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Flux and Energy Spectrum of Cosmic-Ray α Particles during Solar Maximum*

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The fluxes of primary cosmic-ray α particles over Minnesota and Texas have been measured during the present period of maximum solar activity. A value of 136 ± 9 α particles/m^2 sec sterad was measured over Minnesota and of 68 ± 4 α particles/m^2 sec sterad over Texas. In both cases these values are significantly lower than those observed at solar minimum. The energy spectrum of these particles has been determined between 200 Mev/nucleon and 3.0 Bev/nucleon. It is shown that the slope of the integral spectrum is less than that observed at solar minimum and that a significant number of low-energy particles is still present. A possible mechanism for these changes is discussed briefly. The determination of energies of particles from a measurement of their ionization is discussed in detail in an appendix.

I. INTRODUCTION

THE flux values and energy spectra of cosmic-ray α particles have been investigated with nuclear emulsions and counter arrays for at least eight years. During the first half of 1957, during a period of increased solar activity, there was a marked and rather rapid decrease in the total cosmic-ray intensity.[1] In a stack of emulsions exposed on May 17, 1957, the α-particle flux above 200 Mev/nucleon was measured. The flux had decreased by $48\pm10\%$ from the mean value obtained between 1950 and 1954.[2] In order to investigate this decrease further, we have again measured the α-particle flux over Minnesota using nuclear emulsions. The stack, henceforth called the M stack, was exposed during a large Forbush decrease on August 31 to September 1, 1957. In addition, we have measured the α-particle flux over Texas, using the T stack which was exposed on October 19, 1957.

By employing ionization and multiple-scattering measurements, we have investigated the energy spectrum of the α particles between 200 Mev/nucleon and 3.0 Bev/nucleon during this time of decreased intensity. The energy spectrum obtained in this experiment has been compared with those found previously by similar techniques.

II. EXPERIMENTAL RESULTS

1. Exposure Details

The M stack, used to measure the α-particle flux at Minnesota, was launched in the evening of August 31, 1957, as part of a series of flights being made during the IGY. The balloon was launched at 45.1°N and 93.2°W (geographic), and the load was released at 44.5°N and 96°W. The average altitude was 18 ± 2.8 g/cm^2 (see Fig. 1). The absorption of α particles in air is well known, so the fluctuations in altitude could be corrected for in the calculation of the flux. Because of these fluctuations, the energy of individual α particles had an uncertainty of about 10 Mev/nucleon at an energy in the emulsion of 200 Mev/nucleon. The uncertainty in energy is smaller at higher energies.

The altitude of the T stack is also shown in Fig. 1. Its altitude was measured by four methods; the average value is 3.8 ± 0.2 g/cm^2. The trajectory of the flight is given in Fig. 2. The balloon reached altitude at 31.8°N and 98.4°W (geographic), and the load was released at 32.7°N and 95.4°W.

The details of the detection procedure used in the two stacks are given in Table I. A line scan was made at 1.2 cm from the top edge of each emulsion for tracks which satisfied the required geometrical conditions of length and angle and which had ionizations greater than three times the minimum ionization. In the Texas stack we made two independent measurements of the α-particle flux, denoted by T_1 and T_2. The possibility that scanning of this sort should fail to detect all the α particles that crossed the scan line has been discussed extensively in the literature.[3] Checks similar to those used previously (i.e., length, grain density, depth, and angular distributions) were made on the tracks obtained in these three scans. In addition, part of the area was independently re-scanned by different observers (24% of the area in the M stack and 17% of the area in the T_1 scan). All these checks on the scanning efficiency, with the exception of the angular distribution in the M stack (see Sec. III-2), indicated that there were negligible scanning losses.

2. Identification of Particles

In order to distinguish between the α particles and the more numerous background of slow singly-charged particles, measurements must be made on every track found during the scanning. In the M stack, where both slow and fast α particles were expected, measurements were made of the velocity (ionization) and momentum (multiple scattering). In the T stack both ionization and scattering were measured, although the scattering meas-

* This work was supported in part by the joint program of the U. S. Atomic Energy Commission and the Office of Naval Research.
† On leave of absence from a Royal Society Mackinnon Research Studentship.
[1] H. V. Neher and S. E. Forbush, Phys. Rev. Letters 1, 173 (1958).
[2] Freier, Ney, and Fowler, Nature 4619, 1319 (1958).
[3] C. J. Waddington, Nuovo cimento 3, 930 (1956).

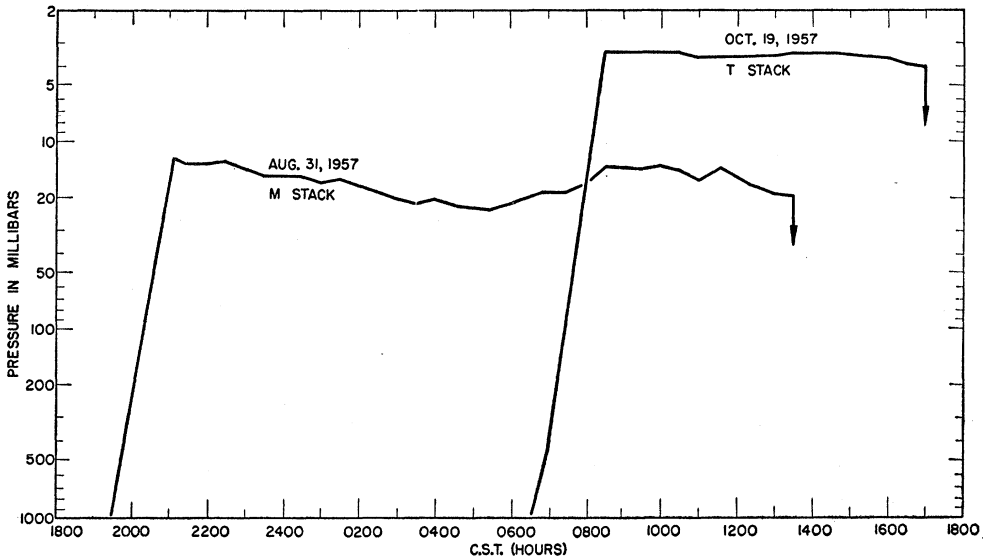

FIG. 1. Time-altitude curves for the two flights.

urement would have been sufficient because of the high cutoff energy of 1.5 Bev/nucleon (see Sec. IV-3).

