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Muon Capture Experiments in Hydrogen and Deuterium

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Abstract

We report about new muon lifetime precision experiments at PSI to measure the singlet μp capture rate Λ_S to ≤ 1% [1] and the doublet μd capture rate Λ_D to ≤ 1.5 % [2]. The goal is to determine precisely the induced pseudoscalar coupling g_P from Λ_S, and the axial two-body current term L_{1A} from Λ_D. We have developed a new hydrogen TPC operating at 10 bar as active muon stop detector. It is surrounded by cylindrical wire chambers and a plastic hodoscope as electron detector. Ultra-high purity of the hydrogen gas ($c_Z < 10^{-7}$) was accomplished by continuous gas circulation and purification. Isotopic purity $c_d < 10^{-8}$ was achieved with a special isotope separation column. ~1.5 10^{10} good events were collected which are now in final analysis. Our first result from 10% of the statistics, $g_P = 7.3 \pm 1.1$, agrees well with theory. - The μd experiment is now in development. We will use a new TPC operating in deuterium gas at T ~30K. The proposed experimental setup is presented.
*Keywords:*Muon Capture, Muon Lifetime, Hydrogen, Deuterium, Isotope Separation, Time Projection Chamber

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1. Introduction – the TPC

A new generation of muon lifetime precision experiments was introduced at PSI to measure the singlet rate Λ_s of nuclear muon capture on the proton

$$\mu + p \rightarrow n + \nu_\mu. \qquad (1)$$

to ≤ 1% [1], and the doublet capture rate Λ_d

$$\mu + d \rightarrow n + n + \nu_\mu \qquad (2)$$

in deuterium to ≤ 1.5% accuracy [2].

The goal of these experiments is to determine precisely fundamental constants of weak interactions, i.e. the induced pseudoscalar coupling g_P from rate Λ_S of reaction (1) which is predicted by heavy baryon chiral perturbation theory [3], and the axial two-body current term L_{1A} from rate Λ_D of reaction (2) which is described by modern effective field theories [4]. The L_{1A} parameter is of astrophysical interest, since it calibrates the solar pp fusion reaction and the ν+d reactions seen by the Sudbury Neutrino Observatory.

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Since direct absolute rate measurements of the neutrons in the output channels are severely limited in accuracy, we have chosen the lifetime method which determines the capture rates from the difference of the $\mu^- p$ ($\mu^- d$) lifetime, λ^-, with respect to the lifetime of the free μ^+, λ^+:

$$\Lambda_{capture} = \lambda^- - \lambda^+ . \qquad (3)$$

This method was first adopted in experiments at Saclay [5] by using liquid hydrogen targets. However, mesomolecular physics, the formation of mesic molecules pμp (dμd), and subsequent processes, i.e. ortho-para transitions in pμp, μd spin flip and fusion of the dμd molecule, made interpretation of the Saclay results difficult, because the hfs populations could not be determined precisely enough. At PSI we have avoided this problem by using low density gas, 1% of liquid H_2 and 5-10% of liquid D_2, respectively. We have developed a new technique based on tracking each incoming muon to its stopping point in a hydrogen time projection chamber (TPC).

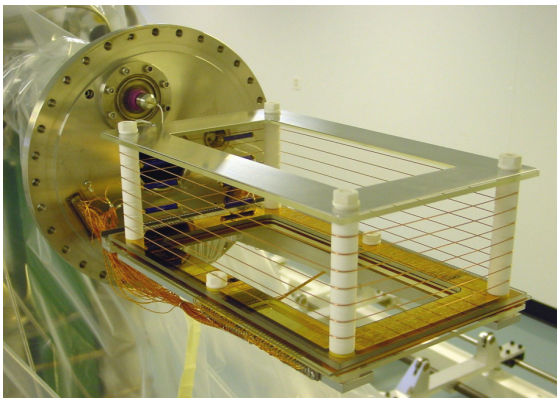

Fig. 1 Foto of the TPC developed at PSI used as active muon target.

