Muon Capture As A Probe Of The Nucleon's Axial Structure – The μCap Experiment*

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Abstract. The goal of the *μCap* experiment is a 1% precision measurement of the muon capture rate on the proton. From the capture rate the pseudoscalar form factor g_P of the nucleon will be extracted with 7% precision. This basic quantity is predicted theoretically with high precision, but the experimental situation is quite controversial. The new experiment should yield an unambiguous value for g_P and a sensitive test of the chiral symmetry of QCD at low energies.

Keywords: Nucleon Axial Form Factor, Pseudoscalar Form Factor, Muon Capture, TPC
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The *μCap* experiment[1] is a measurement of the rate for the semi-leptonic electroweak process $\mu^- + p \rightarrow n + \nu_\mu$ to 1 % precision. This directly determines the pseudoscalar form factor g_P at $q^2 = -0.88\ m_\mu^2$, which is the least well known of the nucleon form factors characterizing the structure of its charged electro-weak current. Effective field theories based on the chiral symmetry of QCD and its breaking can calculate g_P to 3%.

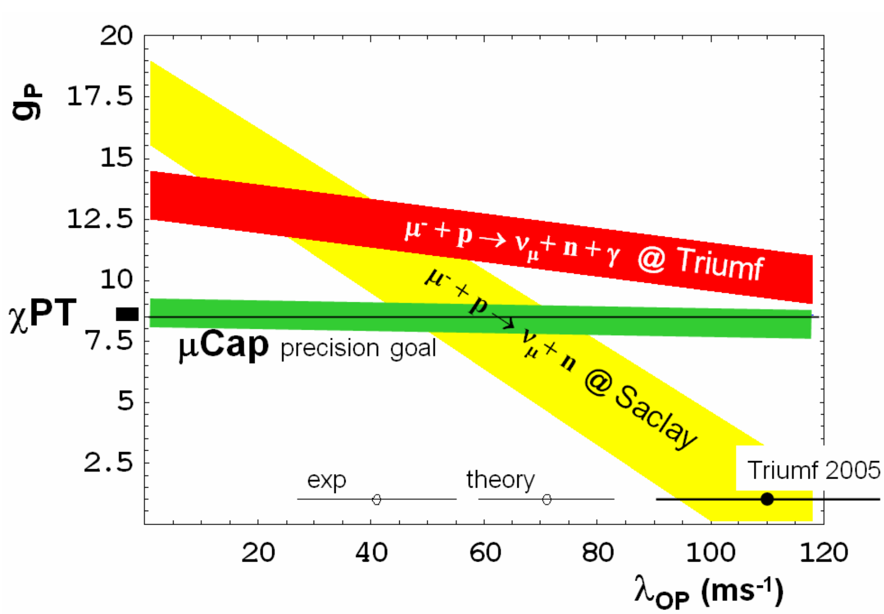

Figure 1. Experimental constraints on g_P. The uncertainty in λ_{OP} implies a large uncertainty in the extraction of g_P. The *μCap* experiment will be more accurate and nearly independent of λ_{OP}.

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Thus, its experimental determination sensitively probes our understanding of QCD at low energies[2]. Despite efforts spanning the last 30 years, existing experiments are unable to meet this challenge, but rather lead to a controversial experimental situation (Fig.1). An additional muon molecular quantity (the rate λ_{OP} of conversion between the molecular $pp\mu$ states where capture occurs) is required for the interpretation of existing experiments on ordinary and radiative[3] muon capture performed with LH_2 targets. Alas λ_{OP} is not well known. In 2005 a new measurement[4] reported a much higher value of this rate than a previous experiment and calculation.

