A Hydrogen TPC for the Mucap Experiment – draft June-19-09

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Abstract

The Mucap experiment at the Paul Scherrer Institute is a high-precision measurement of the singlet rate of the basic electroweak process $\mu^- + p \rightarrow n + \nu_\mu$ (muon capture on the proton). The experimental approach is based on the use of a specially developed Time Projection Chamber (TPC) operating with ultra-pure hydrogen gas at 10 bar and acting as an active muon stop target. Each muon stop in the gas is identified by the TPC and its decay electron is detected by surrounding wire chambers and a plastic scintillation hodoscope. The TPC allows in connection with the electron detector to measure the μ^-p lifetime to highest precision from which the capture rate is deduced. The design of the TPC and its experimental performance is described in detail.

1. Introduction

The Mucap experiment [1,2] at the Paul Scherrer Institute (PSI) is designed to measure the rate Λ_S for the basic electroweak process of nuclear muon capture on the proton in the reaction $\mu^-p \rightarrow n + \nu_\mu$ at the highest possible precision. A measurement of Λ_S with 1% accuracy determines the least well known of the nucleon charged current form factors, the induced pseudoscalar coupling constant g_P, to 7% [3]. The experiment was performed with a specially developed time projection chamber (TPC) using low energy muons at the πE3 beamline of PSI's 590 MeV proton accelerator.

1.1 . Technical requirements for the Mucap experiment

To reach the anticipated precision a number of experimental conditions have to be fullfilled:

- The only known way for a precise determination of the capture rate Λ_S is using the lifetime method, i.e. observing the difference of the μ^-p lifetime λ^- with respect to the

free μ^+ lifetime λ^+, from which Λ_S is deduced according to the relation $\Lambda_S = \lambda^- - \lambda^+$. Other methods, e.g. direct measurement of the absolute neutron yield from the μ^-p capture reaction, do not achieve the required precision.

- The measurements must be performed in hydrogen gas of low density, typically 1% of liquid hydrogen density, corresponding at 300 K to a gas pressure of ~10 bar. At this density lifetime distorting effects from meso-molecular processes like the formation of pμp mesic molecules are small [2].
- The hydrogen gas must be kept under ultra-clean conditions with impurity concentration ratios at or below the 10 ppb level. This stringent requirement is necessary, because the neutral μ^-p atoms can get transferred in atomic collisions to higher Z impurity elements due to their larger binding energies. Muon decays from impurities distort the pure μ^-p lifetime curve.
- The hydrogen gas used for μ^-p formation must be strongly depleted from the naturally abundant deuterium isotope, typically to a level below 100 ppb. Such hydrogen is called “protium”. The use of protium is required to avoid possible transfer reactions μp + d → μd + p, after which the μd atoms can diffuse over large distances (Ramsauer-Townsend effect).
- Each muon stop must be clearly identified to be located well inside the hydrogen gas target, because decays from stops in target walls would also distort the lifetime curve.

1.2. Concept of a TPC as Mucap detector

To meet simultaneously all these technical requirements we have constructed the experimental apparatus shown in Fig. 1 which employs three main functional parts:

1) The muon beam telescope consisting of plastic scintillation counters μSC, μSCA and wire chamber μPC registers each muon before entering the TPC vessel and records the start of the lifetime.
2) The TPC operates in protium gas and acts as active muon target. The tracks of each muon are reconstructed in three dimensions to its stop point. The TPC records also charged particle tracks from nuclear reactions, e.g. from muon capture on impurities.
3) The electron detector surrounds the TPC vessel. It is composed of two cylindrical wire chambers ePC1, ePC2 and a plastic scintillation hodoscope eSC located further outside. It detects the electrons from muon decay and records the end of the muon lifetime. The electron tracks are traced back to the muon stop vertex. This method cleans the data efficiently from accidental background events.

