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Progress Report 2003 and Beam request for 2004

Precision Measurement of Singlet μp 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

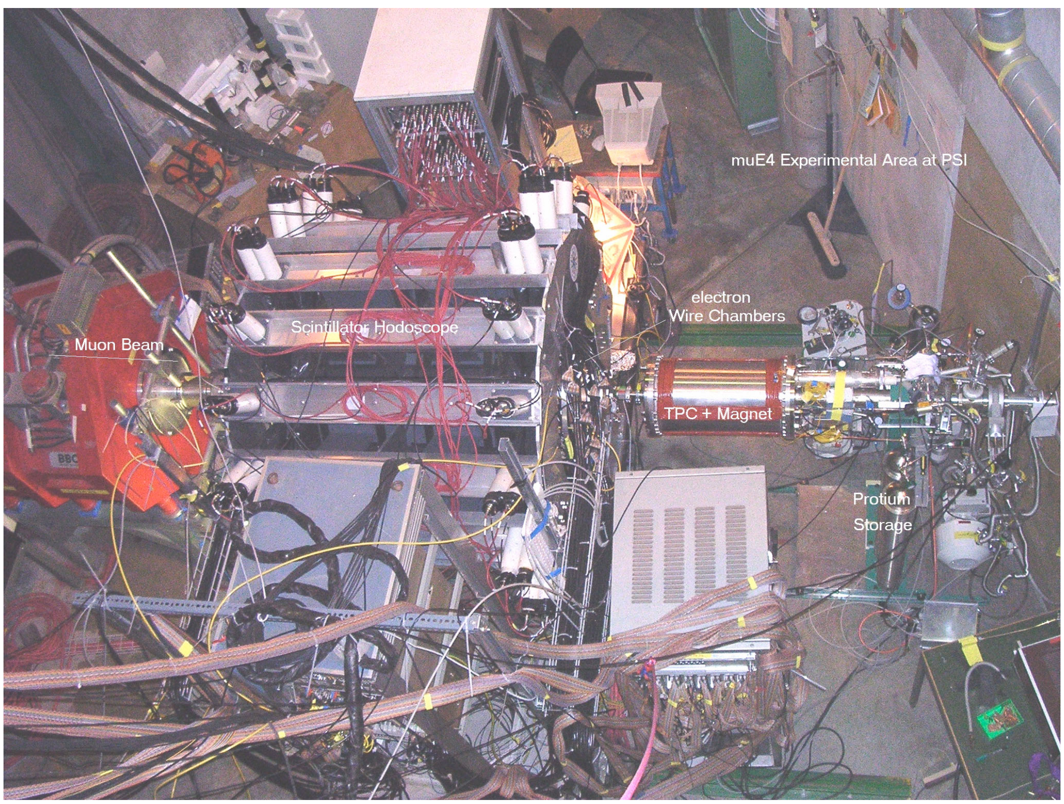

Figure 1: MuCap detector with TPC vessel retracted for preparing new protium filling.

1 Overview

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

$$\mu + p \rightarrow n + \nu. \tag{1}$$

This measurement determines the least well-known of the nucleon charged current form factors, the induced pseudoscalar g_P, to 7%. 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 (the time projection chamber).

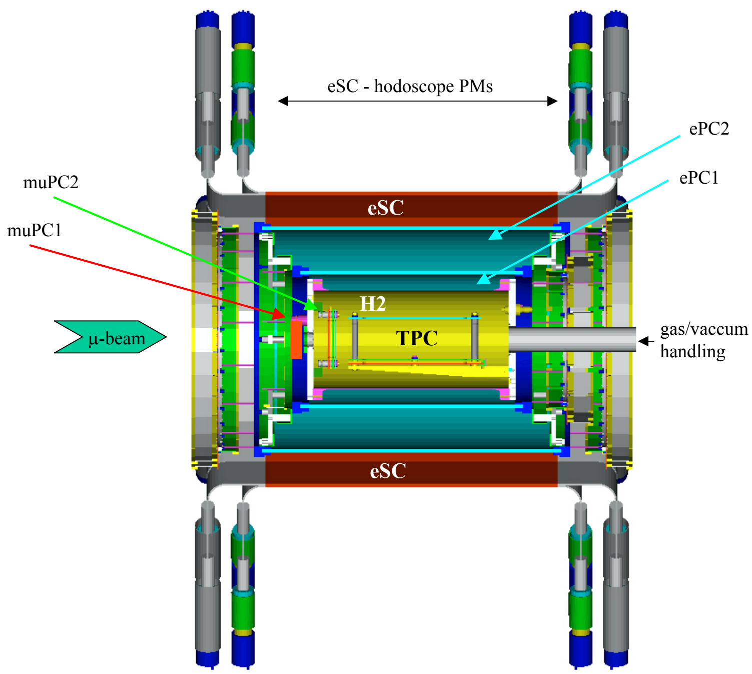

Figure 2: Side view of the MuCap detector setup.

The main MuCap detector components are depicted in fig. 2. This is a complex experiment that imposes stringent requirements on the various subsystems: **beam, beam detectors, time-projection chamber (TPC) and hydrogen vessel, electron detection system, gas system and diagnostics, magnet and data acquisition**. All of these components must work flawlessly for the final production run.

Progress 2003

The main goal in 2003 was to get all essential parts of the MuCap detector functional, commission them, and prove their performance in a first physics run. This ambitious program was achieved in a sequence of milestones:

- The time projection chamber (TPC) was commissioned in the μE4 beam during summer 2003. Its primary purpose is to detect incoming muon tracks and stops. A totally new wire chamber technology was developed for operation in ultra-clean hydrogen at a pressure of 10 bar. Only UHV-proof bakeable materials like metals, glass, and ceramics were chosen. Special frames from polished borofloat glass with a low thermal expansion coefficient were manufactured with metallic coatings onto which the tungsten-gold wires were soldered. The principal difficulty was to get enough amplification to observe charges drifting in the pure H_2 gas. Such high amplification requires voltages (4.8 kV) significantly exceeding those reached in conventional wire chambers.

- Deuterium-depleted hydrogen ("protium") gas of the highest purity had to be produced and maintained within the TPC pressure vessel. This purity was achieved by high-vacuum baking of the entire TPC cylinder vessel at 120^o C and by filling the protium gas through a palladium filter. In September 2003 we suppressed the impurity level to $\sim 10^{-7}$.

- The electron detector worked reliably at full operating conditions. It consisted of two parts: (1) a cylindrical multiwire chamber instrumented with new low-noise, chamber-mounted, front-end electronics, and (2) a brand-new, segmented, double-layer plastic hodoscope. All electron detectors are fastened to the new support structure.

