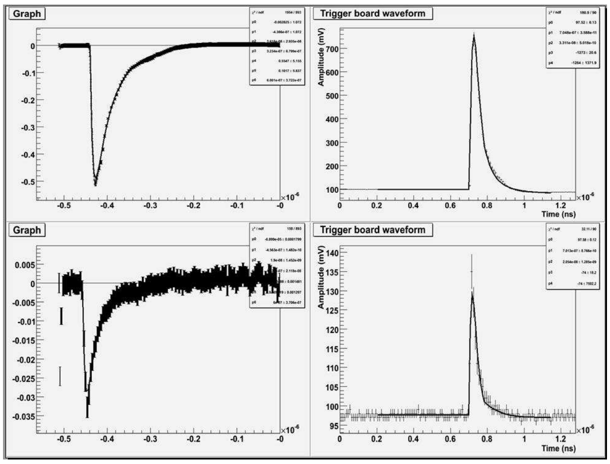

Figure 3. Alpha and γ waveform for DRS (negative) and trigger (positive) digitizer

equation (2), it is possible to obtain a good evaluation of photomultiplier gains (see Figure 4). Five tungsten wires, with a diameter of 100 μm, are mounted inside the calorimeter along the

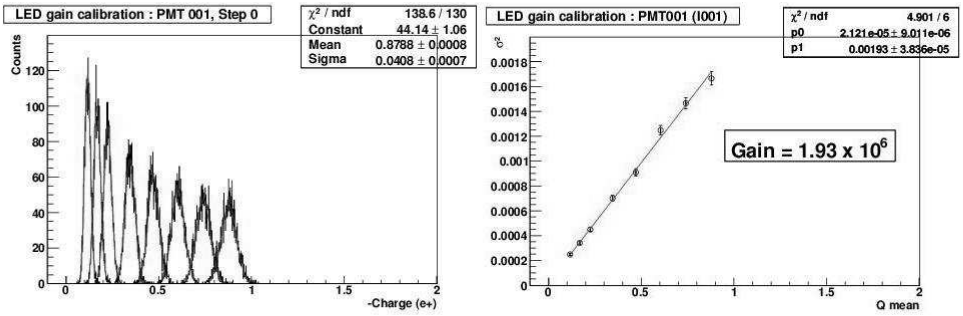

Figure 4. Example of a gain fit for a photomultiplier

beam direction and fixed on lateral faces. On each wire there are five ^{241}Am dots which emit alpha particles releasing their energy in a region about 40 μm around the source. The energy and spatial distribution of these events are known and can be easily simulated. The comparison between the simulated and the real number of photoelectrons of an alpha event provides a good evaluation of the photomultiplier quantum efficiency. The exponential fit of the relation between the ratio of simulated and real photoelectrons number versus the distance of each photomultiplier provides an evaluation of the liquid xenon absorption length (see Fig. 5 (b)).

2.4.2. Cockcroft-Walton accelerator

Normally available radiative γ-ray sources produce photons with energies much below what execpeted for $\mu \rightarrow e + \gamma$ decay (52.8 MeV). The MEG experiment bought therefore a 1MeV Cockcroft-Walton proton accelerator which is used to produce 17.6 and 14.6 MeV lines (see Fig. 5 (a)), by means of the resonant reaction

$$p + {}^{7}_{3}Li \rightarrow {}^{8}_{4}Be + \gamma \tag{3}$$

allowing a simple, precise and fast energy calibration of the calorimeter. The reaction

$$p + {}^{11}_{5}Bo \rightarrow {}^{12}_{2}Be + \Sigma\gamma \tag{4}$$

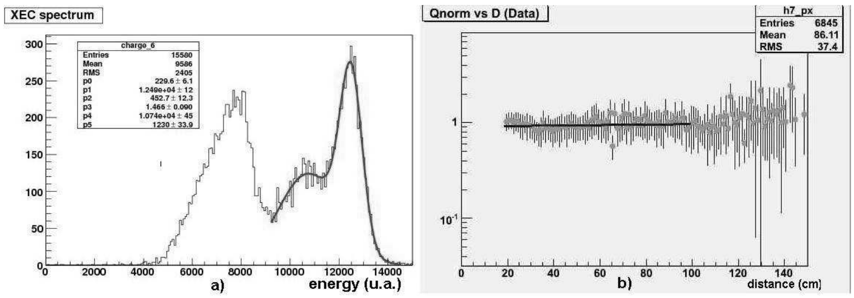

Figure 5. a) Litium peak. b) A distribution of the ratio of simulated and real photoelectrons number versus the distance of each photomultiplier to evaluate Xe purity

with simultaneous emission of two photons (4.4 and 11.7 MeV) useful to study the coincidence between calorimeter and timing counter is also used.

