Progress Report 2005 and Beam request for 2006

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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University of California, Berkeley – University of Illinois at Urbana-Champaign –
Université Catholique de Louvain – Boston University – University of Kentucky –
Technische Universität München

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

Figure 1: Reconstruction of scattering materials in the decay electron path via electron tracking. This procedure displays the sensitivity of our tracking method using the two cylindrical wire chambers, indicated as black circles. The scattering centers are identified as the TPC quartz frames and the hydrogen return line on top of the vessel.
1 Overview

The MuCap experiment [2, 3, 4] is a high-precision measurement of the rate for the basic electroweak process of muon capture,
\[ \mu + p \rightarrow n + \nu. \] (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, the current experimental results suffer 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 2).

Figure 2: Experimental constraints for \( g_P \). The new measurement of the ortho–para conversion rate \( \lambda_{op} \) (TRIUMF 2005) is significantly larger than the previous experimental result. This uncertainty of \( \lambda_{op} \) implies a large uncertainty in the extraction of \( g_P \) from existing experiments. Moreover, theory, ordinary muon capture (OMC) and radiative muon capture (RMC) are mutually inconsistent. The MuCap experiment will be more precise and nearly independent of \( \lambda_{op} \).

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% 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.

- **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 surpassing 0.035 ppm are achieved.
The main components of the MuCap detector are shown in Figure 3. 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 $N_{\mu^+} = 0.2 \times 10^9$. |
      * 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 | * New US CRDF grant approved to build on-site H/D separation system.  
      * New Flash ADC (FADC) system for all TPC wires and neutron detectors.  
      * Main data run towards the proposed statistics goals: $N_{\mu^-} = 10 \times 10^9$, and $N_{\mu^+} = 10 \times 10^9$. |
| 2007 | * Additional statistics or shorter systematics run, depending upon 2006 results. |

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 is well advanced (Section 2). The main upgrades for 2005 have been successfully commissioned and used for physics production (Section 3). Final upgrades are being prepared now and will be employed in the main production run in spring 2006 (Section 4). Our beam requests beyond 2006 will depend on the outcome of the 2006 run.

2 Analysis Experiment 2004

In parallel with MuCap’s ongoing experimental efforts to collect new data, we are continuing to analyze the existing data from the 2004 run. MuCap recorded approximately $2 \times 10^9$ decay events in 2004,
which represents 20% of the $10^{10}$ events needed to reach our 1% capture rate measurement design goal. The 2004 statistics should be sufficient for a 3% capture rate measurement and a 20% $g_P$ determination.

Towards this end, two separate analysis efforts are being led by MuCap graduate students Tom Banks (UC Berkeley) and Steven Clayton (UIUC). They have developed independent software packages within a common MIDAS Analyzer framework, with the goal of extracting the $\mu P$ capture rate from the 2004 data. Although the two sets of software share the same raw data processing algorithms, the routines responsible for the actual physics analysis have been developed separately. Two additional steps have been taken to ensure that the two analyses remain independent:

- In collaboration discussions, results are presented with secret offsets so that the two analyses do not succumb to an inadvertent convergence.
- The $\mu^+$ analysis, which serves as an important control on the $\mu^-$ lifetime measurement, is performed by different collaboration members.

Furthermore, both the UC Berkeley and UIUC analyses are “blind,” since the 2004 experimental clock frequency was slightly detuned and the exact size of the offset has been entrusted to two collaborators not directly involved with the analysis. When the analysis is complete, the Berkeley and Illinois results will be unblinded and compared as an internal collaboration consistency check.

UC Berkeley currently uses the PSI Merlin cluster for its large-scale production analyses, while the UIUC analysis uses local facilities. The UIUC software was initially installed on a 20-CPU Linux farm at the UIUC Nuclear Physics Lab (NPL) but has since been moved to the National Center for Supercomputing Applications (NCSA), also at UIUC. Future UIUC production analyses will be performed at NCSA, and resources are available there for UC Berkeley if needed.

