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Muon Capture in Hydrogen - First MuCap Results and Future Plans

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Abstract. We survey a new generation of high precision experiments on muon capture in hydrogen and on the positive muon lifetime, performed at the Paul Scherrer Institute (PSI). First results and plans for the future are presented.

1 Introduction

A new generation of precision muon lifetime experiments at PSI has published initial results. The goal of the MuCap experiment [1] is the measurement of the muon capture rate Λ_S on the proton to 1%, using the difference between the observed μ^- disappearance rate in hydrogen $\lambda_\mu^- \approx \lambda_\mu^+ + \Lambda_S$ and the μ^+ decay rate λ_μ^+. For the future, the MuSun collaboration proposes to measure the rate for muon capture on the deuteron to 1%, to provide a benchmark result on weak processes in the two-nucleon system and to calibrate fundamental reactions of astrophysical interest. The MuLan experiment [2] is a high precision μ^+ lifetime to 1 ppm, which would determine the Fermi Constant G_F to 0.5 ppm and would significantly reduce the error contribution arising from λ_μ^+ to the muon capture determinations.

2 MuCap Experiment

Muon capture on the proton, $\mu + p \rightarrow n + \nu$, is a fundamental weak interaction process. Its rate Λ_S 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

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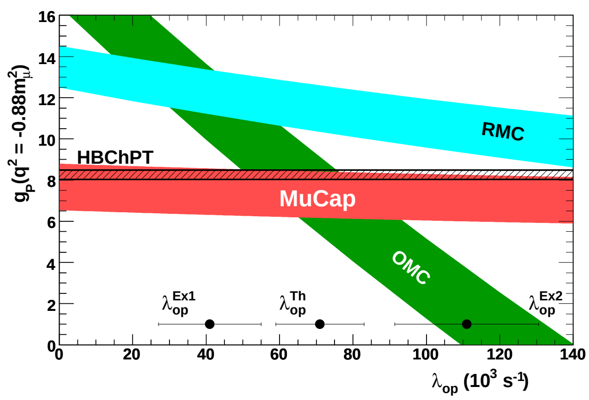

Figure 1. Experimental and theoretical determinations of g_P, presented vs. the ortho–para transition rate $\lambda_{\rm op}$ in the $p\mu p$ molecule. The most precise previous ordinary muon capture (OMC) experiment at Saclay and the RMC experiment at TRIUMF both depend significantly on the value of $\lambda_{\rm op}$, 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.

40 years, the experimental situation remained inconclusive. Experiments lacked sufficient precision and could not be interpreted with confidence, as the 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 experimental 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]. Thus MuCap 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.

3 MuSun Proposal

Once the question of g_P is settled, we plan to study the axial current interacting with the deuteron via the process $\mu + d \to n + n + \nu$. This reaction could be measured far more precisely than any other weak process in the 2-nucleon system for the foreseeable future. Such a benchmark is relevant for fundamental astrophysical processes, like solar pp fusion and $\nu + d$ reactions observed by the Sudbury Neutrino Observatory. 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}

and, in effect, will help to "calibrate the sun." The question, whether the $\mu + d$ process is soft enough to relate to the physics of low energy astrophysics weak reactions, has been answered affirmatively [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.

4 Positive Muon Lifetime Experiments

The Fermi Constant G_F is a fundamental constant of nature, which, together with α and M_Z, defines the gauge couplings of the electroweak sector of the standard model. It is directly related to the free muon decay rate, but, in the past, the extraction of G_F from λ_μ^+ was limited by unknown 2-loop radiative corrections. With those calculated [6], the muon lifetime, known to 18 ppm, became the limiting factor. The MuLan experiment is a high precision measurement of $\tau_\mu = \frac{1}{\lambda_\mu^+}$. A time-structured muon beam is generated by a fast electrostatic kicker and stopped in a target with internal or external magnetic field, to control the initial muon polarization. During the beam off period positrons are recorded by a highly-segmented, symmetric detector. A first publication [2] on a limited data set gives τ_μ(MuLan) = 2.197013(24) 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). Soon afterward, the FAST experiment [7] also released a new result τ_μ(FAST) = 2.197083(35) μs. The next major step is to improve the precision to 1 ppm. MuLan has already collected the required two orders of magnitude higher statistics, which is currently being analyzed.

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