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The 10 bar hydrogen time projection chamber of the MuCap experiment

Johny Egger, Malte Hildebrandt *, Claude Petitjean

Paul Scherrer Institute, Olga/019, CH - 5232 Villigen PSI, Switzerland

On behalf of the MuCap Collaboration

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ABSTRACT

The experimental goal of the MuCap experiment at the Paul Scherrer Institute (PSI) is a high-precision measurement of the singlet capture rate of the nuclear muon capture on the free proton in the reaction $\mu^- + p \rightarrow n + \nu_\mu$. The measuring principle is a lifetime measurement whereas the experimental approach is based on a specially developed Time Projection Chamber (TPC) operating with ultra-pure and deuterium-depleted hydrogen gas at a pressure of 10 bar. The TPC acts as an active muon stop detector and the 10 bar hydrogen operates as target and detector. Design, construction and operation of the Time Projection Chamber are presented.

1. Introduction

The MuCap experiment [1,2] is a new muon lifetime experiment designed to measure the singlet capture rate Λ_S of the semileptonic electroweak process of nuclear muon capture on the proton in the reaction $\mu^- + p \rightarrow n + \nu_\mu$. The measurement of Λ_S to a precision of 1% allows to determine the least well known of the nucleon charged-current form factors, the induced pseudoscalar coupling constant g_p, to a precision of 7% [3].

The interpretation of measurements of ordinary muon capture or radiative muon capture in a hydrogen target of high density relative to liquid hydrogen is difficult, e.g. due to the formation of mesic molecules pμp and subsequent processes, i.e. ortho–para transitions in pμp [4,5]. The MuCap experiment has avoided these problems by using a gaseous hydrogen target with a density of $0.012 \cdot \rho_{liquid}$ where pμp formation is slow and nearly all captures proceed from the μp singlet state [6].

The measuring principle of the MuCap experiment is a lifetime measurement. Each muon stop in the gaseous hydrogen target is identified by the specially developed Time Projection Chamber (TPC) and the decay electron is detected by surrounding wire chambers and a plastic scintillation hodoscope. This setup allows to measure the $\mu^- p$ lifetime to highest precision. The capture rate Λ_S is determined from the difference of the $\mu^- p$ lifetime, λ^-, and the lifetime λ^+ of the free μ^+:

$$\Lambda_S = \lambda^- - \lambda^+.$$

2. The MuCap experiment

The MuCap experiment was performed at the Paul Scherrer Institute (PSI) in Switzerland using the π E3 muon beam line of the 590 MeV proton accelerator. The detector was especially designed to perform a high precision measurement of the $\mu^- p$ lifetime. Fig. 1 shows a simplified cross-section of the setup.

The muon beam enters from the left and each incoming muon is detected by a plastic scintillator (μSC) and a planar multiwire proportional chamber (μPC). By passing through a 0.5 mm thick hemispherical beryllium window the muon enters an aluminum pressure vessel which is filled with ultra-pure and deuterium-depleted hydrogen gas at a pressure of 10 bar and at ambient room temperature. The Time Projection Chamber (TPC) is placed inside the pressure vessel and acts as an active muon detector. The trajectory of each incoming muon is three-dimensionally tracked in the TPC and this allows a 100% μ−stop identification inside the gas volume and the selection of good muon stops by rejecting stops in the detector walls.

The pressure vessel with the TPC is surrounded by two cylindrical multiwire proportional chambers (ePC1 and ePC2) and a scintillation hodoscope (eSC) consisting of 16 segments with two layers of plastic scintillator. This tracking system covers a 3π solid angle acceptance for the outgoing decay electron from the muon decay.

The signal readout of the TPC and the ePCs was realized with custom-built time-to-digital converters (TDCs), whereas the μSC and eSC were recorded in separate CAEN TDCs. For dedicated analysis, the TPC anodes were in addition recorded with FADCs.

* Corresponding author. Tel.: +41 56 310 2145; fax: +41 56 310 2199.
E-mail address: malte.hildebrandt@psi.ch (M. Hildebrandt).

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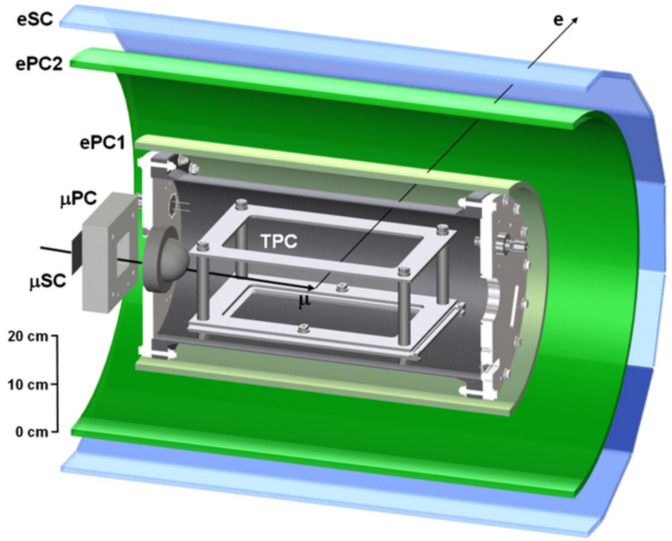

Fig. 1. Simplified cross-section of the MuCap detector. The incoming muons are detected by a plastic scintillator (μSC) and a planar multiwire proportional chamber (μPC) before they are stopped in the TPC. The TPC itself is located in the center, in a pressure vessel, and is surrounded by two cylindrical wire chambers (ePC1 and ePC2) and a scintillation hodoscope (eSC).

