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Muon Lifetime Programme at PSI

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We survey the ongoing and future high precision measurements of the positive and negative muon lifetimes, performed at the Paul Scherrer Institute (PSI). These experiments explore a rich spectrum of physics, ranging from the fundamental electroweak Fermi coupling, to basic tests of QCD symmetries and the calibration of important astrophysics neutrino reactions.

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A new generation of precision muon lifetime experiments at the Paul Scherrer Institute (PSI) has published initial results. The MuLan [4] and the FAST [5] experiment are dedicated high precision μ^+ lifetime measurements using complementary techniques. The final goal is an improved measurement of $\lambda_\mu^+ = \frac{1}{\tau_\mu^+}$ to 1 ppm and 2 ppm precision, respectively. As radiative corrections are now known with sufficient accuracy, these measurements will determine the fundamental Fermi constant to 0.5-1 ppm precision. The goal of the MuCap experiment [6] is the measurement of the muon capture rate on the proton Λ_S to 1%, to determine the basic pseudoscalar form factor of the nucleon g_P, which is accurately predicted, based on the symmetries of QCD. The recently approved MuSun experiment [3] will extend this measurement to muon capture on the deuteron, a process closely linked to basic solar neutrino reactions via modern effective field theory.

1. Positive Muon Lifetime Experiments

The Fermi constant G_F is a fundamental constant of nature. Together with α and M_Z, G_F defines the gauge couplings of the electroweak sector of the standard model. It is directly related to the free muon decay rate by

$$\frac{1}{\tau_\mu} = \lambda_\mu^+ = \frac{G_F^2 m_\mu^5}{192\pi^3}(1+\Delta q), \tag{1.1}$$

where Δq is the sum of phase space and radiative corrections. For 40 years, since the pioneering lowest-order calculations of Δq, the uncertainty for extracting G_F from λ_μ^+ was limited by unknown 2-loop radiative corrections. With those calculated [7], the previously dominant theoretical uncertainty of 30 ppm is reduced to 0.3 ppm. Moreover, the uncertainty due to a finite ν_μ mass became negligible due to ν-oscillation data and direct mass constraints. Thus the muon lifetime, known to 18 ppm, became the limiting factor to determine G_F. This situation motivated several efforts for improved muon lifetime measurements, as part of the general programme to measure, as precisely as possible, the fundamental parameters of the standard electroweak theory, and to provide a benchmark muon lifetime for comparison with the MuCap experiment (see below).

The MuLan experiment used a continuous beam of low-energy "surface" muons, which is pulsed by a fast kicker to provide a 5-μs muon accumulation followed by a 22-μs measuring period. The Michel positrons were detected by a multi-segmented detector made of 170 independent scintillator tile pairs, whose photomultiplier signals were sampled by 450 MHz waveform digitizers. The detector was designed to minimize systematic effects, included multi-particle pileup, muon spin precession, time-dependence of detector gains or electronic thresholds, backgrounds, errant beam muons, and kicker voltage stability. In 2006, a high-internal-field metal alloy provided a ferromagnetic target whose internal field rapidly precesses the muon spins. In 2007, a quartz target was used, which formed a high fraction of the bound muonium (μ^+e^-) state. An external magnet induced a rapid precession for the bound muons and a modest precession for the free muons. A first publication [4] on a limited data set from 2004 gives τ_μ(MuLan) = 2.197013(21)$_{stat}$(11)$_{sys}$ μs. The updated world average τ_μ(World) = 2.197019(21) μs determines the Fermi constant G_F(World) = 1.166371(6) $\times$ 10^{-5} GeV^{-2} (5 ppm). MuLan is currently analyzing the main data set with the goal of 1 ppm precision in the lifetime.

