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ELECTRON COMPONENT OF THE PRIMARY COSMIC RADIATION AT ENERGIES $\gtrsim$15 GeV

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An experiment has been carried out to study the electron[1] component of the primary cosmic radiation at energies $\gtrsim$15 GeV using a nuclear-emulsion stack flown on 6 April 1963 under 10.2 g/cm^2 of residual atmosphere over Hyderabad, India. The emulsion stack consisting of 265 hypersensitive Ilford G-5 emulsions, each of size 20 cm$\times$15 cm$\times$0.06 cm, was flipped through 180° when the balloon reached ceiling altitude, and thereafter was kept oriented in the east-west plane to an accuracy better than $\pm 2°$ for the entire period of 398 minutes at the ceiling altitude. The total vertical depth of the stack was 15 cm or 5.2 radiation lengths (r.l.). Two decisive advantages of nuclear emulsions over other types of detector systems to study electrons of energies >10 GeV are (i) the possibility of identifying without ambiguity the events which are due to electrons, and (ii) the comparatively reliable methods which exist for estimation of energy right up to energies of thousands of GeV.

Scanning was carried out along a "scan line" at a depth of 3.5 cm (or 1.21 r.l.) for at least two parallel tracks separated by $<150\ \mu$m, and having zenith angles $\leqslant 50°$ and dip angles $\leqslant 7.8°$. Selected events were traced back to the top edge of the stack and were classified as due (i) to γ rays if the tracks ultimately led to an electron pair with no associated satellite track within 150 μm, or (ii) to electrons if the event was found to enter the stack as a single track and showed subsequent characteristic electromagnetic multiplication. From observations made on the "electron events," they are conclusively identified as due to electrons. In this way scanning has been carried out on a total length of 334 cm along the "scan line," and 24 electrons of energy >1 GeV have been obtained.

The energies of the electrons were estimated by two methods. For events with $E > 50$ GeV, track counts were made within circles of different radii at various points along their longitudinal development, and the energies at the top of the stack were estimated using the Nishimura-Kidd[2] calculations. For electrons between 1 and 50 GeV, the electron track was traced down the stack as far as possible. The coordinate method of scattering measurements was then employed on the entire track length available. These measurements were divided into a number of successive segments such that each segment had about 20 independent cells for which the mean second difference had values between 3 and 5 times the total noise value. The energy values obtained for each segment from these measurements were then extrapolated to the top of the stack using the exponential energy loss for the electrons; a mean value was then obtained for each event at the top of the stack. The energies obtained for all the electrons at the top of the stack were then extrapolated to the top of the atmosphere.

Errors on the estimated electron energies arise from measurement errors and fluctuations in the electromagnetic cascade development. For electrons with $E > 50$ GeV, the combined errors amount to ±30%.[2] In the case of electrons of lower energy, the errors were estimated by making measurements in an emulsion exposed[3] to 3.5-GeV electrons from DESY, Hamburg, in a manner identical to that employed in the case of cosmic-ray electrons. From this it was found that the mean energy of the electrons (in the DESY stack) was 3.6 GeV and that the errors due to measurement and electromagnetic fluctuation had the same magnitude. This was further confirmed by an analysis of the measurements on the cosmic-ray electrons also. Errors on the estimates of energy for electrons between 1 and 50 GeV were made on this basis.

The probability for the detection of an electron will depend on its energy, and this was calculated as a function of energy for our selection criteria by taking into account all relevant electromagnetic processes. The calculated values were checked by observations on the 3.5-GeV electrons from DESY and also by an analysis of the cosmic-ray electron events. The final detection probabilities used are thought to be correct within about 5% between 5 and 10 GeV and within 10% between 10 and 30 GeV; they reach a value very close to 1.0 at about 50 GeV.

