Muon Capture in Hydrogen

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Muon capture in hydrogen is a basic charged-current electroweak process. Historically, it played an essential role in establishing the structure of the weak interactions. More recently, the connection between nucleon and even few-nucleon observables at low energies and fundamental QCD has been elucidated within effective field theories. Muon capture experiments test the underlying QCD symmetries and will serve as a calibration of important astrophysical neutrino reactions. The current programme of high precision experiments is described.

1. Introduction and Motivation

Ordinary muon capture (OMC) on the proton $\mu + p \rightarrow n + \nu_\mu$ played an important role in establishing the helicity structure and the universality of the weak interactions. The discovery of spontaneous symmetry breaking in the analysis of the axial current [3] laid the foundations for the mass generation in the standard model. It also forged a new understanding of low energy QCD in terms of chiral effective field theories (EFT). These predict the rate for $\mu + p$ capture to high precision, as the induced pseudoscalar coupling g_P in the axial current can be derived. Muon capture experiments thus provide an important test of basic QCD symmetries at low energies [4,5]. The related process $\mu + d \rightarrow n + n + \nu_\mu$ is the simplest weak interaction process on a nucleus, which can both be accurately measured as well as calculated in a fully consistent EFT framework with controlled systematic uncertainty. Moreover, EFTs directly relate this process to fundamental reactions of astrophysical interest [6,7], like $p + p$ fusion in the sun and $\nu + d$ scattering. A precise measurement of $\mu + d$ capture will determine the low energy constant required for calculating these extremely feeble, but fundamental solar reactions. The capture reaction $\mu + {}^3He \rightarrow t + \nu_\mu$ provides a precision benchmark in the more complicated three-nucleon system. The ^{3}He/^{3}H isospin doublet allows microscopic few-body calculations, albeit derived in a hybrid version of EFT. This formalism, which is a powerful tool in a wider range of applications, can be tested in the above reaction.

It is a great privilege and pleasure to present this topic during Pauchy Hwang's birthday session, as he has made numerous seminal contributions to the theoretical understanding of this field. Let me mention just two most relevant to this talk. In his Ph.D. thesis he

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*representing the MuCap [1] and MuSun [2] collaborations.

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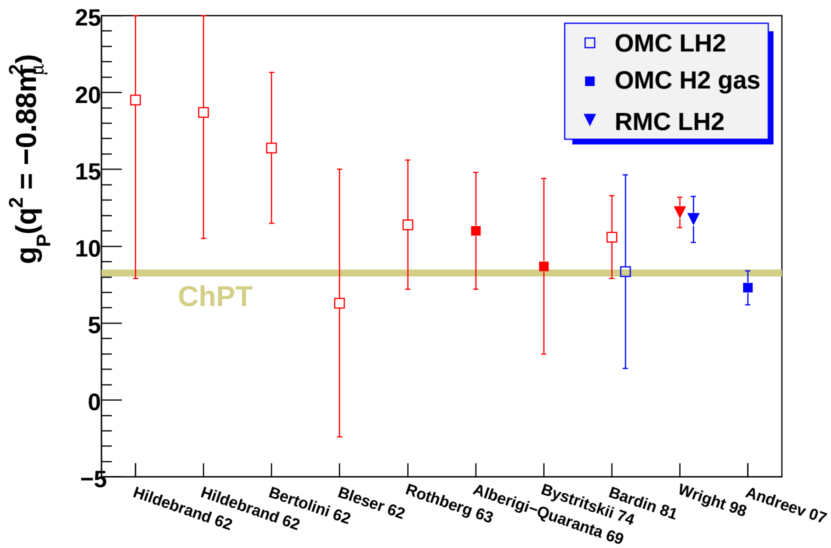

Figure 1. Pseudoscalar coupling g_P determined from muon capture experiments compared to the theoretical prediction (ChPT). Red points present the 2002 evaluation [5]. Our analysis of the data Bardin 81 and Wright 98 (blue points) uses $\lambda_{\rm op} = (6.9 \pm 4.3) \times 10^4 \ s^{-1}$ [11] to account for the current larger uncertainty in this rate [10]. The new MuCap result (Andreev 07) is largely independent of molecular effects and supports the theory prediction.

developed a theory for radiative muon capture (RMC) [8] $\mu + p \rightarrow n + \nu_\mu + \gamma$. His work on the Elementary Particle Method together with Kim and Primakoff [9] formed the basis for model independent predictions of muon capture in few-body systems.

2. Muon Capture on Hydrogen – MuCap Experiment

Muon capture on the proton provides unique information on the pseudoscalar form factor g_P at $q^2 = -0.88 m_\mu^2$, characterizing the axial structure of the nucleon. This basic coupling was already estimated in the pre-QCD era via PCAC and, by now, can be derived within the effective chiral theories of QCD, leading to a precise theoretical prediction $g_P = 8.26 \pm 0.23$ [4]. However, in spite of significant efforts, experiments remained largely inconclusive, owing to the poor knowledge of λ_{op}, the rate of conversion between the ortho- and para-$pp\mu$ states formed after muons are stopped in hydrogen. Because of the strong spin dependence of the V-A interaction, knowing the initial molecular state for the capture reaction is essential to extract g_P. Recently, the uncertainty in λ_{op} even increased due to mutually inconsistent theoretical and experimental results [10]. As shown in Fig.1, the OMC results before MuCap had large errors and the RMC experiment suggested a significantly higher g_P than predicted.

