

First results from the MuLan and MuCap experiments

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Abstract. MuLan and MuCap are ongoing experiments at the Paul Scherrer Institut, Switzerland, that use the muon lifetime to determine fundamental weak interaction parameters. The goal of MuLan is a 1 ppm measurement of the positive muon lifetime τ_{μ^+} to determine the Fermi constant G_F to 0.5 ppm. The goal of MuCap is to make a 1% determination of the rate Λ_S of the process of nuclear muon capture by the proton, $\mu p \rightarrow n\nu$, by measuring the μ^- disappearance rate in hydrogen gas to 10 ppm and subtracting the world average for the μ^+ decay rate. A 1% determination of the capture rate Λ_S is of interest because it would enable a 7% determination of g_P , the induced pseudoscalar coupling of the nucleon.

In 2007, both experiments published first results based upon data collected by each in 2004. MuLan reported an 11 ppm μ^+ lifetime measurement, $\tau_{\mu^+} = 2.197\,013(24)\,\mu\text{s}$, resulting in a new, 9.6 ppm world average, $\tau_{\mu^+} = 2.197\,019(21)\,\mu\text{s}$, which determines the Fermi constant, $G_F = 1.166\,371(6) \times 10^{-5}\,\text{GeV}^{-2}$, to 5 ppm. MuCap reported a 3% measurement of the muon capture rate from the hyperfine singlet ground state of the μp atom, $\Lambda_S = 725.0 \pm 17.4\,\text{s}^{-1}$, from which a 15% value for the pseudoscalar coupling, $g_P(q^2 = -0.88m_\mu^2) = 7.3 \pm 1.1$, was extracted.

Keywords: muon lifetime, Fermi constant, muon capture, pseudoscalar form factor

PACS: 14.60.Ef, 13.35.Bv, 13.60.-r, 11.40.Ha, 14.20.Dh, 23.40.-s

MULAN

The Fermi constant G_F describes the strength of the weak interaction and is one of the fundamental inputs to the Standard Model. The most precise way of determining G_F is from the mean life of the positive muon [1], τ_{μ^+} , where the two quantities are related by

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

For many years the dominant uncertainty in G_F came from higher-order QED corrections to τ_{μ^+} contained in Δq . In 1999, improvements in the calculation of second-order QED corrections [2] reduced the relative uncertainty in G_F due to theory to less than 0.3 ppm, making τ_{μ^+} the limiting factor. MuLan aims to determine G_F to a precision of 0.5 ppm by measuring τ_{μ^+} to 1 ppm, an order-of-magnitude improvement over the more than twenty-year-old existing world average.

The experimental design is simple in concept. Positive muons from the $\pi E3$ beamline at the Paul Scherrer Institut (PSI) are stopped in a thin disk of ArnokromeTM-III (AK-3), whose high internal magnetic field spins out any residual muon polarization. A cycle is imposed on the dc muon beam such that muons are accumulated in the ferromagnetic target for 5 μs , after which the beam is switched off for 22 μs of measurement. Positive muons are used because they can disappear only via the weak process of decay,

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu , \quad (2)$$

and the outgoing Michel positrons are detected by a soccer-ball-shaped array of scintillator panels surrounding the AK-3 target. An example of the resulting decay time spectrum is shown in Figure 1. In 2004, a total of 1.8×10^{10} μ^+ decay events were recorded in this manner. The exponential portion of the spectrum is fit with a function of the form $f(t) = \mathcal{F}(t)[Ne^{-t/\tau_{\mu^+}} + B]$, where $\mathcal{F}(t)$ is a relaxing sinusoidal function that describes timing shifts introduced by the TDC electronics.

The primary challenge in a high-statistics precision measurement such as MuLan lies in minimizing and controlling the systematics. In particular, when measuring the muon lifetime it is essential to avoid early-to-late changes which can arise from missed events (e.g. due to muon pileup and detector deadtime), shifts in detector properties (such as gain or threshold), and time-dependent variations in the spatial acceptance of decay electrons (e.g. due to muon spin rotation). Many of these effects are largely avoided by using an AK-3 target and a spherically symmetric detector. The largest sources of systematic uncertainty were the imperfect extinction of the muon beam during the “beam-off” measurement interval and errant muon stops in materials other than the AK-3 target. Electronics limitations contributed to a lesser extent.