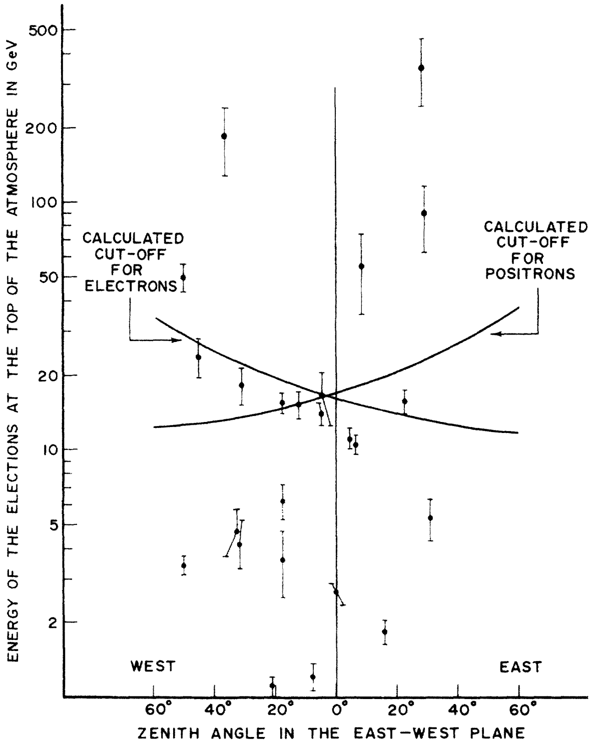

FIG. 1. Plot of electron energies at the top of the atmosphere against their arrival directions in the east-west plane. The two curves represent the calculated geomagnetic cutoff energies for electrons and positrons as a function of zenith angle in the east-west plane.

It is first necessary to separate the secondary—"atmospheric"—electrons from the total sample. In Fig. 1 we have shown the energies of all the 24 electrons at the top of the atmosphere against their angles of arrival in the east-west plane. The two curves drawn in this figure relate to the calculated geomagnetic cutoff energies for electrons and positrons.[4] From this plot we find that there are 12 electrons with energies well below the cutoff energies; these are identified as "atmospheric" electrons. Of these 12, only two have energies between 6 and 14 GeV. The energy spectrum for these electrons weighted according to their detection probabilities is given in Fig. 2. In this figure is also shown the calculated flux of electrons produced in the overlying atmosphere through $\pi^{\pm,0}$ decay; these calculations are believed to be correct within about 20%. On the basis of this calculation it is expected that there can be only 0.5 electron of energy >14 GeV in our sample of primary electrons. The possible excess of observed "atmospheric" electrons over the calculated value could well be due

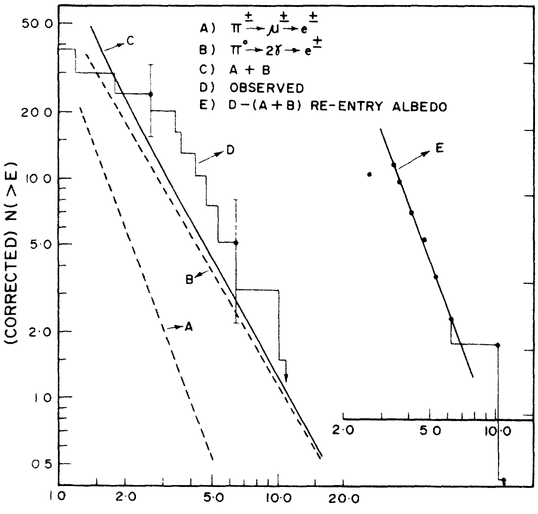

FIG. 2. The flux and energy spectrum of electrons of atmospheric origin. The magnitudes of the contribution through the decay of atmospheric $\pi^{\pm,0}$ has been calculated and shown separately.

to return albedo. We have also considered the contribution arising from "atmospheric" electrons accumulated during the time of descent of the gondola after termination of the flight and over the period the stack was at ground level. For this calculation we made use of the measurements on the flux of the electromagnetic component under atmospheric depth of 220,[5] 550, and 730 g/cm^2.[6] We find that of the cosmic-ray electrons seen by us, <1% could be due to this effect. We therefore consider that the 12 electrons of energy >14 GeV are primary cosmic-ray electrons.