The ionization measurements were made with a photodensitometer similar to that described previously.[4] The ionization measured in this manner we call the opacity and denote by the symbol O. The provisional scattering measurements used for identification were made on 1000-μ cells without noise elimination. A plot of the ionization measurements versus those of multiple scattering in the M stack is given in Fig. 3 showing the clear resolution between α particles and singly-charged particles. Some of the tracks, when aligned on a scattering stage, were obviously protons. They were not completely measured and hence are not on the plot.

In the Texas stack it was readily apparent that when a track was aligned along one of the axes of the microscope stage, the great difference in multiple scattering between fast α particles and slow singly-charged particles—a difference of the order of 10—could be observed by inspection. As a result, particles were identified without being formally measured. It should be emphasized that such a technique is only applicable for long tracks ($\geqslant 8$ mm) and that care must be taken in clearly distinguishing between multiple scattering and local distortion of the emulsions. Measurements of scattering were made on those tracks where there was any ambiguity in the identification by inspection.

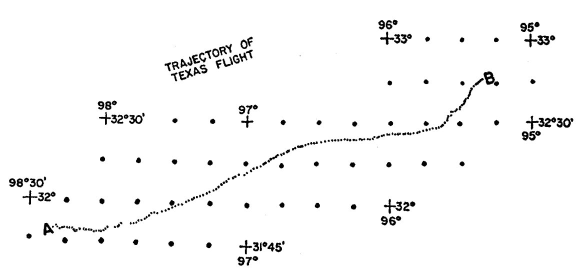

FIG. 2. Flight trajectory for the T stack.

[4] Fowler, Waddington, Freier, Naugle, and Ney, Phil. Mag. 2, 157 (1957).

3. Energy Measurement by Ionization

The opacity of each α-particle track found in the M stack was measured over 1 mm of its length centered about the middle of the emulsion. The distribution in opacity (O) for the 265 α particles is given in Fig. 4. In order to obtain energies from the densitometer ionization measurements, we must calibrate the densitometer using particles of known energy. The calibration procedure is discussed in the appendix. The residual range of each particle at the place where it is measured in the emulsion is determined from the calibration curve. The energy of each particle at the top of the atmosphere was then calculated, taking into account the emulsion the particle had passed through before measurement, the packing material, and the air. For the air path, 18 secθ g/cm^2 was used, where θ is the zenith angle of the track measured in the emulsion. The balloon's altitude did fluctuate somewhat (see Fig. 1). A careful analysis of the altitude record, using 48 g/cm^2 for the air absorption mean free path of α particles, showed that 18 g/cm^2 was the equivalent altitude of this flight; i.e., if it had stayed at a constant altitude for the same flight time, that altitude would have to be 18 g/cm^2 to yield the same number of α particles in the emulsion. This fluctuation in altitude of the balloon produces an uncertainty in the energy of any individual α particle. This uncertainty is small. At 300 Mev/nucleon at the top of the atmosphere, 82% of the particles will have an uncertainty in energy <12 Mev/nucleon; at higher energies the uncertainty is less. About 1% of the α particles enter the stack during ascent; these particles will have a larger uncertainty in their energy.

TABLE I. Exposure and scanning details of stacks used to measure α flux.

Stack	Date	Total No. of emulsions[a]	No. of scanned emulsions[a]	Scan area (cm²)	Min track length (mm)	Max zenith angle	No. of alphas	α flux at top of atmosphere (particles/m² sec sterad)
M	August 31, 1957; September 1, 1957	12	8	2.75	10	45°	265	136 ± 9
T_1	October 19, 1957	117	20	7.19	10	45°	226	65_{-5}^{+7}
T_2	October 19, 1957	117	23	8.47	8	60°	411	70 ± 4

[a] The emulsions were 4 in.×4 in. 600-μ Ilford $G5$ strips.

The upper limit of the energy which we can measure by ionization is determined by the spread in ionization of relativistic particles. The M_1 stack (consisting of only 12 plates, all developed in one batch) gave a sharp distribution in opacity whose half-width is consistent with the statistical fluctuation in the number of grains in the 1 mm of track we measured. (See Fig. 4.) For opacities $\geqslant 11.3$ there is less than 1% probability that any particle is really fast. For opacities between 10 and 11 there is 20% probability the particle is really fast. We have calculated the energy of those particles with opacities $\geqslant 10.8$, corresponding to those particles with less than 800 Mev/nucleon at the top of the atmosphere.

4. Determination of Energies from Multiple-Scattering Measurements

The energies of those α particles which satisfied certain additional geometrical criteria were determined by measuring the multiple Coulomb scattering. In making these determinations, procedures were used similar to those employed by Fowler and Waddington[5] to examine the energy spectrum of α particles over northern Italy. For this reason the results of this earlier work should be comparable with those obtained in the present experiment. The reader is referred to that paper for details of the experimental procedure used to calculate energies and eliminate noise.

