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CHARGE COMPOSITION AND ENERGY SPECTRUM OF PRIMARY COSMIC-RAY ELECTRONS*

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ABSTRACT

The flux, energy spectrum, and charge composition of the electron component of primary cosmic rays was measured in 1965 and 1966 in the range from 170 MeV to 14.3 BeV, and a finite flux of positrons was observed up to 4 BeV. The positron fraction $N^+/(N^+ + N^-)$ is shown to decrease as a function of energy. For the first time, it has been possible to determine the energy spectrum of primary positrons above 220 MeV. To approximate this observed spectrum above 860 MeV by a power law requires an exponent of 2.6 ± 0.5, consistent with negligible modification of the source spectrum below 10 BeV by energy-loss processes. Comparison of the differential energy spectrum of positrons with calculations based on a collision origin leads to a reasonable agreement for a disk model with passage of cosmic rays through 3–4 g cm^{-2} of interstellar material and modulation parameters $\eta = 0.6$ BV and $R_0 = 0.3$ BV.

I. INTRODUCTION

It was first pointed out by Ginzburg (1958) and by Hayakawa, Ito, and Terashima (1958) that a measurement of the charge composition of the electron component of primary cosmic rays is crucial in determining the source of the cosmic-ray electons. In 1963 De Shong, Hildebrand, and Meyer (1964) provided the first experimental evidence on the electron-positron ratio and showed that the fraction of positrons is much smaller than would be expected if the electrons originated predominantly from nuclear collisions in interstellar space. Their work led to the conclusion that a major portion of the cosmic-ray electrons must be directly accelerated in sources of cosmic rays.

Following the initial experiment, considerable effort has been made to establish more accurately the electron-positron ratio and, in particular, to obtain this ratio at different energies (Hartman, Hildebrand, and Meyer 1965; Agrinier *et al.* 1965; Bland *et al.* 1966; Daniel and Stephens 1966; Hartman 1967). As a result of the work by Hartman (1967) it became clear that, for energies between 500 Mev and 10 BeV, the positron contribution amounts to no more than 10 percent of the total electron flux. Because of statistical limitations, however, these results were also consistent with an absence of positrons above 500 MeV.

Here we wish to report further measurements on the electron-positron component which, for the first time, give clear evidence for a finite positron flux above 500 MeV and make it possible to obtain an energy spectrum for the positrons. Since all positrons presumably arise from collisions of nuclear cosmic rays with interstellar matter, their intensity and energy spectrum can be calculated (Perola, Scarsi, and Sironi 1967; Ramaty and Lingenfelter 1968). Two questions are thereby opened for investigation.

1. Electrons lose energy through synchrotron radiation and Compton collisions. This leads to an equilibrium spectrum which is steeper than the source spectrum above some

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critical energy (Ramaty and Lingenfelter 1966; Shen 1967; Jokipii and Meyer 1968). This critical energy depends on the average time for diffusion from the Galaxy by the electrons, as well as the average strength of galactic magnetic fields and the energy density of electromagnetic radiation. Since little is known about the source spectrum of accelerated electrons, they do not provide an unambiguous means for investigating possible modifications of their spectrum. The source spectrum of positrons, however, can be calculated by using the known energy spectra of the nuclear components and the data of nuclear physics. The measured equilibrium spectrum of positrons can therefore be used to infer whether, in the energy range of the observation, the spectrum is influenced by synchrotron and Compton-collision losses.

2. A comparison between the calculated equilibrium spectrum for positrons in the Galaxy and the measured spectrum in the vicinity of the Earth permits one to draw conclusions concerning the absolute amount of solar modulation which the electron component has undergone in the years of minimum solar activity, the period in which the measurements reported here were carried out.