- At the beam entrance a muon detection and tracking geometry was commissioned consisting of a thin scintillator, a collimator, and two wire chamber assemblies. The first wire chamber is outside of the TPC vessel, while the second sits inside in front of the TPC, surrounded by the protium gas.

- A μSR magnet was placed closely around the TPC pressure vessel providing a vertical magnetic field of $\sim$50 Gauss. This field is necessary to control the spin effects of the polarized μ^+, and thereby perform checks and calibration of the lifetime measurement.

- New data compressor units were commissioned to continuously read out the electron chamber signals in a deadtime-free manner.

- We developed new data acquisition (DAQ) software capable of efficiently handling the data flow of $\sim$ 4 MB/s. The DAQ is a Linux-based system integrated in the MIDAS framework. Stable collection and storage of 6 TByte of data to the PSI archive and a tape robot system was achieved.

In September 2003 all of these components were ready for the first commissioning run. After the replacement of a defective Pd filter, we collected roughly two weeks of μ^- data, or approximately 10^9 events. This represents about 10% of the statistics needed to reach our final goal, a μp singlet capture rate with 1% statistical error. The present data already matches the statistics of previous experiments in this field, but the MuCap measurement is cleaner because ambiguities in the interpretation (due to ortho-para conversion of ppμ molecules) are dramatically reduced at our low target density.

Plans 2004

The *major components* of the MuCap apparatus were successfully operated in fall 2003. The focus of our activities in 2004 is the preparation and commissioning of *all components*, in order to achieve the required statistics and minimize the systematic uncertainties commensurate with the proposed precision goal of MuCap. The following subsystem work remains:

- **Beam**. Since the μE4 beam has been decommissioned, the experiment will be moved to πE3. Initial studies indicate that πE3 has excellent beam properties, with the exception of the momentum band which needs to be reduced by at least 50% via a dispersively focused tune (PSI, UIUC).

- **Beam entrance window**. Scattering in the pressure vessel's 100 micron Havar entrance window cut the muon stopping fraction by half. This stopping efficiency will be vastly improved by new Be windows, which have been successfully pressure tested. In order to accommodate the new window geometry, μPC1 and μPC2 will both be situated outside of the TPC vessel. Also, in order to reduce the muon range spread, cathode foils will be used instead of wires (PNPI).

- **TPC**. For chamber operation in ultra-pure hydrogen, very clean and dust-free conditions are required. Any TPC problems could potentially compromise an entire run, since, due to the stringent purity requirements and the slow conditioning process, repairs take several weeks. In order to minimize the risk of failure during a run, the collaboration decided to develop two independent TPC setups based on similar technologies. PSI will try to increase their TPC's operational voltage from 4.8 to 5.5 kV by carefully cleaning and conditioning the system used during the 2003 run. PNPI has constructed a TPC (along with several spare frames) which is currently being conditioned.

- **ePC2**. In 2002 the collaboration began constructing a new wire chamber, ePC2 (The original plan to reuse chamber 5 from the PSI Sindrum I detector could not be realized, as it was found to be damaged). With new UIUC funding and active collaboration among PSI, PNPI, and UIUC, the new chamber has been successfully conditioned at operating voltage. The new frontend electronics (UIUC) as well digitizing electronics (UCL) are ready and the instrumentation of the chamber is currently underway.

- **Data acquisition**. New hardware – faster VME processors (UCB) and FPGA-based logic (UIUC) – and ongoing software development will upgrade the DAQ to a fully pipelined, deadtime-free mode (UCB).

- **Gas purification**. PNPI is building a continuous circulation system to purify the TPC hydrogen gas[1]. During the 2003 run the impurity level in the system gradually increased by about 0.1 ppm per day, which forced us to refill every week. The new system is designed to improve the purity by at least an order of magnitude. After a somewhat lengthy procurement process, all necessary parts have been obtained and the system is under construction.

- **μSR magnets**. New saddle coil magnets for each TPC system will be constructed from aluminum tubing, in order to reduce their scattering contribution by at least 30% (UCB).

The timeline for these projects is discussed in greater detail in section 4. The PNPI gas circulation system and the TPCs are the most critical projects. As currently planned, the gas system will be delivered to PSI in July. Afterwards it must be integrated and commissioned on site. Given the novelty and stringent design requirements of these projects, we should allow for at least one month of contingency work.

Inspired by the success of our 2003 commissioning run and strong interest in the physics community [4], the MuCap collaboration is making a concerted effort – distributed over several institutions – to complete all subsystems before starting main production running in 2004. In order not to compromise this goal, we request to run the last 10 weeks of this running period.

2 Commissioning Run

2.1 Apparatus

During the summer of 2003, the nearly complete MuCap apparatus was assembled for the first time (see the μE4 area photo in Figure 1). The apparatus consists of two parts: the inner muon detectors and

[1]This project is made possible by special funding from US CRDF, which was obtained by a joint proposal between UIUC and PNPI. Additional support comes from PNPI, PSI, and the University of Kentucky.

the outer electron detectors. The inner cylindrical aluminum pressure tank contains 10 bar protium gas and the TPC, which is responsible for muon tracking and stop identification. The outer detectors – a cylindrical wire chamber and a double scintillator hodoscope – are responsible for the decay electron identification. In 2004 a second cylindrical wire chamber will be added, allowing for electron tracking to the muon stop location.

The muon and electron detector groups are mounted on separate rail systems and can be rolled apart for servicing and maintenance work. They also operate independently, recording the muon lifetime measurement's start and stop signals as separate systems. This independence is absolutely essential, because any systematic correlations between the muon and electron time measurements could induce lifetime curve distortions.

Figure 2 presents a side view of the entire MuCap detector. Here are the components, listed in the order of muon propagation from upstream (left) to downstream:

- The muon detector, μSC1, is a 0.5 mm thin scintillator sandwiched between a lead collimator (aperture 35 mm) and μPC1. It provides the fast muon timing signal for the "start" of the lifetime measurement.

- The μPC1 chamber, located in front of the TPC vessel, operates in conjuction with μPC2 to perform muon tracking. In order to reduce muon scattering effects and increase the muon stopping rate, μPC1 was removed in the last week of the 2003 run.

- The μPC2 chamber is located inside the pressure vessel, in front of the TPC. Unfortunately, the μPC2 did not work reliably at the end of the 2003 run. However, as long as we analyze the 2003 data using global pileup suppression, μPC2 is not a crucial element.

