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Precision Measurement of the Singlet Muon Capture Rate on the Proton at PSI

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MuCap, the negative muon capture by a proton, is the first experiment which will unambiguously determine the induced pseudoscalar form factor of the proton, $g_{\rm P}$. While contradictory experimental results for $g_{\rm P}$ are under discussion, a theoretical calculations on the percent level within the framework of Chiral Perturbation Theory are now challenging the measurements. We will describe our experimental efforts and latest achievements.

The $V-A$ description of weak interactions has been tested to a high precision. Processes involving structureless fermions, e.g., muon decay, show equal vector (V) and axial-vector (A) coupling. Lorentz invariance constrains the corresponding weak current matrix elements to six independent terms,

$$\begin{aligned} V_\mu &= G_V(q^2)\gamma_\mu - \frac{iG_M(q^2)}{2m_N}\sigma_{\mu\nu}q^\nu + \frac{G_S(q^2)}{m_\mu}q_\mu \\ A_\mu &= G_A(q^2)\gamma_\mu\gamma_5 + \frac{G_P(q^2)}{m_\mu}\gamma_5 q_\mu + z\frac{iG_T(q^2)}{2m_N}\sigma_{\mu\nu}q^\nu\gamma_5 \ , \end{aligned} \tag{1}$$

with corresponding weak form factors G_i, mass of the nucleon m_N, and muon m_μ. Because of G-symmetry G_S and G_T vanish [2]. Due to the momentum dependence, only G_A and G_V contribute in β-decay at very low q^2. Nuclear muon capture is the process most sensitive to G_P. Therefore, $G_P(-0.88m_\mu^2)$ is dubbed induced pseudoscalar coupling constant $g_{\rm P}$. While the values of G_V, G_A, and G_M are established on the 10^{-3} to 10^{-4} level [3], the situation is totally different for the induced pseudoscalar $g_{\rm P}$.

The theoretical view, historically based on PCAC and pion pole dominance, and recently strictly derived within chiral perturbation theory (χPT) [4], is remarkably precise:

$$\begin{aligned} G_P(q^2) &= \frac{2m_\mu g_{\pi NN}F_\pi}{m_\pi^2 - q^2} - \frac{1}{3c^2\hbar^2}G_A(0)m_\mu m_N r_A^2 \ , \\ g_{\rm P} &= (8.74 \pm 0.23) - (0.48 \pm 0.02) = 8.23 \pm 0.23 \ , \end{aligned} \tag{2}$$

depending on the exact values of the pion-nucleon coupling constant $g_{\pi NN}$ and the mean axial radius of the nucleon r_A. The Standard Model based calculation of the singlet muon capture rate [5] has reached 0.55% precision. Such a measurement will also set tight limits on various theoretical scenarios beyond the Standard Model.

The present experimental knowledge of $g_{\rm P}$ is unsatisfying, and discrepancies cause considerable debate. Determinations via ordinary muon capture in hydrogen (OMC) [6], ^{3}He [7], and larger nuclei essentially confirm the theory result. However the precision of the latter is troubled by model dependencies. A radiative muon capture on the proton (RMC) experiment [8] yielded a different result. The present most likely explanation lies in the insufficient knowledge of the complex kinetics of negative muons in hydrogen [9]. Figure 1 shows the λ_{OP} dependence of the OMC and RMC results. The controversial λ_{OP} values are also shown. Two experimental values from Saclay [10] and TRIUMF [11], which were obtained together within the same experiments performing the OMC and RMC measurements, strongly disagree, and the only theoretical calculation [12] does not clarify the situation. Clearly only a new determination of $g_{\rm P}$ independent of λ_{OP} can resolve this situation.

The experimental principle of the MuCap (**Mu**on **Cap**ture) experiment is based on

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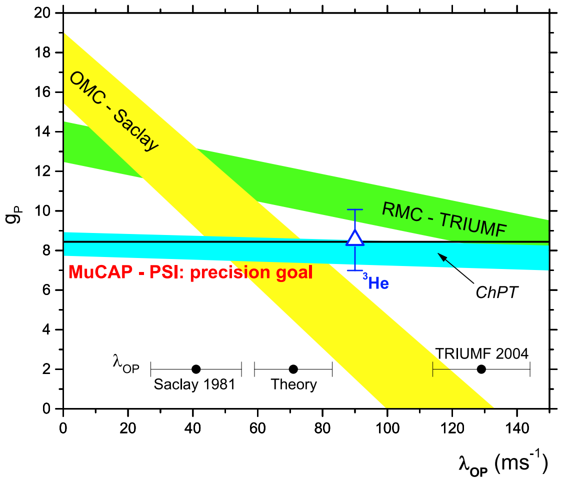

