[1]I. Lindau and P. O. Nilsson, Phys. Lett. A31, 352 (1970); M. Anderegg, B. Feurbacher, and B. Fitton, Phys. Rev. Lett. 27, 1565 (1971).
[2]F. Sauter, Z. Phys. 203, 488 (1967).
[3]A. R. Melnyk and M. J. Harrison, Phys. Rev. B 2, 835 (1970).
[4]F. Forstmann, Z. Phys. 203, 495 (1967).
[5]A. R. Melnyk and M. J. Harrison, Phys. Rev. Lett. 21, 85 (1970).
[6]K. L. Kliewer and R. Fuchs, Phys. Rev. 172, 607 (1968).
[7]P. J. Feibelman, Phys. Rev. B 12, 1319, 4282 (1975).
[8]R. H. Ritchie, Prog. Theor. Phys. 29, 607 (1963); L. Kleinman, Phys. Rev. B 7, 2288 (1973); A. D. Boardman, B. V. Paranjape, and R. Teshima, Surf. Sci. 49, 275 (1975); A. Eguiluz and J. J. Quinn, Phys. Rev. B 14, 134 (1976).
[9]K. L. Kliewer, Phys. Rev. Lett. 33, 900 (1974).
[10]K. L. Kliewer, Phys. Rev. B 14, 1412 (1976).
[11]The expression for the energy density is only valid if the dielectric function and the magnetic susceptibility associated with the polarization currents and charges are independent of the frequency of the electromagnetic wave. If $\mathcal{E}_{pol}$ is not constant $\vec{E}\cdot\vec{D}/8\pi$ should be replaced by $(\partial/\partial\omega)[(\omega\mathcal{E}_{pol})|\vec{E}|^2]/8\pi$ [M. von Laue, Ann. Phys. (Leipzig) 18, 523 (1905)]. The dielectric reponse of the conduction electrons is treated by calculating the charge density ρ and current $\vec{j}$ explicitly within the hydrodynamic approximation and is, therefore, not included in $\vec{D}$.
[12]The term $\vec{E}\cdot\vec{j}$ contains a part which describes the coherent exchange of energy from the fields to the electrons, as discussed in the physics of classical plasmas; see, for instance, J. F. Denisse and J. L. Delcroix, in *Plasma Waves* (Interscience, New York, 1963), Chap. 5.
[13]F. Forstmann and H. Stenschke, to be published.
[14]K. J. Krane and H. Raether, Phys. Rev. Lett. 37, 1355 (1976).

High-Energy Cosmic-Ray Electrons: A New Measurement Using Transition-Radiation Detectors*

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A new detector for cosmic-ray electrons, consisting of a combination of a transition-radiation detector and a shower detector, has been constructed, calibrated at accelerator beams, and exposed in a balloon flight under 5 g/cm^2 of atmosphere. The design of this instrument and the methods of data analysis are described. Preliminary results in the energy range 9–300 GeV are presented. The energy spectrum of electrons is found to be significantly steeper than that of protons, consistent with a long escape lifetime of cosmic rays in the galaxy.

The shape of the energy spectrum of cosmic-ray electrons at high energies is expected to contain unique information with respect to the propagation of cosmic rays in the galaxy. Energy losses of electrons due to synchrotron radiation and inverse Compton scattering in the interstellar medium lead to a "radiative lifetime" $\tau_R = 1/bE$ that is inversely related to the electron energy E (b being a constant proportional to the energy densities of magnetic and photon fields).[1] At high energies, τ_R will become smaller than the "escape lifetime" τ_E which describes the average age of a galactic cosmic-ray particle before escape into intergalactic space. As a consequence, a steepening of the electron spectrum and a reduction in the abundance of electrons relative to that of nuclear cosmic rays are expected at high energies. An observation of this effect yields information on the age of galactic electrons. Until recently, an escape lifetime of a few million years was frequently assumed. A steepening of the electron spectrum should then become noticeable at energies above 100 GeV.

