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POLARIZATION OF COSMIC RAY MUONS AT DIFFERENT ENERGIES

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The absolute values of polarization of 0.14, 0.25, 0.30, 1.45, and 2.0 BeV cosmic ray muons are determined. The ratios K^+/π^+ and $K^+/(K^+ + \pi^+)$ are calculated for energies $E_\mu < 1.0$ BeV and $E_\mu > 1.0$ BeV. The effective energies of the nucleons producing the kaons and pions are estimated.

ALL theoretical [1-4] and experimental [5-15] studies have shown that cosmic-ray muons are partially longitudinally polarized. This is explained by the following circumstance. Part of the vertical flux of muons of definite energy is formed by pion decay into the lower hemisphere (in the rest system of the pion) and is polarized preferentially backwards. The remaining muons are formed by backward decay of higher-energy pions and are polarized preferentially forward. However, complete cancellation of these polarizations does not occur, since the pion spectrum falls off with energy, i.e., pions of low energies predominate in it. Similar arguments are valid also for muons formed in $K_{\mu 2}$ decay. It is clear that by measuring the absolute value of the polarization and investigating its dependence on the muon energy E, one can obtain information on the contribution of kaons to the mechanism of muon generation in the atmosphere.

We have carried out measurements and determined the absolute polarizations at different energies with three different experimental setups. We have observed a total of about 90,000 cases of μ^+-e^+ decay. The polarization was determined by measuring the asymmetry in the angular distribution of positrons from the decay of stopped muons. The measurements were carried out at 1000 meters above sea level.

The polarization of muons for $E_\mu = 0.14$ and 2.0 BeV was determined with a hodoscope arrangement possessing circular symmetry with respect to the absorber. A drawing of the experimental setup with a typical case of decay is shown in Fig. 1. Counter group IV consisted of copper counters 1 cm in diameter and 40 cm long. All

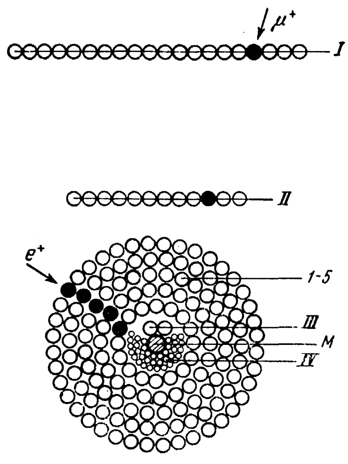

FIG. 1

Table I

E_μ, BeV	Muons			Positrons		
	$N_{\mu l}$	$N_{\mu r}$	$N_{\mu l}/N_{\mu r}$	N_{el}	N_{er}	N_{el}/N_{er}
0.14	4154	4356	0.95±0.03	4209	4301	0.98±0.03
2.0	4483	4528	0.99±0.03	5388	5245	1.02±0.03

the remaining groups consisted of type MS-9 glass counters. M is a cylindrical brass absorber 4 cm in diameter, in which the muons stopped and decayed. Counter groups I and III were connected to a coincidence circuit with a resolving time of 5 $\times 10^{-7}$ sec. Group IV was connected with groups I and III to an anticoincidence circuit. A I + III − IV coincidence pulse selected the muons stopped in the absorber M, and was the controlling pulse. To determine the muon direction, dc hodoscopic networks of MTKh-90 tubes were mounted on counter groups I and II.

To record the decay positrons, counters 1—5 were placed around the absorber M in the form of five concentric layers. To determine the positron direction, pulsed hodoscopic networks of MTKh-90 tubes connected to operate as neon lamps were mounted on the anodes of these counters. Counters 1—5 were operated by a controlled high voltage supply [16]. A I + III − IV coincidence pulse triggered a high-voltage pulse generator consisting of a TGI1-35/3 thyratron with a pulse-forming network connected to its anode. The pulse from this generator, with a height of ~2 kV, a length $\tau = 4.0$ μsec, and a rise time $\tau_r \leq 0.15$ μsec, was fed to groups 1—5 with a delay $\tau_d = 1.0$ μsec after the stopping of the muon. In order that groups 1—5 would not be sensitive to muons, a clearing voltage of −100 V was constantly supplied to their cathodes, and removed the primary ions due to the muons prior to the application of the high-voltage pulse. Consequently groups 1—5 recorded only decay positrons in the time interval 1—5 μsec after the stopping of the muon. The operation of all the hodoscopic networks was photographed by an FR-2 recorder whose shutter was opened only when there were at least three MTKh-90 tubes fired in groups 1—5.