In the M stack, where an appreciable portion of the particles are of low energy, scattering measurements were made on basic cell sizes of 500 μ, 250 μ, or 100 μ, the particular cell size used being selected so as to obtain significant[5] answers. Tracks were accepted for measurement if they had a projected length of greater than 1.4 cm in at least two emulsions and were more than 1 cm from a processed edge. Measurements were made on 126 particles using 500 μ basic cells on 109 particles, 250 μ cells on 15 particles, and 100 μ cells on 2 particles.

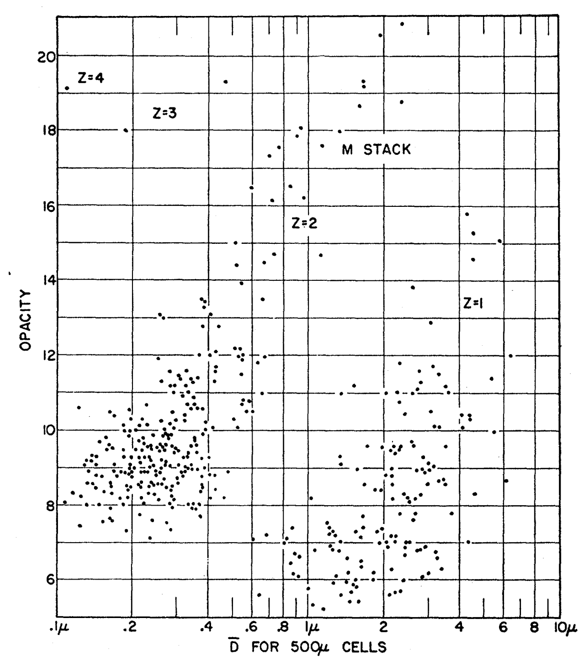

FIG. 3. Ionization (densitometer opacity) as a function of multiple Coulomb scattering ($\bar{D}$ per 500 micron cells) for the particles obtained in the line scan of the M stack.

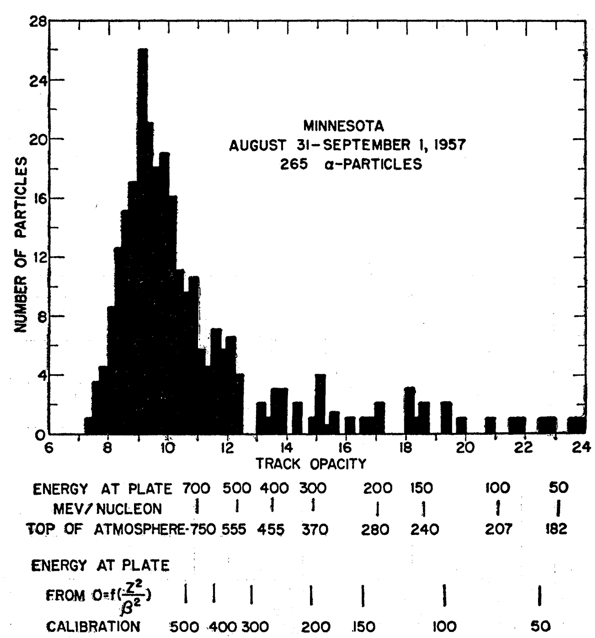

FIG. 4. Ionization distribution (opacity, O) in the emulsion for α particles found in the M stack. The energy scale has been drawn for two calibrations (see Appendix). The upper energy scale is drawn from $O=f(Z^2/\beta^{1.7})$ which we believe is the best fit to the data. The lower energy scale is drawn from $O=f(Z^2/\beta^2)$ which was the calibration used in reference 2.

[5] P. H. Fowler and C. J. Waddington, Phil. Mag. 1, 637 (1956).

In the T stack, where all the particles had relatively high energies ($\geqslant 1$ Bev per nucleon), a basic cell size of 1000 μ was used on all particles. Tracks were accepted for measurement if they had a projected length of greater than 2 cm in at least two emulsions and were more than 1 cm from a processed edge. A total of 187 tracks had measurements made on them in this stack.

The experimental measurements were then analyzed[5] to determine the rate of variation of the noise with cell size. The effect of this noise was then eliminated from the data in order to determine the true multiple Coulomb scattering. In the M stack the noise varied with the cell-size to the power of 0.65 ± 0.08 and in the T stack to the power of $0.70_{-0.11}^{+0.08}$.

On each particle the true multiple scattering was expressed in terms of the scattering parameter, $\bar{\alpha}$, in degrees per 100 μ. The momentum was then calculated from the relation

$$p\beta = KZ/A\alpha \text{ (Mev/c) per nucleon,}$$

where Z is the charge, A is the mass number of a particle of momentum p and velocity β, and K is the scattering constant. Unfortunately, K is not well known experimentally for multiply-charged particles, and it is necessary to use values calculated from the known composition of emulsion.[6] Using a $4\bar{D}$ replacement cutoff, the following values have been adopted for K: 100 μ basic cells, $K=28$; 250 μ basic cells, $K=29.6$; 500 μ basic cells, $K=30.7$; 1000 μ basic cells, $K=32$. The value of $K=32$ for 1000 μ basic cell size is that used previously.[5,7]

To check on the validity of the energy values obtained in this way, values of the noise, determined in microns, $n_1(\mu)$, have been calculated for groups of tracks selected on the basis of their apparent energies, Table II. Also shown in this table is the quantity $27\bar{D}_1^2-\bar{D}_3^2$, in arbitrary units, where $\bar{D}_1$ and $\bar{D}_3$ are the mean deviations on the basic cell size and on a cell size three times as great,

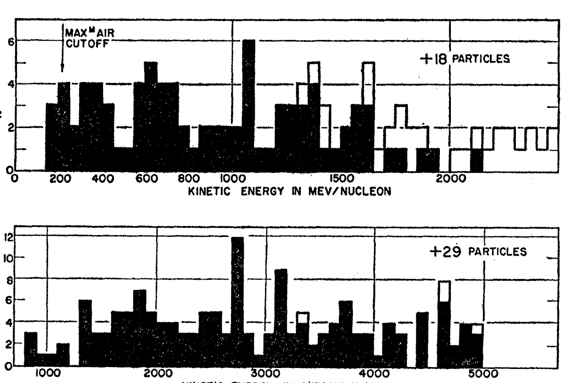

FIG. 5. The distribution in energy as measured by scattering at the top of the atmosphere of α particles observed in the M and T stacks. The unshaded areas represent particles where the energy attained was a lower limit.

