PRECISION MEASUREMENT OF THE RATE OF MUON CAPTURE IN HYDROGEN GAS AND DETERMINATION OF THE PROTON'S PSEUDOSCALAR COUPLING g_P

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1. Introduction

Here we report the first result of the MuCap experiment for the rate Λ_S of the semileptonic weak process of the ordinary muon capture (OMC) by the proton from the singlet ground state of the $\mu^- p$ atom:

$$(\mu^- p)_{1S} \to n + \nu_\mu , \quad BR = 0.16\% . \tag{1}$$

In the framework of the Standard Model, this reaction is parameterized by six induced form factors g_V, g_M, g_A, g_P, g_S, g_T evaluated at the relevant value of the four-momentum transfer $q_c^2 = -0.88\ m_\mu^2$, where m_μ is the muon mass. The second-class (scalar and tensor) form factors g_S and g_T vanish in the limit of exact *G*-parity invariance. The other three form factors $g_V(q_c^2)$, $g_M(q_c^2)$, $g_A(q_c^2)$ are accurately determined by experimental data and Standard Model symmetries. According to the conserved vector current (CVC) theorem, the vector and magnetic form factors $g_V(q^2)$ and $g_M(q^2)$ are identical to corresponding electromagnetic form factors which are determined by the nucleon magnetic moments and by the *ep*-scattering data:

$$g_V(q_c^2) = 0.976 \pm 0.001, \quad g_M(q_c^{\ 2}) = 3.583 \pm 0.003.$$

The axial form factor $g_A(0)$ is determined from the neutron β-decay, and its extrapolation to $q^2 = q_c^2$ can be done using νN-scattering data (Congleton and Truhlik, 1996)

$$g_A(q_c^2) = -1.245 \pm 0.004.$$

The neutron beta decay is sensitive only to the $g_V(0)$ and $g_A(0)$ form factors. On the contrary, due to its larger momentum transfer $q_c^2 = -0.88\ m_\mu^2$, the muon capture reaction (1) is also sensitive to the magnetic and pseudoscalar form factors $g_M(q_c^2)$ and $g_P(q_c^2)$ which vanish at $q^2 \to 0$. That is why the OMC reaction (1) is considered as a source of information on the pseudoscalar form factor $g_P(q_c^2)$. In particular, $g_P(q_c^2)$ can be obtained from measurements of the muon capture rate Λ_S from the 1*S* ground state of the $\mu^- p$ atom. One should point out, however, that such measurements should be very accurate as a 1% error in Λ_S results in a 6.5% error in $g_P(q_c^2)$. In principle, $g_P(q_c^2)$ could be measured also in the radiative muon capture (RMC) reaction

$$\mu^- + p \to n + \nu_\mu + \gamma, \quad BR = 10^{-8}. \tag{2}$$

Though the sensitivity of the RMC rate to $g_P(q^2)$ is by a factor of 3 higher than in OMC, however the RMC studies are complicated by the very low branching ratio and some difficulties in interpretation of the experimental data.

The form factor $g_P(q_c^2)$ arises mainly from the coupling of the weak leptonic current to the nucleon via an intermediate pion, which generates a pole term that dominates at q_c^2. Early theoretical expressions for $g_P(q_c^2)$

were derived using current algebra techniques; now $g_P(q_c^2)$ can be systematically calculated within the heavy baryon chiral perturbation theory (HBChPT) up to two-loop order. The precise QCD result $g_P(q_c^2) = 8.26 \pm 0.23$ (V. Bernard *et al.*, 2002) follows from the basic concepts of explicit and spontaneous chiral symmetry breaking, and thus its experimental confirmation is an important test of the QCD symmetries. The observed deviation of the experimental data on $g_P(q_c^2)$ from the theoretical prediction might be also an indication of the "new physics" beyond the Standard Model.