- The TPC is in the center of the cylindrical pressure tank. It has a sensitive volume of $xyz = 15 \times 12 \times 30$ cm^3, a vertical ($\hat{y}$) electrical drift field of 2 kV/cm, and a drift velocity in 10 bar hydrogen of 0.5 cm/μs. Signals are read out from 75 anode wires and 35 cathode strip assemblies, all spaced by 4 mm.

  The anode wires provide coordinate information in the $\hat{z}$ (beam) direction; cathodes give the x coordinate; the drift time measures the y coordinate. Thus, three-dimensional information is provided for every muon track in the TPC. Three anode and two cathode thresholds enable distinction among incoming muon tracks (threshold "low"), stopping muons ("medium"), and heavily ionizing nuclear recoils ("high," anodes only). The TPC was operated in a stable condition at 4.8 kV, an ideal voltage for observing all slow muon tracks with $E_\mu < 2$ MeV. Observation of minimum-ionizing particles (electrons) requires $\geq$6 kV chamber voltage.

- The ePC1 detector is a cylindrical multiwire proportional chamber (former Sindrum 3 chamber) of diameter 384 mm and active length 580 mm. All three layers – inner cathode strips, anodes, and outer cathode strips – are read out to provide the (ϕ, z, t) of electron passage through the detector. The TPC is nested closely inside ePC1, and ePC1 is in turn nested inside the eSC hodoscope. In the future, ePC1 will work in conjuction with ePC2 to provide directional information on electron tracks, and thereby enable vertex matching between parent muon stops and decay electron tracks.

- The eSC detector is the outermost MuCap detector element. It is a cylindrically arranged, two-layer scintillation hodoscope of diameter 780 mm and active length 900 mm, consisting of 16 double scintillator bars each viewed on both sides by photomultiplier tubes. The eSC provides the electron timing signal, or "stop," of the lifetime measurement. The solid angle of the eSC is about 60% of 4π.

- The μSR magnet is a specially made coil wound closely around the cylindrical Al vessel containing the TPC. When operated with DC current of 250 A it generates a vertical magnetic field of

~50 Gauss. This field is necessary to control the muon spin rotation (μSR) of the horizontally polarized μ^+ beam. By fitting the μSR oscillations, any polarization-induced distortions of the exponential muon decay curve can be accounted for.

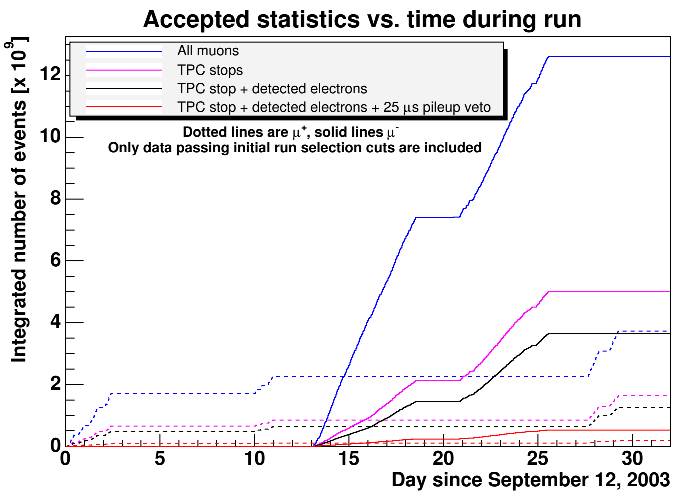

Figure 3: Total integrated statistics of μ^- (solid) and μ^+ (dashed) data vs. time, spanning the period September 12 – October 14, 2003. Only events with fully functional readout electronics and (in the case of the μ^-) sufficiently clean protium have been included. The blue lines illustrate the integrated number of entrance muons as recorded by the μSC detector, ending in a total of 12×10^9 for the μ^- and 3.7×10^9 for the μ^+. The red line illustrates the accumulation of 0.5×10^9 total μ^- decay events and 0.2×10^9 μ^+, identification of which involves all detectors.

2.2 Run overview

The MuCap detector, electronics, and gas purification system were installed in the μE4 area in August 2003. Commissioning started in early September. Shortly afterwards, our TPC-based impurity monitor (see below) indicated that our protium gas contained impurities at the level of several ppm, instead of the expected sub-ppm. This problem was caused by a defect in the palladium filter in the filling line. Nevertheless, we performed diagnostic μ^- measurements, which were valuable for detector commissioning, and μ^+ measurements, which are anyways insensitive to such small impurity levels. High-quality μ^+ data was also collected after the installation of a massive inductive filter in the μSR magnet circuit, which eliminated power supply switching transients that had previously been a major source of electronics noise.

After an emergency replacement filter arrived from the USA, we finally were able to accomplish two clean protium fillings (one week each) starting on September 25. The achievement of an initial impurity level of 0.1 ppm (with impurity increases of 0.1 ppm/day), and the demonstration of our ultra-sensitive in-situ monitoring method were major accomplishments on a critical experimental issue.

The statistics accumulation during this last phase of the run is summarized in fig. 3. During the final days of the run we directly calibrated the impurity effect in our data by filling the TPC with protium containing a controlled impurity admixture of ~20 ppm N_2 (these special measurements are not included in the "clean" filling plot). Variation of the running conditions included reducing the incident muon rate from ~ 30 to 20 kHz and running the TPC with 4.6 kV and 4.8 kV amplification voltage.