[6] C. Fichtel and M. W. Friedlander (private communication).
[7] It should be noted that the signal is calculated from twice and three times the basic cell length.

since this quantity is independent of the value assumed for the rate of variation of noise with cell size. It can be seen from Table II that in the M stack there is no evidence to suggest that some particles have apparently low energies only because they have high noise values or have been appreciably affected by distortion—which would lower the apparent value of the noise. In the T stack, however, those particles with apparent energies of less than 1.5 Bev/nucleon appear to have been affected by distortion which varies faster with cell size than the true multiple scattering, resulting in negative values for the noise. Slow particles scattered on large cell sizes will have noise values which are very sensitive to such distortions due to the subtraction procedure used to determine the noise value. For this reason all those particles with apparent energies less than 1.7 Bev/nucleon were remeasured on a 500 μ basic cell, over as long a path length as was available in the stack, in order to determine the true noise level on them and to reduce the effects of distortion. Calculation of the noise from these measurements gave, after correction for the

TABLE II. Values of $(27\bar{D}_1^2-\bar{D}_3^2)$ in arbitrary units and noise in microns for particles separated on the basis of their apparent energy.

T Stack	$E\geq 3.0$ Bev/N	$1.50<E<3.0$ Bev/N	$E\leq 1.5$ Bev/N
$27\bar{D}_1^2-\bar{D}_3^2$	$6.88_{-0.40}^{+0.76}$	$6.96_{-1.3}^{+1.7}$	-16 ± 5
$n_1(\mu)$	0.194 ± 0.008	0.195 ± 0.020	See text
M Stack	$E\geq 1.5$ Bev/N		$E<1.5$ Bev/N
$27\bar{D}_1^2-\bar{D}_3^2$	$11.2_{-0.75}^{+1.6}$		$11.1_{-1.3}^{+1.9}$
$n_1(\mu)$	0.25 ± 0.015		0.25 ± 0.02

different basic cell size, a value for $n_1(\mu)=0.21\pm0.015$, which is in good agreement with the values found on faster tracks. The individual energy values found from these measurements did not differ significantly from those found previously, nor are there appreciable differences on individual particles between different emulsions. Furthermore, examination of the data shows that there was not a large amount of C-shaped or S-shaped distortion present. For these reasons, the low energy values obtained on these tracks have been considered to represent true energy values.

The distribution in energy, corrected to the top of the atmosphere, of the particles found in the M and T stacks is shown in Fig. 5.

III. FLUX VALUES

1. Flux at Texas

The α-particle flux was calculated in the same manner we have used before.[2] The zenith angular distribution in both the T_1 and T_2 scans showed isotropy. The flux measured at the scan line is corrected for those α particles which have correct geometry and reach the scan line but interact before they go the required length.

The flux is then corrected to the top of the emulsion using a mean free path of 20 cm in emulsion, and to the top of the atmosphere using a mean free path of 48 g/cm^2, The α particles are all followed to their entry point in the stack to verify that they are not the products of a disintegration of a heavy nucleus. We subtract that part of the flux that would come from the interactions of heavy nuclei in the air by assuming that 1 α particle is produced per interaction. The fluxes measured on the two independent Texas scans are given in Table I. The average flux is 68 ± 4 particles/m^2 sec sterad, where the error quoted, like all those in this paper, is the standard deviation.

2. Flux at Minnesota

The total flux over Minnesota was calculated in the same manner. The resulting flux averaged over 45° of zenith is 136 ± 9 particles/m^2 sec sterad. This is the flux of particles with $\geqslant 200$ Mev/nucleon.

This last flux value is somewhat uncertain due to an experimentally observed anisotropy of the α particles. After making corrections for the different geometries and absorption, the zenith angle distribution of α particles down to 45° has always previously been found to be isotropic. That is, in six other scans, three at relativistic cutoff energies and three at low cutoff energies, we have never observed such an anisotropy. This observation practically excludes the possibility that this anisotropy is due to scanning loss. The magnitude of the effect is shown in Table III, which gives the normalized number of particles in each 15° interval, both for the M and T stacks, and the May 17, 1957, stack. We can put limits on the true flux in the M stack by assuming either that there was a scanning loss at large zenith angles, giving an upper limit; or that there was an additional flux of α particles arriving from the vertical, which should not be included in the flux, resulting in a lower limit. These limiting values are 172 and 115 α particles/m^2 sec sterad, respectively.

TABLE III. Zenith angular distribution of α particles in three different stacks. The normalized number of particles is given in the table.