Experimental OMC efforts span a period of more than forty years, and more recently one RMC experiment was performed at TRIUMF (Joukmans *et al.*, 1996). However, as shown in Fig. 1, the situation prior to the present experiment was inconclusive, as the results lacked sufficient precision due to ambiguities in the interpretation as well as to technical challenges.

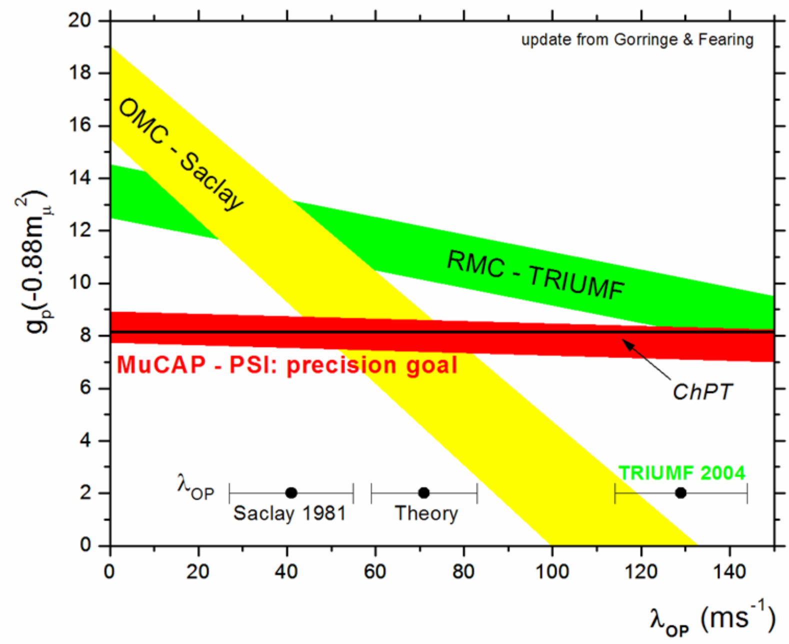

Fig. 1. Experimental and theoretical determinations of $g_P(q_c^2)$ presented *vs* the ortho-para transition rate λ_{op} in the $p\mu p$ molecule. The most precise previous OMC experiment (Saclay, 1981) and the RMC experiment (TRIUMF, 1996) both depend significantly on the value of λ_{op}, which itself is poorly known due to mutually inconsistent experimental (λ_{op}^{Ex1}, λ_{op}^{Ex2}) and theoretical (λ_{op}^{Th}) results. In contrast, the MuCap result for $g_P(q_c^2)$ is nearly independent of molecular effects

Table 1 presents the experimental data on the OMC rates available prior to our experiment. Two experimental methods were applied to measure the OMC rate:

- detection of neutrons from the reaction (1);
- lifetime measurements of μ^- in hydrogen by detecting electrons from the muon decay, $\mu^- \to e^- + \nu_\mu + \tilde{\nu}_e$.

A serious limitation of the neutron detection method is an inevitable uncertainty in determination of the neutron detector efficiency. This leads to an error in measurements of muon capture rates $\delta\Lambda_c/\Lambda_c \geq 9\%$ that corresponds to too high error (≥60%) in the determination of $g_P(q_c^2)$. The lifetime method has no such limitations. In this method, the muon capture rate is determined by the difference between the measured μ^- lifetime in hydrogen, τ_μ^-, and the known μ^+ lifetime, τ_μ^+, assuming that free μ^- and μ^+ decay with identical rates according to the *CPT* theorem. The contribution of the muon capture rate to the total muon disappearance rate being quite small (0.16%), this requires very high precision in measurements of τ_μ^-. For example, in order to reach ~1% precision in determination of the muon capture rate, one should measure τ_μ^- with a precision of $\Delta\tau_\mu^-/\tau_\mu^- \approx 10^{-5}$. This method was used in the Saclay experiment resulting in the most precise measurement of the OMC rate (Table 1). Unfortunately, this experiment was performed with a liquid hydrogen target where unambiguous derivation of $g_P(q_c^2)$ from the measured τ_μ^- was not possible.