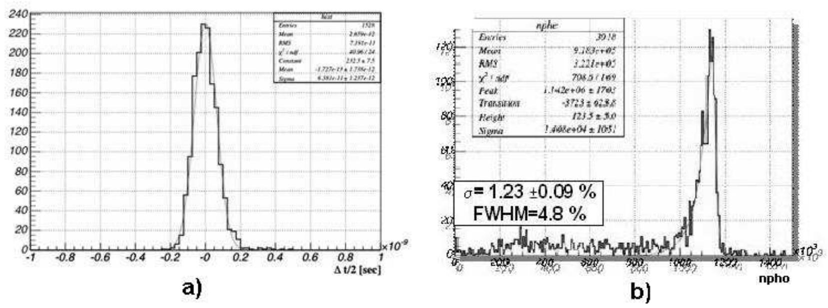

Figure 6. Time (a) and energy (b) resolution on 52.9 MeV photons

2.4.3. Charge exchange reaction
A negative pion beam is stopped in a liquid hydrogen target, when the charge exchange reactions:

$$\begin{aligned} \pi^- + p \rightarrow \quad & \pi^0 + n \\ & \hookrightarrow \gamma + \gamma \end{aligned} \tag{5}$$

The energy spectrum of the two γs from the π^0 decay is flat between $54.9 < E_\gamma < 82.9$ MeV and there is a correlation between their energy and opening angle: in particular when two photons are emitted at 180°, they have 54.9 and 82.9 MeV energies respectively. It is therefore possible to study the calorimeter response at an energy close to interesting one. In particular to select only 54.9 and 82.9 MeV photons, we use an auxiliary segmented NaI detector positioned at the opposite side of the calorimeter, so that only back to back γ pairs are selected. In order to scan the whole ϕ angle, the NaI is mounted on a mechanical structure that allows to move it in different positions.

2.5. Performances of calorimeter
With the aforementioned calibration methods the calorimeter performances have been checked. In particular the energy, position and timing resolution and the linearity of calorimeter response have been measured. In figure 7 (a) the detector linearity is showed: the first four points are from Cockcroft-Walton reactions, the others two from pion charge exchange reactions. In figure

6 the timing and energy resolution obtained with 54.9 MeV photons are showed. For spatial resolution some holes and edge of a lead collimator have been used (see Fig. 7 (b)). In table 1 these results are summarized.

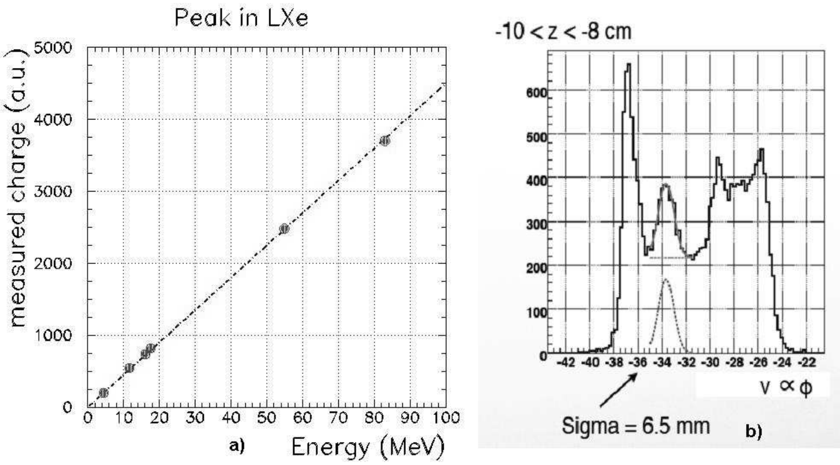

Figure 7. a) Checked charge at different photon energies in the calorimeter. b) Spatial resolution obtained by 52.9 MeV photons using a lead collimator

Table 1. Summary of liquid xenon detector resolution

Measurement	Resolution (FWHM)
γ Energy (on 55 MeV)	4.8
γ Position (mm)	15.0
γ Time (nanosecond)	0.15

3. Conclusions

The MEG calorimeter detector is the biggest liquid xenon scintillation in the world. In order to calibrate and monitor that the required performances are reached and maintained, several complementary and redundant methods are developed. The calorimeter was successfully installed and operated for 2 months in 2007 when, using the calibration methods, it showed resolutions in agreement with what proposed to reach MEG goals. The data taking period of the MEG experiment will start in July 2008.

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