Analysis and selection of μ^+-e^+ decay events were performed directly from the film by means of a slide projector. Only those events were selected for which the muon and positron paths intersected in the absorber M and for which at least three lamps were ignited along the positron path. The muon angles with the vertical in the plane of photography (Z, Y), $\theta_{\mu y}$, were measured, taking into account the sign of this angle. The emission angles of the positron relative to the muon, in the same plane, $\theta_{\mu e}$, were also measured. The asymmetry in the angular distribution was determined from the number of decays in the upper hemisphere ($N\uparrow$) and in the lower hemisphere ($N\downarrow$) relative to the muon direction. To avoid possible distortions in the true angle of the positron distribution due to different efficiencies of the counters 1—5, the latter were periodically, every two hours, rotated by 180° about the absorber M.

Table II

E_μ, BeV	$N_\uparrow$	$N_\downarrow$	$R = \frac{N_\uparrow}{N_\uparrow + N_\downarrow}$	Polarization η
0.14	4916	4140	0.543±0.005	0.33±0.037
2.0	6460	5234	0.552±0.005	0.41±0.033

As a control, the ratio N_{el}/N_{er} was determined from our data, where N_{el} and N_{er} are the numbers of positrons emitted into the left and right hemispheres relative to the muon. It is clear that this ratio is a good index of the symmetry of the apparatus. We also determined the ratio $N_{\mu l}/N_{\mu r}$, where $N_{\mu l}$ and $N_{\mu r}$ are the numbers of muons incident on the apparatus from the left and from the right, relative to the vertical. The results are given in Table I. From the table we can see that the apparatus possessed complete intrinsic symmetry.

During the entire period of measurements with this apparatus, 20,750 cases of μ^+-e^+ decay were observed. The experimental results are listed in Table II.

The polarization η is determined from the formula

$$\eta = K(2R - 1)/K(\delta)K(\theta_{\mu x}).$$

For our apparatus, K = 3.6 is a theoretical coefficient to account for the geometry of the apparatus, the energy spectrum, the angular distribution, the range-energy relation, and range straggling [17] for the decay positrons, and $K(\delta)$ is a correction coefficient to account for the muon depolarization prior to its stopping. From the work of Hayakawa [2], $K(\delta) = 0.95$ for both series of measurements. Our apparatus determined the vertical projection of the polarization in the (Z, X)

Table III

E_μ, BeV	$N_\uparrow(0)$	$N_\downarrow(0)$	$N_\uparrow(H)$	$N_\downarrow(H)$	$R_0=\frac{N_\uparrow(0)}{N_\downarrow(0)}$	$R_H=\frac{N_\uparrow(H)}{N_\downarrow(H)}$	$R=\frac{R_0}{R_H}$	Polarization η
0.25	10170	8054	8845	8736	1.26 ± 0.02	1.01 ± 0.02	1.25 ± 0.025	0.33 ± 0.025
2.0	9454	6958	7645	7400	1.36 ± 0.02	1.03 ± 0.02	1.31 ± 0.025	0.41 ± 0.025

plane, and to determine the total polarization it is therefore necessary to introduce a correction to the angular distribution of stopping muons in the (Z, X) plane. This correction coefficient $K(\theta_{\mu X}) = \cos\theta_{\mu X}$, where $\theta_{\mu X}$ is the angle of the muon with the vertical in the (Z, X) plane, was determined experimentally and turned out to be $K(\theta_{\mu X}) = 0.97$ for $E_\mu = 0.14$ BeV and $K(\theta_{\mu X}) = 0.95$ for $E_\mu = 2.0$ BeV.

