on November 12,[2] may have been responsible for the deflection of the solar-produced particles into the polar regions.

The double-hump structure of the increase in the intensity of the nucleonic component has not been observed previously. The most remarkable feature is the difference in the ratio, ΔI(McMurdo)/ΔI(Thule), in the first hump as compared with the second. For an isotropic distribution of cosmic-ray intensity, the ratio is approximately unity. Hence, a value of the ratio exceeding unity is indicative of an anisotropy in the intensity distribution of the solar-produced cosmic rays in the vicinity of the earth. As is seen in Fig. 1, the anisotropy prevailed during the first hump and isotropy has been almost established near the beginning of the second hump. A possible interpretation may be that, during the first hump, the earth was located near the boundary of the modulating region, which later completely surrounded the earth.

It is interesting to note that the anistropy was evident only during the exceptionally long duration (about 6 hours) of the Hα flare. However, the significance of this coincidence is not clear, especially since a Forbush-type decrease commenced[3] at approximately the same time as the termination of the optical flare.

It is a pleasure to acknowledge the important contributions to the program by Hugo A. C. Neuburg and Jamie Chapman who are in charge of the stations at McMurdo and Thule, respectively. Appreciation is expressed to the Geophysics Research Directorate for maintaining the Arctic Station at its Polar Research Facility, operated by the American Geographical Society under contract with the U. S. Air Force. The Antarctic Station is part of the U. S. Antarctic Research Program.

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[1] A. Schlüter, Z. Naturforsch. 6a, 613 (1951).

[2] We are grateful to Mr. Robert Clements for tracings of the magnetograms recorded at the New Zealand Station at Scott Base.

[3] K. G. McCracken, D. C. Rose, G. Schwachheim, R. Palmeira, and T. Thambyahpillai (private communications).

CLOUD-CHAMBER OBSERVATIONS OF PRIMARY COSMIC-RAY ELECTRONS*

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This Letter reports new measurements of the flux of high-energy (0.3 Bev to 3.0 Bev) electrons and gamma rays at the top of the atmosphere. In 1949, an experiment using essentially identical equipment (a multiplate cloud chamber carried to high altitudes by a balloon) was performed by Critchfield, Ney, and Oleksa.[1] While no evidence for primary cosmic-ray electrons was found in that experiment, improvements in cloud-chamber technique and higher balloon altitude capability now make it possible to demonstrate the existence of a small flux of primary electrons.

Table I summarizes the data pertaining to the balloon flight and to the characteristics of the cloud chamber. Electrons and gamma rays were identified by the characteristic electron-photon cascade showers which they produced in the lead plates of the cloud chamber. These showers, which appear as a sequence of cones of minimum-ionizing nonpenetrating tracks emerging from the lower surfaces of the lead plates, are readily distinguished from events produced by nuclear interactions. The selection criterion that the axis of accepted showers had to pass through the illuminated areas of both the top and the bottom of the cloud chamber ensured that the axis passed through all five plates. In passing through this thickness of material a nuclear shower would almost certainly reveal its nature through the presence of penetrating particles and/or heavily ionizing evaporation tracks. Figure 1 shows a typical example of a shower produced by an electron. The incident electron appears in the top section of the chamber as a single minimum-ionizing track which lies on the axis of the shower. Since it is very unlikely that a background track or a back-scattered track from the shower would coincide accurately with the shower axis, it appears certain that events such as the one shown in Fig. 1 are initiated by high-energy electrons.

Table I. Data on the balloon flight and the cloud chamber.

Balloon flight	
Date:	May 12, 1960
Location:	Minneapolis, Minnesota (geomagnetic latitude 55°N)
Time at ceiling:	12 hours
Pressure altitude:	4 to 6.5 g cm^{-2}. Average: 4.5 g cm^{-2}
Multiplate cloud chamber	
Number of lead plates:	5
Thickness of plates:	0.6 cm - 7.5 g cm^{-2} (1.1 radiation lengths)
Sensitive time per picture:	(0.19 ±0.01) sec
Geometric factor for region bounded by illuminated areas of top and bottom:	(33.5 ±1.5) cm^2 sr

FIG. 1. A cloud-chamber picture of a shower produced by a high-energy electron. The incident electron is visible in the top section of the cloud chamber.

