FINAL RESULTS OF μ^3He-CAPTURE EXPERIMENT AND PERSPECTIVES FOR μp-CAPTURE STUDIES

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1. Introduction

Muon capture on hydrogen gives a unique possibility for measurement of the pseudo-scalar form factor g_p of the nucleonic weak current, thus providing a sensitive test of the QCD chiral symmetry perturbation theory which predicts the value of this form factor with a precision of $\Delta g_p/g_p \simeq 2\%$. For an adequate comparison with the theory, the muon capture rate Λ_c should be measured with a precision of $\Delta\Lambda_c/\Lambda_c \leq 1\%$, that is an order of magnitude better than the precision of the present world data. We report on the project of an experiment designed to provide the required precision. Also, we present the final result of our previous experiment on high precision measurement of the μ^3He-capture rate and compare this result with the PCAC prediction.

Few years ago, our collaboration has performed high precision measurements of the μ^3He-capture rate that made it possible to determine the induced pseudoscalar form factor thus providing a quantitative test of the Partial Conserved Axial Current (PCAC) hypothesis in this reaction [1, 2]. Unfortunately, the PCAC predictions of the μ^3He pseudoscalar form factor suffer from some theoretical uncertainties that put some limitations in testing the fundamental principles of the electroweak theory describing the muon capture process. From this point of view, the study of the μp-capture rate is preferable as the modern chiral perturbation theory is capable in this case to improve considerably the PCAC prediction of the pseudoscalar form factor. However, the high precision measurement of the μp-capture rate proved to be a very complicated task which is far from being solved by now. The precision of the available experimental data on the singlet μp-capture rate must be improved by more than an order of magnitude before these data can be used for valuable tests of the theory. Below we discuss shortly the results of the μ^3He-capture experiment and present our project for precision measurements of the μp-capture rate[1].

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2. Physics grounds

We consider here the μp-capture and the μ^3He-capture reactions:

$$\mu^- + p \longrightarrow n + \nu_\mu, \tag{1}$$

$$\mu^- +^3 \mathrm{He} \longrightarrow^3 \mathrm{H} + \nu_\mu. \tag{2}$$

These reactions have much in common if one considers the ^{3}He and ^{3}H nuclei as elementary particles – as it was first introduced by Kim and Primakoff in 1965 . An essential point is that both (p, n) and (^{3}He, ^{3}H) systems are members of the spin 1/2 isodoublets. In the framework of the Standard Model the weak current in both reactions is parametrized by six form factors:

$$\begin{array}{ll} g_V,\ g_M,\ g_A,\ g_P,\ g_S,\ g_T & \text{in reaction (1)}, \\ F_V,\ F_M,\ F_A,\ F_P,\ F_S,\ F_T & \text{in reaction (2)}. \end{array}$$

The form factors are evaluated at the relevant values of the four-momentum transfer:

$$\begin{array}{ll} q_c^2 = -0.88\ m_\mu^2 & \text{in reaction (1)}, \\ q_c^2 = -0.954\ m_\mu^2 & \text{in reaction (2)}. \end{array}$$

The second class (scalar and tensor) form factors $g_S,\ g_T,\ F_S,\ F_T$ vanish in the limit of exact G–parity invariance. According to the conserved vector current (CVC) theorem, the vector and magnetic form factors $g_V(q^2)$ and $g_M(q^2)$ as well as $F_V(q^2)$ and $F_M(q^2)$ are identical to the corresponding electromagnetic form factors which are determined by the nucleon and the ^{3}He, ^{3}H magnetic moments and by the ep- and e^3He-scattering data:

$$\begin{array}{c} g_V(q_c^2) = 0.976 \pm 0.001,\ g_M(q_c^2) = 3.583 \pm 0.001, \\ F_V(q_c^2) = 0.834 \pm 0.011,\ F_M(q_c^2) = -13.969 \pm 0.052. \end{array}$$

The values for g_V and g_M are taken from Congleton and Truhlik (1996) after small corrections for the q^2-dependence (extrapolation from $q^2 = -0.954\ m_\mu^2$ to $q^2 = -0.88\ m_\mu^2$). The axial form factor $g_A(0)$ is determined from the neutron β-decay, and its extrapolation to $q^2 = q_c^2$ can be done using νN-scattering data (Congleton and Truhlik, 1996):

$$g_A(q_c^2) = -1.239 \pm 0.003.$$

Similarly, the axial form factor $F_A(0)$ is determined from the ^{3}H β-decay: $F_A(0) = 1.212 \pm 0.005$. Unfortunately, the extrapolation to $q^2 = q_c^2$ may in this case relies only on some theoretical considerations as ν^3He-scattering data are not available at present. According to Congleton and Fearing (1993), such an extrapolation gives

$$F_A(q_c^2) = 1.052 \pm 0.010,$$

where the error bar is increased taking into account the uncertainty of the extrapolation.