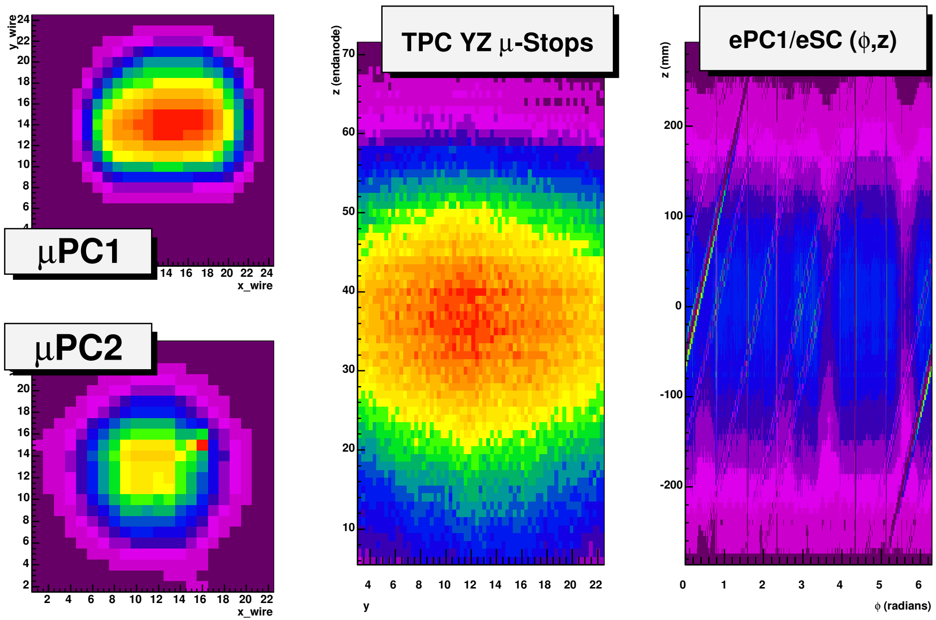

Figure 4: Output from the 2003 MuCap detectors. On the left, the muon beam cross-section is visible as it passes through the μPC1 and μPC2 detectors in succession. In the middle is the y-z (that is, vertical-longitudinal) cross-section of the muon stopping distribution in the TPC, where only μ-stops in coincidence with the entrance muon scintillator (μSC) have been selected. On the right, coincident electron hits in the ePC1 and eSC detectors are plotted in the (ϕ,z) plane.

Detectors and DAQ

Fig. 4 exhibits spectra from each of the MuCap detectors present during the 2003 run. The high-purity TPC worked well over a period of nearly two months with only occasional trips. Though it was unable to reach sufficient voltage for detecting mimimum-ionizing electrons, it served well for its primary functions, the tracking of incident muons and monitoring of impurity capture (see fig. 5). The external muon chamber μPC1 worked without problems, while μPC2, initially operating at 5.5 kV in hydrogen, deteriorated over time.

The electron detector ePC1 was fully operational. In particular, considering its previous susceptibility to noise, chamber ePC1 performed exceptionally well by operating quietly and reliably over the entire run. This improvement in performance was achieved by improved grounding and by placing all digitizing electronics (compressors) in close proximity to ePC1, on the detector support platform.

Hydrogen system

After the extended R&D period (1998 - 2000) using standard chamber materials, this run was the first to prove the functionality of hydrogen chambers constructed exclusively from bakeable high-purity materials. Fig. 6 shows the impurity level as a function of time, as monitored by reactions such as

$$\mu + N \to C^* + \nu \ . \tag{2}$$

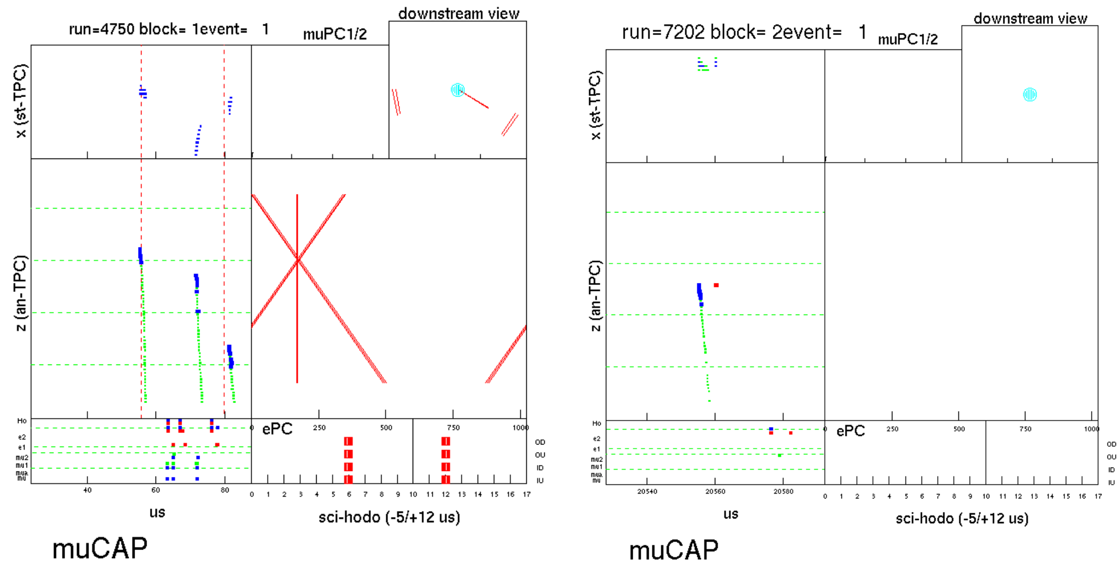

Figure 5: Images of muon tracks and impurity captures, taken from the MuCap event display. In the left picture, three muons are clearly visible as they enter the TPC (green) and stop (Bragg peaks in blue). In the right picture, the nuclear recoil following muon capture on a high-Z impurity has triggered the third TPC threshold, producing a red dot $\sim 2\ \mu$s after the muon stop.

The TPC can detect recoil nuclei (200-350 keV energy) with nearly 100% efficiency, considering both solid angle and threshold effects. The background to this method is naturally estimated from μ^+ data and found to be negigible down to impurity levels of 0.01 ppm. The information is collected both from the digital high-rate TPC readout (see fig. 5) and from 16 TPC anodes which are also instrumented with flash ADCs. Specialized triggers were implemented to selectively collect impurity events with the slower flash ADC system.

These results demonstrate that our current hydrogen system permits a purity close to 0.1 ppm, a level at which it is possible to compute a small correction based on the observed impurity capture events. Most importantly, the observed initial and outgasing levels are compatible with the capabilities of the continuous purification system under construction at PNPI, which will lower the impurity level of our system to ~ 0.01 ppm.

The final MuCap system also requires isotopically pure protium, with ≤ 1 ppm deuterium. The measurement of such low deuterium levels is challenging. Protium samples from MuCap were analyzed at the Ioffe Institute (St. Petersburg), PSI (Institute for Atmospheric Physics), and the AMS facility of ETH Zürich. Initial results indicate the protium generated from isotopically pure water has the required purity, while the sample at the end of the 2003 run has accumulated a few ppm of deuterium. This deuterium contamination may have been introduced by insufficient purging of the replacement palladium filter.

