Measurement of Muon Capture on the Proton

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Abstract. The goal of the μCap experiment is a 1% precision measurement of the muon capture reaction on the free proton. This determines directly the weak pseudoscalar form factor g_P to 7%. At the end of 2004, the μCap detector was completed and commissioned and first physics data were taken. The analysis of these data is in an advanced stage. The muon capture rate will be determined to 3%, translating to a measurement of g_P to 20%. Improvements to the detector, towards reaching the design goal, were made for the 2005 and present 2006 data runs.

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The μCap experiment will determine the rate of muon capture on the free proton to 1% precision by measuring the lifetimes of μ^- and μ^+ in isotopically pure hydrogen gas. The branching ratio of ordinary capture, $\mu^- + p \to \nu_\mu + n$, is 10^{-3} compared to muon decay, $\mu^- \to \nu_\mu + e^- + \overline{\nu}_e$; since μ^+ does not disappear via the former reaction, the difference of inverse lifetimes of μ^+ and μ^- is the μ^- capture rate. Target conditions are such that the state of the μp system at capture is well known, and connection to theory is unambiguous.

Muon capture proceeds via the electroweak charged-current interaction. While the lepton current is simply $\langle \mu | 1 - \gamma_5 | \nu \rangle$, the QCD structure of hadrons requires introduction of form factors in the nucleon current,

$$\langle n | g_V(q^2)\gamma_\alpha + \frac{i g_M(q^2)}{2M_N}\sigma_{\alpha\beta}q^\beta - g_A(q^2)\gamma_\alpha\gamma_5 - \frac{g_P(q^2)}{m_\mu}q_\alpha\gamma_5 | p \rangle,$$

where second class currents, zero in the standard model, are omitted. The values of g_V, g_M, and g_A, from data and standard model symmetries, together contribute $< 0.3\%$ to the error of the capture rate on the free proton. The pseudoscalar form factor, g_P, is precisely predicted by chiral perturbation theory, yet the experimental situation is controversial and dependent on a poorly known, mu-molecular kinetic parameter (see reference [2]). As shown in figure 1, the μCap experiment will yield an unambiguous, precise measurement of g_P.

The μCap detector consists of muon detectors for timing and tracking incident muons to their stop positions in the target volume, and electron detectors for timing and tracking of decay electrons. In the context of what happens when a μ^- is stopped in hydrogen, some key features of the experiment are explained below.

- *Atomic Formation.* The μ^- slows, forms a μp atom, and cascades to the ground state, all within 1 ns. The μp atom, a neutral object ≈ 200 times smaller than regular hydrogen, quickly transitions to the $F = 0$ hyperfine state given sufficient target density.