The search for this feature has motivated several experiments to measure the spectrum of electrons up to energies of several hundred GeV.[2-6] In these experiments, shower detectors have been used to identify electrons, and to measure their energies. However, the results are not conclusive: All observers find that their differential energy spectra are consistent with power laws $E^{-\alpha}$, but the spectral indices α vary widely. For instance, the data of Anand, Daniel, and Stephens,[2] Buffington, Orth, and Smoot,[13] and Müller and Meyer[5] have supported an electron spectrum with a spectral index close to that of protons ($\alpha \approx 2.7$), while other experimenters such as Matsuo *et al.*,[3] Meegan and Earl,[4] and Silverberg[6] have reported steep spectra with spectral indices ranging from 3.1 to 3.4. Three basic difficulties are responsible for this ambiguous situation: (a) Statistical uncertainties result from the limited size and exposure time of the detectors. (b) Serious systematic discrepancies arise due to a substantial background of interacting protons that masquerade as electron showers. Only indirect procedures can be applied to correct for this background (unless the interaction is observed in nuclear emulsions). (c) Until recently, direct calibrations of the detectors at accelerator beams of sufficiently high energy were not possible.

In this Letter, we describe a new experiment which overcomes these difficulties, and we present first results obtained in a high-altitude balloon flight. We have utilized a new technique, transition radiation, to identify individual electrons uniquely. The combination of a transition-radiation detector with a shallow shower detector made possible the construction of a very-large-area instrument,[8] and calibrations could be performed at Fermilab with electron beams covering the energy range 5–300 GeV.

A schematic cross section of the detector is shown in Fig. 1. The main components are the following: (a) a plastic scintillator telescope $T1$, $T2$, $T3$, and $T4$, defining a geometric factor of 0.48 m^2 sr; (b) a transition-radiation detector consisting of six radiators and six multiwire proportional chambers; and (c) a lead-scintillator sandwich, with scintillators $T2$, $T3$, and $T4$ sampling the shower development at depths of 4, 6, and 8 radiation lengths, respectively. Any singly charged particle traversing the detector in the downward direction is a possible candidate for an electron if it produces a set of pulse heights in the shower detector that is typical for an electromagnetic cascade. The shower signals also measure the electron energy. However, to be accepted as an electron, the particle must also produce a characteristic signal due to transition-radiation x rays which are produced when the electron passes through the radiators. The dependence of the transition-radiation yield on the Lorentz factor γ of the particle makes it impossible for a proton in the energy range of concern (~5–3000 GeV) to produce a measurable transition-radiation signal, while all electrons generate transition radiation in saturation.[9,10]

The design of the transition-radiation detector is characterized by the use of 15-cm-thick polyethylene-foam radiators[10] and 2-cm-thick multiwire proportional chambers, filled with xenon (+20% CO_2). The wire directions of consecutive chambers are orthogonal to each other in order to obtain hodoscopic information. For each chamber, groups of five adjacent wires are connected to a common amplifier (thereby limiting the spatial resolution to 5 cm, and with a "track-and-hold" technique all wire groups are pulse-height analyzed. Each scintillator of the shower detector is viewed by eight photomultipliers. The photomultipliers were individually calibrated with a nanosecond light source in order to insure linear response beyond the largest expected shower signals.

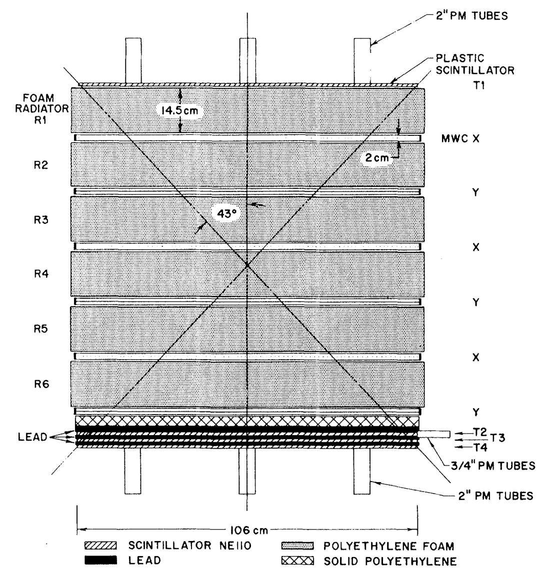

FIG. 1. Schematic cross section of the instrument.

A first balloon flight performed from Palestine, Texas yielded ~30 h of data below ~5 g/cm² of residual atmosphere. In-flight calibration of the detector response was obtained from penetrating cosmic-ray α particles and nuclei.