Angular interval	M stack	T stack (Scan T_1)	May 17, 1957
45– 31	0.78 ± 0.15	0.94 ± 0.18	1.09 ± 0.28
30– 16	0.93 ± 0.16	0.97 ± 0.17	0.97 ± 0.23
15– 0	1.27 ± 0.17	1.03 ± 0.17	1.35 ± 0.23
359–345	1.25 ± 0.18	1.02 ± 0.17	1.04 ± 0.23
344–330	0.71 ± 0.14	1.02 ± 0.17	0.84 ± 0.21
329–315	0.93 ± 0.17	0.97 ± 0.17	0.70 ± 0.22

IV. ENERGY SPECTRUM

1. Differential Energy Spectrum at Minnesota

From the ionization measurement of the energy we have calculated the differential energy spectrum in the M stack. The air and emulsion cutoff limits our measurement of the flux to particles above 200 Mev/nucleon. Figure 6 gives the differential energy spectrum for the M stack and the May 17, 1957, stack. We believe that the difference between these two stacks is significant and is reflected in the lower total flux in the M stack. The flux on May 17 was 157 ± 17 particles/cm^2 sec sterad for α particles $\geqslant 225$ Mev/nucleon. The flux on August 31-September 1 above the same energy is 135 ± 9 particles/cm^2 sec sterad. The flux in the energy interval 225–600 Mev/nucleon was 42 ± 8 particles/m^2 sec sterad on May 17, and 19 ± 3 on September 1.

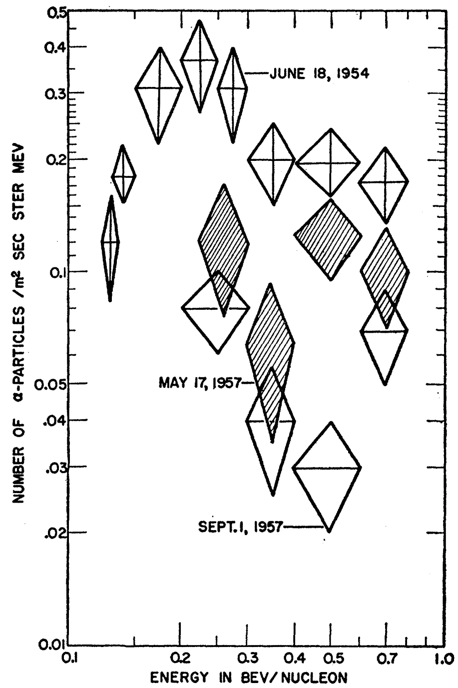

FIG. 6. The differential energy spectrum of the α particles at Minnesota during 1957. The spectrum obtained in June, 1954, is also shown. The data have been recalculated using the $O=f(Z^2/\beta^{1.7})$ calibration rather than the $O=f(Z^2/\beta^{1.6})$ used in reference 4.

2. The Integral Energy Spectrum

The integral energy spectra obtained from scattering measurements is shown in Fig. 7, together with the spectra obtained during the period of sun spot minimum by similar techniques.[1,8] In all cases it appears that for energies appreciably higher than the cutoff energy, these spectra can be represented over this limited energy range by the conventional expression

$$n(>E)=C/(m_0c^2+E)^n,$$

where C and n are constants. The values of C and n found in the present experiment are: $C=185_{-25}^{+35}$ and $n=1.17\pm0.14$. These values can be compared with

[8] C. J. Waddington, Nuovo cimento 3, 930 (1956).

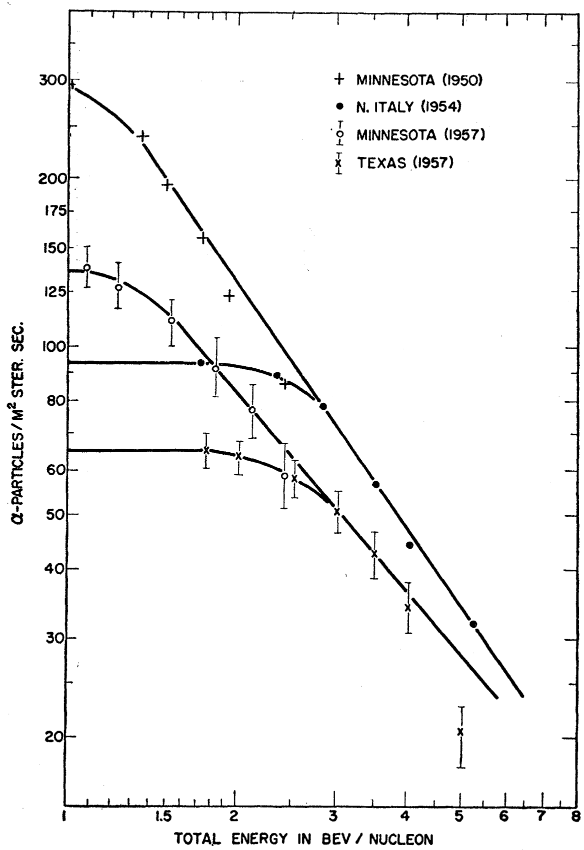

FIG. 7. The integral energy spectrum of α particles obtained from scattering measurements.

those of $C=360_{-30}^{+50}$ and $n=1.48\pm0.12$ found during the sunspot minimum[1] over the same range of energies. It can be seen that the slope of the integral energy spectrum measured in this experiment is appreciably flatter than that observed previously. This result is in agreement with the evidence from neutron monitors.[9]

The integral flux values found in 1954 and on May 17, 1957, and September 1, 1957, are tabulated in Table IV. These values are those obtained from ionization measurements of the energies.

3. The Cutoff Energy

Geomagnetic theory would predict that the cutoff energy for vertically incident particles over Texas should be 1.8 Bev/nucleon. A number of experiments have shown that over Northern America the observed cutoff energies appear to have been lowered by an amount corresponding to a 3–4° shift in geomagnetic latitude.[7,10] Such a shift over Texas would imply that the true cutoff energy should be as low as 1.2 Bev/nucleon. However, as has already been pointed out,[5] the flux of α particles of northern Italy, at a measured cutoff of

TABLE IV. Integral flux of α particles above E_{min} where E_{min} is measured by ionization. Fluxes are in particles/m² sec sterad.

