Precision muon lifetime at PSI

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The goal of MuLan, positive muon lifetime measurement, is the measurement of the positive muon lifetime to 1 ppm, which will in turn determine the Fermi coupling constant $G_{\rm F}$ to 0.5 ppm precision. We will describe our experimental efforts and latest achievements.

Impressive advances in the precise knowledge of many parameters defining the electroweak interaction within the Standard Model have been seen. However, the value of one of the most fundamental weak parameters, the Fermi coupling constant $G_{\rm F}$, has not been improved in over two decades (see Fig. 1), with the most precise experimental determination limited by counting statistics. Usually $G_{\rm F}$ is determined via a measurement of the muon lifetime τ_μ

$$\frac{1}{\tau_\mu} = \frac{G_{\rm F}^2 m_\mu^5}{192\pi^3} F\!\left(\frac{m_e^2}{m_\mu^2}\right)\left\{1 + \frac{3}{5}\frac{m_\mu^2}{M_W^2}\right\}$$
$$\left(1 + \Delta_{\rm QED}(\alpha_{m_\mu})\right),$$
(1)

with

$$F(x) = 1 - 8x - 12x^2 \cdot \ln x + 8x^3 - x^4 \quad (2)$$

as given by Ref. [2]. The QED corrections within the Fermi Model, $\Delta_{\rm QED}$, are included in this definition.

Within the Standard Model one can derive the relation

$$G_{\rm F} = \frac{\pi\alpha(0)}{\sqrt{2}M_W^2\left(1 - \frac{M_W^2}{M_Z^2}\right)}\,(1 + \Delta_r)\;, \qquad (3)$$

with weak radiative corrections being summarized in Δ_r [3]. The calculated quantity Δ_r depends on the entire set of input parameters, e.g., M_Z, M_{Higgs}, m_{top}, and α. Recently, these calculations were improved to the sub-ppm level by including numerically important QCD and
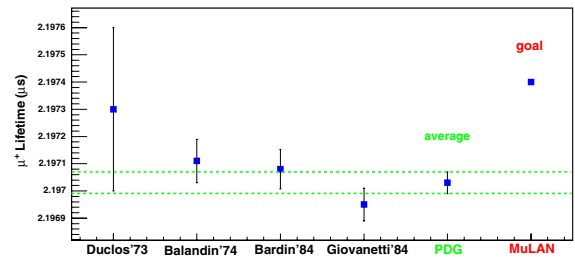

Figure 1. Progression of positive muon lifetime measurements [4]. The 1 ppm error goal of MuLan is too small to be visible on this scale.

electroweak higher–order terms up to 2–loop level. Therefore a precise comparison between theoretical and experimental values, e.g., for M_W, see Eq. (3) is possible [3]. Consequently, $G_{\rm F}$ sets important constraints on the Standard Model and SUSY parameters. Furthermore, $G_{\rm F}$ sets the weak scale and is intimately connected to the vacuum expectation value of the Higgs field. The best possible experimental measurement of $G_{\rm F}$ at the present technological limit is therefore highly desirable, as the 18 ppm precision limit on the PDG average on τ_μ [4] is dominated by experimental counting statistics.

The MuLan experiment, (**Mu**on **L**ifetime **an**alysis), intents to measure a total of 10^{12} μ^+ decays, in order to achieve a 1 ppm statistical error in the lifetime. Since the status report on the MuXprogram in Ref. [5] we have achieved substantial progress. A modification of the continuous high intensity muon beam line at the

Figure 2. *The installed MuLan setup: The helium bag and the AK3 target mounted in the detector center.*

Figure 3. *The installed MuLan setup: View of the soccer ball detector. The visible hexagonal structures are made of six neighboring triangular scintillator pairs.*

Paul Scherrer Institute [6] was necessary to enable the collection of 10^{12} events within a reasonable time. We have built an electrostatic kicker [7] which applies an artificial time structure to the DC beam in the πE3 area and found a kickable beam tune which provides up to 12 MHz of muons. Following a 5 μs muon collection period in the target, the kicker deflects the beam for 27 μs while muon decays are measured.