In the following paragraphs we shall report measurements which were made with an instrument that has been described previously (Hartman 1967; Fanselow 1968; hereinafter referred to as Papers I and II, respectively). After briefly summarizing the facts

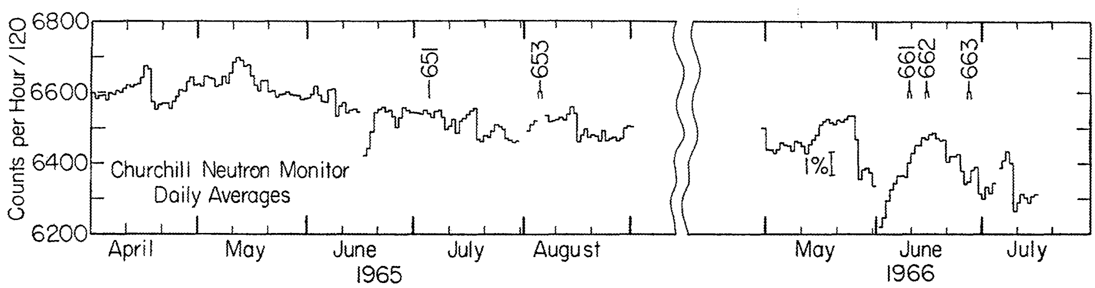

FIG. 1.—Daily averages of the Churchill neutron monitor for the periods of our balloon flights. Times of measurement are indicated.

concerning the experiment and the methods of analysis, we shall present our results and discuss their implications.

II. INSTRUMENTATION AND BALLOON FLIGHTS

The instrument used for measuring the separate electron and positron spectra consists of a counter telescope, a permanent magnet for the deflection of the particles, an array of thin plate, optical spark chambers for obtaining the particle trajetories, and a tantalum-plate spark chamber in which electrons were identified through their characteristic electron-photon showers. This magnetic spectrometer has been described in Papers I and II.

The instrument was flown on high-altitude balloons from Fort Churchill, Manitoba, on 1966 June 10, 15, and 26, and spent a total of 45 hours at an altitude equivalent to 3.2 g cm^{-2} of residual atmosphere, permitting the collection of a much larger sample of electrons than was previously possible. Two flights from Fort Churchill had been made in the preceding year, on July 5 and August 5 (Papers I and II), yielding 12 hours at balloon altitude. We have reevaluated the data obtained in 1965 and included them in the results which we report here. In Figure 1 are shown the daily averages of the Churchill neutron monitor, as well as the days on which our measurements were made. The largest difference in the monitor rate between flights amounts to about 3 per cent.

III. DATA ANALYSIS

The experimental data have been analyzed from two points of view. First, we have attempted to obtain the fraction of positrons as a function of energy with the greatest possible accuracy. Second, we have used the observations to arrive at energy spectra for both negative electrons[1] and positrons within the range of energies to which the instrument is sensitive. The scanning and measuring procedures were similar to those described in Papers I and II, and will not be further discussed. However, the procedures for applying corrections to the data are somewhat improved and will be described briefly.

The charge composition and total electron spectrum were determined by using somewhat different scanning procedures from those pointed out in Papers I and II. To obtain positron and negative-electron spectra, the total observed spectrum was multiplied by the observed positive and negative fractions. Corrections for instrument resolution, energy losses in the instrument and the overlying layer of atmosphere, detection efficiency, atmospheric-secondary electrons, and proton contamination were made independently for each spectrum. With the exception of the method of eliminating atmospheric secondaries, all corrections were made essentially as described in Paper II. For the determination of atmospheric-secondary contributions, we have combined the ascent curves from both the 1965 and 1966 flights, assuming that the flux of protons which produces these secondary electrons in our energy range has not changed appreciably between the two years. This probably is not a bad assumption, since only protons, above 600 MeV contribute appreciably to the flux of secondary electrons, and since the Churchill neutron-monitor rate stayed within a 3 percent range for the five flights (see Fig. 1). We estimate roughly that the flux of secondary electrons did not vary by more than 20 percent between any flights, a variation comparable to the uncertainty in the determination of the secondary flux on any given flight. Comparison of the group of ascent curves of 1965 with that of 1966 yielded no statistically significant difference. Even after combining the five ascent curves we do not have sufficient statistical accuracy to obtain a dependable spectrum of secondary *positrons*. We have therefore multiplied the total secondary-electron spectrum by the positive and negative atmospheric-secondary fractions estimated in Paper I in order to obtain the separate positive and negative secondary spectra.

