EPJ Web of Conferences **66**, 05018 (2014)
DOI: 10.1051/epjconf/20146605018

Final results of μp capture rate Λ_S and pseudoscalar coupling g_P

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Abstract. We present the final results of muon capture on proton $\mu^- + p \rightarrow \nu_\mu + n$, which were obtained by the MuCap Collaboration at the Paul Scherrer Institute. The singlet μp capture rate Λ_S is determined as the difference between the lifetimes of μp and μ^+. Our result is $\Lambda_S^{MuCap} = 714.9 \pm 5.4_{stat} \pm 5.1_{syst}$ s^{-1} in excellent agreement with the prediction of chiral perturbation theory $\Lambda_S^{CHPT} = 712.7 \pm 4.3$ s^{-1}. The induced pseudoscalar coupling constant results as $g_P^{MuCap} = 8.06 \pm 0.48_{exp} \pm 0.28_{th}$ whereas $g_P^{CHPT} = 8.26 \pm 0.23$.

1 Introduction

The MuCap collaboration has now concluded a big and long lasting effort to determine the induced pseudoscalar coupling constant (electro-weak form factor) g_P, by a precision measurement of the nuclear muon capture rate Λ_S on proton

$$\mu^- + p \rightarrow \nu_\mu + n \qquad (1)$$

in the singlet μp system [1]. The theoretical interest is given by the fact that g_P is by far the least known of the electro-weak coupling constants. On the other hand, g_P has been precisely predicted by chiral perturbation theory [2] as

$$g_P^{CHPT}(q^2) = (2\, m_\mu\, g_{\pi NN}\, F_\pi)/(m_\pi^2 - q^2) - 1/3\, g_A(0)\, m_\mu\, M\, r_A^2 = 8.26 \pm 0.23. \qquad (2)$$

MuCap's aim was a 1% measurement of Λ_S which determines g_P^{exp} to a precision of 6%. The measurement of the μp capture rate is the only enough sensitive method to reach such a precision. Experimentally, we had to overcome a number of big challenges which have nullified several previous efforts to reach the anticipated precision:

- the end products of reaction (1) are n and ν: the neutrino escapes, while as far as the neutrons are concerned, it is technically too difficult to achieve 1% accuracies in direct rate measurements. Therefore, MuCap chose the lifetime method, i.e. a high precision measurement of the μp lifetime $\tau_{\mu p}$ which is compared with the μ^+ lifetime $\tau_{\mu+}$. The difference of the inverse lifetimes just yields the capture rate
$$\Lambda_S = \tau_{\mu p}^{-1} - \tau_{\mu+}^{-1}. \qquad (3)$$
- meso-molecular physics of muons in hydrogen. μp atoms in collisions with H_2 molecules form pμp mesic molecules which exist in ortho and para states, each with very different capture probabilities. There is a transition rate λ_{op} between these states which is badly known (the "ortho-para" problem [3]). MuCap avoided this problem by using hydrogen gas at low density (~1% of liquid H_2) where pμp formation occurs at a sufficiently small probability.

- clean muon stops. Each muon must be verified with ~99.999% certainty to stop in hydrogen, because stops in surrounding materials with higher Z distort the lifetime measurement due to much larger capture rates. MuCap developed a time projection chamber (TPC) to record the track of every muon [4].
- highest purity hydrogen gas. μp atoms colliding with nuclei of impurities get quickly transferred and captured with much larger rates, thus distorting the muon decay curve. MuCap developed a special circulation and purification system [5] to keep the gas clean.
- isotopically pure hydrogen (protium). Collisional transfers $\mu p + d \rightarrow \mu d + p$ lead also to distortions of the lifetime distribution, because μd atoms can diffuse out of the sensitive TPC volume (Ramsauer-Townsend effect). MuCap constructed a special isotope separation column which cleaned the gas to isotopic purities with concentrations $c_p < 7$ ppb.
- high data rate. To reach the anticipated precision, more than 10^{10} single good muon decay events within a ±25μs period had to be collected. This statistics was achieved with the muon kicker from the MuLan experiment [6]. It allowed to kick single muons into the target without pile-up from other μ. This method increased the data collection rate by a factor 2 to 3.

2 MuCap apparatus

The central part of the MuCap apparatus is the TPC shown in Fig. 1. It was specially developed for this experiment [4] and is made from UHV compatible materials (metals, ceramics) which could be baked up to 130 C and led to extremely low outgasing rates. In addition the protium gas was continuously circulated at 10 bar and purified by a system using thermodynamical cycles [5]. During the main runs we determined impurity levels (mostly water) below 20 ppb.

