Final results on the $\mu\,^3$He-capture experiment and perspectives for μp-capture studies

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Muon capture on hydrogen gives a unique possibility for a measurement of the pseudoscalar form factor $g_p(q_c^2 = -0.88\ \mathrm{m}_\mu^2)$ 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 adequate comparison with theory, the muon capture rate Λ_c should be measured with a precision of $\Delta\Lambda_c/\Lambda_c \leqslant 1\%$, 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 a high precision measurement of the $\mu\,^3$He capture rate and compare this result with the PCAC prediction.

1. Introduction

Recently, our collaboration has performed high precision measurements of the $\mu\,^3$He-capture rate that made it possible to determine the induced pseudoscalar form factor thus providing a quantitative test of the Partially Conserved Axial Current (PCAC) hypothesis in this reaction [1]. Unfortunately, the PCAC predictions of the $\mu\,^3$He pseudoscalar form factor suffer from some theoretical uncertainties that set 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 new project for a precision measurement of the μp-capture rate.

2. Physics grounds

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

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

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

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

$$g_\text{V}, g_\text{M}, g_\text{A}, g_\text{P}, g_\text{S}, g_\text{T} \quad \text{in reaction (1)},$$
$$F_\text{V}, F_\text{M}, F_\text{A}, F_\text{P}, F_\text{S}, F_\text{T} \quad \text{in reaction (2)}.$$

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

$$q_\text{c}^2 = -0.88\ \text{m}_\mu^2 \quad \text{in reaction (1)},$$
$$q_\text{c}^2 = -0.954\ \text{m}_\mu^2 \quad \text{in reaction (2)}.$$

The second class (scalar and tensor) form factors $g_\text{S}, g_\text{T}, F_\text{S}, F_\text{T}$ vanish in the limit of exact G-parity invariance. According to the conserved vector current (CVC) theorem, the vector and magnetic form factors $g_\text{V}(q^2)$ and $g_\text{M}(q^2)$ as well as $F_\text{V}(q^2)$ and $F_\text{M}(q^2)$ 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 $e\,^3$He-scattering data:

$$g_\text{V}\left(q_\text{c}^2\right) = 0.976 \pm 0.001, \qquad g_\text{M}\left(q_\text{c}^2\right) = 3.583 \pm 0.001,$$
$$F_\text{V}\left(q_\text{c}^2\right) = 0.834 \pm 0.011 \quad [3], \quad F_\text{M}\left(q_\text{c}^2\right) = -13.969 \pm 0.052 \quad [3].$$

The values for g_V and g_M are taken from [4] after small corrections for the q^2-dependence (extrapolation from $q^2 = -0.954\ \text{m}_\mu^2$ to $q^2 = -0.88\ \text{m}_\mu^2$). The axial form factor $g_A(0)$ is determined from the neutron β-decay, and its extrapolation to $q^2 = q_e^2$ can be done using νN-scattering data [4]:

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

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 rely only on some theoretical considerations as ν^3He-scattering data are not available at present. According to [3], 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 $\Lambda_c(\mu^3\text{He})$. At the present knowledge of the other form factors, the ultimate precision reachable in measuring the pseudoscalar form factors is

$$\delta g_P/g_P = 2\% \quad \text{if } \delta\Lambda_c/\Lambda_c \leqslant 0.3\%,$$
$$\delta F_P/F_P = 13\% \quad \text{if } \delta\Lambda_c/\Lambda_c \leqslant 2\%.$$

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 with 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 with the corresponding axial form factor:

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

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

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

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

The contribution from the correction terms was expected to be of the order of 10%. Most recently, $g_P(q_c^2)$ was calculated with higher precision in the framework of the heavy barion chiral perturbation theory:

$$g_P(q_c^2) = 8.44 \pm 0.23 \quad [5], \qquad g_P(q_c^2) = 8.21 \pm 0.09 \quad [6].$$

Thus, the QCD chiral perturbation theory predicts $g_P(q_c^2)$ with $\sim$2% precision, and a 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. Therefore, the PCAC prediction for $F_P(q_c^2)$ may be valid only with 10% precision. To a first approximation, the correction term in (4) can be presented as follows:

