Progress Report 2006 and Beam Request for 2007

Precision Measurement of Singlet $\mu p$ Capture in Hydrogen

PSI Experiment R–97–05, spokespersons P. Kammel, C. Petitjean

MuCap Collaboration [1]

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http://www.npl.uiuc.edu/exp/mucapture

Figure 1: Impact of the first MuCap result: Previous experiments and theory are inconsistent. The experiments cannot be reliably interpreted to extract $g_P$, as they strongly depend on the poorly known ortho-para transition rate in muonic molecular hydrogen - $\lambda_{op}$. MuCap avoids this model dependence and reports the first unambiguous result for the pseudoscalar form factor $g_P$. 
1 Overview

The MuCap experiment [2, 3, 4] is a high-precision measurement of the rate for the basic electroweak process of muon capture,

$$\mu + p \rightarrow n + \nu.$$  \hspace{1cm} (1)

A measurement of 1% accuracy determines the least well-known of the nucleon charged current form factors, the induced pseudoscalar $g_P$, to 7%. This fundamental quantity is directly related to the chiral symmetry of QCD and can be predicted with $2 - 3\%$ precision [5]. The quantity $g_P$ is most directly determined in muon capture on hydrogen, which has the potential for a stringent test of the underlying accurate QCD relations. Alas, all experimental results before MuCap suffered from lack of precision, ambiguities in their interpretation, and inconsistencies. During 2005, the situation became even more confused. A new result on the rate for the ortho–para conversion of $pp\mu$ molecules was released [6]. This rate, $\lambda_{op}$, is essential for the extraction of $g_P$ from experiments with liquid hydrogen targets, where muon capture from $pp\mu$ molecules dominates (Figure 4).

MuCap employs a new method that avoids key uncertainties of earlier measurements. The capture rate is derived from the lifetime difference of positive and negative muons stopped in an ultra-pure and active hydrogen target (time projection chamber, or TPC).

- **Unambiguous Interpretation.** At the low target density of 1.16% LH$_2$, capture from the $F = 0$ hyperfine state of the muonic hydrogen atom dominates, limiting the impact of $pp\mu$ uncertainties.

- **Clean muon stop definition.** With 3D tracking, the TPC selects only $\mu$ stops in the hydrogen gas, eliminating otherwise overwhelming background from stops in higher-Z materials (walls, detector frames).

- **Muon-electron tracking.** Cuts on the muon-electron vertex can be systematically applied using the reconstructed electron vector. This leads to strong background suppression, essential consistency checks and a diagnostic method for monitoring the isotopic purity of the hydrogen.

- **Gas impurity control.** Because MuCap is an active target experiment, very low levels of impurities can be monitored in situ with the TPC. With ultra-clean and bakeable materials in the TPC and a continuous gas circulation system, purity levels slightly surpassing 0.018 ppm are achieved.

![Figure 2: Cut out view of MuCap CAD model showing the main detector components.](image)

The main components of the MuCap detector are shown in Figure 2. The experimental method requires a combination of novel and challenging detector techniques and support systems. Significant R&D was required to optimize the depicted subsystems: beam detectors ($\mu$SC, $\mu$SCA, $\mu$PC), time-projection chamber (TPC) and hydrogen vessel, and electron detection system (ePC1, ePC2, eSC) as well as beam, gas system and diagnostics, magnet and data acquisition.
<table>
<thead>
<tr>
<th>Year</th>
<th>Milestones</th>
</tr>
</thead>
</table>
| 2004 | • Completion and commissioning of the basic MuCap detector, as well as the continuous gas purification system (CHUPS).  
• First physics run with full detector.  
• Recorded decay statistics $N_{\mu^-} = 2 \times 10^9$ and $N_{\mu^+} = 0.2 \times 10^9$. |
| 2005 | • TPC reaches design specifications.  
• Upgrades to detector:  
  - Muon-on-Demand scheme triples data-taking rate.  
  - In-situ diagnostics and improved gas system.  
  - Neutron detectors installed.  
  - New waveform digitizer (WFD) records electron detector (eSC) signals.  
• All components commissioned with beam. Brief physics run.  
• Recorded decay statistics $N_{\mu^-} = 3.5 \times 10^9$ and $N_{\mu^+} = 1.4 \times 10^9$. |
| 2006 | • First MuCap physics result from our 2004 data.  
  - First unambiguous determination of the muon capture rate in hydrogen.  
  - First unambiguous determination of the induced pseudoscalar formfactor $g_P$.  
• Upgrades to setup:  
  - On-site H/D isotopic separation system built (with US CRDF grant money and PSI support).  
  and operated.  
  - Protium with deuterium contamination $\ll 1$ ppm reached.  
  - Flash ADC (FADC) system for all TPC wires and neutron detectors finished and operated.  
  - Full installation of 8 DEMON neutron counters.  
  - MuLan kicker successfully run in Muon-on-Demand mode.  
• Main data run towards the proposed statistics goal finished.  
• Recorded decay statistics $N_{\mu^-} = 8.6 \times 10^9$ and $N_{\mu^+} = 2.5 \times 10^9$. |
| 2007 | • $10^9$ statistics on $\mu^+$ in hydrogen  
• $10^{10}$ statistics on $\mu^+$ in AK-3  
• Systematic studies in ultra-pure hydrogen conditions.  
• Systematic studies with well known impurity doping.  
• Measurement of $p\mu p$ molecular formation rate for MuCap target conditions. |

Table 1: MuCap milestones — past, present, and future.

An overview of recent and future milestones of the experiment is given in Table 1. The analysis of the 2004 data has yielded the first MuCap result (Section 2) and cleared the discrepancy on $g_P$ which has puzzled the community for the last decade. Our result agrees with recent calculations.

The final upgrades for 2006, indicated in our 2005 progress report, were successfully implemented and fully used in the physics production run in spring 2006 (Section 3).

