

The 10 bar Hydrogen Time Projection Chamber of the MuCap Experiment

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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.

Key words: time projection chamber, high pressure, hydrogen, muon capture

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 $p\mu p$ and subsequent processes, i.e. ortho-para transitions in $p\mu p$ [4, 5]. The MuCap experiment has avoided these problems by using a gaseous hydrogen target with a density of $0.012 \cdot \rho_{\text{liquid}}$ where $p\mu p$ 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 $\pi E3$ muon beam line of the 590 MeV proton accelerator. The detector was especially

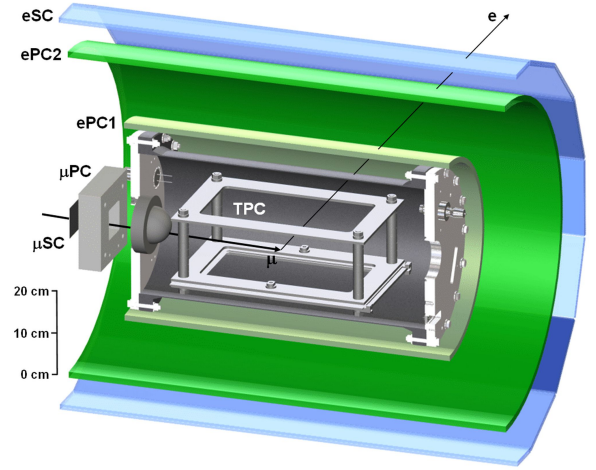


Figure 1: Simplified cross-section of the MuCap detector. The incoming muons are detected by a plastic scintillator (μSC) and a planar multiwire proportional chamber (μPC) before they are stopped in the TPC. The TPC itself is located in the center, in a pressure vessel, and is surrounded by two cylindrical wire chambers ($e\text{PC1}$ and $e\text{PC2}$) and a scintillation hodoscope ($e\text{SC}$).

designed to perform a high precision measurement of the $\mu^- p$ lifetime. Figure 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 3-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 cylin-

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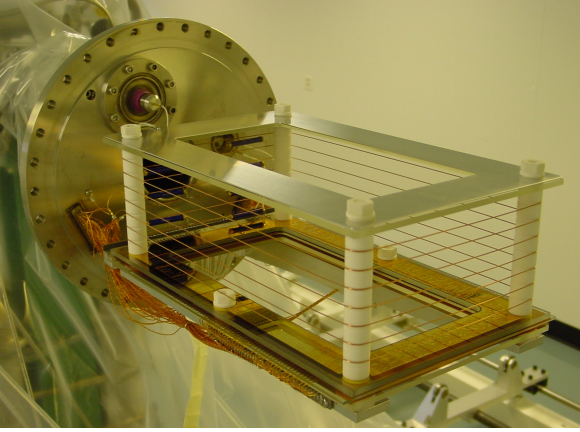


Figure 2: The Time Projection Chamber of The MuCap experiment. The sensitive volume has a size of $(15 \times 12 \times 30) \text{ cm}^3$ and is enclosed by the drift cathode wire plane at the top and by a multiwire proportional chamber at the bottom. The TPC is fixed to the downstream flange of the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

drical 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 ePC s 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.

3. Construction of the TPC

Figure 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 $(15 \times 12 \times 30) \text{ cm}^3$. This volume is enclosed by the high voltage drift cathode on top and by a multiwire proportional chamber with 2-dimensional readout at the bottom.

The high voltage drift cathode on top of the sensitive volume is made of a wire plane consisting of $50 \mu\text{m}$ 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 MACOR¹, 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 Figure 3). Each resistor has a resistance of 5 G Ω .

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

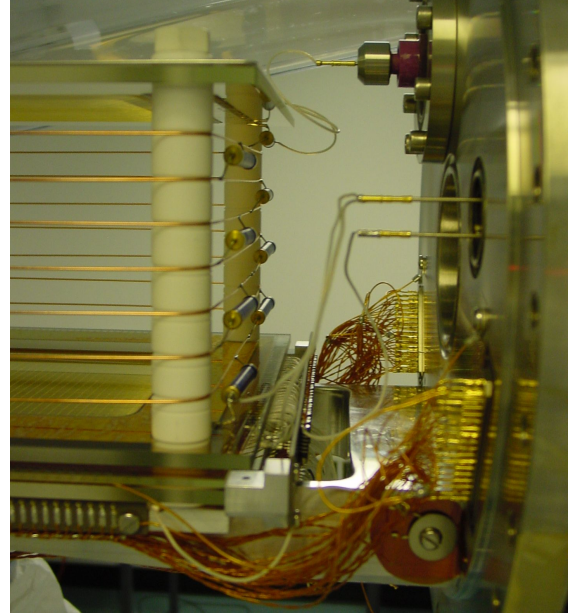


Figure 3: The downstream part of the Time Projection Chamber and the downstream flange of the pressure vessel. The MACOR pillars in the corners of the sensitive volume ensure the mechanical stability. The field forming wires are connected by a resistor chain. The downstream flange of the pressure vessel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

(beam) direction. They have a diameter of $50 \mu\text{m}$ 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 $25 \mu\text{m}$ 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 Figure 2 and Figure 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.