IV. RESULTS

a) The Electron Energy Spectrum

In Table 1 we present a summary of the data which we obtained from our series of measurements in 1965 and 1966. Figure 2 shows the total electron-energy spectrum and includes our results as well as most of the recent work of various experimenters (references can be found in the figure caption). We have eliminated from this figure our data points centered at 69 and 125 MeV because of possible contamination by return albedo electrons. It had first been noted by Jokipii, L'Heureux, and Meyer (1967) and confirmed by Webber (1968) and by Israel and Vogt (1968) that a change in the geomagnetic cutoff occurs at the latitude of Fort Churchill around 0600 and 1800 local time due to the asymmetry of the geomagnetic field. During the day, the cutoff, which has not yet been clearly established, may be as high as 150 MV, leading to a contribution of return albedo electrons below this rigidity. Since 75 percent of our measuring time at altitude was between 0600 and 1800 local time, the flux in the lower two energy intervals is likely to be contaminated with return albedo particles and hence does not properly represent the primary flux.

Above 220 MeV our data points are the only ones obtained with a magnet spectrometer, an instrument which has excellent discrimination against particles other than electrons and which also has optimum resolution in the low-energy portion of the electron-energy spectrum. Within statistics, our spectrum agrees well with other observations, except for the value around 280 MeV which is noticeably below the points quoted by others. This discrepancy was already pointed out by Fanselow (Paper II), who used

[1] Throughout this paper, the word *electron* will be taken to include both positive and negative electrons.

TABLE I
SUMMARY OF PRIMARY AND SECONDARY POSITRON AND ELECTRON FLUXES AND POSITRON FRACTION

Observed Quantity								
Energy Interval at Top of Atmosphere (BeV)	0.053 - 0.088[Δ]	0.088 - 0.173[Δ]	0.173 - 0.44	0.44 - 0.86	0.86 - 1.70	1.70 - 4.2	4.2 - 8.4	8.4 - 14.3
Energy interval at magnet (BeV)	0.042 - 0.076	0.076 - 0.161	0.161 - 0.43	0.43 - 0.84	0.84 - 1.69	1.69 - 4.2	4.2 - 8.4	8.4 - 14.3
Energy for differential flux point (BeV)	0.069	0.125	0.28	0.63	1.23	2.7	6.0	11.0
1965								
Total No. of electrons in interval ($e^+ + e^-$)	26	130	131	98	100	71	21	7
Positive fraction at magnet	0.47	0.47	0.44	0.16	0.072	0.056	0.00	0.3
No. of atmospheric secondaries *§	9.4 ± 4.4	49.6 ± 8.0	55.0 ± 9.3	19.4 ± 7.5	4.3 ± 1.1	1.0 ± 0.2	0.12 ± 0.03	0.027 ± 0.007
Primary positron flux‡ (m^2 sec sterad BeV)$^{-1}$	150 ± 121%	143 ± 40%	33 ± 45%	2.6 ± 215%	1.4 ± 96%	0.27 ± 122%	0.00 ± 0.23 §	0.10 ± 190%
Total primary electron flux‡ (m^2 sec sterad BeV)$^{-1}$	416 ± 59%	367 ± 22%	71 ± 28%	44 ± 23%	31 ± 15%	7.9 ± 17%	1.6 ± 37%	0.36 ± 101%
Positive fraction§	0.36 ± 0.31	0.39 ± 0.11	0.45 ± 0.14	0.06 ± 0.12	0.047 ± 0.043	0.035 ± 0.041	0.00 ± 0.13	0.26 ± 0.43
1966								
Total no. of electrons in interval ($e^+ + e^-$)	82	354	454	343	325	256	64	34
Positive fraction at magnet	0.46	0.52	0.33	0.20	0.11	0.061	0.061	0.19
No. of atmospheric secondaries *§	32 ± 15	169 ± 27	188 ± 32	66 ± 26	14.7 ± 3.7	3.3 ± 0.8	0.39 ± 0.10	0.088 ± 0.022
Primary positron flux‡ (m^2 sec sterad BeV)$^{-1}$	118 ± 109%	107 ± 37%	12 ± 80%	5.5 ± 75%	2.6 ± 32%	0.40 ± 44%	0.016 ± 339%	0.077 ± 171%
Total primary electron flux‡ (m^2 sec sterad BeV)$^{-1}$	410 ± 41%	212 ± 24%	67 ± 20%	44 ± 16%	26.4 ± 11%	8.2 ± 10%	1.0 ± 27%	0.61 ± 46%
Positive fraction§	0.29 ± 0.24	0.51 ± 0.11	0.18 ± 0.12	0.12 ± 0.08	0.098 ± 0.028	0.049 ± 0.020	0.015 ± 0.050	0.12 ± 0.19
Weighted average‖ of 1965, 1966 results								
Primary positron flux (m^2 sec sterad BeV)$^{-1}$	128 ± 82%	119 ± 28%	18.5 ± 44%	4.5 ± 74%	2.3 ± 31%	0.37 ± 42%	0.015 ± 349%	0.084 ± 128%
Total primary electron flux (m^2 sec sterad BeV)$^{-1}$	412 ± 34%	255 ± 17%	68 ± 17%	44 ± 13%	27.5 ± 9%	8.1 ± 9%	1.1 ± 22%	0.51 ± 43%
Positive fraction §	0.31 ± 0.19	0.45 ± 0.08	0.29 ± 0.09	0.10 ± 0.07	0.083 ± 0.024	0.046 ± 0.018	0.013 ± 0.05	0.15 ± 0.18

