Cosmic-Ray Hydrogen and Helium Nuclei during a Solar Quiet Time in July 1961

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The energy spectra of low-energy primary cosmic-ray hydrogen and helium nuclei have been determined from nuclear emulsions flown on a high-altitude balloon launched from Forth Churchill on 8 July 1961. The flight was preceded by a period of three months of low solar and geophysical activity. The results indicated that the differential spectrum of hydrogen nuclei in this low-energy interval decreased toward low energies and did not exhibit the sharp rise found with counters in 1960 and 1961 by other experimenters. The low-energy differential spectrum and integral flux value for helium nuclei were found to be intermediate between those typical of solar minimum and solar maximum and are consistent with a modulation mechanism which yields the same rigidity spectrum for a given intensity both before and after solar maximum. Various modulation models of galactic cosmic rays are examined, and it is concluded that none of them seem to be entirely adequate.

I. INTRODUCTION

THE intensity of the cosmic radiation detected at the earth is subject to a modulation that shows a strong inverse correlation to the eleven-year cycle of solar activity.[1,2] The changes in intensity over the solar cycle are most pronounced for particles of low magnetic rigidity, and it is data from these particles which should yield the most useful information concerning the mechanism of the modulation. In particular, a comparison of the energy or rigidity spectra of particles which have different rigidities for the same velocity, such as hydrogen and helium nuclei, must provide rigid restrictions on any proposed modulating mechanism.

During the period from 1955 to 1960 McDonald and Webber[3–6] made a series of measurements of the proton rigidity spectrum using Čerenkov-scintillation counter telescopes flown on balloons. These spectra were measured between the rigidity of the geomagnetic threshold of the individual balloon flights and about 1.5 BV. In addition the integral flux above 1.5 BV was determined. Although the work of Quenby and Wenk[7] predicts thresholds of 0.7 to 1.3 BV for the different individual balloon flights at high latitudes, the true threshold may be lower and may not be sharp. For these reasons, the lower end of the observed spectrum is difficult to interpret in terms of the spectrum in free space.

During a longer period which overlaps that of these measurements, the low-energy helium nuclei have been examined by many observers using nuclear emulsions.[8–16] In some instances the air cutoff rigidity, typically 0.7 BV for He nuclei, was higher than the geomagnetic threshold, and in almost every case, data were available to about 2.5 BV and sometimes to 4.5 BV. Additional information is provided by the results of Winckler and Anderson[17] and Neher[18] at northern latitudes in 1954 and 1955 which indicate a higher intensity of low rigidity particles at solar minimum than that which would be deduced by extrapolating the results of McDonald and Webber to lower rigidity. There is then the possibility of an additional increase in the proton flux below about 0.5 BV rigidity during solar minimum.

The following conclusions can be drawn from these results. (a) The intensities of the hydrogen and helium nuclei above about 0.7 BV decrease appreciably from

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[2] W. R. Webber, *Progress in Elementary Particle and Cosmic Ray Physics* (Interscience Publishers, Inc., New York, 1962), Vol. VI.

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[14] G. R. Stevenson, Nuovo Cimento **24**, 557 (1962).

[15] G. R. Stevenson and C. J. Waddington, Phil. Mag. **6**, 517 (1961).

[16] C. J. Waddington, Phil. Mag. **45**, 1312 (1954).

[17] J. R. Winckler and K. A. Anderson, Phys. Rev. **108**, 48 (1957).

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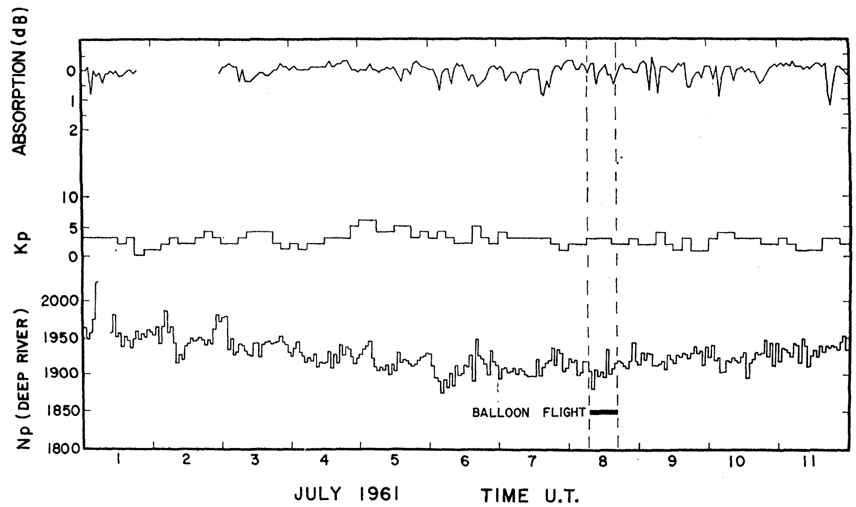

FIG. 1. Geophysical data during early July 1961. From top to bottom are shown absorption of 30-Mc/sec riometer, Fort Churchill; magnetic Kp index; and neutron monitor counting rate, Deep River.

solar minimum to solar maximum. (b) If the degree of transparency in the penumbral region is assumed to depend only on rigidity, these nuclei appear to have similar differential rigidity spectra with a hydrogen to helium nuclei ratio of about 7.0 at least for rigidities above about 1 BV. (c) The helium nuclei, and, if (b) is correct, the hydrogen nuclei also, have a differential rigidity spectrum with a peak intensity at about 1.8 BV at solar minimum and about 2.2 BV at solar maximum.

Because of the present uncertainty of the shapes of the low end of the rigidity spectra at solar minimum, it is important as solar minimum is again approached to study these spectra with instruments flown at high altitude and latitude that are capable of directly detecting and identifying primary particles. Vogt[19] and Meyer and Vogt[20] have made such measurements for protons in 1960 and 1961. At times which they associate with quiet day conditions, they found differential proton spectra that increased toward lower rigidities in a range from 0.38 to 0.63 BV. Furthermore, they found that in 1961 the intensity in this rigidity range had decreased from that observed in 1960. If these low rigidity protons are of galactic origin, one might expect an increase in the intensity as solar minimum is approached and the modulation weakens. The observed spectral shape would also impose an extremely severe constraint on the modulation mechanism. Meyer and Vogt, therefore, suggest that these low-energy protons are mostly of solar origin.

