Measurement of the lifetimes of π^+ and K^+ mesons

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Precise measurements of the lifetimes of π^+ and K^+ mesons have been carried out. The new measurement method makes use of a periodic temporal microstructure of a beam of protons which are interacting with the target. Positive muons from the decay of π^+ and K^+ mesons produced and stopped in the target are detected. The values found are $\tau_{\pi^+}=26.0361\pm0.0052$ ns and $\tau_{K^+}=12.415\pm0.024$ ns. © *1995 American Institute of Physics.*

These precise measurements of the lifetimes of the π^+ and K^+ mesons were based on (a) the production of a beam of positive muons (μ^+) from the decay of π^+ muons stopped in a meson-generating target[1] and (b) a periodic temporal microstructure of the proton beam of the proton cyclotron of the St. Petersburg Institute of Nuclear Physics. This temporal microstructure of the proton beam extracted from the accelerator consists of a train of microscopic bunches with a width at half-maximum of 5 ns and a repetition period $T_0=75$ ns. The probabilities for the appearance of protons in the time intervals $\Delta t=40$ ns and 35 ns between microbunches did not exceed 5×10^{-6} and 10^{-6}, respectively. Consequently, the overwhelming majority of the protons which reach the target generate π^+ or K^+ mesons during the proton microbunches. Immediately after their production, some of the π^+ or K^+ mesons are stopped in the same target. During the time intervals between the microbunches, these particles then undergo an exponential decay into neutrinos and μ^+'s with momenta of 29.8 MeV/c (π^+ decay) or 236 MeV/c (K^+ decay). The μ^+'s which escape from the interior of the target lose momentum as a result of ionization losses and acquire a momentum spread. Under the conditions of these experiments, this spread was 0–29.8 MeV/c or 215–236 MeV/c. Some of these μ^+'s fly off at an angle of $60°\pm5°$ from the direction of the proton beam and are selected by a magnetic spectrometer consisting of two magnets and seven quadrupole lenses, with a momentum resolution of 5% (Ref. 2). The central momentum to which the spectrometer is tuned is 28.5 MeV/c or 230 MeV/c. This spectrometer also captures background μ^+'s produced from π^+ mesons which are emitted from the target toward the spectrometer and which decay in the front part of the latter. However, essentially all the background μ^+'s form in an interval of 5 ns after the instant at which the protons interact with the target, and they do not lie inside the time interval Δt used for the lifetime measurements.

The target was in the vacuum chamber of the spectrometer. The detector was 8 m from the target, behind a thin exit window (consisting of 0.1 mm of a material equivalent to Mylar). The detector of the μ^+'s with a momentum of 230 MeV/c consisted of scintillation counters and was described in Ref. 2. The detector[3] of μ^+'s with a momentum of 28.5 MeV/c consisted of four counters with plastic scintillators, 0.65 mm in diameter and 0.1 mm long, and two anticoincidence counters with plastic scintillators 65 mm in diameter and 0.3 mm long. Our use of $\Delta E/\Delta X$ criteria and fast selection logic (the dead time was 15 ns) resulted in a low efficiency ($<10^{-8}$) of the detection of positrons and π^+ mesons captured by the magnetic spectrometer, while the positive muons were detected at an efficiency approaching 100%. The average number of μ^+'s detected by the detector during the interval T_0 did not exceed 8×10^{-4}.

The signals from the detector went to a time-interval meter, after the selection of exclusively those events which were not preceded or followed, in time intervals T_0, by other events. The average value of a channel of the time-interval meter [$(391764 \pm 8)\times10^{-7}$ ns/channel] during the time interval $\Delta t = 40$ ns and also the integral (3×10^{-4}) and differential (10^{-3}) nonlinearities of the time-interval meter were measured during the experiments, during the time intervals between cycles of extraction of the proton beam. For these measurements we made use of pulses from a quartz generator and random signals from a scintillation counter bombarded by a radioactive Sr^{90} source.