The 2004 MuLan data set ultimately yielded an 11 ppm μ^+ lifetime measurement [3],

$$\tau_{\mu^+}^{\text{MuLan}} = 2.197\,013(21_{\text{stat}})(11_{\text{syst}})\,\mu\text{s} , \quad (3)$$

which is in agreement with the previous world average. At the time of its publication, this result contributed to

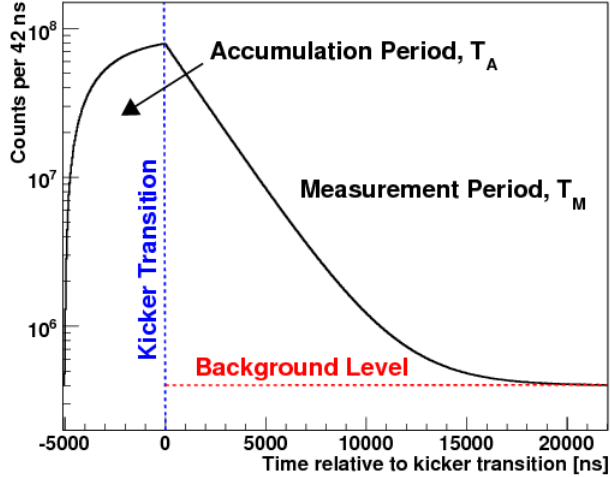


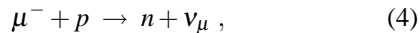
FIGURE 1. Data from a subset of the MuLan detectors, illustrating the the accumulation and measurement periods as well as the background from incomplete extinction of the muon beam.

a new 9.6 ppm world average, $\tau_{\mu^+} = 2.197\,019(21)\,\mu\text{s}$, which determines the Fermi constant to 5 ppm, $G_F = 1.166\,371(6) \times 10^{-5}\,\text{GeV}^{-2}$. Since then, a competing τ_{μ^+} measurement of 16 ppm precision has also been reported [4], altering the world average.

MuLan has now collected more than 10^{12} μ^+ decay events while using better electronics than in 2004. It is expected that the total uncertainty of τ_{μ^+} will be reduced by a factor of 10 from that in Equation 3, reaching the design goal.

MUCAP

The semileptonic weak process of ordinary muon capture (OMC) by the proton,



is of contemporary interest because its large, fixed momentum transfer ($q_0^2 = -0.88m_\mu^2$) makes it sensitive to the nucleon's induced pseudoscalar coupling g_P , which has long been the least well known of the nucleon's electroweak form factors [5]. Several experiments have previously attempted to determine g_P by measuring the muon capture rate in hydrogen, but their results lacked precision due to technical challenges and ambiguities in interpretation. In particular, the formation of muonic molecules in liquid hydrogen (LH_2) targets has presented problems, because muon capture proceeds at different rates in the ortho and para states of the $p\mu p$ molecule, while the ortho \rightarrow para transition rate λ_{op} is poorly known. As shown in Figure 2, the overall situation prior to the advent of MuCap was inconclusive, as there existed mutually inconsistent theoretical predictions and experimental determinations for both g_P

and λ_{op} . The modern low-energy effective QCD theory known as Heavy Baryon Chiral Perturbation Theory (HBChPT) makes relatively precise (3%) predictions for g_P , so an experimental determination of g_P of comparable precision would represent an important test of fundamental QCD symmetries.

In MuCap, negative muons are stopped in an ultra-clean, deuterium-depleted hydrogen gas target of density 1% of LH_2 . The low density inhibits the formation of $p\mu p$ molecules, and 96% of all muon captures proceed from the hyperfine singlet ground state of the μp atom, where the capture rate is predicted to be $\Lambda_S \approx 710\,\text{s}^{-1}$. Background from muon stops in detector materials is eliminated by reconstructing the muon stopping point in a time projection chamber (TPC) that operates in the hydrogen gas. This is a unique and critical capability, as the muon capture rate is determined using the lifetime technique—that is, from the very small (0.16%) difference between the measured disappearance rate $\lambda_{\mu^-} \approx \lambda_{\mu^+} + \Lambda_S$ of negative muons in hydrogen and the μ^+ decay rate $\lambda_{\mu^+} = 1/\tau_{\mu^+} \approx .455 \times 10^6\,\text{s}^{-1}$.

