Measurement of the lifetime of the positive muon

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The lifetime of the positive muon was measured using the synchrocyclotron of the Nuclear Problems Laboratory at the Joint Institute for Nuclear Research. The mean life of the positive muon was found to be 2.19711±0.00008 μsec. The decay positrons were registered with a Cerenkov counter, which had a water radiator that also served as the target and was so designed as to stop the muons at its center. The use of a positron detector with 4π geometry and a high recording efficiency considerably reduced the time required for accumulating adequate statistics and made it possible to avoid some spurious effects.

INTRODUCTION

The first fairly accurate (0.1—0.05%) measurements of the lifetime of the positive muon were made back in 1962 and 1963[1-4]. After that the situation remained unchanged for a long time. The work of Williams and Williams[5] added little to the experimental accuracy that had already been achieved, and only by using a different measuring technique were Duclos et al.[6] able to advance.

Analysis of all the published material revealed certain important methodological limitations on the accuracy achievable in measuring the muon lifetime. Thus, in the traditional experimental setup the apparatus that records the positron from the decay of the muon has a small solid angle of admittance. This reduces the counting rate and makes it difficult to select useful events for which the recording of a positron can be associated with the stopping of a particular muon. Moreover, there are many ways in which a background event can be registered. The small acceptance angle leads to still another difficulty: one must take into account the possible effect of asymmetric emission of the positrons; hence the residual magnetic field at the place where the muon comes to rest must be kept below a few hundredths, or even a few thousandths, of an oersted. Further, up to now experimenters have not taken full advantage of the fact that the decay positrons are highly energetic.

MEASUREMENT TECHNIQUE

Our measurement technique is based on the idea of recording the positron with a Cerenkov detector under conditions of 4π geometry. This made it possible to increase the counting rate, reduce the background, and avoid any effects of asymmetry in the emission of the positrons.

APPARATUS

The measurements were made at the meson channel of the synchrocyclotron at the Joint Institute for Nuclear Research, using a pure beam of 130 MeV/c muons obtained from backward decay of pions captured in the muon channel duct.

Figure 1 is a diagram of the experimental setup. The scintillation counters 1 and 2, measuring 10 × 10 × 1 cm, record the incident muons. The Cerenkov counter with its water radiator was designed to record only the decay positrons. The energy of the muons and the dimensions of the cylindrical radiator (30 cm in both diameter and altitude) were so chosen that the incident muons would be brought to rest at the center of the radiator without emitting Cerenkov radiation, while the decay positrons would still be recorded with high efficiency. In this way we avoid any possible effect of the signal from the stopping of the muon on the time position of the signal from the emitted positron. Under these conditions the solid angle for recording the positrons is 4π.

The entire water radiator, surrounded by a diffusely reflecting layer of MgO (Fig. 2) was viewed by two FÉU-49 photomultipliers, which were selected to have photocathodes that are highly sensitive and similar to one another. The photomultipliers and the radiator were shielded from magnetic fields with permalloy sheet. The entire assembly was mounted in a steel cylinder one meter long. A solenoid of copper wire was wound on the outside of the steel shield and was used to compensate the residual magnetic field. The field was controlled at the 0.01 Oe level with the aid of a fixed built in permalloy transducer. A lead collimator 9 cm in diameter was mounted where the muons enter the Cerenkov counter, and an appropriate window was cut in the steel cylinder.

MEASURING CONDITIONS

As in other studies, in our measurements events were selected in which just one muon (the one that triggers the gate pulse) and one positron appear during a single gate pulse (Fig. 3). In this case the resulting decay curve can be represented by the very simple formula $Ae^{-\lambda t} + B$, where t is the time, λ is the decay rate, and A and B are constants.

As calculations showed, there are optimal conditions for making the measurements, depending on the stopped-muon intensity and the length of time during which positrons are recorded. It is interesting that

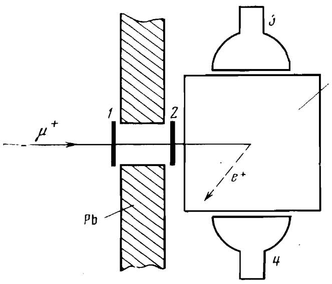

FIG. 1. Experimental setup.