Using the time-interval meter, we measured temporal distributions of the positive muons with respect to reference signals tied to a certain phase of the rf sine wave of the rf oscillator of the accelerator. These reference signals determine the instants at which the protons pass through the target (Figs. 1 and 2). The temporal distributions of positive muons from the decays of π^+ or K^+ mesons stopped in the target are similar to the solid curve in Fig. 1. The smoothly descending right-hand slope of this curve can be described over the interval Δt by $N(t) = N_0 \exp(-t/\tau)$, where t is the lifetime of the π^+ or K^+ mesons. The steep left-hand slope has a transition region whose length is determined by the length of the proton microbunch and by the solid angle, momentum resolution, and length of the spectrometer. In this transition region, the π^+ or K^+ mesons stopped in the target accumulate there, and background μ^+'s form (the narrow dot-dashed peak in Fig. 1).

To determine the time interval Δt during which the contribution from background processes is at a minimum, we carried out some background measurements for μ^+'s with momenta of 210 and 260 MeV/c (K^+ decay) and for μ^+'s and μ^-'s with momenta of 28.5 MeV/c (π^+ decay). For the μ^+'s with a momentum of 28.5 MeV/c, the background distribution was measured after a Mylar filter 0.4 mm thick. This filter was inside the vacuum chamber of the spectrometer, at a distance of 20 cm from the target. It absorbed all the positive muons from π^+ mesons stopped in the target. After the small fraction of positive muons from the decay of π^+ mesons stopped in the filter was subtracted, we obtained the temporal distribution of background μ^+'s, which was identical to the temporal distribution of μ^-'s with a momentum of 28.5 MeV/c measured in the absence of the filter after a polarization reversal of all the magnetic elements of the spectrometer. To monitor the proton beam, in order to subtract the background spectra, and also to find an upper estimate of the relative intensity of the proton beam in the interval Δt between the microbunches, we made use of π^- mesons with a momentum of 600 MeV/c emitted from the target at an angle of 0°.

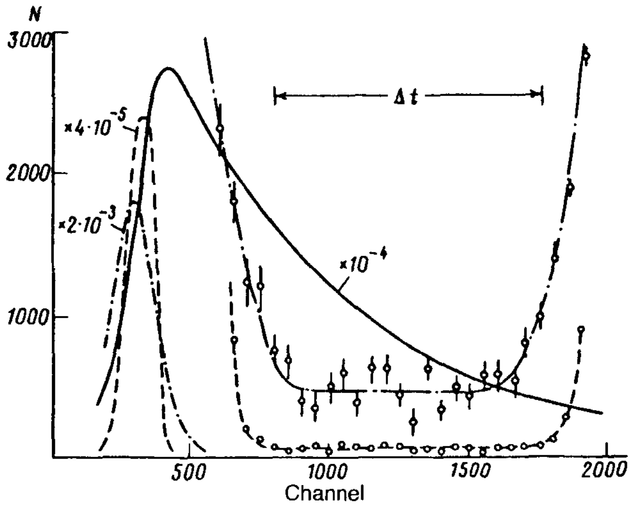

FIG. 1. Temporal distributions of μ^+'s with a momentum of 28.5 MeV/c (solid curve), of π^- mesons with a momentum of 600 MeV/c (dotted and dashed curves), and of background μ^+s with a momentum of 28.5 MeV/c (dot-dashed curves and circles with error bars). The solid curve and the narrow peaks shown by the dashed and dot-dashed curves are drawn through the experimental points (the latter are not shown) after multiplication by factors of 10^{-4}, 4×10^{-5}, and 2×10^{-3}, respectively. A summation was carried out over 50 channels, but the original designations of the channels of the time-interval meters have been retained. One thousand channels of the time-interval meter correspond to 39.1764 ± 0.0008 ns.

The background conditions in these experiments were such that the relative number of background events during the time interval Δt did not exceed 2×10^{-4} (in the case of π^+ decay) or 3×10^{-3} (K^+ decay). The relative systematic error in the results of the measurements due to the background subtraction is therefore $\delta_f\approx3\times10^{-5}$ for π^+ decay and 2×10^{-4} for K^+ decay.

The relative error in the experimental results due to the error in the calibration of the time-interval meter, the nonlinearity function of this meter, and the statistical distortions of the original temporal distribution[4] does not exceed $\delta_k\approx3.5\times10^{-5}$.