The MuCap collaboration has developed a novel experimental technique based on tracking the incoming muons in a time projection chamber (TPC) filled with ultra-pure deuterium-depleted hydrogen. The singlet capture rate Λ_S is determined from the difference between the measured disappearance rate of negative muons in hydrogen

$\lambda_\mu^- \approx \lambda_\mu^+ + \Lambda_S$ and the μ^+ decay rate λ_μ^+. An initial experimental result was published [11], simultaneously with the new MuLan muon lifetime result [12] and a theoretical paper [13], which advanced the theory of electroweak radiative corrections to the required precision. MuCap reports a measurement of the capture rate $\Lambda_S = 725.0 \pm 13.7_{stat} \pm 10.7_{sys}\ s^{-1}$ and derives $g_P = 7.3 \pm 1.1$. The impact of this result is evident from Fig.1. The low gas density in MuCap makes the result much less model dependent, leading to a first precise and unambiguous determination of g_P, which is in agreement with the chiral prediction. During 2008 the experiment completed the data taking phase and the analysis of the full data set, which has 9 times higher statistics than the published data [11], is expected to reduce the uncertainties by a further factor of three.

3. Muon Capture on Deuterium – MuSun Experiment

The MuSun experiment will measure the rate Λ_D for the $\mu + d$ capture process to a precision of better than 1.5%. This precision is required, to provide a definitive measurement of the low energy constant (called L_{1A} in the pion-less theory [7] and $\hat{d}^R$ in ChPT [6]) which integrates all the poorly constrained short-distance physics relevant for $\mu + d$ capture, as well as for solar pp fusion $p + p \to d + e^+ + \nu_e$ and for charged- and neutral current $\nu + d$ scattering of solar neutrinos as observed at the Sudbury Neutrino Observatory [14].

The new MuSun experiment will be about 10 times more precise in statistics and systematics than earlier measurements. It must be performed at conditions such that the experimental result leads to an unambiguous extraction of Λ_D independent of muonic atomic physics complications. At first, this seems a daunting task, as the muon kinetics in deuterium is more complex than in hydrogen. The transition between the upper $\mu d(\uparrow\uparrow)$ to the lower $\mu d(\uparrow\downarrow)$ hyperfine state is slow and, once a $dd\mu$ molecule is formed, nuclear dd fusion occurs at a time scale of nanoseconds (because of the process of muon-catalyzed fusion). However, these uncertainties can be reduced to a negligible level at optimized target conditions of T = 30 K and 5% of liquid hydrogen density [2]. While MuSun will use the same basic TPC and lifetime technique as MuCap, there are distinctive features demanded by physics. To achieve the required target condition, a new high-density cryogenic ionization chamber filled with ultra-pure deuterium is being developed. It will allow us to define the muon stop, identify impurities, and observe muon-catalyzed reactions. The new TPC must have improved energy resolution and full analog readout to avoid systematic uncertainties in the muon stop definition and to detect the charged particles induced by fusion and impurity capture processes. The 5-times higher target density of MuSun, compared with MuCap, implies that the chamber does not have internal gas gain and that drift voltages up to 100 kV are needed. Moreover, a complex cryo-system is being designed. The new MuSun set-up will be commissioned in 2010.

4. Muon Capture on Helium-3

Fig. 2 (lhs) presents the experimental data of the rate $\Lambda_{^3He}$ for the process $\mu + {}^3He \to t + \nu_\mu$, culminating in $\Lambda_{^3He} = 1496.0 \pm 4.0\ s^{-1}$ (uncertainty 0.3%) measured by our collaboration [15]. This precision result stimulated careful theoretical work, which used both the Elementary Particle Method [16], as well as microscopic calculations, employing

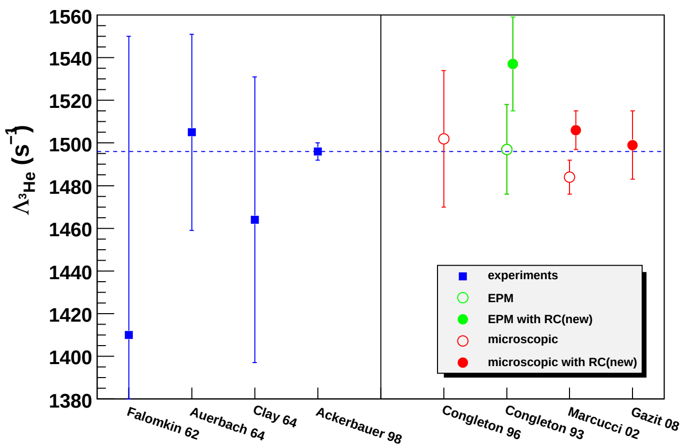

Figure 2. Results for the $\mu+^3He$ capture rate $\Lambda_{^3He}$. (lhs) Experiments , (rhs) theory. The values of two original calculations (open circles) are revised with the recently calculated electroweak radiative corrections RC(new) [13] to give the filled circles.

three-nucleon wave functions based on the realistic potentials including three-nucleon forces. Two-body currents were adjusted to reproduce tritium beta decay. Fig. 2 (rhs) summarizes the latest theoretical results. The recent calculation of electro-weak radiative corrections [13] has important consequences at this precision level and reduces the previous agreement between the data and the EPM results. The microscopic calculations appear consistent with experiment and thus confirm the overall theoretical framework in the more complex three-nucleon system. The comparison of the hybrid EFT calculation[17] with experiment yields $g_P(q^2 = -0.954 m_m^2) = 8.13 \pm 0.6$.

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