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Nuclear Instruments and Methods in Physics Research A 478 (2002) 158–162

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

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Study of high-pressure hydrogen-operated wire chambers designed for a precision measurement of the singlet μp capture rate

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Abstract

This work was carried out as part of a project aiming at a greatly improved measurement of the muon capture rate from the singlet state of the μp atom. The experiment will be performed at the intense muon beam of PSI using a new experimental method allowing high precision measurements of the lifetime of muons stopped in ultra-pure deuterium-depleted hydrogen (protium). The basic element of the detector is a time projection chamber operating in hydrogen gas at 10 bar pressure. The arrival times and trajectories of the incoming muons and the outgoing decay electrons are measured with this device providing effective suppression of background. The system of chambers and electronics is designed for the large muon stop rates required for attaining high statistical accuracy. During four beam periods at PSI, data were taken. Also, various studies of the MWPC performance in hydrogen were made including ageing studies of the chambers under irradiation with stopped muons and with alpha and beta sources. It was demonstrated that the MWPCs can operate in pure hydrogen under 10 bar pressure with gas gains up to 5000, which is sufficient for the detection of relativistic electrons. © 2002 Elsevier Science B.V. All rights reserved.

PACS: 29.40.Cs

Keywords: Hydrogen; MWPC; TPC; Pressure; Capture; Muon

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1. Introduction

The proposed experiment has been described in proposal R-97-05 [1] and in two progress reports [2]. The principal aim of this experiment is to determine the fundamental capture rate Λ_s of the reaction $\mu^- + p \rightarrow \nu_\mu + n$ via the lifetime of μ^- bound in the singlet $p\mu^-(F=0)$ system to an accuracy $\delta\tau_\mu/\tau_\mu$ better than 10^{-5} [3,4]. The comparison of τ_μ for $p\mu$ atoms with that for free μ^+'s will considerably improve the determination of the induced pseudoscalar form-factor g_P to the level $\delta g_P/g_P \leqslant 7\%$. The μ^+ lifetime will be measured simultaneously as a reference and to check systematics. The lifetime measurements will be done with a time projection chamber (TPC) filled with 10 bar of ultra-pure deuterium-depleted hydrogen surrounded by multi-wire proportional chambers and a hodoscope of scintillation detectors. As the previous world experience in using MWPCs in hydrogen was very limited [5,6], we have carried out detailed investigations of the MWPC performance at the expected experimental conditions.

2. Studies of MWPC performance in hydrogen

These studies were conducted by our collaboration since 1997. As a result of optimization, the following basic parameters of the MWPCs have been chosen:

Anode wire plane: W(Au) wires, 25 μm diameter, 4 mm wire spacing.

Cathode wire plane: Fe wires, 80 μm diameter, 1 mm wire spacing.

Anode–cathode gaps: 3.5 mm

The chambers were tested in a vessel filled with clean hydrogen at 10 bar pressure with a gas contamination (N_2, O_2, H_2O) of the 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 2×10^4 and 5×10^3 while detecting relativistic electrons and α-particles, respectively, the difference in GG being due to the space charge effect. Fig. 1 shows the dependence of the gas gain on the HV. The right-side scale shows the absolute current measured with a picoamperemeter under irradiation of the chamber by an α-source. The

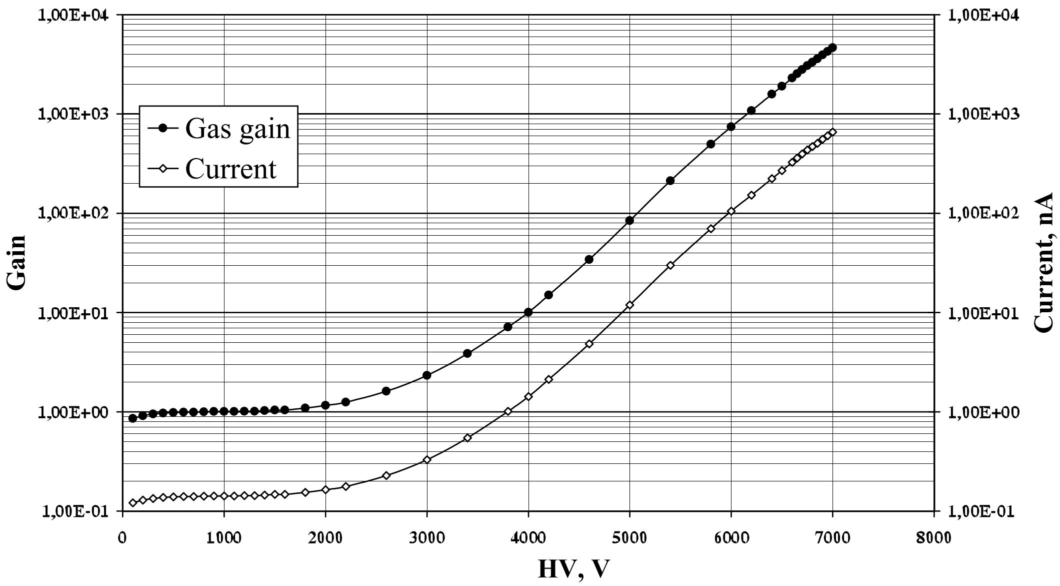

Fig. 1. Gas gain and ionization current vs. HV. Measurement with an MWPC operating in 10 bar hydrogen gas under irradiation with an α-source.