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

where $g_{\pi^3\text{He}\,^3\text{H}}(q_c^2)$ 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 $g_{\pi^3\text{He}\,^3\text{H}}(q^2)$ 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 $\sim$0.3% precision in ordinary muon capture, OMC reaction (1), or with $\sim$1% precision in radiative muon capture, RMC:

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

Table 1 presents the available experimental data on the OMC rate Λ_c. Most of the measurements have been performed with the neutron detection method. Unfortunately, the precision of this method is limited by uncertainties in the neutron detection efficiency ($\sim$10% at best). Another approach was realized in the Saclay experiment [13] where the μ^- disappearance rate in liquid hydrogen, $\Lambda_- = \lambda_o + \Lambda_c$, was measured and compared (assuming CPT-invariance) with the μ^+ decay rate, $\Lambda_+ = \lambda_o$. In this

Table 1
Present status of $p\mu$-capture measurements.

Year	Exptl. place	H_2-target	$\Lambda_c \pm \delta\Lambda_c$ s^{-1}	$\delta\Lambda_c/\Lambda_c$	Ref.	Method
1962	Chicago	liquid	428 ± 85	20%	[7]	neutron detection
1962	Columbia	liquid	515 ± 85	17%	[8]	”
1962	CERN	liquid	450 ± 50	11%	[9]	”
1963	Columbia	liquid	464 ± 42	9%	[10]	”
1969	CERN	gas, 8 atm	651 ± 57	9%	[11]	”
1974	Dubna	gas, 41 atm	686 ± 88	13%	[12]	”
1981	Saclay	liquid	460 ± 20	4.5%	[13]	life time measurement
1981	Saclay	liquid	$531 \pm 33^*$	6%	[14]	”

* Corrected for ortho-para transitions in the $pp\mu$-molecule.

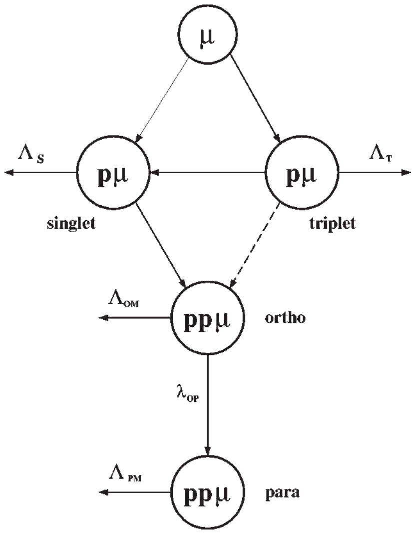

Figure 1. Kinetic scheme of muons stopping in hydrogen.

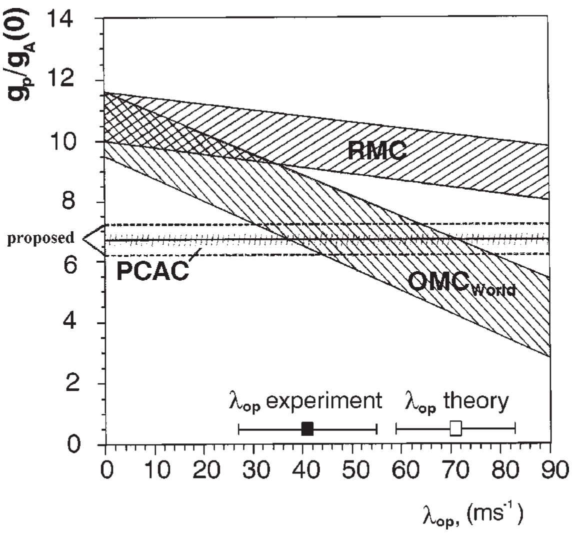

Figure 2. Current constraints on g_p as function of the ortho-para transition λ_{op}.

