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Development of a New Experimental Method for Studies of Muon Capture in Hydrogen

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Abstract. A new experiment is under preparation with the aim to improve considerably the present knowledge of the rate Λ_s, which should be measured on a level of 1% or better, for the basic electroweak capture reaction of a negative muon on the free proton $\mu p_{1s} \longrightarrow n + \nu_\mu$. The capture rate will be determined by measuring the lifetime of μ^- stopped in ultra pure hydrogen at 10 bar pressure and comparing it with the lifetime of the unbound μ^+. A new experimental method was developed for this project which should allow measuring the μ^- lifetime with at least 10 ppm precision. The basic element of the detector is operating in the hydrogen gas time projection chamber (TPC) surrounded by multi-wire proportional chambers (MWPCs) and scintillator counters. The arrival times and trajectories of the incoming muons and the outgoing decay electrons are measured with this device providing effective suppression of background. Using the TPC as an active target, we can monitor on-line the protium contamination by impurities with a sensitivity better than 10^{-8}. This can be done by detecting the charged products of the muon capture reaction on these impurities. It was demonstrated that the TPC and MWPCs can operate in pure hydrogen under 10 bar pressure providing gas gain up to 10 000.

Key words: hydrogen, TPC, captire, muon.

1. Introduction

The project for high-precision studies of the muon capture in hydrogen [1, 2] is based on application of a special Time Projection Chamber for detection of the incoming muons and the outgoing decay electrons.

The idea of using the TPC as an active target for this experiment is based on ten-years experience of working with a Time Projection Chamber operating in the ionization mode. With this chamber, the processes of dd- and dt-muon catalyzed fusion were studied and the rate of μ-capture on ^{3}He was measured very precisely [3]. The transfer to proportional regime was prompted by the necessity to simultaneously register the heavily ionizing particles (slow muons and recoil nuclei of μ-capture on impurities) and weakly ionizing particles (the decay electrons, conversion muons from pdμ-fusion and Auger electrons). This is possible with gas gain $\sim 5 \cdot 10^3$. The target density was chosen $\varphi \sim 0.01$ of LHD (liquid hydrogen density) to assure the μ-capture proceeds predominantly from singlet hyperfine state of the pμ-atoms and ppμ-molecule formation is a minor correction. As the world experience in using MWPCs in hydrogen at such conditions was very limited [4–6] we had to carry out detailed investigations of their performance.

2. Studies of MWPC and TPC performance in hydrogen

These studies were conducted by our collaboration since 1997 [2]. A special test setup was constructed at PNPI to investigate the MWPCs with α- and β-sources. The chambers were tested in a vessel filled with clean hydrogen at 10 bar pressure with gas contamination of order of 10 ppm. The MWPCs showed stable operation up to HV = 7.0 kV ($E = 900$ kV/cm on the surface of the anode wire) providing a gas gain (GG) up to $2 \cdot 10^4$ and $5 \cdot 10^3$ while detecting relativistic electrons and α-particles, respectively, the difference in GG being due to the space charge effect. Figure 1 shows the dependence of the GG on HV. The GG was determined as the ratio of the current at a given HV-value to the ionization current measured at HV $\sim$ 1000 V. The absolute current (I) was measured with a picoampermeter from the ionization region ($I \sim 50$ pA) to the proportional region (I up to 1 μA). The nominal high voltage was chosen to be 6.5 kV. At this HV-value, the detection efficiency of the relativistic electrons was close to 100%.

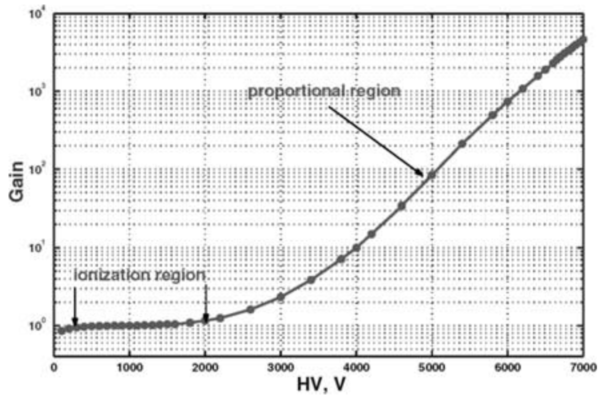

Figure 1. Gas gain vs HV. Measurement with a MWPC operating in 10 bar hydrogen gas under irradiation with an α-source.