A large fraction of the analysis work in 2005 was devoted to software development and detector consistency checks. In particular, we made substantial modifications to the analysis infrastructure with the goal of increasing the processing speed. A full analysis pass over the 5 terabytes of raw 2004 data initially required six weeks to complete. In order to reduce this time, we subdivided the analysis into multiple stages. First we “skimmed” the raw data to select only pileup-protected muon events with a TPC signal (stage 1). The skimmed data is roughly five times smaller in size than the raw data, with a proportional reduction in processing time.\(^1\) Next, we made use of “Ntuples” to subdivide the processing stages even further. Ntuples are produced from the skimmed data (stage 2), then quickly processed to form lifetime histograms according to different criteria (stage 3). In this way, we can quickly and efficiently perform different studies by rerunning only the last stage of the analysis.

\[\text{(a)}\] Muon stops in TPC, sideview

\[\text{(b)}\] TPC shell volume scan: $\mu$ decay rate

![Figure 4: (a) Side view of events in the time projection chamber, which images the $\mu^-$ stop distribution (the muon beam enters from the left). Cuts on the reconstructed stopping point can be applied in all three dimensions. (b) Decay rate vs. muon stop fiducial volume. As the volume of acceptable muon stops in the TPC shrinks, the minimum distance from the muons to the surrounding detector materials increases, and the effects due to muon diffusion and capture on high-$Z$ wall materials disappear.\(^1\)](skimming)

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\(^1\)Skimming will be unnecessary for the 2005-6 data analysis because of the newly-introduced muon-on-demand capabilities. In this case, most of the raw data will already consist of pileup-protected events, thus avoiding the data losses during the skimming stage.
Our analysis has produced several notable successes thus far:

- The addition in 2004 of the second electron wire chamber, ePC2, has enabled us to perform numerous powerful studies involving electron tracking. In particular, the combination of muon and electron tracking capabilities has given us the means to perform a model-independent correction on deuterium-diffusion-generated effects in our $\mu^-$ decay measurement. Since the distribution of decay rates vs. tracking cuts scales with the deuterium concentration (Figure 5), we can use data from deuterium-doped calibration runs to extrapolate to the ideal case of zero deuterium concentration.

- The three independent electron detectors have provided us with the capability to confirm the stability of the lifetime measurement vs. different detector combinations (such as the electron scintillator hodoscope alone versus complete electron tracking with the wire chambers). Similarly, by recording the signals from the electron scintillator hodoscope in parallel in separate TDC systems (CAEN TDCs and our custom-designed Compressor TDCs), we were able to eliminate the possibility that electronics are a significant source of systematic error.

- We have a better understanding of the composition and concentrations of high-Z impurities in the hydrogen gas target, and how to perform the necessary correction. During the 2004 run, we observed unexpectedly large fractions of high-Z capture events in the TPC. In order to reconcile these numbers with the low levels of nitrogen and oxygen measured by our chemists, we hypothesized that water was the primary contaminant. Tests before and during the 2005 run have supported this hypothesis (see Figure 6).

- We have quantified systematic effects in the $\mu^-$ measurement due to the small but unavoidable muon detector inefficiencies, and we have demonstrated that muon diffusion into detector materials can be eliminated with selection of a proper fiducial volume (Figure 4).

![Figure 5: (a) Observed decay spectra showing dramatic accidental suppression due to $\mu - e$ impact parameter cut. (b) Decay rate vs. reconstructed muon/electron track impact parameter cut, from runs with different deuterium concentrations. The distribution of rates scales with increasing deuterium concentration.](image)

One remaining problem in the 2004 analysis is the unexpectedly large variation in the decay rates observed in the 16 hodoscope (eSC) elements. At present we are exploring several hypotheses to explain this effect.

We expect to resolve all remaining issues and obtain a final result from the 2004 data sometime within 2006. Estimates for anticipated corrections and errors in the final result are listed in Table 2.
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<th></th>
<th>Correction [ppm]</th>
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<td>Molecular transition ($\lambda_{op}$)</td>
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<td>6</td>
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</tr>
<tr>
<td>Other (eSC element variations)</td>
<td>*</td>
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</tr>
</tbody>
</table>

**Total**

Table 2: Preliminary estimates of the statistical error, systematic corrections, and systematic errors relevant to the 2004 $\mu^-$ data analysis. Units are given in parts per million with respect to the theoretical prediction for the effective $\mu^-$ lifetime in hydrogen gas, $\lambda_0 + \Lambda_s = 455, 166 \text{ Hz} + 680 \text{ Hz} = 455, 846 \text{ Hz}$. Entries marked with a * are still under development.