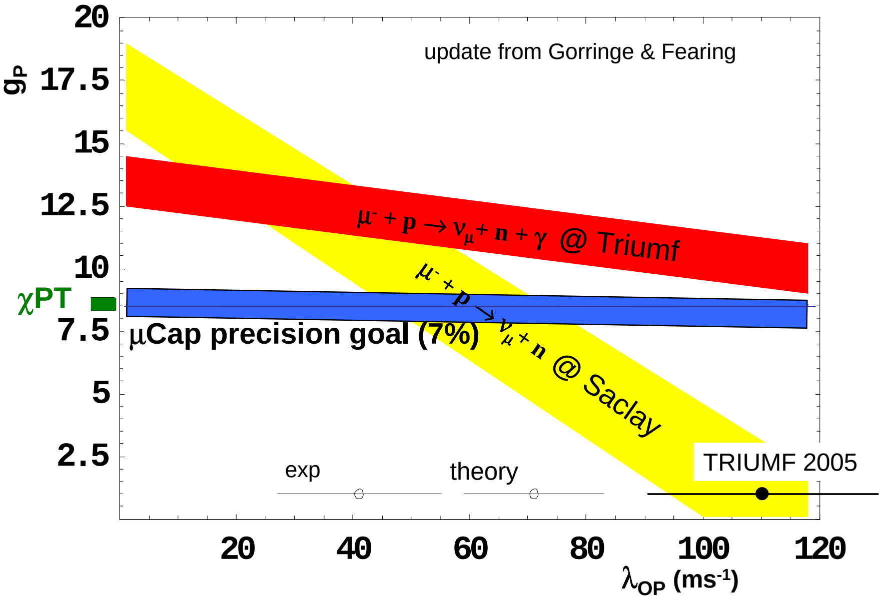

FIGURE 1. Allowed values of the weak pseudoscaler form factor, $g_P(q^2 = -0.88m_\mu)$, from the results of past experiments assuming different values of a μ-molecular kinetic parameter, λ_{OP}. The precise prediction for g_p, from chiral perturbation theory, is indicated by the small box to the left of the vertical axis. The light-blue band, placed arbitrarily at the height of the χPT prediction, shows the precision goal of the present experiment and the weak dependence of the g_P extraction on λ_{OP}.

- *Molecular Formation.* Ortho pμp molecules form with a rate proportional to density, and these transition to the para-molecular state with rate λ_{OP} (horizontal axis of figure 1). In experiments with liquid H_2 targets, capture takes place dominantly from the molecular state. At μCap target conditions (1% liquid density), most capture events take place from the singlet atomic state; thus the connection with g_P is unambiguous.
- *μZ Formation.* These must be eliminated to a high level because of the much higher capture rate compared to the proton ($\Lambda_{cap} \sim Z^4$). The μCap design eliminates impurity captures to a high level in the following ways:
  1. *Wall Stops.* The central μCap detector is a Time Projection Chamber (TPC) operating on the target gas itself. Each muon is tracked to its stop position, and only those within a fiducial volume are accepted.
  2. *Transfer to Gas Impurity.* The target gas is continuously circulated through cryogenic absorbers to maintain a very high level of chemical purity. Also, impurity capture events make a signal in the TPC, allowing *in situ* impurity concentration monitoring.
  3. *Transfer to Deuterium, then Diffusion.* The μd atom in a protium sea has a Ramsauer-Townsend scattering minimum, such that the μd can diffuse $\sim$ 10 cm during the μ lifetime (compare to $\sim$ 1 mm for μp diffusion). This effect is controlled by using deuterium-depleted hydrogen for the main data, followed

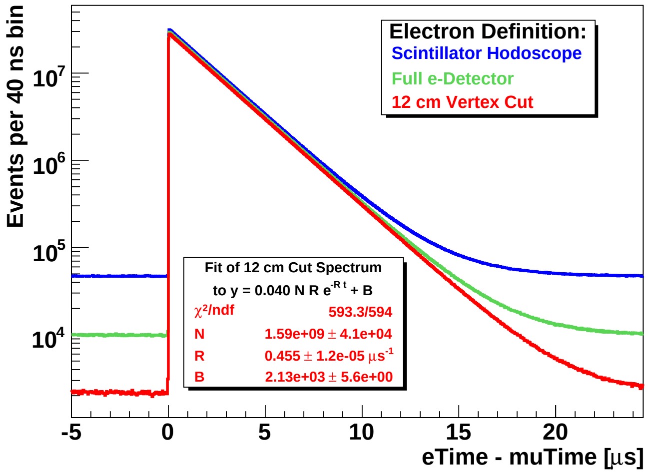

FIGURE 2. μCap first physics data (2004): Lifetime spectra of μ^- in ultrapure, deuterium-depleted hydrogen. The three curves are from the same data set but using different combinations of electron detectors. The clock is detuned by $\sim 10^{-3}$, the precise value blinded.

by calibration data at higher deuterium concentration and zero extrapolation of the μ^- lifetime result.

Significant milestones were reached in the past two years of μCap running.

- 2004: The continuous hydrogen ultrapurification system was commissioned. First physics data were taken, and analysis of these is in an advanced stage (see figure 2). Λ_S will be determined to 3%, giving g_P to about 20%.
- 2005: The μLan beam kicker was installed and operated in muon-on-request mode, increasing the good event rate by a factor of 3.
- 2006: An isotope separation column was commissioned, reducing the deuterium concentration of the target gas to < 60 ppb. 7.8×10^9 good μ^--e^- events were accumulated, which combined with the 2005 data gives the full 10^{10} events of the design goal. μ^+ statistics are still needed.

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