The analysis of the flight data proceeds essentially along the following steps: (a) The trajectories of all singly charged particles are determined, rejecting those events for which no unique trajectory can be established. With the aid of a time-of-flight measurement, only downwards-moving particles are accepted. (b) The response of the shower detector is analyzed. The average expected shower profile of an electron with energy E [i.e., pulse heights $n_i(E)$ with variations $\sigma_i(E)$ $(i=1,\ldots,3)$] is known from the accelerator calibrations (see below) and the energy E is directly related to the total shower signal. Each *measured* set of pulse heights t_i $(i=1,\ldots,3)$ is compared with expected shower profiles, and the parameter

$$\chi^2=\tfrac{1}{2}\sum_{i=1}^{3}[t_i-n_i(E)]^2/\sigma_i^2(E)$$

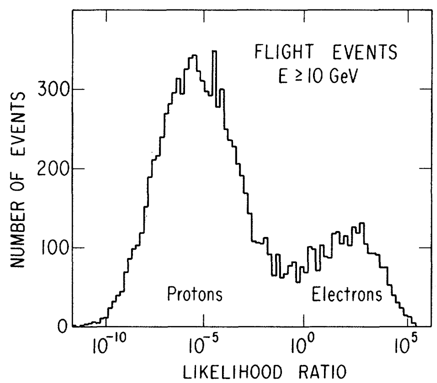

FIG. 2. Likelihood-ratio histogram of a sample of flight data. The likelihood ratio is a measure for the transition-radiation signal (see text). The logarithmic scale should be noted. The events displayed in this histogram are due to singly charged particles with unique trajectories, with total shower signals larger than that of 10-GeV electrons, and with fairly good shower fits ($\chi^2 \leq 4$).

measures the goodness of fit. Obviously, only events with sufficiently small values of χ^2 can be due to electrons. (c) The transition-radiation signal is evaluated with likelihood methods[11]: The probability that a particle without transition radiation produces a pulse height x due to ionization in the ith chamber is given by a Landau-Vavilov distribution $P_p^{(i)}(x)$. The signal of an electron, accompanied by transition-radiation x rays, is on the average twice as large as the ionization signal and follows a different distribution $P_e^{(i)}(x)$. These distributions are known from accelerator calibrations. For each event, we measure six pulse heights x_i ($i = 1, \ldots, 6$) *along the trajectory of the particle*. We then compute the likelihood ratio $L = \pi P_e^{(i)}(x_i)/\pi P_p^{(i)}(x_i)$ as a measure of the transition-radiation signal, and, therefore, as a means to identify each individual particle: $L = 1$ indicates equal likelihood for proton and electron, while $L \gg 1$ is expected for a particle with transition radiation, i.e., an electron, and $L \ll 1$ for a proton.

The histogram in Fig. 2 shows a likelihood distribution of those events that exhibit fairly good shower fits. This histogram demonstrates the clear separation of protons and electrons that is obtained due to the transition-radiation signal, and it also shows that the number of proton-induced showers is still larger than the number of electrons. With the shower detector alone, a comparably clean identification of electrons is not possible.

Before discussing the energy spectrum that we derive from electrons identified in this way, we should mention that energy-dependent biases in the data have been eliminated by the calibration of the instrument at Fermilab. The average shower signals measured up to 300 GeV were found to be in excellent agreement with results from an earlier extrapolation[2] which was based on measurements below 15 GeV, and the energy resolution of the detector was approximately constant at 30% full width at half-maximum over the whole energy range. The effect of backscatter from the shower counter on the efficiency of the trajectory determination has also been investigated. The fraction of electrons with unique trajectories was observed to decrease from 55% at 10 GeV to 21% at 200 GeV. More details about these calibrations will be published separately.

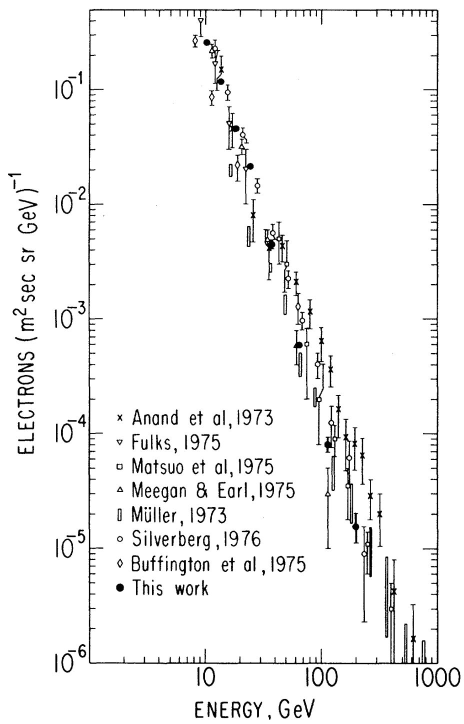

FIG. 3. Differential energy spectrum of cosmic-ray electrons. The error bars in our data are due to statistics only. Results of earlier investigations (Refs. 2–7 and 13) are shown for comparison. In this comparison, we also show the results of previous work of our laboratory (Müller, Ref. 5). However, at low energies this work yielded an electron flux that was too small due to an erroneous dead-time correction. We therefore wish to withdraw the low-energy part of our previous results. (See also Ref. 14).

