New precision determination of $g_P$ and $G_F$: the MuXperiments at PSI

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on behalf of the MuCAP [1] and MuLAN [2] collaborations

We discuss two precision experiments which will measure fundamental weak interaction parameters: MuLAN’s goal is the measurement of the positive muon lifetime to 1 ppm, which will in turn determine the Fermi coupling constant $G_F$ to 0.5 ppm precision. MuCAP is the first experiment which will unambiguously determine the induced pseudoscalar form factor of the proton, $g_P$. While contradictory experimental results for $g_P$ are under discussion, firm theoretical calculations on the percent level within the framework of Chiral Perturbation Theory are now challenging the measurements. We will describe our experimental efforts and latest achievements.

1 Precision determination of $G_F$ - the MuLAN experiment

We have seen impressive advances in our precise knowledge of many parameters defining the electroweak interaction within the Standard Model. However, the value of one of the most fundamental weak parameters, the Fermi coupling constant $G_F$, has not been improved in over two decades (see Fig.1). Usually $G_F$ is determined via a measurement of the muon lifetime $\tau_\mu$

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

(1)

with $F(x) = 1 - 8x - 12x^2 \ln x + 8x^3 - x^4$ [3]. The QED corrections within the Fermi Model, $\Delta_{QED}$, are included in this definition.
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Within the Standard Model one can derive the relation

$$G_F = \frac{\pi \alpha(\theta)}{\sqrt{2} M_W^2 \left(1 - \frac{M_Z^2}{M_W^2}\right)} (1 + \Delta_r),$$

with weak radiative corrections being summarized in $\Delta_r$ [4]. The calculated quantity $\Delta_r$ depends on the entire set of input parameters, e.g. $M_Z$, $M_{\text{Higgs}}$, $m_{\text{top}}$, $\alpha$. Recently, these calculations were improved to the sub-ppm level by including numerically important QCD and electroweak higher-order terms up to 2-loop level. Therefore a precise comparison between theoretical and experimental values, e.g. for $M_W$ (Eq. 2) is possible [4]. Consequently, $G_F$ sets important constraints on the Standard Model and SUSY parameters. Furthermore, $G_F$ sets the weak scale and is intimately connected to the vacuum expectation value of the Higgs field. The best possible experimental measurement of $G_F$ at the present technological limit is therefore highly desirable, as the 18 ppm precision limit on the PDG average on $\tau_\mu$ [5] is dominated by experimental counting statistics.

The MuLAN experiment (Muon Lifetime ANalysis), intents to measure a total of $10^{12}$ $\mu^+$ decays, in order to achieve a 1 ppm statistical error in the lifetime. Since the status report on the MuXprogram in [6] we have achieved substantial progress. A modification of the continuous high intensity muon beam line at the Paul Scherrer Institut was necessary to enable the collection of $10^{12}$ events within a reasonable time. We have built an electrostatic kicker which applies an artificial time structure to the DC beam in the $\pi E3$ area and found a kickable beam tune which provides up to 8 MHz of muons. Following a 5 $\mu$s muon collection period in the target, the kicker deflects the beam for 27 $\mu$s 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 (Fig.2b) 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.2a) 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 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.2b) 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 planned for 2005.

The MuLAN detector (Fig.2a) was successfully commissioned in 2004 and yielded its first physics data. Fig.3 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 present analysis goal with this data is a 5 ppm precision determination of $G_F$. We intend to collect the full statistics in 2006.
2 Precision determination of $g_P$ - the MuCAP experiment

The $V-A$ description of weak interactions has been tested to a high precision. Processes involving structureless fermions, e.g. muon decay, show equal vector ($V$) and axial-vector ($A$) coupling. In $\beta$-decay as well as in nuclear muon capture on the proton $\mu^- + p \rightarrow \nu_\mu + n$ , the axial coupling $G_A$ is modified due to hadronic effects caused by the involved nucleon. Muon capture occurs at higher four-momentum transfer $q = -0.88 m_\mu^2$ than $\beta$-decay. Lorentz invariance constrains the corresponding weak current matrix elements to six independent terms,

$$V_\mu = G_V(q^2) \gamma_\mu - \frac{i G_M(q^2)}{2m_N} \sigma_{\mu\nu} q^\nu + \frac{G_S(q^2)}{m_\mu} q_\mu$$

$$A_\mu = G_A(q^2) \gamma_\mu \gamma_5 + \frac{G_P(q^2)}{m_\mu} \gamma_5 q_\mu + \frac{i G_T(q^2)}{2m_N} \sigma_{\mu\nu} q^\nu \gamma_5 ,$$

with corresponding weak form factors $G_i$ ($i = \text{scalar, pseudoscalar, vector, axial-vector, tensor, weak magnetism}$); mass of the nucleon $m_N$ and muon $m_\mu$. Because of G-symmetry $G_S$ and $G_T$ vanish [7]. Due to the momentum dependence, only $G_A$ and $G_V$ contribute in $\beta$-decay at very low $q^2$. Nuclear muon capture is the process most sensitive to $G_P$. Therefore, $G_P(-0.88 m_\mu^2)$ is dubbed induced pseudoscalar coupling constant $g_P$. While the values of $G_V$, $G_A$ and $G_M$ are established on the $10^{-3}$ to $10^{-4}$ level [5], the situation is totally different for the induced pseudoscalar $g_P$.

