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THE POLARIZATION OF μ^+ MESONS FROM THE DECAY OF K^+ MESONS

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October 4, 1957

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THE POLARIZATION OF μ^+ MESONS FROM THE DECAY OF K^+ MESONS*

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The dilemma posed by the apparently irreconcilable τ and θ decay modes of the K meson led Lee and Yang to re-examine the principle of conservation of parity in decay processes.[1] They concluded that parity might not be conserved in weak interactions and suggested some experimental tests of their predictions. The first of these concerned the angular distribution of electrons in the β decay of oriented nuclei, and the experiment on the decay of Co^{60} nuclei revealed an asymmetry in the electron distribution.[2] Experiments on the $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ decay chain also showed an asymmetry in the angular distribution of the positrons,[3,4,5] in agreement with the two-component theory of the neutrino. The angular distribution of the positrons is of the form $N(\theta)d\Omega = N(\pi/2)\,(1 + a\cos\theta)\,d\Omega$, (1) where θ is the angle between the original direction of motion of the μ meson and the direction of the emitted positron. The value of a is negative, indicating that the positron is emitted preferentially in the backward direction relative to the incoming μ meson.

We have measured the angular distribution of positrons arising in the decay chain $K^+_{\mu 2} \rightarrow \mu^+ \rightarrow e^+$. This mode of decay is similar to that of the π meson in that a single neutrino (or antineutrino) is emitted with the μ meson. The K mesons were produced by bombarding a tantalum target with 6.2-Bev protons in the Bevatron. Those emitted within a small solid angle at 88° to the incident proton beam were focused by means of magnetic quadrupole lenses, and momentum-analyzed by a 30° deflection in a magnetic field (see Fig. 1). The central momentum, as indicated by range measurements, was 480 Mev/c, and the momentum bandwidth, ± 3%. The detector system, located outside the concrete shielding around the

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Bevatron, consisted of plastic scintillation counters, a water Cherenkov detector, and absorbers in the arrangement of Fig. 2. This system was shielded magnetically from the stray field of the Bevatron. It was also enclosed in a radiation shield of lead (4 in.) and boron-loaded paraffin wax (12 in.), which reduced the background, due mainly to low-energy neutrons and γ rays.

K^+ mesons came to rest in a block of polystyrene, S, and the μ mesons emitted downwards from those decaying via the $K_{\mu 2}$ mode entered a stack of scintillation counters 1, 2, ... 6. Protons in the incoming particle beam were stopped in the Cherenkov counter, W; π mesons were rejected in our coincidence circuits because first, they produced a pulse in the Cherenkov counter and, secondly, they passed through S into the anticoincidence counter F. Another coincidence circuit selected those μ mesons which stopped in a 1.5-in. block of aluminum ("precessor"). This block was wound with aluminum wire so that a uniform horizontal magnetic field could be applied to it. A master coincidence indicating a stopped μ^+ meson was used to trigger an oscilloscope trace, and the direction of emission of the positron in the subsequent decay of the μ was indicated by the responses of the scintillators in the stack. These signals were mixed in coincidence pairs to reduce the general background of pulses on the oscilloscope trace.

In carrying out the experiment to determine "a" in Eq. (1), we applied a magnetic field, first of 25 gauss and later 50 gauss, to the precessor. This field causes the spin direction of the μ meson to precess with a frequency given by

$$\frac{\omega}{2\pi} = 1.35 \times 10^4 \text{ B sec}^{-1} ,$$

where B is the magnetic flux density in gauss. As a result, a sinusoidal modulation is superimposed upon the normal exponential detection rate of decay positrons; i.e., the counting rate for positrons observed at an angle θ measured with respect to the initial direction of the muons is a function of time having the form

$$N(t) \propto e^{-t/\tau} \left[1 + a_0 \cos (\theta + \omega t) \right] . \qquad (2)$$

The amplitude of the modulation then gives a_0, the observed asymmetry. This method has an important advantage over that based on measuring the ratio of the backward and forward decay rates with no magnetic field in that the value of a_0

obtained is independent of many instrumental asymmetries. Furthermore, differences between the backward and forward decay rates can be used to determine any remaining instrumental asymmetries.