Δ These energy intervals are likely to contain a contribution of return albedo electrons.

* For energies less than 0.84 BeV, these numbers are based on the observed depth dependence of the total electron flux. For energies greater than 0.84 BeV the shape of the atmospheric secondary electron spectrum calculated by Verma (1967) has been used. However the secondary intensity was adjusted by a factor 0.5 to obtain a smooth fit with the secondary spectrum observed below 0.84 BeV.

‡ Includes corrections for instrument resolution, atmospheric secondary electrons, background protons, electron-detection inefficiencies, energy-dependent geometry factor, and energy losses in the matter between magnet and the top of the atmosphere.

§ Actual error, rather than percent error presented (one standard deviation).

‖ Weighted results obtained using $\bar{x} = (\Sigma [x_i / \sigma_i^2]) / \Sigma [1/\sigma_i^2]$, $\bar{\sigma} = (\Sigma [1/\sigma_i^2])^{-1/2}$

data with much less statistical precision. We are now convinced that the flux of primary electrons in the energy interval from 173 to 440 MeV at solar minimum is indeed lower than claimed on the basis of the counter experiments whose energy resolution is not comparable to the spark chamber–magnet spectrometer.

b) The Fraction and the Energy Spectrum of Positrons

While the work of Hartman (Paper I) indicated that the fraction of primary positrons decreases with increasing energy in the range from a few hundred MeV to 5 BeV, we can now clearly demonstrate this to be the case. Figure 3 gives the positron fraction $N^+/$

