Transparency of a 100 liter liquid xenon scintillation calorimeter prototype and measurement of its energy resolution for 55 MeV photons

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Abstract: **We are developing a liquid xenon calorimeter for the MEG experiment. This experiment, to be performed at the Paul Scherrer Institut (PSI) in Villigen (CH), was designed by an Italian-Japanese-Russian-Swiss collaboration to search for the $\mu^+ \rightarrow e^+\gamma$ decay, forbidden in the Standard Model of Electro-Weak and Strong Interactions. The photon four momentum is to be measured by an innovative C-shaped 800 litres liquid xenon calorimeter read by more than 800 photo-multiplier tubes. An absorption length for Xe scintillation light larger than 100 cm has been measured. The performance of such a detector has been measured using a large volume prototype (100 litres) in a test beam at PSI, using high energy photons from decays of neutral pions from a charge exchange reaction of negative pions on protons. A resolution of 5% FWHM was obtained.**

INTRODUCTION

The Standard Model of the Electro-Weak and Strong Interactions (SM) is presently the theory which successfully explains the particle physics phenomenology. It is nonetheless believed to be a low energy approximation of a more fundamental theory whose effects must be searched for in the possible observation of rare events, forbidden by SM symmetries. In this framework the $\mu^+ \rightarrow e^+\gamma$ decay search provides a sensitive tool to test both the SM and some of its proposed extensions. The present limit on this decay branching ratio (BR) is set to $BR(\mu^+ \rightarrow e^+\gamma) < 1.2 \times 10^{-11}$ by the MEGA experiment [1]. Super-symmetric theories of Grand-Unification generally predict a BR in the range 10^{-12}-10^{-14} [2,3]. It is for this reason that a new experiment, called MEG from the abbreviation of MuEGamma, has been designed in order to reach such a sensitivity [4].

THE MEG EXPERIMENT

The signature of the $\mu^+ \rightarrow e^+\gamma$ decay from muons at rest is the presence of time coincident, back-to-back, positron and photon carrying each half of the muon mass as energy, that is 52.8 mega electron-volts (MeV); this event must be distinguished from the presence in the detector of such a pair coming from an accidental coincidence of a high energy photon coming, *e.g.*, from a radiative muon decay and a high energy electron from the normal muon decay $\mu^+ \rightarrow e^+\nu\nu$.

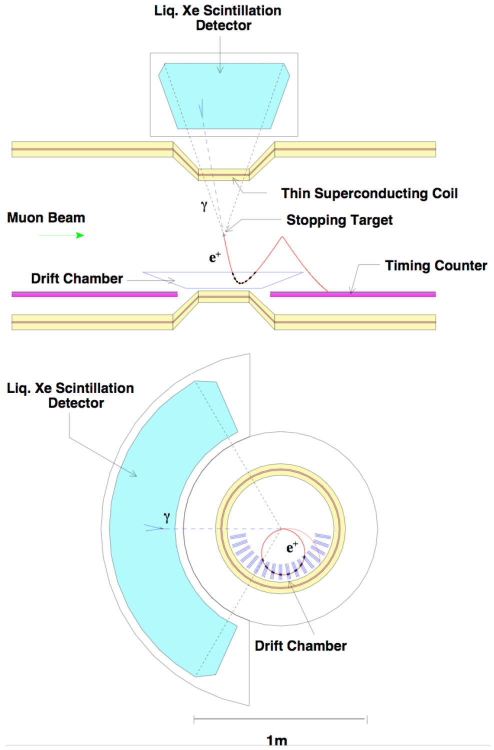

Fig.1. A schematic view of the MEG experiment: a beam of positive muons is stopped in a thin target at the center of a solenoid which produces an inhomogeneous magnetic field. A typical $\mu^+ \rightarrow e^+\gamma$ decay is shown: the positron trajectory and momentum are measured by a set of drift chambers while the photon 4-momentum is measured by a C-shaped homogeneous liquid xenon calorimeter.

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The phase space for these background particle having the correct energy, timing and angular correlation is zero, but the finiteness of the experimental resolutions allows for a mis-identification of this kind of events as true signal. However, the better the experimental resolutions, the better the rejection power on background events.

A schematic design of the MEG experiment is shown in Fig.1. Muons of 29 MeV/c momentum are stopped on a thin Mylar target where they decay at rest. A set of radial drift chambers inside an inhomogeneous magnetic field measure the positron momentum while the positron timing is given by a plastic timing counter.

The photon energy, direction and timing are measured by an innovative scintillation liquid xenon calorimeter. This calorimeter is a C-shaped, 800 litres homogeneous volume filled with liquid xenon. Only the scintillation light is used to evaluate the photon energy and position. The volume is seen by more than 800 photo-multiplier tubes (PMTs) immersed in the liquid at cryogenic temperature (-108 ^{o}C). The 2-inches PMTs are tightly packed on the front face in order to insure a reconstruction of the photon conversion point with a sub-centimeter resolution.