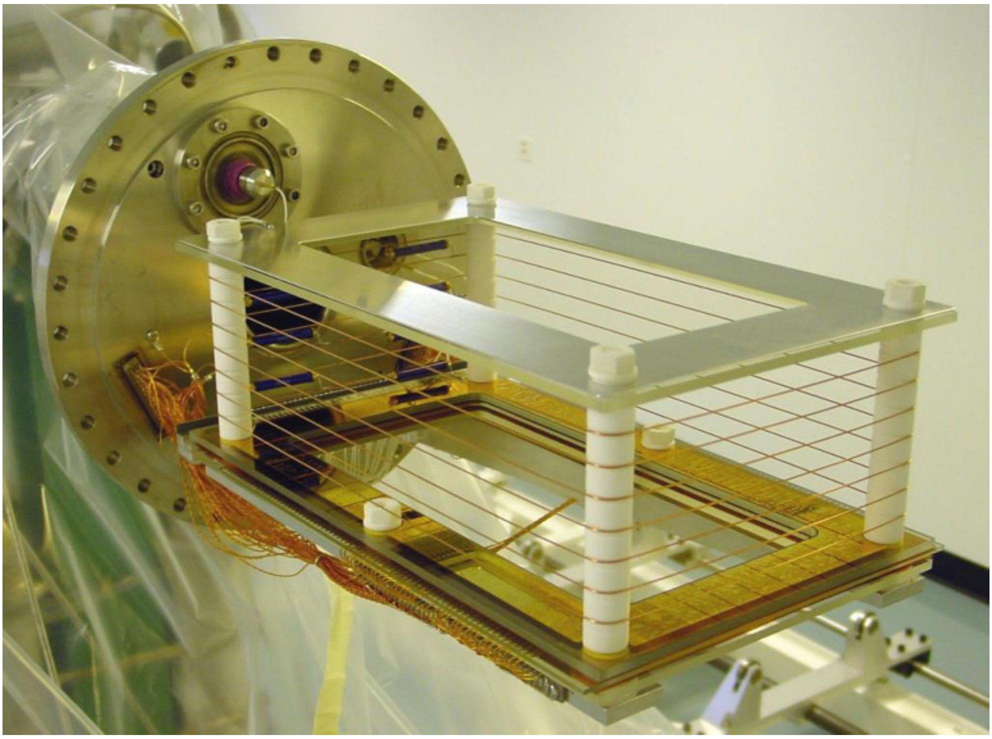

Figure 1. The MuCap Hydrogen TPC acting simultaneously as muon stop detector and active target. Sensitive volume 30x15cm^2 with 12 cm vertical drift space. Gas filling 10 bar ultra-purified, deuterium-depleted hydrogen at 300 K. Electrical field 2 kV/cm. Drift time velocity of electrons 5.5 mm/μs. Two-dimensional readout by a MWPC at the bottom. 3D reconstruction of muon tracks by measurement of the drift time.

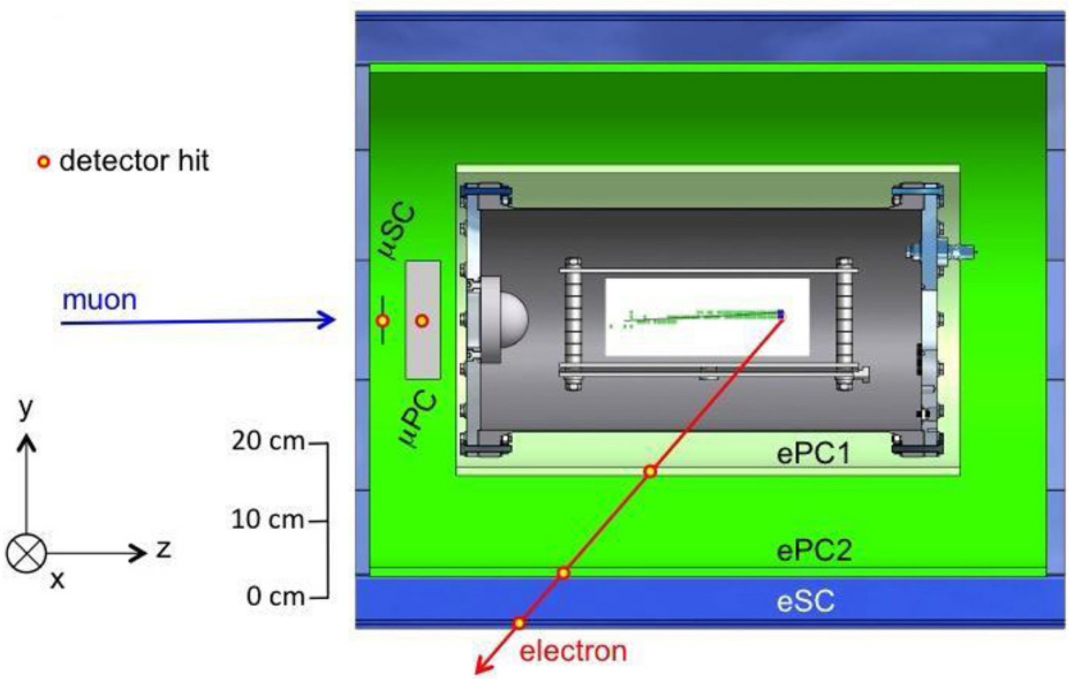

Figure 2. Cross-sectional view of the MuCap apparatus showing a typical muon stop and decay electron. Muon identification by scintillator μSC, wire chamber μPC and the track in the TPC showing the Bragg peak. Electron identification by cylindrical wire chambers ePC1, ePC2 and double scintillator hodoscope eSC.

