Čerenkov Scintillation Counter Measurements Relating to the Isotopic Composition of Helium Nuclei in the Primary Cosmic Radiation

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A balloon-borne scintillation-scintillation Čerenkov telescope has been used to measure the spectrum and geomagnetic cutoff-transmission effects on the low-energy proton and helium components in the primary cosmic radiation. Differences are found in the cutoff effects (assumed to be rigidity-dependent) of these two components in flights at closely adjacent latitudes. It is shown that these differences can be related to the presence of He^3 in the primary radiation. The ratio (He^3/He^3+He^4) is deduced to be 0.30 ± 0.07, essentially independent of energy in the range 120–300 MeV/nucleon. This result is compared with other measurements and some implications regarding the production of the He^3 nuclei are discussed.

THE measurement of the relative abundance of He^3 and He^4 in the primary cosmic radiation has recently received considerable attention. This information, together with other astrophysical data, can give important evidence regarding the origin of the cosmic radiation and its propagation in space.

The results of a number of recent emulsion determinations of the ratio $R=He^3/(He^3+He^4)$ have given values ranging from 0.06 to 0.40 on an energy-per-nucleon basis[1–5] (Table I). Because of the rather wide differences, these measurements have not yet led to a consistent picture for the origin of the He^3 nuclei. The identification of the He^3 and He^4 nuclei presents a formidable problem in emulsions, and even with painstaking analysis of two parameters such as scattering and ionization loss, the resolution of these two isotopes is marginal. Because of these difficulties in analysis, the measurements have essentially been restricted to a single point value of R in the energy range from 160–360 MeV/nucleon or in an equivalent rigidity range.

It seems worthwhile to attack this problem from a somewhat different point of view using counter techniques. This makes use of the fact that He^3 and He^4 nuclei of the same (measured) energy/nucleon have different rigidities. Using the earth's magnetic field as a magnetic analyzer then, it should be possible by comparing the geomagnetic cutoff effects of the primary singly charged component (assumed to be predominately protons at the energies under consideration) with that of the doubly charged component to (1) determine any differences and (2) relate these differences to the isotopic composition of the doubly charged (helium) component.

We shall present results obtained on three balloon flights at different latitudes using a telescope consisting of a scintillation counter and a combination Čerenkov-scintillation counter which leads us to a value of $R\sim0.30$ sensibly constant with energy/nucleon in the range 120–300 MeV/nucleon.

This detector is a modification of the Čerenkov scintillation counter telescope used in the earlier part of this solar cycle by McDonald[6] and McDonald and Webber[7] to measure the low-energy portion of the primary spectrum for protons and helium nuclei. The physical arrangement of detector elements in the telescope is shown in Fig. 1. The telescope has a solid angle area of 70 sr cm^2 and is capable of high resolution of the protons in the range 30 MeV–1 BeV and helium nuclei in the range 30 MeV/nucleon—2 BeV/nucleon. A particular feature of the detector is its low background of unwanted counts, partly caused by a minimum of material in the telescope geometry (<1.5 g/cm^2) and partly because of the unique display characteristics of

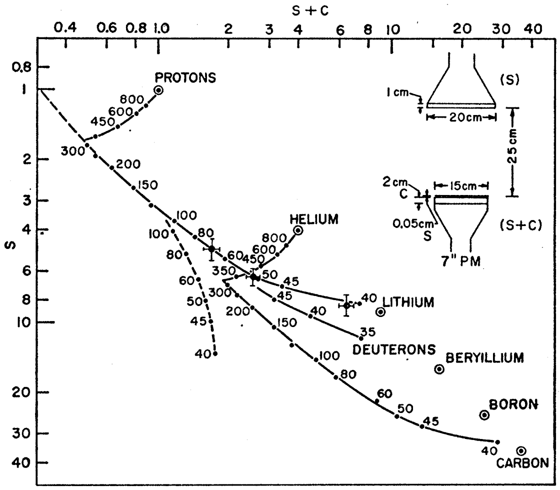

FIG. 1. Response of the Čerenkov scintillator to protons and helium nuclei of various energies/nucleon. Insert shows the outline of the telescope. Measured response for protons of 68, 50, and 38 MeV are shown. Backward-moving particles shown by dashed curve.