The muon polarization at $E_\mu = 0.25$ and 2.0 BeV was determined in a rectangular hodoscope array. The measurements were carried out alternately with a depolarizing magnetic field (symbol H) and without it (symbol 0). Preliminary results have been published[10] only for the second series of measurements ($E_\mu = 2.0$ BeV). In that paper a description is given of the experimental apparatus and the means of determining the absolute polarization. The final data for the second series of measurements, and also the data for the first series of measurements ($E_\mu = 0.25$ BeV) with the rectangular apparatus, obtained in the present work, are given in Table III.

In this case the polarization η is determined from the formula

$$\eta = \frac{R-1}{R+1}\,\frac{K}{K(\delta)K(\theta_\mu)}.$$

The value $K = 2.6$ was obtained for our apparatus with the aid of a computer. From Hayakawa's paper[2], $K(\delta) = 0.95$.

The experiment measured the vertical component of polarization of the muon flux. For determining the absolute polarization we introduced a correction to the spatial angular distribution of stopping muons, $K(\theta_\mu) = \cos\theta_\mu$, where θ_μ is the spatial angle of the muon with the vertical. For our apparatus the value $K(\theta_\mu) = 0.90$ was determined from the experimental data.

In the data presented, corrections have been taken into account in a similar way for background events, which consisted mainly of two types:

1) μ^+-e^+ decays in the counter walls of the controlling groups located above and below the absorber (B_1);

2) μ^+-e^+ decays in the external layer of the solenoid (B_2). B_1 background decays distort the true picture only in measurements without a magnetic field if the counters are glass, and only with a magnetic field if the counters are copper.

The solenoid consisted of three parallel layers. The average field inside the outer, third layer was about 2 Oe, which is insufficient for depolarization of the muons. Consequently B_2 introduces an error into the measurements only with a magnetic field. In the experimental data we have taken into account corrections corresponding to the distorting background, i.e., to only those parts of B_1 and B_2 which distorted the true distribution of decay positrons. The background B_1 was measured experimentally without the absorber and solenoid. We also measured the background under the conditions when a thin copper plate, 0.8 mm thick, equal to the equivalent thickness of one solenoid layer, was inserted in the apparatus. The difference between this background and the value of B_1, reduced to an equal time interval, is B_2. Results of the measurements are listed in Table IV. In our earlier work[10] we did not consider these corrections. On this account we obtained a high ratio $R_H = 1.12 \pm 0.018$ and a correspondingly depressed true polarization value.

Table IV

Background	Total time of measurements, hours	Total number of background decays	Ratio of distorting background to total decays
B_1	224	243	$(3.8\pm0.5)\cdot10^{-2}$
B_2	224	169	$(5.3\pm0.6)\cdot10^{-2}$

Polarization measurements on muons with a residual energy $E_\mu = 0.3$ and 1.45 BeV above the apparatus were made with a cloud chamber. The detailed description and results of this work have been published previously[15]. The final results obtained by us with the aid of all three sets of apparatus are listed in Table V.

Column 2 lists values of η_{theor}, taken from Berezinskiĭ and Dolgoshein[4], which were computed under the assumption that the muons are generated only by pions. Because of the large statistical errors, we cannot draw from the cloud chamber results (lines 3 and 4) any definite conclusions as to the role of $K_{\mu 2}$-decays in muon

Table V

		E_μ, BeV	η_{theor}[4]	η_{exp}	$\bar{E}_\mu$, BeV	$\bar{\eta}_{exp}$
		1	2	3	4	5
a	1	0.14	0.22	0.33±0.037	0.23	0.33±0.021
	2	0.25	0.24	0.33±0.025		
	3	0.30	0.25	0.23±0.09		
b	4	1.45	0.33	0.34±0.09	2.0	0.41±0.020
	5	2.0	0.33	0.41±0.033		
	6	2.0	0.33	0.41±0.025		

generation. All the other results show that η_{exp} is larger than η_{theor} by 2.5–3.0 standard deviations and that the $K_{\mu 2}$-decay contribution to the total flux of cosmic ray muons is already noticeable for the energies studied. The values of $\bar{E}_\mu$ and $\bar{\eta}_{exp}$ listed in columns 4 and 5 were obtained by combining the data of the intervals a ($E_\mu < 1.0$ BeV) and b ($E_\mu > 1.0$ BeV), taking into account their statistical errors. From these average values and with certain assumptions we can calculate the contribution of kaons to the generation of muons in the corresponding energy interval. These questions are discussed in detail by Asatiani and Sharkhatunyan[18]. It is assumed that:

1. Cosmic ray muons owe their origin only to the processes of π-μ and $K_{\mu 2}$ decay.
2. The kaon and pion energy spectra are similar in a certain energy interval, i.e., $\gamma_\pi = \gamma_K$ (γ_π and γ_K are respectively the exponents of the production spectra of pions and kaons).