Our beam request for 2007 is based on the need to further study important systematics: mainly additional statistics on $\mu^+$ in hydrogen and AK3, an iron-cobalt alloy, which allows us a superb cross check with the precise $\mu^+$ lifetime measurement of MuLan, and impurity doped runs, in order to understand more precisely our efficiency of observing high-Z capture events in the TPC (Section 4).
2 First MuCAP result

![Muon decay spectra formed using different combinations of detectors and analysis treatments.](image)

(a) Selecting TPC stops without protecting against muon pileup creates background distortions. (b) Pileup protection eliminates these distortions and improves the signal-to-background ratio. (c) Further background suppression is achieved with an impact parameter cut on the reconstructed muon-electron vertex.

In Figure 3 we present our measured decay electron lifetime spectrum from data recorded in 2004 (MuCap Run8). The large background suppression possible with the MuCap apparatus is demonstrated.

Analysis of these data has yielded our first physics result. We measure a \( \mu^- \) disappearance rate in purified hydrogen of

\[
\lambda_{\mu^-} = 455,854 \pm 15 \text{ s}^{-1}.
\]

We have also made a complementary \( \mu^+ \) measurement of the muon’s “vacuum” decay rate,

\[
\lambda_{\mu^+} = 455,164 \pm 28 \text{ s}^{-1},
\]

which is in agreement with the existing PDG value of 455,160(8) s\(^{-1}\) and thus serves as a valuable control on the \( \mu^- \) measurement. We can extract from \( \lambda_{\mu^-} \) a value for the nuclear capture rate of muons from the hyperfine singlet ground state of the \( \mu p \) atom,

\[
\Lambda_S = 730 \pm 18 \text{ s}^{-1},
\]

from which we can infer a value for the weak induced pseudoscalar coupling of the nucleon,

\[
g_P(q^2 = -0.88m_\mu^2) = 7.0 \pm 1.1.
\]

The statistical and systematic uncertainties involved in the determination of \( \Lambda_S \) are presented in Table 2.

Our result for \( \Lambda_S \) is in good agreement with a recent theoretical prediction of 710 s\(^{-1}\) [7], but differs by several \( \sigma \) from previous experimental and theoretical results which were in the vicinity of 680 s\(^{-1}\) [5]. Our result for \( g_P \), however, is perfectly consistent with established theoretical predictions, and is moreover insensitive to the molecular effects that have plagued the interpretation of previous muon capture experiments (see Figure 4).

We are currently in the process of finalizing the preliminary results presented above, and we are documenting our work in several MuCap Technical Notes [8, 2] for scrutiny within the collaboration. We are also composing a Physical Review Letter on our findings, which we intend to submit for review and publication before the PSI user’s meeting in February 2007. The 2004 data analysis will comprise the Ph.D. theses of Tom Banks (UC Berkeley) and Steven Clayton (UIUC), both of whom will graduate in 2007.
Table 2: Summary of statistical and systematic errors from our preliminary determination of $\Lambda_S$ from the 2004 data. The “Correction” category in column 2 refers to the adjustments we must make to the $\mu^-$ disappearance rate in hydrogen to compensate for impurities and detector shortcomings, while “Offset” refers to steps in the subsequent extraction of $\Lambda_S$. Some of the numbers in the table are only approximate, since the UCB and UIUC analyses observe slightly different values.

<table>
<thead>
<tr>
<th>Source</th>
<th>Correction/Offset (s$^{-1}$)</th>
<th>Uncertainty (s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistics</td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td>$Z &gt; 1$ impurities</td>
<td>-17</td>
<td>4</td>
</tr>
<tr>
<td>Deuterium</td>
<td>-10</td>
<td>1</td>
</tr>
<tr>
<td>$\mu\mu$ diffusion (impact cut)</td>
<td>-3</td>
<td></td>
</tr>
<tr>
<td>Detector performance</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>eDetector treatment</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>$pp\mu$ formation</td>
<td>18</td>
<td>4</td>
</tr>
<tr>
<td>$pp\mu$ ortho-para transition</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>$\lambda_{\mu^+}$</td>
<td>-455,160</td>
<td>8</td>
</tr>
<tr>
<td>$\mu\mu$ bound state correction</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>Total uncertainty</td>
<td>18</td>
<td></td>
</tr>
</tbody>
</table>

Figure 4: Experimental and theoretical determinations of the pseudoscalar form factor $g_P$, plotted as a function of the ortho-para transition rate $\lambda_{OP}$ in $pp\mu$ molecules in hydrogen. The previous experimental measurements using ordinary muon capture (OMC, Saclay 1981) and radiative muon capture (RMC, TRIUMF 1998) obtained results that were mutually inconsistent with the chiral perturbation theory (CHPT) prediction for $g_P$, as reflected in the lack of a common intersection in the plot of their constraints. Moreover, the OMC and RMC experiments both used liquid hydrogen targets which promote $pp\mu$ formation, so their $g_P$ determinations are very sensitive to $\lambda_{OP}$, which itself is poorly known. The two experimental determinations of $\lambda_{OP}$—Ex1$_{OP}$ (TRIUMF, 2005) and Ex2$_{OP}$ (Saclay, 1981)—are inconsistent with each other and with the existing calculations ($\lambda_{OP}$). Because MuCap uses a gaseous hydrogen target the $pp\mu$ formation is slow. Therefore, our result is nearly independent of $\lambda_{OP}$ and thus enables an unambiguous determination of $g_P$, which turns out to be consistent with theoretical predictions.
3 Experiment 2006 (run 10)

3.1 Hardware upgrades

3.1.1 Beam and Muon-on-Demand

Based on the run experiences from previous years and especially the recent beam time in 2005, only minor beam tuning operations were required for the 2006 data acquisition period. First, we re-confirmed the already defined standard beam tunes for the πE3 beam line to give an optimal muon rate and electron suppression. Only one magnet setting was changed in its polarity to significantly improve the electron suppression. In addition, a constant fine tuning was performed in order to compensate for slight changes in the beam line conditions.

