# A NEW MEASUREMENT OF THE POSITIVE MUON LIFETIME

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We present a new measurement of the positive muon lifetime by a pulsed-beam technique. The result is $\tau_\mu^+ = 2197.078 \pm 0.073$ ns.

*1. Introduction.* A technique to measure the muon lifetime has been developed, using the pulsed beam of the Saclay linear accelerator [1]. A muon source is built up by stopping positive pions or muons during the 3 $\mu$s beam burst of the Linac. The time distribution of the $\mu$-decay positrons is measured after the burst. It has to be emphasized that this technique allows, in the period following the end of the beam burst, the simultaneous observation of several stopped muon decays; this fact results in an effective lowering of the background level which is mainly due to cosmic rays and to the beam induced background. A precise measurement of the $\mu^-$ lifetime in liquid hydrogen was carried out in 1981 by this method [2,3]; the comparison with the world average value of the $\mu^+$ lifetime ($\tau_{\mu^+}$) gave the nuclear muon capture rate in liquid hydrogen with a precision of 4%, avoiding the problems associated with the neutron detection. But few $\mu^+$ data were taken at that time, and the corresponding precision on $\tau_{\mu^+}$ was limited. We report here on a high-statistics measurement of the $\mu^+$ lifetime performed by the same technique. Particular care has been used to take into account the polarization effects. Indeed, contrary to the negative muons, which are totally depolarized in liquid hydrogen by cascading down to a singlet S state, the positive muons may have a residual polarization, which is a dangerous source of systematic errors. A set-up has been designed in order to minimize these effects, and measurements have been made to determine their upper limit.

*2. Experimental set-up.* A 140 MeV/$c$ $\pi^+$ beam is stopped in a sulphur target. The stopped pions provide an unpolarized muon source, but the beam contains a fraction (about 5%) of polarized muons from pion decay in flight. The sulphur is known to depolarize the muons rapidly [4]. The target (see fig. 1) has been designed to minimize the number of muons stopped outside the sulphur target. The best geome-

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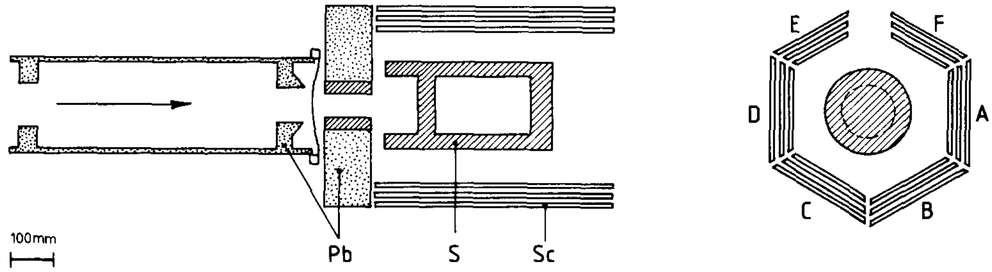



Fig. 1. Simplified scheme of the experimental set-up: Pb = lead collimator, S = sulphur target, Sc = plastic scintillator telescopes, placed at the positions A, B, C, D, E and F around the target.

try, obtained from a Monte Carlo calculation, is a cylinder with a thick bottom for stopping the high-energy muons due to forward $\pi^+$ decays in flight (forward muons). The target region is surrounded by two large Helmholtz coils (150 cm in diameter) in order to compensate the residual magnetic field (mainly the terrestrial field).

The detectors and the associated electronics are described elsewhere [2,3]. The $\mu^+$ decay positrons are measured by six telescopes of plastic scintillators. The axial symmetry along the beam and the large solid angle ($\Omega/4\pi$ = 75%) help to suppress the polarization effects. The positron time distribution is measured using six 500 MHz [1,3] clocks during the 65 $\mu$s gate, which is started 1 $\mu$s after the beam burst. Then three 80 $\mu$s gates are successively opened to study the delayed background.