The *μCap* experiment[1], performed at the Paul Scherrer Institute, is based on a new method that avoids the key uncertainties of earlier efforts, in order to improve the determination of g_p by about an order of magnitude. The experiment is a muon lifetime measurement in ultra-pure and deuterium-depleted hydrogen gas. The measured decay lifetime of the negative muon in hydrogen is shorter, compared with that of the positive muon, because of the additional capture reaction. Thus, the capture rate is extracted from the difference of the μ^+ and μ^- lifetime, each measured with 10 ppm precision. Muons are stopped in an active target made of a specially developed TPC contained in a 10-atm hydrogen pressure vessel. Two cylindrical wire-chambers and a segmented scintillator barrel surround the chamber for detection of the decay electrons. Several unique features will allow a significant improvement in precision. The target density is 1% of LH_2, greatly reducing $pp\mu$ formation and the sensitivity to λ_{op}. With 3D tracking, the TPC selects only μ stops in the hydrogen gas, eliminating otherwise overwhelming background from stops in higher-Z materials (Fig.2a). Muon-electron vertex cuts lead to strong background suppression, essential consistency checks and a diagnostic method for monitoring the isotopic purity of the hydrogen (Fig.2b). Impurities at the ppb level are monitored *in situ* with the TPC. A sophisticated purification system has been commissioned.

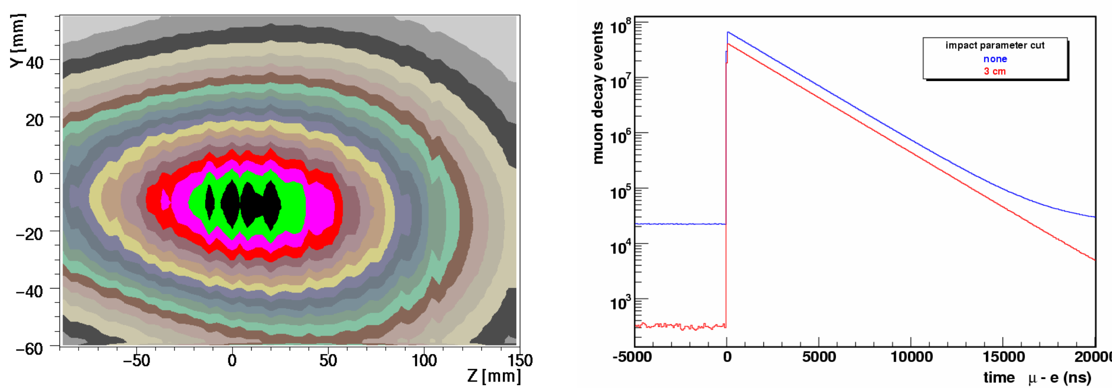

Figure 2. a): TPC side view, which images the μ stop distribution. b) Decay spectra show dramatic accidental suppression improvements due to *μ-e* impact parameter cut.

The overall status of the experiment is described in the documents on the experiment's web page[1]. Past, present and future milestones include

2004 Completion and commissioning of the basic μCap detector and the continuous gas purification system. First high statistics physics run.

2005 TPC reaches design specifications. In-situ gas diagnostics. New Muon-on-Demand[5,6] scheme allows tripling the data taking rate.

2006 New CRDF grant approved to build on-site H/D separation system. New Flash ADC readout for electron detector and TPC. Main data run to increase statistics ~10 fold to achieve the proposal goal.

The analysis of the 2004 data is well advanced and we expect to obtain a result for the muon capture rate on the proton with about 3% uncertainty which translates into a 20% uncertainty for g_p. This already would be a significant step relative to the current world data (Fig.1). The final result based on the statistics of the upcoming 2006 run should be three times more accurate.

As a follow-up experiment, the collaboration is actively exploring the feasibility of a precision measurement of muon capture on the deuteron. In recent years, the response of the two-nucleon system to electroweak probes has been studied intensively[7], partially fueled by astrophysics interest in solar neutrino reactions. The work demonstrated that the same combination of low-energy constants, which parameterizes contributions from short-range axial two-body currents, appears in several fundamental reactions. A 1-percent measurement of μd capture would provide the most accurate experimental information on the axial current interacting with the two nucleon system, and could determine the low-energy constant common to these processes[8,9]. Two immediate questions arise in this context: Can the capture process with energy transfer of the order of the muon mass be directly related to the lower-energy solar reactions? Two recent calculations[10,9] gave an affirmative answer. As past experiments had 10–15 % errors, the second question is whether a high-precision measurement is feasible. Fortunately, *μCap* has developed several key techniques that promise a tenfold reduction in experimental errors. Uncertainties in the interpretation can be largely eliminated by optimizing the target conditions in a new cryogenic TPC.

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