The remaining induced pseudoscalar form factors $g_P(q_c^2)$ or $F_P(q_c^2)$ can be found by measuring the muon capture rates $\Lambda_c(\mu p)$ or $\Lambda_c(\mu^3\mathrm{He})$. At the present knowledge of the other form factors, the ultimate precision reachable in measuring the pseudoscalar form factors is

$$\begin{array}{ll} \delta g_P/g_P = 2\% & \text{if } \delta\Lambda_c/\Lambda_c \le 0.3\%, \\ \delta F_P/F_P = 13\% & \text{if } \delta\Lambda_c/\Lambda_c \le 2\%. \end{array}$$

So we see that high precision (0.3%) measurements of the μp-capture rate could determine $g_P(q_c^2)$ with 2% precision, while the precision in determining $F_P(q_c^2)$ is limited by 13% at present, and for reaching this precision it would be enough to measure Λ_c with 2% accuracy.

The importance of measurements of the induced pseudoscalar form factors is related to the possibility to make a comparison with the theory predictions thus providing a quantitative test of the fundamental principles on which this theory is based. Historically, $g_P(q_c^2)$ and $F_P(q_c^2)$ were predicted by the PCAC approximation based on the chiral symmetry idea. This approximation relates the pseudoscalar form factor to the corresponding axial form factor:

$$g_P(q_c^2) = \frac{m_\mu(M_n + M_p)}{m_\pi^2 - q_c^2}\, g_A(q_c^2) + \textit{correction term}, \tag{3}$$

$$F_P(q_c^2) = \frac{m_\mu(M_{^3\mathrm{He}} + M_{^3\mathrm{H}})}{m_\pi^2 - q_c^2}\, F_A(q_c^2) + \textit{correction term}. \tag{4}$$

Using the above presented values for $g_A(q_c^2)$ and $F_A(q_c^2)$ and neglecting the correction terms, one obtains:

$$g_P^{\mathrm{PCAC}}(q_c^2) = 8.39, \qquad F_P^{\mathrm{PCAC}}(q_c^2) = 20.7.$$

The dominant contribution to the pseudoscalar form factor is given by the pion pole (PCAC), and the leading corrections to the pole term can be derived from the QCD Ward identities (Bernard *et al.*, 1994 and Fearing *et al.*, 1997) confirming the old current-algebra result. Recent calculations of $g_P(q_c^2)$ and the singlet muon capture rates in the heavy-baryon chiral perturbation theory (Table 1) predict $g_P(q_c^2)$ with $\sim$ 2% precision, and Λ_S with $\sim$ 0.5% precision.

Table 1

Theoretical predictions for $g_P(q_c^2)$ and Λ_S

Reference	Bernard *et al.*, 1994	Fearing *et al.*, 1997	Govaerts *et al.*, 2000	Ando *et al.*, 2001	Bernard *et al.*, 2001
g_P	8.44 ± 0.23	8.21 ± 0.09	8.475 ± 0.076		
Λ_S, s^{-1}			688.4 ± 3.8	695	687.4

Therefore, comparison with experiment would be a valuable check of the theory. Unfortunately, so far there is no similar QCD based calculation in the case of μ^3He-capture. Hence, the PCAC prediction for $F_P(q_c^2)$ may be valid only with 10% precision. To a first approximation, the correction term in equation (4) can be presented as follows:

$$\textit{correction term} = 1 - \frac{g_{\pi^3\mathrm{He}^3\mathrm{H}}(q_c^2)}{g_{\pi^3\mathrm{He}^3\mathrm{H}}(0)} \cdot \frac{F_A(0)}{F_A(q_c^2)}\,, \tag{5}$$

where $g_{\pi^3\mathrm{He}^3\mathrm{H}}(q_c^2)$ is the pion-nuclear coupling parameter. The problem is that the q^2-dependence of this parameter is not known at present. Note that the correction term becomes zero if the q^2-dependence of $g_{\pi^3\mathrm{He}^3\mathrm{H}}(q^2)$ is identical to that of $F_A(q^2)$ at small q^2.

3. Status of μp-capture rate measurements

As it was presented above, the QCD chiral perturbation theory predicts $g_P(q_c^2)$ with $\sim$ 2% precision. However, to be comparable in precision with the theory, the muon capture rate should be measured with ~0.3% precision in the ordinary muon capture, OMC reaction (1), or with ~1% precision in radiative muon capture, RMC:

$$\mu^- + p \longrightarrow n + \nu_\mu + \gamma \qquad BR = 10^{-8}. \tag{6}$$

Table 2 presents the available experimental data on the OMC rate, Λ_c.