Shower events in which there was no trace of a track in the top section even though the axis was well illuminated were assumed to be initiated by gamma rays. There is no reason to believe that the upper section was insensitive at any time during the flight. The procedure used to determine the energies of the electrons and gamma rays is identical to that used by Roe and Ozaki[2] and is based on the Monte-Carlo calculations of Wilson.[3]

Figure 2 and Table II summarize the data taken while the balloon was at ceiling altitude. Figure 2 shows the differential energy spectra for the electrons and gamma rays. While it is certain that some electrons were incident upon the chamber, it is not possible to estimate the number of primary electrons without first knowing the number of secondary electrons produced in the atmosphere above the chamber. An upper limit for the number of secondaries can be computed from the observed number of gamma rays under the assumption that all the gamma rays arise from nuclear interactions above the chamber. The dashed histogram in Fig. 2 shows the energy spectrum of secondary electrons computed from the observed gamma-ray spectrum under the following assumptions: (a) The gamma rays arise only as decay products of π^0 mesons; (b) two charged π mesons are produced for every π^0 meson; (c) the charged π mesons and the π^0 mesons are produced with the same energy spectrum; and (d) the Michel parameter which describes the μ-meson decay spectrum has the value $\rho m = 0.75$.[4] Under these assumptions, most of the secondary electrons come from the decay of μ mesons created when the charged π mesons decay (a small contribution from pair production by the gamma rays has also been included). In the simplest approximation, the number of gamma rays and secondary electrons should be equal because there are two gamma rays per π^0 meson and two charged π mesons (each of which should ultimately give an electron) per π^0 meson. A more detailed analysis shows that less than half of the μ mesons decay before they reach the level of the balloon and that many of the electrons from these have energies so low that they could not be primary cosmic rays arriving at the latitude of Minneapolis. The net result is that, in the energy region accessible to primary cosmic rays (above 0.5 Bev), only 1.5 ± 0.4 secondary electrons are expected, while the total number of electrons observed was 11. There-

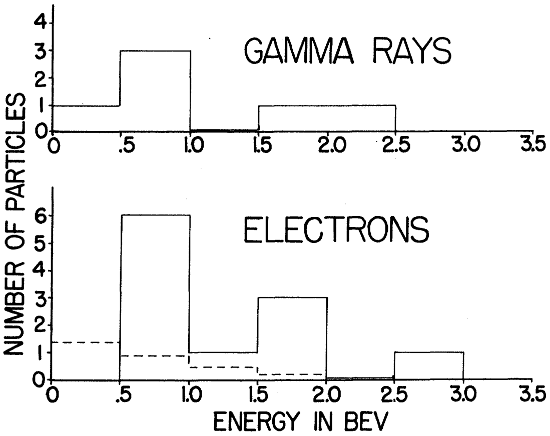

FIG. 2. Differential energy spectra for electrons and gamma rays. The dashed spectrum represents the secondary electrons that would be expected under the assumption that all the gamma rays are secondaries.

fore, most of the observed electrons must be primary cosmic rays. The pronounced peak in the electron energy spectrum between 0.5 Bev and 1.0 Bev is further evidence in favor of this conclusion because such a peak would appear if primary cosmic rays were excluded below the geomagnetic cutoff energy. (The cutoff energy for electrons at Minneapolis is about 0.7 Bev.)[5] While there is a low-energy (about 0.25 Bev) instrumental cutoff arising from the fact that very small showers are not easily recognized, more electrons than are observed would appear in the interval from 0 to 0.5 Bev if the spectrum of the observed electrons had the monotonic increase with decreasing energy which seems to be a characteristic of the spectrum of secondary electrons. A reasonable upper limit on the geomagnetic albedo (upward moving particles produced in the atmosphere which are returned to the earth by the geomagnetic field) is the upward flux at the point of observation. Since no upward moving electrons with energies greater than 0.5 Bev were recorded during the flight, it is very unlikely that the observed electrons arise from this source. (Most of the μ mesons whose decay electrons constitute the upward albedo would be expected to decay before they reach the level of the balloon.)

