Considerations on the Calibration and Monitoring of the MEG experiment *

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A. Baldini, C. Bemporad, F. Cei, M. Grassi, D. Nicolò, A. Papa, R. Pazzi, G. Signorelli

INFN and University of Pisa

Abstract

The MEG experiment studies the lepton-flavour violation by measuring the branching ratio $\mathrm{B}(\mu \to e\gamma/\mu \to tot)$; the sensitivity is $B \approx 10^{-13}$. To reach this goal the experiment must use the most intense continuous beam available ($\approx 10^8\ \mu/s$) and rely on advanced technology (LXe calorimetry, superconducting spectrometer of special design, a flexible and powerful trigger system, etc.). The energy, time and space resolutions are the highest to-day reachable. The data collection will last about two years. On those terms, the only way to ensure that the required performances are reached and maintained in time is to use several complementary and redundant methods to calibrate and monitor the behaviour of all detectors. Qualities and problems of the available methods are briefly discussed. We propose to integrate a 500 keV Cockroft-Walton accelerator into the experiment.

1 Introduction

MEG [1] is an ambitious experiment in terms of the sensitivity in studying the process $\mu \to e\gamma$ [2]. This demands the highest precision in measuring the 4-vectors of the μ-decay products, moreover the precision must be coupled to a great running

*Prepared for the May 10th 2005 INFN referee review stability of all detectors, under a high beam intensity and its possible time variations. These features were evident from the first MEG planning stages. Time and effort were devoted to the development of several C&M (calibration and monitoring) methods and to experimentally demonstrate their potentialities. Other methods came out to be of difficult application because of technical problems, or of high cost, or because of their interference with other experiments. In the future, some possible methods might directly emerge from an analysis of the data collected during the experiment. We briefly discuss the strong points and the weaknesses of all C&M methods. The outcome strongly suggests the integration of a 500 keV C-W (Cockroft-Walton) accelerator into the experiment. The use of such an accelerator for an elementary particle experiment is rather exceptional, but exceptional are also the aims of MEG and the need for ensuring its reliability. Although a C-W is a rather expensive item, its potentialities are great, while its cost is not out of scale, if compared with the total investment into the MEG experiment. The use of a C-W has better and more thorough advantages over other C&M methods. It is important to remark that a C-W allows the C&M of MEG (both of the LXe calorimeter and of the complete magnetic spectrometer) also during the long periods of time during which the PSI machine-time is dedicated to other experiments or during machine-off periods. The possibility of independently tuning MEG implies a better use of the machine-time dedicated to MEG.

2 Calibration and Monitoring

It is worth defining the meaning of the two words in our case and try to list the quantities one has to measure and monitor, mainly referring to the ones of the LXe calorimeter. By "Calibration" one indicates the determination of the photomultipliers relative Q.E., of the PMT amplifications, of the degree of purity of the LXe, of the intensity and spectrum of the Xe light emission, of the optical parameters of the liquid and gaseous Xe (refractive index, Rayleigh scattering-length, absorption-length [3]). It also means the determination of other important global quantities like the calorimeter energy resolution as a function of the γ-ray energy and impact point, the time resolution, the resolution on the position of the impact point, the calorimeter capacity in separating two particles in time and in space, etc. By "Monitoring" one essentially means the check of the stability of all important quantities, as often and as completely as feasible, in conditions which are, as close as possible, similar to the normal running conditions of MEG (COBRA magnet at full field, high beam intensity, minimal modifications to the MEG set-up, etc.). The "complementary and redundant C&M methods" we shall consider, have different potentialities. A single method, even if more powerful than others (i.e.: the use of a C-W), will not be sufficient to solve all problems. At the same time a precise plan of the C&M

of the experiment can be fully defined only by the MEG running experience. It is important for MEG to dispose of a set of C&M methods, fully tested and ready to use.