Table 1

Status of $p\mu$-capture measurements prior to MuCap experiment

Year	Exptl. place	H_2-target	$\Lambda_c \pm \delta\Lambda_c$, s^{-1}	$\delta\Lambda_c/\Lambda_c$	Method
1962	Chicago	liquid	428±85	20%	neutron detection
1962	Columbia	liquid	515±85	17%	-“-
1962	CERN	liquid	450±50	11%	-“-
1963	Columbia	liquid	464±42	9%	-“-
1969	CERN	gas, 8 atm	651±57	9%	-“-
1974	Dubna	gas, 41 atm	686±88	13%	-“-
1981	Saclay	liquid	460±20	4.5%	lifetime measurement
1981	Saclay	liquid	531±33*)	6%	-“-

*) corrected for ortho-para transitions in the $pp\mu$ molecule

The problems of interpretation of the experimental data can be explained by considering the chain of reactions (Fig. 2) possible for negative muons after stopping in a hydrogen target of density ϕ relative to liquid hydrogen (LH_2). Stopped muons immediately form ground state μp atoms whose hyperfine states are populated in a statistical manner.

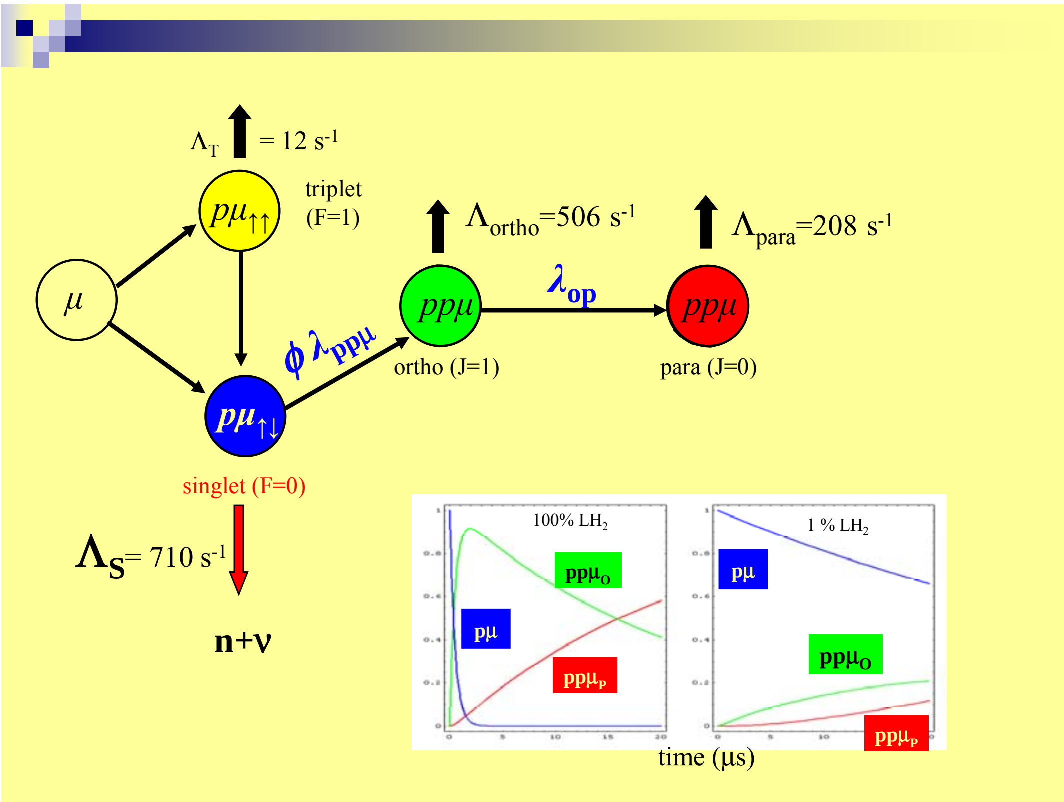

Fig. 2. Scheme of reaction after stopping of negative muons in a hydrogen target. Panels in the right-down corner show percentage of the muon captures from various molecular states for two target densities (LH_2 and 0.01 LH_2) in function of time after the muon stop