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 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 with the molecular effects. In a real experiment, muon capture may occur (figure 1) either from the atomic singlet state ($\Lambda_{\text{s}} \simeq 664\ \text{s}^{-1}$) or from the $pp\mu$-orthomolecule

($\Lambda_{\rm om} \simeq 506$ s^{-1}), or from the $pp\mu$-paramolecule ($\Lambda_{\rm pm} \simeq 200$ s^{-1}). The problem is that the ortho-para molecule transition rate, $\lambda_{\rm op}$, is poorly known at present, and the experimental result on $\lambda_{\rm op}$ differs significantly from the theoretical calculations. The uncertainty in interpretation is especially large for μp-capture in liquid hydrogen where muon capture occurs mostly from the $pp\mu$-molecule states. The current situation is illustrated in figure 2. One can clearly see, that the existing data on OMC cannot be used so far for an adequate comparison with theory.

The RMC rate in reaction (6) was studied in a recent experiment at TRIUMF [15]. This experiment is not so sensitive to $\lambda_{\rm op}$. The obtained result corresponds to a value of $g_{\rm P}$ 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.

4. Status of $\mu\,^3$He-capture rate measurements

One of the 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 high efficiency and good background suppression. The kinetic scheme of the $\mu\,^3$He system is shown in figure 3. Muon capture leads with 70% probability to the triton channel, see reaction (2). Capture occurs from the two hyperfine states of the $\mu\,^3$He 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 [1,15], the hyperfine states are statistically populated, and it is the statistical capture rate

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

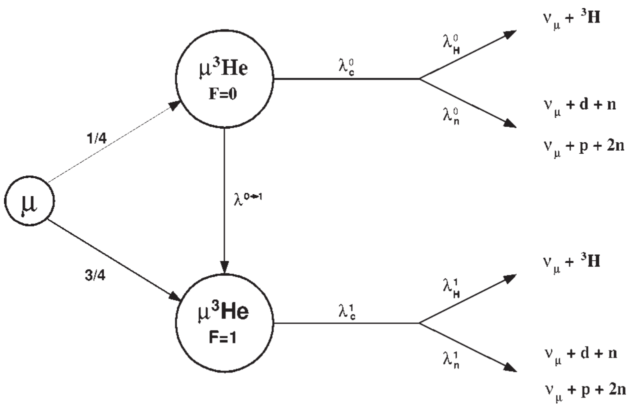

Figure 3. Kinetic scheme of the μ^3He system.

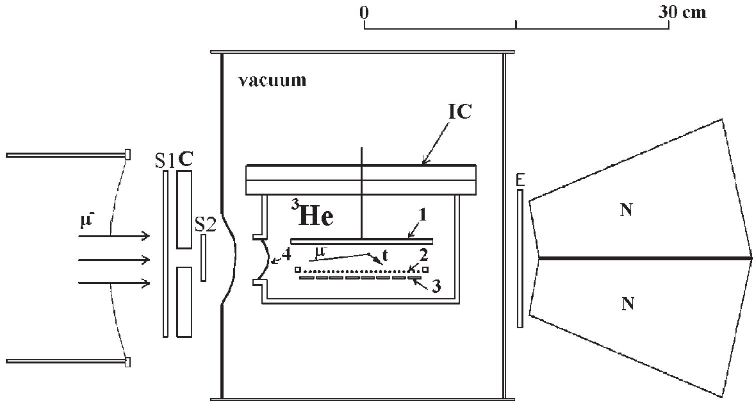

Figure 4. Setup of the $\mu\,^3$He experiment (side view): 1 – cathode; 2 – grid; 3 – block of anodes; 4 – Be window; S1, S2 – scintillator counters; N – neutron counters; E – electron counters; C – collimator. Dimensions: cathode-grid 12 mm, grid-anode 1 mm. Anode area 10 cm^2.