3 Radioactive Wire-Sources

Liquid scintillator calorimeters and in particular liquid cryogenic noble gas detectors can be calibrated and monitored by the use of multiple α-sources distributed in the detector sensitive volume [4]. The wire-source (WS) method is based on a set of thin wires (diameter $\approx$ 100 μm) on which several point-like ^{210}Po or ^{241}Am α-sources (individual activity $\approx$ 300 Bq) are deposited; the wires are then mounted in the LXe sensitive volume (see fig.1, fig.2, fig.3) The development of the ^{241}Am WS required a considerable program of R&D [5]. (The first ^{210}Po test WS -sources for the large-prototype were prepared by the MEG-Genoa group) . After production, the ^{241}Am WS were tested at the ENEA-Casaccia Lab. to investigate their safety at the liquid nitrogen temperature (a test not required for commercial α-sources) [6]. This is also important from the point of view of a possibile Xe contamination. The MEG calorimeter is basically a large LXe volume limited by a UV-light sensitive surface. The photomultipliers ($\approx$ 35% surface coverage) are directly immersed in the cryogenic liquid. The calorimeter physical response depends therefore on the quantum efficiency and amplification of each PMT at low temperature and on the LXe optical properties in the UV, i.e.: the Rayleigh scattering length, the refractive index and the LXe absorption length (intrinsic or possibly dependent on Xe contaminants). It is worth recalling that all PMTs must operate in the rather large fringing field of the MEG experiment superconducting COBRA solenoid ($<$ 50 gauss). The WS method was fully tested in the large-prototype. All QE efficiencies at approximately the LXe temperature were determined in gaseous Xe (very large Rayleigh and absorption scattering-lengths). A reconstruction of the source positions for the four wires mounted in the large-prototype is shown in fig. 4. The sources of the same colour are on the same wire. The resolution in the x,y,z positions has a $\sigma \approx$ 3 mm. An example of the determination, in Xe-gas, of the relative QE for 4 PMTs, by the use of 4 sources which are at different distances from each PMT, is shown in fig. 5. In each graph, relative to a single PMT, the abscissa of each point represents the pulse height predicted by the Monte Carlo method for a QE equal for all PMTs. The distance from the source to the PMT and the consequent solid angle are taken into account. The ordinate of each point is the measured pulse height. One can see that all points arrange themselves, fairly well, along a straight line. The slope of the line, given by a fit, is a determination of the relative QE for the PMT under consideration. After determining all QEs, Xe optical parameters were measured in the liquid state. We try now to summarize the technique strong points and weaknesses.

The WS method turned out to be a most effective way for measuring, with the Xe scintillation light, in the normal MEG operating conditions, the relative PMT quantum efficiencies and for measuring and checking the LXe optical properties. The sources are not a good absolute energy standard, because of the low α-energy and because of the source construction method. The total activity of the WS must be kept low. It is not guaranteed that the sources will be easily visible in the final calorimeter during the normal MEG operation at full beam intensity.

4 Neutral Pions

The production of π°'s by π^{-} charge exchange at rest in liquid hydrogen is quite important for MEG since it produces γ-rays which can be very close in energy to the ones from $\mu \to e\gamma$. It was repeatedly used for calibrating the large-prototype and allowed the determination of the calorimeter energy, position and time resolutions, which resulted to be similar to the ones listed in the proposal. The π°-decay spectrum is flat in the interval $54.9 < E_{\gamma} < 82.9$ MeV. A $E_{\gamma} \approx 54.9$ γ-line can be obtained if one selects events in which the two γ's are emitted in the opposite directions (see fig.6). This in turn is obtained by using lead collimators in front of the LXe calorimeter and in front of a large ancillary NaI detector, used in coincidence with the LXe calorimeter. One requires a γ-energy release of about 83 MeV in the NaI detector. It works very well (see fig.7), although the experimental rate obtained with a high intensity π^{-}-beam is rather low (≈ 10 Hz). This is mainly due to the small solid angles defined by the collimators. Moreover, if one has to explore several calorimeter regions, one has to define a new π°-decay line by moving the NaI detector and the collimators. When the final calorimeter is mounted in MEG, things will become more difficult since, to perform a calibration, one has to modify the set-up in the MEG target region, introduce a hydrogen target, change the polarity and tune a new π^{-}-beam, have the NaI detector behind the COBRA coil. The definition of the γ-ray flying path is obtained by the collimator in front of the NaI, but since there is no space for mounting and keeping in place a lead collimator in front of the LXe calorimeter, one will have to rely on the determination of the γ impact point. A calorimeter scanning becomes a long and complex operation. It will be done during the MEG data taking, but it cannot often be repeated. We did explore some other possibilities to use π°'s more effectively. The first was to ask PSI to provide a permanent, opposite sign, parasiting π^{-} beam reaching the back of the calorimeter and allowing a partial calibration of the LXe calorimeter from its back surface and through an already foreseen thin window entrance port. This would also allow a partial monitoring of the calorimeter response during the experiment. The parasiting beam proposal is technically realizable, it would require modifications in the PSI shielding and the use of a few beam elements. The cost is certainly nonnegligible, but the real reasons for its "silent withdrawal" are twofold: it affects the running time of other PSI users and, as already said, the obtainable event rate is rather low, while the method allows only a partial monitoring of the calorimeter. It is worth pointing out that these limitations in the use of the π° C&M were the main trigger for exploring the use of an independent method based on a C-W . Another interesting possibility, we are presently studying, is the one of defining a γ-line from π°-decay, without the use of the ancillary NaI detector and of the lead collimators. One could use a thin ($\approx 0.1\ X_0$) converter close to the hydrogen target and select the right γ-rays by measuring the conversion e^+e^--pair (almost always only the e^+ can be measured) in the spectrometer chambers. The positron direction is close to the original converted-γ direction. We are also investigating the possibility of adding a simple silicon-tracker after the converter for triggering purpose and for better identifying the γ conversion vertex. The versatile MEG trigger can be used for selecting the right events. The conversion efficiency reduces the available γ-rate, but the use of the spectrometer for the e^+e^--pair allows the calibration of all the calorimeter at the same time. This corresponds to an important increase in the 55 MeV γ-rate due to the large calorimeter and spectrometer solid angles. The calibration can be performed in all the window $55 < E_\gamma < 83$ MeV, since the "pair-spectrometer" tags all γ's in this energy window. Problems remain even if the method works: the ones related to the beam polarity change and to a fast and simple insertion of the hydrogen target at the COBRA center. They require better studies.