The data reported here are from a time when the sun was comparatively quiet and had been so for several months. It is of interest to compare these proton data with those of Vogt[19] and Meyer and Vogt[20] to see how the low-energy proton component varies with time. Also, in principle, a comparison of the rigidity spectra of the hydrogen and helium nuclei would show whether the apparently similar spectra observed by McDonald and Webber at higher rigidities continues down into this low rigidity region. The results of this latter comparison are ambiguous, however, because the presence of any solar injected particles will alter the abundance ratio. Finally, for the helium nuclei it is important to determine, by comparison with the previously published data how the spectrum varies, since this information will place restrictions on the modulation mechanism.

II. EXPERIMENTAL DETAILS

A. Balloon Flight

The balloon flight on 8 July 1961, was made at a time of low solar activity preceded by a period of three months during which no significant Forbush decreases or polar cap absorption events were observed. The last solar particle event detected by riometers preceding the flight was that on 21 November 1960. Figure 1 shows the cosmic noise absorption of the Churchill 30-Mc/sec riometer,[21] the counting rate of the Deep River neutron monitor,[22] and the geomagnetic 3-h range indices[23] K_p for the early part of July 1961. As can be seen, there were no signs of unusual activity prior to the flight nor after the flight until the solar particle event of 11 July. It would appear, then, that the particle intensities obtained from this balloon flight are truly indicative of undisturbed conditions appropriate to this period of the solar cycle.

The balloon flight path was essentially straight west from Fort Churchill and was at all times at a latitude where the air "cutoff" energy was considerably greater than the geomagnetic threshold for both protons and α particles. The balloon altitude profile is shown in Fig.

[19] R. Vogt, Phys. Rev. **125**, 366 (1962).
[20] P. Meyer and R. Vogt, Phys. Rev. **129**, 2275 (1963).

[21] The data from which this absorption curve was deduced were provided through the courtesy of Dr. T. R. Hartz and Dr. E. L. Vogan of the Canadian Defense Research Telecommunications Establishment.
[22] H. Carmichael (private communication).
[23] J. V. Lincoln, J. Geophys. Res. **66**, 3949 (1961).

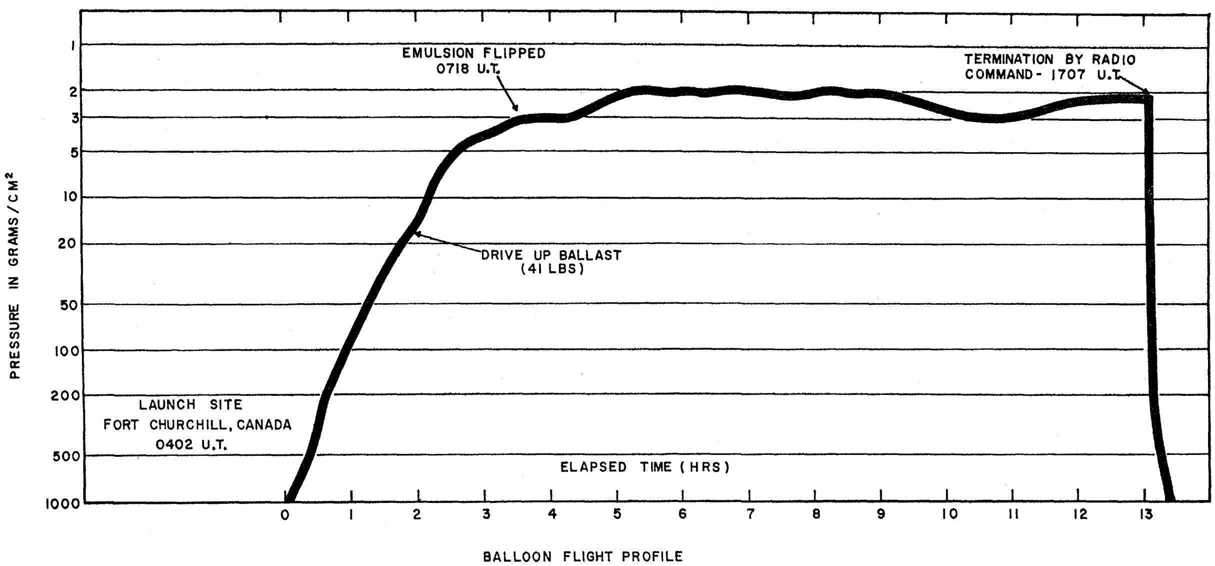

FIG. 2. Balloon flight profile.

2. The pressure below 20 g/cm² was measured to within ± 0.1 g/cm² by photographing a Wallace and Tiernan (0–20 mm Hg) gauge.

The detector consisted of a large stack of 20-cm $\times$10-cm$\times$600-μ-thick Ilford emulsions of various sensitivities, of which 20 at one end were electron sensitive G5 emulsions. This stack was rotated through 180° at the ceiling altitude, and a supplementary emulsion package, the drop stack, intended to be used for the ascent correction, was released at the same time. This stack was unfortunately not recovered, and in its place drop stacks from a balloon flight at Sioux Falls, South Dakota, on 5 December 1961, and a balloon flight at Fort Churchill on 4 August 1962 were used for portions of the ascent correction.

B. Proton Analysis

The emulsions used in the proton analysis were the 20 G5 emulsions from the main flight stack and G5 emulsions from the Sioux Falls and Churchill drop stacks. Five different scans were made: (1) 1 cm from the top edge of the Churchill main stack, (2) 1 cm from the bottom edge of the main stack, (3) 1 cm from the bottom edge of the Sioux Falls drop stack, (4) 0.2 cm from the top edge of the main stack, and (5) 0.2 cm from the bottom edge of the Churchill drop stack. The top of the main stack faced the top of the atmosphere after rotation and faced the earth prior to rotation. The bottoms of the drop stacks faced the earth, and hence were oriented in the same way as the top of the main stack during balloon ascent. The scans were made to include tracks that lay within a pre-set solid angle. In no case did the zenith angle exceed 32°. Tracks with all grain densities were accepted in the first three scans while only those with grain densities ≥ 3 times the proton minimum were accepted in the last two.