Data analysis and first results

Two MuCap graduate students, Tom Banks (UC Berkeley) and Steven Clayton (UIUC), are currently fashioning the analysis software necessary to extract a μp capture rate from the 2003 data. The Berkeley and Illinois analyses are being developed independently as separate software packages, but they can nonetheless run simultaneously within a shared MIDAS Analyzer framework. The analysis development is a learning-intensive process and we are constantly encountering new questions and problems which must be carefully and diligently addressed. However, we have made excellent progress,

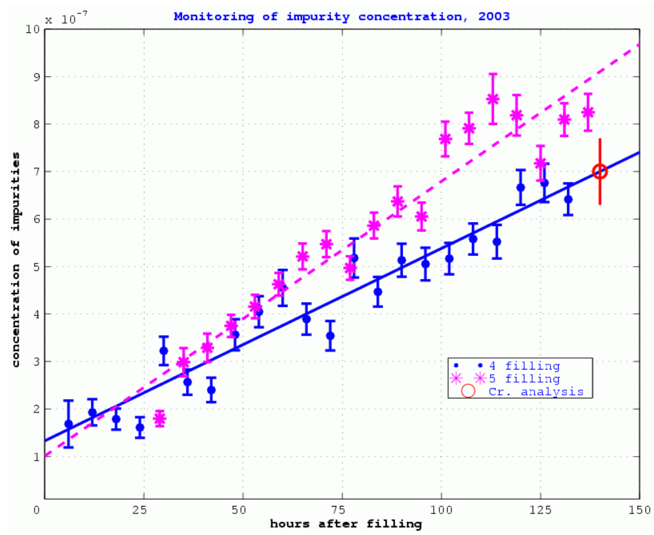

Figure 6: The gradual increase in the impurity level with time is plotted above, in the hours following the September 25 clean filling (blue) and the October 2 clean filling (red). This information was derived in-situ by monitoring capture events with the flash ADC system and calibrated by gas chromatography of a sample taken on October 1 (point with open circle).

and we are gradually building up a better understanding of the subtle effects associated with our complex detector arrangement. This accumulated knowledge and the resultant software should provide us with a reliable first muon capture result, as well as an invaluable foundation for future runs.

Thus far we have used the PSI Merlin cluster to perform two full analysis passes over the 2003 data. A second analysis center, utilizing the UIUC Linux farm and the UCB LTO-2 tape robot, is close to completion. The emphasis of our initial analyses has been on checking data quality and detector performance. In this early phase of a systematic analysis, preliminary results look promising.

e-Detector	Number of e in Fit	$\delta\lambda_{fit}/\lambda_{fit}$	$\lambda_{fit}/\lambda_{fit,Full}$	Accidentals Fraction
Full	2.28×10^8	8.8×10^{-5}	1	1.18×10^{-3}
eSC	2.77×10^8	9.1×10^{-5}	1.000050	8.43×10^{-3}
ePC1 Anodes	3.57×10^8	8.1×10^{-5}	1.000021	5.74×10^{-3}

Table 1: μ^- decay rate λ_{fit} found for each electron detector used, normalized to $\lambda_{fit,Full}$ of the full electron detector (ePC1 anodes, ePC1 inner cathodes, ePC1 outer cathodes, and eSC, all in coincidence).

Fig. 7 shows μ^- lifetime results for data from the last clean fill, taken October 2 – 8. The analysis is based on so-called *global pileup protection*, wherein we only consider entrance muon candidates that are isolated in time by at least 25 μs. While this approach results in a significant reduction of the statistics, it safely avoids problems which arise from mistakenly associating uncorrelated muons and decay electrons. A simple fit to a function containing an exponential decay and a uniform background describes the data well at this level of statistics, which is approximately half of the total available from the clean protium runs. The rest of the clean protium data will be included as the analysis software is further refined. The fit parameter values are summarized in Table 1. Lifetime results are given in relative units, as the analysis is currently performed in a blind, unbiased mode, with the accurate time

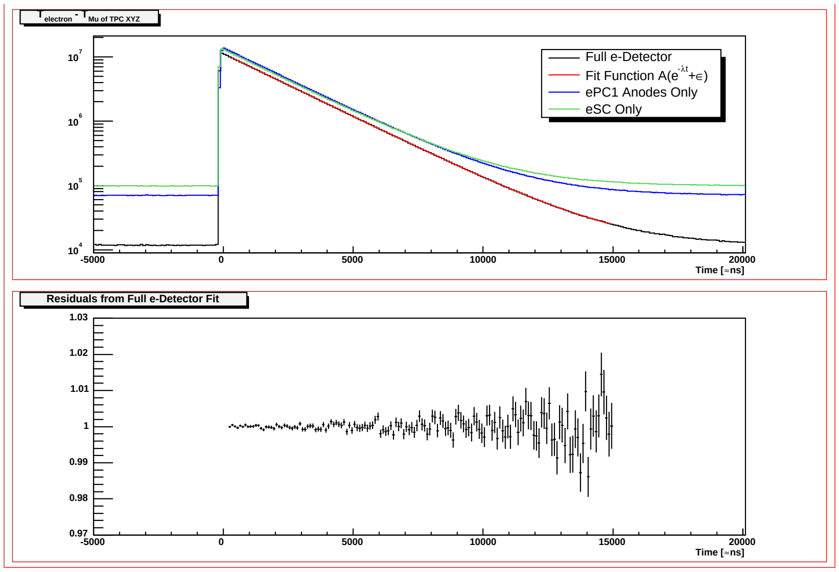

Figure 7: Top: μ^- decay time spectra for each full electron detector: ePC1 and eSC in coincidence, ePC1 Anodes only, and eSC only. These data are from the last clean H_2 filling with a μ^- beam, and they represent only part of the statistics available. Bottom: residuals from a simple exponential plus background fit to the data set from the full electron detector.

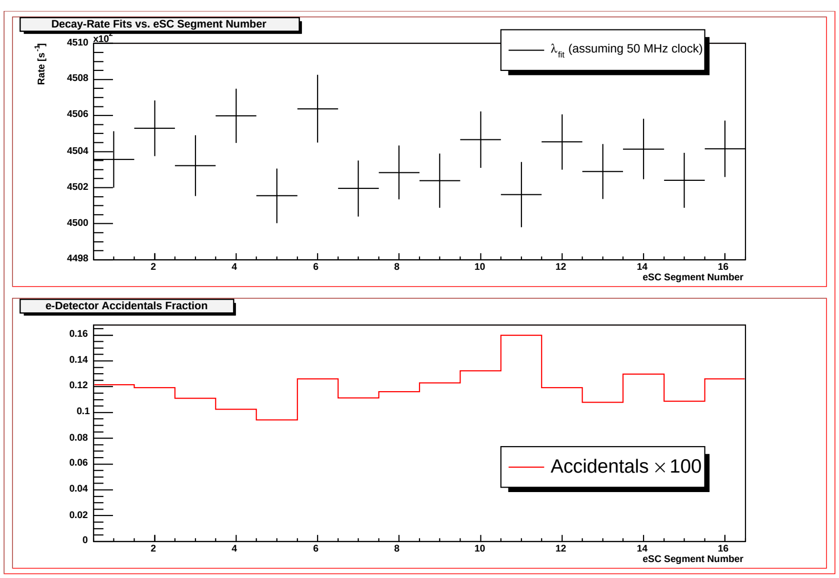

Figure 8: Top: fit results to decay time spectra from individual eSC hodoscope segments in coincidence with ePC1. The data set used is the same as in Figure 7 and Table 1. Bottom: accidentals fraction from the time spectra.

calibration unknown to the analysis team. The consistency of the ePC results with the simpler eSC scintillators is especially encouraging, as the experience of precision lifetime experiments with wire chambers is quite limited.