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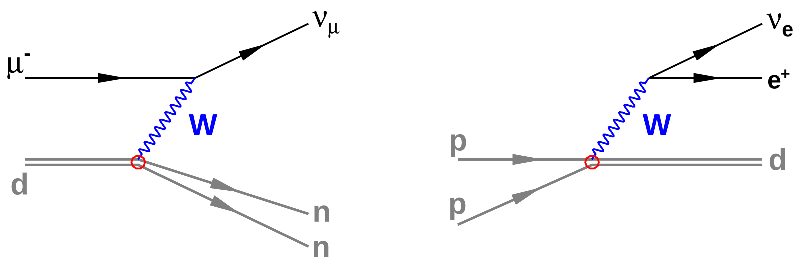

Figure 1: The μd capture reactions(left) and the solar pp fusion (right) depend on the same weak hadronic matrix element (red circle). The MuSun experiment will determine the low-energy constant, which characterizes the short-distance physics in the two-nucleon axial current.

Recently, the FAST experiment [5] released a new result τ_μ(FAST) = 2.197083(32)$_{stat}$(15)$_{sys}$ μs. The experimental method is based on a fast imaging target constructed from plastic scintillator bars providing 32×48 pixels. A DC π^+ beam is stopped in the target and the decay times of the full $\pi^+ \to \mu^+ \to e^+$ decay chain are registered, which strongly suppresses muon precession effects. As the detector simultaneously measures several decays in a compact volume, it has to cope with high data rates and needs carefully designed online triggers to manage the data flow. The experiment will be taking data during most of PSI's 2008 accelerator cycle to achieve its statistics goal of 2 ppm in τ_μ.

2. Muon Capture on Hydrogen Isotopes

The processes $\mu + p \to n + \nu_\mu$ and $\mu + d \to n + n + \nu_\mu$ are fundamental weak reactions between a muon and the nucleon and the simplest nucleus, respectively. Historically, they have played an important role in establishing the helicity structure as well as the universality of the weak interaction. Today, the electro-weak interaction is understood and verified at the quark-lepton level. Thus, the charged lepton current serves as a clean probe for exploring the weak couplings and QCD structure of the nucleon and nuclei. Over the last decade the connection between nucleon and even two-nucleon observables at low energies and fundamental QCD has been elucidated by the development of modern effective field theories (EFT). In this framework, $\mu + p$ capture can be calculated in a model-independent way with controlled systematic uncertainty. As the EFT predictions derive from basic concepts of explicit and spontaneous chiral symmetry breaking, their experimental verification is an important test of our understanding of the underlying QCD symmetries [8, 9]. As regards the two-nucleon sector, EFT calculations have proved that reaction $\mu + d$ is closely related to fundamental weak reactions of astrophysical interest [10, 11], like $p + p$ fusion in the sun and $\nu + d$ scattering observed at the Sudbury Neutrino Observatory [12]. A precision measurement of $\mu + d$ capture determines the low energy constant required for calculating these extremely feeble solar reactions (see Fig. 1).

MuCap experiment. Muon capture on the proton provides unique information on the pseudoscalar form factor g_P, characterizing the axial structure of the nucleon. This basic coupling was already estimated in the pre-QCD era via PCAC and, by now, is understood as a derived quantity within the effective chiral theories of QCD, leading to a precise theoretical prediction

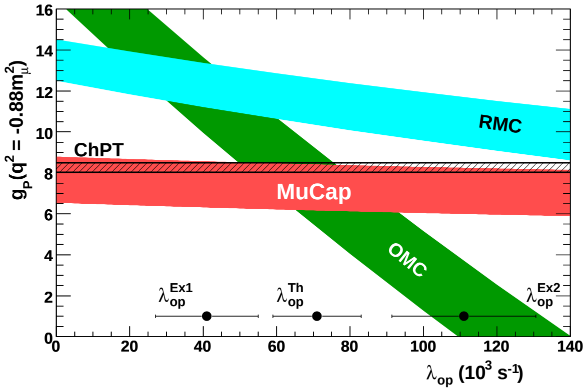

Figure 2: Experimental and theoretical determinations of g_P, presented vs. the ortho–para transition rate $\lambda_{\rm op}$ in the $pp\mu$ molecule. Previous experiments (OMC [14], RMC [15]) are inconclusive because their determination of g_P strongly depends on the poorly known ortho-para transition rate in muonic molecular hydrogen $\lambda_{\rm op}$. The first MuCap result supports precise theory (HBChPT) and is nearly independent of molecular effects.