Figure 1. *Present knowledge of g_P: The OMC [6] and RMC [8] results are shown together with the error goal for MuCap plotted at the PCAC value. The blue triangle shows the ^{3}He result [7] at an arbitrary λ_{OP} value. The line shows the calculation from Ref. [4]. The λ_{OP} values from experiments [10,11] and theory [12] are indicated on the bottom.*

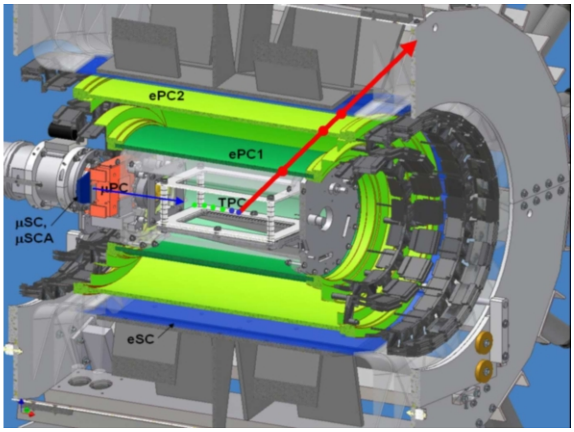

Figure 2. *Schematic view of the detectors showing the muon entering (blue arrow), hitting the scintillator and a small wire chamber which serves as additional pile-up counter, and then stopping in the TPC. The muon stop position is detected via a high signal caused by the Bragg peak (blue) after a track of low signals (green). The decay electron (red) is observed in 2 cylindrical wire chambers (ePC1/2) for track reconstruction. Outside is a doubled-layered scintillator hodoscope (eSC) with readout at both paddle ends, which records the decay time.*

the measurement and comparison of the decay time of positive and negative muons in hydrogen. The MuCap experiment is designed to overcome the multiple difficult problems of previous experiments. The important conceptual advantage of MuCap is the selection of target hydrogen at gaseous density (10 b at RT), which minimizes the kinetics dependence of the result on g_P. At low densities, muon capture occurs almost exclusively from the singlet state on the proton, and even a large estimated error on λ_{OP} results only in a systematic error on the 10 ppm level. The full setup is shown in Fig.2. The active gaseous hydrogen target, a TPC, allows for a full 3-dimensional reconstruction of the muon path to its stopping point and therefore a selection of clean muon stops away from walls and wires.

The TPC also detects muon capture events on impurity atoms ($Z > 1$) via the very large signals generated from capture products. Thus the TPC serves also as a very sensitive impurity monitor. The high rates of muon transfer to and nuclear capture on high-Z atoms can cause a deflection of the exponential lifetime even at very low impurity concentrations as these rates are typically orders of magnitude higher than muon decay. In order to minimize this effect, target purity requirements are very stringent, with the goal to be on the 10^{-8} contamination level. Consequently, the hydrogen gas is filled via a Pd filter and continuously run through a purification system. The CHUPS system [13] is specifically designed to maintain the hydrogen flow with negligible variations in density or hence in TPC gain. In fall 2004 we maintained clean target conditions ($\sim$ 70 ppb impurities) for over 5 weeks.

MuCap fully separates the muon and electron detectors to avoid dangerous cross-correlations. Decay electron times are measured in the scintillator hodoscope (eSC) surrounding the hydrogen vessel. Two cylindrical wire chambers track the electron back in 3-D to its μ-stop origin, thus largely reducing the background.