3 Experiment 2005

3.1 Hardware Upgrades

**Beam**

At the beginning of the run, we studied the beamline in order to optimize the settings for both the negative and positive muon beam. The aim was to generate similar beam spots and positions at the entrance muon counter for both species. Simultaneously, the profile of the beam was focused on the target to produce a good stopping distribution. After fine tuning, we adjusted the detector center to the empirical beam position. The standard beam tune was defined for both muon species at a beam rate in the range of 25-70 kHz, where the higher beam rate was needed for the muon-on-demand mode described below.

The performance of the beamline matched our needs well. At the beginning of the measuring period, a magnet drifted which was finally fixed by replacing a power supply. In the last week of the run, we lost the remote control of one magnet due to a breakdown in the control unit. However, a manual access for switching the beam polarity was still available, and this problem will be fixed by the local staff during the shutdown period. Apart from observed smaller drifts, the reliability of the beam line is good and no major efforts are needed for our production run in 2006.

**Kicker and Muon-on-Demand**

Starting in June 2005, several steps were performed to ensure the operability of the MuLan [8] kicker for the upcoming MuLan and MuCap runs as described in detail in the MuLan progress report. When we took over, we benefited from the operation experience and calibration measurements of the MuLan group. The kicker was working reliably during the MuCap run period, apart from a breakdown caused by a short circuit. The cause of the short was a metallic beam collimator plate that had fallen out of position and came into contact with both the HV plate and the grounded beam pipe. During the upcoming shutdown period, the collimators will be reinstalled in a more reliable way to avoid future problems.

The muon-on-demand mode was first implemented during the 2005 run, allowing us to realize the full potential of the kicker [9]. In this configuration, an incoming muon triggers the kicker to turn on for 25$\mu$s so that most of the beam is prevented from reaching the target area. Hence, the so called pileup events, where a second muon enters the detector, are strongly suppressed. Before the usage of the kicker, the rejection of such pileup events in the offline analysis lead to a reduction of around 70% of the collected statistics. In comparison, the muon-on-demand mode had an extinction factor$^2$ of around 50, and the pileup rate was reduced to less than 5%! The new muon-on-demand running mode will allow us to acquire the full proposed statistics in the next run.

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$^2$ The extinction factor is the ratio of the muon rate with kicker on to that with kicker off.
TPC

The TPC sits in the center of the MuCap detector and is an active muon stopping target. It is placed inside an aluminum pressure vessel filled with 10 bar of ultra-pure deuterium-depleted hydrogen gas (protium). Together with the scintillation counter, $\mu$SC, and a two-plane multiwire chamber, $\mu$PC$_{x,y}$, the TPC identifies and tracks each muon to its stopping location in all three coordinates, as depicted in Figure 4. This method allows us to eliminate in the analysis any wall stops that would otherwise cause a prohibitive background for the capture measurement.

In the previous runs (2003-04) we operated the TPC successfully at $\sim$5 kV, which was sufficient to detect all tracks from slow muons (energies below 1-2 MeV) and muon capture reactions on impurities (nuclear recoils). However, discharges in the amplification region of the TPC (hotspots) prevented operation at higher voltages, e.g. at 5.4 kV, where the less ionizing 5.3 MeV muons emitted from $p\mu d$ fusion would become visible (so called “Alvarez muons”). The detection of this process is important for determining the residual deuterium content ($\sim$3 ppm) contained in the protium gas which necessitates a correction of our data.

In a ten-month all-out effort, we have therefore completely overhauled the TPC by replacing both cathodes and a number of damaged anode wires. We also doubled the insulating Kapton foil between the anode-cathode frame, which slightly increased the chamber gap, changing the gain to high voltage relationship between 2004 and 2005. For a direct comparison, $\text{Gain}(HV_{2005}) = \text{Gain}(HV_{2004} + 100)$. We succeeded in reaching stable operating conditions in protium gas at 5.6 kV without any discharging currents. During the eight-week run in November-December 2005, the TPC was operated at 5.45 kV without any flaws.

