ELECTRON SPECTRUM AT 3200 m ABOVE SEA LEVEL

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Using a magnetic spectrometer in conjunction with a multiplate cloud chamber, a momentum spectrum was obtained for cosmic-radiation electrons in the range from 4×10^8 to 4×10^9 ev/c. The penetrating power of fast electrons ($E \geq 4 \times 10^8$ ev) is discussed.

1. INTRODUCTION

THE energy spectrum of cosmic-radiation electrons at sea level and at various altitudes in the atmosphere has been studied in Refs. 1 — 10 and elsewhere. The principal methods of investigation were: (1) a comparison of the absorption of cosmic rays in heavy and light substances such as Pb and Al,[1,2] (2) a cloud chamber with lead plates,[3,6,7] (3) large flat scintillation counters separated by lead absorbers,[8,9] (4) a cloud chamber with lead plates in a magnetic field,[4] and (5) an old form of the magnetic mass spectrometer of Alikhanian and Alikhanov.[5]*

In the present work the electron spectrum was studied by means of an Alikhanian-Alikhanov mass spectrometer in conjunction with a multiplate cloud chamber.[11] The principal advantages of this method are that, unlike methods 1, 2, and 3, it enables us to determine the energy of an electron directly by measuring the radius of curvature of its trajectory in the magnetic field and to determine the sign of the charge in each instance. The transmission is much greater than for method 4. The advantage over method 5 is the possibility of identifying electrons reliably by their multiplication in the lead plates of the cloud chamber.

2. ELECTRON SPECTRUM

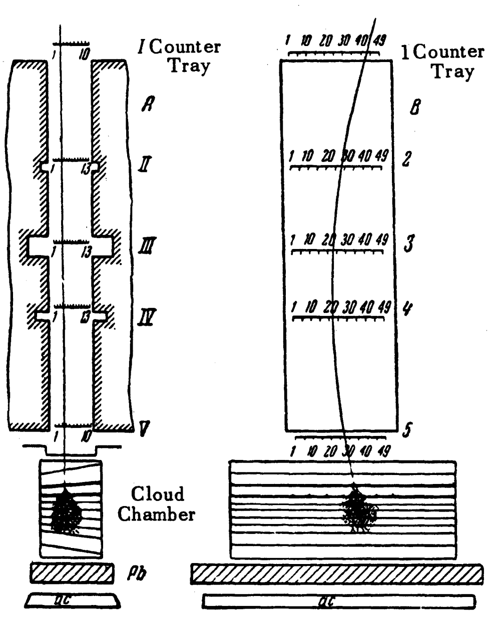

FIG. 1. Experimental arrangement

Our measurements were obtained at 3200 m above sea level and pertained to electron energies E in the range from 4×10^8 to 4×10^9 ev. For the same altitude and for the same energy region the electron spectrum was previously obtained by Muskhelishvili,[5] and the electron and photon spectrum was obtained by Hazen[3] and Lovati, Mura et al.[6] using a multiplate cloud chamber.

In Ref. 3 the energy of the primary particles was determined on the basis of the calculations of Rossi and Greisen[12] from the observed number of particles in the shower maximum. In Ref. 6 the electron and photon energies were determined from the total number of shower particles, using the cascade curves of Wilson[13] for (for $E < 3 \times 10^8$ ev) and of Arley[14] (for $E > 3 \times 10^8$ ev). Both methods are indirect, because the energies of the primary electrons and photons are determined from theoretical cascade curves by using the number of secondary particles observed in the cloud chamber. However, as we know, the cascade curves have recently been considerably improved (as in Ref. 15) and lead, in particular, to different values of the average number of particles at given depths. It

*In Ref. 10 a magnetic spectrometer was used in conjunction with a proportional counter.

TABLE I

Counter Tray	Number of counters in tray	Counter diameter, mm	Distance between centers of adjacent counters, mm	Counter length, mm	Material and wall thickness, mm
1 and *5*	49	4,6	5.3	120	0,1 Cu
2, 3, 4	49	4,6	5.3	120	0,1 Al
*I*and*V*	11	10	10.3	290	0,1 Cu
II, III, IV	13	8	8.5	290	0.1 Al
Anticoincidences, *ac*	27	20		900	0.15 Cu

must also be noted that aside from the errors in determining the primary electron energy, (errors associated with fluctuations in the number of secondary particles), the secondary particles in multiplate cloud chambers can often be determined only approximately because of the background of extraneous particles and the relatively large number of slow electrons, as was pointed out by Wilson in Ref. 16.