During the beginning of our experimental program, we were unfortunately confronted with unstable beam conditions due to failures of the accelerator. The efforts of the PSI accelerator staff finally solved the break downs in some crucial parts of the machine. However, the data taken during this period is not optimal due to the regular beam loss and subsequent ramping and the overall rate was low compared to our later stable running period. Therefore, we truly began collecting our production statistics during the middle of April. From that time on, there was only one major beam interruption of around 4 days at the end of April. During the run we faced some slight misbehavior of a few magnets in the area. Without any change in demand, the current in the magnet drifted leading to a loss in rate and/or a drop of our extinction factor\(^1\). However, the local staff was able to eliminate this drift by exchange of a relay in the power supply. Apart from these smaller drifts, the reliability of the beam line was good and its performance matched our needs well.

After commissioning the MuLan kicker system \([10, 11]\) for the operation in the so called muon-on-demand\(^2\) mode \([12]\) in 2005, no major effort was needed to operate the run in 2006 in this configuration. Through the entire beam time, the kicker system satisfied our expectations completely. The extinction factor started out to be at around 80. Ongoing improvements with the beam line settings led to a final value of 110. Our online monitored pile-up protected event rate was on the order of 24 kHz. This increased the rate of completely reconstructed events by a factor of three compared to runs without the kicker system because of the strong suppression of beam related pileup. Only the operation in the muon-on-demand mode allowed us to obtain the anticipated goal of \(10^{10} \mu^-\) events in the given time period.

3.1.2 Time projection chamber

Since the TPC worked very reliably at 5.45 kV during the 2005 production run, we decided to keep it untouched and enclosed in the aluminum pressure vessel under steady high vacuum pumping. In this condition, the TPC was continuously baked out at 120 C for most of the shutdown period (about three months from January until April 2006). The hope was to significantly improve the gas purity for the 2006 run, because the main source of impurities was clearly identified as outgassing water molecules from the TPC walls and materials (wires, etc) inside the vessel.

Unfortunately, at the end of the heating cycle, when the 10 bar protium was refilled, a broken high voltage connection inside the vessel was discovered. So, the TPC had to be open for a few hours to repair this connection. Luckily the repair was easy and successful, but it may have prevented us from reaching the ultimate purity (\(<10^{-7}\)) anticipated for the main 2006 production run. Still, the preliminary analysis of our new data has shown a reduction of gas impurities by about 1/3 as compared to the 2004 run. The impurity level reached in 2006 was slightly below 18 ppb.

For 2007 our plan is to make a renewed large vacuum pumping and baking effort, this time hopefully with no incident that would require the very clean interior of the TPC vessel to be opened again.

3.1.3 Full neutron counter setup

The experimental principle of MuCap has largely reduced the dependence of the extracted result for \(g_P\) on the ortho–para transition rate \(\lambda_{op}\). However, due to MuCap’s precision and the large inconsistency of existing experimental results, \(\lambda_{op}\) contributes to our result an uncertainty roughly comparable to

\(^1\)The extinction factor is the ratio of the incident muon beam rate over the muon rate during the kicker-on period.

\(^2\)In this mode the kicker is triggered by an incoming muon to deflect the beam for a period of 25 µs.
Figure 5: Pulse height versus pulse shape parameter from the neutron counter pulses as observed in a \(\mu^-\) data run for a small data subset of a single neutron counter. (a) Requiring no hit on the electron hodoscope counters, (b) requiring a coincident hit on the hodoscope counters. The electron hodoscope has a low detection efficiency for neutrons. Therefore the neutrons are not visible in b).

our final precision goal for \(G_P\). (see Fig. 4). This argument, as well as the possibility that the gas density might affect this rate, makes it desirable to directly verify the reaction kinetics. The method of choice is the direct observation of the time distribution of neutrons from reaction (1). No absolute efficiency determination is required.

We successfully tested three liquid scintillator neutron detectors borrowed from the DEMON collaboration during our 2005 run. As a consequence we have upgraded the MuCap setup with in total 8 DEMON detectors to reach an acceptable neutron detection efficiency.

The neutron detectors were read out by the new 12-bit waveform digitizers. A comparison of the slow and fast component of the detector pulse allows a neutron-gamma separation. Together with our mustop and decay electron counters we can then clearly identify capture neutrons and determine their time distribution. Fig. 5 shows the \(n - \gamma\) separation for a short data run with and without coincidence with the electron hodoscope located directly in front of the neutron counters. The branch of capture neutrons is clearly disappearing with the requirement for a coincident eSC signal because of the very low neutron detection efficiency in the thin hodoscope scintillators.

A thorough analysis of our 2006 data should allow us to better constrain \(\lambda_{op}\) which will reduce our systematics further.

### 3.1.4 Waveform digitizers

The 500 MHz waveform digitizers (WFDs) originally developed for the MuLan experiment [10] have successfully been incorporated into the frontend electronics of the MuCap apparatus. The role of the WFDs in MuCap consists of digitizing signals from both the 64-channel electron scintillator hodoscope eSC and the two entrance muon counters. The timing information from these detectors have been deduced from CAEN model V767 multihit TDCs and are now additionally analyzed from WFDs. The use of WFDs has several advantages over regular TDCs and opens up new perspectives in the reconstruction of physical information from the detector signals.

Most importantly, a more precise signal timing and additionally a signal size can be deduced from recorded waveforms by a fitting procedure.

The better timing characteristics will reduce some errors originating in the CAEN TDC electronics. It will allow us to resolve the position of the decay electron hit even within a scintillator sub-panel of the hodoscope counter and hence better join it to a track already identified by the ePCs. In this way the background suppression is improved.

The area under a waveform contains information about the energy deposited by an ionizing particle in the scintillator material. This information, allows the monitoring of gains, pedestals and thresholds in all scintillation detectors. Due to the energy information from the entrance muon counters we can now also monitor and fine tune the separation of beam muons and beam electrons. Also a precise identification of muon pile-up is possible from signal shape analysis.
The WFD setup was commissioned and tested during run 9 and fully implemented in run 10 with several improvements.