Fig 1. shows the TPC which was used in the MuCap experiment. It is constructed from bakable UHV materials (glass, ceramics, metals) in order to reach ultra-high gas purities. In the volume 30x15x12 cm^3 a vertical electrical field of 2 kV/cm is applied. The electrons from ionizing particles drift down towards a MWPC plane. The amplified signals are read out in both plane coordinates while the vertical position is determined by the drift time (0 - 24 μs). The TPC is also sensitive to reactions with charged particle emissions, e.g. nuclear recoils from muon capture on impurities. Such events were used to monitor continuously the impurities. μ-e vertex tracking allows clean identification of each μ-e event inside the sensitive TPC volume with extremely high suppression of background and accidentals.

2. The MuCap Experiment

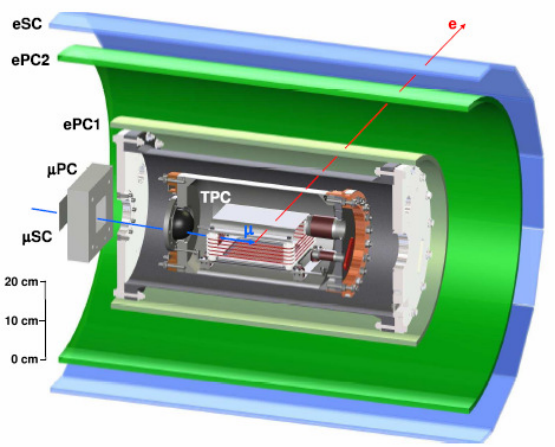

Fig. 2 Cut out view of the MuCap experimental setup.

The full MuCap apparatus is shown in Fig. 2. Good muon stops are identified by the scintillator μSC, the wire chamber μPC and the TPC which is mounted in the center of a cylindrical aluminum pressure vessel and operated at 300K with 10 bar of ultra-pure protium gas (deuterium-depleted hydrogen). The μ-decay electrons are detected by two cylindrical wire chambers ePC1, ePC2 and a plastic hodoscope eSC surrounding the chambers. To obtain an undistorted μ-e decay time spectrum muon transfers to higher Z elements and also to deuterium nuclei must be avoided to a level $< 10^{-5}$ which leads to the stringent requirement of keeping the gas impurity levels below 10^{-7}. We have accomplished this task by developing a gas cycling and purifying system [6] and an isotope separation plant to remove deuterium. Both systems were designed and partly fabricated in Gatchina.

Fig. 3 shows the scheme of the circulation system which was run with a constant flow of 3 stp-liters/s during all runs to maintain gas impurities at lowest levels. With three Zeolite based cryo-adsorption pumps the protium gas is pushed through active carbon filters at liquid nitrogen temperature. The main impurity in the protium was water vapour and could be kept at levels ≤ 20 ppb during the main runs.

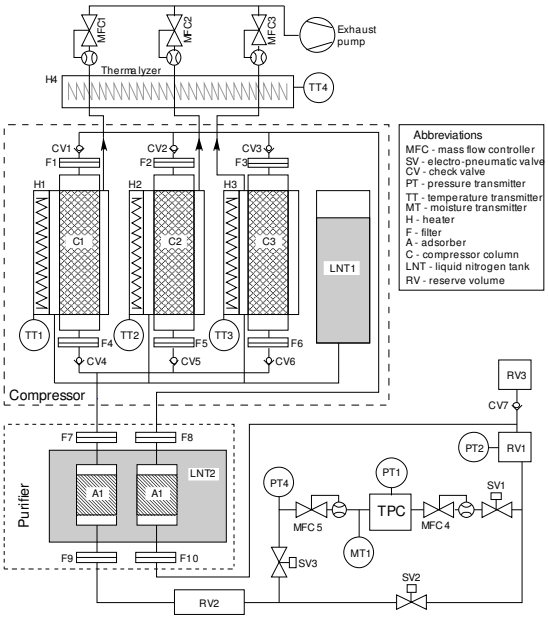

Fig. 3 Hydrogen circulation system to maintain highest gas purity.