With respect to Ref. 5 it can be stated that although electron energies were here determined directly by measuring the radius of curvature of trajectories in a magnetic field, the electrons were identified by an insufficiently reliable method. In approximating the differential spectra by the law $N(p)\,dp = N_0 p^{-\gamma_d}\,dp$ in Refs. 3, 5, and 6 the values $\gamma_d = 3.0$, 1.5, and 2.5 were used, respectively. It was important to determine the electron spectrum by a direct method which would be free of the shortcomings mentioned above.

Figure 1 shows the experimental arrangement.* In the 100 × 30 × 12 cm gap of the electromagnet, which provided a field of 4500 oersteds, we placed a hodoscopic system of Geiger counters which enabled us to "trace" the trajectory in two mutually perpendicular planes A and B, using 5 points in each plane. Details concerning the counters are given in Table I. Between the poles of the magnet we placed a rectangular cloud chamber (620 × 280 × 180 mm) containing 7 lead plates each 7 mm thick. An 8 cm thick lead block was below the cloud chamber and counter tray ac was below this block. Practically all of the electrons which entered the apparatus could be registered because the total thickness of the matter above ac was ~ 28 shower units. At the same time there was a considerable reduction of the dead time resulting from the elimination of the "hard" component, which is of no interest here.

TABLE II

No. of interval	Momentum $p \times 10^{-8}$ ev/c	Integral number of registered electrons and positrons	Integral number of electrons and positrons (corrected for the "transmission" of the apparatus): Assuming isotropic scattering	Assuming a $\cos^3\theta$ distribution
1	4.0	307	311	319
2	4.5	264	266	270
3	5.0	233	234	236
4	6.0	172	172	172
5	7.0	138	138	138
6	8.0	117	117	117
7	9.0	96	96	96
8	10.0	88	88	88
9	11.0	71	71	71
10	13.0	65	65	65
11	16.0	37	37	37
12	20.0	22	22	22
13	30.0	10	10	10

Electrons were identified by their cascade multiplication in the lead plates of the cloud chamber, because for electrons with $E > 4 \times 10^8$ ev there is practically no possibility of passage through two or three lead plates without multiplication. The momentum p of a primary electron was determined from the measurement of its radius of curvature in the magnetic field. The probable error in momentum determinations because of the finite dimensions of the counters is given by (see Ref. 11)

$$(\Delta p/p)_{\text{prob}} = 0.66 \cdot 10^{-10}\, p.$$

The electron momentum measurements are given in Table II.† Column 3 of the table contains the integral number of registered electrons. In order to determine the true ratios of the numbers of particles in different intervals it is necessary to take into account the relative transmission in the recording of particles of a given momentum. The method used in calculating the transmission of the mass spectrometer is described in Ref. 11. We note that the relative transmission depends not only on the geometry of the apparatus but also on the angular distribution of the primary particles that enter the apparatus. However, under our experimental conditions the trajectories of particles with $p \geq 4 \times 10^8$ ev/c form a small angle with the vertical and the

*A detailed description of the apparatus is given in Ref. 11. In the present experiment the thickness of the layer of light material over the apparatus was about 2 g/cm². The roof of the chamber was 8 mm of Al.

†We shall give henceforth the total number of electrons and positrons.

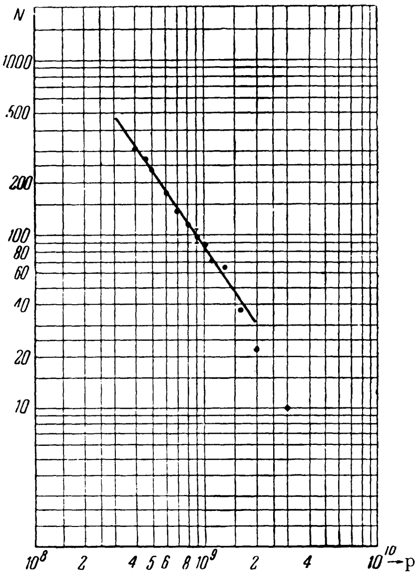

FIG. 2. Integral electron spectrum

transmission is relatively insensitive to the angular distribution of the particles. Column 4 gives the numbers of electrons corrected for the transmission upon the assumption of isotropic scattering of incident particles. Column 5 gives the corresponding numbers for a $\cos^3\theta$ distribution.