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[2] M. M. Shapiro, B. Hildebrand, F. W. O'Dell, R. Silberberg, and B. Stiller, *Space Research III, Proceedings of the Third International Space Science Symposium, Washington, D. C.* (North-Holland Publishing Company, Amsterdam, 1962), p. 1097.
[3] F. Foster and J. H. Mulvey, Nuovo Cimento **27**, 93 (1963).
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TABLE I. Measurements of helium isotopes in the primary cosmic radiation.

Reference	Location	Lat	Date	Alt. (g/cm^2)	Energy range (MeV/nucleon)	Ratio $(He^3)/(He^3+He^4)$
1	Minneapolis	55°	6-30-57	8.5	200–400	0.38±0.09
1	Neepawa	61°	8-3-58	3.8	160–355	0.31±0.08
2	Minneapolis	55°	4-21-61	3.8	250–360	0.06±0.03
3	Neepawa	61°	8-3-58	3.8	160–350	0.15±0.05
4	Souix Falls	53.5°	9-4-59	2.0	155–320	0.10±0.05
5	Churchill	70°	8-4-62	...	160–370	0.20±0.06
	These data			6.0	120–300	0.30±0.10

the S, $S+C$ combination that is used. In the lower or $S+C$ detector the sum of the light outputs of a 2-cm-thick Lucite Čerenkov radiator and 0.5-mm-thick plastic scintillator are viewed by a 7-in. photomultiplier tube. The thicknesses of these elements are adjusted to give a suitable ratio of scintillator to Čerenkov light, the so called S/C ratio. The optimum ratio for the best resolution of the different charges, and for discrimination against upward-moving albedo was chosen to be 0.4 for minimum ionizing particles. (The top of the plastic scintillator is painted black.) With this ratio the theoretical response of the telescope to particles of different charge, energy and direction is shown in Fig. 1.

Thus this telescope is seen to have many of the advantages of a double-scintillation Čerenkov detector along with some advantages that even this detector does not have, particularly in the measurement of protons and helium nuclei lying below the Čerenkov threshold.

The response of the detector to low-energy protons has been calibrated using the University of Minnesota linac operating at 40 and 68 MeV. These points along with others obtained by inserting absorbers in the beam are shown in Fig. 1. The predicted and observed energy losses (or more correctly, light outputs) relative to those of minimum-ionizing particles are seen to agree within 10% up to energy losses ~10 times that for a minimum-ionizing particle. Thus the proper operation of the $S+C$ detector is checked at low energies, and the nonlinearities between energy loss and light output, which are known to occur at high-energy losses in plastic scintillators are seen to be unobservable out to at least 10 times minimum.

Since possible nonlinearities in the energy-loss light output for the plastic scintillators is one of the most important of the conceivable reasons for observing differences in the relative geomagnetic cutoff effects for protons and helium nuclei we shall return to a discussion of this point after presenting our data.

The results we wish to discuss were obtained on balloon flights made at Minneapolis, Devils Lake, and Churchill (cutoff rigidities 1.35, 1.12, and 0.13 BV, respectively[8]) during the summer of 1963. The counting rates of high-latitude neutron monitors at the times of the three flights differed by <2% suggesting that primary intensity variations are not an important factor in the analysis. All flights attained altitudes of 5–7 g/cm² of residual atmosphere. The counting rates of protons and helium nuclei were such that statistical uncertainties affected only the very lowest energy points, the other differential points being limited by systematic analysis errors and believed correct to ±5%.

The spectra of primary protons and helium nuclei obtained in these flights have already been presented.[9] The spectra of primary protons obtained at the three locations are shown in Fig. 2. The spectra of primary helium nuclei are shown in Fig. 3. The true primary differential spectra for protons and helium nuclei are represented by the Churchill data. Both of these spectra are decreasing sharply at the lowest energies measured. If the helium-nuclei spectrum is multiplied by a factor of 6.7 to adequately normalize it to the protons in the rigidity range 1.5–20 BV, then a distinct splitting of the two spectra is observed at low rigidities.