Tracks from the first three scans were selected for subsequent analysis if they had an ionization greater than 1.8 times the proton minimum. Tracks due to mesons, tracks (except those which ended) which could not be followed out of the scan plate (and hence were produced before the stack was assembled), and tracks of multiply charged particles were rejected. The remaining tracks, which were due to singly charged particles, were followed in both directions from the scan line until they ended, interacted, or left the stack, and their direction of motion was determined, if possible. The energy at the scan line of each particle that did not end in the stack was determined by making blob-gap counts of the ionization,[24] and using a calibrated relation between these counts and the proton residual range. Each ionization estimate had a precision of about 5%.

The tracks from the scan 1 cm from the top of the main stack fall into three classes: (I) tracks of particles whose direction of motion was toward the bottom of the stack and which did not arise from an interaction in the emulsion between the scan line and the blackened edge of the emulsion, (II) tracks of particles whose direction of motion was toward the bottom of the stack but which originated in an interaction between the scan line and the blackened edge of the emulsion, and (III) tracks of particles whose direction of motion was toward the top of the stack.

In addition to true primary particle tracks which traversed the residual atmosphere above the balloon and entered the top of the emulsion stack while it was at the ceiling altitude, class I includes tracks of particles which

[24] P. H. Fowler and D. H. Perkins, Phil. Mag. 46, 587 (1955).

entered the stack from underneath during the balloon ascent while the stack was inverted, tracks which were formed on the ground after the stack was assembled and before and after it was flown, and tracks of particles which were produced in interactions between the blackened edge of the emulsion at the top of the stack and top of the atmosphere.

The corrections for that portion of the ascent up to a residual atmosphere of 4.5 g/cm^2 and for tracks formed in the stack before and after the flight were made directly from the scans in the Sioux Falls drop stack. The ascent between 4.5 g/cm^2 and 3.5 g/cm^2 was not covered by the drop stack, and the correction for this contribution was made from the scans at the bottom of the main stack. While the balloon was rising from 4.5 g/cm^2 to 3.5 g/cm^2, where the stack was rotated 180°, the top of the stack was looking toward the ground and particles which entered the stack at that time were produced in interactions below the stack. This, however, is the same component that was seen by the bottom of the stack for the remainder of the flight, after the stack rotation, when the balloon was at only a slightly higher altitude. Since the intensities for the bottom of the stack are very similar to those found from the top of the stack scan, and since the correction is small, one can approximate the correction sufficiently well by merely multiplying the bottom of the stack intensity corrected for ascent by a factor which is the fraction of time from 4.5 g/cm^2 to 3.5 g/cm^2 before stack rotation divided by the total flight time from 4.5 g/cm^2 to cutdown.

The remaining correction, that for particles from interactions in the atmosphere above the balloon and in the blackened edge of the emulsion, was made using the tracks from interactions observed in the emulsion above the scan line. It was assumed that the energy spectrum of secondary grey track[25] particles is the same for interactions with air nuclei as for interactions with emulsion nuclei. The internuclear cascade calculations of Metropolis *et al.*[26,27] and Bertini[28] show that this is a reasonable assumption in the range of secondary particle energies considered here. The energy lost by a particle in the amount of emulsion in which these interactions above the scan line are observed was almost identical to that lost in the amount of air above the balloon. Hence, the energy spectrum, but not the intensity, of these particles at the scan line is the same as the spectrum at the top of the stack produced by interactions in the residual atmosphere above the balloon. Once the intensity of this secondary component has been determined, as described below, the pseudospectrum of the particles arising from observed interactions in emulsion with energies corrected from the scan line through an amount of air equivalent to the amount of air above the balloon at ceiling and with the intensity normalized can be subtracted from the spectrum of particles of class I, corrected for ascent, and with energies corrected to the top of the atmosphere to yield the true primary spectrum.

The ratio of the intensity of particles from interactions in the atmosphere plus the obscured edge of the emulsion to that from observed interactions in the emulsion is given by the following equation:

$$S=\left(\frac{N_{ga}}{N_{ge}}\right)\left(\frac{n_{pa}+I_{pa}f_a n_{\alpha a}}{n_{pe}+I_{pa}f_e n_{\alpha e}}\right)+\left(\frac{x_{eu}}{x_{e0}}\right), \quad (1)$$

where N_{ga}/N_{ge} is the ratio of the number of grey track secondaries per interaction in air nuclei to that in emulsion nuclei; n_{pa} and n_{pe}, the number of interactions per incident proton in air and in emulsion for this experiment; $n_{\alpha a}$ and $n_{\alpha e}$ the same, but for α particles; $I_{p\alpha}=0.133$, the ratio of the primary alpha intensity to the primary proton intensity; f_a and f_e the ratios of grey track secondaries from proton interactions to that from alpha-particle interactions in air and in emulsion, and X_{eu} and X_{e0} are the depths of emulsion in which interactions were obscured by edge blackening and in which they were observed, respectively. The various values of n_{ij}, the number of interactions per incident particle are given by $n_{ij}=1-\exp(-x_j/\lambda_{ij})$, where x_j is the absorber thickness and λ_{ij} is the interaction mean free path. The values of λ_{ij} used here are $\lambda_{pa}=100$ g/cm^2, $\lambda_{\alpha a}=45$ g/cm^2, $\lambda_{pe}=38$ cm, and $\lambda_{\alpha e}=19.3$ cm.

The most uncertain parameters are the ratio N_{ga}/N_{ge}, f_a and f_e. There is very little experimental information available from which the ratio N_{ga}/N_{ge} can be determined.

