

# Precision muon lifetime and capture experiments at PSI

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on behalf of the  $\mu\text{Lan}^\dagger$  and  $\mu\text{Cap}^\ddagger$  Collaborations.

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The  $\mu\text{Lan}$  experiment at the Paul Scherrer Institute will measure the lifetime of the positive muon with a precision of 1 ppm, giving a value for the Fermi coupling constant  $G_F$  at the level of 0.5 ppm. Meanwhile, by measuring the observed lifetime of the negative muon in pure hydrogen, the  $\mu\text{Cap}$  experiment will determine the rate of muon capture, giving the proton's pseudoscalar coupling  $g_p$  to 7%. This coupling can be calculated precisely from heavy baryon chiral perturbation theory and therefore permits a test of QCD's chiral symmetry.

## 1. Muon lifetime

The muon lifetime  $\tau_\mu$  is closely related to the Fermi coupling constant  $G_F$ , which sets the

strength of the weak interaction:

$$\frac{1}{\tau_\mu} = \frac{G_F^2 m_\mu^5}{192\pi^3} (1 + \delta q) .$$

The term  $\delta q$  includes the QED radiative corrections which, until 1998, were only known to a precision of 30 ppm. Van Ritbergen and Stuart [1] have now calculated these corrections through two-loop order, with a residual uncertainty at the level of 0.3 ppm. Consequently, the determination of  $G_F$  is now limited only by our knowledge of the muon lifetime at the 18 ppm level.

There is a deep connection between  $G_F$  and the Higgs vacuum expectation value, represented by the relation [2]  $G_F = 1/\sqrt{2}v^2$ , which may be read as “the weak interaction is the generator of mass in the universe.” It therefore becomes clear that  $G_F$  is a truly fundamental parameter of the standard model. To take an example of its impact, the LEP electroweak working group [3] performs a global fit to the standard model using  $G_F$  together with the LEP observables such as  $M_Z$  and  $\alpha$  and is able to determine the top quark mass with a precision of 9.7 GeV (5.4%) without producing a single real top quark. As a fundamental constant,  $G_F$  should be measured as precisely as possible with today's technology, even though a corresponding improvement in the precision of  $M_Z$  will probably await the construction of a linear collider or muon collider. Our collaboration also has a more immediate motive for measuring the muon lifetime: we will use the  $\mu^-$  capture rate in hydrogen and deuterium as a probe of the inter-

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nal structure of the proton and the deuteron, as we discuss in the second part of this paper. A precise measurement of the  $\mu^+$  lifetime will directly improve the precision of these capture rates.

The standard technique to measure the muon lifetime is to stop low-energy muons in a target, observe the Michel electrons from muon decay, and fit the exponential distribution of  $t_e - t_\mu$ , the time between the muon stop and its decay. Previous experiments have operated at muon rates of order  $1/(10\tau_\mu) \simeq 25$  kHz, where typically only a single muon is present in the target at a time; an offline cut suppresses events where two muons arrive too close together. However, it would be difficult to make a ppm-scale measurement in this mode, since it would take more than 250 days of operation to record the requisite  $10^{12}$  events. A number of efforts have attempted to solve this problem by “parallel processing” of muons. Like the RIKEN-RAL experiment [4],  $\mu$ Lan uses a pulsed beam structure, stopping an ensemble of muons in the target and observing their decays. The muon bunches are, however, much smaller in the case of  $\mu$ Lan, typically 20 muons at a time, rather than of order  $10^4$  as at RIKEN-RAL, so the systematic uncertainty due to overlapping pulses should be dramatically smaller. The time structure, optimized for measuring the muon lifetime, is obtained using a fast kicker to modulate the continuous beam available at PSI. This approach is in contrast with that of the FAST experiment [5], also conducted at PSI, which stops pions continuously in a finely segmented scintillating fiber target, separating muons by space rather than by time.

The kicker will cycle between beam-on and beam-off states, accumulating muons in the target for  $5 \mu\text{s}$  and observing their decays for the next  $22 \mu\text{s}$ . The beam-off state is achieved by charging two pairs of plates, each  $(75 \times 20) \text{ cm}^2$ , to a  $\pm 12.5 \text{ kV}$  potential, deflecting the beam into an absorber. The rise and fall times are expected to be  $45 \text{ ns}$ , limiting the time in which muons are deflected to a poorly-defined position. Tests with a static field on the kicker plates suggest that an extinction factor of greater than 300 will be achieved. The beam will be continuously monitored by a wire chamber that has been optimized



Figure 1. The  $\mu$ Lan detector in place in the  $\pi$ E3 beamline at PSI.

for high rates to ensure the stability of this extinction factor on both long and short time scales. The beam is collimated upstream of the kicker to a rate of 12 MHz, giving 2 MHz of muons at the target during the beam-on period.