*3. Polarization effects.* The number of muon-decay positrons, emitted in a direction defined by the unit vector $\boldsymbol{u}$, is proportional to

$$D = 1 + \alpha \boldsymbol{P} \cdot \boldsymbol{u} , \qquad (1)$$

where $\boldsymbol{P}$ is the polarization of the positive muon, and $\alpha$ depends on the energy of the detected positrons (in the present experiment, $\alpha \cong 0.4$). Unless the detection system is totally isotropic, any time dependence on $\boldsymbol{P}$ produces a distortion of the exponential distribution and a systematic error on $\tau_{\mu^+}$. The vector $\boldsymbol{P}$ can either vary owing to spin precession around the magnetic field, or decrease in amplitude owing to the depolarization process.

To determine the precession effect, several measurements have been performed in various conditions of the muon polarization, the magnetic field and the stopping target. In fig. 2 the polarization effect shows up clearly in the observed values of $\tau_{\mu^+}$ as a function of the telescope position around the target. A large effect is obtained with a polarized muon beam ($P$ = 80%) stopped in a carbon target with a 5 G magnet-

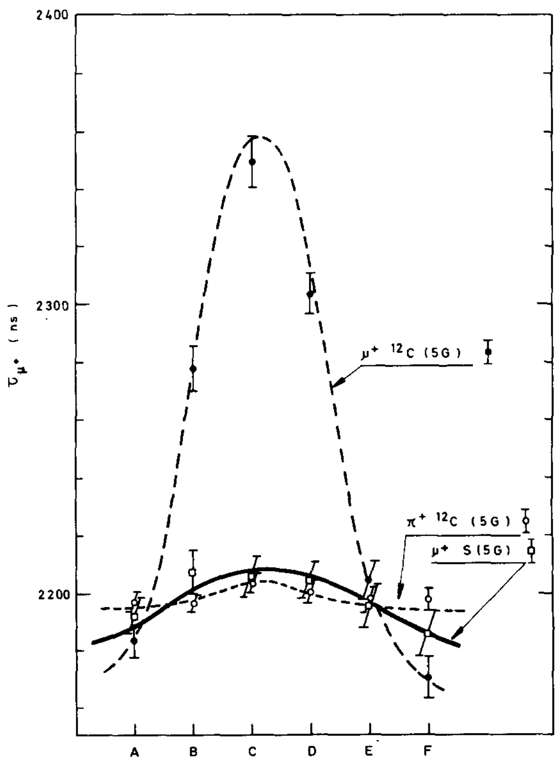



Fig. 2. Display of the observed values of $\tau_{\mu^+}$ as a function of the telescope position (see for reference fig. 1) around the target. The experimental points correspond to $\mu^+$ or $\pi^+$ beams, stopping in carbon ($^{12}$C) or sulphur (S) target, and to a 5 G magnetic field.

ic field: the value of $\tau_{\mu^+}$ averaged over the six telescopes turns out to be too high by 50 ns. Replacing carbon by sulphur reduces the effect by a factor larger than 7, and another reduction factor of 30 is obtained by switching from the $\mu^+$ beam to a $\pi^+$ beam. These results can be explained as follows. The muons are totally depolarized in sulphur when the measurement starts (relaxation time: 30 ns), but a residual effect is brought about by the "forward muons" stopping outside the sulphur target. The relative number of these muons has been measured with a negative pion beam with the same characteristics. Negative pions and muons stopped in sulphur are rapidly captured, and the amount of muons stopped in the scintillators can be extracted: it is less than $7 \times 10^{-3}$. By simulating these various processes with a Monte Carlo program, we have been able to reproduce the results of fig. 2. The corresponding precession effect was also calculated in the experimental conditions where the magnetic field is reduced to 0.1 G, thereby compensating the earth's magnetism. We found a residual precession effect on $\tau_{\mu^+}$ smaller than 0.01 ns. Moreover, according to existing data on relaxation times [4], the depolarization effect of these muons turns out to be negligible.