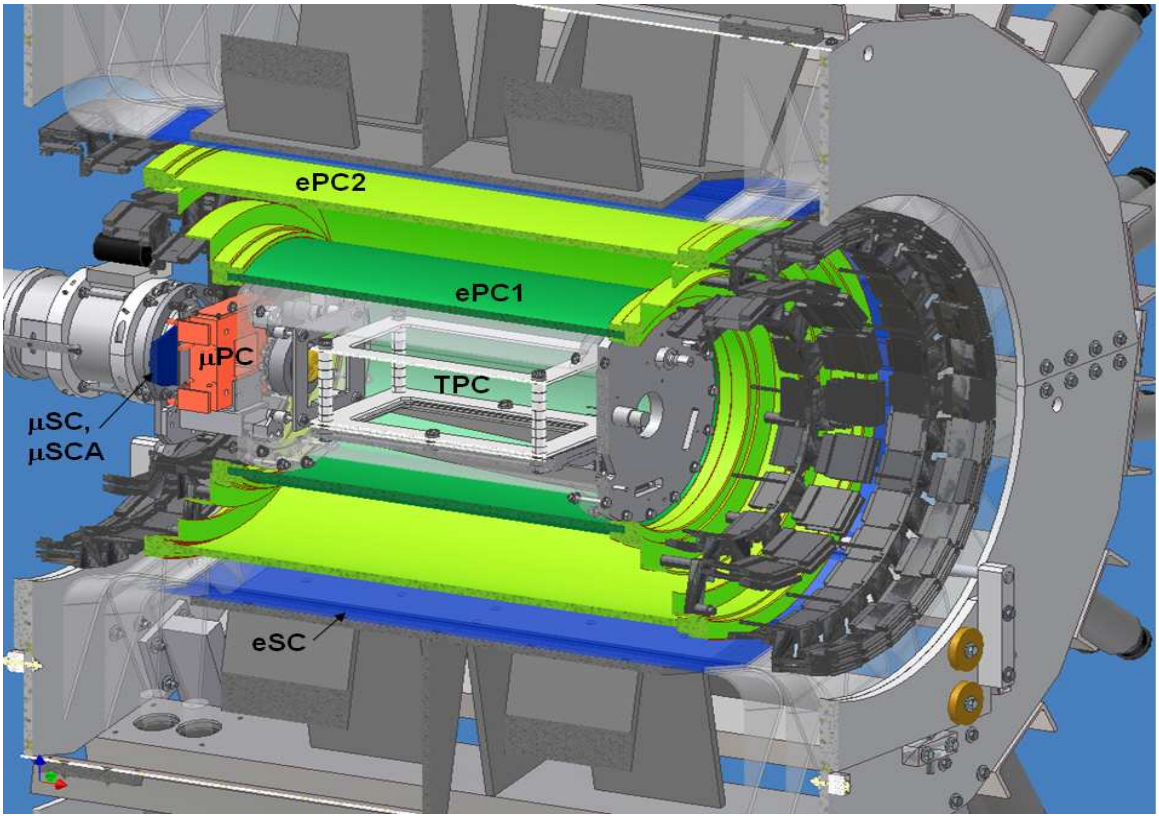

Fig. 1. Cut-out view of the Mucap apparatus. μ^- beam from the left. TPC in the center of a cylindrical pressure tank surrounded by electron detector. The downstream holding structure of the TPC vessel is not shown.

A detailed general description of the Mucap experiment and its apparatus is published in Refs. [2,4,5]. In this paper we describe mainly the TPC and its infrastructure. The TPC sits in the center of a thin walled aluminum pressure cylinder filled with ultra-pure protium gas at 10 bar. It collects the charges of each incoming muon and tracks it to its stop point. Moreover, it visualizes heavily ionizing charged particles, e.g. from muon capture reactions on higher-Z nuclei leading to emission of charged particles and nuclear recoils. The TPC can identify and monitor muon transfers even at lowest impurity levels allowing correction of small distortions of the observed muon lifetime curves.

A first prototype TPC of almost full size was built 1997 in Gatchina and tested during 1998-2000 in a muon beam at PSI [6]. The feasibility to operate it with a stopped muon beam in 10 bar hydrogen was successfully demonstrated. Although the prototype TPC did not fulfill the impurity requirements necessary for the muon capture measurement, it contributed decisively to the expertise needed for the final technical design and construction of the full ultra-pure TPC.

2. Technical design of the final TPC

2.1. TPC construction

The final TPC was constructed and tested in 2001-2004 at PSI. A photo of the first assembly is shown in Fig. 2.