Metropolis *et al.*[26,27] from a Monte Carlo calculation on internuclear cascades have obtained extensive data on the secondary cascade nucleons emitted in the bombardment of a number of target elements ranging from aluminum to uranium with incident protons in the range of incident proton energies from 82 MeV to 1.8 BeV. Bertini[28] has recently completed a similar calculation including elements down to carbon and incident proton energies up to 400 MeV. The curves of average number of cascade protons per interaction versus atomic number of the target nucleus of these two calculations are similar in shape and the results of Bertini indicate that the average number of cascade protons per interaction of Metropolis *et al.* can be reasonably extrapolated to air nuclei.

The value of N_{ga}/N_{ge} can be found from these data by summing the average number of cascade protons per interaction as a function of incident proton energy for air nuclei and emulsion nuclei over the cosmic-ray proton spectrum. The result of this calculation was $N_{ga}/N_{ge}=0.85$, and this is the value which was used in the calculation of S. Though this result is sensitive to the shape

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[25] A grey track is conventionally defined as one with an ionization that is greater than 1.4 or 1.5, and less than 6 times the proton minimum.

[26] N. Metropolis, R. Bivins, M. Storm, A. Turkevich, J. M. Miller, and G. Friedlander, Phys. Rev. **110**, 185 (1958).

[27] N. Metropolis, R. Bivins, M. Storm, J. M. Miller, G. Friedlander, and A. Turkevich, Phys. Rev. **110**, 204 (1958).

[28] H. W. Bertini (private communication).

of the curve of average number of cascade nucleons versus atomic number, it is not sensitive to the absolute number of cascade protons per interaction, because it is a ratio.

A rough experimental estimate of N_{ga}/N_{ge} can be obtained from emulsion data by comparing the number of grey track secondaries for interactions characterized by $N_h \leq 7$ with the number of grey track secondaries from all interactions in emulsion[29] Lock *et al.*[30] studying interactions of 950-MeV incident protons in emulsion find that within limited statistics the number of grey plus shower particles is independent of N_h. Though this result was quoted for interactions on heavy nuclei only, the method of separation into interactions on heavy nuclei and on light nuclei was biased in such a way that almost no interactions with $N_h \leq 3$ were classified as interactions on light nuclei. However, Brown[31] studying star prong distributions in a nitrogen-filled cloud chamber at mountain altitude, found that most of these interactions had $N_h \leq 3$. Further, since the separation of Lock *et al.* excluded only 10% of the total number of interactions from being heavy nuclei, one could reasonably apply their result to all interactions in emulsion. Assuming then the interactions with $N_h \leq 7$ to represent air nuclei and that the average numbers of grey and shower particles are individually independent of N_h, the data of Lock *et al.* would indicate that $N_{ga}/N_{ge} \simeq 1$ for 950-MeV incident protons. This is completely consistent with the value deduced from the cascade calculations of Metropolis *et al.* The results of Beliakov *et al.*[32] and Zhdanov *et al.*[33] from interactions of 9-BeV protons in emulsion indicate a ratio of $N_{ga}/N_{ge} \simeq 0.5$. This result is consistent with an extrapolation of the data of Metropolis *et al.* to higher energy.

The values of f_a and f_e are not known, but are probably close to unity as evidenced by the fact that the average value of N_h for interactions in emulsion produced even by incident nuclei with $Z \geq 20$ is only 8.3 as compared with 8.0 for proton-induced interactions.[34] The values chosen here were $f_a = f_e = 1$.

Tracks in the scan 0.2 cm from the top of the main stack were followed to a distance of 1 cm from the top of the stack and only tracks which ended were accepted.

[29] N_h is conventionally defined as the number of secondary tracks from an interaction which have an ionization ≥ 1.4 times the proton minimum.

[30] W. O. Lock, P. V. March, and R. McKeague, Proc. Roy. Soc. (London) **231**, 368 (1955).

[31] W. W. Brown, Phys. Rev. **93**, 528 (1954).

[32] V. Beliakov, Van Shu-fen', V. Glagolev, Dalkhazhav, L. Kirillova, P. Markov, R. Lebedev, K. Tolstov, E. Tsyganov, M. Shafranova, Jao Tsyng-se, B. Bannik, G. Bajatjan, I. Gramenitskij, M. Danysz, N. Kostanashvili, V. Lyubimov, A. Nomofilov, M. Podgoretskij, E. Skshipchak, D. Tuvdendorge, O. Shahulashvili, N. Bogachev, S. Bunyatov, T. Vishki, Yu-Merekov, and V. Sidorov, Proc. 1958 Annual Conf. on High Energy Phys. at CERN, 309 (1958).

[33] G. B. Zhdanov, V. M. Maksinenko, M. I. Tret'Yakova, and M. N. Shcherbakova, Zh. Eksperim. i Teor. Fiz. **37**, 620 (1959) [translation: Soviet Phys.—JETP **10**, 442 (1960)].

[34] C. J. Waddington, Phil. Mag. **5**, 311 (1960).

TABLE I. Differential hydrogen nuclei fluxes. All intensities are in particles/m² sr sec MeV.

Energy interval at top of atmosphere (MeV)	59–74	80–160	160–250
Uncorrected intensity	1.40±0.36	0.77±0.12	0.81±0.11
Intensity corrected for ascent	0.98±0.39	0.63±0.15	0.69±0.14
Intensity at top of atmosphere (corrected for ascent and for secondary production in the atmosphere above the balloon)	0±0.5	0.34±0.17	0.50±0.16

These tracks were those of protons with energies between 59 and 74 MeV at the top of the atmosphere. The same corrections were required as for the scans at greater depth in the emulsion and were made in the same way. The ascent correction was made using the scans 0.2 cm from the bottom edge of the 1962 Churchill drop stack emulsions and the scans at the bottom of the main Churchill flight stack, and the secondary contributions from interactions above the stack were calculated from the tracks from observed interactions above the scan line found in scan 1.

The differential fluxes of hydrogen nuclei are shown in Table I. The uncorrected intensity and the intensity corrected for ascent alone are also given in order to show the magnitude of the corrections which are made to the raw data. The uncertainty in the ratio N_{ga}/N_e is not included in the listed error. No attempt was made to separate deuterons or tritons, and all of the energies calculated at the top of the atmosphere assume that the particles are protons.