To measure the disappearance rate of stopped muons, the emission time and trajectory of decay electrons are also monitored. The time differences between muon arrivals and decay electron emissions, $\Delta t = t_e - t_\mu$, are histogrammed into lifetime spectra, which are fit with the exponential function $f(t) = N\lambda e^{-\lambda t} + B$, where the free parameters are the number of reconstructed decay events N , the disappearance rate λ , and the accidental background level B . The experimental μ^- lifetime is not a pure exponential, however, due to time-dependent contributions from $p\mu p$ molecules and small amounts of hydrogen gas impurities, both isotopic and elemental. These effects are sufficiently small that their perturba-

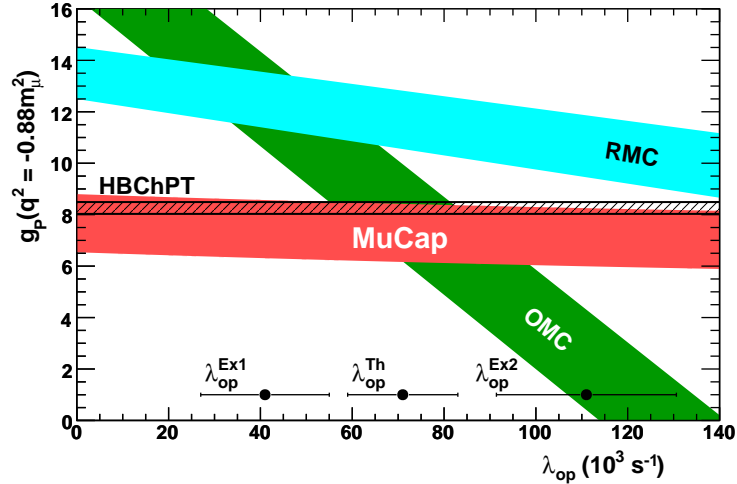


FIGURE 2. Experimental and theoretical determinations of g_p , presented vs. the ortho–para transition rate λ_{op} in the $p\mu p$ molecule. The most precise previous OMC experiment [6] and the lone radiative muon capture (RMC) experiment [7] both depend significantly on the value of λ_{op} , which itself is poorly known due to mutually inconsistent experimental ($\lambda_{op}^{\text{Ex1}}$ [8], $\lambda_{op}^{\text{Ex2}}$ [9]) and theoretical (λ_{op}^{Th} [10]) results. In contrast, the MuCap result for g_p is nearly independent of molecular effects.

tions to λ are linear and can be corrected in turn, using values in the literature and results from our own impurity-doped calibration runs.

In 2004, $N = 1.6 \times 10^9$ fully tracked μ^- decay events were recorded. After correcting for effects from target impurities and detector imperfections, the μ^- disappearance rate in pure hydrogen gas was found to be $\lambda_{\mu^-} = 455\,851.4 \pm 12.5_{\text{stat}} \pm 8.5_{\text{syst}} \text{ s}^{-1}$. Next, taking into account (i) the unavoidable but small amount of $p\mu p$ formation and (ii) a small shift to the muon decay rate in the bound μp system, and using the world average $\lambda_{\mu^+} = 455\,162.2 \pm 4.4 \text{ s}^{-1}$ [3], the muon capture rate from the μp singlet state was found to be [11]

$$\Lambda_S^{\text{MuCap}} = 725.0 \pm 13.7_{\text{stat}} \pm 10.7_{\text{syst}} \text{ s}^{-1}. \quad (5)$$

This 3% result is consistent with theoretical predictions for Λ_S that take recently calculated radiative corrections into account [12]. The result in Equation 5 determines the pseudoscalar coupling, $g_p(q_0^2) = 7.3 \pm 1.1$, to 7%.

The present information on g_p is summarized in Figure 2. The low gas density in MuCap renders the result relatively insensitive to λ_{op} and thus avoids most model dependence. Our result agrees with present theory to within 1σ and is consistent with the predictions of HBChPT.

Since 2004, roughly 1.5×10^{10} μ^- decay events have been collected in total. This data is expected to yield a more than twofold reduction in the statistical and systematic uncertainties, below the design goal.

ACKNOWLEDGMENTS

MuLan is supported in part by the U.S. Department of Energy (DOE) and the U.S. National Science Foundation (NSF). MuCap is supported in part by the U.S. DOE and Civilian Research and Development Foundation, the U.S. NSF, PSI, and the Russian Academy of Sciences.

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