A NOVEL MEASUREMENT OF THE MUON CAPTURE RATE IN LIQUID HYDROGEN
BY THE LIFETIME TECHNIQUE

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ABSTRACT

The muon nuclear capture rate by protons has been measured by comparing the lifetime τ_{μ^-} of negative muons stopped in liquid hydrogen with the lifetime τ_{μ^+} of positive muons. We get $\tau_{\mu^-} = (2194.903 \pm 0.066)$ ns and $\tau_{\mu^+} = (2197.182 \pm 0.121)$ ns. Taking into account also the previous determinations of τ_{μ^+} , we present the updated determination of the muon lifetime, and correspondingly we obtain for the capture rate of muons from the $p\mu p$ molecular ions the value $\lambda_c = (460 \pm 20) \text{ s}^{-1}$.

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1. INTRODUCTION

The two main weak processes which contribute to the disappearance of a negative muon stopped in pure hydrogen are the muon decay

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu \quad (1)$$

and nuclear capture

$$\mu^- + p \rightarrow n + \nu_\mu \quad (2)$$

$\hookrightarrow 5.2 \text{ MeV}$

Process (2) takes place only after the muon has formed one of the possible bound systems with the protons of the target.

Reaction (2) in hydrogen is described directly by the elementary muon-proton weak interaction theory¹⁾; under specific conditions, moreover, this process is unambiguously sensitive to the induced pseudoscalar coupling constant g_p^μ , whose value is not well established experimentally.

Among the main difficulties one meets while measuring and interpreting the rate of process (2), the following should be kept in mind: i) in the most favourable case, the rate of process (2) is about 10^{-3} times the rate of process (1); ii) owing to the V-A character of the weak interaction Hamiltonian, the rate of process (2) depends strongly on the total spin state of the muon-proton system, which therefore must be known for a significant comparison with theory; iii) because of the high transfer rates of muons from the primary muonic systems (μp atoms) to deuterons or heavier nuclei¹⁻³⁾, the hydrogen in the target must be highly purified and isotopically pure (protium); iv) in most of the experiments on reaction (2) performed so far⁴⁻⁷⁾, the process was observed by detecting the outgoing neutrons. A significant limitation on the accuracy of these measurements was set by the error with which the absolute efficiency of the neutron detectors was known, as a result of rather elaborate Monte Carlo calculations.

We present here the results of an accurate experimental determination of the capture rate λ_c of process (2), observed stopping negative muons in isotopically pure liquid hydrogen. These results are the first ones obtained by comparing the

disappearance rate $\lambda_- = 1/\tau_{\mu-}$ of negative muons stopped in liquid protium with the disappearance rate $\lambda_+ = 1/\tau_{\mu+}$ of positive muons. Both $\tau_{\mu-}$ and $\tau_{\mu+}$ were measured by detecting the delayed muon decay electrons (lifetime method)^{8,9}. The present method, therefore, does not rely on the detection of the 5.2 MeV neutrons from process (2) to measure λ_c .

Quite generally, after a negative muon has stopped in a liquid-protium target, an atomic system $(\mu p)_{1s}$ is formed in a time shorter than 1 ns; within 500 ns, owing to collisions with the neighbouring hydrogen molecules, such a system gets bound in a $p\mu p$ molecular ion. The strong dominance of the $1s\sigma_g$ ortho-state for the newly formed $p\mu p$ systems is well established by theory¹⁰; the rate λ_{op} of the transition to the ground para-state ($\Delta E_{op} = 148$ eV) is expected to be small¹¹). The experimental upper limit on λ_{op} is^{4,5})

$$\lambda_{op} \leq 5 \times 10^4 \text{ s}^{-1} . \quad (3)$$

If Λ_{om} and Λ_{pm} are the rates of nuclear muon capture in the ortho- and para-molecular states, and Λ_s and Λ_t the rates of capture in the singlet and triplet atomic state, respectively, it has been shown that¹¹)

$$\Lambda_{om} = 2\gamma_0 \left(\frac{3}{4} \Lambda_s + \frac{1}{4} \Lambda_t \right) \quad (4)$$

