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, $g_P$. While contradictory experimental results for $g_P$ 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,

$$V_\mu = G_V(q^2)\gamma_\mu - \frac{iG_M(q^2)}{2m_N}q^\nu \sigma_{\nu\mu} + \frac{G_S(q^2)}{m_\mu}q_\mu$$

$$A_\mu = G_A(q^2)\gamma_\mu\gamma_5 + \frac{G_P(q^2)}{m_\mu}q_\mu + z^2G_T(q^2)\sigma_{\mu\nu}q^\nu\gamma_5,$$

(1)

with corresponding weak form factors $G_i$, mass of the nucleon $m_N$, and muon $m_\mu$. Because of G-symmetry $G_S$ and $G_T$ vanish [2]. Due to the momentum dependence, only $G_A$ and $G_V$ contribute in $\beta$-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 $g_P$. 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 $g_P$.

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

$$G_P(q^2) = \frac{2m_\mu g_{\pi NN}F_\pi}{m_\pi^2 - q^2} - \frac{1}{3c^2h^2}G_A(0)m_\mu m_N r_A^2,$$

gp = (8.74 \pm 0.23) - (0.48 \pm 0.02) = 8.23 \pm 0.23,

(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 $g_P$ 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 $\lambda_{OP}$ dependence of the OMC and RMC results. The controversial $\lambda_{OP}$ 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 $g_P$ independent of $\lambda_{OP}$ can resolve this situation.

The experimental principle of the MuCap (Muon Capture) experiment is based on
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 $\lambda_{OP}$ 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 $\mu$-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 $\mu^-$ 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.

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” $\mu$ decay events are presently being analyzed, and a first result on $g_\mu$ is expected in late 2005.

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REFERENCES