The impact parameter, defined as the minimal distance between detected muon stop and electron track, serves as an important handle on a

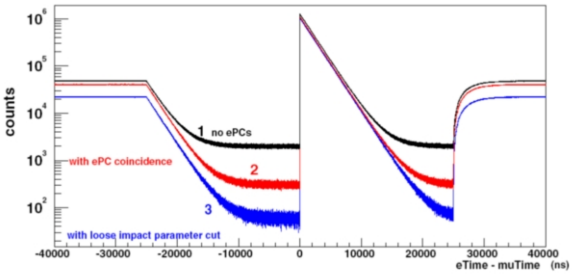

Figure 3. *Preliminary muon lifetime spectrum obtained with μ^- from the fall 2004 run. The three curves show the benefits of the decay electron detection by the two wire chambers. Curve 1 is obtained with requirement of a clean pileup-free muon stop in the TPC and a four-fold eSC coincidence hit. Curve 2 requires a time coincident hit in both ePC1 and ePC2. Curve 3 additionally tracks the observed electron and requires less than 10 cm impact parameter (approximately the sensitive TPC volume). The huge reduction in background is obvious. The necessary $\pm 25\,\mu s$ pileup veto is responsible for the background's shape.*

very subtle systematic effect on the lifetime: the diffusion of muons which transfer to deuterium, an isotope always present in hydrogen. Although we are using special deuterium-depleted hydrogen ($c_d \sim 1.5$ ppm), this deuterium concentration is still high enough to cause a visible effect in our setup via electron tracks with dislocated origin. Eventually MuCap needs 10^{10} cleanly observed decay electrons and positrons to statistically reach the goal of 1 % in the capture rate, reflecting 10 ppm in the respective muon lifetimes. This is possible in several weeks of running in the fully pile-up protected mode.

Figure 3 shows a preliminary lifetime plot from our fall 2004 data. One can clearly see the huge improvement in background reduction due to the implementation of the two cylindrical wire chambers. The shown $\sim 2 \times 10^9$ "clean" μ decay events are presently being analyzed, and a first result on g_P is expected in late 2005.

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REFERENCES

1. **MuCap Collaboration:** D. Chitwood, S.M. Clayton, P.T. Debevec, D.W. Hertzog, P. Kammel, B. Kiburg, R. McNabb, F. Mulhauser, C.J.G. Onderwater, C.S. Özben, and D. Webber *(University of Illinois at Urbana-Champaign)*; T.I. Banks, K.M. Crowe, F.E. Gray, and B. Lauss (*University of California, Berkeley and LBNL)*; R.M. Carey and J. Paley *(Boston University)*; T. Gorringe, M. Ojha, and P. Zolnierzcuk (University of Kentucky); L. Bonnet, J. Deutsch, J. Govaerts, D. Michotte, and R. Prieels (Université Catholique de Louvain); F.J. Hartmann (Technische Universität München); P.U. Dick, A. Dijksman, J. Egger, D. Fahrni, M. Hildebrandt, A. Hofer, L. Meier, C. Petitjean, and R. Schmidt (Paul Scherrer Institute); V.A. Andreev, B. Besymjannykh, A.A. Fetisov, V.A. Ganzha, V.I. Jatsoura, P. Kravtsov, A.G. Krivshich, E.M. Maev, O.E. Maev, G.E. Petrov, S. Sadetsky, G.N. Schapkin, G.G. Semenchuk, M. Soroka, V. Trofimov, A. Vasiliev, A.A. Vorobyov, and M. Vznuzdaev (Petersburg Nuclear Physics Institute); *http://www.npl.uiuc.edu/exp/mucapture/*
2. S. Weinberg, Phys. Rev. **112** (1958) 1375.
3. S. Eidelmann *et al.*, Phys. Lett. B **592** (2004) 1.
4. V. Bernard, L. Elouadrhiri, U.-G. Meissner, J. Phys. G **28** (2002) R1.
5. J. Govaerts and J.-L. Lucio-Martinez, Nucl. Phys. A **678** (2000) 110.
6. G. Bardin *et al.*, Nucl. Phys. A **352** (1981) 365.
7. P. Ackerbauer *et al.*, Phys. Lett. B **417** (1998) 224.
8. G. Jonkmans *et al.*, Phys. Rev. Lett. **77** (1996) 4512.
9. B. Lauss, Proc. Int. Workshop on Exotic Atoms - EXA05, to be published.
10. G. Bardin *et al.*, Phys. Lett. B **104** (1981) 320.
11. D. Armstrong *et al.*, Private Communication.

12. D.D. Bakalov *et al.*, Nucl. Phys. A **384** (1982) 302.
13. A. Vasilyev *et al.*, Proc. "NHA Annual Hydrogen Conference 2005", Washington DC, USA, March 2005.