With these assumptions for the energy region b, where $\gamma_\pi = 2.65$, we obtain the ratio values

$$K^+/\pi^+ = 0.36 \pm 0.11, \qquad K^+/(K^+ + \pi^+) = 0{,}26 \pm 0.06.$$

Dolgoshein et al[12] obtained for the second ratio the value 0.18 ± 0.15. These results agree within the experimental errors, but the error is so large that we cannot very well claim good agreement.

To obtain statistically more accurate results we combined our data with those of other experiments performed with similar apparatus. Our work[15] and that of Sen-Gupta and Sinha[14] were carried out under almost identical conditions and for identical energies, and we therefore considered it permissible to combine the results of these studies completely. From the work of Sen-Gupta and Sinha[14] we determined the values of N↑ and N↓, combined them with our values of the corresponding quantities, and then computed the polarization η in the manner described by us earlier[15]. The combined results are listed in Table VI (rows 5 and 8). Table VI also lists the results of Dolgoshein et al.[12], obtained with apparatus similar to ours, which can be combined with our data.

The values of $\bar{E}_\mu$ and $\bar{\eta}_{exp}$ were calculated taking into account statistical errors for the two intervals $E_\mu < 1.0$ BeV and $E_\mu > 1.0$ BeV. For $E_\mu > 1.0$ BeV, with the assumptions described above, we obtained the values

$$K^+/\pi^+ = 0.30 \pm 0.09, \qquad K^+/(K^+ + \pi^+) = 0.23 \pm 0.05.$$

In the region $E_\mu < 1.0$ BeV, the exponent γ_π changes rather rapidly and can have a large uncertainty, and therefore it is difficult to discuss the accuracy of the ratio K^+/π^+ in this region, regardless of the magnitude of the statistical errors.

For this energy region all calculations were made using the effective value $(\gamma_\pi)_{eff} = 2$ found from the formula of Gol'dman[1] for $\eta_\pi = 0.24$. According to Berezinskiĭ and Dolgoshein[4] this value of η_π corresponds to the energy $E_\mu = 0.25$ BeV. For $E_\mu < 1.0$ BeV with the foregoing assumptions we obtained the values

$$K^+/\pi^+ = 0{,}29 \pm 0.07, \qquad K^+/(K^+ + \pi^+) = 0.22 \pm 0.04.$$

The value $E_\mu = 0.25$ corresponds to an initial energy at the time of creation E = 2.0 BeV. A muon of this energy can be formed either in the decay of a pion with energy ϵ_π in the range 2–3.5 BeV, or from the decay of a kaon with energy ϵ_K in the range 2.0–44.00 BeV. The value $E_\mu = 1.88$

Table VI

	E_μ, BeV	η_{theor}[4]	η_{exp}	$\bar{E}_\mu$, BeV	$\bar{\eta}_{exp}$	No. of cases	Source
1	0.14	0.22	0.33±0.037	0.25	0.31±0.015	9 056	present work
2	0.20	0.23	0.24±0.045			6 000	[12]
3	0.25	0.24	0.33±0.025			35 805	present work
4	0.30	0.25	0.29±0.08			1 500	[12]
5	0.21–0.31	0.24	0.28±0.06			1 756	[14, 15]
6	0.55	0.28	0.25±0.035			10 000	[12]
7	1.05	0.33	0.40±0.08	1.88	0.40±0.017	1 500	[12]
8	1.2–1.45	0.33	0.34±0.07			1 370	[14, 15]
9	1.4	0.33	0.35±0.05			5 000	[12]
10	1.55	0.33	0.40±0.05			5 000	[12]
11	2.0	0.33	0.41±0.033			11 694	present work
12	2.0	0.33	0.41±0.025			31 457	,, ,,

BeV corresponds to E = 4.0 BeV, ϵ_π in the range 4.0–7.0 BeV, and ϵ_K in the range 4.0–87.0 BeV.