Also, the aging studies of the MWPCs were performed under intense irradiation from the α- and β-sources. After 45 days of continuous irradiation by α-particles with four intermediate gas refillings we did not see any changes in the currents, in the signal shapes, and in the counting rates. It was demonstrated that the MWPCs can operate without degradation at least up to accumulated charges of 0.1 Coul/cm·wire.

Based on the developed MWPC, a time projection chamber has been constructed and tested with the β- and α-sources. Figure 2 shows a schematic view of the TPC. The TPC contains four wire planes. The drift space is defined by the cathode and the grid planes. The ionization electrons are driven through the grid to the anode wire plane creating avalanches around the anode wires. The signals are detected from the anode wires and also from the cathode strips (groups of wires) in the strip plane. After optimization, the following basic parameters of the MWPCs and TPC were chosen:

Anode wire planes: W(Au) wires 25 μm diameter, 4 mm wire spacing. Cathodes of MWPC, grid, and strips of TPC: Fe wires 55 μm diameter, 1 mm wire spacing. Cathode plane of TPC: Fe wires 100 μm diameter, 1 mm wire spacing. Anode–cathode gap of MWPC, anode-grid and anode-strip gaps of TPC: 3.5 mm. The drift volume: $15 \times 12 \times 30$ cm^3. The high voltage applied to the planes: -35 kV (cathode), -6.5 kV (grid), 0 kV (anode), and -6.5 kV (strips). The electron drift velocity in the drift space of 12 cm is 0.7 cm/μs.

Using the TPC similar to described above, a prototype of the μp-capture detector was designed and tested in a muon beam at PSI. It consisted of two muon beam MWPCs, the TPC, and four planes of electron MWPCs located above the TPC (Figure 3). The anode wires in the detection plane were oriented in the x-direction (75 wires). The wires in the strip plane oriented along the z-direction were joint in 4 mm strips to detect the x-coordinate of the stopped muon (38 strips). Figure 4 shows an event from our test run. The muon can be seen stopping in the region of anode 4. The track of decay electron is seen on anodes 4–12 going to the upper right.

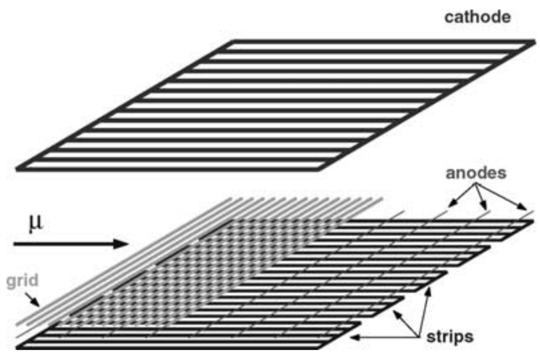

Figure 2. Schematic view of the TPC.

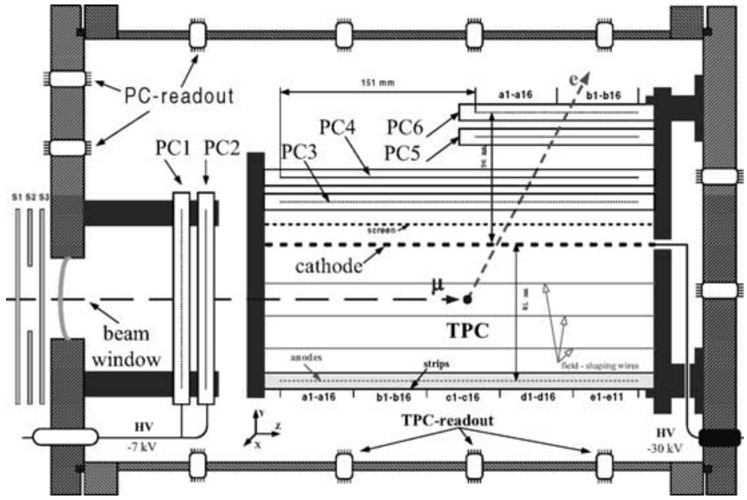

Figure 3. Prototype of the experimental setup with TPC and 6 MWPCs (PC1-PC6).

