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High precision measurement of the muon capture rate on the proton and determination of the pseudoscalar coupling G_p

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Abstract. The goal of the MuCap experiment was a high precision measurement of the ordinary capture (OMC) rate Λ_S from the ground state of $p\mu$-atoms:

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

The experiment was designed for 1% precision measurement, thus improving the existing world data of Λ_S by an order of magnitude. This gives a possibility to determine the unknown nucleon pseudoscalar form factor G_P. The experiment was carried out by international collaboration of scientists from Russia, Switzerland, USA, and Belgium. The MuCap experiment was performed in the high intensity muon beam of the "meson factory" of Paul Scherrer Institute (PSI, Switzerland) using the experimental method developed at PNPI NRC "Kurchatov institute.

INTRODUCTION

In the limit of isospin symmetry, the V-A structure of the electroweak interaction on the nucleon level can be described by introducing four form factors: G_V, G_M, G_A, and G_P.

$$V_\alpha = G_V(q^2)\gamma_\alpha + \frac{iG_M(q^2)}{2M_N}\sigma_{\alpha\beta}q^\beta \tag{2}$$

$$A_\alpha = G_A(q^2)\gamma_\alpha\gamma_5 + \frac{G_P(q^2)}{m_\mu}q_\alpha\gamma_5 \tag{3}$$

Three of them, G_V, G_M and G_A, were determined by available experimental data, while the pseudoscalar form factor G_P remained practically unknown in spite of the efforts of experimentalists during the five previous decades. On the other hand, the value of g_P is predicted by the Chiral Perturbation Theory. Therefore, a precision measurement of g_P has an additional motivation as a crucial test of this theory. Measurement of the muon capture rate on the proton is a unique way to determine the value of G_P. The relatively large transfer momentum makes muon capture, contrary to neutron beta decay, sensitive to G_P. However, this sensitivity is rather limited: 1% precision measurement of the muon capture rate determines G_P with only 6% precision. Therefore, to be scientifically valuable, the muon capture rate should be measured with at least 1% precision. There is also a strict requirement to the experimental conditions: the observed muon capture should occur in a well defined μp atomic state to avoid controversial interpretation of the experimental data. All previous studies of the μp capture rate were unable to satisfy these requirements. That is why the results of previous experiments allowed G_P values ranging from 2 to 14.

Strategy and experimental set-up of the MuCap experiment

New experimental method developed by the MuCap collaboration made it possible to measure with high precision the muon capture rate Λ_S from the $1S$ singlet state of the μp atom. The strategy of the experiment was to measure with 10^{-5} precision the disappearance rate of μ^- stopped in ultra-pure 10-bar pressure hydrogen (protium) and to compare it with the decay rate of free positive muons μ^+ known at present with 10^{-6} precision. The disappearance rate is determined by measuring the time distribution of muon decay electrons. The relatively low hydrogen gas pressure guaranties that the muon capture occurs predominantly from the 1S state of the $p\mu$ atom. The ultra-high chemical and isotopic purity of the protium gas ($1{\cdot}10^{-8}$ content for overall chemical impurities and $6{\cdot}10^{-9}$ content for HD molecules) prevents from other muon disappearance channels (muon capture on impurities, diffusion of $d\mu$ atoms). The apparatus consisted of an active hydrogen gas target (a Time Projection Chamber (TPC)) which registered every single muon stop, and a surrounding electron detector (two sets of cylindrical wire chambers (ePC1, ePC2) and a plastic counter hodoscope eSC) which registered the electrons from muon decay (Fig. 1).