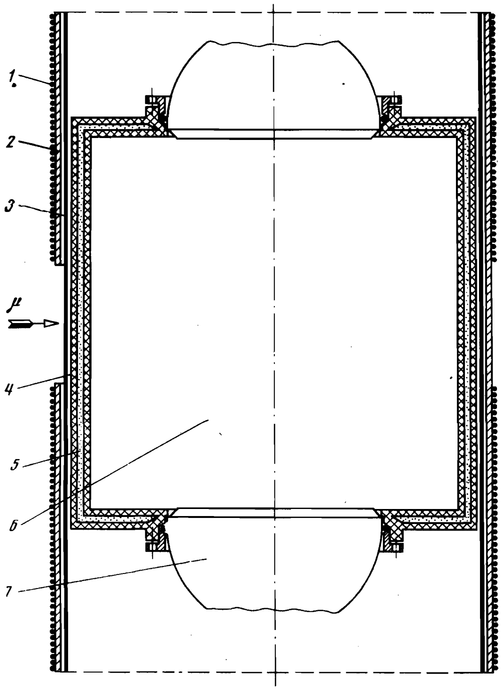

FIG. 2. Design of the Cerenkov counter: 1—solenoid for magnetic field compensation, 2—steel magnetic shield, 3—permalloy magnetic shield, 4—Plexiglas radiator wall, 5—MgO reflecting layer, 6—water, 7—type FÉU-49 photomultiplier.

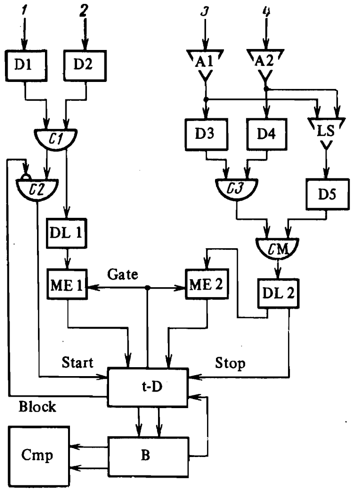

FIG. 3. Block diagram of the electronic equipment: D—discriminator, C—coincidence circuit ('and' gate), M—mixer, DL—delay line, A—amplifier, t-D—time digitizer, ME—multiple-event detector, B—buffer memory, Cmp.—computer.

there is a practical limit, somewhere near the 10^{-5} level, to the accuracy with which the muon lifetime can be measured using the technique adopted here. A different technique will be required if better results are to be achieved.

With the muon intensity available to us (7×10^3 sec^{-1}, without allowing for the off-duty factor) a gate-pulse length of 20 μsec was chosen. The zero instant on the time scale for recording the appearance of positrons was set at 5 μsec after stopping of the muon. This avoided any possible distortion of the desired signal resulting from the appearance on its flanks of pulses from particles that entered the detector before the gate was opened.

ELECTRONIC EQUIPMENT

Figure 3 is a simplified block diagram of the electronic equipment. Counters 1 and 2 registered the incident muon (via coincidence circuit C1), and counters 3 and 4 registered the decay positron. The gains in the channels of counters 3 and 4 were selected so that the pulses from the light flash would have equal amplitudes. Then these channels would have the same counting rate under working conditions. The following measures were taken in order to improve the isotropy of the positron recording efficiency: First, coincidences between counters 3 and 4 were taken (coincidence circuit C3); this made it possible to reduce the energy threshold for recording positrons without encountering interference from photomultiplier noise. Second, the discriminator D5 following the linear summator LS was used to select events in which only one of the pulses from photomultipliers 3 and 4 was large. Such a situation is possible when the positron is emitted in the direction of one of the photomultipliers and the greater part of the light cone falls on its photocathode.