Some data (16%) have been taken with a $\pi^+$ beam stopped in the liquid hydrogen target [2]. The magnetic field in the stopping region was reduced to 0.01 G by surrounding the target with a 2 mm thick mu-metal cylinder. But in this case two dangerous distortions have to be considered. The "forward muons" can stop in the mu-metal and give a precession effect, and the muons stopped in the copper walls at low temperature are depolarized with a relaxation time of 5 $\mu$s [5]. For the two effects, an upper limit of 0.06 ns on $\tau_{\mu^+}$ has been deduced from a measurement with a polarized muon beam and the results of a Monte Carlo calculation.

*4. Data taking and analysis.* The data were taken during several runs of about 5 days each. The time distribution $R(t)$ (see fig. 3a) from each telescope were recorded on magnetic tape every four hours, in histograms of about $3 \times 10^6$ events. The rate of events was limited to $r = 0.1$ electrons per gate and per telescope, by reducing the pion-beam intensity. High-rate data ($r = 0.5$) were also taken during about 10% of the time to determine the rate effect. As established previously [1,2], the time distribution has the following form:

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

where $\lambda$ represents the muon-decay rate to be measured. The first term represents the expected pure exponential law. The second term includes all the corrections proportional to the rate coming from the finite resolution of the electronic circuits. (The average value of $A$ is $\cong 4 \times 10^{-3}$). The background $B$ can be written as

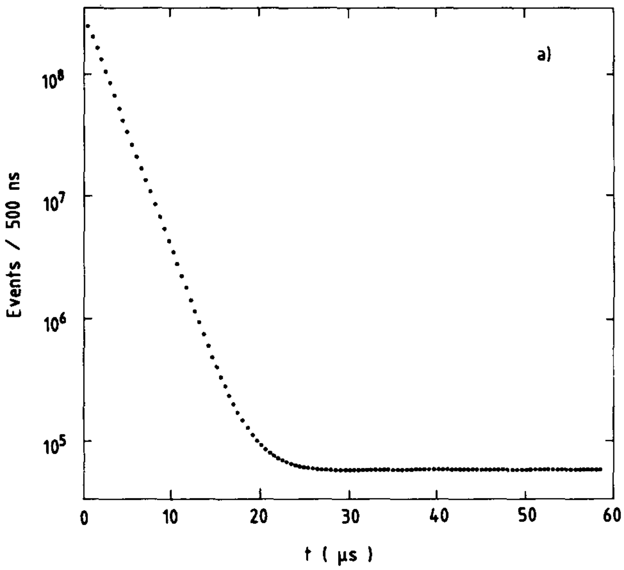
$$B = B_0 + B_1 \exp(-t/T) \quad (T = 160 \, \mu\text{s}). \qquad (3)$$

The constant term $B_0 \cong 2 \times 10^{-4}$ is due to cosmic rays. The small time-dependent term $B_1 \cong 5 \times 10^{-6}$ is due to X-rays from thermal neutron captures [2, 6]. The background, whose parameters $B_0$, $B_1$, and $T$ are accurately measured between two bursts, is first subtracted from the content of each channel according to a procedure defined previously [2]. The mean lifetime of the remaining events is calculated according to

$$\tau_{\mu^+} = \left(\sum_1^k n_i t_i\right) \Big/ \left(\sum_1^k n_i\right) + \epsilon_k \,, \qquad (4)$$

where $n_i$ represents the content of the channel $i$ and $\epsilon_k$ is a correction for the finite integration $k$. Following the procedure described elsewhere [2], the correction for the rate effect is determined for each run by comparing the value of $\tau_{\mu^+}$ obtained from the high-rate data with an expected value $\tau_R^+$. This value, arbitrarily assumed at first, is varied by iteration until it coincides with the final result of $\tau_{\mu^+}$. The correction found in this way is checked in fig. 4, which shows the values of $\tau_{\mu^+}$ obtained analysing the data with different initial times, corresponding to different initial rates. Both corrections depend on the electronics and beam settings and vary slightly with the experimental periods.