Table 2

Present status of $p\mu$-capture measurements

Year	Exptl.place	H_2-target	$\Lambda_c \pm \delta\Lambda_c$, s^{-1}	$\delta\Lambda_c/\Lambda_c$	Method
1962	Chicago	liquid	428±85	20%	neutron detection
1962	Columbia	liquid	515±85	17%	-"-
1962	CERN	liquid	450±50	11%	-"-
1963	Columbia	liquid	464±42	9%	-"-
1969	CERN	gas, 8 atm	651±57	9%	-"-
1974	Dubna	gas, 41 atm	686±88	13%	-"-
1981	Saclay	liquid	460±20	4.5%	life time measurement
1981	Saclay	liquid	531±33*)	6%	-"-

*) corrected for ortho-para transitions in the $pp\mu$ molecule

Most of measurements have been performed with the neutron detection method. Unfortunately, the precision of this method is limited by uncertainties in the neutron detection efficiency (~ 10% at best). Another approach was realized in the Saclay experiment where the μ^- disappearance rate in liquid hydrogen, $\Lambda_- = \lambda_0 + \Lambda_c$, was measured and compared (assuming the CPT-invariance) with the μ^+ decay rate, $\Lambda_+ = \lambda_0$. In this method, the disappearance rates are determined from the time distributions of the decay electrons. Such measurements are complicated by the low muon capture branching ratio, $BR = 10^{-3}$. To reach the 1% precision in Λ_c, one should measure both Λ_- and Λ_+ to a precision better than 10^{-5}. At present, such a precision is not yet reached even in the case of Λ_+. A serious problem in interpretation of the experimental results is related to the molecular effects. In a real experiment, the muon capture may occur (Fig. 1) either from the atomic singlet state ($\Lambda_S \simeq 664$ s^{-1}) or from the $pp\mu$-orthomolecule ($\Lambda_{om} \simeq 506$ s^{-1}), or from the $pp\mu$-paramolecule ($\Lambda_{pm} \simeq 200$ s^{-1}). The problem is that the ortho-para molecule transition rate, λ_{op}, is poorly known at present, and the experimental result on λ_{op} differs significantly from the theoretical calculations. The uncertainty in interpretation is especially large for the μp capture in liquid hydrogen where muon capture occurs mostly from the $pp\mu$-molecule states. The current situation is illustrated by Fig. 2. One can clearly see that the existing data on OMC cannot be used so far for an adequate comparison with the theory.

The RMC rate in reaction (6) was studied in a recent experiment at TRIUMF (Joukmans *et al.*, 1996). This experiment is not so sensitive to λ_{op}. The obtained result corresponds to a value of g_P which is 1.5 times higher than the theoretical prediction. It should be noted, however, that the RMC has $BR \simeq 10^{-8}$ that might imply not only experimental but also theoretical complications. Obviously, new high precision experiments on OMC are needed to clear up the situation.