Comparison of lifetimes and background levels extracted from individual electron detector segments indicates that the detectors are functioning properly, and illustrates the possibilities for reducing accidental background. As can be seen in Fig. 8, the fit results and accidentals fractions[2] are consistent. Using the full electron detector–that is, including both eSC layers and ePC1 anodes and cathodes–the accidentals level is $\sim 10^{-3}$. We expect an order-of-magnitude improvement when the new ePC2 is in place, as it will allow backtracking to the muon stop location in the TPC (although this will require that more attention be paid to understanding μd diffusion effects [3]).

Finally, initial μ^+ analyses, using a fitting function that includes the effects of μSR oscillations, give consistent results.

3 Final MuCap Upgrades in 2004

Following the strategy defined in our technical proposal, and guided by our experience from the last run, we are preparing to complete the final MuCap setup in time for production running in 2004. Table 2 addresses the primary issues by comparing the 2003 MuCap performance with the stated design goals.

Subsystem	Parameter	Run 2003	Design goal	Comment
beam	Incident muon flux (kHz)	30	30	Δp/p $\sim$ 2-3% in πE3 required
window	Stopping/incident muon ratio	0.33	0.8	Be instead of Havar
TPC	HV (kV)	$\sim$ 4.8	$\sim$ 6	Relevant for D diagnostics
e detection	Electron detection efficiency	0.65	0.65	ePC2 in preparation
DAQ	Lifetime fraction	0.8	1	Hardware/software upgrade

Table 2: Main issues where design specifications still need to be met.

Beam and muon stopping fraction

Table 2 shows that the 2003 muon stopping fraction[3] was only about half of the design goal. This discrepancy was the result of inadvertant changes to the longitudinal (z) and the transverse (xy) phase space of the beam inside the TPC.

Longitudinal phase space. We had previously operated the μE4 beam at 33 MeV/c and a momentum spread of $\sigma_p/p \sim 2\%$, which should be sufficient to stop most muons along the TPC length of 64 mg/cm^2 carbon equivalent mass. The beam properties were confirmed with careful range measurements. However, in the full MuCap setup we observed a low-energy tail in the TPC stopping distributions. We improved the situation by removing μPC1; after that, the stopping fraction increased by 20%, suggesting that the wider range distribution was caused by nonuniform energy loss on the μPC1 cathode wires. For 2004 we are constructing new *cathode foil*-based external muon chambers to replace the *cathode wire*-based μPC1 and μPC2. This should increase the stopping fraction by another 10-20%. In addition, we will construct a new muon entrance scintillation counter with thickness 250 μm (instead of 500 μm) to reduce the overall amount of material in the muon beam. These items will be delivered in June 2004.

A new challenge will be the use of the πE3 beamline, as the new μE4 beam will not be ready for some time. We have made preliminary measurements at πE3 that indicate good beam intensity and

[2] Defined as the level of the flat part divided by the peak of the decay-time histogram.

[3] Defined as the ratio of stops in the TPC fiducial volume (at least 1 cm distance to closest wall) to the number of muons seen by the external beam scintillator μSC.

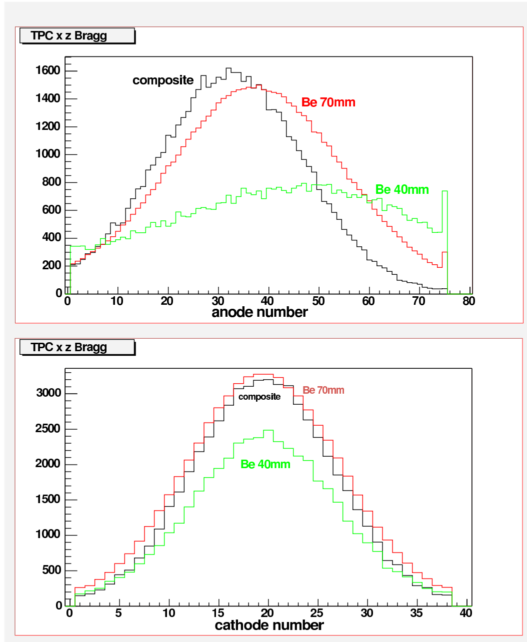

Figure 9: Monte Carlo results for muon stopping distributions for i) a fiber composite window (Kevlar/Zylon with aluminized 100 μm Mylar); ii) a spherical 70 mm diameter beryllium window; iii) a 40 mm diameter spherical beryllium window.

spot size, and electrons were sufficiently suppressed with the separator at around 160 kV. The width of the momentum distribution, however, is twice that of μE4. It can be reduced by using a tune with a dispersive focus, but at the cost of some intensity. Nevertheless, initial simulations performed in the context of the MuLan kicker development are promising. They will need to be refined, verified, and optimized during a beam tuning session of approximately one week with μ^- in πE3.

Transverse phase space. Most of the 2003 run's muon losses were caused by the entrance window to the hydrogen pressure vessel, which is made from a 100 μm thick Havar foil. While Havar was a conservative choice for the engineering runs, its high-Z components considerably widen muon range straggling and muon scattering. Extensive Monte Carlo simulations have been performed in order to understand the behavior of this setup, with the ultimate goal of increasing the muon stopping fraction and narrowing the range width. We are presently investigating two window replacement options:

1. A large Beryllium entrance window, 70 mm in diameter and 0.5 mm thick. Some Beryllium windows have been provided by PNPI, and new vessel flanges to hold them are already under construction.

2. A thin composite window made from high-strength fiber materials like Kevlar, with a thin, glued-on aluminized Mylar foil. This approach is a new technical development that promises low Z and low thickness, together with high-tensile strength. We are presently building a pressure test stand and investigating various fabrics and bonding options.