- A firmware bug has been fixed by electronics engineers at Boston University which caused some inefficiencies at times shortly after the beginning of the signal digitization.

- It became obvious during run 9 that all WFDs produce a data rate that is significant compared to the total data rate from all other modules. Therefore we implemented data compression prior to writing them into the data stream. A lossless data compression algorithm has been chosen based on the general purpose compression library \textit{zlib} \cite{14}.

- The WFD-readout MIDAS frontend has been thoroughly rewritten to implement multi-threading functionality. The on-line data compression in parallel to reading-out of frontend electronics has now become possible on dual-CPU PC’s. The new frontend reduces the data stream through the computer network and improves the dead time of the whole DAQ system.

One example of the benefits using WFDs is demonstrated in Fig. 6, where the energy loss distribution is shown for one of the eSC channels (Gondola 1, photomultiplier 1). The blue histogram corresponds to the WFD only energy spectrum, whereas the red histogram was accumulated when a coincidence with the CAEN TDC was required. The discrepancy between the two histograms originates from different threshold settings in the TDC and WFD modules. Thus, the WFD-only spectrum contains a noise component, whereas the TDC thresholds were set above the noise. From comparison of the two distributions the shape of the TDC threshold can be deduced and the recorded data can be corrected for the portion of events below the threshold. Noise levels can be identified unambiguously.

The identification of pile-up events and reconstruction of times requires the development of special off-line procedures for pulse-shape analysis, a task in progress.

\subsection*{3.1.5 Gas purity - CHUPS operating experience}

MuCap has two complementary procedures for determining the concentration of high-Z impurities in the target protium gas. One is the direct observation of muon capture events on impurity high-Z atoms, easily recognizable by their large energy deposit and specific event topography in the TPC. The second method is the analysis of target samples in a highly sensitive gas chromatograph and the in-situ monitoring of moisture at the ppb level. All volumes are checked using an online mass spectrometer before gas filling. A continuous hydrogen purification system (CHUPS \cite{9}) continuously cleans the target volume by removing high-Z impurities. The system performs excellently and reliably and can maintain the high-Z purity of the hydrogen over a several months long running period on the \(\approx 30\) ppb level, with the main contaminant being moisture. Therefore, we have a Pura PUR-TX-120 humidity transmitter located in the hydrogen stream just after the TPC in order to monitor this contaminant. The system which was successfully operated during the experiment in 2005 (run 9) was only slightly upgraded. Several modifications of the CHUPS control software were done before run 10. These changes were intended mainly to obtain a better usability of the software. The microprocessor control block software was also updated.
3.1.6 Drying of the TPC during the run

In run 10 we have observed the most reliable drying of our TPC and gas system. It is connected with the best initial TPC conditions in MuCap history. Before the run, the TPC had been exposed to continuous (about 3 months) vacuum pumping with a simultaneous baking up to 120 C. This treatment provided sufficient elimination of adsorbed water and a practically complete removal of most other contaminants fixed on the inner surfaces. Unfortunately, this excellent state was partly lost during a short opening for TPC maintenance. Nevertheless, the state of the TPC was sufficiently better than before all previous runs. The measured initial level of humidity in the hydrogen at the moment of CHUPS connection to the TPC vessel was $\sim 60$ ppb of water. During 400 hours of continuous cleaning with a mean hydrogen flux rate of 3 l/min the humidity exponentially decreased to $\sim 18$ ppb and remained at this level up to the end of the main $\mu^-$ data taking part of the run, thus providing a stable operation over more than 1000 hours.

The removal of humidity in the hydrogen is illustrated in Fig. 7a. The minor fluctuations of the humidity are explained by fluctuations of the environmental temperature in the experimental area. This temperature change affects the adsorption-desorption equilibrium in the chamber and, consequently, its outgassing rate.

3.1.7 Comparison of direct humidity measurements and the capture yield observed in the TPC at different hydrogen flux rates.

Additional tests of the CHUPS cleaning power were carried out during the period of systematic studies in run 10. We checked the influence of the CHUPS mean hydrogen flux alteration on the humidity measurement and on the TPC impurity capture yields. The mean hydrogen flow was changed from 3 l/min (regular conditions for run 10) to 0.5 l/min. Consequently, the humidity in the chamber shifted to a different equilibrium value. This change was measured simultaneously by the PURA humidity sensor in the outlet line of the TPC and the observed impurity capture events in the TPC. They jointly track in a linear relation the humidity increase of about a factor 3 at the lower flow rate (see Fig. 10).

3.1.8 CHUPS cleaning power

The efficiency of CHUPS cleaning a large contamination of nitrogen in the target hydrogen was tested by adding a “high” 22 ± 1 ppm nitrogen admixture from a known amount of nitrogen previously diluted in a vessel with high purity protium. This “nitrogen doped” condition was intended for a detection efficiency calibration of high-Z capture events in the TPC.
After measuring with a large nitrogen contamination (flat region) the CHUPS circulation through the TPC vessel was re-established and the nitrogen was removed. The cleaning progress observed online via high-Z capture events in the TPC is shown in Fig. 7b. The cleaning started at a yield of more than 1000 ppm and proceeded until leveling off around $\sim 30$ ppm, a value established before the doping.

### 3.1.9 Deuterium removal unit

The Deuterium Removal Unit (DRU) is a device for manufacturing ultra pure protium via isotope separation in a distillation column. This facility is the largest change and gain to the MuCap gas system in 2006. In winter 2005-06 the PNPI manpower was concentrated on the construction of this new unit. It is designed to clean the already deuterium depleted hydrogen, isotopically pure on the few ppm level, to a deuterium content far below 1 ppm. The construction of this unit was made possible by a joint US-CRDF grant for PNPI and UIUC. An additional difficulty for the DRU manufacturing was the short time between the initial idea and the data run. The unit was designed and manufactured at PNPI-Gatchina between December 2005 and March 2006. The completion, extended testing and the final commissioning was done on site with the support of PSI.