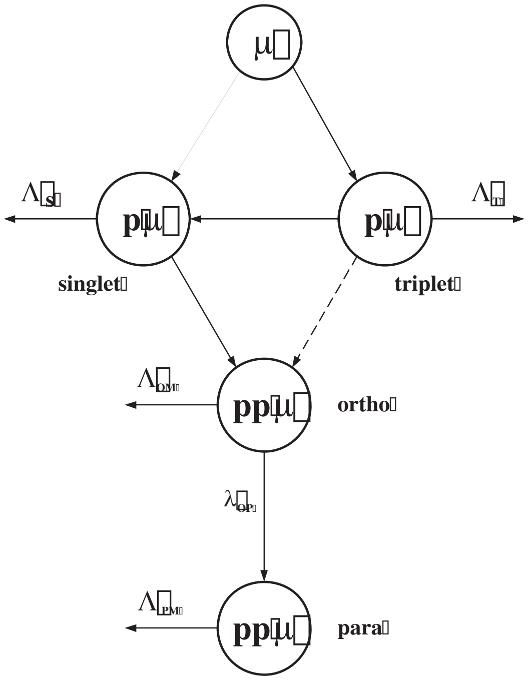

Fig. 1. Kinetics scheme of muon stopping in hydrogen

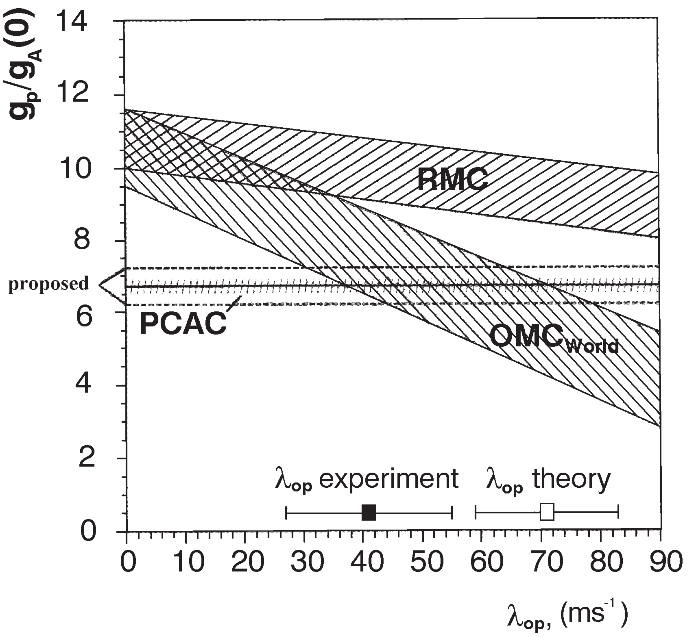

Fig. 2. Current constraints on g_p as a function of the ortho-para transition rate λ_{OP}

4. Status of μ^3He-capture rate measurements

One of main advantages in measuring muon capture on ^{3}He, compared to hydrogen, is the production of a charged particle in the final state, which can be detected with a high efficiency and good background suppression. The kinetics scheme of the μ^3He-system is shown in Fig. 3. The muon capture leads with 70% probability to the triton channel, see reaction (2). The capture occurs from the two hyperfine states of the μ^3He muonic atom, of total spin $F = 0$ and $F = 1$. Since the ^{3}He target is not polarized and the spin-flip rate is negligibly small, the hyperfine states are statistically populated, and it is the statistical capture rate

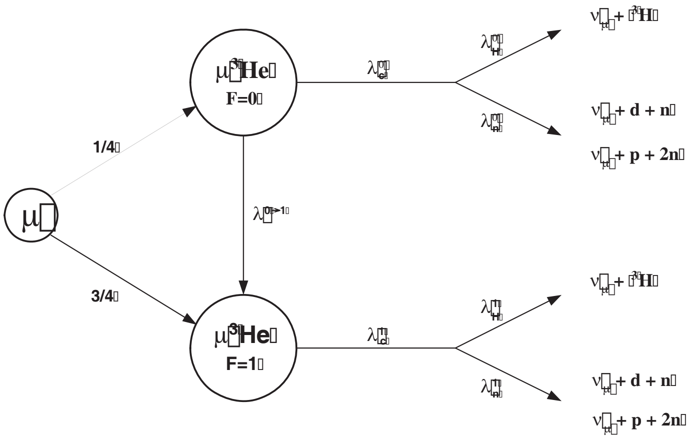

Fig. 3. Kinetics scheme of the μ^3He-system

$$\Lambda_{\rm stat} = \frac{1}{4}\lambda^0_{\rm H} + \frac{3}{4}\lambda^1_{\rm H}\ , \tag{7}$$

which is measured. So, the μ^3He capture takes place from the accurately known initial state of the μHe atom, and there is no ambiguity in the theoretical interpretation of the experimental data.

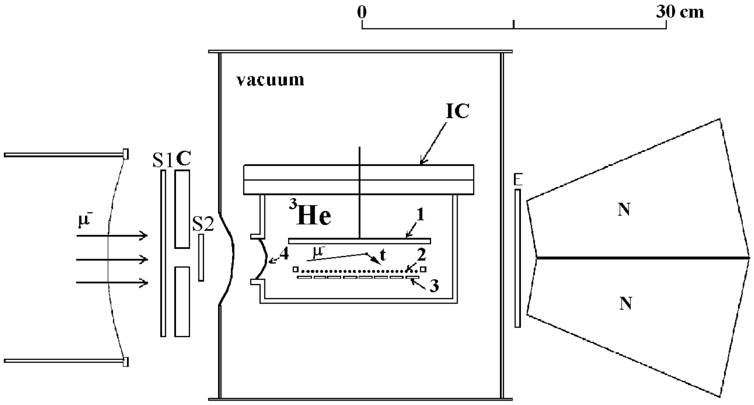

Fig. 4. Setup of the μ^3He experiment (side view): 1 – cathode; 2 – grid; 3 – block of anodes; 4 – Be window; S1, S2 – scintillator counters; N – neutron counters; E – electron counters; C – collimator. Dimensions: cathode–grid 12mm, grid–anode 1mm. Anode area is equal to 10 cm^2