The data were also analysed by fitting the low-rate and the high-rate data to formula (2). The values of the parameters $\lambda$, $A$, $B_0$, $B_1$, and $T$ obtained in this way were found to be in agreement with those provided by the mean lifetime method [see eq. (4)] and by the measurements of $A$, $B_0$, $B_1$, and $T$.



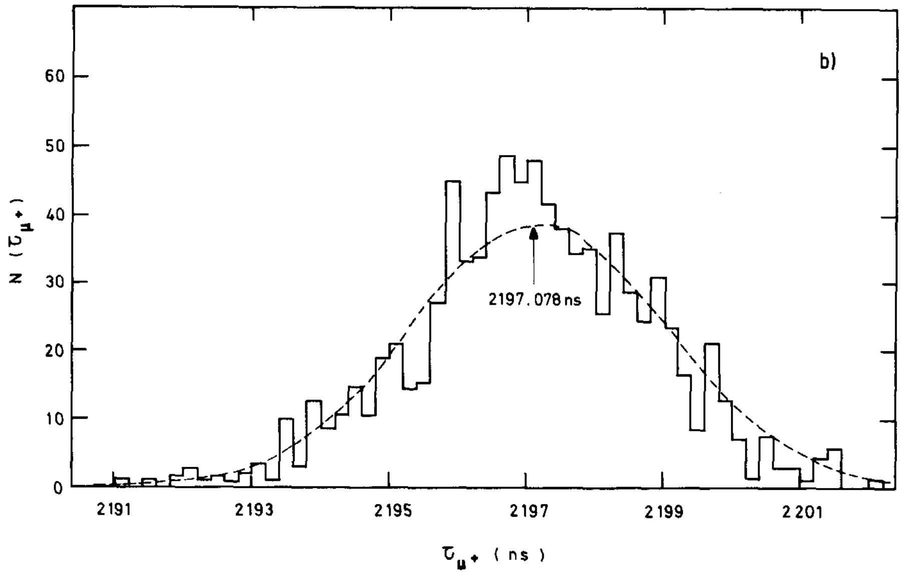




Fig. 3. (a) Typical time distribution of the observed events. (b) Distribution of the $\tau_{\mu^+}$ values as observed by the different telescopes in the different partial runs.

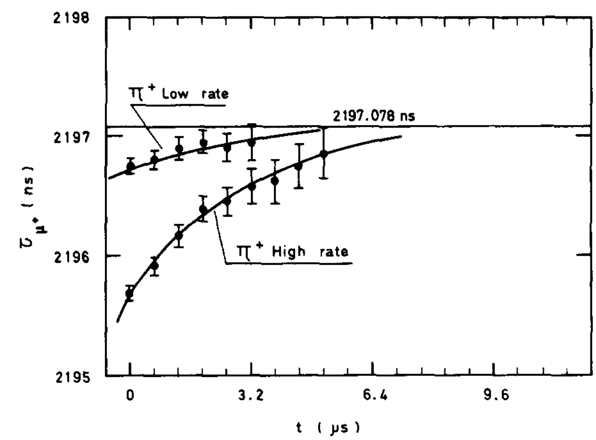



Fig. 4. Rate dependence of the observed values of $\tau_{\mu^+}$, as obtained by analysing the data starting from different initial times $t$ within the measuring gate.

Table 1
Results of the different runs. The first three runs contain the data already published [2]. The runs taken with the liquid-hydrogen and sulphur target are labeled by LH and S, respectively. $\delta\tau_r$ and $\delta\tau_{B_1}$ are the corrections due to the rate ($r$) and to the time-dependent background ($B_1$) effects, respectively. The $\chi^2$ values are obtained by comparing the number of events in the first 500 (32 ns) channels with the predictions of formula (2), using the experimental values of $\lambda, A, B_0$, and $B_1$.