5 Thermal-Neutron Capture-Lines

The use of thermal neutron capture lines is very important for MEG since it provides the simplest way of "partially" monitoring the calorimeter behaviour at frequent intervals (triggered pulsed operation is possible). It is worth clarifying what one means by "partial monitoring". γ's from thermal neutron capture on nickel can only be introduced from the back of the calorimeter through a thin window port, at the center of the back-face. It is therefore impossibile to scan the calorimeter surface, in particular its front-face. One of the reasons is that the production of neutrons is based on a neutron generator which has to be shielded and the thermalization of neutrons implies certain minimum moderator dimensions, defined by the material characteristics. This means that the thermal neutron generating device is rather bulky and cannot be introduced into COBRA at the position of the normal target. Some limitations also come from the need of avoiding the neutron activation of different materials. C&M is instead possible from the back of the calorimeter, without any particular problem.

The technique is based on a commercial neutron generator (obtainable from INFN-Pavia), a moderator made of polyethylene slabs and several nickel plates for the thermal neutron capture. The capture on Nickel is efficiently producing ≈ 9 MeV γ-lines, since Nickel has a high binding energy and concentrates all its after-capture de-excitation energy in a few high energy lines, in 50% of the cases [7]. The method was fully tested by the use of 40 kBq Am/Be source, as a neutron-source, and by a large NaI detector (see fig.8, fig.9) It was then successfully applied to the calibration of the large-prototype. The neutron generator foreseen for MEG is a triggerable device, which can be used even during the experiment data taking. The C&M from the calorimeter back can test the stability of the calorimeter performances, at frequent and regular intervals. It can disclose instabilities, but the "partial monitoring" can be insufficient to understand their causes.

6 Protons on Lithium and C-W accelerator

The reaction ${}^7_3Li(p,\gamma)^8_4Be$ is resonant at $E_p = 440$ keV, with a resonance-width $\Gamma \approx 15$ keV. It produces a 17.6 γ-line, an energy a factor of three smaller than the one of the γ's from the $\mu \to e\gamma$ decay, but in an interesting region for C&M (see fig.10). This reaction, which is excitable with very low-energy protons, is highly exothermic; in fact it is almost unique in providing high-energy γ-rays with a large peak cross-section ($\sigma_{peak} \approx 5$ mb), since, for this particular reaction, the normally preferred particle emission (i.e.: α-emission) is depressed [8, 9]. The reaction has also a non-resonant component, but its cross-section, at energies larger or smaller than 440 keV, drops by a factor > 100. Since the ${}^7_3Li(p,\gamma)^8_4Be$ has unique properties, it has already been used to C&M other experiments. A previous version of the $\mu \to e\gamma$ experiment, around 1980, had a Van der Graaf permanently attached to the set-up [10]. This same Van der Graaf, although somewhat degraded in performances, was recuperated and is presently C&M the calorimeter of the GLAST experiment [11]. A more complex and costly scheme (about a factor of three in respect of what we propose for MEG) was at the base of the calorimeter calibration of the L3 experiment at CERN. They used a RFQ-accelerator, accelerated H^--ions to about 2 MeV, neutralised the beam, so obtaining an accelerated H-beam, which could then enter a strong magnetic field region and interact with a LiF target. This system is not advisable for MEG and is, anyway, no longer available. The accelerator best suited for MEG is a 500 keV Cockroft-Walton accelerator, insulated by pressurized SF_6, in a simplified version for proton acceleration (no other ion required). The proton source is of a RF-type. The machine is very compact (vessel length ≈ 2 m), it has no moving parts, it is sturdy and reliable, it normally requires some servicing only once a year. The life-time of such machines is typically ≈ 25 years. The proton current we need is $\approx 50\ \mu$A, lower than the normal maximum current ($\approx 200\ \mu$A) and less trying on the accelerator. The optical properties of the beam are excellent (i.e.: a beam diameter $\phi \approx 3$ cm, $\Delta\theta \approx 0.25\ ^\circ$ at a 3 m distance from the C-W). The X-ray level around the machine is guaranteed to be $< 2\mu$Sv/h. In the energy/current niche of interest for MEG, a C-W is an optimized solution. It corresponds to a machine produced by "HV Engineering Europe B.V." [12] under the name of "coaxial singletron" (see fig.11). The "coaxial" version of the accelerator is more compact than the "in-line" version, the former has a somewhat lower energy stability, which is anyway largely sufficient for our purposes. We visited HV Engineering for discussing several aspects of the machine, for evaluating the company reliability and for obtaining a detailed offer. We also visited the LUNA experiment [13] at the Gran Sasso Lab. LUNA is using a similar C-W for the measurement of cross-sections relative to the reactions of solar interest.