$$\Lambda_{pm} = 2\gamma_p \left(\frac{3}{4} \Lambda_t + \frac{1}{4} \Lambda_s \right) , \quad (5)$$

where¹²) $2\gamma_0 = (1.01 \pm 0.01)$ and $2\gamma_p = (1.15 \pm 0.01)$. A recent calculation of Λ_s and Λ_t provides¹³) $\Lambda_s = 664 \pm 20 \text{ s}^{-1}$ and $\Lambda_t = 11.9 \pm 0.7 \text{ s}^{-1}$, from which one deduces¹³)

$$\Lambda_{om} = 506 \pm 20 \text{ s}^{-1} \quad (6)$$

$$\Lambda_{pm} = 201 \pm 8 \text{ s}^{-1} . \quad (7)$$

As we will show in the conclusions, a sufficiently significant comparison of our accurate experimental value of λ_c with the theory can be done only if more precise experimental information is obtained about the stability of the $p\mu p$ ortho-molecule. For this reason, at present, using a slightly modified apparatus,

we are performing a measurement which will determine whether the $\text{p}\mu\text{p}$ ortho-molecule is stable, and if not, will provide a value of λ_{op} sufficiently accurate to interpret λ_c in terms of g_p^μ .

2. EXPERIMENTAL SET-UP

The experiment has been performed at the Saclay 600 MeV electron linear accelerator, which supplies a 125 MeV/c μ^+ (π^+) or μ^- beam in bursts 3 μs long at 3000 Hz. The apparatus is shown in Fig. 1. The ultrapure protium*) is contained in a spherical copper vessel (24 cm in diameter and 3.5 mm thick). The target is surrounded by a steel vacuum chamber (1.5 mm thick) and by 6 telescopes, each one made of three 1.5 cm thick plastic scintillators. The muon beam enters the target through a lead collimator and a copper degrader. Most of the muons (90%) stop in hydrogen; the rest in lead and copper, where the negative muons are rapidly captured. It has been checked that less than 10^{-4} of them reach the plastic scintillators or any light material outside the target vessel and the vacuum chamber¹⁴⁾.

The various atomic and molecular processes which occur when a negative muon is stopped in liquid hydrogen are known¹⁾, and summarized in Fig. 2. Before the muon has formed a $\text{p}\mu\text{p}$ system, it can be transferred to a deuteron or to a high-Z nucleus. When the measurement starts, the muons are almost entirely within $\text{p}\mu\text{p}$ molecular ions: only a small fraction of them are bound in other muonic systems ($\mu^3\text{He}$ or eventually in a $\mu_Z\text{Y}$ atom -- $_Z\text{Y}$ being an extraneous impurity), where the nuclear capture rate is higher. The most dangerous impurities for the present purposes are the intermediate-Z elements (O, N, Ne ...): their concentration must be smaller than 5×10^{-9} in order that their effect on the present lifetime measurements be smaller than $10^{-5} \tau_\mu$ ¹⁴⁾. Such a level of purity is usually obtained by a palladium purifier.

A concentration of a few ppm of deuterium is acceptable; the relevant correction can in fact be calculated from the corresponding parameters of the chain in Fig. 2, which are known¹⁾.

*) The protium gas was supplied by the Département des Radioisotopes, CEN, Saclay, where the spectroscopic analysis was done.

Before purification the protium gas was analysed by a mass spectrometer¹⁴⁾ many times during the course of the experiment: the deuterium concentration was found to be $c_D = (2.7 \pm 0.1)$ ppm, while the concentration of intermediate Z elements (O, N, Ne ...) was found to be less than 200 ppm. The target was filled through a palladium purifier, according to the diagram of Fig. 3. The efficiency of the palladium filter was measured by applying on the input side a neon or nitrogen pressure of 5 bars. The corresponding rate of pressure rise in the target was then less than 10^{-4} Torr/h, ensuring an impurity leaking of less than 10^{-9} in concentration during the filling operations with the protium gas. Before each run, the target was evacuated by a cryogenic pump down to 2×10^{-7} Torr and baked for several days, until the outgassing was found to be less than 10^{-4} Torr/d at room temperature. The much lower outgassing one expects at the temperature of liquid hydrogen (that is in the ordinary working conditions) corresponds to a contamination well below the 10^{-9} concentration level requested for the present measurements¹⁴⁾.