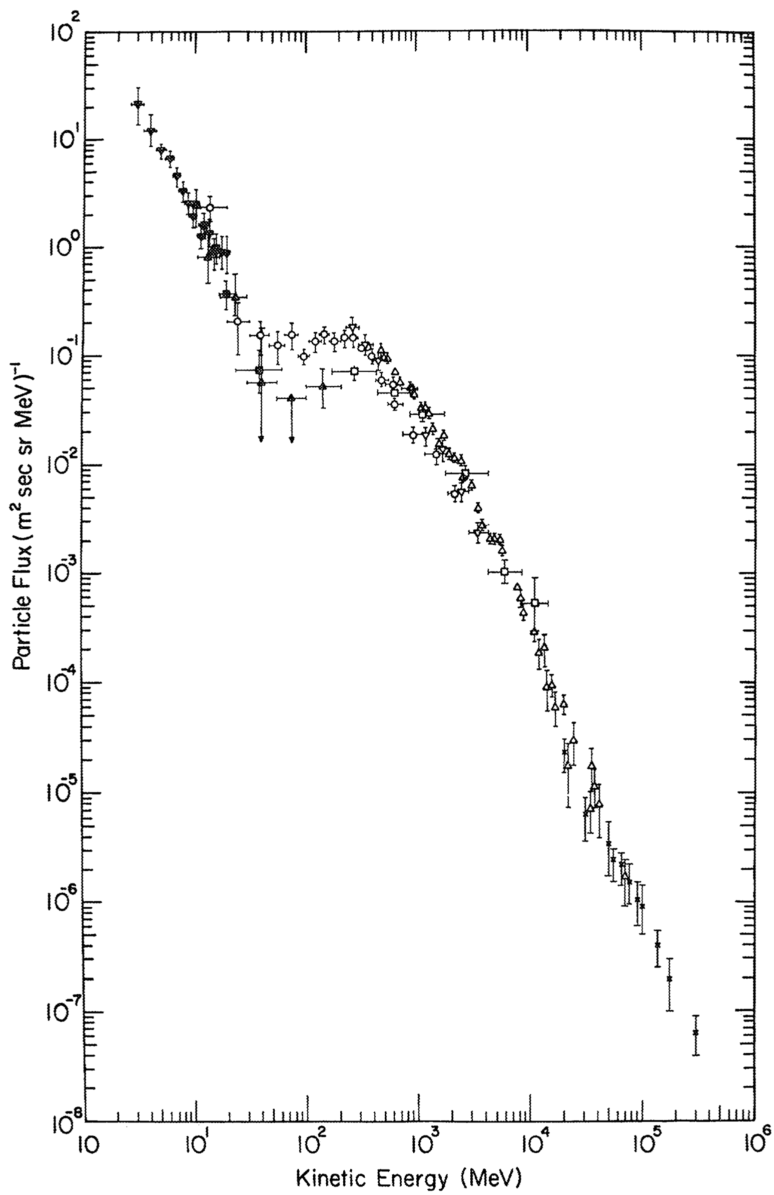

FIG. 2.—Energy spectrum of primary cosmic-ray electrons, ×, Anand *et al.* (1968); △, Bleeker *et al.* (1968*a*); ■, Fan, L'Heureux, and Meyer (1969); ▲, Beuermann *et al.* (1969); ▽, L'Heureux and Meyer (1968); ▼, McDonald and Sinnett (1968); ○, Webber (1968); □, this work.

$(N^+ + N^-)$ as a function of energy. As can be seen, there exists a substantial primary-positron contribution in the energy interval around 280 MeV, in agreement with the results of Paper I, and a measurable, finite contribution up to the interval from 1.67 to 4.2 BeV. For the two highest energy points, we can only quote upper limits (see Table 1). We did not include the lowest energy intervals of Table 1, for reasons which were discussed above. The upper limit for the positron fraction around 6.0 BeV is considerably lower than previously determined (Paper 1; Agrinier *et al.* 1965). Between 8.4 and 14.3 BeV an upper limit of 0.15 ± 0.18 for this fraction could be established. The position of the corresponding point in Figure 3 should not be construed as indicating an increase of the positron fraction toward higher energies. This point is at the limit of our ability to measure the deflection of electron tracks.

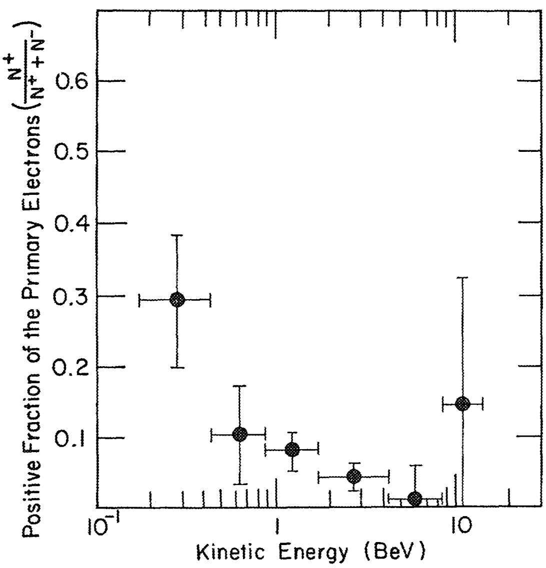

FIG. 3.—The positron fraction $N^+/(N^+ + N^-)$ as a function of energy

After establishing a finite flux of primary positrons, it is possible to obtain an energy spectrum for these particles. The total primary-electron spectrum and the spectrum of primary positrons alone which were obtained from this experiment in 1965 and 1966 are shown in Figure 4. The errors in this figure include contributions from all corrections and are one-sigma limits. The straight lines represent least-squares fits to power laws $E^{-\gamma}$, for all data exceeding 860 MeV in energy. For the total spectrum this results in a power-law exponent $\gamma = 1.87 \pm 0.09$ in the interval 0.86–14.3 BeV. More interesting than the total spectrum is the shape of the positron spectrum. In the same interval a least-squares fit to a power law yields an exponent $\gamma = 2.56 \pm 0.54$ and consequently the same value for negative electrons which arise from interstellar nuclear collisions. For the negative electrons whose source is different from interstellar collisions we obtain $\gamma = 1.84 \pm 0.11$ in the same energy interval.