In a parallel effort, the Gatchina team has in the past years built and tested a second, almost identical TPC with the purpose of having a replacement ready in case of failure of this critical device. During fall 2005, TPC2 reached operating voltages up to 5.9 kV with a $^{90}\text{Sr}$ beta source. At this voltage, it is expected that minimum ionizing electrons may become visible in the TPC volume.

Gas Purity

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. Figure 6a shows the impurity capture yield observed in the TPC over a five-day period. 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 (Figure 6b).

All volumes are checked using an online mass spectrometer before gas filling. A hydrogen purification system (CHUPS [7]) continuously cleans the target volume by removing high-Z impurities. When commissioned in 2004, CHUPS was able to decrease the N and O contaminations by an order of magnitude compared to previous years. The system performance was further improved in 2005 by the following newly installed hardware and software upgrades:

- A second mass-flow controller, a second reserve volume and an additional pressure sensor. This allows CHUPS to run at hydrogen flow rates from 0.5 L/min up to 3.2 L/min. The observed pressure stability at the outlet of the TPC hydrogen volume at flow rates of 1.3, 2.9 and 3.2 L/min, was 0.006%, 0.02% and 0.03%, respectively. The system stabilizes the density-dependent TPC gas-gain factor well enough to prevent systematic uncertainties due to gain drifts.
- A SAES Micro Torr getter for additional gas cleaning immediately before the TPC inlet.
- A Pura PUR-TX-120 humidity transmitter for direct online water vapor measurement in the hydrogen flow with a sensitivity down to a few ppb. A temperature stabilization unit was designed and built to assure a controlled and stable humidity sensor environment in order to fully exploit its measurement capabilities.
- A new liquid nitrogen filling system which can be operated during data taking. This allowed us to typically gain two hours per day of useful data-taking and minimized disturbance in the experimental area.
- A new completely revised control block with new microprocessor controller and specially designed power supply providing a customized power distribution for several CHUPS control devices.
A software upgrade provided running stability with a new regulation algorithm for pressure stabilization, a new interface for user convenience, and an improved instrument safety and alarm system.

Overall, the performance of the CHUPS system was very reliable and stable during the two month run. Several analyses using the gas-chromatography system showed that CHUPS successfully cleaned the protium to a stable ∼0.01 ppm nitrogen level, and an even lower oxygen level, below the measurement sensitivity.

The online humidity sensor worked reliably during 2005 and provided strong evidence for our initial concern that most of the observed impurity events are caused by water/moisture outgassing. This sensor reliably tracked changes in the system which we performed as systematic checks. The readings on this sensor could be directly compared with the observed impurity event yields in the TPC. During CHUPS circulation, a stable 0.035 ppm water contamination was reached (Figure 6). Measuring the stabilized impurity yield at two different hydrogen flow rates of 3.2 and 0.8 L/min allowed us to directly compare the humidity sensor readings and TPC event yields. The expected linear relation was corroborated. Consequently, this humidity sensor provides a very important handle on one impurity correction factor in the MuCap data analysis which would otherwise increase the systematic error.

Figure 6: a) Impurity capture yield (red dots) observed directly via high-Z muon capture events in the TPC over a 5 days period. Each point represents 15 runs (∼75 min). The green dots display the stable background (control) events. b) Observed humidity in the Pura sensor showing stable running conditions at a humidity level of 0.035 ppm with the protium TPC volume connected to CHUPS. When the protium volume is disconnected CHUPS shows that its internal cleaning performance is significantly better. Hence we can conclude that the humidity is introduced in the TPC part of the system.

**DAQ and Electronics**

The general structure of the data acquisition system remained similar to previous years. However, the stability of the software was improved, so that the system typically ran continuously for several days at a time without problems.

Waveform digitizers constructed for the MuLan experiment were installed to collect pulse shape data from all channels of the eSC hodoscope. These modules use 8-bit flash ADCs to sample their input at a rate of 500 million samples per second (MSPS). The ADC continuously digitizes the input signal, but zero-suppression logic records only intervals near pulses. Offline, the waveforms may be fit to determine the pulse amplitude and time. The time provides a cross-check on the primary measurement by the CAEN V767 TDC, and the amplitude and shape information allow the detection of overlapping pulses. The amplitude is also used to check the detector gain calibration; Figure 7 shows the spectra collected for electrons from muon decay.