Figure 2 is a logarithmic representation of the integral electron spectrum. Electron momentum (or energy) is denoted on the horizontal axis, while the vertical axis denotes the numbers of electrons which possess energy above each given amount. In the energy range $4 \times 10^8 - 2 \times 10^9$ ev the points fall on a straight line and the corresponding integral spectrum can be approximated by $N(p) = N_0/p^{\gamma_{int}}$ with $\gamma_{int} = 1.45 \pm 0.20$. It should be noted that the passage of an electron through the telescopic system is accompanied by the triggering of counters which do not lie on the trajectory of the particle. This may be caused by extraneous particles, random coincidences, etc. Yet even in such instances it is easy to establish the true trajectory, because the counters which determine the latter lie on a straight line in plane A and on a circle in plane B. In addition to the total spectrum in Fig. 2 we have plotted the spectrum of single electrons, which is described by the exponent $\gamma_{int} = 1.55 \pm 0.20$ and does not differ from Fig. 2 within the limits of statistical error.

3. ELECTRON FLUX

For the purpose of determining the absolute electron flux we used data on the proton component which we obtained at the same time. Taking the transmission into account, approximately 135 protons, which were stopped in plates 3 — 6 were registered during the measurements. Taking into account the increase of the range due to the inclination of the trajectories with respect to the planes of the plates as well as due to scattering in the plates, the proton momentum interval corresponding to these residual ranges is approximately $4.8 \times 10^8 - 6.15 \times 10^8$ ev/c. From the data of Ref. 17, obtained at the same altitude, the absolute proton flux in this momentum interval is 0.18×10^{-3} cm^{-2} sterad^{-1} sec^{-1} and comprises $(0.18 \times 10^{-3})/(13.8 \times 10^{-3}) = 1.3\%$ of the muon flux with momenta $p > 370$ Mev/c. Since the 311 electrons which we counted exceed by 2.3 times the number of protons in the same solid angle, it can be concluded that the electron flux for momenta $p > 4 \times 10^8$ ev/c is $\sim 3\%$ of the muon flux for momenta $p > 370$ Mev/c.

The absolute flux of electrons with momenta $p \geq 4 \times 10^8$ ev/c is 0.41×10^{-3} cm^{-2} sterad^{-1} sec^{-1}. This value is probably somewhat too low because it is not always possibie to take into account all of the electrons in dense showers. References 3, 5, and 6 give the intensity of the electron-photon component as a percentage of the flux of "hard" particles, which are muons with momenta $p \gtrsim 1.6 - 2.0 \times 10^8$ ev/c and protons with momenta $p \gtrsim 5 - 8 \times 10^8$ ev/c. If for convenience of comparison with these references we relate our electron count to the flux of "hard" particles, we obtain $\sim 2.5\%$ for the electron flux with momenta $p \geq 4 \times 10^8$ ev/c.

We shall now compare our results with those of Refs. 3, 5, and 6. According to Muskhelishvili[5] the electron flux for $2 \times 10^8 \leq p \leq 10^9$ ev/c is $\sim 3\%$, while for $4 \times 10^8 \leq p \leq 10^9$ ev/c it is 1.5%. According to our data the number of electrons in the interval $4 \times 10^8 \leq p \leq 10^9$ ev/c is $\sim 1.8\%$ of the number of "hard" particles. Hazen[3] gives the total intensity of the electron-photon component as 7% and the ratio 2.5 : 1 for the numbers of electrons and photons with $p > 2 \times 10^8$ ev/c. Thus, according to Hazen, the electron flux for $p > 2 \times 10^8$ ev/c is $\sim 5\%$. Lovati, Mura, et al.[6] give the total intensity of the electron-photon component in the same momentum range ($p > 2 \times 10^8$ ev/c) as 12.2%, which is almost 1.7 times greater than the result obtained by Hazen. Using Hazen's ratio between the numbers of electrons and photons, from the data of Lovati et al. we obtain 8.6% for the electron flux. For comparison