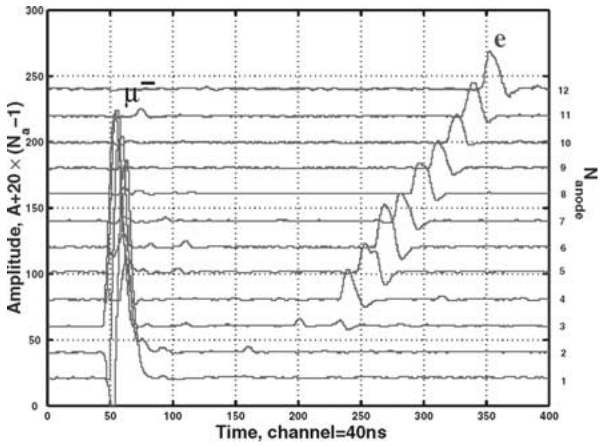

Figure 4. The signals on TPC anode wires from μ–e decay event.

The three coordinates of the muon stop were measured with the resolution (RMS) of 1 mm (y), 2 mm (x), and 2 mm (z). This device is designed to select clean muon stops in 3D space and also to measure the muon decay electron trajectory. Tracking these trajectory back to the muon stop allowed to reduce drastically the background. This is crucial for the high precision measurement of the muon lifetime. The read out electronics is designed for large muon stop rates (up to 50 kHz) that is required for attaining the high statistical accuracy [2]. A careful signal tail cancellation allowed to detect the signals from relativistic electrons in the presence of much higher signals from the stopped muons with the time resolution (RMS) about 100 ns.

3. Experimental monitoring of impurities

A serious requirement of the μp-capture experiment is high gas purity. The concentration of impurities with $Z > 2$ should be less than 10^{-8}. This requires a special gas circulation and purification system and the control of the impurity concentration with high sensitivity. Another special requirement is to know precisely the amount of deuterium in H_2 gas. The D_2 concentration should be less than 1 ppm to avoid the muon transfer to dμ-atoms resulting in significant diffusion of the muon-stop area caused by large ranges of the dμ-atoms in hydrogen due to Ramsauer effect. Fortunately, our detector can provide direct control of the levels of impurities. Using TPC as an active target, we can detect the charged products of muon induced reactions with impurities: the recoil nuclei (200–0350 keV) from the μ-capture on impurities with $Z \geqslant 2$ and the charged products of the pdμ-fusion channel ^{3}He (0.2 MeV) + μ (5.3 MeV). This was demonstrated in our test run at PSI. The information was collected from 12 central anodes of TPC instrumented with FADCs that provided detailed characteristics of signals.

The μ-capture reactions with impurities are identified as events with two big signals on the muon stop anode separated in time, where the first one is the signal from the stopped muon with the amplitude up to 220 keV and the second one is from the nuclear recoil. For selection of such events, special amplifiers and discriminators with high threshold about 70 keV and also a trigger control unit were developed. An example of the μ-capture event is shown in Figure 5.