E_{min} (Mev/nucleon)	June 18, 1954	September 1, 1957	May 17, 1957
140	302±21		
200	283±19	136±8	
225			157±17
300	250±19	128±8	146±16
400	230±18	124±8	140±14
500	211±17	120±6	127±13
600	190±16	117±6	115±13
700	177±16	109±8	109±12
800	155±15	103±7	96±12

1.55±0.06 Bev/nucleon, is not significantly different from the flux observed over Texas, and therefore it might be expected that the cutoff energies would be closely similar.

By putting the observed value for $N(>E_0)$ into Eq. (1), we can determine the cutoff energy on the assumption that it is a sharp cutoff. The value found for the cutoff energy is 1.5±0.1 Bev/nucleon, in agreement with that found over Northern Italy.

V. CONCLUSIONS AND DISCUSSION

The principal features of the data obtained in this experiment are[11]:

1. The total flux of cosmic ray particles arriving at the earth at geomagnetic latitudes sufficiently near the poles so that the flux is not seriously distorted by the earth's magnetic field can be reduced by an external agency to only 50% of the value recorded at solar minimum. Furthermore, this reduction can be maintained for at least three months, and from neutron monitor data, has been maintained for over a year.
2. This decrease is not due to a sharp cutoff removing only the lower energy particles, nor is it due to an incremental increase in the cutoff energy at all latitudes.
3. Although particles with at least 3 Bev/nucleon, and presumably considerably higher energies, are removed, it is still possible to observe particles with energies down to the minimum value imposed by our experimental techniques. Furthermore, the differential energy spectrum of the low-energy α particles observed in this experiment does not show the maximum, followed by a sharp falling off, of the sort predicted by most screening mechanisms previously proposed (see, for example, Parker[12]).

A number of mechanisms have been proposed to explain the 11-year variations in cosmic-ray intensity and the long-scale large-magnitude decreases of the sort observed in this experiment. The majority of these have suggested some form of screening of the earth which

[9] Peter Meyer and J. A. Simpson, Phys. Rev. **106**, 568 (1957).
[10] Fowler, Freier, and Ney, reported at the *Proceedings of the 1957 Varenna Conference* [Suppl. Nuovo cimento **8**, 492 (1958)].

[11] In what follows it will be implicitly assumed that the behavior of the cosmic-ray α particles reflects that of all the primary cosmic-ray particles.
[12] E. N. Parker, Phys. Rev. **110**, 1445 (1958).

reduces the number of galactic cosmic-ray particles which can reach the earth. The screening mechanisms proposed all assume some form of diffusive barrier which is more efficient for low-energy particles than for those of high energy. None of them appears to be able to explain satisfactorily the relatively large number of low-energy α particles observed, and to allow an appreciable diminution of those high-energy particles entering at the equator—although neutron monitor data show that there is an appreciable decrease in the intensity at the equator.

We would like to suggest, therefore, consideration of an alternative mechanism which appears to satisfy such experimental data as we have at present and has the added advantage that it should be capable of experimental check.

If the sun should itself emit cosmic-ray particles during the period of minimum activity, but be unable to do so at solar maximum, then we can readily explain our experimental data. Under this hypothesis, during a period of solar minimum we would observe a superposition of the solar cosmic rays on those of galactic origin, while at solar maximum we must be assumed to be observing only those particles of galactic origin.

Such a hypothesis may be confirmed or disproved although, unfortunately, not completely, by the following experiment. It is, *a priori*, unlikely that the cosmic-ray particles of solar origin should pass through the same amount of interstellar material as those of galactic origin. Thus, aside from any source differences, they should have different chemical compositions. This point could be readily checked by determining the abundance of the elements lithium, beryllium, and boron having energies between, say, 200 and 600 Mev/nucleon at solar maximum and solar minimum.

ACKNOWLEDGMENTS

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APPENDIX

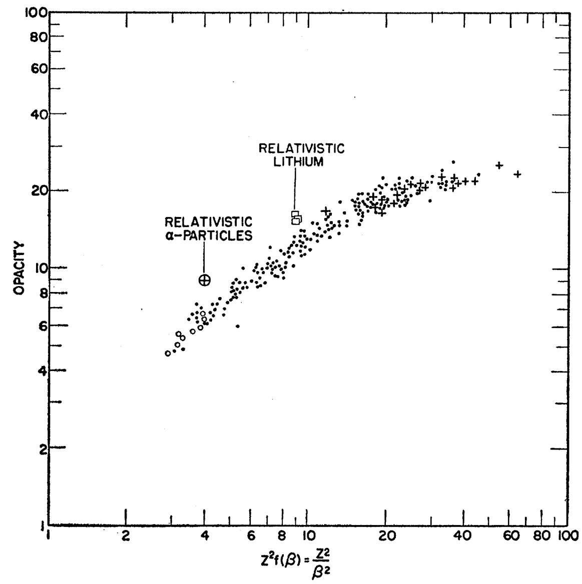
In work on determining the energy spectrum of α particles in cosmic rays, one is frequently faced with the problem of convertlng a measurement of the ionization to a range or energy for the α particles. In the earliest work on this subject,[4] namely the determination of the energy spectrum of primary α particles in Saskatoon, Canada, in 1954, the determination of the α particle energies was straightforward over much of the energy range because of the presence of low-energy α particles which came to rest in the photographic emulsion. The emulsions were large enough so that α particles of ranges as great as 20 cm could be brought to rest. This allowed direct calibration of the emulsion in which the measurements were made up to α particle energies of 300 Mev/nucleon at incidence in the plate.