TABLE III

Author	Momentum range, ev/c	Electron flux as a fraction of the flux of "hard" particles, %	Electron flux from the previous experiment, %
Hazen[3]	$\geq 4 \cdot 10^8$	1.6—1.8	~ 2.5
Lovati et al.[6]		3.0—3.6	
Muskhelishvili[5]	$4 \cdot 10^8 - 10^9$	1.5	1.8

with our own results we take $\gamma_{int} = 1.5$ as the exponent of the integral electron spectrum in the momentum range $2 - 4 \times 10^8$ ev/c (for $p < 2 \times 10^8$ ev/c this exponent is apparently reduced[18]). Then for the electron flux with $p > 4 \times 10^8$ ev/c we obtain 1.8[3] and 3%[6] instead of our result, ~ 2.5%.

According to Refs. 3 and 6 it is possible to estimate the electron flux by another method. From the histograms given in these references it follows that the total number of electrons and photons with $p \geq 4 \times 10^8$ ev/c is 2.2% (Ref. 3) and 5.1% (Ref. 6). Assuming the electron-photon ratio to be 2.5 : 1 in this momentum range, we find that the electron flux with $p \geq 4 \times 10^8$ ev/c is 1.6% (Ref. 3) and 3.6% (Ref. 6).

It is clear that these values for the electron component (with $p \geq 4 \times 10^8$ ev/c), based on the data of Refs. 3 and 6 for the total electron-photon component with $p > 2 \times 10^8$ ev/c, must be regarded as very approximate. We also note that even the value given for the total intensity of the electron-photon component in Ref. 3 is in need of correction. For example, Hazen determined the energy of a primary electron (or photon) on the basis of Rossi and Greisen's calculations[12] and assumed that a given number of particles in the shower maximum corresponds to identical energy for a primary electron or photon. Specifically, it was assumed that when the energy of the primary electron (or photon) is 2×10^8 ev, the average number of particles in the maximum is 5. According to more recent data (see Ref. 15) this number of particles corresponds to higher energy for the primary electron or photon, that is, 2.4×10^8 ev for electrons and 3.3×10^8 ev for photons. Therefore Hazen's form for the total spectrum of electrons and photons can hardly be regarded as correct and his value for the intensity of the electron-photon component is too low.

In conclusion we summarize the data for the electron component in Table III. Keeping in mind the low accuracy for all of the results presented, we find our data in agreement with those of Refs. 3, 5, and 6.

4. REMARK ON THE PENETRATING POWER OF FAST ELECTRONS

We know that calculations of cascade curves for lead, which take into account the energy dependence of the photon absorption cross section as well as electron scattering (see Ref. 15), lead to essentially new results concerning the penetrating power of fast electrons.* As an illustration, Table IV shows the average number of particles at depths of 22 and 28 t-units (shower units) for a few fixed values of the primary electron energy, based on both older work[19] and the most recent work of Ivanenko.[15]

TABLE IV

Energy of the primary electron, ev	Average number of particles at depths: 22 *t*-units		28 *t*-units	
	According to Rossi[19]	According to Ivanenko[15]	According to Rossi[19]	According to Ivanenko[15]
$7\cdot10^8$	0.0026	0.19	0	0.03
10^9	0.0045	0.48	0	0.07
$5\cdot10^9$	0.049	3.93	0.002	0.62
10^{10}	0.3	11.6	0.013	2.10

We see from the table that: (a) according to Rossi the average number of particles at depths of 22 and 28 t-units is negligibly small even for showers produced by electrons with the high energy $E \sim 5 \times 10^9$ ev; (b) Ivanenko's work yields much larger values for the average number of particles at the same depths and thus greater penetrating power of the showers.