Liquid xenon was chosen for its high light yield (comparable to that of sodium iodide) high atomic number and fast scintillation time. The main characteristics of liquid xenon useful for the detector are summarized in Table I.

Table I. Main properties of liquid xenon as a scintillation detector medium

Property	Value
Density	2.98 g/cm^3
Atomic Number	Z=54
Scintillation wavelength	178 nm (14 nm FWHM)
Boiling temperature (1 atm)	167.1 K
Radiation length	2.77 cm
Moliere radius	4.1 cm
Scintillation decay time	5,22,45 ns

THE CALORIMETER PROTOTYPE

Description

In order to verify the stable operation of a large detector and to evaluate its performance, we built a large prototype of the liquid xenon calorimeter, which uses approximately 100 litres of liquid xenon viewed by 240 PMTs. It is a (40x40x50) cm^3 box in which up to (6x6x8) PMTs can be housed. The box is immersed in liquid xenon, which is kept cold by a high-power pulse tube refrigerator. This prototype (called "large prototype" or, for short, LP) is depicted in Fig.2.

The LP is equipped with blue LED for the PMT gain evaluation and monitoring, and with alpha sources, to measure the PMT relative quantum efficiencies (QE). At the beginning of our tests we had alpha sources on the detector walls, but to better exploit the uniqueness offered by a homogeneous liquid detector the alpha sources were later deposited on thin tungsten wires (∅50 μm) that were suspended inside the detector volume. This allowed a more uniform illumination of all the PMTs. In our last tests we had four such wires with two ^{210}Po sources each, for an overall activity of about 1 kBq.

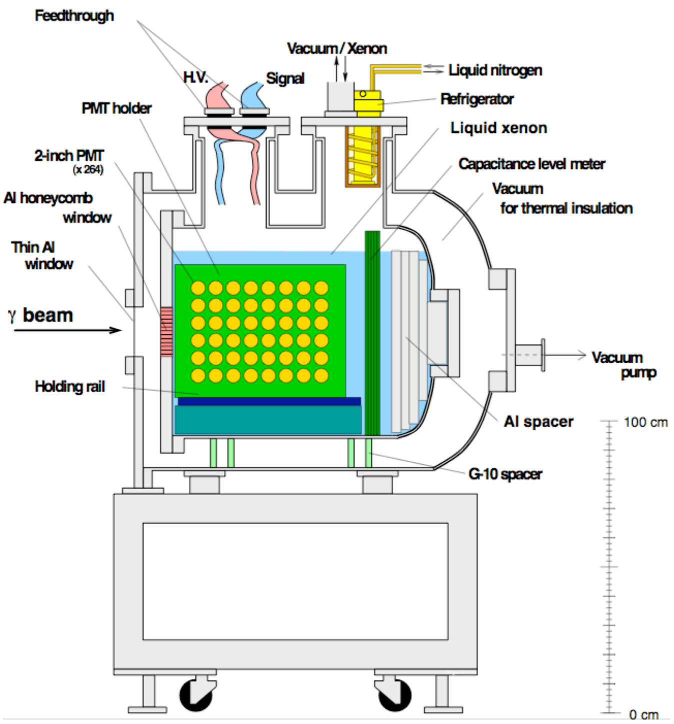

Fig.2. A schematic view of the liquid xenon calorimeter large prototype (LP).

Absorption of scintillation light

We developed detailed Monte Carlo (MC) simulations of the detector which showed that its energy resolution was heavily dependent on xenon absorption length of its scintillation light. Before going on we want to make a clear distinction between the absorption and scattering processes: we call "absorption" the process that removes the scintillation photon, therefore worsening the photostatistics, while we call "scattering" the process in which the original photon is removed, but eventually re-emitted in a different direction (e.g. Rayleigh scattering).

In principle, due to its peculiar scintillation mechanism, xenon should be transparent to its scintillation light, whose spectrum is centered at 178 nm. There are however substances that strongly absorb light of this wavelength. It was shown, in fact, that even parts per million of water and oxygen dissolved in xenon can give an absorption length as short as few centimeters [5], which was actually the situation at the beginning of our tests.

For this reason we introduced a continuous circulation and purification system: xenon is continuously evaporated and passed through an Oxisorb cartridge and a molecular sieve, and is eventually recondensed inside the chamber.