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 captures on impurities distort the measured lifetime curve, the impurities must be kept at a ppb level during physics data taking.

Therefore, all materials for the TPC, like e.g. glass, ceramics, Kapton or Teflon, were carefully selected to be low-outgassing and suitable for high vacuum operation. In order to remove

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

water from the surfaces of the aluminum pressure vessel and of the TPC construction and to further reduce the outgassing rate, all materials needed to withstand longterm heating cycles up to temperatures of 110 °C which were executed in advance of each physics data taking run period.

Due to these requirements all wire frames are made of borofloat glass to match their thermal expansion with the soldering pads. The thickness of the frames is 5 mm for the cathode frames and 2.5 mm for the anode frame, respectively. The soldering pads for the wires are composed of a special Au-Ni-Au sandwich layer and they are applied directly on the glass frame using a titanium undercoating. This special composition ensures that there is no cracking or peeling off of the soldering pads during the heating cycles. In addition, due to the low thermal expansion coefficient of borofloat glass any additional forces on the wires during the heating cycles are prevented. After soldering the wires the soldering flux was immediately removed with hot water and alcohol. Prior to the assembly of the TPC all wire planes were cleaned in an alcohol bath which was equipped with a circulation pump and dust filters. The MACOR pieces and all cables were cleaned in an ultra-sonic bath filled with alcohol.

All cleaning procedures, the final assembly of the TPC and the closing of the pressure vessel took place inside a clean room.

4. Gas System

A sophisticated high vacuum and gas handling system was constructed, including e.g. a turbomolecular pump combined with an oil-free fore-vacuum pump, stainless steel tubes and valves, vacuum connections sealed with metallic gaskets and a mass spectrometer.

The main pumping down of the pressure vessel was performed through a tube with ~70 mm inner radius. Prior to physics data taking the complete setup with the TPC was heated up to 110 °C under high vacuum for several weeks to remove water and remaining impurities. After this treatment a residual pressure of less than 10^{-7} mbar was reached in the system during pumping.

The initial filling of the system with deuterium-depleted hydrogen was done through a palladium filter to remove impurities from the gas. For the filling procedure the gas handling system was equipped with several stainless steel bottles with a volume of 10 l each, a Zeolite bed and two hydride storage beds.

To remove traces of impurities from the unavoidable remaining outgassing and to keep the impurity level below 50 ppb during long data taking periods a "Circulation Hydrogen Ultra-high Purification System (CHUPS)" [7] was constructed. The gas was continuously circulated by an absorption cryopump system and it was cleaned by Zeolite and activated carbon filters at liquid nitrogen temperature.

In addition, the high vacuum and gas handling system was equipped with several ports for sample volumes of up to 1 l which allowed to take gas samples for gas chromatography

analysis. The gas handling system was also used to generate gas samples with a precisely defined admixture of impurity gases and to inject a well defined portion of these "impurity" samples into the pressure vessel. This gave the opportunity to study and to calibrate the effect of impurities on the muon capture event data.

5. Gaseous Physics

The Time Projection Chamber is operated with hydrogen at 10 bar which acts as target and as counting gas. Gaseous physics and the operation of the detector are rather challenging, as hydrogen is not a suitable gas for operating gaseous detectors. Hydrogen has a low breakdown voltage and does not provide absorption of ultraviolet photons. There is no "quenching" of ultraviolet photons originating e.g. from the avalanche process close to the anode wires. Consequently these photons may travel over long distances and they may generate new charges due to the photo-electric effect on metallic surfaces.

Although there is world-wide only limited experience with proportional chambers operating with hydrogen, some basic parameters were established in [8]. Several prototypes were constructed at PNPI (Gatchina, Russia) [9] and at PSI [10], and they were tested with radioactive sources in the laboratory as well as with muon beams at PSI in order to achieve two goals: firstly, to optimize the operating conditions, and secondly, to establish ultra-clean chamber construction procedures for a stable longterm operation during physics data taking.

The drift field of 2 kV/cm in the sensitive volume of the TPC leads to a drift velocity of 0.55 cm/ μ s for the electrons from primary ionization along the incoming muon tracks. Due to the short drift length and the relatively high granularity of the anode wire spacing and of the cathode signal readout, neither longitudinal nor transversal diffusion are limiting the performance of the TPC. Electron attachment to electronegative impurities does not play a role because of the ultra-clean running conditions with an impurity level of lower than 50 ppb.

Gain factors of up to $1 \cdot 10^4$ could be achieved in the multi-wire proportional chamber for the charge amplification [9, 10]. However, during the main physics data taking lower gas gains of 100 to 300 were chosen due to longterm stability issues.