The flux of the primary electron component at a mean energy of 16 GeV and greater at the top of the atmosphere is then 0.68 ± 0.20 per m^2 sec sr. Since it is now agreed, in general, that the primary cosmic rays traverse a mean amount of about 3 g/cm^2 of interstellar matter before reaching the earth, one could calculate the flux of electrons arising from $\pi^\pm$ produced in collisions of cosmic rays traversing this amount of matter. It is found that the flux so calculated at energies >16 GeV is about 20 times smaller than that observed by us (see Fig. 3).

We have attempted to deduce the shape of the integral energy spectrum of electrons at high energies from our observations and those of Agrinier *et al.*[7] These are shown in Fig. 3. Above 50 GeV the flux of electrons (based on five events) is shown in the form of a histogram. It is found that the best estimate of the exponent of the integral spectrum is $\gamma = 1.15$ for the energy region 5-100 GeV. The highest electron energy observed by us is 320 ± 30 GeV, and there seems to be no indication for any serious steepening of the spectrum for energies >50 GeV. [It may be mentioned here that L'Heureux and Meyer[8] have reported a value of $\gamma = 0.6$ for the energy region 500 MeV-3 GeV. From an analysis of 18 events observed by them, Agrinier *et al.*[7] have indicated a steeper spectrum ($\gamma \approx 2$); a similar analysis of the 12 events observed by us indicates a value of $\gamma \approx 0.9$.]

In spite of the large errors involved in the individual observations, there is now reasonable evidence to indicate that the exponent of the integral energy spectrum of the galactic electrons in the energy region 5-100 GeV is about 1.0. This probable value seems to be lower than that of the proton spectrum of $\gamma = 1.6$ at energies >100 GeV, but in view of the low statistical weight one cannot rule out now the possibility that it is as steep as the proton spectrum.

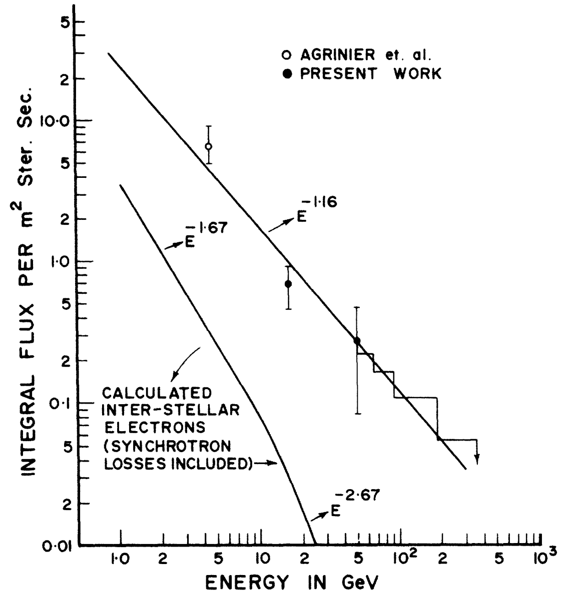

FIG. 3. The integral energy spectrum of primary electrons in the energy region 10-100 GeV. The calculated spectrum for electrons arising from collisions of cosmic rays in 3 g/cm^2 of interstellar matter is also shown.

The proportion of positrons among the electron component of the galactic cosmic rays, $R = e^+/(e^+ + e^-)$, is of great importance. It can be seen from Fig. 1 that from the present investigation it is possible to get information on R from the ratio $N_\mathrm{W}/N_\mathrm{E}$ of the number of particles arriving from the west compared to those from the east. The best measure of R is obtained by considering only the points lying between the two calculated curves for the geomagnetic cutoff rigidities for positrons and electrons shown in Fig. 1 and for zenith angles between 10° and 50°. This indicates $R = \frac{4}{5}$. If this result is to be literally interpreted, it would mean that an overwhelming fraction of the electron component at energies between 15 and 50 GeV is positrons. The observed and calculated values of $N_\mathrm{W}/N_\mathrm{E}$ using different criteria for the selection of events are shown in Table I. The results in Table I suggest that there is a large excess of positrons over electrons.

