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Positron spectrometer of MEG experiment at PSI

O.A. Kiselev *

Paul Scherrer Institut, Villigen CH-5232, Switzerland

For the MEG Collaboration

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ABSTRACT

The Muon to Electron and Gamma (MEG) experiment aims to measure the lepton flavour violating decay $\mu^+ \to e+\gamma$ with a sensitivity $\sim 10^{-13}$ in order to probe new physics beyond the standard model. One of the most important part of the experimental setup is the new positron spectrometer built at the Paul Scherrer Institute. The positron spectrometer consists of a superconducting solenoidal magnet with a highly graded field, a very low-mass drift chamber system and a precise time measuring system. The layout and the parameters of the positron spectrometer are described.

1. Introduction

The main goal of Muon to Electron and Gamma (MEG) experiment [1] is the search for the lepton flavour violating decay $\mu^+ \to e+\gamma$ with a sensitivity of 10^{-13} in branching ratio. This is two orders of magnitude better than the last measured value [2]. The above-mentioned decay is a forbidden process in the Standard Model (SM) of the electroweak interactions but allowed in the supersymmetric extensions of the SM, such as Grand Unified Theories (GUT) within, for example the SO(10) framework [3,4].

The $\mu^+ \to e+\gamma$ signal has a simple topology and appears as 2-body final state of a positron and γ, emitted in the opposite directions with the energy of 52.8 MeV each, corresponding to half of the muon mass. In spite of the simplicity of the signal, the experiment will have a substantial background originating from the accidental coincidence of the positrons coming from the Michel decays and the γ-rays coming from the radiative muon decay or positron annihilation. Measurements of the rare reactions beyond the Standard Model require specially designed detectors and setups. In the case of MEG, they are the liquid xenon calorimeter; the precise timing counter and the positron spectrometer. All the components have been built aiming at ultimate performance.

One should also mention that the importance of experiments like MEG is due to their providing a complementarity to the CERN Large Hadron Collider (LHC) experiments as probes of SUSY-GUT scenarios. Even in the presence of a discovery machine like the LHC, flavour physics experiments will still play an important role in the hunt for new physics. Potentially, an experiment with low-energy leptons might be cleaner and more sensitive to LFV than a high-energy hadron experiment. Moreover, the MEG experiment has some chances to provide a hint of new physics before the LHC will run at the full luminosity.

2. General considerations of the spectrometer design

The detection of the γ-rays will be performed by the liquid xenon calorimeter [5], one of the largest in the world and the detection of the positrons by the positron spectrometer. The MEG positron spectrometer has been designed according to the Monte Carlo simulations taking into account all the detector material and the support structures. Lessons learned from the previous experiments that studied the same reactions are also taken into account. The spectrometer has to fulfill several strict requirements: (a) it must work with a very high muon rate of up to 10^8 per second provided by the PSI accelerator; (b) since the momentum resolution is limited primarily by multiple scattering, the tracker must have as small as possible mass but good 2D position resolution and (c) the timing resolution should also be as good as possible. A low mass system also prevents the generation of γ-particles.

3. Superconducting magnet

The MEG positron spectrometer "COBRA" (COnstant Bending RAdius) consists of a special superconducting solenoidal magnet [6] with the tracker inside, accomplished by a fast timing system. The COBRA magnet changes radius along the z-axis as one can see in Fig. 1. As a result, its field changes from 1.27 T at $z=0$ and decreases as $|z|$ increases, reaching 0.49 T at $z=1.25$ m). The graded magnetic field forces positrons with the same absolute momenta to follow trajectories with a constant projected bending radius, independent of the emission angles.

* Tel.: +41 56 310 3671; fax: +41 56 310 5230.
E-mail address: oleg.kiselev@psi.ch

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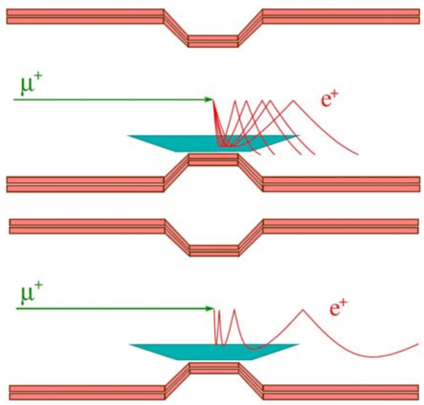

Fig. 1. A typical movement of positrons emitted at different angles in a graded solenoidal field of COBRA. Trapezoids schematically show the drift chambers.

This allows a discrimination of high-momentum signal positrons from the Michel positrons originating from the target—the positron background. Thus, tracking is not required at smaller radius. Drift chambers will measure the high-momentum positrons and will not see most of the softer positrons. Another feature of the spectrometer is that the positrons emitted at angles very close to 90° are quickly swept away from the sensitive volume. In comparison, in a uniform solenoidal field they would make few turns before leaving the detector. All these features make the track reconstruction and the operation of the drift chambers more effective.

4. Design of the drift chambers

One of the most difficult requirements was to minimize the amount of material used in the drift chambers. The concept of open-frame construction was chosen—the frames holding the anode and field wires have an opening on the side close to the muon stopping target, this allows positrons to be detected without scattering in the chamber frames. The frames themselves are made out of carbon fibre—a light and strong material, and are pre-tensioned before attaching the wires. The whole procedure of assembling the chambers is very delicate, so prototypes were made to verify all the steps.