Fig. 2 shows a cross-section of the full MuCap apparatus with illustration of a typical event. Every muon was tracked individually to its stopping point. The electrons were tracked back to the muon stop location. Thanks to fiducial cuts, background from accidental electrons was suppressed to the 10^{-4} level.

3 Final results

During three independent production runs we have collected $1.2 \cdot 10^{10}$ fully reconstructed μ^- decays plus $0.6 \cdot 10^{10}$ μ^+ decays for systematic controls. The final results of lifetime fits and systematics are summarized in Table 1. The systematic corrections include distortion effects due to impurities,

Table 1. Final numbers of μp lifetime fits, correction factors and capture rates

	run-2004 (Ref. [7])	run-2006	run-2007	units
statistics	$1.6 \cdot 10^9$	$5.5 \cdot 10^9$	$5.0 \cdot 10^9$	events after cuts
systematic corrections	-32.1 ± 8.4	-23.3 ± 5.2	-14.7 ± 3.9	s^{-1}
$\lambda_\mu = 1 / \tau_\mu$ (μp lifetime)	455’851.4 ± 15.1	455’857.3 ± 9.3	455’853.1 ± 9.1	s^{-1}
$\Delta\Lambda_{p\mu p}$ correction	19.8 ± 1.9	17.7 ± 1.9	17.7 ± 1.9	s^{-1}
Λ_S (singlet μp capture rate)	713.4 ± 15.2	717.3 ± 9.5	713.1 ± 9.4	s^{-1}

removal of μp scatter events, μp and μd diffusion, uncertainties of fiducial volume cuts, inefficiencies and electron track definitions. For more details we refer to Ref. [1].

Averaging these data and using the μ^+ decay constant measured by the MuLan experiment [6], $\lambda_{\mu+} = 455'170.05 \pm 0.46\ s^{-1}$, we obtain our final singlet muon capture rate on proton

$$\Lambda_S^{MUCAP} = 714.9 \pm 5.4_{stat} \pm 5.1_{sys}\ s^{-1}\ , \quad (4)$$

which is in excellent agreement with theory $\Lambda_S^{CHPT} = 712.7 \pm 4.3\ s^{-1}$.
From Λ_S^{MUCAP} we deduct [1]

$$g_P^{MUCAP} = 8.06 \pm 0.48_{exp} \pm 0.28_{th} \quad (5)$$

also in excellent agreement with chiral perturbation theory $g_P^{CHPT} = 8.26 \pm 0.23$. Fig. 3 shows g_P values as function of the poorly known transition rate λ_{op} of pμp molecules (ortho-para problem). In contrast to earlier experiments which were carried out using liquid hydrogen, the MuCap experiment is rather insensitive to λ_{op} which solves finally this longstanding problem.

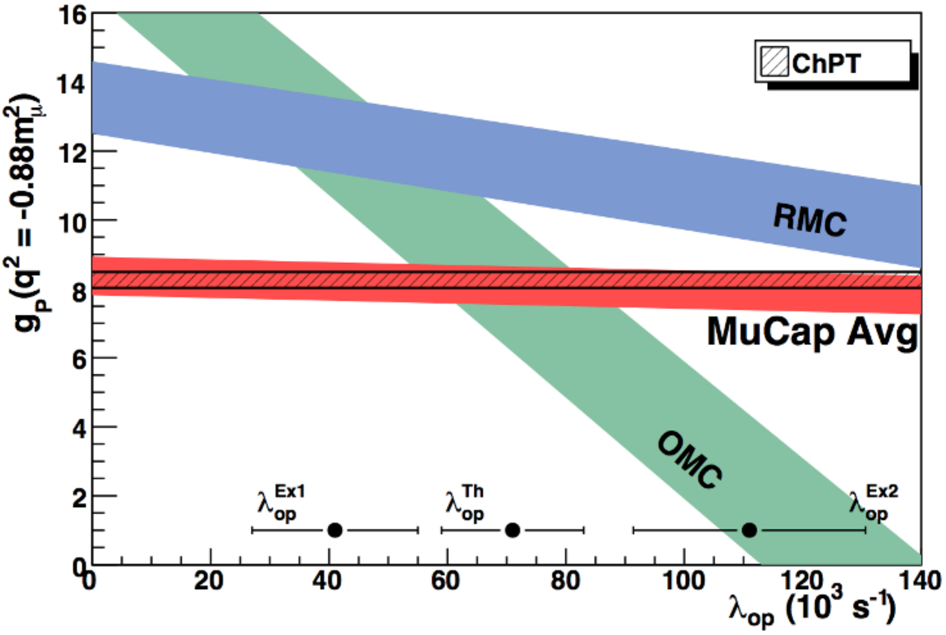

Figure 3. Extracted values for g_P as a function of the poorly known molecular transition rate λ_{op}. OMC = Saclay experiment [8], RMC = TRIUMF experiment [9]. Also shown are results of two inconsistent λ_{op} measurements (Ex1 from Saclay, Ex2 from TRIUMF), and the theoretical calculation λ_{op}^{Th} by the Ponomarev group [10].

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