3. Construction of the TPC

Fig. 2 shows an overall view of the Time Projection Chamber (TPC) which was especially developed for the MuCap experiment. The TPC is operated at ambient room temperature and with hydrogen at 10 bar and acts as an active muon stop detector. The detector has a sensitive volume of $(15 \times 12 \times 30)\,\mathrm{cm}^3$. This volume is enclosed by the high voltage drift cathode on top and by a multiwire proportional chamber with two-dimensional readout at the bottom.

The high voltage drift cathode on top of the sensitive volume is made of a wire plane consisting of 50 μm thick gold-plated W wires (containing 3% Re) with a spacing of 1 mm. The vertical drift height of the sensitive volume is 12 cm. Four pillars, made of the glass-ceramics MACOR,[1] ensure the mechanical stability of the complete assembly. Seven field forming wires made of copper are stretched around the pillars and are connected via a resistor chain to form a homogeneous drift field (see Fig. 3). Each resistor has a resistance of 5 GΩ.

The multiwire proportional chamber at the bottom of the sensitive volume consists of two cathode wire planes and one anode wire plane. The cathode wires are stretched in longitudinal (beam) direction. They have a diameter of 50 μm and a spacing of 1 mm. Four adjacent cathode wires are each grouped together for the cathode signal readout. The anode wires have a diameter of 25 μm and they are mounted perpendicular to the beam direction with a wire spacing of 4 mm. The half gap of the multiwire proportional chamber is 3.5 mm.

The high voltage applied to the wire planes during physics data taking was typically −29.4 kV for the high voltage drift cathode and −5.4 kV for the cathode wire planes of the multiwire proportional chamber. This high voltage configuration created a vertical drift field in the TPC of 2 kV/cm. The anode wires were kept on ground potential.

The TPC is mounted on an aluminum fork which is fixed to the downstream flange of the pressure vessel (see Figs. 2 and 3). All feedthroughs for the signal and high voltage lines are routed through this downstream flange made of stainless steel. In order to keep electrical noise pickup and wire capacities as low as possible the preamplifiers for the anode and cathode signals are mounted close to the outside part of the downstream flange.

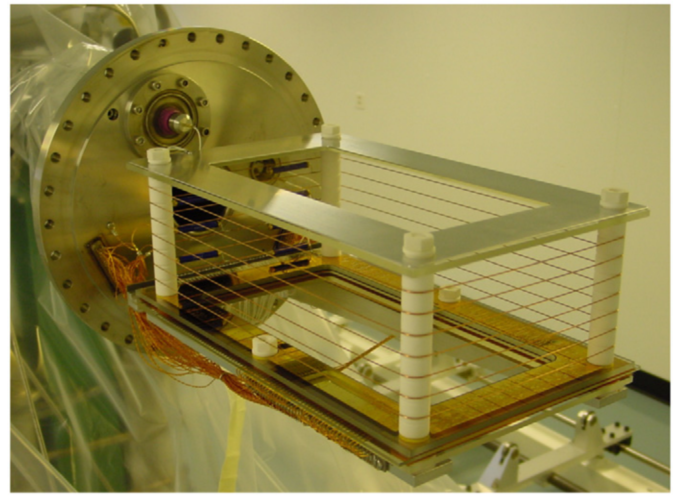

Fig. 2. The Time Projection Chamber of The MuCap experiment. The sensitive volume has a size of $(15 \times 12 \times 30)\,\mathrm{cm}^3$ and is enclosed by the drift cathode wire plane at the top and by a multiwire proportional chamber at the bottom. The TPC is fixed to the downstream flange of the pressure vessel, whereas the cylindrical part of the pressure vessel is removed for this photo.

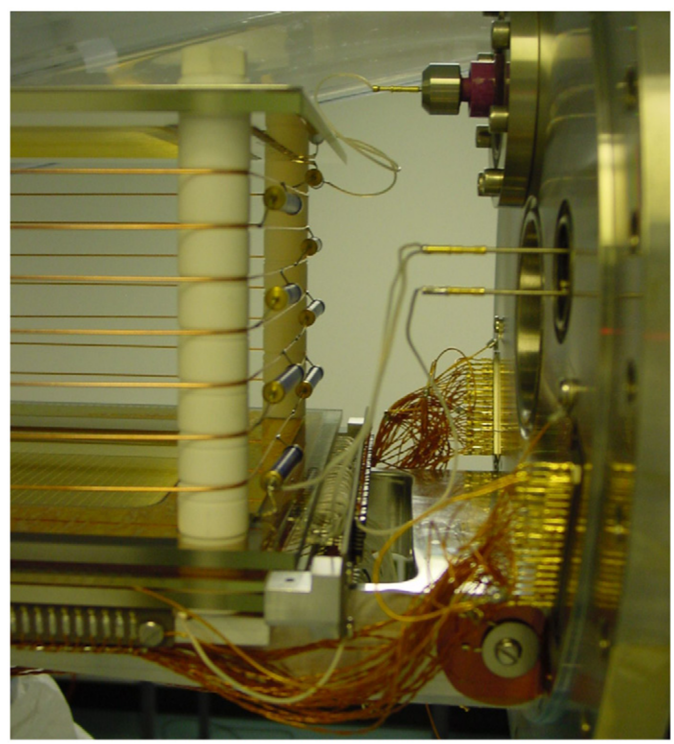

Fig. 3. The downstream part of the Time Projection Chamber and the downstream flange of the pressure vessel. The MACOR pillars in the corners of the sensitive volume ensure the mechanical stability. The field forming wires are connected by a resistor chain. The downstream flange of the pressure vessel houses the feedthroughs for signal cables and HV.

3.1. Selection of materials

The rate for muon transfer and muon capture to high-Z impurities (e.g. C, N, O) is enhanced by several orders of magnitude due to their larger binding energies. As the muon

[1] Registered trademark, Corning Inc., New York, USA.