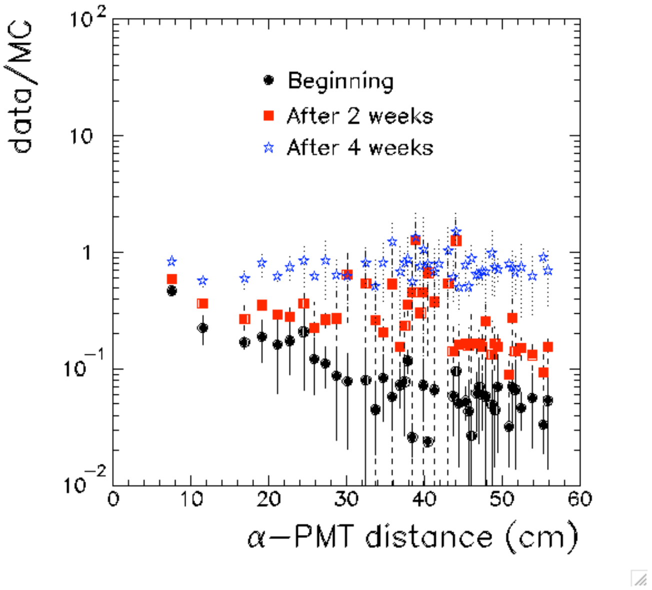

Fig.3. Absorption length plot for scintillation light in liquid xenon. Black dots = beginning of data taking, red squares = after two weeks purification, blue stars = after four weeks purification. See the text for details.

We developed a method to evaluate the absorption length [5]: for each alpha source and for each photo-multiplier we compute the ratio between the light observed and that expected in the case of negligible absorption (but with realistic scattering length), and we plot this ratio as a function of the alpha-PMT distance. The slope of the curve is a measure of the xenon absorption length (λ_{Abs}).

In Fig.3 we show, as black closed circles, such a plot at the beginning of one of our data taking. The red squares and the blue stars show the same plot after two and four weeks of circulation and purification, respectively. One can see that the purity of xenon continuously increases. After some time the distribution is compatible with an horizontal line. The slope of this line, together with its uncertainty, gives an estimate of the absorption length inside our detector: recent measurements set a 90% confidence limit of $\lambda_{Abs} > 150$ cm. The sensitivity on this value is limited by the finite size of our detector. The presence of water inside xenon was also confirmed by mass-spectrometric analysis.

Our Monte Carlo simulation shows that such a large absorption length is sufficient to achieve an energy resolution below 5% FWHM at 52.8 MeV. However a test to verify these computations has been performed at PSI with photons of energy as close as possible to the expected one.

ENERGY RESOLUTION MEASUREMENT

Setup

The validation of a new detector requires test in a condition as close as possible to that envisaged in experiment. We tested the response of the calorimeter prototype with 55 MeV photons from π^0 decays. Negative pions from the πE5 beam line at the Paul Scherrer Institut were stopped on a liquid hydrogen target. Monochromatic neutral pions are produced in the charge exchange reaction $\pi^- p \rightarrow \pi^0 n$, which eventually decay in two photons. The energy and opening angle of the two photons are correlated in such a way that for a back-to-back pair the energies of the two photons are 55 MeV and 83 MeV respectively, with an uncertainty smaller than 0.5 MeV even with a modest collimation.

One of the two photons was detected with the LP while the other photon was detected by a hybrid detector composed by a Lutetium-Yttrium Ortho-Silicate (LYSO) crystal used as a pre-shower, followed by a large sodium iodide (NaI) detector for the energy containment.

Large prototype PMT calibration

Blue LEDs were used to measure the PMT gain. The LEDs are flashed at different amplitudes and the charge of each PMT is recorded. By exploiting the linear relation between the square of the distribution sigma and the distribution mean value, the gain for each PMT is computed. This method provides the gain of each PMT to a better than percent level. A gain of 10^6 is typical for an applied voltage of 800 V.

The scintillation light emitted by the alpha sources on the wires in cold gas xenon was used to compute the relative quantum efficiencies of the photo-multipliers. It is in fact known the close similarity between the emission spectrum in gas and in liquid xenon and the measurement in gas allows to get rid of effects related to absorption and Rayleigh scattering. The light collected by each PMT is plotted against the expected one from each alpha source, and the slope of the resulting diagram is used as an estimate of the PMT quantum efficiency. We estimate the uncertainty of this determination to be of few percent by comparing the QE determined for the PMTs at different times and with different alpha-sources and alpha-source positions.

Photon spectra

In Fig.4 we plot the correlation between the energy of the photon measured by the liquid xenon detector and the energy of the photon measured by the opposite side NaI detector. The correlation between the 55 MeV and the 83 MeV lines is apparent. An additional correlation is present which is due to the negative pion radiative capture reaction $\pi^- p \rightarrow \gamma n$. In this latter case the 129 MeV photon is measured in the

NaI+LYSO detector in coincidence with the 9 MeV neutron in the xenon detector.