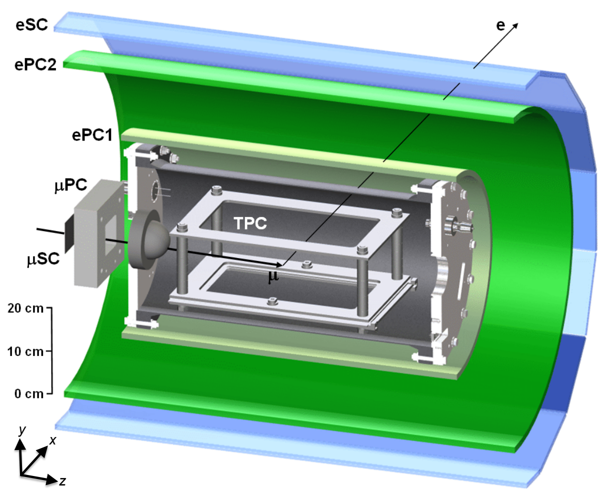

FIGURE 1. MuCup setup.

Measurements and results

The experiment was carried out in the PSI high flux muon beam. The measurement procedure started with selection of the muon stops within the 10.4×8.0×20.4 cm^3 fiducial volume inside the TPC accompanied by outgoing electrons reconstructed in the wire chambers ePC1 and ePC2. Special care was taken to select clean muon stops inside the TPC fiducial volume isolated by at least 15 mm from any material in the TPC. The muon pile-ups were eliminated also. $1.2{\cdot}10^{10}$ μ stops with fully reconstructed $\mu^- e$ pairs were registered, and the muon life time distribution was measured (Fig. 2). From this distribution, the disappearance rate of the negative muons stopped in the TPC has been obtained [1]:

$$\lambda_{\mu^-} = 455855.2 \pm 5.4(stat) \pm 4.2(syst) s^{-1}. \tag{4}$$

Two small corrections have been added to this value: $\Delta\lambda_{p\mu} = 12.3 \pm 0.0 s^{-1}$ (the $p\mu$ bound state correction) and $\Delta\lambda_{pp\mu} = 17.72 \pm 1.87 s^{-1}$ (a correction for the small, about 3% muon capture probability from the molecular states).

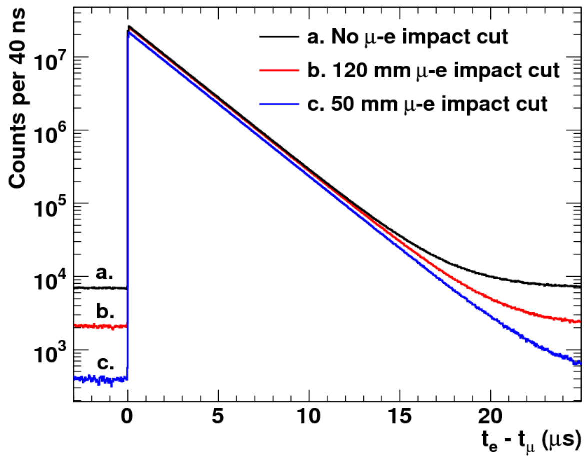

FIGURE 2. μ^{-} life time distribution.

Then, the muon capture rate from the atomic singlet state Λ_S has been determined according to the expression:

$$\Lambda_S = \lambda_{\mu^-} - \lambda_{\mu^+} + \Delta\lambda_{p\mu} + \Delta\lambda_{pp\mu}, \tag{5}$$

where

$$\lambda_{\mu^+} = 455170.05 \pm 0.46 s^{-1} \tag{6}$$

is the decay rate of free μ^+ muons [2]. The result is:

$$\Lambda_S = 714.9 \pm 5.4(stat) \pm 5.1(syst) s^{-1} \tag{7}$$

Within the existing formalism for calculations of Λ_S, this result corresponds to the following value of the nucleon pseudoscalar form factor:

$$G_P^{MuCap}(q^2 = -0.88 m_\mu^2) = 8.06 \pm 0.48(stat) \pm 0.28(syst). \tag{8}$$

With this measurement, the last of the four nucleon form factors G_P became well determined. Moreover, the measured value of G_P proved to be in close agreement with the prediction [3] of the Chiral Perturbation Theory,

$$G_P^{ChPT}(q^2 = -0.88 m_\mu^2) = 8.26 \pm 0.23, \tag{9}$$

thus supporting the basic principles of this theory.

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