In the apparatus shown in Fig. 1, a decay electron is defined by a triple coincidence between the scintillators of a telescope. The threshold of each counter is set at 2 MeV; both the triple coincidence request and the total energy threshold (6 MeV) bring down to a very low level the main time-dependent background (which is due to γ -rays from neutron capture).

A 65 μ s gate (G_1) starts 1 μ s after the beam burst (see Fig. 4), when all the high-Z muonic atoms have disappeared by muon capture and the linac RF is sufficiently cut down to make impossible the creation of any further muon. Three 80 μ s gates (G_2 , G_3 , and G_4) are opened in sequence in order to study the delayed background, starting 65 μ s after the beam burst. The total amount of events in G_2 , G_3 , and G_4 are recorded.

The gate G_1 opens 6 digitrons, supplied by a single 500 MHz quartz oscillator (stable to better than 10^{-5}). The digitrons were calibrated by referring to the official time, and the average channel width was found to be 1.99989(1) ns.

Each digitrone is closed by the first triple electron event of the corresponding telescope. This method gives the exact time distribution of the electrons,

provided no more than 1 event occurs in the gate from each telescope. The multiple events (about 10%) are rejected by a proper electronic circuit. The efficiency of the multiple rejection was checked by measuring a flat distribution from a radioactive source (see Fig. 5). The same distribution is also a test of the linearity of the digitrons. The difference between the number of events in the odd and even channels is 2%, indicating a slightly larger width of the odd channels. The effect on the muon lifetimes of such a difference has been calculated to be smaller than $10^{-6} \tau_{\mu}$.

3. DATA TAKING AND ANALYSIS

A total amount of 1.3×10^9 events of μ^- decay in purified protium were recorded during 6 runs, between June 1978 and September 1979. The average rate of decay electrons (per telescope and gate) was $r = 0.08$. During three runs in the same period, 3.8×10^8 events of μ^+ decay were gathered, at an average rate $r = 0.1$. For each μ^- and μ^+ run, about $10^8 \mu^+$ events were recorded, at an average rate $r = 0.5$, in order to measure the rate effects.

The μ^+ data were taken stopping a π^+ beam in such a way as to reduce the polarization effects. The residual polarization of the beam (due to the μ^+ 's from π^+ decays in flight) was about 5%. The relevant effect was evaluated by taking data with a μ^+ beam, 80% polarized. Two different effects could influence the measurement: i) The depolarization of the muons during the μ^+ lifetime (such an effect was observed for instance with a Be target). ii) The precession of the muon spin in the residual magnetic field; this effect would show up by comparing the results obtained in the different telescopes. However, owing to the symmetry of the detectors around the beam axis, in practice most of this effect was cancelled in the present measurements.

Therefore, most of the π^+ data were taken by stopping the beam in a sulphur target (where the muons are known to depolarize rapidly). Some of the π^+ runs were taken with the protium target surrounded by a magnetic shield. In both cases, the polarization effects were shown to be negligible.

For both μ^+ and μ^- data, the rate $R(t)$ of single events is expected to follow the exponential law

$$R(t) = R_0 \exp(-\lambda t) . \quad (8)$$

The actual distribution, instead (see Fig. 6), must account for the following additional small terms:

i) A physical background, which is made of a flat component in addition to a slowly-varying one. The constant part, which is easily measured, is mainly due to cosmic rays. Its level is about $10^{-4} R_0$. The small time-dependent component (level of $10^{-5} R_0$ with a period of about 160 μ s) is observed in the delayed part of the distribution, and is presumably due to γ -rays from the capture of slow neutrons. In order to check its behaviour in the earlier part of the gate (during the muon lifetime), data have been taken with negative muons, keeping the target empty (see Fig. 7). The background extrapolated from the delayed part of the spectrum fits correctly the experimental points, except for a very short-lived component due to the muons stopped in copper, and for a small contribution due to the muons stopped in the plastic scintillators. These two components are enhanced by a factor of about 10 in the empty target with respect to the full target case, where their effect is negligible.

ii) A distortion of the exponential law, due to rate effects. The amplitude of these effects is proportional to r (rate of events per gate).