The problem of inserting a proton beam into COBRA to reach a LiF target at the COBRA center is very similar to the one of the normal μ-beam. The particle momenta are similar and so are the optical properties of the beam. The p-beam has to reach the LiF target under vacuum. The accelerator has optical elements for optimizing the beam at the target. The p-beam will be introduced into the spectrometer from downstream, in the opposite direction to the normal μ-beam. The accelerator can be positioned in the space available downstream from MEG. The optics of the p-beam was studied by a Monte Carlo method simulation and it did not present any problem. The COBRA magnet has a fringing field which reaches the accelerator. At a distance of > 3.5 m between the COBRA center and the front-face of the accelerator, the magnet/accelerator interference is reduced to acceptable levels. It is worth pointing out that, for accelerators of higher energy than the 500 keV of a C-W , other reaction channels open, with an unwanted increase of the background level in the experiment. At the resonance for ${}^7_3Li(p,\gamma)^8_4Be$ the expected reaction rate, dependent on the cross-section integrated over the 440 keV resonance, also depends on the total number of ${}^7_3Li$ nuclei reached by the protons. One operates in the so-called "thick target" mode; this actually corresponds to an effective target thickness of a fraction of a μm. The resulting rate is a convenient $\approx 10^6\ s^{-1}$, isotropic, 17.6 MeV γ's. The ${}^7_3Li$ reaction also produces a less intense and wider 14.6 MeV γ-line. (Other lines at lower energies correspond to the fluorine in the target). For completeness we note that another possibile reaction excitable by protons is the ${}^{11}_5B(p,\gamma)^{12}_6C$, resonant at $E_p = 163$ keV, which produces γ-lines at 16.1, 11.7, 6.5, 4.4 MeV, although with a rather low, but not impossible, cross-section.

The advantage of the proton-reaction approach is that one generates γ-rays which are isotropically illuminating the calorimeter from the COBRA center, testing the uniformity of its energy and spacial responses. We aim at performing this calibration at least once a day. This requires modifications in the target region to insert the accelerator vacuum pipe containing the target (the accelerator system is movable on wheels). In principle the accelerator beam could also reach the back of the calorimeter, by another beam line leading to a second LiF target, thus allowing also the permanent monitoring of the calorimeter during the normal running of the experiment. The accelerator high voltage and beam can be rather easily switched on and off. We are presently studying if also the 17.6 MeV γ-rays can be converted into an e^+e^--pair, and the positron be used for checking the magnetic spectrometer. While the calorimeter calibration can and must be done at the full COBRA field, this is not possibile for the spectrometer check, since the γ and the e^+ pair-branch have always an energy which is too low to effectively enter the spectrometer. One has to lower the COBRA field for reaching a sufficient positron detection efficiency. It is worth stressing that a C-W allows a full check of MEG even during the PSI-cyclotron operation for other users. As a consequence, the MEG allocated data taking periods will presumably be more efficient. The C-W system will be invaluable for the MEG setting-up, if available in time.

7 Summary

We make an attempt to grade the different C&M methods according to their properties and to the options they offer. A mark (from 0 to 3) is given to the proposed calibration method. "0" means impossibility or great difficulty in applying the method for the requested purpose. We then produce a summary table. The relevant points we consider are:

A) *C&M of the whole calorimeter, from the front face, at the same time.*

B) *Possible frequency of the C&M .* "3" means the possibility of a very frequent monitoring, i.e.: at five minute intervals, "2" means of the order of once a day, "1" means of the order of once in 6 months.

C) *Partial C&M from the calorimeter back.*

D) *Determination of PMT quantum efficiencies.*

E) *Determination of Xe purity and optical properties.*

F) *Energy scale calibration.*

G) *Energy scale monitoring.*

H) *Determination of the resolution in time.*

As already said, the C-W accelerator is the most versatile C&M method, which can be used with continuity and which, because of the high statistics reachable with the ${}^7_3Li(p,\gamma){}^8_4Be$ reaction, allows a fast calibration of the whole detector. The C-W is a low-radiation device which can be used without generating additional background

Table 1: Evaluation of the proposed calibration and monitoring methods.

C&M	WS	Neutron	π°	${}^7_3Li(p,\gamma)^8_4Be$
A)	0	0	2	3
B)	2	3	1	2
C)	0	3	1	3
D)	3	0	1	1
E)	3	1	2	2
F)	1	2	3	2
G)	2	3	1	3
H)	0	0	3	1

close to the experiment. Its operation does not require a difficult training, it is indeed a "fool-proof" accelerator usable by any shifter. Two people of the collaboration (and a technical support from PSI) must have a deeper training for the rare interventions requiring the opening of the pressure vessel for simple repairs. In conclusion, the C&M methods are the key to success for the difficult measurement MEG wants to perform. The C-W is at the base of the most complete and permanent control of the MEG detectors. An increased and proved reliability of the experiment is in the interest of physics and of INFN.

Acknowledgements

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Figure 1: Micropicture of a Am-source mounted on a 100 μ m-diameter wire.