In certain other stacks which we have studied, however,[2] one wishes to determine the α-particle energies when lower energy α particles are completely absent. An example of this is the determination of the cutoff energy for α particles in Missouri, where no α particles were present with ionization as great as that of a relativistic lithium. It is necessary in such cases to be able to calibrate the emulsion using protons of various ranges and to infer from the proton ionizations and the corresponding α-particle ionizations what energy α particles are being detected. What is required is some procedure for converting in any stack a densitometer opacity reading to an energy for the α particles. Even in a very large stack with all energy α particles incident, there is a region of energies in which it is very difficult to obtain direct calibration points from the α particles themselves. At an energy of about 300 Mev/nucleon, the α-particle range is about one mean free path in emulsion. Therefore, a direct calibration at higher energies than this requires examination of large numbers of α particles in stacks with very long possible residual ranges. For example, an α particle of energy 1 Bev/nucleon has a residual range of about 125 cm of emulsion or approximately 6 mean free paths. In order to find such a particle ending, one would need to examine approximately 400 incoming α particles in order to obtain one which did not interact. In addition to this, the largest stacks at our disposal do not have enough emulsion range to stop α particles of this energy. At the present time, α particles in the energy range of 500 Mev/nucleon to 1 Bev/nucleon are not available from machines; if they were available, they would allow a direct calibration of the emulsion development in terms of α-particle energy.

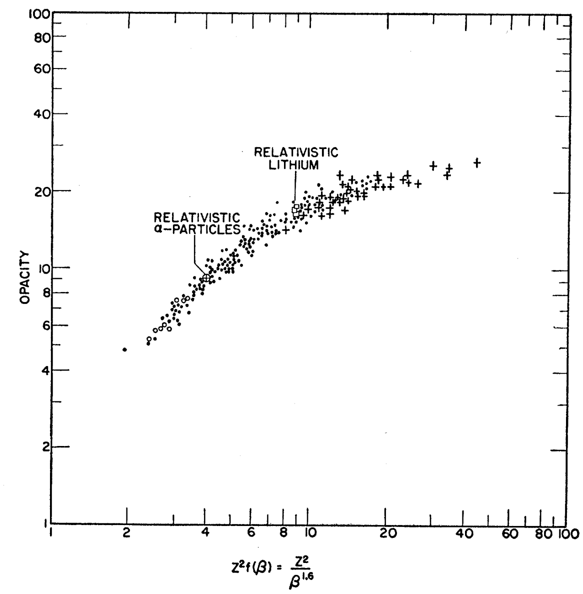
Certain experimental facts are known about the ionization of various particles in photographic emulsion, and a number of observers agree on the approximate values of the following quantities:

1. The residual range of protons which produce the same densitometer reading as relativistic alphas. Our measurements show that a proton of residual range 2.8 cm has the same densitometer reading, and therefore the same core density, as a relativistic α particle. Protons of this range are readily available in any emulsion exposed to cosmic rays. Relativistic α particles can be positively identified by scattering and ionization measurements.

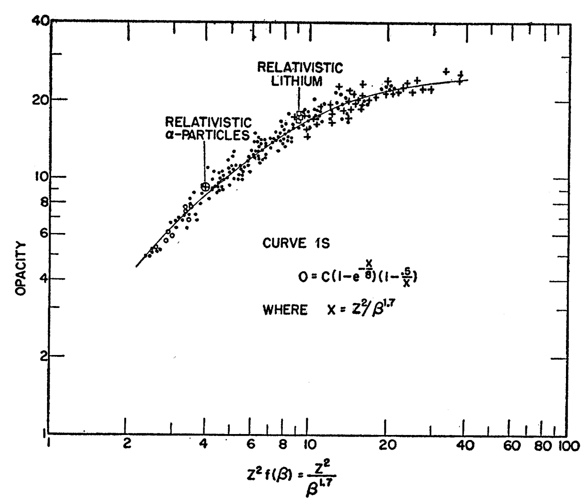
2. The residual range of alpha particles which ionize like relativistic lithium. In our emulsions we find the densitometer reading that corresponds to a relativistic lithium is obtained on an α particle of 10-cm residual range. In addition to this, a proton of 4-mm residual range has the same ionization as the relativistic lithium and the 10-cm α particle.



(a)



(c)



(b)

FIG. 8. Normalized opacity (*O*) measurements for calibration particles measured in three different stacks. The circled points are mesons, the dots protons, and the crosses α particles. The opacity readings for relativistic α particles and lithium nuclei are also shown. These are: (a) $Z^2f(\beta) = Z^2/\beta^2$; (b) $Z^2f(\beta) = Z^2/\beta^{1.7}$; (c) $Z^2f(\beta) = Z^2/\beta^{1.6}$. Curve (b) corresponding to the restricted energy loss is the calibration curve we have adopted.

Since these two calibration points are fairly readily available, we have attempted to construct in a consistent way a general calibration curve which applies to all our stacks and which allows us to determine the $f(\beta)$ $(\beta = v/c)$ or range of an α particle, given its densitometer opacity and the densitometer opacity corresponding to relativistic α particles. The procedure is to plot the densitometer reading against various functions $Z^2f(\beta)$. The functions of β we have plotted are $1/\beta^2$, the function of β given by the total energy loss, and the function of β given by the restricted energy loss.[13] Calculations show that in the range of β's required, excluding the extreme relativistic particles, both the total energy loss or the restricted energy loss may be expressed with adequate accuracy as power laws in β, i.e., $1/\beta^n$. In these terms the function of β corresponding to the total energy loss in nuclear emulsion is $1/\beta^{1.6}$, and that corresponding to the restricted energy loss is $1/\beta^{1.7}$. We have tried to determine which of these functions of β allows all particles observable for calibration to fall on a smooth curve without systematic differences between protons and α-particles and between protons and relativistic α particles.