The results of the experiment are contained in Figs 3 and 4. The values of a_0 deduced from these results are given in Table I. In order to compare the results with the predictions of the Lee-Yang theory, we have to revise the observed values of a_0 upwards for the following effects. (a) There is a geometrical correction of about 6% which included an edge effect and an apparent depolarization due to the finite angle subtended by the precessor at the position where the K mesons stop and decay. (b) The range curve of the μ meson indicates that about 10% of the μ mesons do not stop in the uniform-field region, and these contribute a background which dilutes the true asymmetry. (c) Averaging the data for calculation purposes into the finite time intervals of Figs. 3 and 4 has the effect of reducing the asymmetry by about 5%. When these corrections are made, we obtain the values of a_0(corr) given in Table I.

As an additional check on our observed effects, we measured the backward and forward rates of the positrons with no magnetic field on the precessor (see Fig. 5). Here, in addition to making a geometrical correction, we must increase the observed backward/forward ratio by about 12% to allow for an instrumental asymmetry that favored forward decays over backward. The magnitude of this correction was estimated from the data of Figs. 3 and 4.

The weighted mean value from all the data, treating each result as independent, is

$$a_m = -0.31 \pm 0.04. \qquad (3)$$

To be detected, the positron from a μ meson decaying at the center of the precessor must have a minimum range of 9 g of aluminum, corresponding to a minimum average positron energy of about 25 Mev. This is almost the same energy discrimination as that in the Columbia Group's experiment on the $\pi \to \mu \to e$ decay chain.[6] They found $a = -0.305 \pm 0.033$ for positrons of range $\gtrsim 9.3$ g/cm^2 carbon.

The theoretical value of a may be found by integrating the electron spectrum given by Lee and Yang above the minimum energy, and is $a_{theor} \approx -0.43\,\xi P$. Here ξ is the coupling-mixture parameter of Lee and Yang, and P is the fractional polarization of the μ^+ meson in K_{μ_2} decay. If we assume that the μ meson is

Table I

Asymmetry of K-μ-e decay.

$$N(\theta)\, d\Omega = N(\pi/2)\,(1 + a \cos \theta)\, d\Omega.$$

Precessor field (gauss)	Direction of emission of positrons	a_0	a_0(corr)
25	Backward	-0.27 ± 0.05	-0.34 ± 0.07
25	Forward	-0.21 ± 0.05	-0.26 ± 0.07
50	Backward	-0.31 ± 0.09	-0.38 ± 0.12
50	Forward	-0.35 ± 0.10	-0.43 ± 0.13
0	Backward/Forward	-0.20 ± 0.03	-0.28 ± 0.06

Average $a_m = -0.31 \pm 0.04$

completely polarized, the asymmetry a_m corresponds to a value of $\xi \approx 0.72$. In arriving at this result, we have not made any corrections to our observed data for the effects of radiation by, and Coulomb scattering of, the positrons. Consequently, our value is a lower limit. It is in reasonable agreement with the value of ξ estimated for μ mesons from π-meson decay.[7,8]

We conclude that the μ mesons from K_{μ_2}-meson decay are highly, if not completely, polarized, and the direction of polarization is the same as that occurring in $\pi \to \mu \to e$ decay. This result strongly suggests that the spin of the K meson, like that of the π, is zero. With this conclusion we note that the observed direction of μ polarization is opposite to that predicted by the "attribute" scheme for the fundamental particles.[9,10]

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CAPTIONS FOR FIGURES

Fig. 1. Plan view of particle-selection system (schematic).

Fig. 2. Side elevation of detector system.

A through H and 1 through 6 are plastic scintillation counters.

W is a water Cherenkov detector.

S is the K^+ stopper, a 3-in. cube of polystyrene.

A $K^+_{\mu 2}$ meson stopping in S and its decay μ stopping in the precessor are indicated by the counter response - W + A + B + C + D + E - F + G + H + 1 + 2 + 3 4. Decay positrons are indicated by +3 +2 + (1) - 4 - G or +4 + 5 + (6) - 3 - G. G acts as a guard counter against possible background of scattered π^+ mesons entering the counter system 1, 2, ... 6.

Fig. 3. Detection rate of decay positrons as a function of time.