In addition, a prototype of a new 12-bit waveform digitizer was tested in the last days of the run. The board requires minimal external infrastructure and uses a simple network protocol over an Ethernet interface. Two rather different applications are immediately envisioned, both requiring a large dynamic range:
Figure 7: (a) Pulse amplitude spectrum for a single eSC photomultiplier, measured with the MuLan waveform digitizer. (b) Similar spectra for 62 of the eSC channels, viewed “from above”; the other two are missing because of a readout problem (also present in MuLan) that caused channels to disappear on a run-by-run basis.

- Recording of waveforms from each wire in the TPC for selected externally-triggered events, generally corresponding to muon-catalyzed $p-d$ fusion or muon capture on high-$Z$ impurities in the gas. Relevant tracks involve energy deposition over several orders of magnitude, from recoiling impurity nuclei down to nearly minimum-ionizing “Alvarez” muons from the fusion events. Sampling rates of 50 to 100 MSPS are sufficient for these tracks.

- Readout of liquid scintillator neutron detector cells to directly establish the time distribution of neutrons generated in muon capture events. Pulse shape discrimination will be used to distinguish neutrons from gamma events by comparing the charge deposited in the pulse tail to that in the peak. In this case, the board will be self-triggering. High sampling rates are useful, since the pulse FWHM is of order 10 ns.

This board was successfully integrated into the general MIDAS data acquisition system, and waveforms were recorded from one of the neutron detectors. However, due to firmware problems, reliable timestamps were not available.

**Neutron Detectors**

Figure 2 shows that the current large uncertainty in $\lambda_{OP}$ contributes an uncertainty roughly comparable to our final precision goal for $g_P$. 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. Following the plan formulated in our 2004 progress report, we have modified the electron detector mounting structure to accommodate neutron detectors (Figure 8(a)). Three large neutron detectors were borrowed from the DEMON collaboration, mounted and operated during the 2005 data taking. We are currently analyzing the data. If successful, we will upgrade MuCap with 8 DEMON detectors, which should allow us to observe $2 \times 10^5$ capture neutrons and reduce the $\lambda_{OP}$ correction even further.

The neutron detectors were tested in conjunction with the new 12-bit waveform digitizers described in the previous section. A $^{241}$Am-Be source, which generates a broad spectrum of neutrons up to a maximum energy of $\sim 12$ MeV, was used to check the neutron/gamma separation. To measure the fast and slow components of the pulse, integration ranges were defined from (-10–25 ns) and (25–275 ns) respectively; two bands are clearly visible when these integrals are plotted together, as shown in Figure 8(b). When a $^{22}$Na source is used, only the lower band remains.
3.2 Run Overview

During the 2005 run, we commissioned the electrostatic kicker and achieved the design goal voltage of 5.45 kV with the TPC. Systematics related to the TPC and impurities in the target were investigated and running conditions for the production data were established. Ten terabytes of data were recorded which corresponded to $3.5 \times 10^9$ $\mu^-$-e pairs, $1.4 \times 10^9$ $\mu^+$-e pairs, and $1.7 \times 10^9$ $\mu^+$-e pairs with an AK3 target.

TPC and CHUPS upgrades and associated systematics

The hardware improvements to the TPC allowed it to run stably at 5.45 kV during this run. This higher gain should allow the detection of $pdp$ fusion events that are directly proportional to the deuterium concentration in the target, which is needed for systematic corrections.

The CHUPS system also received several upgrades that improved the experimental efficiency during the run. Many studies were performed to understand the relationship between the CHUPS flow rate and the outgassing of the TPC volume. We determined that the TPC functioned properly, but the outgassing of impurities in the entire system was higher than previously, probably due to insufficient pumping time. We obtained steady-state results of 0.35 ppm $H_2O$ and $<0.01$ ppm $N_2$ after several complete volume exchanges. Additional precautions will be taken during the first months of 2006 to reduce all possible sources of impurities from the gas lines.

Systematic studies also included doping the target with argon which is a method to identify the $ppp$ formation rate noted in Table 2. The effect of deuterium admixtures was calibrated by filling the target volume with natural hydrogen.