The  $\mu$ Lan detector (Figure 1) is a truncated icosahedron (“soccer ball”) surrounding the stopping target, with two pentagons removed to permit the beam to enter and exit. It consists of 170 nested pairs of triangular plastic scintillator tiles. A coincident signal in the inner and outer tiles of a pair will be required in order to reduce accidental backgrounds. These detectors give on average 80 photoelectrons per minimum ionizing particle in each layer.

The muon’s spin precesses in any external magnetic field. Because parity violation in muon decay sends the electrons preferentially along the axis defined by the spin, any geometric inhomogeneity in the electron detector acceptance distorts the measured time spectrum. We reduce this effect in several ways. The detector covers a large solid angle and is as spherically symmetric as practical to permit cancellation of the asymmetry in the sum of each opposing pair. For most of our running time, we will use a target made of a ferromagnetic alloy (Arnokrome-3) with large ( $\sim 4 \text{ kG}$ ), nonuniform internal magnetic fields. As a control, we can swap it with a silver target disk, which preserves the polarization. Finally, we ap-

ply a uniform external magnetic field of approximately 120 G; each of the muons within a bunch arrives at a different time, so their spin motion in this field is dephased.

The high segmentation of the detector reduces the impact of overlapping pulses (“pileup”). It will be further reduced by recording each detector’s output with a waveform digitizer (WFD), using a flash ADC to sample the signal at 500 MHz. The resulting waveforms will be reduced to times and amplitudes by an online computing “farm,” which should be able to resolve pulses at separations as close as  $\delta t \sim 4$  ns based on a fit to the pulse shape. The separation in pulse amplitude between single and double hits will provide an additional pileup suppression factor of  $\sim 25$ . The final systematic uncertainty from overlapping pulses should be less than 0.1 ppm.

Following a number of successful beam and detector test runs,  $\mu\text{Lan}$  will have its first data collection period this fall with a kicked beam. Because the WFD construction has been delayed, we will have to use conventional discriminators and multi-hit TDCs, with the goal of reaching a 3 ppm measurement of  $\tau_\mu$ . In 2005, we will have a major production run with the WFD to reach the full proposed  $10^{12}$  statistics.

## 2. Muon capture

The current associated with the weak interaction between a muon and a “free” quark inside the proton is a maximally parity-violating  $V - A$  form, proportional to  $\gamma_\mu(1 - \gamma_5)$ . However, the QCD binding of quarks within the proton adds several induced form factors to the problem; the most general form of the interaction between a muon and a proton becomes [6]

$$\begin{aligned} J_\alpha = & g_v(q^2)\gamma_\alpha + i\frac{g_m(q^2)}{2m_N}\sigma_{\alpha\beta}q^\beta \\ & -g_a(q^2)\gamma_\alpha\gamma_5 - g_p(q^2)\frac{q_\alpha}{m_\mu}\gamma_5 \\ & +\text{second class currents .} \end{aligned}$$

The first three form factors ( $g_v$ ,  $g_a$ , and  $g_m$ ) are known very precisely, to at worst a few tenths of a percent, but there is considerable experimental ambiguity in the case of  $g_p$ , which is only known

to about 20%.

However, there are reliable theoretical predictions. A heavy baryon chiral perturbation theory calculation gives [7]

$$g_p(q^2) = \frac{2m_\mu g_{\pi NN} F_\pi}{m_\pi^2 - q^2} - \frac{1}{3}g_a(0)m_\mu m_N r_A^2$$

$$g_p(q^2 \rightarrow (p_n - p_p)^2) = 8.26 \pm 0.23 (\pm 3\%) .$$

This calculation, an expansion parameterized by the light quark mass, is a precise result of a low-energy expression of the fundamental chiral symmetry of QCD, so it is extremely important to verify it. Furthermore, it is consistent with older partially conserved axial current (PCAC) calculations, which give

$$g_p(q^2) = \frac{2m_\mu m_N}{m_\pi^2 q^2} g_a(0)$$

$$g_p(q^2 \rightarrow (p_n - p_p)^2) = 8.7 .$$

Typically, the negative muon decays just as the positive muon does. However, in hydrogen gas, it has an additional possibility: about 0.15% of the time, it is instead captured by the proton. It is this 0.15% value that we aim to measure to high precision by comparing the lifetimes of positive and negative muons in hydrogen and computing  $\Lambda_s = 1/\tau_{\mu^-} - 1/\tau_{\mu^+}$ . Each of the lifetimes will be measured to 10 ppm by  $\mu\text{Cap}$ ; a significant improvement in precision could be obtained by instead taking  $\mu\text{Lan}$ ’s 1 ppm measurement of  $\tau_{\mu^+}$ . The quantity  $\Lambda_s$  may in turn be related to  $g_p$  [8]; a 1% measurement of  $\Lambda_s$  should give  $g_p$  to 7%.