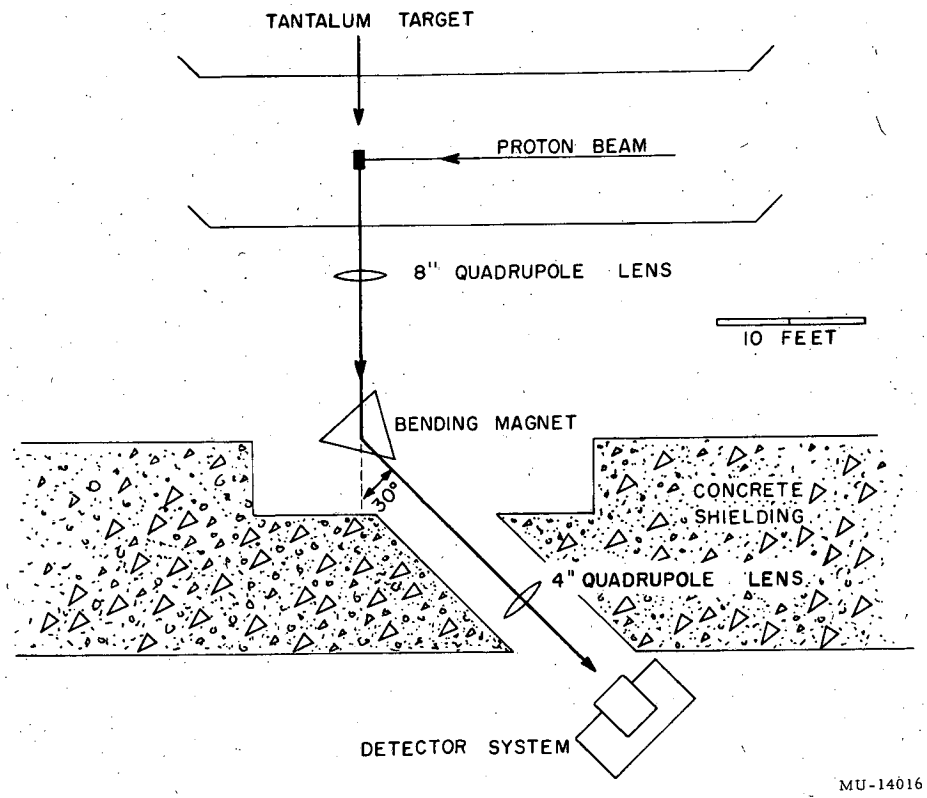
Magnetic field of 25 gauss in precessor.

Fig. 4. Detection rate of decay positrons as a function of time.

Magnetic field of 50 gauss in precessor.

Fig. 5. Detection rate of decay positrons as a function of time.

No magnetic field in precessor.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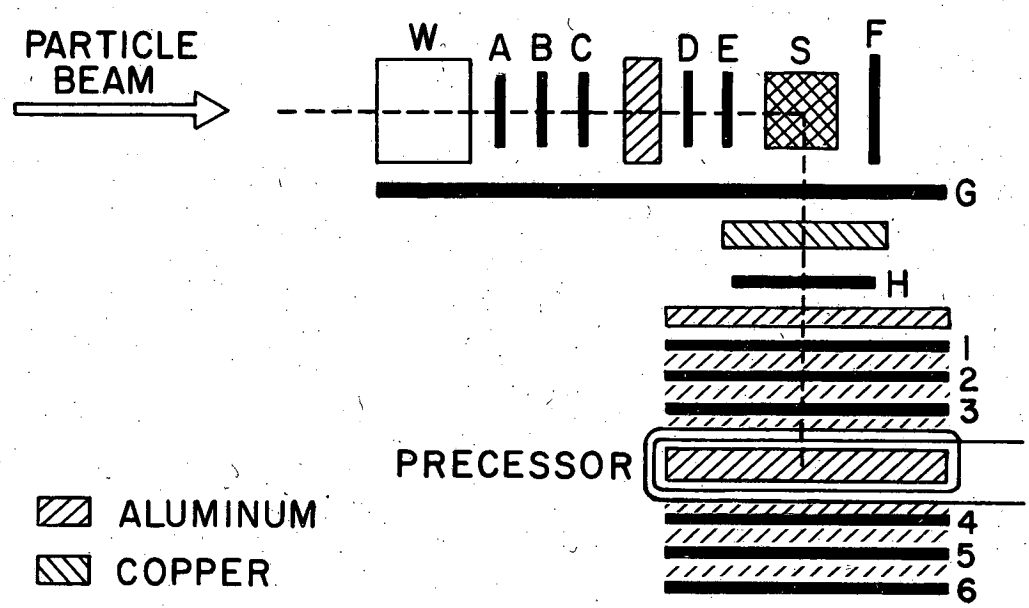
PROTON BEAM
8" QUADRUPOLE LENS
10 FEET
BENDING MAGNET
30°
CONCRETE
SHIELDING
4" QUADRUPOLE LENS
DETECTOR SYSTEM
MU-14016