MuLan is designed to minimize the systematic errors in several ways:

– **Muon polarization:** The beam muons are highly polarized, and the preferential emission of decay positrons in muon spin direction could cause a position- and time-dependent positron detection efficiency as polarized muons rotate in an external magnetic field. We are currently investigating two specific targets:

  i) Arnokrome-3, AK3, (Fig. 2) is a proprietary chromium-cobalt-iron alloy sheet, which, due to an internal field of a few Tesla, precesses muons very fast with respect to muon decay. Therefore polarization effects are negligible.
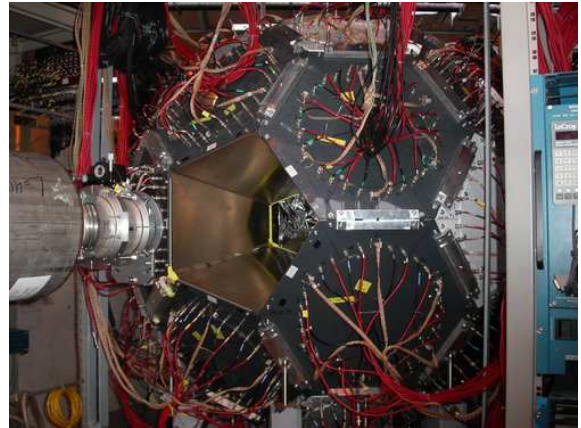
  ii) A solid sulfur target which maximizes the depolarization of the beam muons. It is placed in a homogeneous 120 Gauss magnetic field which causes a fast visible muon rotation and allows us to fit the corresponding decay positron asymmetry.

We are presently investigating samples of 10^{10} decay positrons from each target to select the optimal material choice. Additionally, a polarization-preserving silver target is being used for control purposes. MuLan's highly modular detector (Fig. 3) of 174 coincident scintillator tile pairs in "soccer ball" geometry allows us to compare opposite counters, thus strongly reducing precession effects in the count rate sum.

– **"Sneaky muons:"** A fast thin entrance muon counter (EMC) records beam muons and looks for muons sneaking in during the measurement interval. A magnet positioned behind the EMC precesses the tiny fraction of muons stopped in the
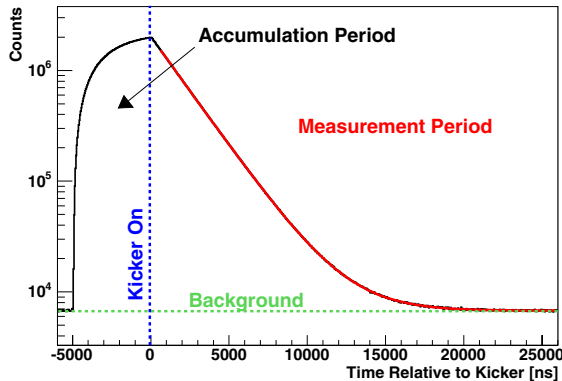
Figure 4. *Lifetime spectrum (decay positron minus start of beam kick time) obtained in a single 10 minute run displaying accumulation and measurement period.*

detector materials, otherwise they too could cause small detection inefficiencies.

– **Off-target muon stopping:** Muon stops before the target are minimized by decreasing the materials in the muon path. Consequently we installed a helium bag (Fig. 2) and used very thin mylar windows and EMC materials.

– **Pile-up:** The high detector modularity and the fast scintillator response time reduce pile-up. Additional time resolution will be gained via new 500 MHz waveform digitizers (WFD) presently under construction, which will provide a double pulse resolution better than 4 ns. Final WFD implementation to all detector channels is taking place during the fall 2005 run period.

The MuLan detector (Fig. 3) was successfully commissioned in 2004 and yielded its first physics data. Figure 4 shows a 10 minute snapshot from our AK3 target data. We used multi-hit TDCs for detector readout. The muon accumulation time and the decay recording time are indicated. Our ongoing analysis with this data is reaching a 5 ppm statistical precision in the determination of G_{F}. Fall 2005 run period is taking nearly 10^{11} muon decay electrons with the WFD. We intend to collect the full statistics in 2006.

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