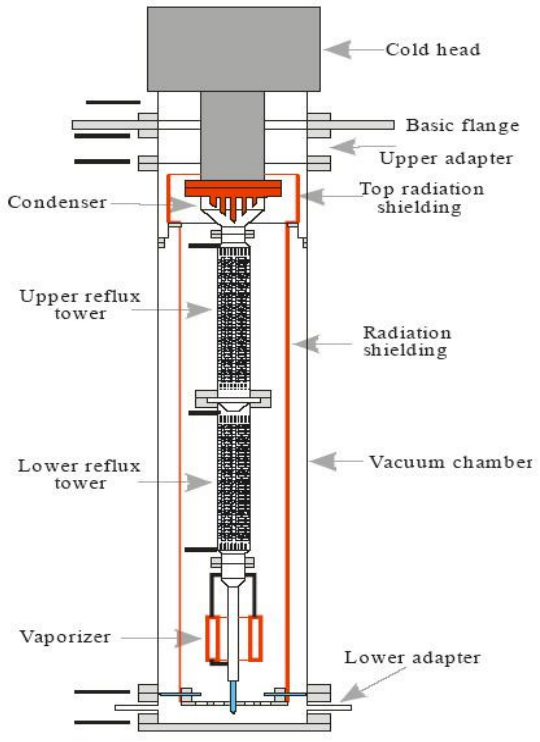

Fig.4 Isotope separation column to remove deuterium traces.

Fig. 4 shows the scheme of the isotope separation plant, a cryogenic column which functions on the basis of the vapor pressure difference between hydrogen and deuterium. The hydrogen gas gets liquefied at the cold head on top. The liquid droplets run down and evaporate. This leads to a depletion of the heavier isotope in the gas phase. In AMS measurements at ETH we haved determined a deuterium depletion level in the protium of < 6 ppb.

The MuCap experiment was successfully operated during four data runs, and a statistics of ~1.5×10^{10} good μ^--e events was accumulated which will be sufficient to reach and (hopefully) even surpass the goal of a 1% determination of the singlet μp capture rate. The first run with about 10% of the final statistics has been evaluated and is published in [7].

Fig. 5 shows the final μ-e decay time spectra of this first run using different selection criteria. We have evaluated a first precise result of the μp singlet capture rate

$$\Lambda_S^{MuCap} = 725.0 \pm 13.7_{stat} \pm 10.7_{syst}\ s^{-1} \quad . \quad (4)$$

The main systematic error came from uncertainties of impurity corrections. This result leads to an induced Pseudoscalar Coupling Constant $g_P^{MuCap} = 7.3 \pm 1.1$ in good agreement with theory $g_P^{Theory} = 8.26 \pm 0.25$ [3]. For the final result of the MuCap experiment we expect a ~3 times better accuracy.

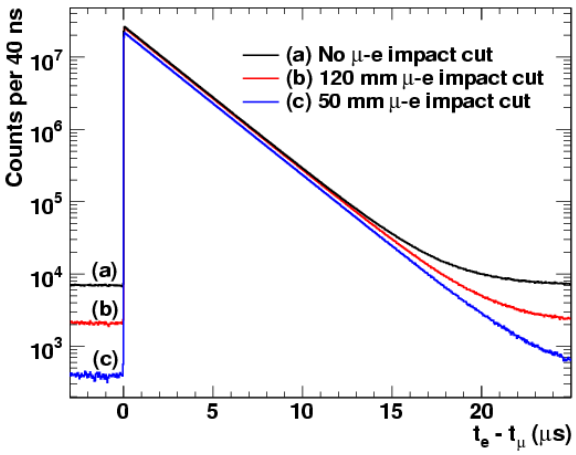

Fig.5: μ-e decay time spectra of the first data run.