In previous work^{8,9,14}) it was shown that the distortion due to the finite resolution of the electronics (which is the main source of the rate effect) is proportional to the square of the exponential in Eq. (8).

The actual rate is then

$$R(t) = R_0 [\exp(-\lambda t) + A r \exp(-2\lambda t) + B] , \quad (9)$$

where

$$B = B_0 + B_1 \exp(-t/T) \quad (10)$$

and $T = 160 \mu$ s.

The exact formula can still be slightly different for higher order effects. For example, in the μ^- data an ortho-para transition in the initial state would induce a non-exponential decay. A rate effect of a different shape can also be induced by a non-constant response of the phototubes illuminated during the beam burst. Therefore, the final correction to the rate effect is best obtained by extrapolating the results from high-rate and low-rate data to $r = 0$.

The data have been analysed in two different ways:

i) The Peierls method¹⁵⁾. The B term obtained from the delayed events was subtracted out first, and the mean lifetime was calculated according to the formula

$$\tau_{\text{exp}} = \left(\sum_1^K n_i t_i \right) / \left(\sum_1^K n_i \right) + \epsilon_K . \quad (11)$$

The error $\Delta\tau_{\text{exp}}$ and the correction ϵ_K due to the limitation $i < K$ ($t_K = 15 \mu\text{s}$) of the integration are calculated as shown by Peierls¹⁵⁾. The muon lifetime is then given by

$$\tau_{\mu} = \tau_{\text{exp}} (1 + ar) \quad (12)$$

[the rate effect of formula (9) corresponds to $a = A/4$]. For each run, the value of a was obtained by comparing the result of the high-rate μ^+ data with the expected value of τ_{μ^+} . This value, arbitrarily assumed at first, was varied by iteration to coincide with the final result of τ_{μ^+} . Table 1 gives the values obtained from the analysis of the different μ^+ and μ^- runs. The χ^2 's are obtained assuming that the rate effect has the shape given by Eq. (9).

ii) The best-fit method. The lifetime values were also obtained by fitting the data to Eq. (9). For each run, the value of A was determined from a fit of the high-rate μ^+ data; the values of τ_{μ^+} and τ_{μ^-} were obtained in turn by fitting the low-rate data, A being constrained by the high-rate data fit. The average value of τ_{μ^+} from the high-rate data, although inaccurate, is slightly lower than the corresponding low-rate value: this difference is interpreted as a residual rate effect, and the low rate values of τ_{μ^-} and τ_{μ^+} are corrected in consequence.

4. RESULTS AND DISCUSSION

The final lifetime values obtained by the Peierls method (combining the different runs) are listed in Table 2. The χ^2 values indicate the compatibility between the various runs and demonstrate the stability of the apparatus during the experiment.

The final results obtained by the best-fit method are also reported in the table. One can see that the agreement between the two different procedures is rather good, both for the values $\tau_{\mu+}$ and $\tau_{\mu-}$, and for the rate effect corrections and background parameters.

In order to treat later the effect of a possible ortho-para transition, we shall retain for the present the value of $\tau_{\mu-}$ obtained from Eq. (12), which has a simpler mathematical meaning [see Eq. (11)]

$$\tau_{\mu-} = (2194.903 \pm 0.066) \text{ ns} . \quad (13)$$

The value of $\tau_{\mu+}$ obtained from the present measurements

$$\tau_{\mu+} = (2197.182 \pm 0.121) \text{ ns} \quad (14)$$

is in fair agreement with the world-average value $\tau_{\mu+}^W = (2197.134 \pm 0.078) \text{ ns}^{16}$. Combining the value of Eq. (14) with $\tau_{\mu+}^W$ we get

$$\tau_{\mu+} = (2197.148 \pm 0.066) \text{ ns} , \quad (15)$$

which updates the determination of the muon lifetime.