left-side scale gives the gas gain determined as the ratio of the current at a given HV-value to the ionization current measured at HV$\sim$1000 V. The nominal high voltage was chosen to be 6.5 kV. At this HV-value, the detection efficiency for relativistic electrons was close to 100%.

Ageing studies of the MWPCs were performed under intense irradiation by α- and β-sources. It was demonstrated that the MWPCs can operate without degradation, at least up to accumulated charges of 0.1 C/cm wire. The electron microscopic and X-ray analysis of the anode and cathode wires revealed no serious signs of destruction of the wire surfaces. However, in several radiation tests the appearance of dark currents was observed, the nature of which is not yet clearly understood. The current explanation is an appearance of microdeposits on the cathode wires due to traces of oil in the pumping system.

3. Time projection chamber

Based on the developed MWPC, a time projection chamber has been constructed and tested with a β-source. Fig. 2 shows a schematic view of the TPC. The TPC contains four wire planes. The drift space of 8 cm 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. Signals are detected from the anode wires and also from the cathode strips (groups of wires) in the strip plane. The geometry parameters of the TPC are as follows:

Cathode plane: Fe wires 300 μm diameter, 3 mm wire spacing.

Grid: Fe wires 80 μm diameter, 1 mm wire spacing.

Anode plane: W(Au) wires 25 μm diameter, 4 mm wire spacing.

Strip plane: Fe wires 80 μm diameter, 1 mm wire spacing, groups of 4 wires joined together to form strips.

The distance from the anode plane to the grid and to the strip plane was 3.5 mm. The drift volume was $15 \times 8 \times 30$ cm^3. The high voltages applied to the planes were -23 kV (cathode), -6.5 kV (grid), 0 kV (anode) and -6.5 kV (strips). The electron drift velocity in the drift space was 0.7 cm/μs. The TPC was tested using a β-source (Sr^{90}) placed outside the TPC close to the mylar window. The β-particles penetrating inside the TPC created signals on the anode wires which were detected with a set of FADCs. As an example, Fig. 3 displays a β-track as seen by the FADCs. The detection efficiency of each wire was found to be better than 98%.

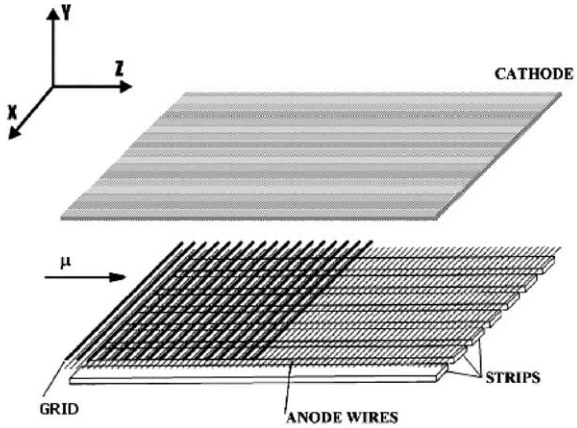

Fig. 2. Schematic view of the TPC.

4. Setup for the μ-capture experiment

Using the TPC 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 two planes of electron MWPCs, located above the TPC (Fig. 4). 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 joined in 4 mm strips to detect the X-coordinate of the stopped muon (38 strips). The three coordinates of the muon stop were measured with a resolution of ± 1 mm (Y), ± 2 mm (X) and ± 2 mm (Z). The device is designed to select clean muon stops in 3D space and also to measure the muon decay electron trajectory. Tracking these trajectories back to the muon stop allowed to drastically reduce the background. This is crucial