The circuits for detecting multiple events (ME1 and ME2) make it possible to select events at the time digitizer (t-D) in which only one muon arrived and only one positron was registered during the time that the gate was open. The delay line DL2 shifted the pulse signalling the emission of a positron (the "stop" pulse) with respect to the pulse signalling the stopping of a muon (the "start" pulse) by 5 μsec; i.e., it shifted the origin of the exponential. The delay line LD1 (also 5 μsec) was introduced to equalize the conditions for detecting events involving two stopped muons or two decay positrons in blocks ME1 and ME2, respectively.

In order to avoid temporal effects associated with shifts in the dc current level resulting from changes in intensity, direct coupling was used throughout the electronic circuits wherever possible. Where it was not possible to use direct coupling, bipolar signals were formed.

THE TIME DIGITIZER

The time digitizer is the essential part of the apparatus. It was developed especially for the present study and therefore has a few special features. Figure 4 is a simplified block diagram of the digitizer. A "start" pulse (signalling a stopped muon) flips the flip-flops F1 and F2; these open the 'and' gates (coincidence circuits) C1 and C2, thus permitting clock pulses from the crystal controlled oscillator Osc to enter registers R1 and R2a, where they accumulate. A "stop" pulse (signalling the appearance of a decay positron) returns F2 to its initial state, thus closing gate C2 and stopping the accumulation of clock pulses

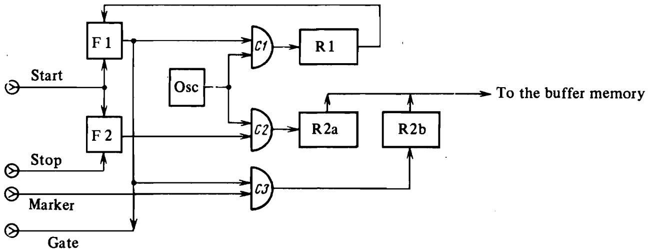

FIG. 4. Block diagram of the time digitizer: F—flip-flop, Osc—crystal controlled oscillator, C—coincidence circuit ('and' gate), R—register.

in R2a, which now contains a number of pulses corresponding to the time interval to be measured. Flip-flop F1 returns to its initial state only when a specified number of clock pulses have accumulated in R1; thus, R1, together with its associated blocks F1, C1, and Osc, determines the duration of the gate pulse. As long as this pulse lasts, the 'and' gate C3 is held open so that any marker pulses (indicating the arrival of a second muon or the appearance of a second positron) that may arrive can be registered in R2b. For each event, ten bits (in R2a) are available for the time measurement and two bits (in R2b) for markers. When the gate pulse ends, the contents of registers R2a,b are transmitted to the buffer memory (a type AI-4096 pulse height analyzer) at the Measuring Center of the Nuclear Problems Laboratory, where the events are classified and counted.

The frequency of the crystal controlled clock oscillator used in these measurements was about 50 MHz and was known within 100 Hz.

CONTROL MEASUREMENTS

To make measurements of high accuracy one must check the operation of the apparatus. Here, the most important characteristic is the differential nonlinearity of the entire electronics unit from the counters to the time digitizer. Such nonlinearity can arise both from coupling between the "start" and "stop" channels and from pileup of pulses in either channel.

The effect of differential nonlinearity on the measured muon lifetime can be estimated numerically from the change in the mean time for the appearance of decay positrons. In the absence of nonlinearity the mean time for the appearance of positrons is of course equal to the mean life of the muon. If the average differential nonlinearity of the electronics unit be expressed in the form $1 + \alpha\lambda t$, the relative change in the measured mean life of the muon will be α. The differential nonlinearity of the apparatus was measured under conditions similar to those obtaining in the actual measurements. Random pulses from two scintillation counters were fed to the inputs of the system to simulate pulses from muons and positrons. In these tests the counting rate in each channel was about 50% greater than the intensity of the muon beam. Measurements extending over several days showed that the entire electronics unit is free from differential nonlinearity at the $\alpha = \pm 10^{-5}$ level. As an example, we show intermediate test results in Fig. 5 that clearly demonstrate the high quality of the operation of the electronics unit.