The upper triplet spin state is rapidly depopulated in collisions with H_2 molecules, and for densities $\phi \geq 0.01$ all muons reach the μp singlet state 1S well before 100 ns. From there, muons can either decay with a rate close to $\lambda_\mu^+ \equiv 1/\tau_\mu^+ \approx 0.455 \times 10^6$ s^{-1} or be captured *via* reaction (1) at the predicted rate $\Lambda_S \approx 710$ s^{-1}. Complications arise at higher densities, however, as the μp atoms increasingly collide with target H_2 molecules to form $p\mu p$ molecules. The $p\mu p$ molecules are initially created in the ortho state at the density-dependent rate $\phi \cdot \lambda_{of}$, where $\lambda_{of} \approx 2.3 \times 10^6$ s^{-1}, and then de-excite to the para state at rate λ_{op}. The nuclear capture rates from the ortho and para states, $\Lambda_{om} \approx 506$ s^{-1} and $\Lambda_{pm} \approx 208$ s^{-1} are quite different from each other and from Λ_S, so knowledge of the relative populations of the μp and $p\mu p$ states is crucial for a correct determination of $g_P(q_c^2)$. Alas, λ_{op} is poorly known. The available experimental and theoretical data are mutually inconsistent. This prevents a clear interpretation of the Saclay OMC experiment which was performed on LH_2 target where muon capture occurs predominantly in $p\mu p$ molecules (Fig. 1).

The RMC process is less sensitive to λ_{op}, but it difficult to draw firm conclusions from the RMC experiment, whose results suggested a nearly 50% higher value for $g_P(q_c^2)$ than predicted (Fig. 1).

2. Strategy of the MuCap experiment

The MuCap experiment employs a new experimental method, first suggested at PNPI [1], aimed to avoid the described above problems. The main features of this method are as follows.

- The capture rate is determined by measuring the μ^- lifetime in ultra-clean deuterium-depleted hydrogen gas at relatively low density $\phi \approx 0.01$, where the formation of $p\mu p$ molecules is slow and 96% of all captures proceed from the μp singlet state. The hydrogen contamination by impurities with Z > 1 should be on a level of $C_Z \leq 10^{-8}$ to avoid the muon disappearance due to capture by these impurities. The concentration of deuterium in hydrogen should be $C_d \leq 10^{-6}$ to prevent the formation of $d\mu$ atoms which could diffuse far from the muon stop.
- The muons are detected in an active target consisting of a hydrogen time projection chamber (TPC) which determines the muon stopping point well isolated of all materials of the chamber [1]. The trajectory and the emission time of the muon decay electrons are measured with an external detector. The space-time correlation of the muon stops and the electron trajectory serves to reduce the accidental background. TPC also provides a self-control for presence of $Z > 1$ impurities on a level of 10^{-8} by detecting recoil nuclei from the μZ capture.
- The high intensity muon beam in combination with fast read out electronics enables collection of the required statistics (~ 10^{10} events) for reasonable running time to provide measurements of the muon capture rate Λ_S with a precision of 10^{-5} or better.

The experiment was planned to be carried out at a muon beam at the Meson Factory of Paul Scherrer Institute. The proposal was presented and approved with the high priority in 1997 [2]. The first physics run was performed in 2004. Then measurements were going on in 2005, 2006 and 2007 with continuous improvements of the experimental setup and the muon beam line. This report contains the results of analysis of the 2004 data set. The analysis of the data obtained in 2005–2007 runs will require some more time.