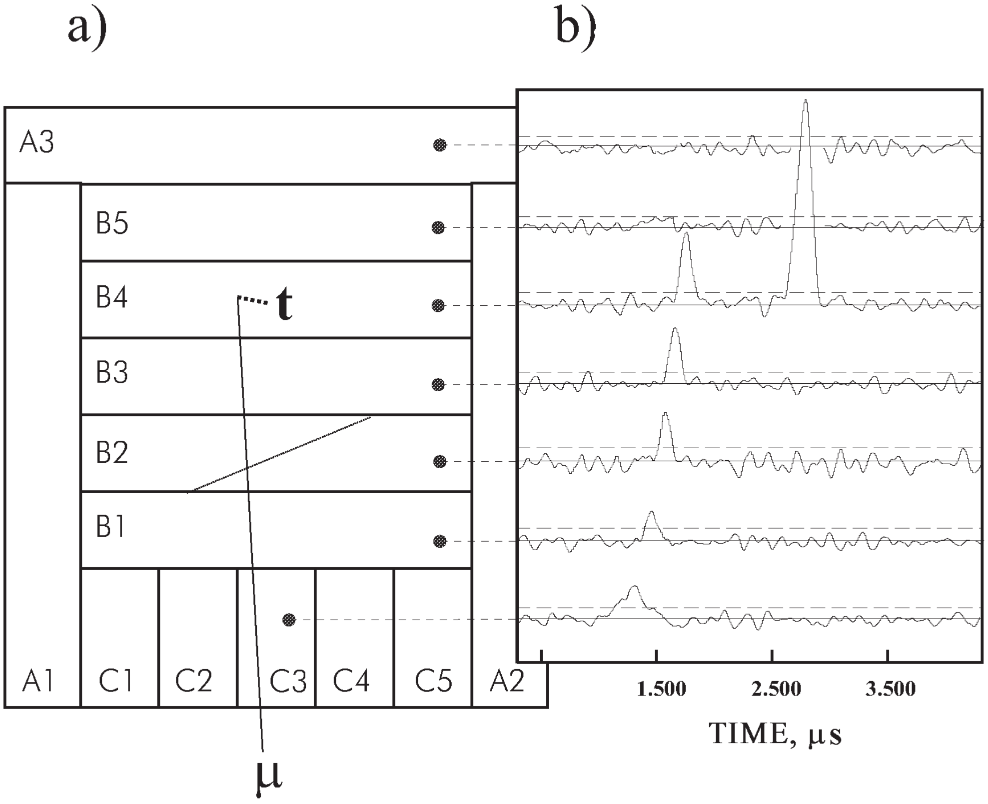

Fig. 5. **a)** Anode layout of the ionization chamber, **b)** a typical sequence of anode signals registered by the flash ADCs

Prior to our experiment, there were three measurements of the μ^3He-capture rate, all done more than 30 years ago, with precision in Λ_c ranging from 3% to 10% (Dubna, 1963; Berkeley, 1965; Brookhaven, 1965). A new experimental technique in combination with the excellent properties of the PSI muon beam allowed us to improve this precision by an order of magnitude. The basic element of the setup was a gridded multi-anode ionization chamber (Figs. 4, 5). The chamber was filled with 120 bar of clean ^{3}He gas. Muons were stopped inside the sensitive volume of the chamber which detected both the stopping muons and the 1.9 MeV tritons with the energy resolution of $\sigma = 30$ keV (Fig. 6). The strategy was to select clean muon stops well isolated from the chamber electrodes and to provide 100% efficiency for the 1.9 MeV triton detection. Then the ratio $N_t/N_{\mu_{\rm stop}}$ was a direct measure of the muon capture rate. More than 10^6 tritons were detected in this experiment, and the muon capture rate was determined with 0.3% precision [1]:

$$\Lambda_{\rm stat} = 1496 \pm 4 \ {\rm s}^{-1}.$$

The interpretation of the results is illustrated by Fig. 7. The measured value for $\Lambda_{\rm stat}$ together with the known values for $F_V(q_c^2)$ constrains the allowed region in the $F_P(q_c^2)$–$F_A(q_c^2)$ plot. Taking into account the $F_A(q_c^2)$ value mentioned above with its error bars, we obtain

$$F_P(q_c^2) = 20.8 \pm 2.8,$$

where the error is dominated by the error in $F_A(q_c^2)$.

Comparison with $F_P^{\rm PCAC}(q_c^2) = 20.7$ calculated from the PCAC relation (4) shows a remarkable agreement. The fact that the correction term proved to be insignificant means that the q^2-dependences of $F_A(q^2)$ and $g_{\pi^3{\rm He}^3{\rm H}}(q^2)$ are nearly identical at small q^2. Mukhopadhyay and Junker in 1996 used this observation to determine $g_{\pi^3{\rm He}^3{\rm H}}(q_c^2) = 31.9 \pm 1.3$.