The theoretical view, historically based on PCAC and pion pole dominance, and recently strictly derived within chiral perturbation theory ($\chi$PT) [8], is remarkably precise:

$$G_P(q^2) = \frac{2m_\mu g_{\pi NN} F_\pi}{m_\pi^2 - q^2} - \frac{1}{3c^2 r_A^2} G_A(0)m_\mu m_N r_A^2 ,$$

$$g_P = (8.74 \pm 0.23) - (0.48 \pm 0.02) = 8.23 \pm 0.23 ,$$

depending on the exact values of the pion-nucleon coupling constant $g_{\pi NN}$ and the mean axial radius of the nucleon $r_A$. The Standard Model based calculation of the singlet
muon capture rate by Govaerts and Lucio-Martinez [9] has reached 0.55% precision. This precision in calculation will allow a high precision measurement to distinguish between the pion pole contribution to $g_P$ and the correction term. Moreover, such a measurement will also set tight limits on various theoretical scenarios beyond the Standard Model [9].

The present experimental knowledge of $g_P$ is unsatisfying, and discrepancies cause considerable debate. Determinations via ordinary muon capture in hydrogen (OMC) [10], $^3$He [11] and larger nuclei essentially confirm the theory result. However the precision of the latter is troubled by model dependencies. A radiative muon capture on the proton (RMC) experiment [12], which measured an additionally very rarely emitted high energy $\gamma$ ray in conjunction with the muon capture process, yielded a different result. The present most likely explanation lies in the insufficient knowledge of the complex kinetics of negative muons in hydrogen. The $\mu p$ atom is formed in statistically populated singlet and triplet states, and the muon capture rate from these states differ by a factor of $\sim 60$ due to the strong spin dependence of weak interactions. An exact knowledge of the spin populations is therefore mandatory for the interpretation of a measurement. The initial $\mu p$ populations are modified via spin flip and molecular formation processes, which eventually yield a fraction of muonic hydrogen molecules ($pp\mu$). The respective rates for both types of process scale with density, and hence are high in the liquid hydrogen targets

1While the RMC process has a $10^5$ times lower branching than OMC, the emitted $\gamma$ can have energies up to 100 MeV. Therefore these $\gamma$'s come closer to the pion pole and the measurement is in principle four times more sensitive to $g_P$ than OMC.
Figure 5: The setup of the MuCAP experiment:

a) Schematic view of the detectors showing the muon entering from the beam channel (blue arrow), hitting the 200 μm thick time=0 scintillator (muSC) and a small wire chamber (muPC) which serves as additional pile-up counter, and then stopping in the TPC. The muon stop position is detected via a high signal caused by the Bragg peak (blue) after a track of low signals (green). The decay electron (red) is observed in 2 cylindrical wire chambers (ePC1/2) for track reconstruction. Outside is a doubled-layered scintillator hodoscope (eSC) with readout at both paddle ends, which records the decay time.

b) Installed setup in PSI’s πE5 area with the hydrogen vessel rolled back, displaying the mounted μSR saddle-coil magnet.

which were used in Refs. [10] and [12]. However, a large μ-molecular population causes a large correction to the lifetime and hence a corresponding uncertainty. Specifically the ortho to para spin-flip rate in $pp\mu$ molecules $\lambda_{OP}$ (Fig.4b) is a prime suspect to cause the experimental discrepancy in $g_P$. Figure 4, updated from [13], shows the $\lambda_{OP}$ dependence of the OMC and RMC results. The controversial $\lambda_{OP}$ values are also shown. Two experimental values from Saclay [14] and TRIUMF [15], which were obtained together within the same experiments performing the OMC and RMC measurements, strongly disagree, and the only theoretical calculation [16] does not clarify the situation. It is evident that using the $\lambda_{OP}$ rate from the same measurements brings the $g_P$ value in agreement with theory. However, the use of the other $\lambda_{OP}$ value enlarges the disagreement to the prediction or lowers it to an unphysical negative value. Clearly only a new determination of $g_P$ independent of $\lambda_{OP}$ can resolve this situation.