In Fig. 3 we show the differential energy spectrum of cosmic-ray electrons in the interval 9 to 300 GeV. A correction for the amount of residual atmosphere has been applied. Results from previous investigations[2–6,7,13] are shown for compar-

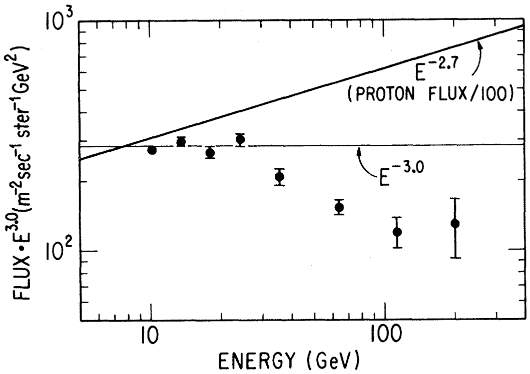

FIG. 4. The differential energy spectrum of electrons, multipled with $E^{3.0}$ (solid data points). The spectrum of protons, averaged from various measurements, is indicated for comparison.

ison. We find that our data are in good agreement with the results of Meegan and Earl,[4] and are also in fair agreement with the spectrum reported by Silverberg.[6] These experiments have yielded data consistent with a power-law spectrum with a constant power-law index $\alpha = 3.4 \pm 0.1$,[4] and $\alpha = 3.1 \pm 0.08$,[6] respectively. We also note that our new data yield significantly higher fluxes at low energies than the results reported earlier by this laboratory.[14]

In order to investigate the spectral slope of our data in more detail, we show in Fig. 4 our data points, multiplied with $E^{3.0}$. This figure shows clearly that our electron spectrum is significantly steeper than the proton spectrum. With the customary assumption that electrons at the sources are accelerated with the same power-law spectrum as protons, our data would indicate that the shape of the electron spectrum is influenced by radiative energy losses at rather low energies, below ~30 GeV. Assuming a combined energy density of 1 eV/cm^3 for the magnetic and photon fields, this would suggest a long escape lifetime of cosmic electrons, $\tau_E \gtrsim 10^7$ y. A more quantitative estimate of the escape lifetime can be obtained by a numerical fit of our data to the predictions of the homogeneous model[15] of cosmic-ray propagation. As Fig. 4 indicates, a power-law spectrum with a constant power-law index α does not appear to be a good fit to our results. While $\alpha \approx 3.0$ might be indicated below 30 GeV, the spectrum may become as steep as $\alpha \approx 3.5$ at higher energies. This important feature makes a fit to the predictions of the homogeneous model particularly sensitive. An escape lifetime $\tau_E = (7-11) \times 10^6$ y provides a good fit to our data. This lifetime is close to the value $\tau_E > 1.2 \times 10^7$ y estimated by Meegan and Earl,[4] but it is larger than the lifetime of $\tau_E = 3 \times 10^6$ y inferred by Silverberg.[6] Finally, we note that a long cosmic-ray lifetime has also been inferred from recent observations of the beryllium isotopes.[16]

We are continuing our data analysis, and we shall soon discuss the implications of our results in more detail.

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[1]A detailed discussion of these effects, and references to earlier papers, are given by R. Ramaty, in *High Energy Particles and Quanta in Astrophysics*, edited by F. B. McDonald and C. E. Fichtel (MIT Press, Cambridge, Mass., 1974).

[2]K. C. Anand, R. R. Daniel, and S. A. Stephens, in *Proceedings of the Thirteenth International Conference on Cosmic Rays, Denver, Colorado, 1973* (University of Colorado, Denver, Colo., 1973), Vol. 1, p. 355.

[3]M. Matsuo, J. Nishimura, T. Kobayashi, K. Niu, E. Aizu, H. Hiraiwa, and T. Taira, in *Proceedings of Fourteenth International Conference on Cosmic Rays, Munich, West Germany, 1975* (Max-Planck-Institut für Extraterrestrische Physik, Garching, West Germany, 1975), Vol. 1, p. 361.

[4]C. A. Meegan and J. A. Earl, Astrophys. J. 197, 219 (1975).