The effect of the geomagnetic cutoff is clearly observed in the spectra of both protons and helium nuclei obtained at Devils Lake and Minneapolis. The fact that

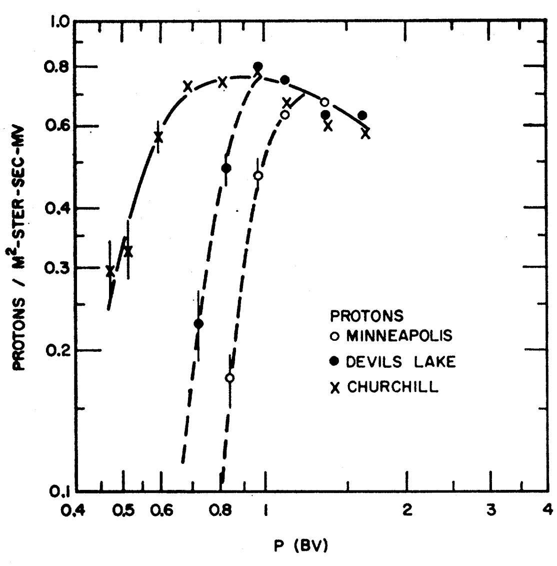

FIG. 2. Differential intensities of primary protons observed at three locations in 1963. P is the particle rigidity in BV.

[8] J. J. Quenby and G. J. Wenk, Phil. Mag. 7, 1457 (1962).

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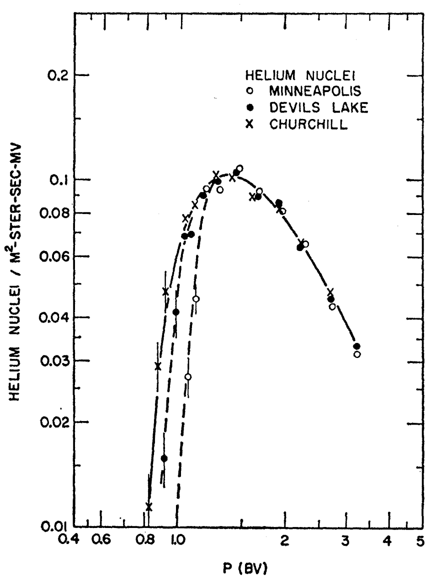

FIG. 3. Differential intensities of primary helium nuclei observed at three locations in 1963. P is the particle rigidity in BV.

this cutoff is not sharp has been demonstrated previously and can be reasonably well understood at these latitudes on the basis of the usual Störmer theory of particle motion in the earth's field.[10] In particular, we know of no "transmission" effects through the earth's field that would affect protons and helium nuclei of the same rigidity differently.

The proton spectra measured at Devils Lake and Minneapolis begin to deviate from that obtained at Churchill at 1.2 and 1.0 BV, respectively. Representing the cutoff by a particle transmission factor $T \sim e^{-P/P_0}$ gives $P_0 = 120$ MV at Minneapolis and 110 MV at Devils Lake. The spectra of helium nuclei measured at Devils Lake and Minneapolis begin to deviate from that obtained at Churchill at 1.5 and 1.25 BV, respectively, and show much larger values of P_0. In order to put these differences on a more quantitative basis and allow for the fact that the proton-to-helium-nuclei ratio is changing at low energies, we have taken the ratios of differential intensities measured at Minneapolis and Devils Lake to that at Churchill. These results are presented in Figs. 4(a) and 4(b). This figure clearly shows the differences in the geomagnetic cutoff for protons and helium nuclei at both locations. We have examined carefully all the instrumental or analysis effects that might cause this difference (including the effects of nonlinearity of energy loss versus light output in the plastic scintillators). None of these effects can cause more than $\sim 10\%$ of the observed difference.