To deduce from the values (13) and (15) the muon capture rate in liquid hydrogen λ_c , the following corrections still have to be performed:

- i) A small relativistic effect is to be taken into account, owing to the fact that the decaying negative muons are bound. The effect, as calculated by Uberall¹⁷⁾ is to lower the observed capture rate by 6 s^{-1} .
- ii) As was already said, the protium contains $2.7 (0.1) \text{ ppm}$ of deuterium; therefore, a small number of μd , $\mu p d$, and $\mu^3\text{He}$ systems are formed (see Fig. 2), where the negative muons can undergo nuclear capture. Owing to this fact, a correction of $(+18 \pm 4) \text{ s}^{-1}$ must also be taken into account.

Once these effects are included, we get

$$\lambda_c = (460 \pm 20) \text{ s}^{-1}. \quad (16)$$

Taking into account for $\tau_{\mu+}$ only the value (14), obtained with the present apparatus (see Table 2), we get

$$\lambda_c = (467 \pm 29) \text{ s}^{-1}. \quad (17)$$

To deduce from value (16) an experimental determination of Λ_{om} , some hypothesis has to be made regarding the rate λ_{op} with which the $p\mu p$ system undergoes the ortho-para transition.

To evidence out this point, we have done a calculation computing the expected electron yield $N_e(t)$, assuming the chain of processes shown in Fig. 2 (with $c_y = 0$). From $N_e(t)$ the theoretical capture rate [to be directly compared with the experimental value (17)] is defined as

$$\lambda_c = \frac{\int_{T_1}^{\infty} N_e(t) dt}{\int_{T_1}^{\infty} t N_e(t) dt} - \lambda_o, \quad (18)$$

where T_1 is the beginning of the gate G_1 and the incoming muons are contained in an interval of time as shown in Fig. 4. Of course value (18) will depend also on the values of Λ_{om} [or better on λ_s as shown by formula (4)] and of λ_{op} assumed in the computation.

In Fig. 8 the region of values of Λ_{om} and λ_{op} compatible with our experimental result (16) is shown (dashed line). In the same figure is also shown the region defined by the Columbia group result (i.e. $\lambda_c'' = 465 \pm 42 \text{ s}^{-1}$)⁵, after taking into account the different experimental conditions.

From Fig. 8 one sees that:

- i) With the present novel technique it has been possible to reduce the experimental inaccuracy on Λ_{om} by more than a factor of two.
- ii) The agreement between the present experimental result and the Columbia group result is good.
- iii) The agreement between the experimental value (16) and the theoretical value (6) is poor unless $\lambda_{op} \neq 0$.

In any case we have to conclude that the lack of more precise information on λ_{op} precludes, at present, the full exploitation of the more accurate result (16) to infer information on g_p^{u} and carry out a more detailed comparison with the previous experimental results^{4,5)} on process (2).

Because of this fact we have surrounded the target also with neutron counters, to detect the 5.2 MeV outgoing neutron in process (2). As was shown in Ref. 4, in fact, a comparison between the time distribution of the neutron events with the time distribution of the detected negative electrons [and assuming the V-A theory for process (2)] gives information on the ortho-to-para conversion rate λ_{op} . Preliminary results¹⁸⁾ of these measurements show an effect corresponding to $\lambda_{\text{op}} \approx 5 \times 10^4 \text{ s}^{-1}$.

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be the subject of a forthcoming paper.

Table 1

Results of the different μ^- and μ^+ runs on the lifetime of positive muons and of negative muons stopped in liquid hydrogen, as obtained by the Peierls method. $(\Delta\tau)_r$ and $(\Delta\tau)_{B_1}$ are the corrections due to the rate (r) effect and to the time-dependent background (B_1), respectively. The χ^2 values are obtained by comparing the experimental points according to the prediction of formula (9) with parameters τ_μ , A, B_0 , B_1 obtained by the Peierls method.