C. He-Particle Data Reduction

In order to obtain the basic data for the helium nuclei, Ilford G5 nuclear emulsion plates from that part of the stack where the G5 plates were interleaved with G2 plates were scanned along a line parallel to the top edge of the stack for all tracks above a minimum grain density within a specified solid angle. In addition to a set of scans to determine the integral intensity and low-energy end of the energy spectrum, additional scans were performed specifically to obtain more information on the low-energy helium nuclei so that the modulation phenomenon could be studied with greater statistical accuracy. In both instances, the minimum grain density to be accepted in the initial scan was set about three standard deviations below the lowest value to be used in the analysis. The usual scanning efficiency checks[35,36] such as comparing the distribution of the numbers of tracks found as a function of the zenith angle, the dip angle, the depth in the emulsion, and grain density with the expected distributions and rescanning of about 30% of the total area by a second scanner were performed. In

[35] C. J. Waddington, Nuovo Cimento Suppl. **19**, 37 (1961).

[36] C. E. Fichtel, Nuovo Cimento **12**, Suppl. **19**, 1100 (1961).

addition, the finally accepted solid angle was reduced from the original one set for scanning in order to avoid possible scanning loss near the limits even though none seemed to be present. With these precautions, the maximum correction for scanning loss was only 2%. All tracks coming from interactions above the scan line were rejected.

The helium nuclei were separated from singly and multiply charged nuclei by visual observation of the scattering and grain density or by measurement of these quantities if necessary. The energy of the helium nucleus which produced the track was then determined from the range of the particle in the stack if it ended, or from its ionization in a G2 emulsion if it did not. The ionization curve was determined in three different ways. For all tracks, a calibration was obtained by a comparison with the energy determined from multiple scattering measurements at high energies and range at low energies. In measuring the mean angle of deflection, the sagitta method[37] was employed with the noise elimination procedure of Menon *et al.*,[38] and the scattering constants calculated by Fichtel and Friedlander.[39] In addition, 30% of tracks with energies less than about 600 MeV/nucleon were analyzed by the method developed by Freier *et al.*[40] wherein it is assumed on the basis of theoretical considerations that the ionization is only a function of Z^2/β^n in the region of interest, namely, from 100 to 600 MeV/nucleon. A good fit for the set of data considered for protons and helium nuclei was obtained for $n=1.75$. The remaining 70% of the tracks were analyzed by assuming the Fowler-Perkins ionization curve[24] for protons multiplied by Z^2 and corrected for saturation, held for helium nuclei over the same energy region. Good agreement was obtained with the energies estimated from scattering data. In both cases it was noted that helium nuclei with appreciably higher energies, energies/nucleon $\gtrsim 1$ BeV, seemed to have a higher grain density than would have been predicted.

All helium nuclei whose grain density indicated that they might stop in the stack[41]; i.e., whose energy was less than about 200 MeV/nucleon, were followed until they stopped, interacted, or did leave the stack. In general, in addition to having a better estimate of the energy for particles with energies less than 200 MeV/nucleon, their direction was also known. This fact aids in the analysis to be described below.

In the whole of this calculation it has been assumed that the particles were He^4 nuclei. This assumption is based on the small percentage, $\sim 20\%$, of He^3 observed in the experiments of Hildebrand *et al.*,[42] and Foster and Mulvey.[43] The experimental effect on the differential energy spectrum produced by as much as 50% of He^3 incorrectly identified as He^4, has been investigated by Waddington[44] and shown to be small, although the astrophysical significance of a large percentage of He^3 may be very great.[45] Furthermore energies determined from ionization depend only on the charge and the only error made is in the correction for energy loss to the top of the atmosphere.

TABLE II. Integral helium particle flux as a function of kinetic energy/nucleon.

Kinetic energy/nucleon (MeV)	Integral flux in particles/(m² sr sec)
65.5	207.6±11.3
100	205.0±11.2
200	197.7±11.2
300	187.7±11.1
400	173.8±11.1
500	158.9±10.8
600	151.2±10.6

In order to calculate the intensity and the differential energy spectrum, a smooth trial function which consisted of the He-particle density divided by an estimated effective exposure time was assumed. The shape of this trial function after passing through various amounts of atmosphere was constructed from range energy tables[41] and then reduced in magnitude in accordance with the combined effects of the absorption by interaction of He-particles and the production of He-particles by heavy nuclei interactions in the air. The mean free paths and fragmentation parameters for emulsion and air were those listed in the review article by Waddington.[46] The secondary helium nuclei were assumed to have the same energy spectrum as the primary particles and the effect of the different rate of energy loss of the heavy primary parents was ignored since secondary helium nuclei formed in the air and the emulsions amount to only a few percent of the total and changes in the energy spectrum from the above considerations are small and uncertain.

In principle, the total contribution to the particle density by the trial function can then be calculated by integrating the appropriate energy spectrum at a given point and angle over the entire solid angle of acceptance for the known orientation of the stack at that time and then integrating over the entire flight. In practice, these integrals were approximated by sums consisting of average values within periods. The ascent was broken into steps and the floating altitude was divided into the short por-

[37] P. B. Fowler, Phil. Mag. **41**, 169 (1950).

[38] M. G. K. Menon, C. O'Ceallaigh, and O. Rochat, Phil. Mag. **49**, 932 (1951).

[39] C. E. Fichtel and M. W. Friedlander, Nuovo Cimento **10**, 1032 (1958).

[40] P. S. Freier, E. P. Ney, and C. J. Waddington, Phys. Rev. **114**, 365 (1959).

[41] J. H. Atkinson, Jr., and B. H. Willis, University of California Laboratory Report No. UCRL 2426, Revision II (unpublished).

[42] B. Hildebrand, F. W. O'Dell, M. M. Shapiro, R. Silberberg, and B. Stiller, Bull. Am. Phys. Soc. **7**, 311 (1962).

[43] F. Foster and J. H. Mulvey, Nuovo Cimento **27**, 93 (1963).

[44] C. J. Waddington, Proc. of XIXth Varenna Summer School (1961).