The value computed from the data in Tables I and II for the flux of electrons incident on the cloud chamber with more than 0.5-Bev energy is

$$I_e = (32 \pm 10) \text{ particles m}^{-2} \text{ sec}^{-1} \text{ sr}^{-1}.$$

No more than $(13 \pm 10)\%$ of this flux is due to secondaries if the assumptions given earlier are correct. Since the correction for secondaries is small and since it is partially offset by absorption of the primary electrons, this flux is a close approximation to the true flux of primary electrons at the top of the atmosphere. The flux of protons determined from the number of minimum-ionizing penetrating particles selected by the same geometric criterion that was applied to shower axes is

$$I_p = (1100 \pm 100) \text{ particles m}^{-2} \text{ sec}^{-1} \text{ sr}^{-1}.$$

A correction based on a mean free path for nuclear interactions of protons in lead of 140g cm^{-2} has been applied in computing this flux. The ratio of the electron flux to the proton flux is

$$I_e/I_p = (3 \pm 1)\%.$$

In 1949 Critchfield, Ney, and Oleksa set an upper limit on this ratio of 0.6%. The reasons that the above-measured value is larger than this upper limit are the following: (1) The minimum energy of the accepted showers was larger in the earlier experiment (1.0 Bev vs 0.5 Bev); (2) the proton flux was higher in 1949 than in 1960 (2200 p m^{-2} sec^{-1} vs 1100 p m^{-2} sec^{-1}); and (3) the thickness of the air above the balloon was less in the present experiment (4.5g cm^{-2} vs 15g cm^{-2}). The conclusion that primary electrons exist was made possible in the present experiment by (1) a clear separation of electrons and gamma rays which enabled a rigorous calculation of background effects to be made, and (2) the high altitude obtained which ensured that the flux of secondary electrons would be small.

Calculations by Ginzburg[6] indicate that synchrotron radiation from high-energy electrons would account for the observed intensity of galactic

Table II. Tabulation of particles whose paths passed through illuminated areas of both top and bottom of cloud chamber.

Total number of electrons	11
Total number of gamma rays	6
Number of minimum-ionizing particles which penetrated all 5 plates	284
Number of penetrating particles corrected for nuclear interactions	380
Total number of pictures at ceiling	541

radio emission if the density of electrons with energy greater than 1 Bev is on the order of 3 $\times 10^{-13}$ cm^{-3}. The density computed from the measured electron flux is 1.3×10^{-12} cm^{-3}, which appears to be more than enough to account for the observations of galactic radio noise.

An upper limit for the flux of electrons arising from nuclear interactions of cosmic rays with interstellar hydrogen gas can be obtained from the data which were used earlier to determine the number of secondary electrons produced in the atmosphere. Although the average thickness of matter traversed by a cosmic ray within the galaxy is about 1 g cm^{-2} (this thickness is suggested as an upper limit by considerations based on the relative abundances of protons and heavy nuclei in the cosmic-ray beam), the number of electrons produced in this thickness of interstellar hydrogen is about the same as the number produced in the 4 g cm^{-2} of air above the balloon. This occurs because the interaction probability per g cm^{-2} for hydrogen is about twice that for air and because all of the μ mesons produced in space decay while only half of those produced in the atmosphere above the balloon do so. (The flux of gamma rays from interstellar nuclear collisions is very small compared to the electron flux because the time that the electrons are trapped by galactic magnetic fields is large compared to the time required for the gamma rays to leave the galaxy on straight paths.) If the mean distances traversed in the galaxy by protons and electrons are equal, the electron flux arising from nuclear interactions in interstellar space is no larger than the flux arising from nuclear interactions in the atmosphere above the balloon. Since this flux was estimated to be only 13% of the total electron flux, it appears unlikely that all of the observed electrons arise from nuclear interactions of cosmic rays with interstellar hydrogen.