It should be noted that in each of the ratios obtained above the kaons and pions are attributed to approximately the same energies. This is explained by the fact that their production spectra fall off sharply with energy and the effective energies of the kaons and pions forming muons with energy E are close to the lower limits of ϵ_π and ϵ_K.

For the region $\bar{E}_\mu = 0.25$ BeV we can consider that

$$\varepsilon'_{\text{eff}} = \varepsilon_{K\,\text{eff}} \approx \varepsilon_{\pi\,\text{eff}} \approx 2.5 \text{ BeV},$$

and for the region $\bar{E}_\mu = 1.88$ BeV

$$\varepsilon''_{\text{eff}} = \varepsilon_{K\text{eff}} \approx \varepsilon_{\pi\,\text{eff}} \approx 5.0 \text{ BeV}.$$

From the values of ϵ'_{eff} and ϵ''_{eff} we can also evaluate the effective energy $E_{N\text{eff}}$ of the nucleons forming these kaons and pions in nuclear interactions in the upper layers of the atmosphere. These evaluations gave $E_{N\text{eff}} \approx 12$ BeV for the region $\bar{E}_\mu = 0.25$ BeV, and $E_{N\text{eff}} \approx 55$ BeV for the region $\bar{E}_\mu = 1.88$ BeV.

Let us compare the experimental data obtained in our experiments with data presently available in the literature on muon polarization. This comparison has been made in Fig. 2. The smooth curve corresponds to the theoretical calculation of the polarization by Berezinskiĭ and Dolgoshein[4] for the condition that cosmic ray muons are generated only by pions. The data of Kocharyan et al.[7] and Barmin et al.[9] have been omitted from Fig. 2 because their statistics are inadequate. Furthermore, Kocharyan et al.[7] did not select muon stoppings in the standard way with an anticoincidence circuit, which for such poor statistics (563 events in all) could strongly distort the result because of the large number of accidental coincidences. In the work of Barmin et al.[9], as the authors themselves point out, the results could be distorted by possible decays in the lower part of the apparatus. The data of Bradt and Clark[13], indicated by crosses, are relative values of polarization, and therefore in comparison with our data not much weight should be given to such a large disagreement. The absence of any increase in polarization with energy in this same work can probably be explained by exaggeration of the polarization values at low energy, due to the fact that the apparatus recorded decays of muons incident over a very wide solid angle of $\sim 2\pi$. Berezinskiĭ and Dolgoshein[4] showed that in just this energy region the polarization of an inclined beam of muons is greater than that of a vertical beam. Johnson's

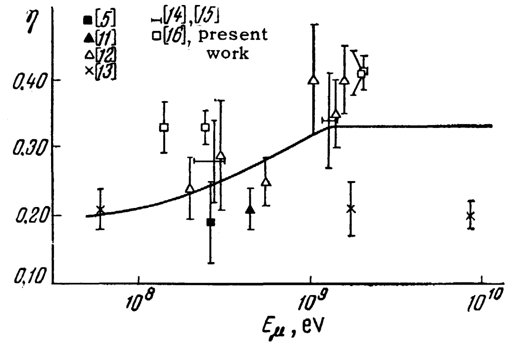

FIG. 2

results[11], in the words of the author himself, do not give the absolute polarization value. In particular, Johnson has not taken into account even the correction for depolarization of the muon up to its stopping. The data of Clark and Hersil[5], while they have good statistics (26,000 events), have a rather large error. These authors did not correct for decays in the scintillators above and below the absorber. For the method used by Clark and Hersil to compute the polarization, this correction could be important.

The results of Dolgoshein et al.[12], Sen-Gupta and Sinha[14], Asatiani et al.[15], and the present work (although some of them have large errors) agree satisfactorily with each other and in aggregate do not exclude the possibility that the contribution of $K_{\mu 2}$-decay to cosmic ray muon generation is appreciable even at the energies considered here. If only our results are considered, then this assertion becomes more explicit.

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