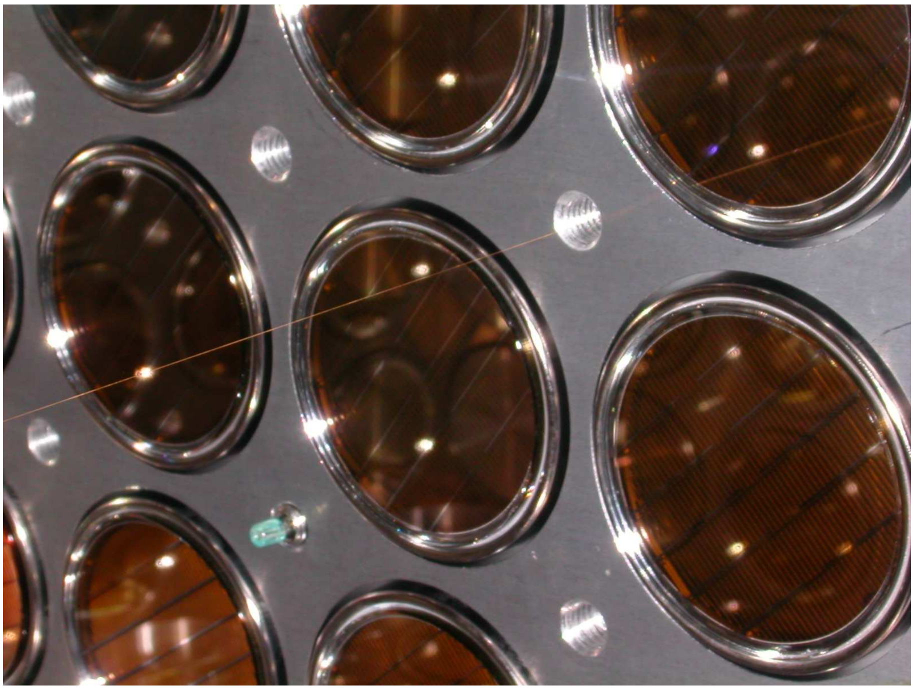

Figure 2: A two-source wire mounted in the large-prototype detector.

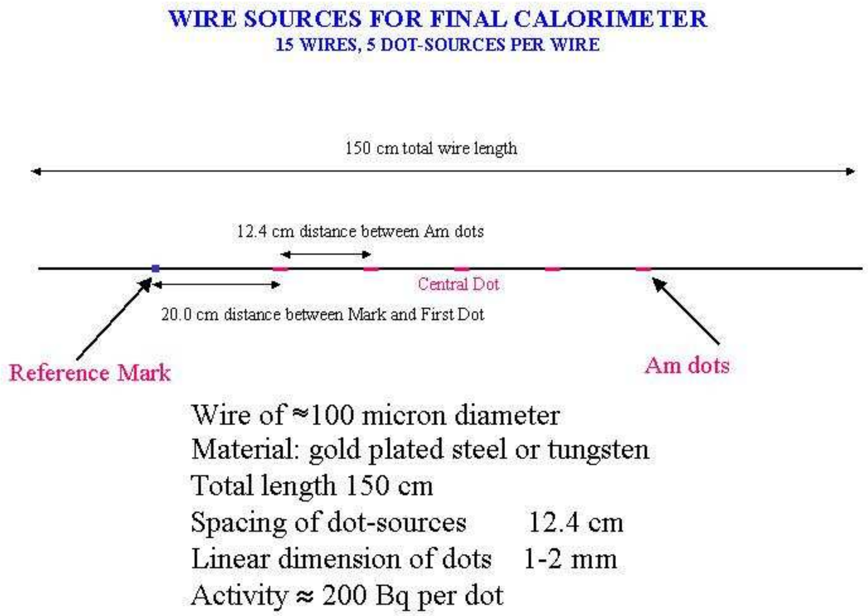

Figure 3: A wire-source prepared for the final detector. Five dot-sources per wire.

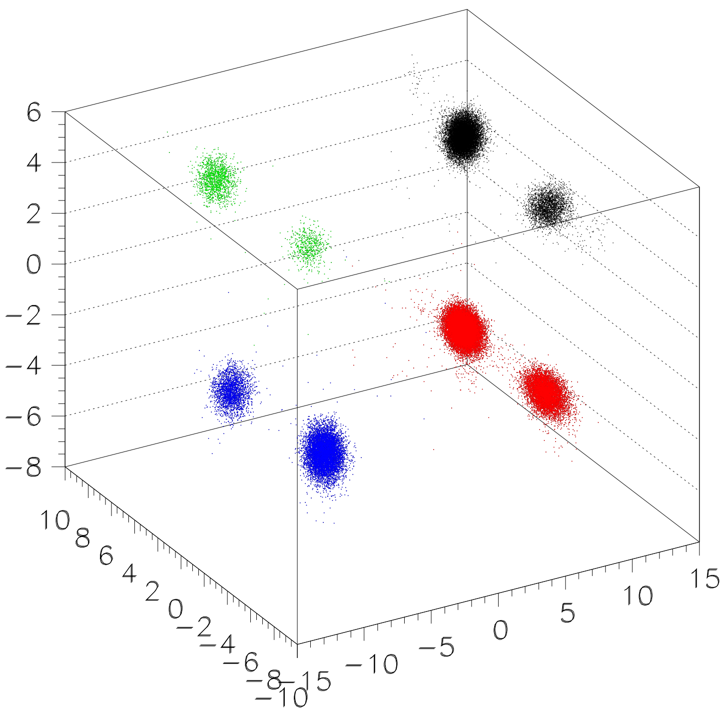

Figure 4: Reconstruction of the positions of eight sources in the large-prototype. Two dot-sources per wire in gaseous Xe.