| Run | Events (units of $10^8$) | $r$ (events per gate) | $\delta\tau_r$ (ns) | $\delta\tau_{B_1}$ (ns) | $\tau_{\mu^+}$ (ns) | $\chi^2$ (500 dof) |
|---|---|---|---|---|---|---|
| 1 LH | 0.96 | 0.118 | 0.435 | −0.123 | 2197.136 (0.245) | 524 |
| 2 LH | 0.63 | 0.110 | 0.862 | −0.000 | 2197.362 (0.297) | 466 |
| 3 S | 2.24 | 0.112 | 0.388 | −0.011 | 2197.151 (0.159) | 496 |
| 4 LH | 0.43 | 0.134 | 0.306 | −0.011 | 2196.945 (0.350) | 513 |
| 5 S | 2.20 | 0.110 | 0.294 | −0.013 | 2196.588 (0.162) | 498 |
| 6 S | 1.48 | 0.107 | 0.311 | −0.026 | 2197.153 (0.205) | 515 |
| 7 S | 4.60 | 0.104 | 0.239 | −0.013 | 2197.213 (0.111) | 503 |

*5. Results.* The lifetime values obtained for the different runs are listed in table 1. The value of $\tau_{\mu^+}$ measured in liquid hydrogen is in good agreement with the results obtained from the sulphur target. The muon lifetime, after combining all the runs, turns out to be

$$\tau_{\mu^+} = 2197.078 \pm 0.073 \text{ ns}. \tag{5}$$

This result is an updated value for the measurement done at Saclay by the pulsed beam technique since 1978, and includes the value of $\tau_{\mu^+}$ already published [2,7]. The quoted error takes into account the weighted average uncertainties due to the polarization effects ($\delta\tau_P = 0.020$ ns). The total error due to the rate effects is $\delta\tau_r = 0.027$ ns, and includes the uncertainty on the expected value $\tau_R^+$, which, after iteration, becomes equal to the result (5). The overall error due to the time-dependent background correction $B_1$ is $\delta\tau_{B_1} = 0.010$ ns. Fig. 3b is a histogram of the different values of $\tau_{\mu^+}$ obtained from each telescope and each elementary sequence of the various runs. The distribution is correctly fitted by the expected gaussian curve with a $\chi^2$ value of 92 for 80 channels.

*6. Discussion.* The value (5) [‡1] is in good agreement with the world average value corresponding to measurements performed before 1978: $\tau_{\mu^+}^{W} = 2197.120 \pm 0.077$ ns. Combining the value (5) with $\tau_{\mu^+}^{W}$ we get $\tau_{\mu^+}^{c} = 2197.093 \pm 0.052$ ns [‡2].

In order to compare $\tau_{\mu^+}^{c}$ with the lifetime of the free negative muons, $\tau_{\mu^-}^{f}$, we assume for the latter parameter the value measured by us in liquid hydrogen [2,3,9,10] and we correct it, taking into account the muon nuclear capture rate and the ortho-to-para transition rate obtained in liquid hydrogen by measuring the neutron yield [6,10,11]. We get in this way:

$$\tau_{\mu^-}^{f} = 2197.025 \pm 0.155 \text{ ns}. \tag{6}$$

If compared to the $\mu^+$ lifetime [see eq. (5)], the value (6) corresponds to the ratio

$$R_{CPT} = [(\tau_{\mu^+}^{c}) - (\tau_{\mu^-}^{f})]/\tau_{\mu^+}^{c} = (3 \pm 8) \times 10^{-5}, \tag{7}$$

which represents a test of validity of the *CPT* theorem in the muon decay to within $8 \times 10^{-5}$.

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‡1 The value of the positive muon lifetime quoted in ref. [8] contains some of the data used to obtain the result of eq. (5).

‡2 From this value, and the published values of the fundamental constants (see ref. [8]), one gets for the Fermi coupling constant the value $G_\mu = (1.16633 \pm 0.00002 - \delta) \times 10^{-5}$ GeV$^2$. Here $\delta$ is a term including radiative corrections of order higher than 2 (only partially calculated).

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