First Results from the New Muon Lifetime Experiments at PSI

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Abstract

We survey a new generation of precision muon lifetime experiments at the Paul Scherrer Institute, and present their first results and plans for the future.

Key words: Muon lifetime, Axial nucleon structure, Form factor, Fermi Constant, TPC
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A new generation of precision muon lifetime experiments at the Paul Scherrer Institute has published initial results. The goal of the MuCap experiment[1] is the measurement of the muon capture rate on the proton Λ_S to 1%, using the difference between the observed disappearance rate in hydrogen $\lambda_\mu^- \approx \lambda_\mu^+ + \Lambda_S$ and the μ^+ decay rate λ_μ^+. The MuLan experiment[2] is a high precision μ^+ lifetime measurement with the final goal of improving the present knowledge of λ_μ^+ to 1 ppm, which would determine the Fermi Constant to 0.5 ppm.

1. MuCap Experiment

Muon capture on the proton, $\mu + p \to n + \nu$, is a fundamental weak interaction process. It is uniquely sensitive to the pseudoscalar form factor $g_P(q^2)$ at $q^2 = -0.88\, m_\mu^2$, which is the least-well-known of all form factors characterizing the QCD structure of the nucleon in charged current reactions. Advances in modern effective field theories allow the systematic calculation of $g_P = 8.26 \pm 0.23$. As this precise prediction follows from basic concepts of explicit and spontaneous chiral symmetry breaking, its experimental verification represents an important test of QCD symmetries. However, in spite of efforts spanning the last 40 years, the experimental situation remained inconclusive. Experiments lacked sufficient precision and could not be interpreted with confidence, as the

[1] representing the MuCap [1] and MuLan [2] collaborations

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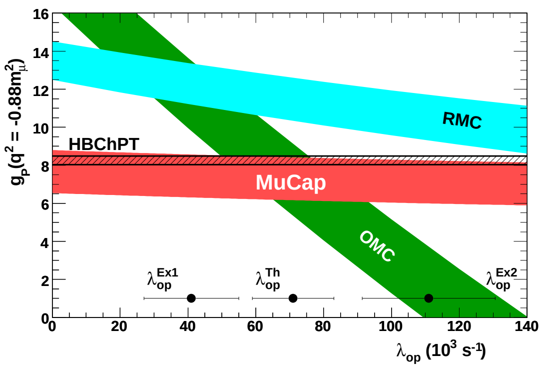

Fig. 1. Experimental and theoretical determinations of g_P, presented vs. the ortho–para transition rate $\lambda_{\rm op}$ in the $p\mu p$ molecule. The most precise previous ordinary muon capture (OMC) experiment at Saclay and the RMC experiment at TRIUMF both depend significantly on the value of $\lambda_{\rm op}$, which itself is poorly known due to mutually inconsistent experimental ($\lambda_{\rm op}^{\rm Ex1}$, $\lambda_{\rm op}^{\rm Ex2}$) and theoretical ($\lambda_{\rm op}^{\rm Th}$) results. In contrast, the MuCap result for g_P is nearly independent of molecular effects.

formation of muonic molecules in high-density LH_2 targets led to large uncertainties. A first measurement of radiative muon capture (RMC) on the proton suggested a value for g_P exceeding the chiral prediction by nearly 50% (c.f. reviews [3]).

The MuCap experiment has developed a novel technique based on a time projection chamber filled with ultra-pure hydrogen as an active target. This allows for a first precise measurement of muon capture in low-density gas, where the ambiguities in the interpretation of earlier experiments are largely avoided. An initial result[1] has just been released which clarifies the previously confusing landscape (Fig. 1). The MuCap result $g_P = 7.3 \pm 1.1$ agrees within 1σ with theory predictions, after updating them with the new calculation of radiative corrections[4]. The new measurement does not support a dramatic discrepancy to theory as the RMC result had initially implied. The experiment is ongoing, with improved systematics and nearly ten times higher statistics, and about three times reduced uncertainties are expected for the final result.