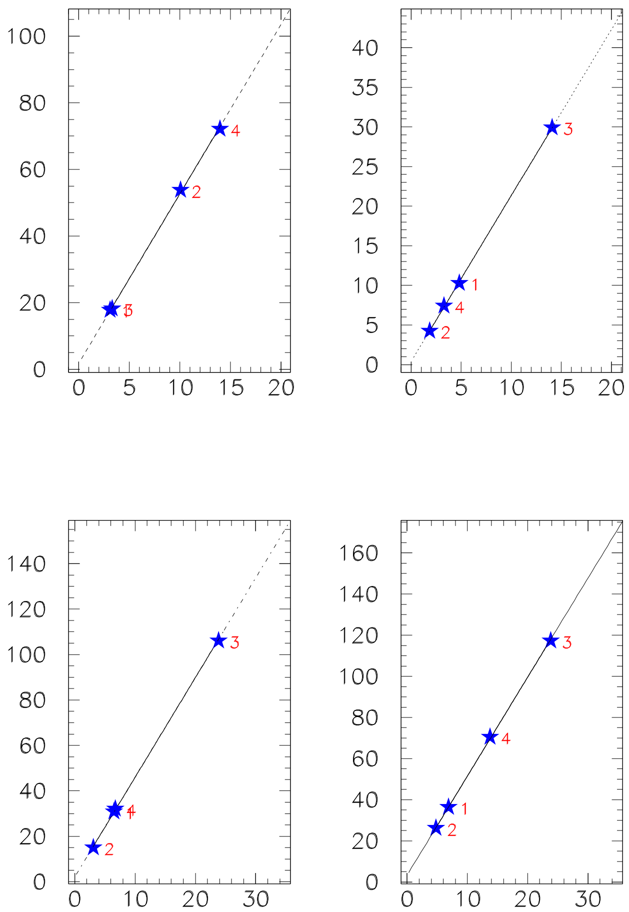

Figure 5: Example of the determination of the relative QE for 4 PMTs in gaseous Xe, by the use of 4 dot-sources which are at different distances from each PMT.

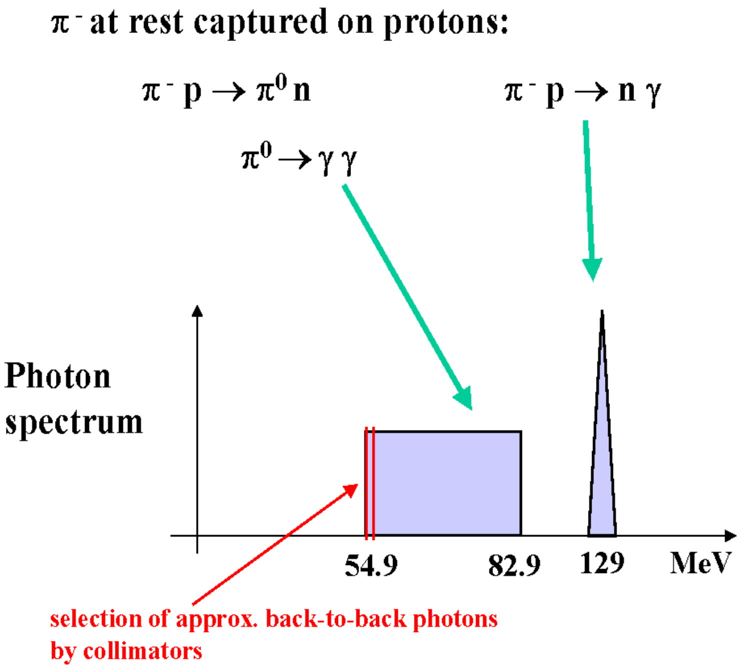

Figure 6: π^0-decay γ-spectrum and selection of 54.9 MeV γ-line.