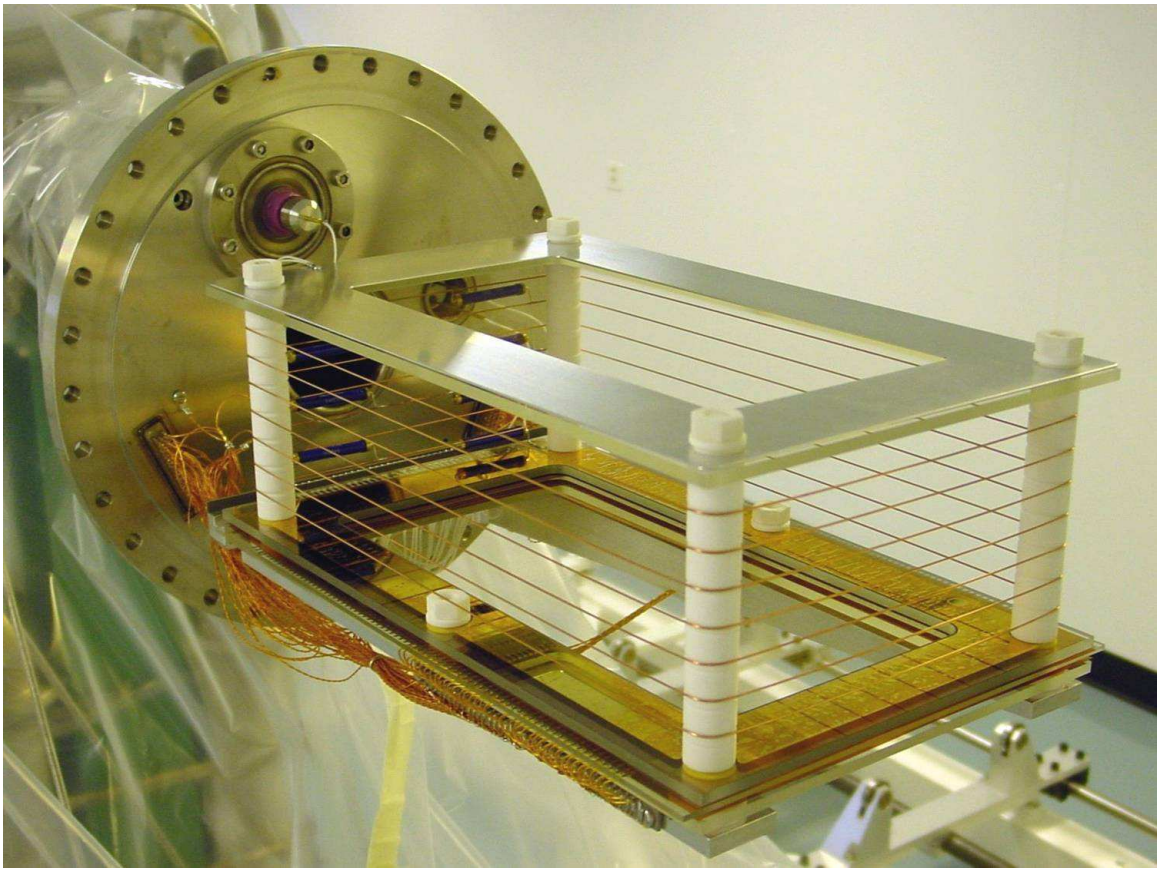

Fig. 2. The final MuCap TPC during first assembly in 2004.

The sensitive TPC volume has dimensions 300 x 150 x 120 mm^3, defined by the frames of the high voltage cathode on top and the multi-wire proportional chamber (MWPC) at the bottom. The free vertical drift length between the frames is 120 mm. The MWPC consists of a set of three frames - upper cathode, anode and lower cathode – spaced 3.5 mm apart, with approximate side dimensions 230 mm x 380 mm (outer edges) and 150 mm x 300 mm (inner free aperture). The whole assembly is fixed by four MACOR metal-oxyde pillars in the corners. The frames are made from special Borofloat glass (thickness of cathodes 5 mm, anode 2.5 mm). On the glass surfaces Ti-Au-Ni pad structures are implanted on which gold-plated tungsten wires are soldered under mechanical tension. The glass frames are made from a material with low temperature expansion coefficient to avoid any excess forces on the wire

tensions during heating cycles. The cathode planes are wired in longitudinal (beam) direction with wire spacings 1 mm, diameter 50 µm. The anode wires are mounted perpendicular to the beam direction with wire spacings 4 mm, diameter 25 µm.