6. Performance

The MuCap experiment was successfully operated during four physics data taking runs between 2004 and 2007. For physics data taking a dc muon beam of ~20 kHz with a central momentum of 32.6 MeV/c was used. Taking into account pileup protection, dead times and efficiencies, good μ -stops were recorded with a rate of ~3.5 kHz. The stopping distribution inside the TPC is shown in Figure 4. A total statistics of $\sim 1.5 \cdot 10^{10}$ good μ^- events was accumulated. The data from the first run in 2004, representing about 13 % of the final statistics, has been analysed and published in [2].

During the physics data taking run periods the TPC worked as a fully efficient μ -stop detector. This was essential to ensure

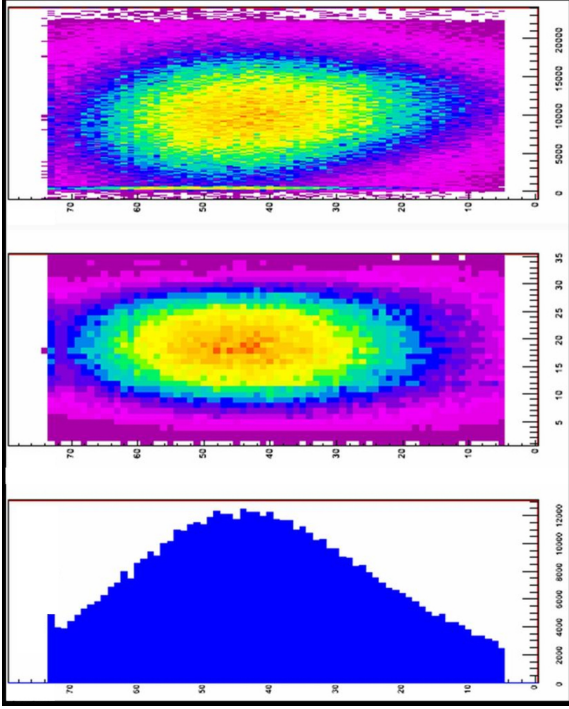


Figure 4: Stopping distribution inside the Time Projection Chamber when the μ beam enters from the right side. Top: side view, middle: top view, bottom: anode stopping distribution along the beam direction.

a clear μ -stop identification inside the gas volume and to reject wall stops for the selection of good μ -stops.

The gas gain of the multiwire proportional chamber was even large enough to detect the signals from reactions with charged particle emission, e.g. the signals of the recoil nuclei from muon captures to high-Z impurities or of the Auger-electrons from the de-excitation of impurity muonic atoms.

Figure 5 shows, as a proof of the detection capability of the TPC, an example of a rare impurity capture event, recorded with the FADC readout of the TPC. An incoming muon stops and transfers to an impurity atom, e.g. C, N or O. During the de-excitation of the impurity muonic atom an Auger electron is emitted and detected by the TPC. After some time, but on the same anode as the μ -stop, a huge signal from the capturing nucleus recoiling against the neutrino is observed.

7. Conclusion

The experimental goal of the MuCap experiment is the measurement of the singlet capture rate Λ_s of the nuclear muon capture on the proton in the reaction $\mu^- + p \rightarrow n + \nu_\mu$. The central idea of this new approach is the use of an active muon target.

The MuCap collaboration therefore developed a new Time Projection Chamber (TPC) which is operated with hydrogen at a pressure of 10 bar and which acts as target and detector. The impurities in the hydrogen gas could be kept below the 50 ppb level and consist primarily of water vapour and nitrogen.

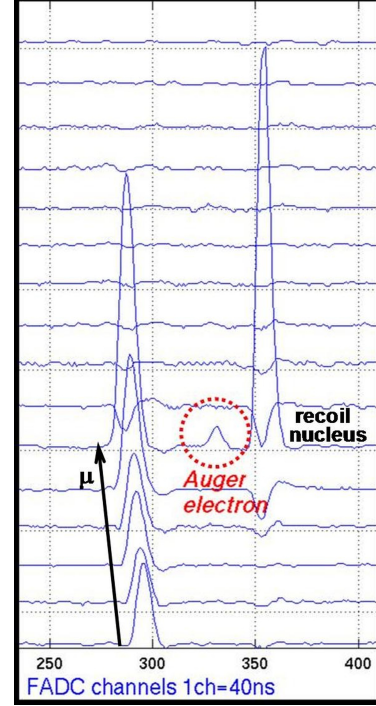


Figure 5: Rare impurity capture event occurring at the 10^{-5} level, recorded with the FADC readout of the TPC. The incoming muon (black arrow) stops and transfers to an impurity atom. An Auger electron is emitted during the de-excitation of the impurity muonic atom. Separated in time, but on the same anode as the μ -stop, a huge signal from the recoil nucleus is observed.

The new MuCap hydrogen TPC described in this paper has reached and maintained excellent performance as a muon stop and capture detector. During about 40 weeks of operation in the PSI muon beam a statistics of $\sim 1.5 \cdot 10^{10}$ good muon stops were recorded allowing to reach the experimental goal to determine the singlet $\mu^- p$ capture rate Λ_s to 1 % accuracy.

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