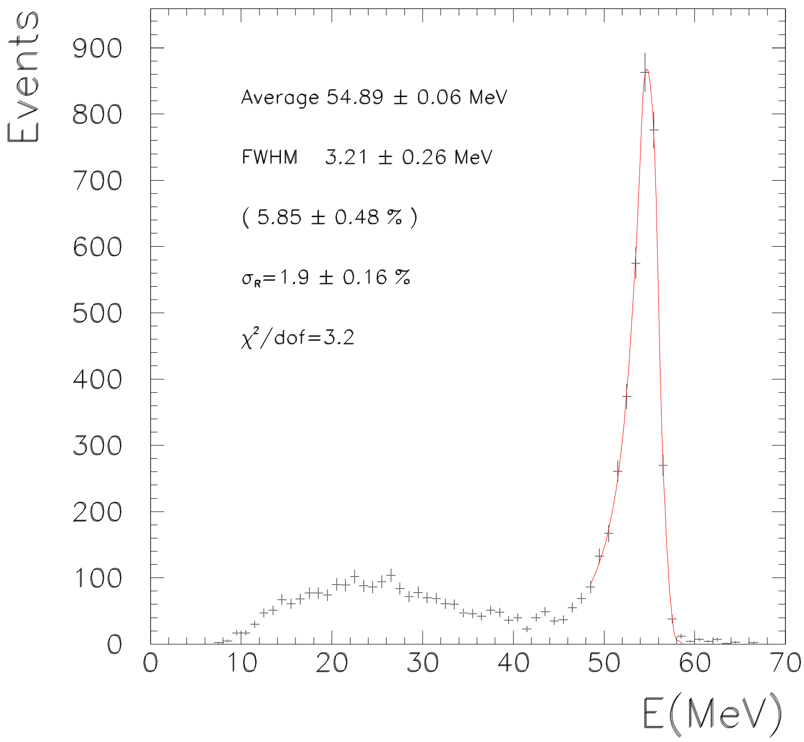

Figure 7: The 54.9 MeV γ-line from π^0-decay, as measured in the large prototype (without any selection in position and any correction applied).

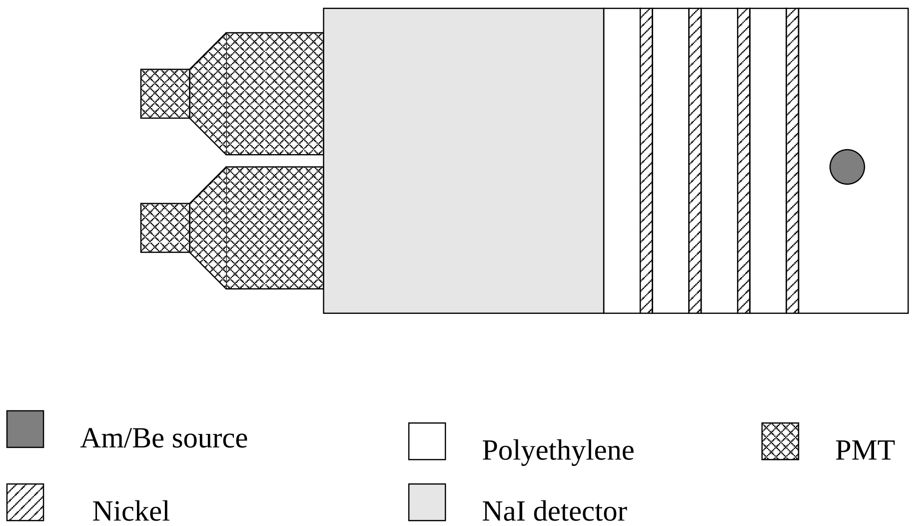

Figure 8: NaI and Nickel + Polyethylene slab set-up used for generating the Nickel thermal-neutron capture γ-line.

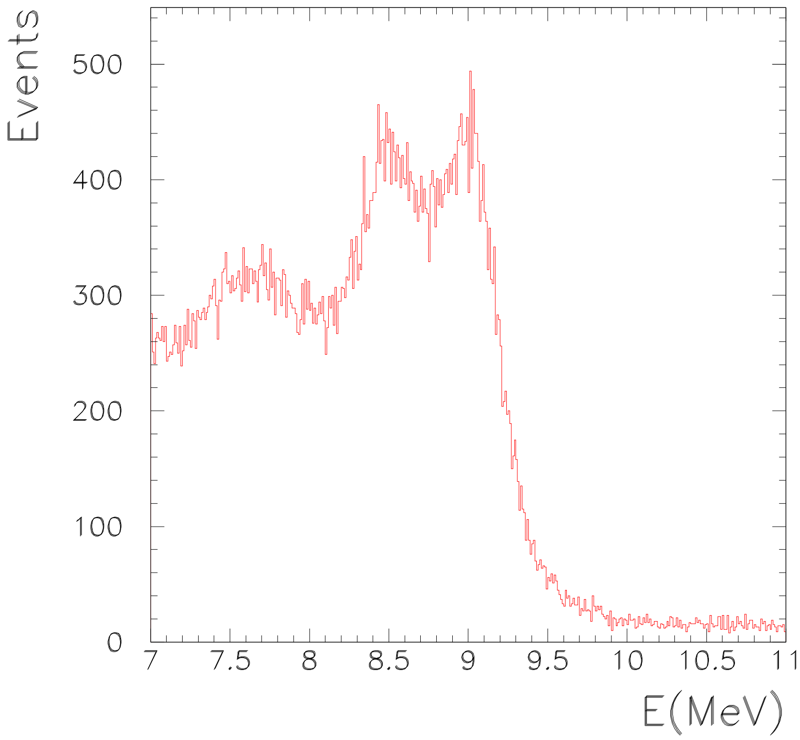

Figure 9: The thermal-neutron capture γ-lines in Nickel as measured by a large NaI detector