The signal spectra are shown in Figure 6. We have found 3876 μ-capture events with the μ^- beam and only one event under the same requirements with the μ^+ beam.The number of monitored muon stops in the sensitive TPC volume was about 10^6. The overall level of impurities (N_2, O_2, and H_2O) was estimated by chemical analysis to be about 30 ppm. Based on these data, we can conclude that our method has reached a sensitivity in detection of impurities with $Z > 2$ on a

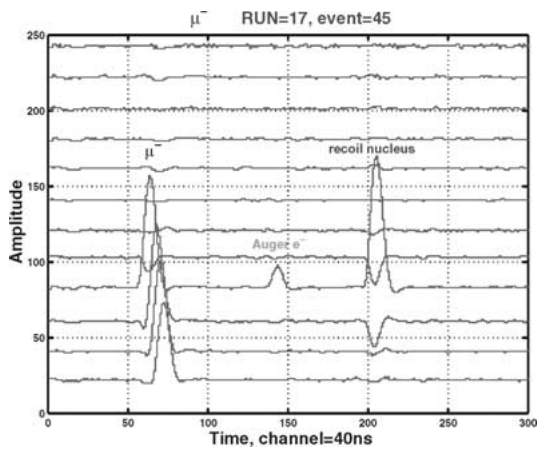

Figure 5. Display of flash ADSs showing a typical event with the μ-capture reaction on impurity.

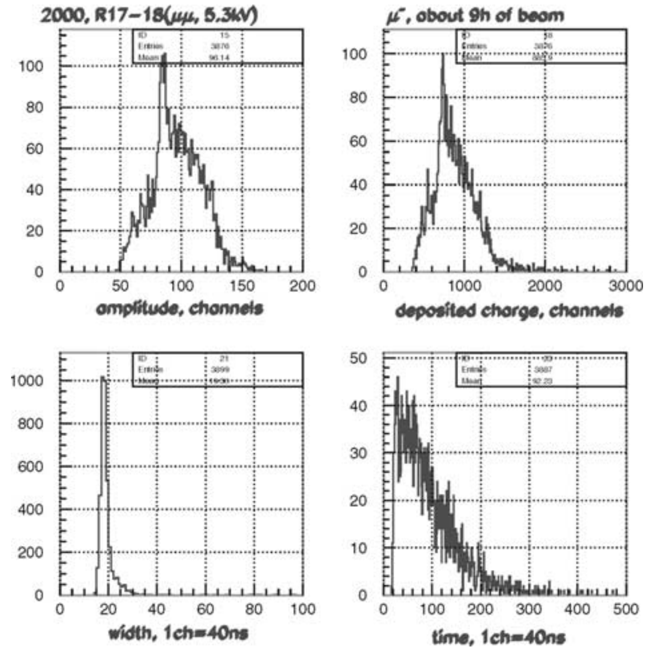

Figure 6. Spectra of the μ-capture events.

level of 0.01 ppm. We also found evidence for presence of μd atoms by observing the capture products far separated in space from the muon stop because of the μd diffusion. Finally, we obtained preliminary data on pdμ-fusion, which can be used as a monitor for the deuterium concentration. Our current sensitivity for c_d is around 2 ppm. An important step in the future is the absolute calibration of the measured yields to the impurity concentration measured by chemical analysis and the accumulation of high statistics.

Also, we should mention some additional abilities of our setup for studying the μ-capture on nuclei with $Z > 2$. As one can see from Figure 5, there is a small signal between the signals from the stopped muon and the recoiled nucleus. This signal is produced by the Auger electrons which arise in deexcitation of the mesoatom. About 40% of the detected μ-capture events are accompanied by such signals with the amplitude of 6–30 keV. The direct observation of the Auger electrons before the μ-capture allows to separate the transfer of the muon from the hydrogen mesoatom to the heavier element from the μ-capture reaction, thus providing precision measurements of the rates of both processes in one experiment.

4. Conclusion

It was demonstrated that the TPC can operate as an active target at 10 bar of clean hydrogen with the gas gain up to 10^4 that is sufficient not only to define the 3D muon stops in the sensitive volume of the TPC but also to measure the trajectories of the muon decay electrons. A remarkable feature of the TPC is a capability to detect the products of the muon capture reactions on the gas impurities thus providing a sensitive control for the hydrogen purity. Also, TPC can be used as a detector for precision measurements of the muon transfer rates from the hydrogen mesoatom to nuclei with $Z > 2$, as well as the μ-capture rates on impurities. The experience accumulated in the test runs allowed to design the final setup for the μp-capture experiment. The start up of the experiment is planned for the fall 2001.

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