The schematic layout of one chamber is shown in Fig. 2. The pitch of anode-field wires is 4.5 mm; all the wires are positioned horizontally along the z-axis of the spectrometer, forming sensitive cells in the radial direction. As one can see, each chamber consists of two sections, shifted by a half-pitch, allowing solving of the left–right ambiguity. The sections are separated from each other by the cathode planes made out of polyamide foils with a thickness of 12.5 μm. The same kind of foils form the gas volume of the chamber. During the assembly, these foils were stretched in order to keep them flat and avoid distortions of the electric field due to a variation of anode–cathode distance. The amount of material in the fiducial volume due to very light construction together with the use of He–C_2H_6 gas mixture, corresponds to only $1.5\times10^{-3}\,X_0$.

Good position resolution along the z-axis is obtained by using resistive anode wires and cathode strips, having a zigzag structure, the so-called “vernier pads” [7]. This allows the number of readout channels (and the electronic boards inside the spectrometer) to be kept relatively small. The reconstruction of a coordinate works in a following way—first the fired cell and preliminary position is defined by the charge division method from the resistive anodes and second, this position is corrected using the information from the cathode strips. As one can see

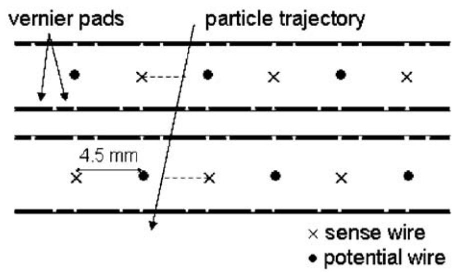

Fig. 2. Layout of the double-layer drift chamber. Vernier pads are printed on the inner sides of the 12.5 μm foils forming the gas volume. Anode–cathode distance is 3.5 mm.

from Fig. 2, one anode wire and two cathode strips on both sides of the plane define the active cell. Two signals from the anode and four signals from cathodes are recorded for each hit; this allows the determination of the z coordinate with a precision of ~300 μm, demonstrated using the test setup [8].

As one needs to make a precise comparison of the charges as well as a good determination of the drift time, it has been decided to digitize the wave forms of all signals. This solution allows the suppression of pile-up more effectively than in the case of having conventional electronics. The same type of readout is used for the liquid xenon calorimeter and the timing counter. For this purpose, a new Domino Ring Sampling (DRS) chip has been developed at PSI [9]. Each chip contains eight channels which are digitized at up to 5 GHz (adjustable) with a resolution of 12 bits. Custom-built VME boards have 4 DRS chips (total 32 channels) and an FPGA which makes a calibration and zero suppression in real time. It has been demonstrated that this solution allows the effective separation of events at less than 10 ns.

The extremely thin foils of the drift chambers require controlling the gas pressure inside the chambers and the pressure difference between the inside and the outside volume very precisely. Calculations show that in order to keep gas gain and drift-time variations small enough, one needs to have gas pressure difference less than 1 Pa. It has been demonstrated that an electronically controlled gas mixture system with precise gas flowmeters, valves and differential pressure sensors allows the pressure difference to be kept at less than 0.5 Pa, independent of the variation of atmospheric pressure and gas flow.

5. Time and position resolution of the spectrometer

Time coincidence between γ-rays and positrons is an important observation of the experiment. The time of positron production is deduced from the signal in the timing counter projected back to the target. The timing counter consists of two separate subsystems—the scintillating bars (with PMT readout) providing the time measurement and the scintillating fibres (with APD readout) for measurement of the z-position of the positron track. Careful design of the key components enabled the apparatus to record one of the best time resolutions measured at 43 ps (σ). This result completely fulfills the requirement of the experiment.

The intrinsic spatial resolution of the drift chambers has been carefully studied before the production of the full set of detectors started. A spatial resolution of 200 μm (σ) is obtained in the transverse direction (via drift time measurement). The position resolution in the longitudinal direction (along the anode wires) is varied from 300 to 500 μm (σ). All 16 double-layer chambers have been installed in 2007 (Fig. 3) and long-term operation of the MEG gas system verified. It has been shown that the pressure difference between outside (COBRA magnet) and inside (drift chambers) gas volumes could be kept with even better than the required

Fig. 3. Drift chambers and muon stopping target installed inside the COBRA magnet.

precision for a long time. The positions of all chambers and the muon stopping target have been measured via a precise optical system. The final alignment of the chambers in space is performed using the high statistics of positron tracks. The momentum resolution of the order 0.4% for 52.8 MeV positrons has been estimated using Geant3 simulations taking into account all material in the sensitive area and resolutions of the drift chambers measured during the tests. Data accumulated during the commissioning run in 2007, show that the momentum resolution, even using adaptive Kalman filter technique, was slightly worse than the simulated value. One reason is the electronic noise coming from the environment, which was higher than expected. This prevented proper treatment of the hits with a small energy deposition. An intensive effort is underway to reduce the electronic noise; in any case, the momentum resolution reached allows an efficient reconstruction of the positron tracks.

6. Conclusions

The positron spectrometer of MEG with a very high time, position resolution and having extremely low mass detectors is a unique device of its kind. All parts of the spectrometer are installed, tested and show a stable operation. The physics run of MEG started in the second part of 2008; data analysis is ongoing. Taking into account parameters of the positron spectrometer and the liquid xenon calorimeter and the power of pulse shape analysis of all signals, one expects very high sensitivity to the branching ratio of $\mu^+ \rightarrow e+\gamma$ decays will be reached.

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