[5]D. Müller, in *Proceedings of the Thirteenth International Conference on Cosmic Rays, Denver, Colorado, 1973* (University of Colorado, Denver, Colo., 1973); D. Müller and P. Meyer, Astrophys. J. 186, 841 (1973).

[6]R. F. Silverberg, J. Geophys. Res. 81, 3944 (1976).

[7]G. J. Fulks, J. Geophys. Res. 80, 1701 (1975).

[8]G. Hartmann, D. Müller, and T. Prince, in *Proceedings of Fourteenth International Conference on Cosmic Rays, Munich, West Germany, 1975* (Max-Planck-Insitutt für Extraterrestrische Physik, Garching, West Germany, 1975), Vol. 9, p. 3272.

[9]M. L. Cherry, G. Hartmann, D. Müller, and T. A. Prince, Phys. Rev. D 10, 3594 (1974).

[10]T. A. Prince, D. Müller, G. Hartmann, and M. L. Cherry, Nucl. Instrum. Methods 123, 231 (1975).

[11]M. L. Cherry, D. Müller, and T. A. Prince, Nucl. Instrum. Methods 115, 141 (1974).

[12]D. Müller, Phys. Rev. D 5, 2677 (1972).
[13]A. Buffington, C. D. Orth, and G. F. Smoot, Astrophys. J. 199, 669 (1975).
[14]As pointed out by Müller and Meyer (Ref. 5), the electron flux below 30 GeV was possibly too low in these data due to an instrumental malfunction. It appears now that this was indeed the case, and we therefore wish to withdraw the previous low-energy results.
[15]R. F. Silverberg and R. Ramaty, Nature (London) 243, 134 (1973).
[16]M. Garcia-Munoz, G. M. Mason, and J. A. Simpson, Astrophys. J. 201, L141 (1975).

Irreversible Thermodynamics of Black Holes

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Black holes are shown to obey the principles of irreversible thermodynamics in the form of a fluctuation-dissipation theorem for their zero-point quantum fluctuations. Moreover Hawking radiation is shown to be related to the macroscopic radiation of a nonstationary black hole in accordance with Onsager's principle.

Recent work on black holes, culminating in Hawking's[1] remarkable discovery of their quantum radiance, has shown that they obey the laws of equilibrium thermodynamics.[2] In this Letter we show that they conform also to the principles of *nonequilibrium* and *irreversible* thermodynamics, in the form of a fluctuation-dissipation theorem.[3] The dissipation is associated with the absorption of ordered energy by the black hole and its subsequent reradiation by the Hawking process. It has been shown[4] that Hawking radiation has the same stochastic properties as black-body radiation, and so is completely disordered. A black hole is thus a perfect dissipator.

To help understand this property of black holes, we apply the theory of dissipative processes.[5] This theory is based on the following ideas: (a) A dissipative system D possesses a large number of closely spaced energy levels lying near to the ground state. (b) In consequence, when this system is coupled to another system S, it exerts a force on it which fluctuates in time and is usually initially uncorrelated with the natural fluctuations of S. The cumulative effect of this fluctuating force is to dissipate the excess energy of S by distributing it among the many energy levels of D. (c) The effect of S on D, in linear approximation, is to produce a deviation from its equilibrium state which on average cannot be distinguished from a purely spontaneous fluctuation of D (Onsager's[6] principle). (d) The fluctuating force exerted by D represents a source of noise *power* as well as of dissipation. The fact that S and D can come into equilibrium depends on both the dissipative and exciting aspects of the force. The *rate* at which equilibrium is approached, and therefore the associated impedance function, are determined by the statistical properties of the fluctuations. The formal statements of these relations are the various fluctuation-dissipation theorems. The first version of this theorem was in fact discovered by Einstein[7] in the course of his work on Brownian motion. (e) The fluctuation-dissipation theorem can also be regarded as providing an expression for the energy density residing in the fluctuations. In this expression the (frequency-dependent) impedance takes on a new significance as a quantity proportional to the *density of states* of the dissipative system.

We now apply these ideas to the dissipative action of a black hole. In this Letter, we confine ourselves in the main to the dissipation of gravitational disturbances. A more comprehensive and detailed discussion will be given elsewhere.

It has been known—at least since the work of Callen and Welton[3]—that it is possible to ascribe the radiation damping of the motion of an accelerated charge to a coupling between the radiating charge and the quantum fluctuations of the electromagnetic vacuum. In order to proceed in