Previous measurements of the muon capture process have been limited by the molecular physics of the liquid hydrogen target. Specifically, the transition rate  $\lambda_{op}$  between the ortho- and para- states of the muonic hydrogen molecule is not well-determined, and the capture rates from these two states are quite different.  $\mu\text{Cap}$  is much less sensitive to these effects because it uses a 10 bar hydrogen gas target, which has only 1% of the density of liquid hydrogen. The muons initially statistically populate the atomic hyperfine singlet and triplet states, but quickly drop through thermal collisions to the singlet state and stay there rather than entering molecular states.

The hydrogen is contained in a time projection chamber (TPC) where it is used as both the target material and the active chamber gas. In the TPC, each muon is tracked to its stopping point where the Bragg peak is identified, guaranteeing that it stopped in hydrogen. The TPC is surrounded by a cylindrical electron detector with two wire chambers and two layers of scintillator.

The hydrogen gas must be very pure, since muons would transfer to and subsequently capture on heavier impurity nuclei, and the capture rate is roughly proportional to  $Z^4$ . The TPC is constructed of materials that can be baked in vacuum to 130° C to reduce outgassing. The protium is filled through a palladium filter, and a system has been constructed to continuously circulate it through a Zeolite absorber cooled by liquid nitrogen. An in-situ analysis is performed by searching for a second track in the TPC corresponding to the recoil nucleus following a muon capture on the impurity. This technique supplements an external chromatographic analysis of the gas.

Deuterium is more problematic than higher- $Z$  impurities. Typically, a  $\mu d$  atom diffuses a long distance from the muon stopping point; there is a minimum of the  $\mu d$ -p scattering cross section at 1.6 eV, giving it a long mean free path. It therefore leaves the fiducial volume and is probably captured in the TPC frame. The recoil nucleus is not observed; however, it may be possible to make an in-situ measurement by tracking the electrons back to the decay vertex and relating the concentration to the distribution of drifts from the muon stop to decay. Also, if the TPC gain can be increased sufficiently, it may be possible to identify muon catalyzed fusion events where  $\mu d + p \rightarrow \mu$  (5.3 MeV) +  ${}^3\text{He}$  (0.2 keV).

In 2003, we collected  $5 \times 10^8$  clean muon decay events (Figure 2), which would lead to a statistical uncertainty of about 5% on the capture rate. The systematics, especially from deuterium, are still being evaluated. This autumn, we intend to collect an order of magnitude more data, amounting to half of the total proposed statistics of  $10^{10}$  muons. The upgrades relative to last year's run include the gas circulation system, the outer wire chamber in the electron detector, and somewhat higher gain in the TPC. We will then

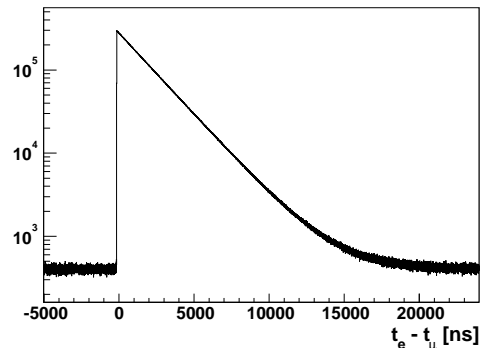


Figure 2. Time spectrum from the 2003  $\mu\text{Cap}$  run including  $5 \times 10^8$   $\mu^-$  decays.

complete the proposed data-taking in 2005. In 2006 and beyond, we will consider operating the experiment in a “muon-on-request” mode with the  $\mu\text{Lan}$  kicker to increase the rate at which statistics can be collected. We will also continue to investigate the feasibility of modifying our apparatus to measure the muon capture rate in deuterium, which would provide a sensitive test of two-body currents and constrain the effective field theory parameter  $L_{1,A}$ , an important ingredient in the absolute neutrino flux at SNO [9].

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