The experimental principle of the MuCAP (Muon CAPture) experiment is based on the measurement and comparison of the decay time of positive and negative muons in hydrogen. The MuCAP experiment is designed to overcome the multiple difficult problems of previous experiments. The important conceptual advantage of MuCAP is the selection of target hydrogen at gaseous density (10 bar at room temperature), which minimizes
Figure 6: a) Observed $2 \times 10^9$ muon stopping positions in the TPC (fall 2004).

b) Observed special event in the TPC: A muon stops after leaving a track over several anodes with a few times higher energy deposition in the last anodes. In fall 2004 we observed a fraction of $\sim 10^{-6}$ high-$Z$ capture events, corresponding to a $10^{-8}$ concentration of impurities, with a clear signature of a very high signal within 25 $\mu$s after a muon stop.

The kinetics dependence of the result on $g_P$ as shown in Fig.4a. At low densities, muon capture occurs almost exclusively from the singlet state on the proton, and even a large estimated error on $\lambda_{OP}$ results only in a systematic error on the 10 ppm level. The full setup is shown in Fig.5. The active gaseous hydrogen target, a time projection chamber (TPC), allows for a full 3-dimensional reconstruction of the muon path to its stopping point and therefore a selection of clean muon stops away from walls and wires. The observed stopping distribution of muons is shown in Fig.6a.

The TPC also detects muon capture events on impurity atoms ($Z > 1$) via the very large signals generated from capture products. Thus the TPC serves also as a very sensitive impurity monitor. The high rates of muon transfer to and nuclear capture on high-$Z$ atoms (Fig.4b) can cause a deflection of the exponential lifetime even at very low impurity concentrations as these rates are typically orders of magnitude higher than muon decay. In order to minimize this effect, target purity requirements are very stringent, with the goal to be on the $10^{-9}$ contamination level for the sum of high-$Z$ atoms. Additionally, the exact knowledge of these contaminations is necessary to calculate the correction factor to the lifetime. Consequently, the hydrogen gas after production in electrolysis is filled via a palladium filter and continuously run through a Zeolite based purification system (CHUPS). The CHUPS system [19] is specifically designed to maintain the hydrogen flow with negligible variations in density or hence in TPC gain. In fall 2004 we maintained clean target conditions (as low as 70 ppb impurities) for over 5 weeks.
MuCAP fully separates the muon and electron detectors to avoid dangerous cross-correlations. Decay electron times are measured in the scintillator hodoscope (eSC) surrounding the hydrogen vessel. Two cylindrical wire chambers track the electron back in 3 dimensions to its $\mu$-stop origin, thus largely reducing the background.

The impact parameter, defined as the minimal distance between detected muon stop and electron track, serves as an important handle on a very subtle systematic effect on the lifetime: the diffusion of muons which transfer to deuterium, an isotope always present in hydrogen. Although we are using special deuterium-depleted hydrogen, ("protium"), with deuterium content as low as 1.5 ppm, this deuterium concentration is still high enough to cause a visible effect in our setup via electron tracks with dislocated origin. This dislocation, due to $\mu d$ diffusion over macroscopic distances is possible because of a Ramsauer-Townsend minimum in the $\mu d + p$ scattering cross-section at low energies. Such $\mu d$'s can hit a wall or wire, transfer and then undergo unobserved nuclear capture outside the sensitive volume. The electron wire chamber tracking identifies such events and the corresponding lifetime dependence on the impact parameter will allow us to determine the deuterium contamination in situ [17]. Additionally, we have been developing a precision
trace deuterium detection method via $pd\mu$ fusion [18].

As in MuLAN, MuCAP applies a magnetic field to control muon spin rotation effects in the $\mu^+$ measurement. A water-cooled aluminum coil was developed to minimize decay electron scattering.

Eventually MuCAP needs $10^{10}$ cleanly observed decay electrons and positrons to statistically reach the goal of 1% in the capture rate, reflecting 10 ppm in the respective muon lifetimes. This is possible in several weeks of running in the fully pile-up protected mode. In the future we also intend to use the MuLAN kicked beamline with the MuCAP experiment and operate it in a “muon on request mode” [20].

Fig. 7 shows a preliminary lifetime plot from our fall 2004 data. One can clearly see the huge improvement in background reduction due to the implementation of the two cylindrical wire chambers. The shown $\sim 2 \times 10^9$ “clean” $\mu$ decay events are presently being analyzed, and a first result on $g_P$ is expected in late 2005.

3 Summary

Both experiments, MuCAP and MuLan, are on the way to reach ultimate precision in their respective measurements. First physics results are expected in late 2005.

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[15] The TRIUMF RMC group (D. Armstrong et al.) has not yet released their final result on the $\lambda_{OP}$ measurement. At the APS 2004 spring meeting in Denver, CO (USA), the following values have been presented, depending on the final deuterium concentration in the protium target: $\lambda_{OP} = 13.8 \pm 1.6 \times 10^{-4} s^{-1}$ (for maximum estimated $D_2$ contamination), and $\lambda_{OP} = 12.2 \pm 1.6 \times 10^{-4} s^{-1}$ (for no $D_2$ presence).