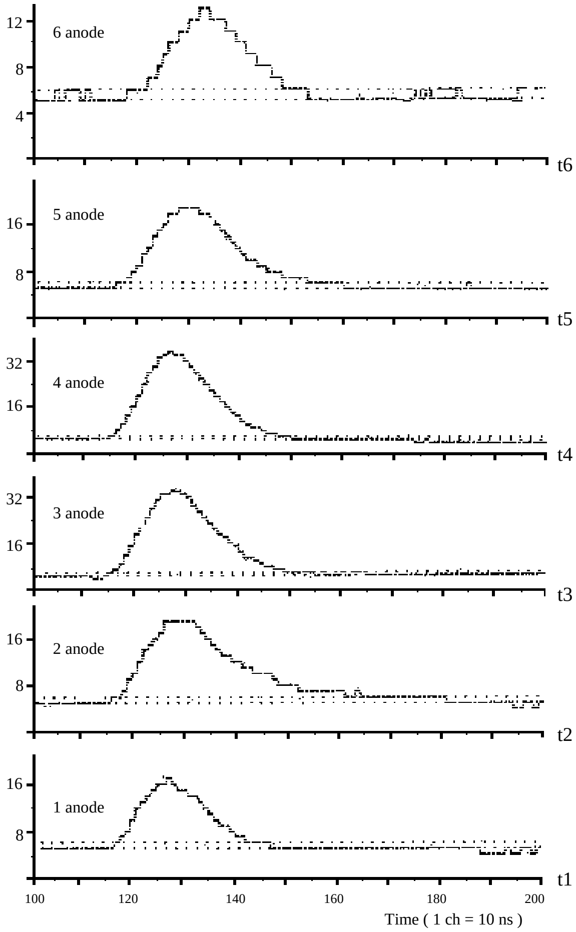

Fig. 3. Sequence of signals from FADC created by a β-particle crossing TPC nearly parallel to the anode plane.

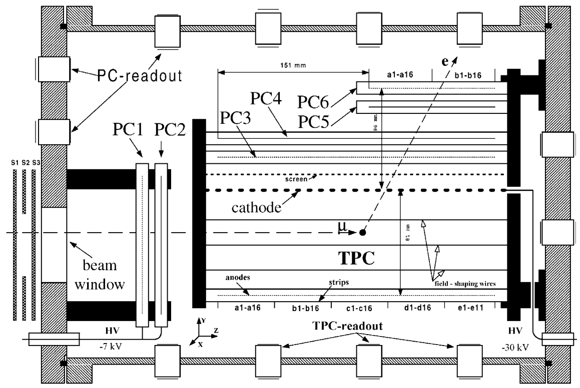

Fig. 4. Prototype of the experimental setup with TPC and 6 MWPCs (PC1–PC6).

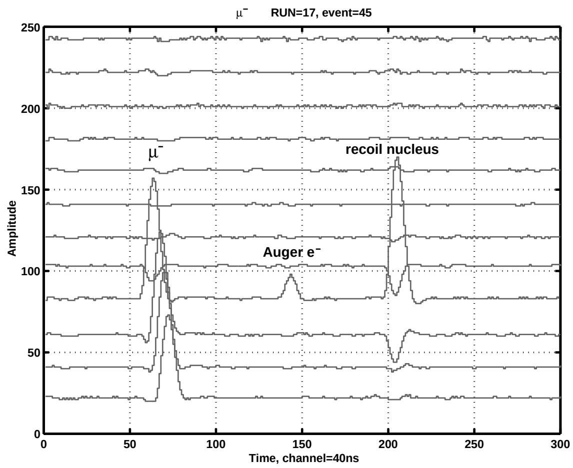

Fig. 5. Display of flash ADSs showing a typical event with a μ-capture reaction on an impurity.

for a high precision measurement of the muon lifetime. The readout electronics is designed for the large muon stop rates (up to 50 kHz) which are required for attaining the high statistical accuracy. A careful signal tail cancellation allowed to detect the signals from relativistic electrons in the presence of the much higher signals from the stopped muons.

Besides muons and muon decay electrons, the TPC can also detect recoil nuclei after muon capture on these nuclei (Fig. 5), as well as other reactions followed by muon transfer to possible impurities in the protium gas. In between the two large signals, one can see also a signal from an Auger electron caused by muon transfer from μp to μZ. This feature proved to be extremely useful as it allows to control the protium contamination on a level of 10^{-8}.

5. Conclusion

It was demonstrated that the TPC can operate at 10 bar of clean hydrogen with a gas gain of up to 10^4, which is sufficient not only for defining the 3D muon stops in the sensitive volume of the TPC but also for measuring the trajectories of the muon decay electrons. A remarkable feature of the TPC is the capability to detect the products of muon capture reactions on gas impurities, thus providing a sensitive check of the hydrogen purity. The experience accumulated in the test runs allowed to design the final setup for the μp-capture experiment [7]. The start-up of the experiment is planned for the fall of 2001.

Acknowledgements

This work is supported by the Russian Ministry of Sciences and Technology, by the Paul Scherrer Institute and by INTAS. The authors also wish to thank G.E. Gavrilov, L.A. Shipounov and E.V. Kuznetsova for the gas gain measurements in hydrogen.

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