Fig. 9 shows the equally favorable behavior of the 70 mm diameter beryllium window and the composite window with respect to muon stopping. The existing and tested Be windows are our baseline option; a successful composite window will fit the existing vessel flange.

Hydrogen vessel and TPC

Our intention is to have two fully interchangeable TPC systems for the production run, one produced by PSI and the other by PNPI.

PSI design. PSI is preparing a new vessel flange with a 70 mm diameter Be window. In order to provide space for the inward-pointing window, μPC2 has to be removed from the vessel's interior. The TPC served well in the 2003 run as a muon detector, but it did not reach its intended voltage. We have set up a full test station with individual channel ADC monitoring in order to fully understand every wire's behavior. We have performed careful cleaning of wires on which hot spots were detected. The hot spots are likely correlated to tiny anode wire whiskers, whose nature and origin are yet unknown. We are confident that several careful cleaning cycles will remove these hotspots. A fine mesh gas filter on the gas inlet has been inserted to protect the chamber from any dust particles. High voltage may be applied to the TPC grounding plate to serve as a catcher for all micro-particles. PSI will try to operate the TPC at voltages around 5.5 kV in hydrogen.

PNPI design. PNPI-Gatchina has been developing an alternate ultra-clean time projection chamber, based on technology similar to PSI's chamber. The PNPI vessel was tested up to 15 bar pressure, and the new entrance flange (with a 70 mm diameter Be window) is under construction and will be ready by the end of February. Significant effort at PNPI is going into this second TPC, with a small clean room being built for the assembly work. At this time, three sets of TPC chambers (three anodes, three upper cathodes, and three strip cathodes) have been produced. Two of the chambers have soldered wires; the chambers were tested up to a temperature of 150^o C with no noticeable change in the wire tension. The first set of the TPC chambers will be tested starting of February, using nitrogen and protium. Eventually, the TPC will be fully integrated and tested with the new hydrogen purification system. The commissioning at PNPI should be finished in June 2004, and then the setup will be shipped to PSI in July and assembled in August.

Electron wire chamber - ePC2

In 2002, we decided to construct a new outer electron wire chamber ePC2, since the one originally provided by PSI from the Sindrum experiment was not functional due to physical damage. The construction of this new chamber was finished in summer 2003; fig. 10 shows ePC2 in the PSI detector laboratory. It was not possible to include the new chamber in the 2003 run, as careful conditioning and minor repairs in the clean room were still required. During fall 2003 the chamber was gradually brought to higher voltages and fully conditioned up to 2.6 kV. After relocation to a new PSI laboratory in January of 2004, the chamber is now being brought into full operation. This includes installation of the HV cards, construction of additional shielding meshes, anode and cathode frontend instrumentation, and integration of the $\sim$ 1500 new channels in the DAQ. By March we expect to have completed ePC2 testing, and to have mounted ePC1 and ePC2 in their concentric configuration. In April we will measure the performance of the combined chambers in the laboratory before installing them in the MuCap detector in May/June. This latter activity will take place after the MuCap detector is moved from its current storage position to a staging area in the experimental hall, which will become available to us after the winter shutdown ends.

Hydrogen system

Filling and high vacuum system These systems are required for realistic testing of the TPCs, as well as the development of the advanced continuous circulation system.

The PSI protium and cleaning system is basically ready. For 2004 we plan to improve the redundancy of critical components such as the palladium filter and the hydride storage tanks.

PNPI has acquired a second oil-free vacuum system, with a membrane forepump, turbopump, vacuum valves, and gauges already available. A new protium-filling system–including a new purification

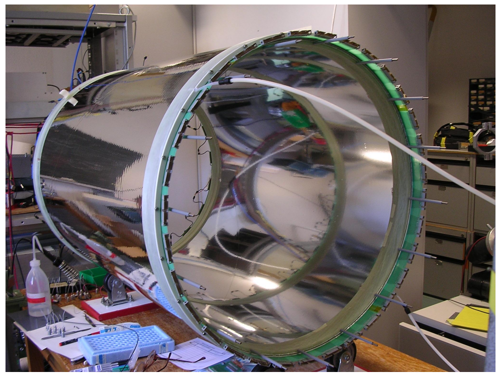

Figure 10: The outer wire chamber in its test configuration.

column, absorber and compressor, and two new 10 l storage vessels–is under construction. The mounting of the gas and vacuum system will be finished by mid-February. Commissioning of the full TPC setup will then start.

Continuous purification system The MuCap hydrogen system should contain $Z > 1$ impurities of less than 0.1 ppm, ideally less than 0.01 ppm. One step towards this goal was the successful construction of fully bakeable TPC's. The second step is the design of a continuous purification system. We initiated this major effort in 2001 by succesfully competing for a CRDF grant of US$60K. The initial grant was a UIUC-PNPI joint effort, but by now the entire MuCap collaboration has made contributions to this critial project, which has made decisive progress (see fig. 11). During 2003 the main components of the gas recirculation system were produced at the PNPI workshop: flanges and vessels for the cryogenic portion, along with the bodies of three adsorber-compressors with heating and cooling lines. The design of electronics and the mounting of heating power elements were also finished. Software and some testing programs were developed and used for simulation. The important components, including a mass flow controller, solenoid valves and dry clean pumps, are available. The system will be tested together with the PNPI-built H_2 vessel and TPC and should arrive PSI by the end of summer of 2004.

Isotopic purity Measuring and minimizing the deuterium content in our protium target are major conerns for the final experiment. Based on last year's experience, we will carefully flush and condition our entire hydrogen system with pure protium, in order to understand the source of the observed deuterium increase between the initial filling and the final sample. Protium gas will be generated from Canadian protium water, of which we have an amount equivalent to 2500 standard atmospheric liters available.