![Diagram of the MuCap Deuterium Removal Unit](image)

**Figure 8:** The MuCap Deuterium Removal Unit for isotope separation in hydrogen gas: (a) Layout and (b) photo of the installation at PSI.

### 3.1.10 Working principle and performance

The principle of hydrogen cryogenic distillation was used as a basis for the design of the DRU. This method uses the difference in saturation vapor pressure to separate isotopic species above the surface of the mixture. It can be considered as a multi-step distillation with the use of a column filled with special packing. The column, sketched in Fig. 8a has a length of about 2 m. It has a condenser and a re-boiler connected with its upper and lower part. The condenser condenses vapor and returns it into the column in liquid form. A COOLPOWER 140T cryo-generator with the maximal cooling power of 20 W at 20 K was used for the cold operations. The packing is intended to provide a maximal contact surface between hydrogen in different phases. The packing consists of prismatic spirals made from 0.2 mm stainless steel wire. The separated mixture boils in the re-boiler equipped by electric
heater forming the vapor. The vapor rises upward along the column and interacts with the counterflow of draining reflux: the liquid is being saturated by the high-boiling component, and the gas by the low-boiling component. Throughout the contacting tower, liquid and vapor are brought into repeated contacts that multiply the elementary separation effect. In our case the separating mixture is the mixture of regular hydrogen ($\text{H}_2$) and “deutero-hydrogen” (HD). A photo of the installed DRU in the PSI experimental hall in front of the $\pi E3$ area is shown in Fig. 8b.

In April and May 2006 the DRU was tested in a few long (up to 7 days) periods of operation. The total amount of pure protium produced by the column in this period was 1300 liters. Most of the tests of the column performance were carried out in the so called “total reflux mode”, with zero feed flow and withdrawal flows from the column top and bottom.

A fast method for analyzing the residual deuterium content in the depleted product was not available at the moment of operation. A chromatographic analysis of the ortho– to para–hydrogen ratio was proposed as a method of indirect estimation of the column separation efficiency. The measured concentration of ortho– and para– components in the top and bottom section of the column estimates its separation performance and allows us to recalculate the concentration profile for deuterium. An $\text{Al}_2\text{O}_3$-filled chromatographic column immersed into liquid nitrogen and neon as a carrier gas was used for the analysis.

<table>
<thead>
<tr>
<th>Probe Location</th>
<th>Deuterium Content (ppm)</th>
<th>Ortho–Hydrogen Concentration (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original gas</td>
<td>126.7</td>
<td>75</td>
</tr>
<tr>
<td>Top of the column</td>
<td>-1.9</td>
<td>14.6</td>
</tr>
<tr>
<td>Middle of the column</td>
<td>-</td>
<td>32.2</td>
</tr>
<tr>
<td>Bottom of the column</td>
<td>56.2</td>
<td>85</td>
</tr>
<tr>
<td>Average concentration calculated from the mass balance</td>
<td>7.7</td>
<td>53.5</td>
</tr>
</tbody>
</table>

Table 3: Results obtained with the natural hydrogen sample.

The first DRU test was carried out with natural hydrogen containing 126.7 ppm of deuterium. The column was filled with liquid hydrogen in large excess. After 1 hour of operation the excess gas (84 liters) was withdrawn from the column bottom. This explains the low final deuterium concentration in the bottom as given in Tab. 3. The measurement method of direct deuterium concentration is based on the extrapolation of the isotopic concentration measurement in the natural hydrogen sample. Unfortunately it has a low accuracy close to zero concentration and showed a negative deuterium concentration at the column top (-1.9 ppm). Four modes of protium production were experimentally tested:

- “feed through” with purging,
- “feed through” without purging,
- the so-called “Raleigh depletion”,
- continuous circulation through CHUPS.

The results of the cleaning runs are shown in Tab. 4.

A number of deuterium depleted probes were collected (“zero protium samples”) and then analyzed in the ETH accelerator mass spectroscopy lab, as will be explained in section 3.1.11.

### 3.1.11 Results from trace deuterium analysis

In the main experiment the TPC was filled with deuterium depleted hydrogen which was produced with a “Whatman” generator by electrolysis of depleted water samples from Ontario Hydro Generation Inc., Canada. The residual deuterium content was certified to be $\sim$1 ppm or better.

Since a ppm quantity of deuterium still requires corrections of the $\mu p$ lifetime in the order of 10-20 ppm, it was necessary to determine the deuterium content in our protium gas by precision mass
Table 4: Results obtained with different methods of running the deuterium removal unit for isotope separation in hydrogen.

spectrometry. We have approached two groups capable for performing such measurements:

1) The mass spectrograph of the Laboratory of Atmospheric Chemistry at PSI (M. Saurer, PSI). This instrument is a high performance spectrometer based on conventional mass spectrometry by ionization under UHV conditions, designed for determining isotopic differences of atmospheric precipitation. For the measurement of near zero depletion it was necessary to use extrapolations from the hydrogen standard (155.75 ppm) which induced some uncertainties about the zero deuterium point. For this reason we could finally only estimate the deuterium contents of our protium gas used in the runs 2004 and 2005 to be within 0-3 ppm.

2) The new “MICADAS” compact radiocarbon AMS system at the PSI/ETH Laboratory for Ion Beam Physics at ETH Zurich (M. Suter and M. Doebeli) [13]. After several years of methodical development at the big ETH Zurich Tandem accelerator, it was found that this new system, equipped with a specially developed aluminum sputtering cathode, is ideally suited to measure near zero deuterium admixtures, due to its extreme background suppression and very good zero point determination.

Table 5: AMS results for the isotopic deuterium concentration $c_d$ in the MuCap target hydrogen gas. Sample A-2006 and B-2006 are fully independent.

