POLARIZATION OF LOW-ENERGY COSMIC RAY MUONS AT SEA LEVEL

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The degree of polarization of positive muons in the 0.2—1.55 BeV range has been measured at sea level. The degree of polarization increases over the indicated energy range by a factor of 1.50 ± 0.19, which corresponds to an increase in the slope of the pion energy spectrum over a range of the order of several BeV. A value $K^+/\pi^+ = 0.22 \pm 0.18$ has been obtained for the ratio of K^+ to π^+ mesons produced in the atmosphere by estimating the possible contribution of the $K_{\mu 2}$ decay to muon production.

1. INTRODUCTION

THE study of polarization of cosmic ray muons at sea level [1,2,3] yields information concerning their production mechanism in the upper layers of the atmosphere. By comparing, e.g., the change of the degree of polarization in the muon flux with the theoretical calculation [4] for the muon production in the π—μ decay, we can obtain information on the contribution of the $K_{\mu 2}$ decay to the production of cosmic ray muons. On the other hand, the study of the polarization of muons in the low-energy range provides a direct method for determining the shape of the pion production energy spectrum, since the contribution of the $K_{\mu 2}$ decay should be small in that energy range.

Measurements of the degree of polarization of the muon flux in a relatively low-energy range (0.2—1.55 BeV) are described below.

2. EXPERIMENT

For the determination of the degree of polarization of the muon flux, we have measured the asymmetry in the angular distribution of decay positrons emitted by μ^+ mesons which stopped in an absorber.

The experimental arrangement (Fig. 1) consists of an absorber A with dimensions 700 mm × 1400 mm × 20 mm surrounded by several layers of gas-discharge counters. Copper was chosen for the material of the absorber. This enabled us to detect the decay of positive muons only, which conserve the direction of polarization after having stopped. Negative muons captured by copper nuclei have a very short life, of the order of $\sim 10^{-7}$ sec, and decay before being detected.

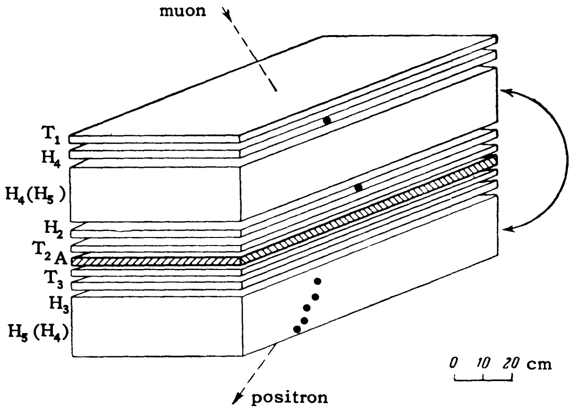

FIG. 1. Experimental arrangement

The moment of stopping of a muon in the absorber is fixed by the trigger trays of Geiger counters T_1, T_2, T_3 (anticoincidence T_1, T_2, $\overline{T}_3$). All remaining counters (H_1—H_5) are operated with pulsed high voltage [5] and are connected to the hodoscope. The trays H_1, H_2, and H_3 constitute the muon detector; a muon stopping in the absorber is accompanied by a discharge of the neon lamps of the corresponding counters in the trays H_1 and H_2. Tray H_3 serves for a check and symmetrizes the array with respect to the absorber A.

The hodoscope counter groups H_4 and H_5 consist of five trays each and constitute the positron detectors. The high tension (HT), and the delay and duration of the HT supply pulses of the trays H_1—H_5, were selected so that the trays H_1, H_2, and H_3 detect only muons (and do not record the decay positrons), and the trays of H_4 and H_5 detect only the decay positrons. [6]

Two types of counters were used in the array: 1) glass counters SI-6G (30 mm diameter and 60 mm length) were employed in the trays T_1,

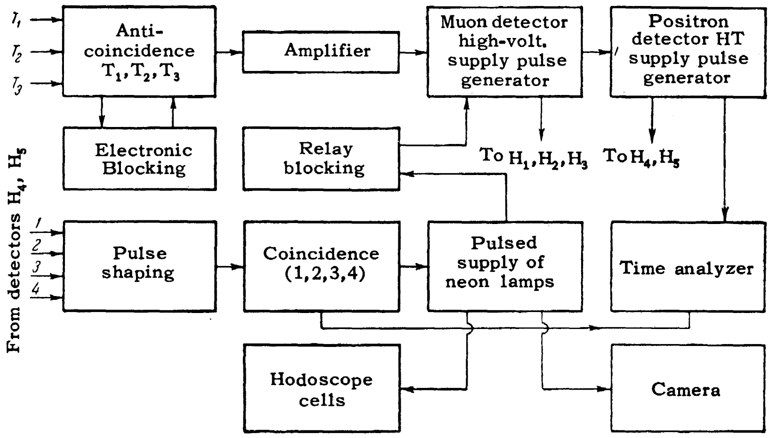

FIG. 2. Block diagram of the electronic circuitry.