[45] M. V. K. Appa Rao and M. F. Kaplon, Nuovo Cimento **21**, 369 (1961).

[46] C. J. Waddington, Progr. Nucl. Phys. **8**, 3 (1960).

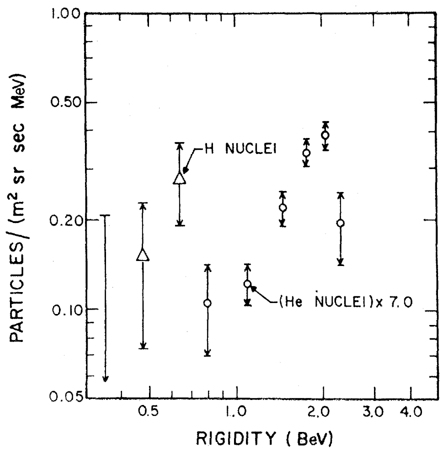

FIG. 3. Differential rigidity spectra for hydrogen nuclei, and helium nuclei times 7.0.

tion when the stack was still inverted and the portion when it was upright. For particles whose energy was less than 200 MeV/nucleon, only the last portion was included since the particle direction for these low-energy particles was known and particles whose direction was opposite to the downward one at ceiling were rejected. The resulting particle density in units of particles/(cm^2 sr) was then compared with the observed particle density. On the basis of this result, a better estimate of the primary spectrum, or in essence the effective time, was made. The second trial function fitted the observed data. Both the particle densities and the flux values are given in Table II, and the differential spectrum is plotted in Fig. 3 along with the proton data.

III. COMPARISON WITH OTHER RESULTS

Before discussing the implications of the experimental results with regard to the time variations of cosmic rays and specific modulation mechanisms, the experimental results will be compared with those obtained at other times in the solar cycle. The combined picture will then give a better basis for comparison with any particular theory.

A. Hydrogen Nuclei

In Fig. 4 the differential energy spectrum is plotted together with the results of Vogt[18] and Meyer and Vogt[19] from balloon flights at Fort Churchill on 22 August 1960; 15 September 1960; and 8 August 1961, and the Explorer XII results of Bryant *et al.*[47] on 18 August 1961. The lowest energy point of Bryant *et al.* has a somewhat greater uncertainty than that shown because of calibration changes. This point is currently being recalculated.[48] At energies above about 150 MeV the differential proton flux values are seen to be approximately the same for each measurement. However, at lower energies there exists a marked difference between the data obtained by Meyer and Vogt and the present work. Whereas Meyer and Vogt observe a definite increase in the differential intensity at lower energy both in 1960 and 1961, the pretent data indicate a decrease. At least in the case of the 1961 flights, the difference in intensity in the energy inserval from approximately 80 to 160 MeV may possibly be largely explained in terms of the different corrections used for secondary production in the atmosphere above the balloon. If the method of correction used in this work is applied to the Meyer and Vogt[20] raw data, a differential flux of 0.59 ± 0.10 particles/m^2 sr sec is obtained rather than their value of 0.82 ± 0.05 particles/m^2 sr sec, whereas this work gives 0.34 ± 0.17 particles/m^2 sr sec. When the correction used by Meyer and Vogt is compared to that of this work, it is seen that the major difference is the absolute number of secondary grey tracks assumed to be produced on the average by cosmic ray particles in a nuclear emulsion and not the conversion from interactions in nuclear emulsions to those in air. Meyer and Vogt's estimate of the number of grey secondaries in air is about a factor of 1.7 smaller than the one of this work. This correction used here is based on direct measurements made on secondary cosmic-ray particles formed in the same emulsions from which the flight data was obtained. Meyer and Vogt[19] used the previous calculations of Vogt[19,49] which are based on the analysis of area scans for stars in nuclear emulsions flown at lower altitudes and the extrapolation of these results to the top of the atmosphere. A combination of factors, such as statistical fluctuations, uncertainties in extrapolation, the possible low detection efficiency for one- and two-prong stars by the area scanning method, and small differences in other factors, may combine to account for the discrepancy.

Another possible contribution to the difference in in-

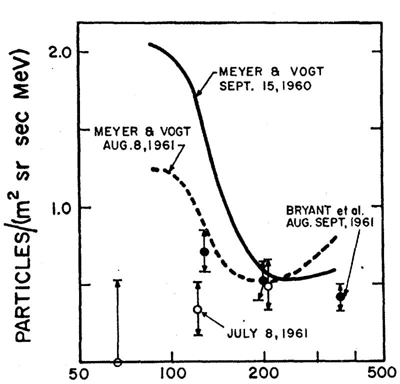

FIG. 4. Differential energy spectra for hydrogen nuclei measured at various times.

[47] D. A. Bryant, T. L. Cline, V. D. Desai, and F. B. McDonald, J. Geophys. Res. **67**, 4983 (1962).

[48] F. B. McDonald (private communication).

[49] R. Vogt, thesis, The University of Chicago, 1961 (unpublished).

tensities is the fact that, although the flights of Meyer and Vogt considered here were not made immediately following a known injection of solar particles and are considered by them to be typical of a quiet day, they were flown at times during which the sun was quite active. The flight on 22 August 1960 was flown after a large Forbush decrease following a probable solar particle event on 11 August,[50] and the flight on 15 September 1960 was flown during the recovery phase of a Forbush decrease following the solar particle event of 3 September 1960. The flights in August 1961 were also flown during the recovery phase of a Forbush decrease and following the series of large solar particle events of 11–26 July. It might then be said that, while these flights were not flown when known injections of solar particles were in progress, they were flown either at times when such injections were likely to occur, or when it was possible that some of the radiation from a previous solar particle event was still trapped in a region of the solar system containing the earth.

The flight reported here, on the other hand, was flown at a time that was much less disturbed as indicated in Sec. IIA. These data do not conflict, then, with the results of Meyer and Vogt, but rather, they are a measurement of the spectrum of hydrogen nuclei at a time of much lower solar activity.