The AMS has the advantage of completely suppressing the $H_2$ molecular background by up to ten orders of magnitude. The hydrogen gas is guided onto the surface of an aluminum sputter cathode which is bombarded by a cesium beam. Negatively charged ions extracted from the surface are mass analyzed in a first mass spectrometer and injected into a small 200 keV Tandem accelerator. At the high voltage terminal of the accelerator two electrons are stripped off the ions in a gas filled canal, and the positively charged beam is further accelerated towards ground. The collisions in the gas also very efficiently destroy molecular ions present in the beam. Molecular fragments are then removed in a second mass spectrometer. While the proton beam current was determined in a Faraday-cup at
the entrance of the accelerator, the deuteron current was measured in a cup behind the second mass spectrometer. From the ratio of the two current measurements the deuteron concentration was calculated. A hydrogen standard was used for normalization. In order to account for hydrogen background in the ion source, the deuteron current without gas flow was determined and subtracted from the current with gas flow.

The results of the AMS measurements are given in Tab. 5.

Additionally to the direct trace deuterium determination the MuCap apparatus is also capable to internally measure the deuterium concentration via analysis of diffused decay events. The effect of the macroscopic \( \mu d \) diffusion, where decay electrons can be found centimeters away from the corresponding muon stop, is reflected in an impact parameter dependence of the observed lifetime which scales with deuterium concentration. After accounting properly for the much smaller diffusion of \( \mu p \) atoms (mm scale), the data analysis yielded a deuterium concentration in full agreement with the direct AMS results (see Tab. 5).

### 3.1.12 New FADC electronics

New 12-bit flash ADC electronics modules were designed and built in a joint project of UC Berkeley and UC Louvain during 2005 and 2006. They were installed and operated during the 2006 run. These new modules are intended for two principal applications within MuCap: timing and pulse shape discrimination for the DEMON neutron detectors, and recording of analog waveforms from all TPC anodes and cathodes for triggered events, typically corresponding to interactions of muons with impurities. The TPC flash ADC data should be used to build energy spectra for the recoil nuclei in muon capture on high-Z impurities and to search for muon-catalyzed \( p + d \) fusion events in order to further constrain the systematic uncertainty from deuterium.

The Maxim MAX1213 12-bit flash ADC device is at the core of these new modules. It has a maximum sampling rate of 170 MHz and an input range of \( \pm 0.75 \) V. In order to minimize noise pickup, all connections to the device are differential; its digital inputs and outputs employ LVDS (Low Voltage Differential Signaling) levels, which are also used where possible for fast digital signals elsewhere on the board. The measured RMS noise level is 1.1 ADC codes, corresponding to 0.2 mV. Data pass from the ADC to a frontend Xilinx Spartan-3 field-programmable gate array (FPGA), which provides an application-specific trigger mechanism as well as a first layer of buffering. In the neutron detector mode, the frontend logic is self-triggering, retaining waveforms when the ADC code exceeds a threshold value, while the TPC ADCs are externally triggered. The data are then transferred to a backend FPGA, which formats them as Ethernet packets for transmission directly to the event-builder computer in the MuCap data acquisition system. The boards operate from a single +3.3 V power supply except for an optional negative analog bias voltage; they are physically the same size as 6U VME modules, but no complex backplane interface is required.

A prototype board was used to reliably record neutron detector waveforms for the entire 2006 run. The first set of production boards, sufficient for all TPC anodes and most of the cathode strips, was installed on May 17; the rest of the cathodes were instrumented the following week. Consequently, TPC FADC data exist for approximately the last 4 to 5 weeks of the run. The rate at which this system could be triggered was limited to about 20 Hz by problems with the Ethernet transfer to the DAQ computer; this rate was sufficient for the production data, while a rate of 100 to 200 Hz would have been useful for the impurity calibration runs. Work is in progress to improve the throughput for next year’s systematic tests.

### 3.2 Run overview

The main focus of run 10 in 2006 was to acquire the anticipated goals of \( 10^{10} \) pileup protected muon decays for both \( \mu^- \) and \( \mu^+ \). As can be seen from Fig. 9 showing our accumulation of fully reconstructed \( \mu^- e^- \) pairs during the run, we reached \( 8.58 \times 10^8 \) \( \mu^- \) events (blue). Together with the combined statistics from previous runs, we therefore reached the total statistics goal for the \( \mu^- \) data set. In addition, we accumulated a good portion of the anticipated amount of \( \mu^+ \) events (red), namely \( 2.56 \times 10^9 \). Towards the end of our run we also had several systematics studies (green curve), mainly for the purpose of calibrating the influence of water and nitrogen (see below). Please note that the vertical dashed lines in the plot correspond to Wednesdays where the accelerator is shutdown for either beam development
or maintenance. Hence, the figure also demonstrates our high running efficiency due to an excellent performance of all critical detector components. One other key element to achieve this high statistics within the beam time was the stable operation of the kicker system [11] in the so called muon-on-demand mode [12].

Figure 9: The acquired statistics of \( \mu^-(\text{blue}) \) and \( \mu^+(\text{red}) \) for the run 10 in 2006. The selected events are after pile-up protection, a fiducial cut in the TPC and signal selection in the drift chambers ePC1/2 and the scintillator hodoscopes eSC. The selection criteria are very close to the final selection of events in the detailed offline analysis. The green line represents the acquired statistics during our systematic studies with additional controlled amounts of water and nitrogen in the hydrogen gas.

Due to a delayed start of our main production mainly caused by accelerator down-time at the beginning of our beam time, we were not able to acquire the full amount of \( 10^{10} \) decays for both \( \mu^- \) and \( \mu^+ \). Therefore, the collaboration clearly focused on the \( \mu^- \) since the running conditions with respect to both the deuterium and the humidity level in the hydrogen gas as well as the TPC performance were very satisfying.

With the commissioning of the new deuterium removal unit (see section 3.1.9), one major “impurity” component – leading to a change of the measured rate – was removed from the hydrogen gas. An upper limit for the deuterium concentration \( c_d \leq 0.07 \) ppm was measured using the AMS system MICADAS (c.f. section 3.1.11) at the ETH Zurich. At this level of deuterium, the correction to the \( \mu^p \) lifetime is small enough to be of no concern for the final result.