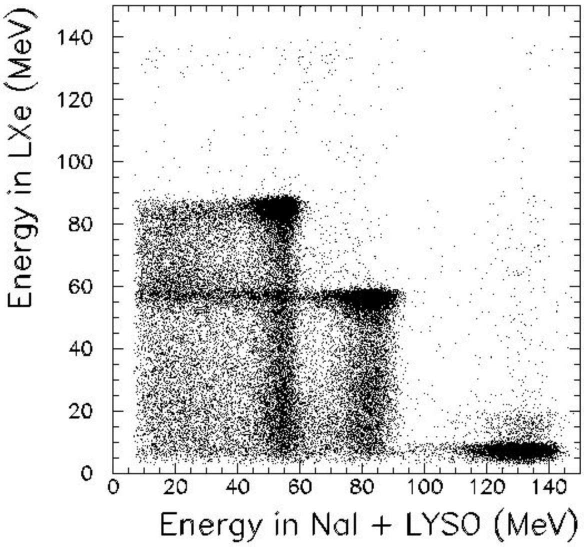

Fig.4 Correlation between the energy measured by the liquid xenon calorimeter prototype (E_{Rec}) and the one measured by the hybrid NaI + LYSO detector. The additional blob due to the negative pion radiative capture reaction $\pi^- p \to \gamma n$ is present. In this latter case the 129 MeV photon is measured in the NaI+LYSO detector in coincidence with the 9 MeV neutron in the LP.

Selection of the 55 MeV peak

The 55 MeV peak was selected by requesting the presence of the 83 MeV photon in the NaI detector. The spectrum is further cleaned in the following way: the photon conversion point inside liquid xenon is estimated by fitting the charge distribution of the PMTs of the front face. In this way it is possible to select only those photons inside the lead collimator acceptance. A further cut in this preliminary analysis is applied on the events whose ADC channel is saturated: we have for the central PMTs the attenuated charge but the relative analysis is still in progress. This cut can be shown to be equivalent to a depth cut: those photons are discarded which convert at less than 2 cm in front of the PMTs. The overall efficiency of those cuts on the total number of 55 MeV photon candidates after the NaI energy cut is 65%.

The resulting peak is shown in Fig.5. A resolution of $(4.9\pm0.4)\%$ FWHM is obtained. We studied the dependence of the peak position and width as a function of the photon reconstructed impinging position but no significant deviation has been observed.

The MEG experiment sensitivity

We can combine the obtained resolution with the results and/or expectations for the other sub-detectors to estimate the expected sensitivity of the MEG experiment, defined as the 90% confidence level upper limit on the branching ratio in case of observation of no $\mu^+ \to e^+\gamma$ candidate. For a muon stopping rate on target of 1.2×10^7 μ^+/sec and a data-taking time of 3.5×10^7 sec, the observation of no candidate would set a limit on the $\mu^+ \to e^+\gamma$ branching ratio of $BR(\mu^+ \to e^+\gamma)<1.2\times10^{-13}$.

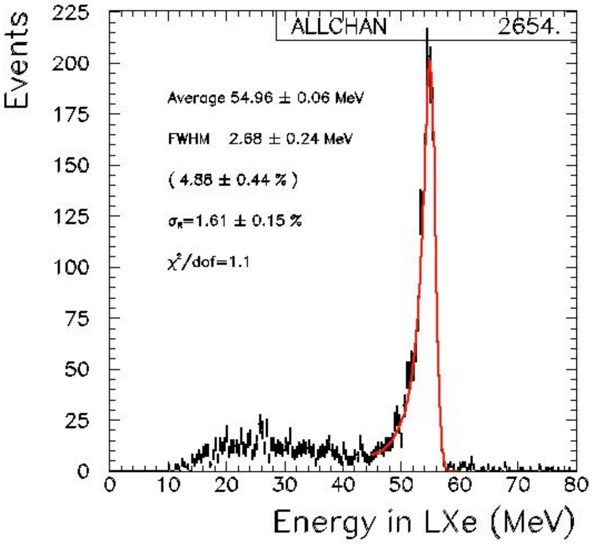

Fig.5. Spectrum of the 55 MeV photon reconstructed in the liquid xenon calorimeter prototype

CONCLUSION

The MEG experiment was designed to improve the present experimental limit on the SM-forbidden $\mu^+ \to e^+\gamma$ decay by two orders of magnitude. Its most innovative detector, namely a liquid xenon homogeneous scintillation calorimeter, has been intensively tested by means of a large volume prototype. The construction of the full-size calorimeter will proceed during 2005. The first engineering run is expected to start in mid-2006.

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