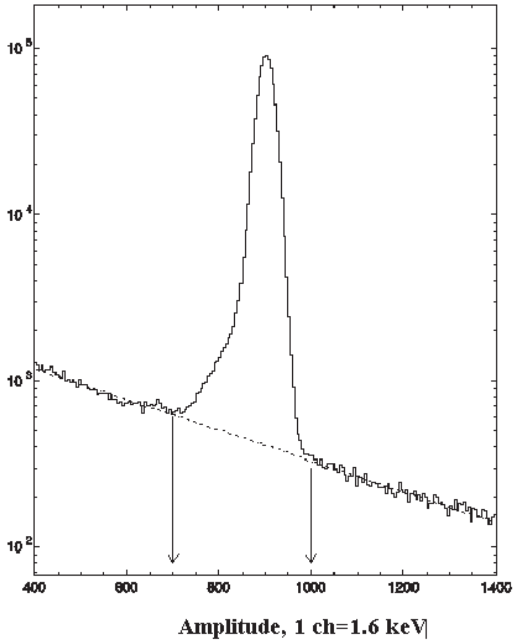

Fig. 6. Energy spectrum of 1.9 MeV tritons from reaction (2) measured with the ionization chamber. The arrows indicate the region of background subtraction

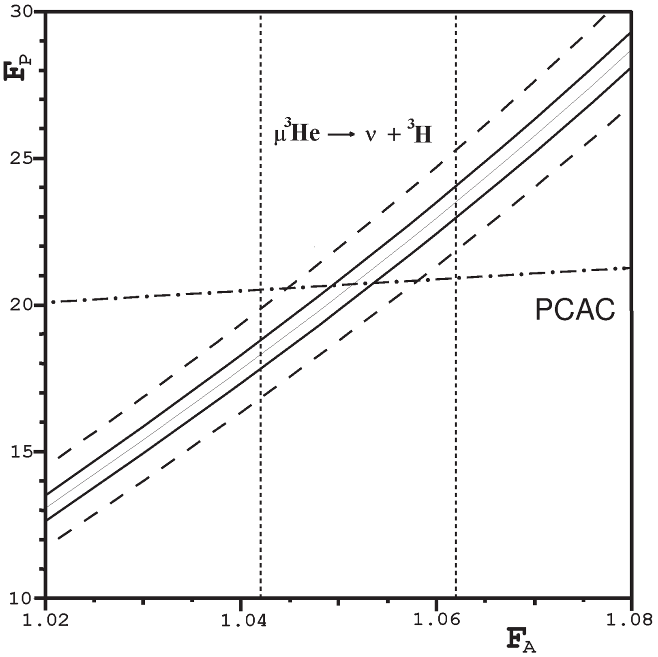

Fig. 7. Constrained on F$_A$ and F$_P$ form factors. Solid lines – from Λ_c with its errors only; dashed lines – from Λ_c with errors in F$_V$ and F$_M$ added; vertical lines are the constraints from tritium β-decay; horizontal dash-dotted line is the PCAC relation

5. New project for μp-capture experiment

In 1997 our collaboration proposed [3] a new experiment (μCAP) at PSI aimed at a high precision measurement of the μp-capture rate (OMC). In order to avoid the problems with interpretation of the experimental results related to the unknown transfer rate from the ortho to paramolecular states, λ_{op}, in the $pp\mu$ molecules, our experiment will be performed in hydrogen gas at 10 bar pressure. At this pressure, the majority of the μp-capture events will occur from the singlet $p\mu$-atomic state, therefore possible errors in the $pp\mu$-molecule formation rate, $\lambda_{pp\mu}$, as well as an uncertainty in λ_{op}, may introduce less than 1% error to the measured muon capture rate from the singlet μp-state, Λ_S [4]. The experimental method is based on the lifetime measurements of the negative muons stopped in the hydrogen gas. The μ^--decay rate, Λ_-, will be determined from the slope of the time distribution of the μ^--decay electrons. For comparison, the μ^+-decay rate Λ_+ will be also measured in the same experimental conditions. The goal is to measure both Λ_- and Λ_+ with at least 10 ppm precision. The experimental setup will have a close to 4π-geometry. The statistics needed for our precision is at least 10^{10} decay events registered in one run, and there should be several such runs to control the systematic errors. It means that the rate of muon stops in the detector should be about 30 kHz. At such rates, there will be more than one muon stop in the detector volume during the measuring time of 40 μs, and we cannot introduce a 40 μs dead time before and after each muon stop – the method usually applied in such experiments. To cope with this problem, we proposed a space-time correlation method which is as follows. The detector provides the coordinates of each muon stop and measures the trajectory of each decay electron. The arrival times of the muons and the electrons are also measured. Then, tracing back the electron trajectory, one finds the intercept with the muon stop volume thus identifying the parent muon for each decay electron. During last years we have designed and constructed a few prototypes of the detector and performed different researches to optimize the parameters of the detector and to choose the optimal conditions of the experiment. The result of this work is a design of the final experimental setup (Fig. 8) which is under construction now [5].