In the figures which follow, all the particles used for calibration have their energies, and therefore β, determined by their residual ranges. Figure 8 shows the collected data from three stacks in which approximately equal numbers of particles were measured, normalized to a single curve. The normalizations were obtained by multiplying the individual densitometer readings by the appropriate ratio to make the relativistic α particles in all the stacks have the same value. Consideration of these three plots shows the following facts: in the plot,

[13] B. Stiller and M. Shapiro, Phys. Rev. **92**, 735 (1953).

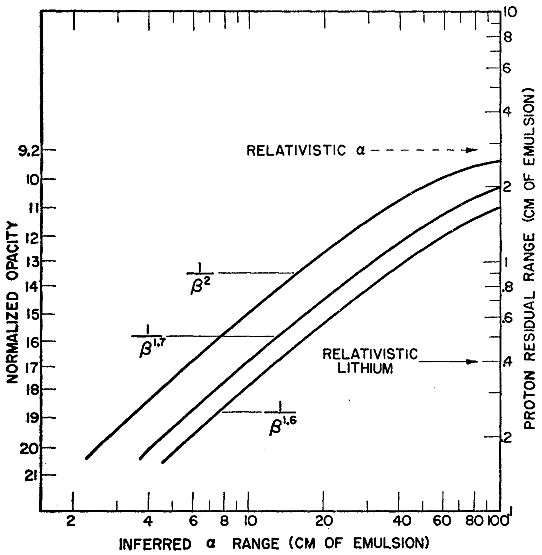


FIG. 9. α-particle ranges as a function of normalized densitometer opacity for three different calibrations. The curve marked $1/\beta^{1.7}$ is for the calibration we have adopted.

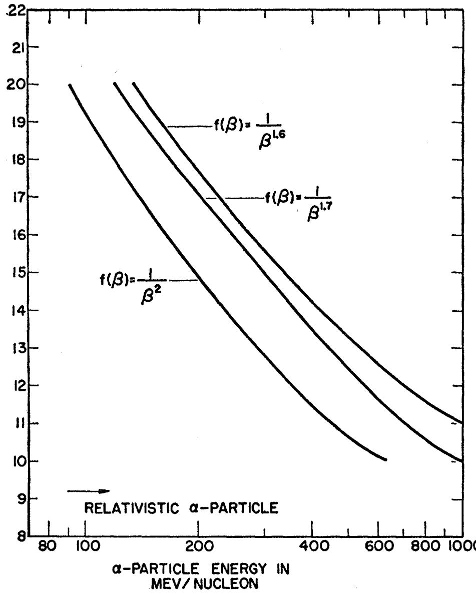


FIG. 10. α-particle energies as a function of normalized densitometer opacity for three different calibrations. The curve marked $1/\beta^{1.7}$ is for the calibration we have adopted.

8(a), of opacity O *vs* Z^2/β^2, the agreement between low-energy α particles and low-energy protons is quite good. Relativistic α particles, however, do not have the same Z^2/β^2 as do protons of the same ionization. In other words, α-particle point falls very far away from the calibration curve as does the point corresponding to relativistic lithium. On the curve for restricted energy loss, 8(b), the α-particle point and the lithium point fall slightly above the best proton curve, but very much closer to it than when the function of β plotted was $1/\beta^2$. Finally, in Fig. 8(c) in which total energy loss is plotted, the relativistic α particles and protons fall together, but there seems to be a systematic separation of the low-energy α particles and low-energy protons.

We believe that the use of the restricted energy loss function, or in our approximation $1/\beta^{1.7}$, represents the best approach to the calibration problem at the present time. It can be seen from Fig. 8 that all of the data from the three flights presented, although the emulsions themselves had quite different developments, are well represented by a single calibration curve. The equation for this curve is shown in Fig. 8(b). The fact that the α particle and relativistic lithium points fall slightly above the best-fit curve could be consistent with the relativistic increase in the average ionization of fast primary cosmic-ray particles. We are not, however, suggesting that our data indicates the presence of a relativistic increase.

The procedure for normalizing a new stack, therefore, is to measure the value of densitometer reading obtained for relativistic α particles, match that to the α-particle point shown on Fig. 8(b), i.e., slightly above the proton line, and draw the universal calibration curve. The equation of this curve is

$$O=C(1-e^{-x/8})(1-0.5/x),$$

where $x=Z^2/\beta^{1.7}$ and C is a constant. The correctness of this curve can be checked in any stack, of course, by measuring a few proton points and seeing that they do indeed fall on the line. This allows a normalized opacity to be determined and in turn a value of β for each α particle. Our stacks have all been normalized to an opacity for relativistic α particles of 9.2. Figure 9 gives the inferred range of α particles in terms of this normalized opacity and shows also the proton ranges corresponding to various values of normalized opacity. This graph also shows the values that would be inferred for the α-particle ranges using the other two calibrations. The calibration that best fits our data is the $1/\beta^{1.7}$ curve. Figure 10 shows the corresponding normalized opacity, that is, normalized to 9.2 for relativistic α particles, as a function of the kinetic energy of the incident α particles. Again, the curve marked $1/\beta^{1.7}$ is the one used by us to convert densitometer reading to kinetic energy.

To summarize our calibration procedure, we use the curve of Fig. 8(b) in which all opacity measurements for α particles are normalized by direct multiplication so that the value for relativistic α particles corresponds to the alpha circle given in this figure. By the use of this standard curve, each normalized opacity can be used to determine directly the value of x, or of β, and therefore the range or energy of the α particle under consideration.