In view of the small numbers with which we are dealing at present, these results should be treated with caution, and it is possible that the numbers of electrons and of positrons might be equal; but it seems unlikely that there could

Table I. Comparison of the experimental ratio N_W/N_E, with that calculated for different assumptions.

Selection of events from Fig. 1	Calculated values of N_W/N_E Electrons only $\gamma = 1.5$	Electrons only $\gamma = 1.0$	Positrons only $\gamma = 1.5$	Positrons only $\gamma = 1.0$	Observed value of N_W/N_E
Events between the two calculated curves and $\theta = 10°-50°$	0.25	0.38	4.54	2.92	4.0 (4/1)
All events between 10° and 50°	0.46	0.62	2.12	1.66	2.0 (6/3)
All events	0.54	0.68	1.82	1.50	2.0 (8/4)

be an appreciable excess of electrons over positrons.

In a recent paper, Hartman, Meyer, and Hildebrand[9] have reported a value of $R = 0.35 \pm 0.15$ for energies between 100 MeV and 3 GeV; these authors conclude that there is an electron excess at these energies. If this is so, then our observations suggest that there is a change in the composition of the electron component between the energy range around about 1 GeV and that above 20 GeV.

Taking the observations as they stand at present, the inferences which can be made from this experiment are the following:

(i) The observed flux of electrons of energy >16 GeV is larger than that calculated to arise from collisions of cosmic rays in 3 g/cm^2 of hydrogen, by a factor of about 20.

(ii) The observed energy spectrum of the electron component in the energy region 5 to 100 GeV is probably flatter or, at the most, has the same shape as that of the proton spectrum for energies >100 GeV. It is to be expected that synchrotron-emission losses would make the electron spectrum much steeper than its production spectrum (i.e., the proton spectrum).

These two observations together make it unlikely that the electron component is genetically related to the proton component.

(iii) There is indication of an excess of positrons over electrons at high energies. If this observation is to be interpreted literally, one would have to consider the existence of a source which predominantly emits positrons. As is obvious, for many reasons, this inference requires confirmation from further work.

We have given here a status report on this experiment since we consider that the results already obtained are of some interest. In particular, we wish to emphasize, and this is one of the main purposes of this report, that using nuclear emulsions and with the techniques available at present—as discussed here—it is possible to obtain decisive information concerning the primary cosmic-ray electron component at very high energies; and this information has considerable astrophysical significance.

Our thanks are due to Professor M. G. K. Menon for constant encouragement, to the balloon group at the Tata Institute for the successful balloon operations, to Professor B. Dayton and Mr. P. Kunte for developing the orienting device, to Miss S. D. Mhatre for the careful and painstaking scanning, and to Dr. N. Durgaprasad and Mr. P. J. Kajarekar for much assistance in the early stages of this experiment.

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[1] The word "electron" is used to indicate both electrons and positrons unless otherwise stated explicitly.

[2] J. Nishimura and J. Kidd, Nuovo Cimento, Suppl. 1, 1039 (1964); see Appendix 2.

[3] We are thankful to Professor K. Gottstein for kindly making this plate available to us.

[4] R. R. Daniel and A. Stephens, Proc. Indian Acad. Sci. (to be published).

[5] J. Duthie, P. H. Fowler, A. Kaddoura, D. H. Perkins, and K. Pinkau, Nuovo Cimento 24, 122 (1962).

[6] Emulsion-chamber project of Japan-Brazil collaboration, in Proceedings of the International Conference on Cosmic Rays, Jaipur, India, 1963, edited by R. R. Daniel et al. (Commercial Printing Press, Ltd., Bombay, India, 1964-1965), Vol. 5, p. 326.

[7] B. Agrinier, Y. Koechlin, B. Parlier, G. Boella, G. D. Antoni, C. Dilworth, L. Scarsi, and G. Sironi, Phys. Rev. Letters 13, 377 (1964).

[8] J. L'Heureux and P. Meyer, Phys. Rev. Letters 15, 93 (1965).

[9] R. C. Hartman, P. Meyer, and R. H. Hildebrand, J. Geophys. Res. 70, 2713 (1965).