The TPC was brought to normal operation at 5.45 kV after a short repair at the beginning of our production run. This operation required opening the vessel, leading to an increase of the humidity to \( \sim 60 \) ppb. The continuous drying of the system during the run led to an exponential drop in humidity to a final value of \( \sim 18 \) ppb. Nevertheless, the overall humidity level was sufficiently better than during all previous runs and the TPC was running very reliable with no major problems.

Table 6 summarizes the two production sets for \( \mu^- \) and \( \mu^+ \). It is worth to note, that there was no necessity to change the two important running conditions, namely the TPC high voltage and kicker mode and HV.

<table>
<thead>
<tr>
<th>Year</th>
<th>Particle</th>
<th>Kick Mode</th>
<th>High Voltage [kV]</th>
<th>Statistics ( 10^9 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>( \mu^- )</td>
<td>Muon on Demand</td>
<td>5.45</td>
<td>8.58</td>
</tr>
<tr>
<td></td>
<td>( \mu^+ )</td>
<td>Muon on Demand</td>
<td>5.45</td>
<td>2.56</td>
</tr>
</tbody>
</table>

Table 6: Statistics of fully reconstructed \( \mu-e \) pairs obtained for the main production conditions.
In addition to accumulating production data, several systematic studies were planned and executed during run 10. The primary objective was to calibrate the efficiency to observe a muon capture signal on a known high-Z impurity. We have previously observed outgassing of nitrogen and oxygen (water) into the target without observing evidence for other elements. As such, the systematic studies focused on nitrogen and moisture.

3.2.1 Runs with controlled water doping

In order to calibrate the muon capture signal on the oxygen bound in water, we established various methods for introducing additional known and controlled amounts of water into our system. Since the equilibrium water concentration in the TPC depends on the hydrogen flux rate through the CHUPS circulation system, we began by decreasing the mean flux rate to 0.5 l/min (see sect. 3.1.5). An increase in both the PURA humidity sensor reading and the high-Z impurity capture signature in the TPC was observed.

During the production data, the water concentration was about 18 ppb. We chose to introduce a large quantity of water in order to extract a more sensitive calibration of the capture signal. A permeation tube was used in order to dope the system with a stable level of humidity. It was installed in the circulation system together with a heating coil and a temperature monitor, in order to produce a fixed source of humidity for the system. By this method, an equilibrium water concentration of approximately 2.2 ppm was achieved. Figure 10 shows the relationship between the PURA humidity sensor readings and the measured impurity capture signal in the TPC. This measurement will allow us to correct the production data for the presence of a small level of water.

![Captures per mustop [ppm], humidity sensor](image)

Figure 10: The black points show the high-Z capture yield detected by the TPC signal analysis. The red curve comes from the PURA humidity sensor and has been scaled by 250 to match in amplitude. This shows the direct relationship between the measured humidity and the observed impurity concentration signal.

3.2.2 Runs with controlled nitrogen doping

Previous runs have included extensive systematic studies to quantify the capture yield from nitrogen in the TPC. A brief measurement was performed during run 10 for consistency as some conditions, such as TPC gain and deuterium concentration, were different with respect to previous years.

A known amount of $21 \pm 1$ ppm nitrogen was introduced into the TPC with the CHUPS system disconnected. After the system equilibrated, a sample was taken and gas chromatography measured
24±1 ppm. This mixture produced a capture yield of about 1740 ppm, which is in good agreement with expectations based on previous nitrogen doped measurements. This calibration confirmed previous evaluations of the efficiency of the nitrogen capture event finder. In this way we have established method with all parameters known to directly correct our final lifetime result for the small (<0.01 ppm) nitrogen presence in our production data.

3.3 Analysis of run9 and run10

3.3.1 High Z systematic comparison between runs

While the analysis of the run 10 production data is in its preliminary stages, we have already extracted some results from the high-Z impurity analyses on nitrogen and water (oxygen). The impurity finding algorithm which was refined for the run 8 analysis has been used to examine our nitrogen doped data from run 10. We confirmed the findings from run 8 that our impurity finder efficiency is about 64%. We also observe a deviation in the observed decay rate of about 1.3 Hz/ppm capture yield of nitrogen. Since our production data contains <10^{-2} ppm nitrogen, the correction due to the nitrogen impurity should be very small. We now have a large quantity of consistent nitrogen data from the various runs that will contribute to reducing the uncertainty of our production measurement.

This year has also produced the first quantitative water/oxygen impurity measurements. Due to the electron affinity of O_2 molecules in our protium gas, we were unable to calibrate the oxygen capture yield by direct doping as we did for nitrogen. Instead, we doped the TPC with water to produce a reasonable signal in our apparatus, which is practically a much more sophisticated process.

A preliminary analysis of this calibration data shows a finding efficiency for impurity captures on oxygen of about 55%. Additionally, the deviation in the observed rate of 1.5 Hz/ppm is similar to the value found for nitrogen. Figure 11 shows the relationship between the humidity sensor reading and the observed impurity capture event yield. The red production data point is to the right of the best fit line, indicating that the production data contains a mixture of different impurity species. This analysis indicates a promising start in understanding the effects of oxygen contamination on the production data.

![Figure 11: This plots show a fit to the four calibration methods for water. The capture yield increases linearly with oxygen concentration.](image)

3.3.2 \( \mu^+ \) data in AK-3

At the beginning of the fall 2005 run, as the final commissioning of the TPC was in progress, data were collected for a measurement of the positive muon lifetime in an Arnokrome-3 (AK-3) target.
These data have now been analyzed. A disk of this material, which has large inhomogeneous internal magnetic fields (\(\sim 0.5 \text{ T}\)) that suppress the polarization of the muon population, was suspended in the center of the electron detector in place of the TPC. With a 15 \(\mu\text{s}\) pileup rejection time, \(1.4 \times 10^9\) decay events were collected in unkicked mode, while \(3.8 \times 10^8\) were observed with the kicker. This level of statistics permits a measurement of the positive muon lifetime with a precision of 30 ppm. The analysis tracks the decay electron back to the target plane, and a radial cut in this plane is used to suppress backgrounds.