3. The MuCap experimental setup

The MuCap experiment was conducted in the πE3 beam line at Paul Scherrer Institute, using *a* ≈20 kHz DC muon beam tuned to a central momentum of 32.6 MeV/c. As illustrated in Fig. 3, incident muons first traverse a plastic scintillator (μSC) and a multiwire proportional chamber (μPC), and then pass through a 0.5-mm-thick hemispherical beryllium window to enter an aluminum pressure vessel filled with ultra-pure, deuterium-depleted hydrogen gas at a pressure of 1.00 MPa and at ambient room temperature. In the center of the vessel is the TPC (sensitive volume $15 \times 12 \times 28$ cm^3), which tracks incoming muon trajectories and thus enables the selection of muons that stop in the gas at least 15 mm away from chamber materials. Approximately 65% of the muons passing through the μSC stop within this fiducial volume. The ionization electrons produced by incoming muons drift downwards at velocity 5.5 mm/μs at applied field of 2 kV/cm, towards a multiwire proportional chamber containing perpendicular anode and cathode wires. The anode plane consists of wires with 25 μm diameter and 4 mm spacing, and a high voltage of 5.0 kV across the 3.5 mm half-gaps provides a moderate gas gain of ~100 in hydrogen. Digital signals from three-level discriminators are recorded, with the energy thresholds adjusted to trigger on (i) the fast muons, (ii) the Bragg peaks near the muon stopping points and (iii) the larger energies that may be deposited by recoiling nuclei following muon capture by gas impurities.

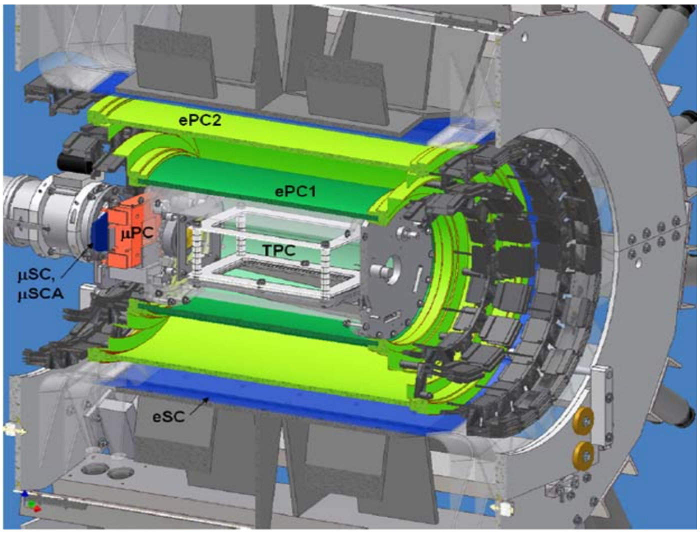

Fig. 3. Simplified cross-sectional diagram of the MuCap detector. The detector components are described in the text

The TPC is surrounded by two cylindrical wire chambers (*e*PC1, *e*PC2), each containing anode wires and inner/outer cathode strips, and by a hodoscope barrel (*e*SC) consisting of 16 segments with two layers of 5-mm-thick plastic scintillator. This tracking system detects outgoing decay electrons with 3π solid angle acceptance. All data are recorded in a trigger-less, quasi-continuous mode to avoid dead time distortions to the lifetime spectra. Custom-built time-to-digital converters (TDCs) digitize hit times for the TPC and the electron wire chambers. The muon and electron times t_μ and t_e are established by the μSC and *e*SC detectors, and recorded in separate CAEN V767 TDC modules. Figure 4 shows a general view of the MuCap experimental setup.