PARTICLE BEAM
W
A B C
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1
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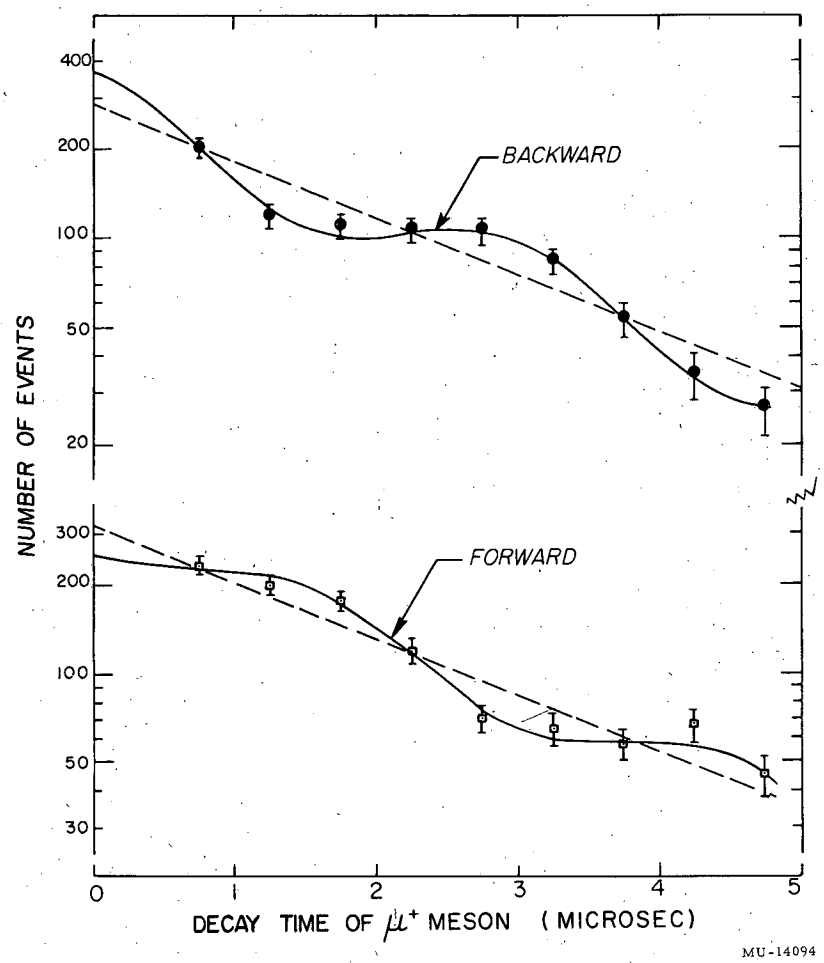
3
PRECESSOR
4
5
6
ALUMINUM
COPPER