Run		Events (in 10^8 units)	r (Event/gate)	$(\Delta\tau)_r$ (ns)	$(\Delta\tau)_{B_1}$ (ns)	τ_μ (ns)	χ^2 for 500 D. of F.
μ^-	1	2.00	0.106	0.421	-0.296	2195.045(173)	512
	2	1.20	0.052	0.418	-0.095	2194.652(220)	466
	3	1.11	0.053	0.130	-0.089	2194.806(220)	472
	4	1.13	0.064	0.210	-0.096	2194.785(217)	511
	5	4.26	0.068	0.146	-0.046	2195.068(113)	436
	6	3.32	0.116	0.330	-0.164	2194.766(131)	496
μ^+	1	0.96	0.114	0.455	-0.124	2197.155(244)	524
	2	0.63	0.109	0.884	-0.048	2197.336(296)	466
	3	2.24	0.101	0.383	-0.011	2197.150(157)	496

Table 2

Results on the μ^- and μ^+ lifetimes obtained from the present data by combining all the runs listed in Table 1. The results in the first row are those obtained by the Peierls method; the results in the second row are those obtained by the best-fit method.

Muon	Events (in 10^8 units)	r	$(\Delta\tau)_r$ (ns)	B_0 (in 10^{-4} units)	B_1 (in 10^{-5} units)	τ_μ (ns)
μ^-	13.01	0.083	0.265	2.58	1.71	2194.903(066)
			0.236	2.59	1.67	2194.872(073)
μ^+	3.83	0.106	0.483	2.11	0.66	2197.182(121)
			0.492	2.06	0.89	2197.183(154)

Figure captions

- Fig. 1 : Simplified scheme of the experimental arrangement: Pb = lead collimator; Cu = copper degrader; C = copper vessel; T = steel chamber; SC = plastic scintillator telescopes.
- Fig. 2 : Muon chemistry in liquid hydrogen. At any time, the muon can decay (rate λ_0) or be captured in various atomic or molecular systems. The dashed line represents the transfer to a possible impurity ${}_ZY$. For the rates λ_{pp} , λ_{pd} , λ_f and λ_Y , and for ϵ , measured by different authors, see Refs. 1-3 ($1/\lambda_{pp} \approx 200$ ns, $1/\lambda_{pd} \approx 160$ ns).
- Fig. 3 : Scheme of the target filling device. The protium gas is contained in a 1 m³, 10 bars tight tank. The target is filled through V_1 , V_2 , and V_3 , the palladium filter, and a heat exchanger. After one run, the target is emptied through V_4 and V_1 .
- Fig. 4 : Relative timing of the various gates used to observe the muon decay and the background counts. G_1 is the digitron gate. G_2 - G_4 are calibrated to 80 μ s by a quartz oscillator.
- Fig. 5 : Time distribution recorded by the present apparatus for delayed random coincidences obtained from a radioactive source. The flat distribution is the one recorded when the multiple rejection circuit was operating. The slope of the other distribution (no multiple rejection), which corresponds to a rate of 4950 s⁻¹, emphasizes the importance of the multiple rejection operation. The two spectra have been normalized to the same number of events in the first channel. The response of the digitron with the multiple rejection circuit is constant ($\chi^2 = 32$ for 39 degrees of freedom).
- Fig. 6 : Typical time distribution of the events from negative muons stopped in liquid protium.

Fig. 7 : Time distribution recorded after stopping negative muons in the empty target. The energy of the muon beam in this case was lowered, to compensate for the liquid hydrogen stopping power, so that the muons are stopped in the inner part of the target walls. The continuous curve fitting the experimental points is obtained by adding the contributions of the background C obtained from the delayed events, of the exponential B ($T = 1.9 \mu s$) coming from the muons stopped in the plastic scintillators, and of the exponential term A ($T = 160 \text{ ns}$) corresponding to the muons stopped in copper.

Fig. 8 : Muon capture rate (Λ_{om}) in the ortho-state of the $p\bar{p}p$ molecule as a function of the ortho-para transition rate λ_{op} : regions of values allowed (a) by the present experimental result [see Eq. (16)] (included within the full lines); (b) by the previous experiment at Columbia (see Ref. 5) (included within the dashed lines); (c) by the theoretical value¹³⁾ -- Eq. (6) -- (included within the dashed-dotted lines).

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8