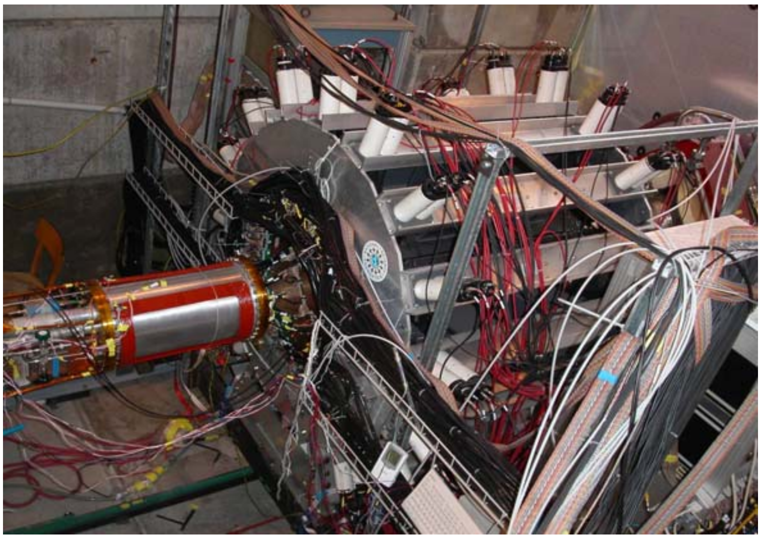

Fig. 4. General view of the MuCap experimental setup

4. Purity of hydrogen gas in TPC

All TPC materials were carefully selected for high vacuum operation. Prior to the run, the TPC system was heated to 115°C under vacuum for several weeks to remove impurities. The system was filled with deuterium-depleted hydrogen through a palladium filter. However, these precautions were not enough to provide the high gas purity during the run. It was found that, due to outgasing of the TPC materials, the impurity concentration (N_2, H_2O) increased in time with the rate of $dC_Z/dt = 10^{-7}$ per day. Therefore, a special gas circulation/purification system was designed and constructed at PNPI [3], and implemented into the MuCap setup. During data taking, the gas was continuously circulated *via* an adsorption cryopump system and cleaned by cooled Zeolite filters, which achieved an equilibrium concentration of $C_Z < 5 \times 10^{-8}$, as monitored by direct TPC detection of recoil nuclei from muon capture by impurities. The primary contaminant was H_2O outgasing, while concentration of N_2 was below 10^{-8}, as shown by gas chromatography measurements.

The isotopic purity of the hydrogen is critical. Muons preferentially transfer from μp to μd at the rate $\phi \cdot C_d \cdot \lambda_{pd}$, where C_d is the deuterium concentration and $\lambda_{pd} \approx 1.4 \times 10^{10}$ s^{-1}. Whereas the μp diffusion is of the order of mm, μd atoms can diffuse cm-scale distances due to a Ramsauer-Townsend minimum in the $\mu d + p$ elastic scattering cross section. As a result, the μd atoms can drift sufficiently far away from the muon's original stopping point so that the decay event will be rejected by the μ-e vertex reconstruction cut in a time-dependent manner. In addition, the μd atoms can drift into surrounding materials and be captured there. Our target gas was produced *via* electrolysis of deuterium-depleted water, provided by Ontario Power Generation Company (Canada). The accelerator mass spectrometry (AMS) analysis of this gas determined that $C_d = (1.44 \pm 0.13) \times 10^{-6}$, roughly 100 times below deuterium's natural abundance. This was the best deuterium-depleted hydrogen available on market, and it was used in our 2004 and 2005 runs. Later, a new cryogenic isotopic exchange column was designed and constructed at PNPI [4], which was able to reduce the deuterium concentration in hydrogen down to $C_d < 0.06 \times 10^{-6}$. This highly deuterium-depleted hydrogen was used in our 2006 run.

5. Measurements and results

The time differences between muon arrivals and decay electron emission, $\Delta t = t_e - t_\mu$, are histogrammed into lifetime spectra (Fig. 5). Only muons that are separated in time by ± 25 μs from other muon arrivals are accepted. While this condition reduces considerably the usable statistics, it is essential for avoiding ambiguities in resolving multiple muon tracks in the TPC. Note, that this pile up protection was not needed in our 2006 run when the so-called "muon-on-request" facility was put into operation on the muon beam at PSI. This facility deflected the muon beam for a requested time as soon as a signal on the muon stop in the TPC was registered. Implementation of this method in our experiment allowed to increase the data taking rate by a factor of 3 and also helped to reduce the background. As shown in Fig. 4, the background suppression can be improved by performing a vertex cut on the impact parameter between each decay electron's trajectory and its parent muon's stopping point. In the final analysis of the 2004 run data we employ a loose impact parameter cut of 120 mm as an optimal compromise between the competing demands for a good signal-to-background ratio and minimization of losses due to μd diffusion out of the cut volume.