In the following paragraphs we wish to discuss some of the implications of these results.

V. IMPLICATIONS AND DISCUSSION

The observations of a finite positron intensity and the determination of the positron-energy spectrum make it possible to draw a number of conclusions which could not previously be obtained.

We observe that the positron fraction of the electron component of primary cosmic rays decreases with increasing energy in the energy range 173 MeV–14 BeV. Thus in that energy range the spectrum of accelerated electrons is flatter than the spectrum of the electrons and positrons which originate in nuclear collisions in interstellar space. The electron component, in the energy range which we observe, is overwhelmingly made up of directly accelerated particles, to more than 80 per cent between 400 MeV and 1.7 BeV, and as much as 90–95 percent between 1.7 and 8.4 BeV. It has been argued elsewhere (e.g., Meyer 1969) that this is strong evidence for a galactic origin of the electron component, if a universal blackbody radiation corresponding to a temperature of 2.5° K exists throughout the Universe.

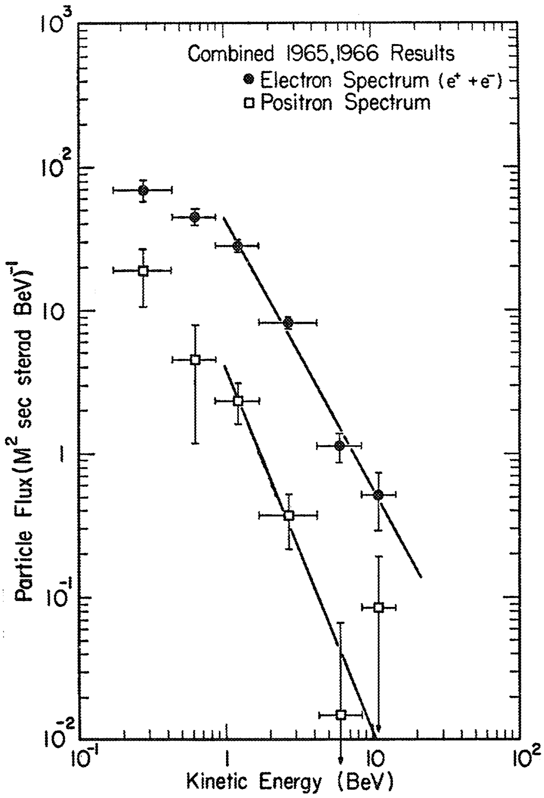

FIG. 4.—The energy spectra of primary electrons ($e^+ + e^-$) (*filled circles*), primary positrons (*open squares*). Lines are least-squares fits of power laws to the data for energy >860 MeV.

Attempts have been made in the past to interpret the shape of the electron spectrum in terms of the average time in which the particles are stored in the Galaxy. In particular, the question has been raised as to whether the change in spectral slope which occurs around 2–3 BeV might be due to the influence of energy losses by synchrotron radiation and inverse Compton collisions. This interpretation would imply a storage time of around 10^8 years which the electrons spend between source and observer (see, e.g., Ramaty and Lingenfelter 1966; Shen 1967; Jokipii and Meyer 1968). There are major objections to interpreting the break of the energy spectrum in this manner. First, this would require an electron source spectrum much flatter than the source spectra of protons and nuclei; second, it uses the unproved assumption that the electron source spectrum is a pure power law over a wide range of energies. In contrast, the positrons, at the energies which we consider here, presumably originate exclusively in interstellar nuclear collisions, and the shape of their source spectrum is therefore known. In the energy range from 1 to 10 BeV the calculated shape is very similar to the primary spectrum of high-energy protons with $E > 5$ BeV and therefore follows a power law with an exponent $\gamma \approx 2.6$. As shown in Figure 4, we observe a positron power-law spectrum with $\gamma = 2.56 \pm 0.54$, which seems to indicate that the positron source spectrum is not modified by energy losses in this range of energies. However, the accuracy of the observation does not fully exclude alternative interpretations. Since the electron spectrum extends with a simple power law from 10 to about 300 BeV (see Fig. 2), it is likely, therefore, that the electrons, as well as the nuclear components, spend not more than 10^6 years within the Galaxy. This evidence points toward storage and diffusion in the galactic disk alone, without requiring a galactic halo for long-term storage.