T_2, T_3 and H_4, H_5; 2) copper counters (18 mm diameter, 650 mm length) in the trays H_1, H_2, H_3.

A block diagram of the electronic circuitry is shown in Fig. 2. An event of the type T_1, T_2, $\overline{T}_3$ triggers the pulsed HT supply of the muon detectors and then the HT pulse generator of the positron detectors, which produces high-voltage pulses of 5 μsec duration delayed by 0.8 μsec with respect to the μ meson stopping. During the pulse duration (within 0.8—5.8 μsec after the meson has stopped), the positron is detected and the time of the decay is recorded by a time analyzer. The moment of the positron emission is fixed by the coincidence (1, 2, 3, 4) of the four trays of the detector $H_4(H_5)$ close to the absorber A. An event (1, 2, 3, 4) causes a pulsed voltage supply to be fed to the neon lamps and operates the recording camera.

A typical photograph of a $\mu^+ \to e^+$ decay is shown in Fig. 3.

The internal symmetry of the apparatus was ensured 1) by the total symmetry of the array construction with respect to the absorber, 2) by a periodic (every two hours) interchange of the positron detectors $H_4(H_5)$, and 3) by connecting together the corresponding trays 1, 2, 3, 4 of the detectors $H_4(H_5)$ and by using the same electronic circuitry for recording the positrons in H_4 and H_5.

For an experimental check of the internal symmetry of the apparatus, a special series of measurements was carried out with iron used as an absorber. Because of total depolarization of the muons in the strong magnetic fields of the domains, the distribution of the positrons of the $\mu \to e$ decay in iron should be isotropic. The results of the measurements are given below.

3. SOURCES AND MEASUREMENT OF BACKGROUND

Background events imitating the $\mu \to e$ decay in the absorber can be divided into two categories:

a) Chance coincidences of two events: a particle stopping in the absorber and an independent passage of another particle through positron detectors during the time in which the latter are sensitive (0.8—5.8 μsec after the stopping). In addition, a coincidence in "space" is necessary, i.e., crossing of the muon and positron trajectories at a point lying within the absorber.

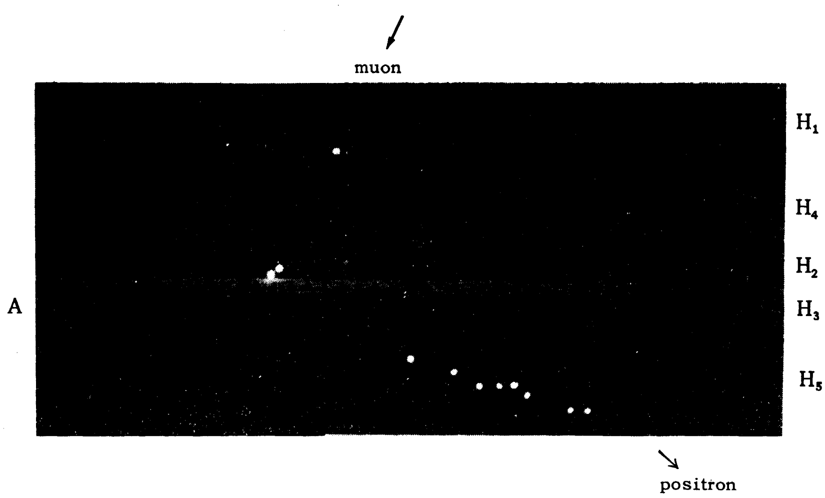

FIG. 3. Photograph of a $\mu^+ \to e^+$ decay.

Table I

Type of background	Time of measurement, hours	Number of background events		Expected number of decays	Ratio of background to the effect
		up	down		
a)	24	3	0	686.4±1.2	$(4\pm2.5)\cdot10^{-3}$
b)	212	292	310	6063±10.4	$(5\pm0.6)\cdot10^{-2}$

This type of background was measured as follows: the high-voltage supply pulse of the positron detectors was delayed for 30 μsec. The results of the measurements are given in Table I. In view of its smallness ($< 10^{-2}$), the type a) background was subsequently neglected.

b) Events "genetically" related to muon decays. To this category belong mainly the stopping and decay of muons in the glass walls of the counters of the trays T_2 and T_3.