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

Prior to our experiment, there were three measurements of the $\mu\,^3$He-capture rate, all done more than 30 years ago, with a precision in Λ_c ranging from 3% to 10% [16–18]. 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 (figures 4 and 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 $\sigma = 30$ keV (figure 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 $N_t/N_{\mu_{\text{stop}}}$ 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]:

$$\Lambda_{\text{stat}} = (1496 \pm 4)\ \text{s}^{-1}.$$

The interpretation of the results is illustrated in figure 7. The measured value for Λ_{stat} together with the known values for $F_{\text{V}}(q_{\text{c}}^2)$ constrains the allowed region in the $F_{\text{P}}(q_{\text{c}}^2) - F_{\text{A}}(q_{\text{c}}^2)$ plot. Taking into account the $F_{\text{A}}(q_{\text{c}}^2)$ value mentioned above with its error bars, we obtain

$$F_{\text{P}}\left(q_{\text{c}}^2\right) = 20.8 \pm 2.8,$$

where the error is dominated by the error in $F_{\text{A}}(q_{\text{c}}^2)$.

Comparison with $F_{\text{P}}^{\text{PCAC}}(q_{\text{c}}^2) = 20.7$ calculated from the PCAC relation (4) shows a remarkable agreement. The fact that the correction term proved to be insignifi-

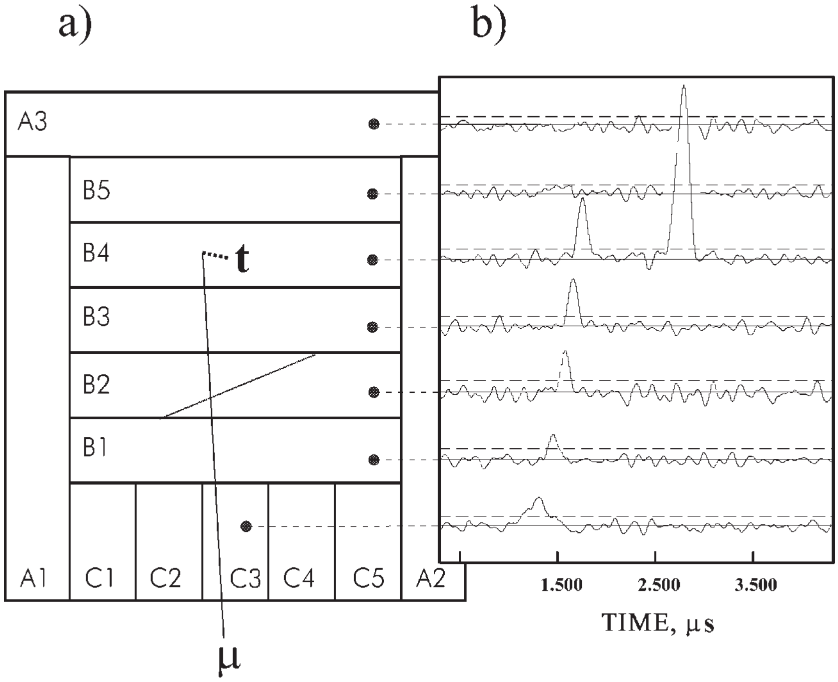

Figure 5. a) Anode layout of the ionization chamber. b) A typical sequence of anode signals registered by flash ADCs.

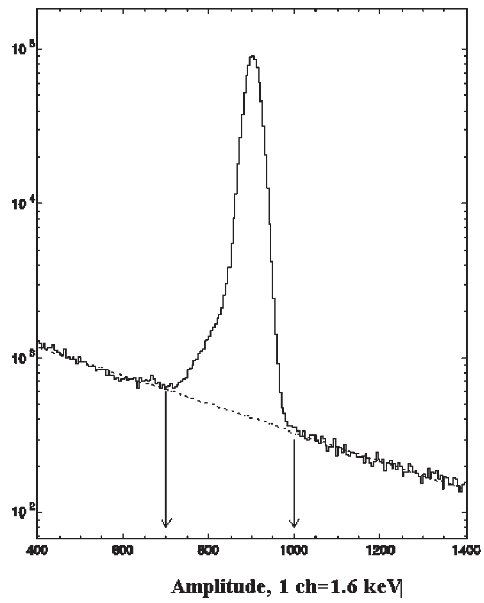

Figure 6. Energy spectrum of the 1.9 MeV tritons from reaction (2) measured with the ionization chamber. The arrows indicate the region of background subtraction.