To check these conclusions experimentally, we measured the electron spectrum again with a somewhat different experimental arrangement (Series II) in which the total absorber thickness above counter tray ac was 22 shower units instead of the 28 units of Series I. It is clear that according to Rossi's theory[19] this reduction in the thickness of absorbing material should have practically no effect on the form of the spectrum. A quite different result follows from Ivanenko's work:[15] Since in a considerable number of instances electrons are able to pass through 22 t-units of absorbing material and enter counters ac, thus being eliminated from consideration, the resultant spectrum must be steeper. In Fig. 3 the electron spectrum of Series II is represented by crosses. The spectrum of Series I is given for comparison after adjustment for the total number of electrons. Despite the small statistical accuracy, we can affirm qualitative agreement with Ivanenko.[15]

We shall now attempt, on the basis of Ref. 15, to introduce a correction into spectra I and II by taking into account the electrons which escaped registration in our experiments because their multiplication products entered counters ac. It is obvious that after this correction spectra I and II must be approximated by curves with the same exponent γ, which is the true exponent for the spectrum of the electron

*References to earlier work are given in Ref. 15.

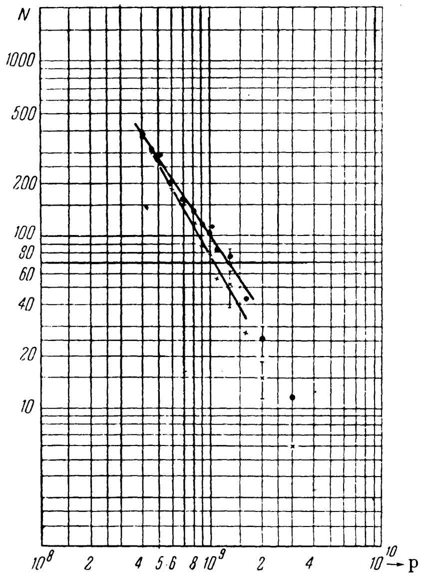

FIG. 3. Electron spectrum. ×—for Series II (22 t-units); •—for Series I (28 t-units)

TABLE V

$E\cdot10^{-8}$ ev	22 t-units			28 t-units		
	$\bar{n}$	$\bar{n}/2$	σ, %	$\bar{n}$	$\bar{n}/2$	σ, %
4.0	0.014	0.007	99.3	0.01	0.005	99.5
6.0	0.12	0.06	94.0	0.025	0.012	99.0
8.0	0.27	0.135	87.4	0.045	0.022	98.0
10.0	0.48	0.24	78.7	0.072	0.036	96.5
12.0	0.59	0.295	74.4	0.088	0.044	95.7
15.0	0.77	0.385	68.0	0.13	0.065	93.7
20.0	1.09	0.545	58.0	0.18	0.09	91.0
30.0	1.89	0.945	38.8	0.297	0.148	86.0
50.0	3.93	1.965	14.0	0.62	0.31	73.0
100.0	11.6	5.8	0.3	2.1	1.05	35.0

flux entering the apparatus, and that the straight lines which approximate these spectra must be parallel if Ivanenko's cascade curves, upon which the calculation is based, are correct. Since the exclusion of high-energy electrons occurs because their multiplication products enter counters ac, it is necessary to calculate the probability σ that, for a primary electron of given energy, the number of secondary electrons at a given depth (above ac) becomes zero when the average number of secondary electrons is $\bar{n}$. σ is thus the probability that our apparatus will register an electron of a given energy.

At the present time this problem cannot be solved exactly, because the distribution function of the number of particles is unknown. However, there are some grounds for assuming that the Poisson distribution can be used to approximate σ. For example, Wilson's data[16] on the fluctuations of the number of particles, which were obtained by the Monte Carlo method, show that the numerical value of σ is approximately that calculated from Poisson's formula.* In determining σ we have not used the average number of particles at our depths $\bar{n}$ as given by the theory but rather $\bar{n}/2$, because the theory takes into account the reflux of electrons back-scattered in lower-lying layers of lead, which constitutes about half of the total number of electrons. Figure 1 shows that this reflux is absent in our experimental arrangement.

Table V contains the values of σ which were calculated from the Poisson distribution for lead filters 22 and 28 t-units thick. The energy of the primary electron is given in column 1. Columns 2 and 5 give the average number of electrons at depths of 22 and 28 t-units, respectively, which we calculated from the formulas in Ref. 15. The table shows that with an absorber thickness of 28 t-units the efficiency of electron registration is large even at the high energy $E \sim 2-3\times10^9$ ev. With 22 t-units of absorber thickness the picture is quite different: At $E \sim 8\times10^8$ ev $\sigma \approx 87\%$ and at $2-3\times10^9$ ev σ is below 50%.