Monitoring of the deuterium concentration will require the support of different analysis methods which have been introduced over the last year, including a high resolution mass spectrometer at PSI, as well as more accurate methods in Zürich and St. Petersburg. Furthermore, we plan to optimize different methods for in-situ calibration of the deuterium content directly from our experimental data

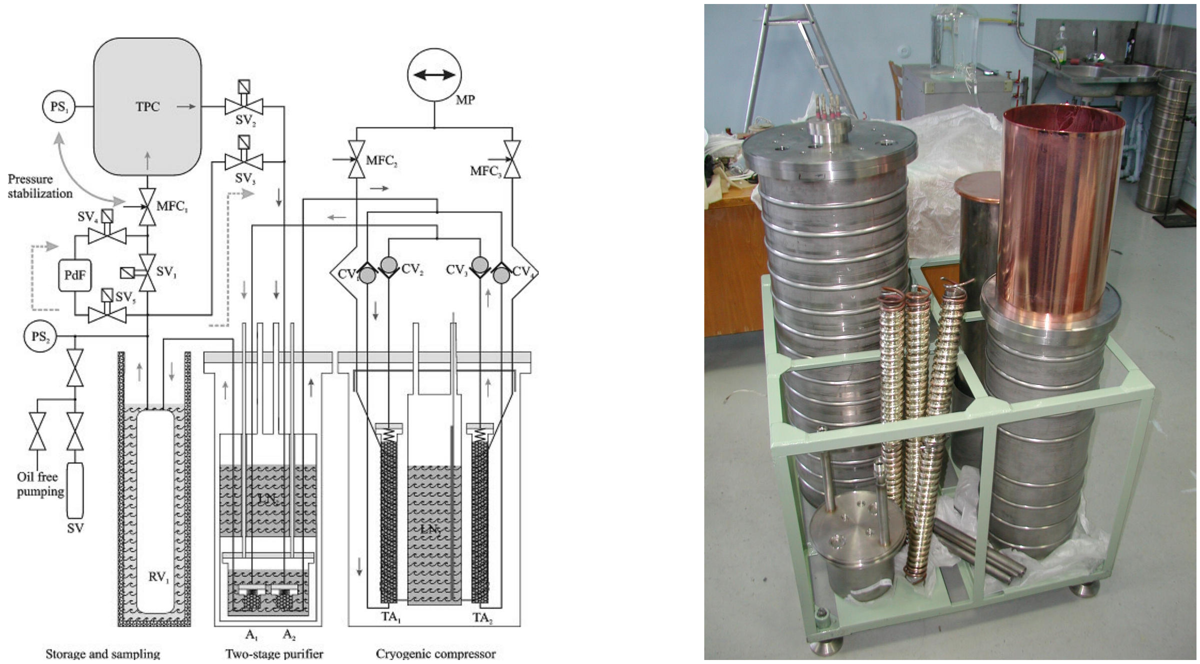

Figure 11: Left: diagram showing the basic principle of the cryogenic continuous purification system. Right: flanges and vessels for the cryogenic part, and the bodies of three adsorber-compressors with heating and cooling lines, produced in the PNPI workshop.

(c.f. [3]). These methods include:

- **Monitoring the $pd\mu \rightarrow {}^3$He $+\mu$ process in the TPC**. The TPC must operate with a high voltage of at least 5.5 kV in order to see the 5.5 MeV muon produced in this reaction.
- **Dependence of the observed time spectra on vertex cuts** . Because of deuterium diffusion effects, the decay spectra are very sensitive to the vertex cut between muon stop and decay electron origin. The application of this method requires ePC2 for accurate electron track reconstruction.
- **Monitoring dμ diffusion in the TPC**. This method would require TPC sensitivity to Michel decay electrons, achievable with a high voltage above 6 kV.

These internal monitoring methods require the planned hardware upgrades (increased TPC voltage and ePC2 implementation) as well as detailed simulations of the diffusion kinetics, which are currently being performed by UIUC student Brendan Kiburg.

Data acquisition system

We have acquired a set of VMIC VMIVME-7740 single-board computers which are several times faster than the Motorola PowerPC-based boards used in the 2003 run. In addition, we plan to replace most of the discrete NIM logic that coordinates the DAQ operation with an FPGA-based solution which should be more reliable. Aside from the TPC, the detectors are read out by electronics modules that contain FIFO buffers which are constantly serviced by the data acquisition system. The current logic requires that the FIFOs be periodically drained during an electronics deadtime. The FPGA upgrade will allow us to implement a fully-pipelined mode in which this draining step is not necessary, and this should allow us to eliminate data acquisition deadtime. We have developed lossless compression algorithms, based on run-length encoding and Huffman coding, that take full advantage of the geometry of the tracks in the TPC. In offline tests we have been able to compress data files from the 2003 run by a factor of 5.2 without losing any information; we will employ this compression software online during data collection.

μSR magnet

Decay electron scattering in the copper tubing of the μSR magnet led us to construct two new aluminum saddle coils, one for each TPC system. This change of material will reduce the scattering in the magnet by at least 30% and will therefore improve the vertex tracking of the two ePC detectors. Both magnets will be ready by June.

4 Beam Time Request

The goals for the 2004 run are twofold: First, we want to test all upgrades as described in this report, at the full beam intensity of 30-50 kHz in the TPC volume; second, we intend to start full production running toward our design goal of 10^{10} analyzed μ^- decays and $10^{10}\mu^+$ decays.

Since the superconducting μE4 channel is no longer available, we propose to use the πE3 beam line in combination with an electrostatic separator. This beam is also well-suited for running low-energy muon beams. Our beamtime needs can be stated as follows:

- Setup of the beamline with electrostatic separator, assembly of the entire experimental apparatus, and testing of all components: 2 weeks.
- Tuning of new 35 MeV/c muon beam for small spot size ($\sim$3 cm FWHM) and momentum bite ($\sigma \sim 2\%$): 1 week.
- Test runs with full apparatus, and finding optimal settings: 1 week.
- Production runs with μ^- and μ^+ beams (we expect to achieve 6 kHz of fully reconstructed and pile-up protected muon decays): 2 x 2.5 weeks
- Contingency buffer for unforeseen problems, gas exchanges, failures of components or beam: 1 week.

In total, our beamtime request is thus 10 weeks of πE3 beam time in fall 2004 (i.e. from October to December 2004).

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[2] D.V. Balin et al., *High precision measurement of the singlet μp capture rate in H_2 gas*, PSI proposal R-97-05.1 and documentation

[3] V.A. Andreev et al., *High precision measurement of the singlet μp capture rate in H_2 gas*, Technical Proposal, PSI proposal R-97-05.2, February 2001

[4] The April Meeting 2004 of the American Physical Society features a Minisymposium on "Axial Currents in Mesons, Nucleons, and Nuclei." A main theme will be muon capture, led off with an invited talk by Tim Gorringe on *Muon Capture and the Pseudoscalar Form Factor*, followed by two other contributions from MuCap team members. We also note that a very 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. Invited and contributed papers were presented by MuCap members at recent international conferences (P. Kammel, International Workshop on Exotic Atoms: Future Perspective (EXA 2002), Vienna, Austria, Nov 2002, nucl-ex/0304019; B. Lauss, Conference on the Intersections of Particle and Nuclear Physics, New York, USA, 2003, nucl-ex/0401005) and several national physics meetings.