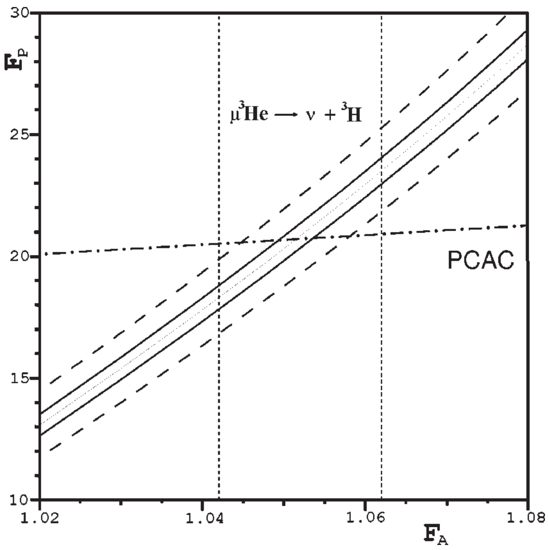

Figure 7. Constraints on F_A and F_P form factors. Solid lines – from Λ_c with its errors only; dashed lines – from Λ_c with errors in F_V and F_M added; vertical lines are the constraints from tritium β-decay; horizontal dash-dotted line is the PCAC relation.

cant means that the q^2-dependences of $F_A(q^2)$ and $g_{\pi^3\mathrm{He}^3\mathrm{H}}(q^2)$ are nearly identical at small q^2. The authors of [19] used this observation to determine $g_{\pi^3\mathrm{He}^3\mathrm{H}}(q_c^2) = 31.9 \pm 1.3$.

5. New project for μp-capture experiment

Recently, our collaboration proposed [20] a new experiment at PSI aiming 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 para molecular 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 the uncertainty in λ_{op}, may introduce less than 1% error to the measured muon capture rate from the singlet μp-state, Λ_S. The experimental method is based on the life-time measurements of negative muons stopped in 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 at the same experimental conditions. The goal is to measure both Λ_- and Λ_+ with at least 10 ppm precision. To avoid possible distortions of the e^+ time distributions caused by polarization of the stopped μ^+-muons, the experimental setup will have a close to 4π-geometry. Note that the negative muons reach the 1S state in the μp-atoms with very low polarization. The 4π-geometry helps also to collect large statistics. The statistics needed for our precision is

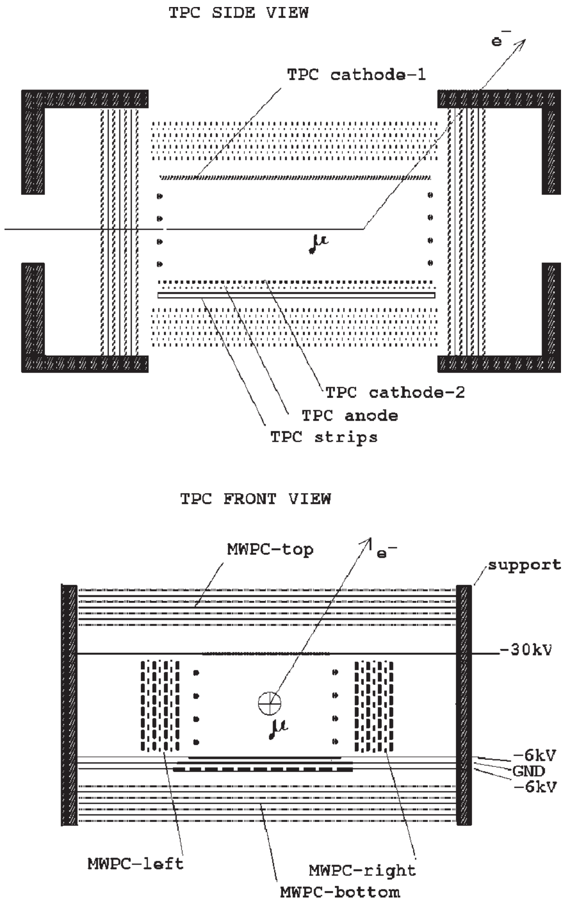

Figure 8. Schematic view of the TPC/MWPC combination.