The voltages applied to the wire planes are typically -29.5 kV (HV cathode), -5.5 kV (MWPC cathodes), while the anode is on ground potential. This configuration generates in the TPC a vertical drift field of 2.0 kV/cm. Seven field wires of diameter 1 mm are vertically spaced 15 mm apart and wound around the MACOR pillars. They are connected in series by five high impedance resistors of 5 Giga-Ohm each to define a homogeneous electrostatic potential which ensures in the sensitive volume a field constancy within 1%. Electrons from ionization charges drift down with velocity ~5 mm/µs and get amplified in the MWPC. The maximum drift time top to bottom is 24 µs. Electronic signals are read out from the anode wires to provide the z-coordinate (along the beam) and from the lower cathode wires to provide the x-coordinate (perpendicular to the beam). The (vertical) y-coordinate is defined by the drift time. This setup allows three-dimensional reconstruction of tracks from charged particles.

The TPC is mounted on an aluminum fork fixed downstream of beam to a stainless steel flange which carries all feed-throughs for signals and high voltages (Fig. 2). The flange is held in space by a strong tube downstream along the beam axis. The tube is also used for high vacuum pumping. Outside of the holding flange all preamplifiers are attached. They are mounted as close as possible to keep noise pickup and wire capacities low. The TPC sits in the center of a cylindrical pressure vessel with aluminum walls of thickness 4 mm, inner free diameter 282 mm and length 600 mm. The upstream end the vessel is closed by a second stainless steel flange which carries the beam entrance window, a beryllium half-sphere of thickness 4 mm and radius 35 mm. The thicknesses of aluminum wall and beryllium window are chosen as thin as possible, keeping however the safety standards against possible ruptures.

2.2 Technical concept of TPC and infrastructure

Driven by the extreme purity requirements for the protium gas, a new technical concept of the TPC was developed with a number of important special features. UHV materials are used for all inner surfaces and equipment parts. The materials are mostly metals (Be, Al, Cu, W, Au, stainless steel), metal oxydes (keramics), Borofloat glasses, and Kapton insulated wires. Some small epoxy surfaces are also present. The whole TPC vessel can be baked out under high vacuum conditions up to a temperature of 130 C to reduce outgasing rates as much as possible.