We next wish to turn toward the comparison of the measured positron spectrum with the equilibrium positron spectrum calculated on the basis of a collision origin (Ramaty and Lingenfelter 1968; Perola, Scarci, and Sironi 1967) and make an attempt to deduce the amount of solar modulation which the electron component has undergone in the period of minimum solar activity. We make this comparison with models involving storage in the galactic disk only, in view of the fact that the exponent of a power-law fit to our positron spectrum agrees much better with models of this kind than with those which invoke halo storage. We first show, in Figure 5, the measured positron spectrum, extrapolated to the top of the atmosphere, together with the equilibrium spectra calculated by Ramaty and Lingenfelter (1968, indicated by R1) and by Perola *et al.* (1967, indicated as P1). R1 and P1 are both for disk models; however, they are based on different mean amounts of interstellar matter traversed by the cosmic rays. While Ramaty and Lingenfelter use for this quantity $x = 4$ g cm^{-2}, a value arrived at from the work on ^{3}He, D, and the light nuclei, Perola *et al.* chose a value of $x = 1$ g cm^{-2} for their model P1. This appears to be the main reason for the difference in the two respective equilibrium spectra at low energy. At energies exceeding 1 BeV there is an additional difference in intensity of a factor of 2 in the *source* spectra calculated by the two authors (Perola *et al.* 1967).

As can be seen from Figure 5, the calculated positron spectra agree reasonably well with the measurement for energies above 1 BeV, indicating that the production of positrons by collisions in interstellar space is taking place at the predicted rate. Only at lower energies does our measured positron flux fall below the calculated values.

At these energies, solar-modulation processes are likely to affect the flux of electrons observed at the Earth. Little is known as yet about the modulation of the electron component, and contradictory claims exist in the literature (L'Heureux *et al.* 1968; Webber 1967; Bleeker *et al.* 1968*b*). Studies of the nuclear components, on the other hand, show that, near solar minimum and at the location of the Earth, the reduction of the interstellar flux can be described satisfactorily by the modulation factor

$$\begin{aligned} &\exp(-\eta/R\beta) \quad \text{for} \quad R > R_0 \\ \text{and} \quad &\exp(-\eta/R_0\beta) \quad \text{for} \quad R \leq R_0\,, \end{aligned} \tag{1}$$

where β is the velocity of the particles in units of c and where R is their rigidity. This corresponds to predictions from the diffusion-convection theory of solar modulation (Parker 1963; Jokipii 1966, 1967). The values of the parameters η and R_0 are not well determined by experiment, and both range between 0.1 and 1 BV. Using the work of O'Gallagher (1967) and of Ramaty and Lingenfelter (1969), one obtains $\eta \sim 0.5$ BV, $R_0 \sim 0.5$ BV, as the most likely values.

We have used the expressions (1) for modulating the equilibrium spectrum R1, and we obtain a reasonable fit between the data and the theoretical curve by using $\eta = 0.6$ BV and $R_0 = 0.3$ BV, as shown in Figure 6.

It must be pointed out that the agreement of the measurement with the calculations and the above modulation parameters is restricted to the energy range covered by our experiment. Results on the positron spectrum by Beuermann *et al.* (1969) indicate a modulation at low energy which is quite different from that shown in Figure 6. We are in no position to check the rigidity dependence of the modulation factor suggested by Beuermann *et al.* It would, however, not be in disagreement with our observations.

Neither the calculations of the positron equilibrium spectrum nor the measurements have sufficient accuracy to put tight limits on the modulation parameter η and R_0. Uncertainties in the calculations arise from assumptions for the interstellar density of matter, the strength of galactic magnetic fields, and the photon energy density, as well as nuclear-physics parameters. Most of the uncertainty in the positron flux arises from