We fit μ^- lifetime spectra with a simple exponential function $f(t) = N \cdot \omega \cdot \lambda \cdot e^{-\lambda t} + B$, where the free parameters are the number of reconstructed decay events N, the disappearance rate λ, and the accidental background level B; ω is the fixed 40 ns histogram bin width. The typical time range was 0.1–24 μs. The result was stable under variation of different cuts with typically χ^2/dof = 0.95–1.02 for 600 degrees of freedom. The main corrections to λ were derived directly from experimental data, with some additional information from external measurements and literature. These corrections are summarized in Table 2.

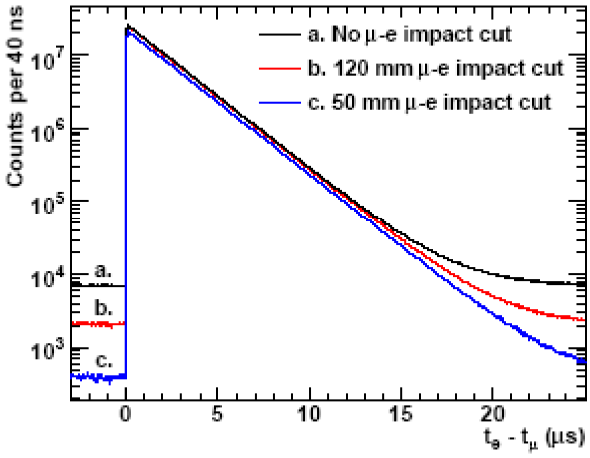

Fig. 5. Lifetime spectra of negative muons. The signal-to-background rate is improves with tighter cuts on the *μ-e* vertex

Table 2

Systematic corrections and uncertainties applied to the observed μ^- disappearance rate λ

Source	Correction, s^{-1}	Uncertainty, s^{-1}
$Z > 1$ impurities	−19.2	5.0
μd diffusion	−10.2	1.6
μp diffusion	−2.7	0.5
$\mu + p$ scattering		3.0
μ pileup veto efficiency		3.0
Analysis methods		5.0
Total	−32.1	8.5

The final result for the μ^- disappearance rate in pure hydrogen, based on $N = 1.6 \times 10^9$ fully tracked, pileup-protected decay events from our 2004 data set, is $\lambda_\mu^- = 455851.4 \pm 12.5_{stat} \pm 8.5_{syst}$ s^{-1}. As a consistency check, we also measured the μ^+ decay rate from $N = 0.5 \times 10^9$ events to be $\lambda_\mu^+ = 455164 \pm 28$ s^{-1}, in agreement with the world average.

The observed μ^- disappearance rate can be written as

$$\lambda_\mu^- = (\lambda_\mu^+ + \Delta\lambda_{\mu p}) + \Lambda_S + \Delta\Lambda_{p\mu p} . \quad (2)$$

Here $\Delta\lambda_{\mu p} = -12.3$ s^{-1} describes a small reduction in the muon decay rate in the bound μp system (H.C. von Baeyer and D. Leiter, 1979). The term $\Delta\Lambda_{p\mu p} = -23.5 \pm 4.3 \pm 3.9$ s^{-1} accounts for captures from $p\mu p$ molecules and is calculated from the full μ^- kinetics in pure hydrogen. Its error terms come from our estimates $\lambda_{of} = (2.3 \pm 0.5) \times 10^6$ s^{-1} and $\lambda_{op} = (6.9 \pm 4.3) \times 10^4$ s^{-1}, respectively, which cover most of the existing literature values. Using the new world average $\lambda_\mu^+ = 455162.2 \pm 4.4$ s^{-1} (μLAN experiment, to be published), we determine the rate of muon capture by the proton to be

$$\Lambda_S^{MuCap} = 725.0 \pm 13.7_{stat} \pm 10.7_{syst}\ s^{-1} . \quad (3)$$