MU-14015


400
200
100
50
20
BACKWARD
NUMBER OF EVENTS
300
200
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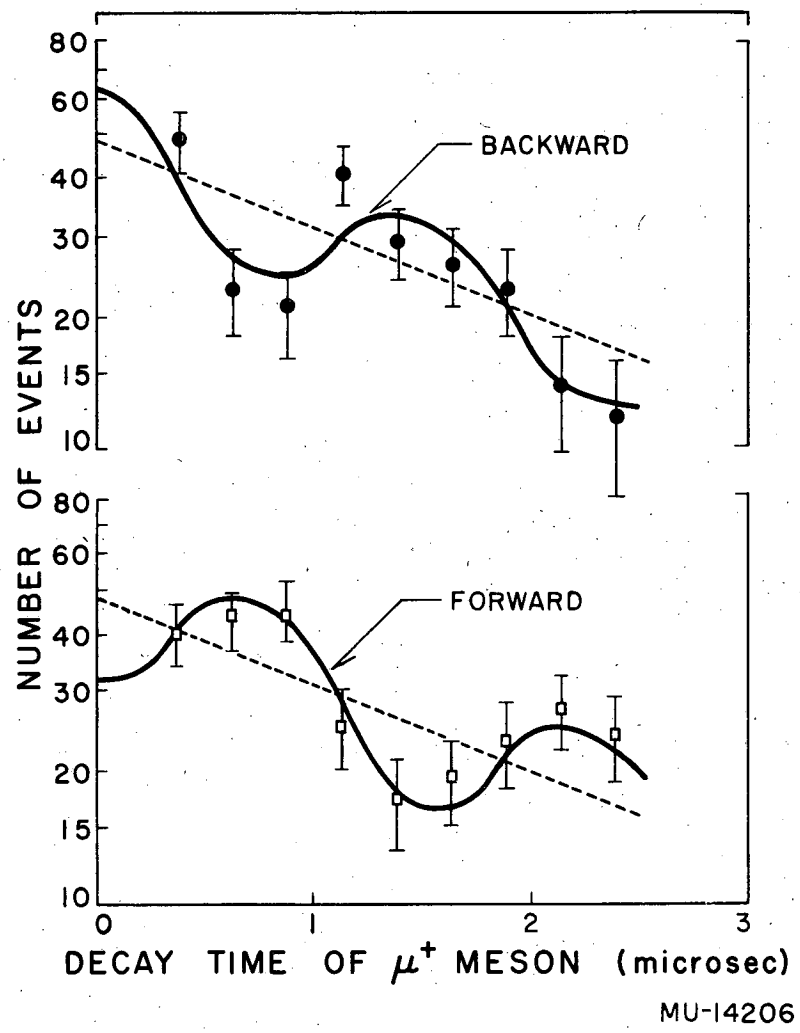
30
FORWARD
0
1
2
3
4
5
DECAY TIME OF μ^+ MESON (MICROSEC)
MU-14094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60
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10
BACKWARD
NUMBER OF EVENTS
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20
15
10
FORWARD
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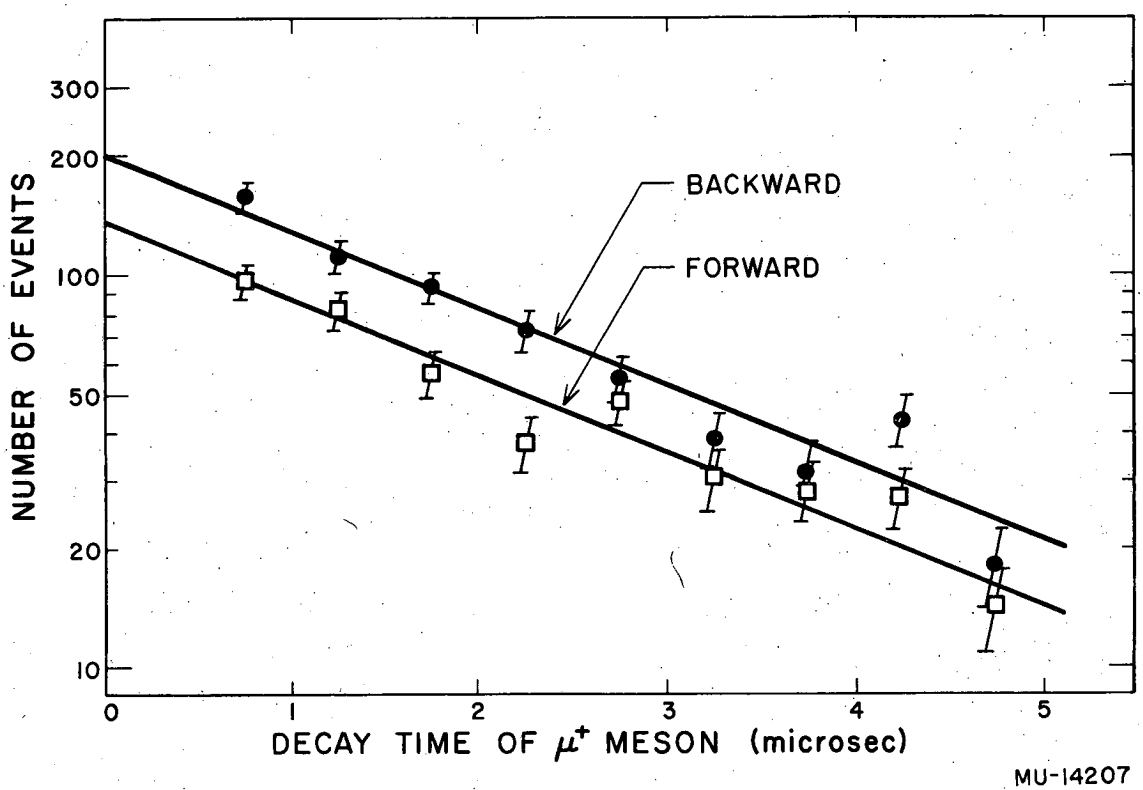
1
2
3
DECAY TIME OF μ^+ MESON (microsec)
MU-14206


300
200
100
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20
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NUMBER OF EVENTS
BACKWARD
FORWARD
0
1
2
3
4
5
DECAY TIME OF μ^+ MESON (microsec)
MU-14207