The time resolution of the Cerenkov detector at the max/10^4 level is 100 nsec. The results of the measuring runs indicate that the positron recording efficiency was 90%.

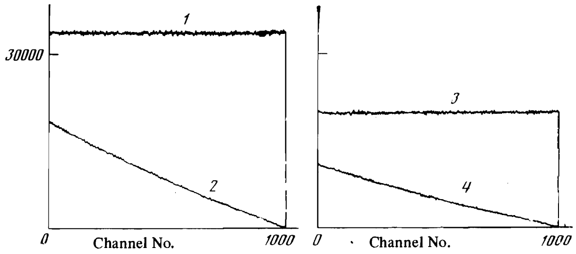

FIG. 5. Control time spectra: 1—one "start" pulse and one "stop" pulse arriving during the gate pulse; 1—one "start" and two "stop" pulses; 3—two "start" and one "stop" pulse; 4—two "start" and two "stop" pulses.

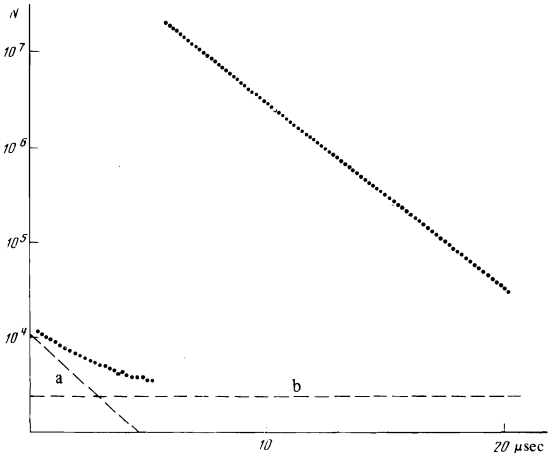

FIG. 6. Decay curve from one run.

MEASUREMENTS AND DATA PROCESSING

The measurements were made in four runs at the synchrocyclotron on different days. During a run the data were transmitted to the computer by direct line every two hours and were immediately processed by a simplified program. The results were presented in both tabular and graphical form.

Figure 6 shows the decay curve obtained in one of the runs. The exponential curve a in the 0—5 μsec region is due to the recording of decay positrons from muons that were stopped in the Cerenkov counter more than 5 μsec before the arrival of the muon that triggered the time digitizer. The horizontal line b marks the background of accidental events.

At the end of a run the time spectra obtained were processed by the χ^2 method: the background part of the spectrum ($0 < t < 5$ μsec) was represented by the formula $Ce^{-\lambda t} + B$, and the rest of it ($5 < t < 20$ μsec) by the formula $Ae^{-\lambda t} + B$, and the parameters were evaluated by minimizing χ^2 for the entire spectrum. As a check, the two parts of the spectrum were also processed separately; the parameter values obtained by the two methods agreed with one another within the limits of error. In processing the spectra, the first channel to be analyzed was taken 320 nsec from the beginning of the exponential.

The finite resolution of the circuits for detecting events involving two muons (30 nsec) or two positrons (70 nsec) gives rise to a term of the form $De^{-2\lambda t}$ in the time spectrum. Taking this term into account changes λ by one part in 10^5. The corrections due to other effects are considerably smaller. The results of processing the data are collected in the table. Our final value for the mean life of the positive muon is 2.19711 ± 0.00008 μsec. These results are based on the analysis of 10^9 useful events accumulated during 100 hours of work at the accelerator.

Further significant improvement of the accuracy

Run	Mean life, μsec	$\chi^2/\langle\chi^2\rangle$	Run	Mean life, μsec	$\chi^2/\langle\chi^2\rangle$
1	2.19740±0,00031	0.82	4	2.19709±0.00013	0.87
2	2.19687±0,00014	1.02	Average	2.19711±0.00008	0.87
3	2.19731±0.00014	1.18	Ref. 6	2.1973±0.0003	—

could be achieved with the setup of Duclos et al.[6] by shortening the response time of the positron detectors and increasing their acceptance angle to 4π sr.

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