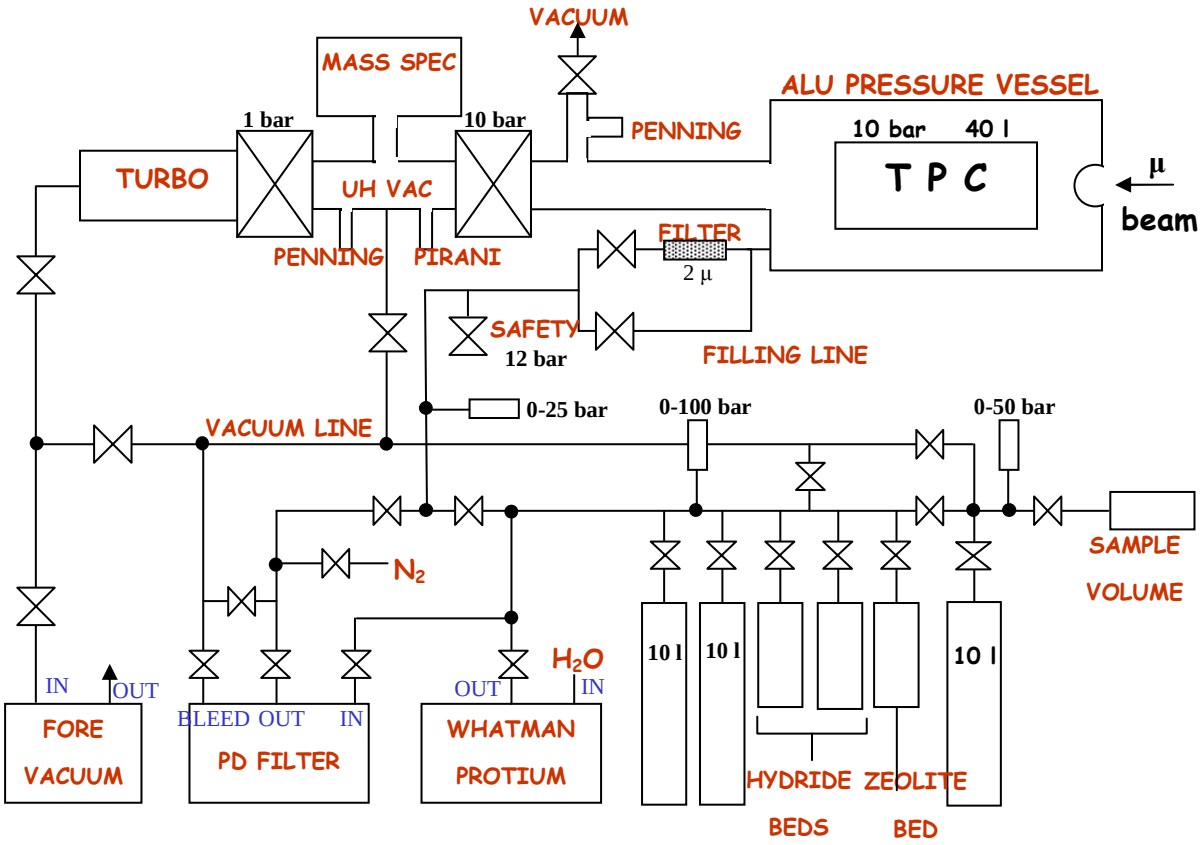

Fig. 3. Schematic layout of the high vacuum and protium gas handling system of the TPC

An elaborate high vacuum and gas handling system was constructed, schematically shown in Fig. 3. High vacuum pumping is performed with a 200 l/s turbomolecular pump combined with oil-free forevacuum pumping. The main pumping of the TPC vessel is made through a 600 mm long holding tube along the axis with 71 mm inner free aperture. The vessel sides are kept free for the electron detection. Vacuum connections are sealed with metallic gaskets, except the two big flanges whre Viton O-rings are used. A purely metallic valve of aperture 70 mm closes the vacuum recipient from the high pressure part. After heating out he whole system a residual pressure below 10^{-7} mbar can be maintained during high vacuum pumping. The vacuum is monitored with penning and pirani gauges. A quadrupole mass spectrometer is installed to determine and survey the composition of the residual gas.

The gas handling system consists exclusively of stainless steel components which can also be heated out. The system is adapted up to pressures of 60 bar. There are several protium gas handling and storage devices present:

- Stainless steel bottles (volume 10 liters each). They can be filled with pressurized gas (maximal storage capacity 600 stp-liters). Small volumes of one liter are used for gas mixing and sampling duties.
- Hydride storage beds (volume ~2 liters). In these containers the protium gas is bound as a hydride with residual pressures of 1-10 bar, dependent on filling state and temperature. Typical storage capacities are 500 to 800 stp-liters per unit.
- A zeolite bed (volume ~1 liter). At liquid nitrogen temperature it adsorbs up to 120 stp-liters of protium. At room temperature, the protium gas gets desorbed and gets pressurized up to ~100 bar which allows to push it into the steel bottles.
- Several ports for sample volumes are installed where gas samples from the TPC vessel (up to ~10 stp-liters) can be extracted for impurity analysis. The method of gas chromatography was employed to determine small admixtures of light elements (N_2, O_2) down to levels of 10 ppb. The humidity was measured online with a special "PURA" sensor.

The gas handling system was also used to generate samples with precisely defined admixtures of impurity gases. Such samples were injected into the TPC to study and calibrate their effects with muons.

The protium gas was produced by electrolysis of commercially bought protium water [7] using a Whatman generator. A deuterium depletion of 1.44 ppm was obtained which still required significant corrections of the lifetime measurement [2]. Therefore, an isotope separation column was designed in Gatchina to produce ultra-depleted protium gas. A description of this system is published in Ref. [8]. The separation column employs hydrogen liquefaction and evaporation cycles and makes use of the different evaporation rates of hydrogen isotopes. A deuterium depletion below 6 ppb was determined in sample analysis at the ETH AMS facility [9].

Since impurities are steadily accumulated due to outgasing effects, the protium must be cleaned before injection into the TPC vessel. This was done by pressing it through a Palladium filter which is capable of removing all elements other than hydrogen isotopes. Although such a protium filling yields ultra-high purity of the gas, this purity cannot be maintained without continued cleaning. After several weeks long heating and pumping, still a typical impurity accumlation rate of ~1 ppm was observed. In the analyzed samples nitrogen and water vapour were identified as the main impurity components [4,5]. To maintain the highest possible purity a "Circulation Hydrogen Ultrahigh Purification System" (CHUPS) was designed in Gatchina and successfully run during the Mucap data taking. A detailed

description of CHUPS and its performance is published in Ref. [10]. The system works on the basis of thermodynamical adsorption and desorption cycles using activated carbon. The impurities are removed by pushing the protium through zeolite filters in a liquid nitrogen environment.

3. Performance of the TPC

3.1 Tests with the TPC

3.2 Production Runs

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