We determined τ by a least-squares fit of the temporal distributions, corrected for the background and the nonlinearity, over an interval Δt selected in such a manner that the values of τ for shorter intervals within Δt agreed with each other, within the measurement errors. The possible relative systematic error due to the uncertainty in the choice of the working interval Δt was $\delta_{\Delta t}=6\times10^{-5}$ (π^+ decay) or 5×10^{-4} (K^+ decay).

The total relative systematic error, $\delta_c=\sqrt{\delta_f^2+\delta_k^2+\delta_{\Delta t}^2}$, is 7.5×10^{-5} for π^+ decay and 5.5×10^{-4} for K^+ decay. This error was added quadratically to the relative statistical error found through an analysis of the spectra corrected for the background and the nonlinearity. The latter error was the governing factor in these experiments. Under these particular experimental conditions, the results obtained without subtraction of the background or without consideration of the nonlinearity function differed from the actual results by no more than one standard deviation.

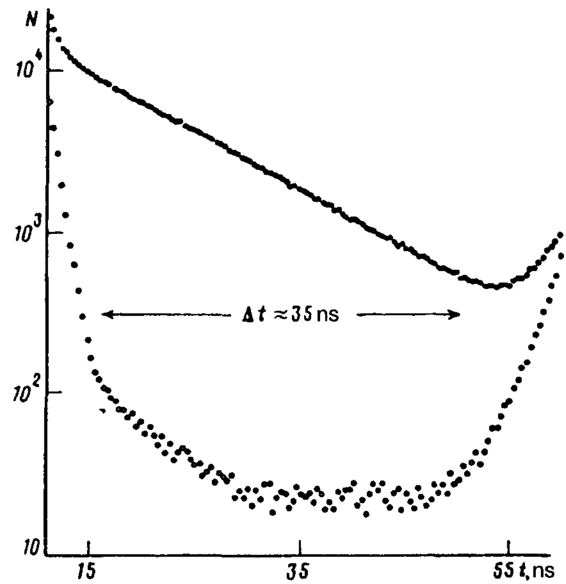

FIG. 2. Part of a temporal distribution (inside the transition region) of μ^+'s with a momentum of 230 MeV/c (upper curve) and total background spectrum of μ^+' s with momenta of 210 and 260 MeV/c.

To eliminate possible systematic errors stemming from the experimental conditions which we have not considered, we measured the lifetime of the π^+ meson with copper, carbon, and quartz targets. These measurements led to changes in the flux of background positrons (by a factor of 10) and of π^+ mesons (by a factor of 2). They also led to a change in the load of positive muons on the detector (by a factor of 2). The measurements carried out with different targets yielded the following values, which agree within the errors: $\tau_{\pi^+}(\mathrm{C})=26.0349\pm0.0078\mathrm{ns}$, $\tau_{\pi^+}(\mathrm{Cu})=26.0329\pm0.0076\mathrm{ns}$, and $\tau_{\pi^+}(\mathrm{SiO_2})=26.0418\pm0.0096$ ns. The resultant spectrum from all three targets consists of 1.5×10^8 events in $\Delta t=38$ ns. The lifetime of the π^+ mesons found from an analysis of this resultant spectrum is

$$\tau_{\pi^+}=26.0361\pm0.0052 \text{ ns}, \quad \chi^2=0.97, \text{ C.L.}=0.60.$$

The accuracy here is four times as good as that of the average existing results.[5]

The lifetime of the K^+ mesons was measured for copper and uranium targets. The numbers of events in the time interval $\Delta t=35$ ns were 1.5×10^5 and 2.5×10^5, respectively. We found $\tau_{K^+}(\mathrm{Cu})=12.368\pm0.041$ ns ($\chi^2=1.06$, C.L.$=0.66$) and $\tau_{K^+}(\mathrm{U})=12.451\pm0.030$ ns ($\chi^2=1.07$, C.L.$=0.63$). These values differ from each other by two standard deviations. The average weighted value of these times is

$$\tau_{K^+}=12.415\pm0.024 \text{ ns}.$$

This result supports the value found previously for the K^+ lifetime by a stopping method.[5]

The accuracy of the measurements of the π^+ lifetime could be improved by using this method at meson factories.[6]

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