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[1] C. L. Critchfield, E. P. Ney, and Sophie Oleksa, Phys. Rev. 85, 461 (1952).

[2] B. P. Roe and S. Ozaki, Phys. Rev. 116, 1022 (1959).

[3] R. R. Wilson, Phys. Rev. 79, 204 (1950).

[4] W. F. Dudziak, R. Sagane, and J. Vedder, Phys. Rev. 114, 336 (1959).

[5] F. B. McDonald and W. R. Webber, Phys. Rev. 115, 194 (1959).

[6] V. L. Ginzburg, Progress in Elementary and Cosmic Ray Physics, edited by J. G. Wilson and S. A. Wouthuysen (North Holland Publishing Company, Amsterdam, 1958); Vol. 4, Sec. 5.

MEASUREMENT OF THE ANOMALOUS MAGNETIC MOMENT OF THE MUON

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By storing polarized μ mesons in a magnetic field for as long as 1000 cyclotron periods it has been possible to measure directly the anomalous magnetic moment. We find the anomaly in agreement to within 2% (that is, 2×10^{-5} accuracy on the total magnetic moment) with that expected from the quantum electrodynamics of a Dirac particle.

At present the muon appears to be a heavy electron with no interactions except the electromagnetic and the weak. This concept gives no explanation for the muon-electron mass difference, but allows the muon magnetic moment to be calculated from the Dirac equation and quantum electrodynamics as[1-6]

$$\mu = g(e/2Mc)\times(\hbar/2), \qquad (1)$$

with $g\equiv2(1+a)$, the anomalous part of the moment, a, being

$$a_{\text{th}} \equiv (g-2)/2 = (\alpha/2\pi) + 0.75(\alpha^2/\pi^2) + \cdots = 0.001165, \qquad (2)$$

with $\alpha^{-1}\equiv\hbar c/e^2 = 137.04$, the fine-structure constant of atomic physics. The first term in Eq. (2), $\alpha/2\pi$, arises from the emission and reabsorption of single photons, which alter the Dirac moment in two distinct ways, by the muon recoil, and by the muon spin-flip during the period of

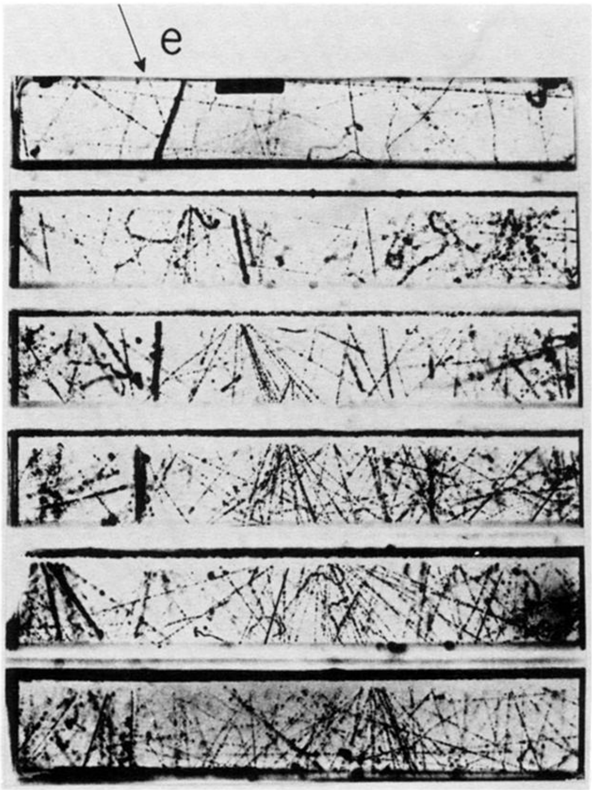

FIG. 1. A cloud-chamber picture of a shower produced by a high-energy electron. The incident electron is visible in the top section of the cloud chamber.