5.1. Experimental setup

The central part of our detector is a time projection chamber (TPC), see Fig. 9, embedded in a pressure vessel filled with 10 bar of ultra-pure deuterium-depleted hydrogen (protium). The TPC was specially developed for this experiment. It has a sensitive volume of $15 \times 12 \times 30$ cm^3 and acts as an active target monitoring all muon stops and electrons from the muon decay. The vertical drift field of ~ 2.3 kV/cm causes electrons to drift with a velocity of ~ 0.7 cm/μs toward a multiwire proportional plane at the bottom. There, the charges are amplified by typically a factor of 5000 and read out by 75 anode wires in X-direction (which is normal to the beam direction and lies in the plane of the anodes) and by 38 strip cathode wires in Z-direction (the beam direction). The Y-coordinate, defining the height in the TPC, is determined by the drift time which ranges from 0 to 17 μs. Incoming muons are detected also by two planes of wire chambers in front of the TPC. The track reconstruction inside the TPC clearly selects the muon stops in H_2 well separated from the walls.

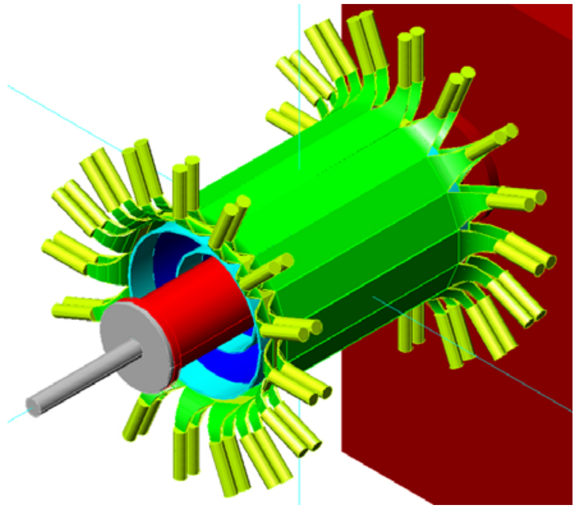

Fig. 8. Stereo view of the final setup for μCAP experiment (scintillator array, wire chambers, and TPC vessel)

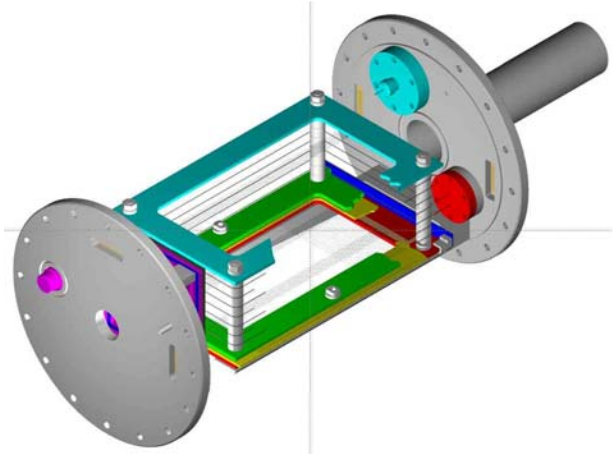

Fig. 9. Stereo view of TPC in the final setup for μCAP experiment

The TPC performance can be illustrated with an event from our test run in the muon beam at PSI (Fig. 10). The muon can be seen stopping in the region of the anode 4. The track of decay electron is seen on anodes 4–12 going to the upper right.