The values of σ which are given here were used to correct our experimental electron spectra. Numerical values for intermediate energies were determined by interpolation. For each energy interval we related the number of registered electrons to σ, after which we plotted the integral spectra I′ and II′ shown in Fig. 4. It can be seen that in the energy range which is of interest spectrum I′ duplicates spectrum I (Fig. 2) and the exponent $\gamma_{int} = 1.4-1.45$ remains practically unchanged. The total number of particles in the spectrum increased by only ~ 4%.

Spectrum II′, which was obtained by correcting spectrum II (Fig. 3), differs considerably from the latter in its slope and in the integral number of particles, which have increased by ~ 23%. The figure shows that the straight lines which approximate II′ and I′ are now practically parallel.

It is interesting that the ratio of the total numbers of electrons in spectra II and I is $N_2/N_1 = 370/319 = 1.16$, whereas the ratio of the durations of the measurements is $t_2/t_1 = 1.4$ For the corrected spectra II′ and I′ we have the ratio $N_2'/N_1' = 1.4$; this also shows that the total number of unregistered electrons has been taken into account correctly. Our results show† that Ref. 15 gives the correct average number

*We note that according to the same data the probability that one or two particles will appear at a given depth, given the average number $\bar{n}$, differs greatly from that calculated using the Poisson distribution.

†If the comments made in connection with the calculation of σ are valid.

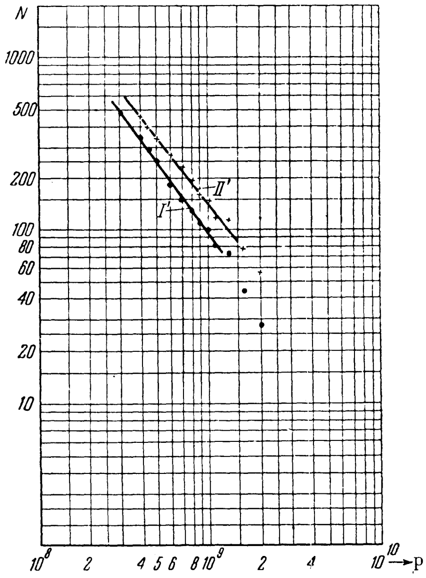

FIG. 4

TABLE VI

Momentum Interval $p \times 10^{-8}$ ev/c	Number of Electrons	Number of Positrons
4—6	178	153
6—10	99	92
10—15	48	53
15—20	15	14
>20	19	18
Totals	359±19	330±18

of secondary electrons at various depths for primary electron energies $E \geq 4 \times 10^8$ ev. Of course, the low statistical accuracy of our experimental data must also be kept in mind.

5. ELECTRON-POSITRON RATIO

There is apparently no reason to expect a predominance of either electrons or positrons, but it is of interest to obtain pertinent data. Table VI gives the results for the two series of measurements. In all energy intervals the electrons and positrons are equal in number within the limits of statistical accuracy.

6. GENERAL RESULTS OF THE INVESTIGATION

(a) The integral electron spectrum in the energy range $4 \times 10^8 \leq E < 2 \times 10^9$ ev at 3200 m above sea level can be approximated by $N(p) = N_0/p^{\gamma_{\text{int}}}$, where $\gamma_{\text{int}} = 1.5 \pm 0.2$.

(b) The vertical flux of electrons possessing momenta $p \geq 4 \times 10^8$ ev/c is 0.41×10^{-3} cm^{-2} sterad^{-1} sec^{-1}, which comprises ~ 3.0% of the flux of muons with momenta $p > 370$ Mev/c.

(c) The number of electrons is equal to the number of positrons in all momentum intervals with $p \geq 4 \times 10^8$ ev/c.

(d) Our experimental data concerning penetration by fast electrons ($p \geq 4 \times 10^8$ ev/c) are in approximate agreement with calculations based on Ivanenko's cascade curves.[15]

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