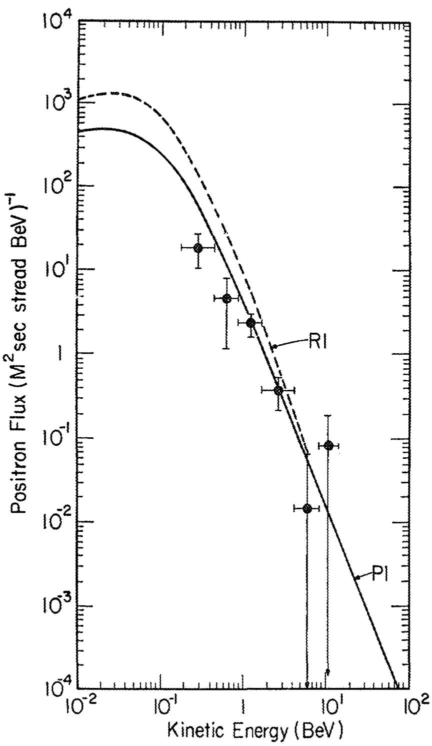

FIG 5

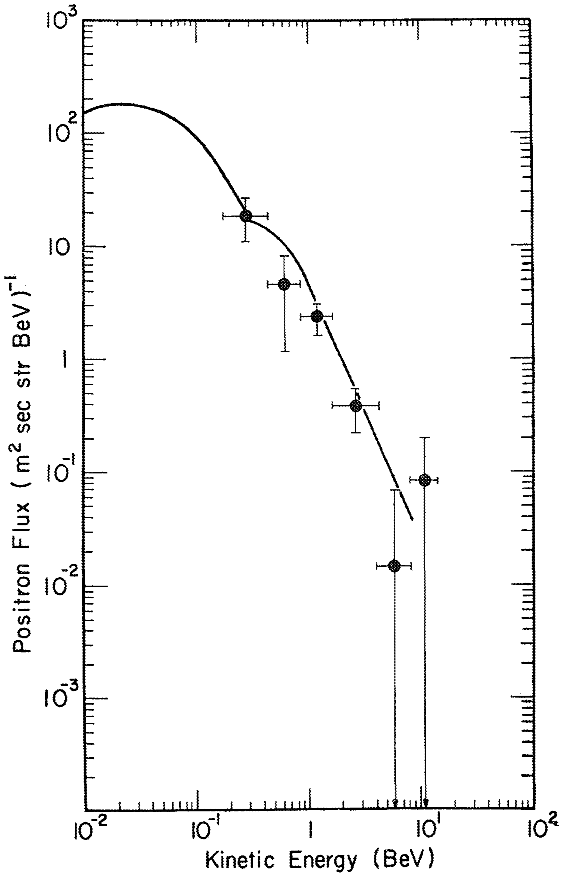

FIG. 6

FIG. 5.—Observed positron spectrum and the interstellar equilibrium spectrum of positrons as calculated from disk models by Perola *et al.* (1967) (P1) and by Ramaty and Lingenfelter (1968) (R1).

FIG. 6.—Observed positron spectrum and the modulated interstellar equilibrium spectrum of model R1, using modulation parameters η = 0.6 BV and R_0 = 0.3 BV.

the extrapolation of data to the top of the atmosphere. In this connection, we should point out that our corrections for atmospheric-secondary electrons and positrons are somewhat smaller than those used by other experimenters but agree quite well with detailed calculations of Beuermann (private communication).

The modulation parameters obtained for electrons cannot be directly compared with those based on measurements of cosmic-ray nuclei since adiabatic deceleration in interplanetary space affects nuclei and electrons of the same rigidity in a different manner. Jokipii (private communication) predicts for the modulation factor, including adiabatic deceleration,

$$\exp\left[-\tfrac{2}{3}\left(1+\frac{\alpha\gamma}{2}\right)\left(\frac{(L-r_E)v_w}{5\times 10^{21}R^{1/2}\beta}\right)\right],$$

provided that $v_w L/5 \times 10^{21} R^{1/2}\beta \ll 1$.

Here $\alpha = (2mc^2 + T)/(mc^2 + T)$, $\gamma = -\partial \log J/\partial \log T$, and J = particle flux, T = kinetic energy, R = rigidity, βc = velocity, r_E = 1 a.u., L = radius of the modulating region, and v_w = velocity of the solar wind.

Since the electrons under consideration are highly relativistic ($T \sim pc$) while the nuclei are not ($T \sim p^2$), the contribution to the modulation by adiabatic deceleration should be about twice as large for nuclei as for electrons. Unfortunately, the accuracy of our determination of the positron spectrum does not yet permit us to distinguish between the modulation factors with or without inclusion of the terms due to adiabatic expansion, and we therefore have used expressions (1) for our comparison with the data.

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