$g_P = 8.26 \pm 0.23$ [8]. However, in spite of significant efforts, experiments remained largely inconclusive, owing to the imprecise knowledge of λ_{op}, the rate of conversion between the ortho- and para-$pp\mu$ states formed after muons are stopped in hydrogen. Because of the strong spin dependence of the V-A interaction, knowing the initial molecular state for the capture reaction is essential to extract g_P. As shown in Fig.2, mutually inconsistent theoretical predictions and experimental determinations of both λ_{op} and g_P prevailed before MuCap.

The MuCap collaboration has developed a novel experimental technique based on tracking the incoming muons in a time projection chamber (TPC) filled with ultra-pure deuterium-depleted hydrogen. The singlet capture rate Λ_S is determined from the difference between the measured disappearance rate of negative muons in hydrogen $\lambda_\mu^- \approx \lambda_\mu^+ + \Lambda_S$ and the μ^+ decay rate λ_μ^+. An initial experimental result was published [6], simultaneously with the new MuLan result [4] and a theoretical paper [13], which advanced the theory of electroweak radiative corrections to the required precision. MuCap reports a measurement of the capture rate $\Lambda_S = 725.0 \pm 13.7_{stat} \pm 10.7_{sys}$ s^{-1} and derives $g_P = 7.3 \pm 1.1$. The impact of this result is evident from Fig.2. The low gas density in MuCap makes the result much less model dependent, leading to a first precise and unambiguous determination of g_P, which is in agreement with the chiral prediction. During 2007 and 2008 the experiment completed the data taking phase. The final data set, which has 9 times higher statistics than the published data, was achieved by implementing a muon-on-request scheme. Several hardware upgrades significantly reduced the systematic uncertainties. These included an on-site H/D isotope separation system having unmatched performance worldwide and continuous hydrogen purification [16] to a level better than 10 ppb. The analysis of the full data set is expected to reduce the uncertainties by a factor of three compared to Ref. [6].

The MuSun Experiment. The MuSun experiment will measure the rate Λ_D for the $\mu + d$ capture process to a precision of better than 1.5%. This precision is required, to provide a definitive measurement of the low energy constant (called L_{1A} in the pion-less theory [11] and $\hat{d}^R$ in ChPT [10]) which integrates all the poorly constrained short-distance physics relevant for $\mu + d$ capture, as well as for solar pp fusion $p + p \to d + e^+ + \nu_e$ and for charged- and neutral current

$\nu + d$ scattering of solar neutrinos.

The new MuSun experiment will be about 10 times more precise in statistics and systematics than earlier measurements. Most importantly, it must be performed at conditions such that the experimental result leads to an unambiguous extraction of Λ_D independent of muonic atomic physics complications. At first, this seems a daunting task, as the muon kinetics in deuterium is more complex than in hydrogen. The transition between the upper $\mu d(\uparrow\uparrow)$ to the lower $\mu d(\uparrow\downarrow)$ hyperfine state is slow and, once a $dd\mu$ molecule is formed, nuclear dd fusion occurs at a time scale of nanoseconds (because of the process of muon-catalyzed fusion). In the MuSun proposal [3] it was demonstrated that these uncertainties are reduced to a negligible level at optimized target conditions of T = 30 K and 5% of liquid hydrogen density. While MuSun will use the same basic TPC and lifetime technique as MuCap, there are distinctive features demanded by physics. To achieve the required target condition, a new high-density cryogenic ionization chamber filled with ultra-pure deuterium will be developed. It will allow to define the muon stop, identify impurities, and observe muon-catalyzed reactions, which serve as an powerful monitor to prove that the muon kinetics is quantitatively understood. The new TPC must have improved energy resolution and full analog readout using FADCs to avoid systematic uncertainties in the muon stop definition and to detect the charged particles induced by fusion and impurity capture process. The 5-times higher target density of MuSun, compared with MuCap, implies that the chamber does not have internal gas gain and that drift voltages up to 100 kV are needed. Moreover, a complex cryo-system is being designed. The MuSun experiment has been approved recently and will have a first engineering run with a room temperature deuterium chamber in fall 2008.

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