3. The MuSun Experiment

The MuSun experiment on μd capture will be based on the same method and to a large part also on the same equipment and electronics. In one respect, however, the apparatus needs a total redesign: the μd measurements must be performed at low temperature (T ~ 30K) and at higher gas density, φ ~ 0.05 - 0.1 (φ = 1 is the density of liquid hydrogen), while MuCap used φ = 0.011. This requirement is mainly due to the much smaller spin flip cross section $\sigma(\mu d^{F=3/2}+d \rightarrow \mu d^{F=1/2}+d')$ and because only at low temperature the μd spin states can be monitored precisely by muon molecular processes. This is done by observing the time distribution of dμd fusion events. Fig. 6 shows the time development of the μd hyperfine states at 30K, φ = 0.1. This information is quite well known due to the phenomenon of resonant formation of dμd molecules which proceeds at low temperatures only from the upper $\mu d^{F=3/2}$ hfs state [8,9]. This state gets rather quickly depopulated at our chosen conditions. The μHe^3 population, which is also shown in Fig. 6, originates from dμd fusion events followed by sticking on the He^3 fusion product.

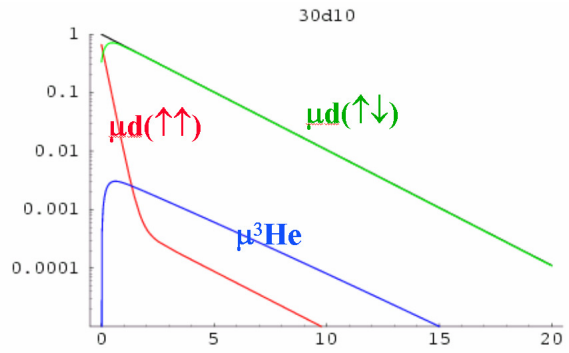

Fig.6: time development of μd hyperfine states and μHe^3 atoms.

The MuSun collaboration is presently designing a Cryo-TPC which will operate at the required new target conditions. A side-view scheme of the new detector setup is shown in Fig. 7. The TPC is embedded in an inner cylinder which is kept at 30K by circulating liquid Neon. The outer chamber acts as insulation vacuum for the cryogenic part and fits into the existing electron detector. The new TPC will have a pad structure of size 100x100 mm^2, a vertical drift length of 80 mm and an electrical field of ~10 kV/cm. Very similar conditions were used in previous dμd fusion experiments at PSI [9], although the chamber geometry was considerably smaller.

The purity of the deuterium gas is again of crucial importance. Due to the higher density and to the larger μd→μZ transfer cross sections as compared to the μp experiment, impurity levels (N_2, H_2O) of 1 ppb must be achieved and maintained. We expect, that the existing circulation system (Fig. 3) will suffice due to cryo-temperatures. Several methods to monitor the impurities at ppb levels are under investigation.

It will also be important – in order to avoid any complications from H/D-kinetics – to use isotopically pure deuterium. This will be achieved by the isotope separation column (Fig. 4).

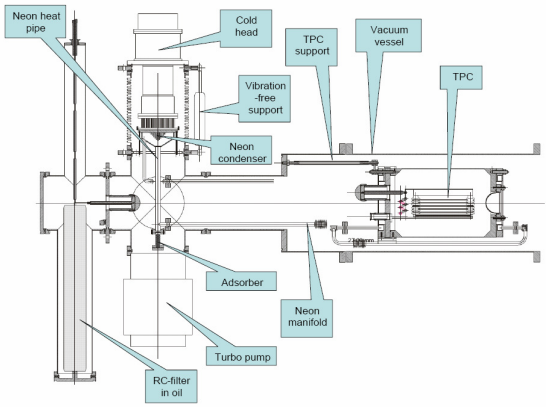

Fig.7 Scheme of the new Cryo-TPC apparatus (side-view).

Our plans are, first to test prototypes of the new TPC geometry and electronics (2008-09), then to commission the new Cryo-TPC by the end of 2009. We plan to collect $3x10^{10}$ good events, of which one third will be with μ^+ beam to study the systematics.

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