Commissioning of the Kicker

Since the analysis requires a single muon, isolated in time by 50 $\mu$s, the presence of additional beam muons results in the rejection of many candidate events. In muon-on-demand mode, a trigger determines when a muon has entered the target and signals the electrostatic kicker to deflect the beam. This allows a higher incident beam rate on target and reduces pileup losses at the same time. Figure 9 compares the software muon rejection by the pileup cut in the muon-on-demand mode compared to the dc method. The kicked beam increased the effective data rate by roughly a factor of 3, as shown in Figure 10. There will be a preliminary analysis of the kicked data prior to the 2006 run to determine potential systematic effects introduced by this device.
Figure 9: a) In 2004, the analysis rejected a large fraction of the raw events due to multiple muons entering the target within a 25 µs time window. b) In 2005, the kicker prevented multiple muons from entering the target during that time window. Far fewer events were rejected by the analysis as pileup events.

Figure 10: The effective data rate achieved with (right side) and without (left side) the electrostatic kicker. The kicker suppresses accidental beam muons which are rejected in the analysis due to pileup effects.

AK3 Measurement

A study was performed to understand the systematic effects related to the TPC. The TPC was removed from the detector ensemble and a disk of AK3 (Arnokrome 3) metal was installed. This highly magnetized material (~0.5 Tesla) was placed in the center of the cylindrical electron detectors as a target for positive muons. The high field rapidly precesses the muon spin, so residual polarization effects are highly suppressed. The tracking tools in the analysis will allow us to determine the vector corresponding to the decay electron trajectory and will thus allow us to veto events which did not come from the target. In this manner, the unbiased nature of the electron detector will be demonstrated.

Data Collection

During the 2005 run we collected nearly 10 terabytes of good data. A summary of the running conditions for the principle data sets are shown in Table 3, with comparisons to 2004. A data rate of about $2.5 \times 10^9$ good events per calendar week was obtained under ideal operating conditions. With the improvements generated by the kicker, we will be able to collect $10^{10}$ events for both $\mu^+$ and $\mu^-$ during 2006.
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Table 3: Statistics of fully reconstructed $\mu$-e pairs obtained with various running conditions in 2005 with comparisons to 2004.

4 Plan and Beam Time Request 2006

Since November 2005 the MuCap experiment has been in a full production state and is ready to resume data acquisition in April 2006, immediately after the 600 MeV ring shut down.

The shutdown will be used for the following tasks to prepare for the upcoming main production run.

- The TPC will be baked out and pumped for extended time periods in order to reduce the residual humidity which was observed in December 2005 to be at the 0.035 ppm level. We expect this procedure will significantly reduce the background of impurity capture events.

- The 2005 data set will be analyzed in a first production pass. The focus of this preliminary analysis will be on systematic issues related to the new and highly efficient Muon-on-Demand acquisition mode.

- In March 2006 we plan to install a new isotope separation column, presently in construction at Gatchina. It will allow us to deplete our protium gas from the current concentration of $\sim$3 ppm deuterium to about 0.1 ppm.

- The waveform digitizer data for the electron scintillators will be analyzed and the stability of the new electronics improved. The full set of FADCs for the TPC and neutron detectors will be constructed and commissioned.

These efforts will strongly reduce systematic corrections to the muon decay time distribution and will verify, that we can benefit from the threefold higher data rate provided by the kicker.

In 2004/5 we have already accumulated a statistics of $\sim 4.5 \cdot 10^9$ fully reconstructed pileup-free $\mu^-e$ events in ultra-pure protium and $\sim 1.6 \cdot 10^9$ $\mu^+$ events. Thanks to the successful operation of the muon beam kicker, in the upcoming 10 week run we expect to accumulate $10^{10}$ fully reconstructed events for each muon sign which is the final goal of our proposal. The proposed schedule is aggressive, but the advantage of quietly preparing our complex experiment for three months in the experimental area is crucial to achieve our final goal.

Therefore, we maintain the beam request for 2006 that was formulated last year of 10 weeks ($+ \frac{1}{2}$ week contingency) in area $\pi E3$, immediately following the ring shutdown.

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 Nuclei 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.
   MuCap presentations at national meetings in 2005 included the APS April-Meetings, Tampa, Florida, USA; the joint APS/JPS DNP Meeting, Kapalua, Maui, USA; the APS California Section Meeting, Sacramento, USA; and the Swiss Physical Society Meeting, July 2005, Bern, Switzerland.

   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.