The background of type b) was measured with the array without the absorber. The results of the measurements are shown in Table I. It was assumed that the measurements without the absorber should give a background twice that produced during the measurements. This is due to the fact that, under operating conditions, muon decays are detected by the counter T_2 only when the positron is emitted upwards, and by the counters T_3 only when emitted downwards (the remaining decay positrons are stopped in the absorber A). The value of the background of type b) is therefore decreased by a factor of two in Table I.

4. RESULTS OF THE MEASUREMENTS

During about 1500 hours of operation of the experimental array, we have obtained more than 3×10^4 photographs of the $\mu^+ \to e^+$ decay of muons stopping in copper and iron absorbers. The measurements were carried out for the muon energy range of 0.2–1.55 BeV at sea level. The muon energy was determined by the amount of matter above the experimental array.

1. Temporal distribution of the decay positrons. For the construction of the temporal distribution of the decay positrons, we have measured first the detection efficiency of positrons as a function of time within the 5 μsec detection interval.

For this purpose, we have used particles randomly detected by the array during the time the positron detectors were sensitive. Since the distribution of such particles in time is uniform, the measurement of their temporal distribution enabled us to calibrate directly the efficiency of the time-analyzer channels. The temporal distribution of the decay electrons for the total set of data for iron and copper, constructed taking the detection efficiency into account, is shown in Fig. 4. The solid curve corresponds to the muon lifetime of 2.22 μsec. Reduction of the experimental data by the maximum likelihood method[7] gives 2.19 ± 0.04 μsec for the muon lifetime.

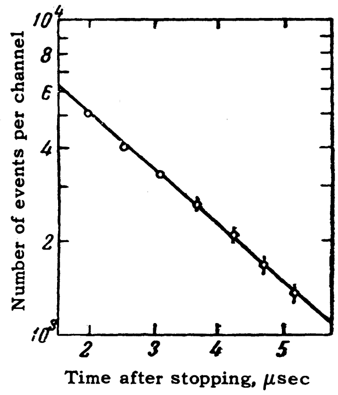

FIG. 4. Temporal distribution of decay positrons.

2. Asymmetry of the angular distribution of positrons. As a measure of the asymmetry of the angular distribution of the decay positrons we have used the quantity R, the ratio of the number of positrons detected by the upper and lower detectors. The values of the asymmetry parameter R for three values of muon energy for which the measurements were carried out in the copper and iron absorbers are given below:

Energy, BeV	0.2	0.55	1.40	0.55
R	1.13±0.025(Cu)	1.135±0.020(Cu)	1.195±0.030(Cu)	1.020±0.023 (Fe)

The value of R given above for decays in the iron absorber is in good agreement with the expected value R = 1, and therefore confirms the internal symmetry of the apparatus. The dependence of the asymmetry parameter R on the time interval between the stopping of the muon and the positron emission is given in Fig. 5. Johnson[2] has obtained an indication that slow depolarization of the muon in the copper absorber occurs during this time in the absence of external magnetic fields

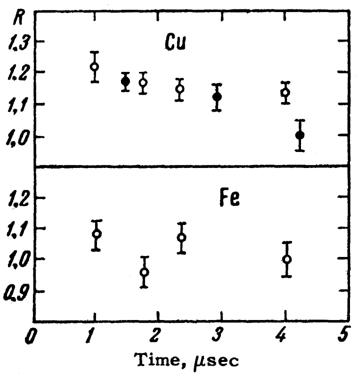

FIG. 5. Asymmetry of decay positrons as a function of time after stopping (for the decay in Cu and Fe). o—our data, •—data of[5].

Table II

Muon energy at sea level, BeV	Number of events	Polarization	
		experiment	theory
0.20	6663	0.24±0.045	0.23
0.30	1415	0.29±0.08	0.25
0.55	11066	0.25±0.035	0.28
1.05	1485	0.40±0.08	0.33
1.40	5701	0.35±0.05	0.335
1.55	4900	0.40±0.05	0.335
Control experiment with iron absorber	7848	0.04±0.045	0.00

(the data of [2] are shown in the figure). It follows from our data that the change in the parameter R with time in the decay in copper, if it exists, is very insignificant. This enables us to conclude the absence of any significant depolarization of muons after stopping in copper.

The value of the asymmetry parameter R for decays in iron is independent of time, as should be expected, and undergoes statistical fluctuations about the value R = 1.

5. DISCUSSION OF RESULTS

1. Polarization of the muon flux. In order to calculate the degree of polarization from the experimental values of the parameter R, we have carried out a calculation which took into account the geometry of the array, the angular and energy distributions of the decay positrons, and also the range-energy relation for positrons. For the range-energy relations, and for the straggling of the range, we have used in the calculation the analytical expressions obtained by Wilson, [8] which take into account the ionization and radiation energy losses and also the multiple scattering.