To compare with theory we consider the two recent NNLO calculations of Λ_S: 687.4 s^{-1} (V.Bernard *et al.*, 2001) and 695 s^{-1} (S. Ando *et a*l., 2000) here are averaged to 691.2 s^{-1}. Adding the very recently calculated radiative correction $\Delta_R = 19.4$ s^{-1} (A. Czarnecki, W.J. Marciano, A. Sirlin, to be published) increased from $\Delta_R = 4.5$ s^{-1} (M.R. Goldman, 1972) yields the value $\Lambda_S^{\mathrm{Th}} = 710.6$ s^{-1} and enables us to calculate

$$g_P^{\mathrm{MuCap}}(q_c^2) = g_P^{\mathrm{Th}}(q_c^2) + (dg_P/d\Lambda_S)(\Lambda_S^{\mathrm{MuCap}} - \Lambda_S^{\mathrm{Th}}) = 7.3 \pm 1.1\,, \qquad (4)$$

where $g_P^{\mathrm{Th}}(q_c^2) = 8.26$ (V. Bernard *et al.*, 2002), $dg_P/d\Lambda_S = -0.065$ s (J. Govaerts and J.L. Lucio-Martinez, 2000), and only experimental uncertainty from Eq. (3) is propagated. The linear expansion in Eq. (4) is valid because of the small difference $\Lambda_S^{\mathrm{MuCap}} - \Lambda_S^{\mathrm{Th}}$.

The current information on $g_P(q_c^2)$ is summarized in Fig. 1; the constraints (T. Gorringe and H.W. Fearing, 2004) from the Saclay OMC experiment (G. Bardin *et al.*, 1981) are updated to reflect the larger Δ_R. The situation before the MuCap experiment was inconclusive and exhibited mutually inconsistent theoretical predictions and experimental determinations of both $g_P(q_c^2)$ and λ_{op}. The low gas density in the MuCap experiment renders our result relatively insensitive to λ_{op} and thus avoids most model dependence, enabling us to report the first unambiguous, precise determination of $g_P(q_c^2)$. This experimental result agrees with present theory to within 1σ and does not support a dramatic deviation from the chiral prediction as the RMC result originally had implied.

6. Conclusion

We should point out that analyzed up to now the 2004 data set constitutes only 10% of the statistics collected in the 2004–2007 runs. Moreover, the 2006 and 2007 runs, besides the largest statistics, had other important advantages (reduced deuterium concentration, $C_d < 0.06$ ppm, and the "muon-on-request" mode) which should help to reduce the background and possible systematic errors. So one could expect that the presented in this report error in $g_P(q_c^2)$ will be reduced by a factor of three in the final analysis of all MuCap data.

Earlier, in 1998, we have studied the muon capture on ^{3}He [5]. The muon capture rate in the channel $\mu^- + {}^3\mathrm{He} \rightarrow {}^3\mathrm{H} + \nu_\mu$ was measured with a high precision: $\Lambda_c = 1496.0 \pm 4.0$ s^{-1}. This result have been used in some theoretical analyses (T. Gorringe and H.W. Fearing, 2004) for deriving the proton's pseudoscalar coupling $g_P(q_c^2)$. They applied the microscopic theory based on impulse approximation supplemented by explicit calculations of the meson exchange corrections. Their result was $g_P(q_c^2) = 8.77 \pm 1.58$. Though this result was considered as the best measurement at that time, however, it is model-dependent, its precision depends to a large extent on calculations of the meson exchange corrections. Now one can reverse the task, using our direct measurement of $g_P(q_c^2)$, to control various aspects of the microscopic theory of μ^3He capture.

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