The question remains whether or not the low-energy spectrum measured in this experiment represents the galactic cosmic-ray protons during this time in the solar cycle or whether there is a contribution of solar particles even during this period of a very quiet sun. The question cannot be unambiguously answered without further measurements as solar minimum is approached, if even then. If the intensity is observed to decrease, it would indicate that at least a portion, if not all, of these low-energy protons are probably of solar origin. If the intensity is observed to increase with the approach to solar minimum, it is possible, although not necessarily true, that the spectrum represents the modulated galactic cosmic-ray proton intensity.

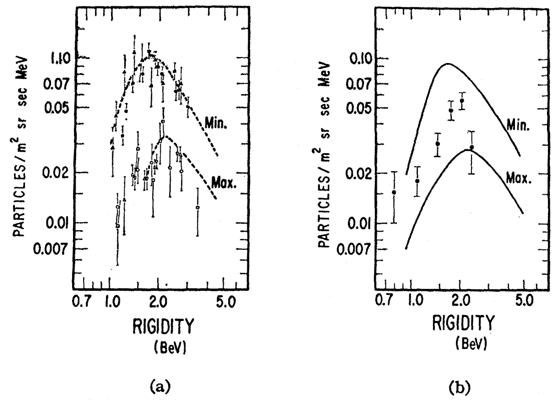

FIG. 6(a). Differential spectra of helium nuclei at solar maximum and solar minimum. ▲ Ref. 13, ■ Ref. 4, ● Ref. 4, ▽ Ref. 4, △ Ref. 4, ○ Ref. 10, □ Ref. 8, ---Ref. 6. (b) Data from the flight of 8 July 1961, compared with curves 6(a).

B. Helium Nuclei

Webber[2] has compared the variation in the He-particle intensity above 1.5 BV, 260 MeV/nucleon, with the Mt. Washington neutron monitor rate during the period when the cosmic-ray intensity declined from its maximum value to its lowest values, specifically the years 1954 to 1959, and shown that there is a unique relation between these two parameters. As Webber has noted, the total He flux varies at a rate of 2.1 to 3 times as fast as the neutron monitor counting rate, as expected since the neutron monitor rate reflects primarily the variations in the flux of high-rigidity particles, which vary less than the flux of low-rigidity particles. Webber's smooth curve is shown in Fig. 5 along with the experimental result of this work. This figure shows that the experimental data of this work were obtained at a time between maximum and minimum intensity, and that the flux observed falls on this smooth curve which was determined from data taken during the decline of the cosmic-ray flux. A similar analysis by Stevenson and Waddington[15] of the relation between the α-particle flux, $J_\alpha{}^0$ above 200 MeV/N and the Ottawa neutron monitor hourly rate N showed that the data were best fitted by a quadratic of the form.

$$J_\alpha{}^0-189=-(13.4\pm9.9)+(N-285)(2.48\pm0.41)+(N-285)^2(0.043\pm0.0024).$$

At the time of this flight N was 291.0 counts/h (scaling factor 64), which predicts $J_\alpha{}^0=192\pm10$ particles/cm² sr sec and compares well with the value of 198 ± 11 found in this experiment. Therefore, since the neutron monitor rate is a measure of the high-energy intensity, this result suggests that during the period of increasing cosmic-ray intensity the ratio of low-rigidity particles to high-ri-

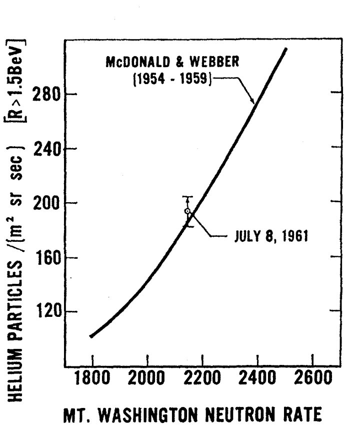

FIG. 5. Counting rate of Mount Washington neutron monitor versus helium nuclei flux.

[50] J. B. Gregory, J. Geophys. Res. 68, 3097 (1963).

gidity ones at a given intensity is the same as during the declining phase.

Having examined the coarse features of the variation, the detailed differential energy spectrum is now compared with those observed at solar maximum and minimum. The results of experiments during these two periods are shown in Fig. 6(a). From these data smooth curves are then drawn in Fig. 6(b) and compared with the results of the present experiment. The values of this experiment are seen to lie between the spectra typical of solar minimum and maximum. In addition, the peak in the spectrum appears to have moved to a rigidity intermediate between the peak rigidities during the other two periods.

This result, together with the earlier figures showing helium particle intensity as a function of neutron monitor counting rate, supports the hypothesis that the recovery of the differential intensity is continuous over the whole rigidity range, that is, there is no tendency for the high- or low-rigidity particles to recover preferentially.

C. Modulation of Cosmic Rays

A large number of theories attempting to describe the modulation of cosmic rays have been developed in recent years. We shall discuss here only those known to us which have been developed quantitatively and for which there is at least partial agreement with experimental results. A summary of modulation models has recently been made by Webber,[2] and the reader is referred to this article and the references contained therein for a more complete discussion.

Nagashima[51] originally suggested that the modulation of the primary cosmic radiation could be explained by the positive cosmic-ray particles having to pass through a geocentric decelerating static electric potential, which then could vary throughout the solar cycle, while Ehmert[52] has considered the effect of a heliocentric potential. By Liouville's theorem, the quantity $(dj/dP)/p^2\beta$, and hence $(dj/dW)/p^2$, must remain constant for a set of particles. Here, j is the particle flux, p the particle momentum, and β the particle velocity. Hence, for a decelerating potential V, the following expression can be obtained for a particle of charge Ze and atomic number A:

$$\left.\frac{dJ}{dW'}\right]_{[W-ZeV/A]}=\left.\frac{dJ}{dW'}\right]_{[W]}\left[\frac{(W-ZeV/A)^2-M_0C^2}{W^2-M_0C^2}\right],$$

where W is the total energy per nucleon before deceleration and M_0C^2 is the rest mass per nucleon. Hence, if the energy of the particle decreases, dj/dW will decrease also by an amount which increases with decreasing energy. McDonald and Webber[3] and Fichtel[36] have shown previously that reasonable agreement can be obtained with experimental data for helium and heavy nuclei. Ehmert[52] has shown that if a potential of about 1 BeV exists at sunspot minimum, the peak in the differential spectrum even at that time can be explained.