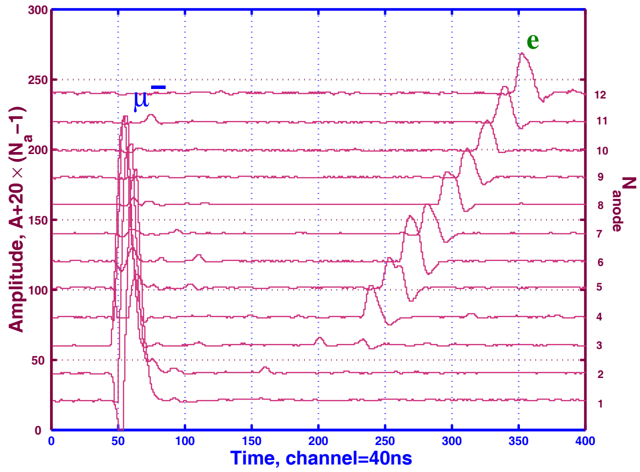

Fig. 10. Signals on the TPC anode wires from a μe-decay event

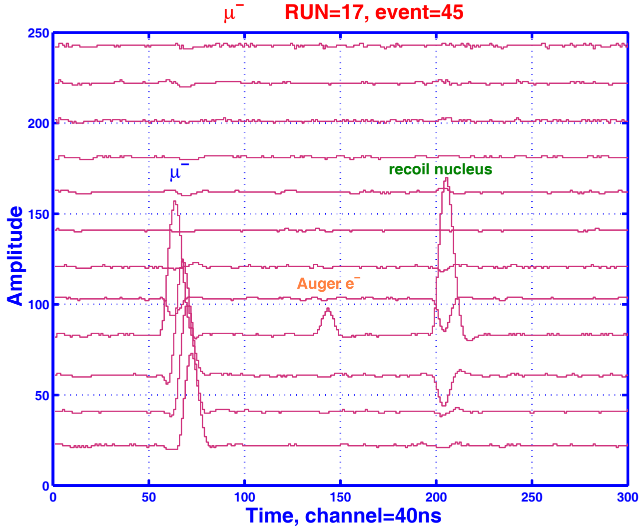

Fig. 11. Display of flash ADSs showing a typical event with the μ-capture reaction on an impurity

The pressure chamber has cylindrical walls made of 4 mm aluminum to reduce multiple scattering of through-going decay electrons. The hydrogen vessel and its interior wire chambers are made of clean materials (metals, ceramics, quartz-glass frames, *etc.*) that can be baked out up to 150°C and evacuated down to 10^{-7}–10^{-8} mbar. This level is required to maintain a required hydrogen purity of 10^{-8}. Ultra clean protium is filled *via* a specially developed gas system using chemical purifying methods. The gas can be circulated and purified during the measurements. Since this is an active target experiment, we can determine very low levels of impurities from the chamber signals themselves, in addition to chromatographic gas analysis.

Surrounding the pressure tank, two cylindrical proportional chambers and an array of plastic detectors are mounted covering an effective solid angle $\Omega/4\pi \sim 75\%$. For the electron time determination, the measurements will rely entirely on the detectors outside the hydrogen pressure vessel, *i.e.* on the two wire chambers for directional back tracking and on the plastic hodoscope for the absolute time measurement. The separation of detector functions for electrons from those for muons ensures independent absolute time measurements without the danger of electronic cross-talks and tail effects. The tracking chambers can handle event rates of ~ 30 kHz, since pileup problems can be reduced by identifying the muon-electron pair originating from a common vertex. This method also suppresses other possible background.

A serious requirement of the μCAP experiment is the high gas purity. The concentration of impurities with $Z > 2$ should be less than 10^{-8}. This demands for a special system for the gas circulation, purification and control of the impurity level with a high sensitivity. Another special requirement is to know precisely the amount of deuterium in H_2 gas. The D_2 level should be less than 1 ppm to avoid muon transfer to $d\mu$ atoms resulting in significant diffusion from the muon-stop area caused by large ranges of the $d\mu$ atoms in hydrogen due to the Ramsauer effect.

Fortunately, our detector can provide the direct control of the levels of impurities. Using the TPC as an active target, we can detect the charged products of muon induced reactions with impurities: the recoil nuclei (200–350 keV) from the μ-capture on impurities with $Z \geq 2$ and the charged products of the $pd\mu$-fusion channel ^{3}He(0.2 MeV) + μ(5.3 MeV). This was demonstrated in our test run at PSI. The μ-capture reactions on impurities are identified as events with two big signals on the muon stop anode separated in time, where the first one is the signal from the stopped muon with an amplitude up to 220 keV and the second one is from the nuclear recoil. For selection of such events, the special amplifiers and discriminators with high thresholds about 70 keV and also a trigger control unit were developed. An example of the μ-capture event is shown in Fig. 11. Using this method we have reached a sensitivity in the detection of impurities with $Z > 2$ on a level of 0.01 ppm. We also found an evidence for presence of $d\mu$ atoms by observing the capture products far separated in space from the muon stop because of the $d\mu$ diffusion. Finally, we obtained preliminary data on $pd\mu$ fusion, which can be used as a monitor for the deuterium concentration C_d. Our current sensitivity for C_d is around 2 ppm.

There are many technical problems to be solved before this setup allows us to collect first data. At present the μCAP experiment is in the finish of preliminary stage, and we plan to start to collect data in 2003.

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