2. MuSun Project

Once the question of g_P is settled, the precision technique developed enables the study of the axial current in the 2-nucleon system with the process $\mu+d \to n+n+\nu$. A 1-percent measurement of $\mu + d$ capture would provide a benchmark result, an order of magnitude more precise than all present experiments on weak processes in the 2N system, and could impact reactions of astrophysical interest, like solar pp fusion and $\nu + d$ reactions observed by the SNO experiment. Recent EFT calculations have demonstrated, that, up to NNLO, all these reactions are related by a single axial two-body current term, parameterized by the low-energy constant L_{1A}. Muon capture can determine L_{1A} with precision and, in effect, will help "calibrate the sun." The question whether the $\mu + d$ process is soft enough to relate to low energy astrophysics weak reactions has been answered affirmatively by two theoretical studies[5]. Present experiments on μd capture are at the 10% precision level only, but MuCap has advanced the measurement techniques so that a tenfold improvement in precision is within reach. A first stage of the experiment will use the present set-up for an initial measurement and, potentially, for studying spin observables in $\mu + d$ capture for the first time. In order to control uncertainties due to the presence of μd atoms in two hyperfine states, an optimized final setup using a higher density, cryogenic TPC is being studied and a proposal is under preparation.

3. MuLan Experiment

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

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

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. In 1999 this problem was solved[6], which reduced the uncertainty in Δq from 30 ppm to less than 0.5 ppm. Thus the muon lifetime, known to 18 ppm, became the limiting factor to determine G_F.

The MuLan experiment is a precision measurement of τ_μ to 1 ppm. The design of the experiment is driven by the huge statistics requirement of 10^{12} recorded decay events as well as careful attention to systematics. A time-structured muon beam is cut out from the original DC beam by a fast electrostatic kicker and stopped in a target with internal or external magnetic field, resulting in a dephasing of the initial spin directions. During the measuring interval, the Michel positrons are recorded by a highly-segmented, symmetric detector, featuring 170 independent scintillator tile pairs. Each element is read out by a photomultiplier tube, whose signal is sampled at 450MHz by a custom-built waveform digitizer. The detector both minimizes and monitors the main systematic error sources related to pileup, muon spin precession, muon decays outside the fiducial volume of the detector, time dependence of detector gains or electronic thresholds, and backgrounds. A first analysis[2] of a limited data set results in $\tau_\mu = 2.197013(24)\mu s$. The new world average $\tau_\mu = 2.197019(21)\mu s$ determines the Fermi constant $G_F = 1.166371(6) \times 10^{-5} GeV^{-2}$ (5 ppm). The new result improves the precision of the τ_μ world average by a factor of two and demonstrates the viability of the new technique. Two orders of magnitude higher statistics have been collected in runs with two different targets (ferromagnetic alloy, quartz) and are currently being analyzed.

References

[1] V. A. Andreev et al., Phys. Rev. Lett. **99**, 032002 (2007).
[2] D. B. Chitwood et al., Phys. Rev. Lett. **99**, 032001 (2007).
[3] V. Berhard, L. Elouadrhiri, U.-G.Meissner , J.Phys. G **28**, R1 (2002); T. Gorringe and H. W. Fearing, Rev. Mod. Phys. **76**, 31 (2003).
[4] A. Czarnecki, W. J. Marciano and A. Sirlin, Phys. Rev. Lett. **99**, 032003 (2007).
[5] S. Ando, T. S. Park, K. Kubodera and F. Myhrer, Phys. Lett. B **533**, 25 (2002); J. W. Chen, T. Inoue, X. D. Ji and Y. D. Li, Phys. Rev. C **72**, 061001 (2005).
[6] T. van Ritbergen and R. G. Stuart, Nucl. Phys. B **564**, 343 (2000); Phys. Lett. B **437**, 201 (1998); Phys. Rev. Lett.**82**, 488 (1999).