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 50 kHz. At such rates, there will be more than one muon stop in the detector volume during the measuring time gate 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, tracking back the electron trajectory, one finds the intercept with the muon stop volume thus identifying the parent muon for each decay electron. The proposed detector is shown in figure 8. This is a Time Projection Chamber (TPC) surrounded from all sides by Multi-Wire Proportional Chambers (MWPC). Both TPC and MWPCs are inside a vessel filled with hydrogen at 10 bar pressure. All electrodes are made of wires fixed on the frames outside the sensitive volume. In this way the

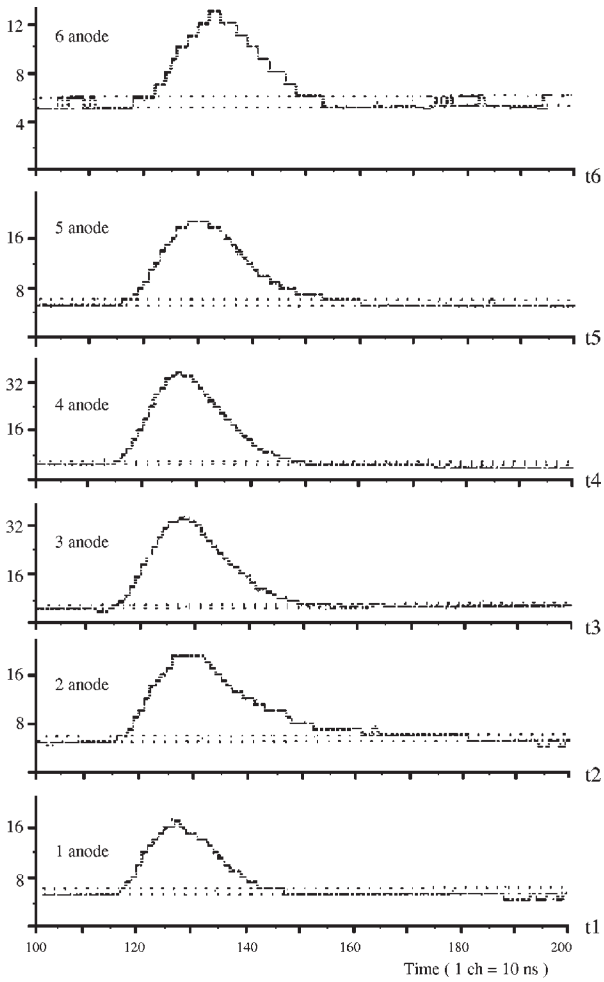

Figure 9. Signals on TPC anode wires from an electron track.

amount of material in this volume is minimized. The TPC provides 3D-information on the muon stops. The MWPCs determine the electron trajectory and the arrival times of the muons and electrons. The TPC can also detect electron signals as demonstrated in figure 9. A serious requirement in this experiment is high gas purity. The contamination by N_2, O_2, H_2O, etc. should be less than 10^{-8}. This requires a special gas circulation and purification system and the control of impurity levels with high sensitivity. Fortunately, our detector can provide such a control by detecting signals from muon nuclear capture on the impurities. 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. The problem is that the $d\mu$-atoms produced by muon transfer from $p\mu$-atoms have rather large ranges due to Ramsauer effect, therefore they may escape from the muon stop region and destroy the correlation with the decay electron trajectory. The diffusion of the μp-atoms enlarges also the μ-stop region. But our calculations showed that the fraction of muons decaying beyond 10 mm from the point of μ-stop is below 10^{-5} even 20 µs after the μ-stop.

There are many technical problems to be solved before such a detector will be fully understood and constructed. Even the operation of the MWPC in 10 bar H_2 is not a trivial task, and the world experience in this field is very limited [21,22]. Preliminary tests at PNPI showed that an MWPC can operate in 10 bar H_2 quite reliably up to gas gains of 5000 which is acceptable for our purposes. A first prototype of the TPC/MWPC detector was designed and constructed at PNPI, and the first test run is scheduled at the end of 1998.

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