Since the degree of asymmetry of the positrons with respect to the vertical, as measured in the experiment, determines the projection of longitudinal polarization of the muon flux on the vertical, η_{vert}, the value of the longitudinal polarization is given by the expression

$$\eta_{vert} = \frac{\int_{\vartheta_{min}}^{\vartheta_{max}} \eta(\vartheta_\mu)\cos\vartheta_\mu F(\vartheta_\mu)\, d\Omega}{\int_{\vartheta_{min}}^{\vartheta_{max}} F(\vartheta_\mu)\, d\Omega}. \quad (1)$$

where ϑ_μ is the angle between the direction of motion of the muon and the vertical, and $F(\vartheta_\mu)$ is the corresponding angular distribution. If η is independent of ϑ_μ, which is correct only for muon energies $E_\mu \gtrsim 0.2$ BeV at sea level, [2] then

$$\eta = \eta_{vert}/\overline{\cos\vartheta_\mu}. \quad (2)$$

The calculation of $\overline{\cos\vartheta_\mu}$ was carried out directly from the experimental angular distribution of the detected stopping muons. The obtained values of the degree of polarization with different muon energies are shown in Table II. The same table also shows the data of our earlier experiments [3] with an analogous experimental setup. The last column of Table II shows the results of the theoretical calculation [4] which took into account the production of μ mesons by π mesons only. It can easily be seen that the experimental results are in satisfactory agreement with the theory.

2. Possible contribution of the $K_{\mu 2}$ decay. It is interesting to estimate from the experimental data a possible contribution of $K_{\mu 2}$ decay in the production of muons detected at sea level. Such an estimate enables us to obtain information about the ratio between the intensities of K^+ and π^+ mesons produced in the atmosphere. We shall use experimental data on the polarization of muons at sea level with energy ~ 1.5 BeV, lumping the data for energies 1.4 and 1.55 BeV and using the obtained value of $\eta(E_\mu \approx 1.5 \text{ BeV}) = 0.375 \pm 0.035$.

To the muon energy of 1.5 BeV at sea level corresponds an effective total energy at the moment of production $E \approx 4.0$ BeV. [9]

We shall assume that the energy spectrum of the K meson production is analogous, in a certain energy interval, to the corresponding pion spectrum. It is then easy to calculate the polarization of muons produced by pions and K mesons, [10] and, from the known polarization of the mixture of muons of different origin, to determine α —the fraction of muons produced in the K decay. Moreover, the ratio ω of the intensities of K and π mesons will then be given by the expression

$$\frac{0.6\omega\int\limits_{\varepsilon_K^-}^{\varepsilon_K^+}\varepsilon_K^{-\gamma}w(\varepsilon_K, E)\,dE\,d\varepsilon_K}{\int\limits_{\varepsilon_\pi^-}^{\varepsilon_\pi^+}\varepsilon_\pi^{-\gamma}w(\varepsilon_\pi, E)\,dE\,d\varepsilon_\pi} = \alpha/(1-\alpha). \quad (3)$$

where $\epsilon^{-\gamma}d\epsilon$ are the energy spectra of the π and K mesons, $w(\epsilon, E)dE = dE/2p^*\epsilon v$ is the probability of production of a muon with energy between E and E + dE in the decay of a pion (K meson) with an energy ϵ, p^* is the muon momentum in the system in which the pion (K particle) is at rest, v is the velocity of the muon (in units of c). The factor 0.6 takes into account the fact that K particles decay by the $K_{\mu 2}$ decay in about 60% of all cases. The values of ϵ^+ and ϵ^- are the limiting values of the energy of particles producing a muon with an energy E;

$$\varepsilon^{\pm}_{\pi(K)} = \frac{EE^* - pp^*}{m_\mu^2}\, m_{\pi(K)}. \quad (4)$$

The results of the calculation of α and ω are as follows:

Muon energy at sea level, BeV	1.5
Muon energy at production, BeV	4.0
Polarization	0.375 ± 0.035
Energy interval of the parent particles, BeV	π^+ 4.0 – 7.0 K^+ 4.0 – 84.0
Fraction of muons produced by K^+ particles, α	0.07 ± 0.055
Fraction of K particles, $\omega = K^+/\pi^+$	0.22 ± 0.18

It should be noted that the value of ω obtained from experimental data is the ratio of the intensity of K^+ mesons and pions at the same energy in a unit energy interval. Since the production spectra decrease strongly with energy, it is reasonable to refer the obtained value to the energy of K mesons and pions near the left-hand limit of the production interval (about 4–5 BeV). The value $K^+/\pi^+ = 0.22 \pm 0.18$ does not contradict experimental data obtained with cosmic rays and with accelerators.[11,12]

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