[51] K. Nagashima, J. Geomag. and Geoelec. 3, 100 (1951).
[52] A. Ehmert, Proc. Moscow Cosmic Ray Conf. **IV**, 142 (1960).

The presence of a quasistatic electric field sufficiently large to cause the observed reduction in intensity seems inconsistent with the present estimates of the physical conditions existing in the solar system, particularly the high conductivity, and the low abundance or absence of energetic electrons which would have been accelerated by the electric field. In addition, McDonald[4] and McDonald and Webber[53] have shown that to within experimental errors, when measurements were made on the helium and proton components at about 1.3-BV rigidity the intensities were reduced by the same proportion between solar minimum and maximum. For a given rigidity, the electric deceleration model predicts that helium nuclei should be more suppressed than protons because their charge-to-mass ratio is half that of the protons.

In this experiment an extrapolation of the α-particle spectrum would suggest a splitting in the rigidity spectra of the proton and helium nuclei components in a manner consistent with a decelerating model; however, in view of the physical implausibility of such a model, and the previous work of McDonald and Webber it seems reasonable to look for another explanation. Obviously the presence of additional solar protons would provide an explanation for the observed splitting.

Parker[54,55] has proposed a diffusion model, wherein the solar wind, a flow of gas consisting of a distorted magnetized plasma whose existence was first deduced by Biermann[56,57] is considered to be responsible for the modulation. In this theory, an equilibrium state is established wherein both the effects of diffusion through the shell and removal by convection are considered. He obtains an equation of the form

$$dJ/dR=(dJ/dR_{(\infty)})[\exp-\{K(t)/(\beta\lambda)\}],$$

where λ is proportion to R^2 if the average dimension of the scattering clouds is much smaller than the radius of curvature and is a constant if the average dimension is much larger than the radius of curvature.

As in the case of the electric deceleration model and other diffusion models, the modulation at a given rigidity is different for particles with different charge to mass ratios because β appears, and therefore, the comments made previously concerning relevant experimental results apply here also. Further, it seems difficult to find a reasonable choice of parameters and a reasonable dJ/dR_∞ which will yield an expression which agrees with both the helium and the hydrogen nuclei spectral data for λ either a constant or proportional to R^2.

[53] F. B. McDonald and W. R. Webber, *Proceedings of the First International Space Science Symposium, Nice* (North-Holland Publishing Company, Amsterdam 1960), p. 968.
[54] E. N. Parker, Phys. Rev. **109**, 1874 (1958).
[55] E. N. Parker, Phys. Rev. **110**, 1445 (1958).
[56] L. Biermann, Z. Astrophys. **29**, 274 (1951).
[57] L. Biermann, Observatory **77**, 109 (1957).

The modulation of the cosmic radiation by a dipole field of the sun was first proposed by Janossy.[58] In order to be effective the dipole moment of the sun needs to be about 10^{34} G cm^3, and hence a polar field of about 30 G should exist. The actual general solar field has an intensity of about 1 G at the poles[59] and, in fact, seems to go through zero at sunspot maximum[60] when the depression of the cosmic-ray intensity is greatest.

Elliott[61] tried to overcome this difficulty by suggesting that large current systems exist in the corona at a distance between 5 and 15 solar radii from the sun and that these ring currents should produce a dipole field at the earth's orbit and beyond. This ordered field should often be disturbed by plasma streams from the sun. These perturbations scatter particles into orbits which then enter a disordered field region around the sun, resulting in absorption of particles which reduces the intensity in the forbidden regions. This theory predicts a rigidity dependence of the modulation which can be brought into satisfactory agreement with experimental rigidity spectra by suitable adjustment of the parameters. There are, however, at least two experimental measurements which are apparently in conflict with this model. Firstly, measurement of the magnetic field at distances up to 32 earth radii from the earth by Explorer X[62] show that during "quiet" periods the field direction is apparently not that of a dipole. Secondly, the lack of any detectable variation in the radiation between the earth and Venus, as measured on Mariner II,[62] is inconsistent with the variation of about 30% predicted by Elliot.[63]

[58] L. Janossy, Z. Physik **104**, 430 (1937).
[59] H. D. Babcock, Astrophys. J. **130**, 364 (1959).
[60] H. D. Babcock, Astrophys. J. **133**, 572 (1961).
[61] H. Elliot, Phil. Mag. **5**, 601 (1960).
[62] H. R. Anderson, Science **139**, 42 (1963).
[63] H. Elliot, Nature **186**, 299 (1960).

IV. SUMMARY

The helium-particle data shows that during the recovery phase of the cosmic-ray modulation cycle the differential helium rigidity spectrum lies in between that at solar maximum and solar minimum. Further, a comparison of the relation of the integral helium flux and neutron monitor counting rate with those during the declining phase of cosmic-ray intensity, namely, from solar minimum to solar maximum, indicated that the functional dependence was the same. Therefore, there was good reason to believe that the modulation mechanism produced the same rigidity dependence both during the declining and recovery phase.

Because there is apparently a decrease in the proton flux in the vicinity of 0.5-BV rigidity with decreasing solar activity, whereas the proton flux above 1.0 BV shows an inverse correlation with solar activity, it seems likely that there was a non-negligible solar proton component at 0.5-BV rigidity at least during the two flights of Vogt[19] in 1960. Considering the proton and helium nuclei data of this work together, it seems that either there is a modulation mechanism wherein the relative depression of the protons with respect to the helium nuclei is nearly the same at 1.3-BV rigidity, but is markedly different at 0.5 BV, or there is a small solar proton component. The possibility of a significant solar contribution seems less likely because the proton differential flux in this work shows no increase with decreasing energy whereas a leveling off and an increase might be expected if there were an appreciable solar component. Further, none of the low-energy differential flux values of Meyer and Vogt[20] are below those of this experiment, even if the correction used in this work is applied to their data. Data from subsequent years should help to answer this question.