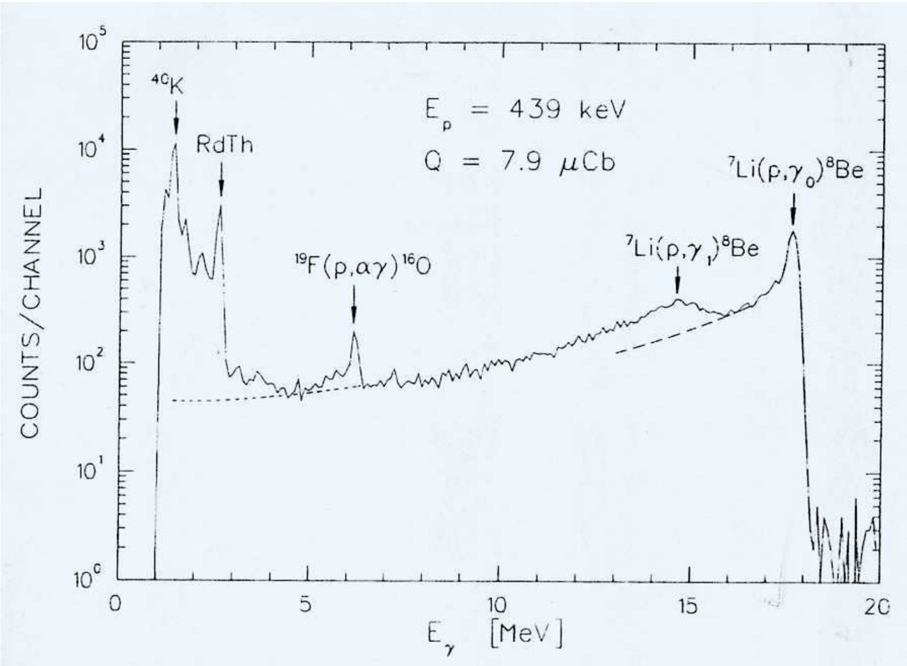

Figure 10: γ-lines from 440 keV protons on a LiF target

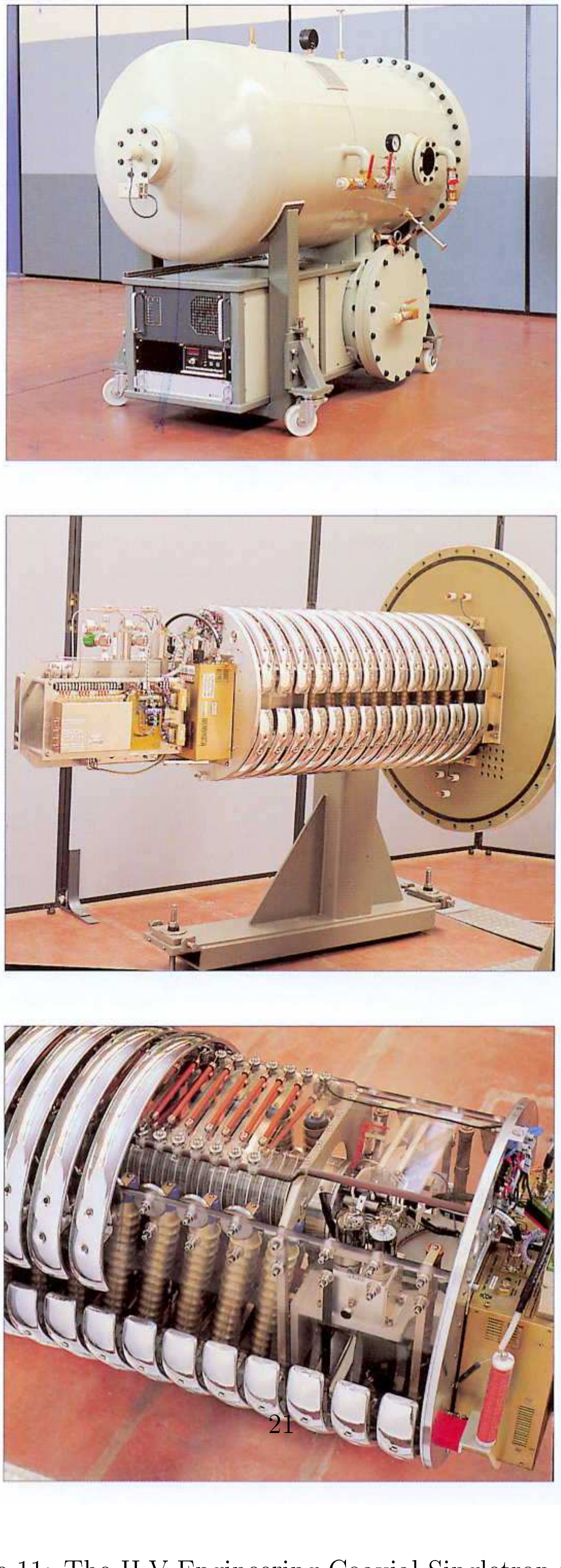

Figure 11: The H.V.Engineering Coaxial Singletron C-W .