While the result has not yet been unblinded, initial fits indicate an acceptable \(\chi^2/\text{dof}\) and consistent decay rates as a function of the fit start time, the azimuthal coordinate, and the \(z\) (beam axis) coordinate at the electron detector. The unkicked result is also entirely consistent as a function of radial coordinate at the target plane, even at unphysically large radii. On the other hand, the fitted rate for the data collected with the kicker increases by 70 Hz (150 ppm) when no radial target plane cut is applied, suggesting a time-dependent background component related to the kicker; it is stable for radial cuts from 75 to 150 mm. The analysis of this AK-3 data will continue in parallel with the rest of the 2005/2006 analysis, and it should be available for publication together with that data set.

4 Plan and beam time request 2007

In fall 2006 the MuCap experiment completed the collection of the main data with \(\mu^-\) beam and accumulated a statistics integrated over three production runs (2004/2005/2006) exceeding \(1.2 \times 10^{10}\) clean and fully analyzable events. This is sufficient to reach the proposal’s goal of a 1\% determination of the singlet \(\mu^-p\) capture rate in terms of statistics.

Our integral accumulated \(\mu^+\) statistics, on the other hand, has only reached about \(4 \times 10^9\) analyzable events (runs with solid targets not included). Agreement of our \(\mu^+\) lifetime result with the world average \(\mu^+\) lifetime (as recently improved by MuLan) will demonstrate insensitivity of the MuCap result to possible systematic errors common to both muon charges. For example, such a common systematic effect in the high precision lifetime measurement could be caused by the relatively slow responses of the electron wire chambers. Another possibility is the production of delta-electrons along Michel electron paths in the TPC which may interfere with muon tracks in a decay-time-dependent way. \(\mu^+\) data are also essential as a control set for \(\mu^-\)-specific effects, such as \(\mu^-p\) diffusion and \(\mu^-Z\) impurity captures.

- We consider a direct comparison of \(\mu^+\) with \(\mu^-p\) lifetime measurements taken under the same experimental conditions at our originally aimed precision level \(\sim 10\) ppm as very important. Therefore, we plan to upgrade our main \(\mu^+\) statistics to the level of \(10^{10}\) events which will require \(\sim 4\) weeks of beam time.

- We intend to reach the best ultra-pure conditions ever for the next run via preparation of the TPC with a specific long baking and pumping time. Measuring the impurity captures with \(\mu^-\) in this ultra-pure condition will serve as important systematics test and calibrate the sensitivity of our TPC impurity detection together with simultaneous sensitive gas-chromatography measurements (\(\sim 1\) week beam time).

Furthermore, there are a number of other systematic issues left which need to be addressed by a number of special runs in order to keep all systematic errors clearly below the statistical one:

- Measurement of the \(ppp\) formation rate \(\lambda_{ppp}\) at the MuCap experimental conditions. Although our experiment was designed to operate in low density hydrogen gas where the probability for \(ppp\) formation is small, this process still induces a 40 ppm correction with \(\pm 9\) ppm uncertainty, because the literature values of \(\lambda_{ppp}\) vary by a factor of two. This uncertainty can be strongly reduced by measuring \(\lambda_{ppp}\) via the \(\mu^-\) lifetime in argon doped protium (\(\sim 2\) weeks beam time).

- Exact determination of the effects of residual water impurities on the measured muon lifetime with a new high precision absolute humidity calibration. Measurement of the TPC detection efficiency for impurity capture events on oxygen (water). This will allow us to control the impurity corrections (38 \(\pm 9\) ppm in the 2004 run) to a significantly smaller level (\(\sim 1\) weeks beam time).
In addition to the above mentioned collection of more $\mu^+$ statistics we plan to study possible systematic effects of the TPC by making a $\mu^+$ lifetime measurement using a special solid target ("AK-3") instead of stopping the muons in the hydrogen of the TPC. We plan to collect a total of $10^{10}$ observed $\mu^+$ decay events in AK-3. In this manner, the unbiased nature of the electron detectors will be demonstrated and we will have a superb cross-check with the MuLan experiment. (~1 week beam time).

With these systematic tests and $\mu^+$ measurements we intend to reach the precision goal which was originally formulated in our Proposal [2, 3].

Together with a one week contingency for setup and failures (beam or apparatus), we request for area $\pi E3$ a period of 10 weeks duration starting in early August 2007.

This beam request has been discussed with and agreed upon by the other main users of the $\pi E3$ area, R. Scheuermann for the $\mu$SR community and D. Hertzog for the MuLan collaboration.

References


[4] Recent invited and contributed MuCap presentations at international conferences were:
   P. Kammel, Particles and Nuci Int. Conference (PANIC’05), Santa Fe, NM - Oct.24-28, 2005.
   F. Mulhauser, 7th Int. Workshop on Neutrino Factories & Superbeams (NuFact’05), Laboratori Nazionali di Frascati, Frascati (Rome) June 21-26, 2005.

   We also note that a recent ChPT calculation by N. Kaiser (Phys. Rev. C 67 (2003) 027002), confirmed the stability of the theoretical predicted capture rate at two-loop order.


[8] Selected MuCap Technical Notes relevant for the analysis.
- T. Banks, MuCap Run8 analysis report - UCB.
- S. Clayton, MuCap Run8 analysis report - UIUC.
- B. Lauss, T. Banks, Impurity report of Run8.
- B. Lauss, Impurity report Run9.
- T. Banks, P. Kammel, Revisions to the High-Z impurity correction numbers.
- B. Kiburg, Run 10 impurity report.
- T. Banks, eDetector Run7 Analysis.
- T. Banks, muDet inefficiency systematics.
- S. Clayton, muP diffusion and impact parameter cuts.
- P. Winter, Run9 overview.
- P. Kammel, Deuterium effects in MuCap.
- S. Clayton, P. Kammel, B. Kiburg, Analysis of time distributions in the MuCap experiment.