Let us examine the effects of the energy-loss light-output nonlinearity in the plastic scintillators more closely. We regard this as the most likely cause for any differences between the measured cutoff effects of the proton and helium components in the primary radiation. A good review of the nonlinearity problem in organic scintillators is to be found by Brooks.[11] Using data presented in this article we would expect the nonlinearity effects to result in $\sim 10\%$ less light output than expected for singly charged particles of $10\times$ minimum specific ionization loss. This effect increases so that a saturation light output $\sim 50\times$ that of minimum-ionizing particles occurs for energy losses $> 100\times$ minimum. Our results up to a dE/dx of $10\times$ minimum for protons in plastic scintillators are in agreement with these data.

For nuclei with $Z > 2$ the data presented in the above reference are meager. However, results on the light output of relativisitic helium nuclei and heavier nuclei up to a charge, $Z = 26$ also observed in our detectors have a direct bearing on this problem. Careful calibration of our detectors with light sources shows that the minimum-ionizing nuclei identified as carbon nuclei that we observe at balloon altitudes give light pulses $(16 \pm 2)\times$ those for minimum ionizing protons. For O nuclei this is 29 ± 3, for Ne nuclei 44 ± 4 and for Fe nuclei this value is 72 ± 5. The saturation effects thus observed for relativistic heavier nuclei reproduce those for protons given by Brooks up to specific energy losses of $\sim 600\times$ those of minimum-ionizing protons. This data on the nonlinearity of light output in plastic scintillators for heavy nuclei will be discussed in a future publication. With it we can internally calibrate our detector directly in terms of energy loss provided we can clearly identify the pulse heights that are due to the heavier nuclei at minimum ionization. This can be done, we believe, quite unambiguously in the range up to $Z \sim 14$; dE/dx of $200\times$ minimum ionization for protons.

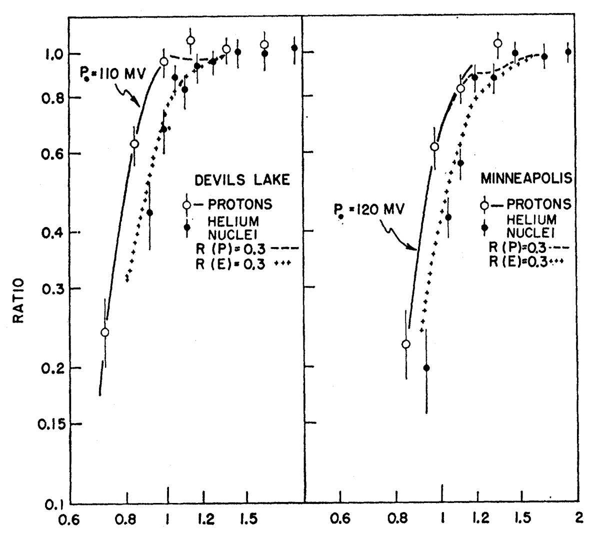

FIG. 4. (a) and (b). Ratios of measured proton and helium nuclei intensities at Devils Lake and Minneapolis, respectively, to those at Churchill. Calculated ratios for dependences of R on energy/nucleon $R(E)$ and rigidity $R(P)$ are also shown.

[10] W. R. Webber and F. B. McDonald, J. Geophys. Res. **69**, 3097 (1964).

[11] F. D. Brooks, Progr. Nucl. Phys. **5**, 252 (1956).

For the helium nuclei for which cutoff effects are important, the range of energy loss is between (7–15)× that for minimum-ionizing protons. In this range, using the curves presented by Brooks and verified by us as applicable for heavier nuclei in plastic scintillators, the maximum nonlinearity in light output for protons is ~12%. Assuming that our helium-nuclei energies are inferred incorrectly because of such a nonlinearity, we may correct the helium spectrum. The changes thus calculated (which are regarded as an upper limit since we believe the system can be correctly calibrated internally) are in any case quite small and comparable to the statistical uncertainties and therefore we believe this effect is not the cause of the observed difference in cutoffs. That such a systematic compression of the apparent scale of dE/dx resulting from nonlinearities in light output does not materially change the spectrum is a result of two compensating effects. If we take a region with n counts, originally identified with the energy interval ΔE at E then correctly these counts should be identified in an interval ΔE_c at E_c. Now E_c will be less than E, and ΔE_c will be greater than ΔE as a result of the light output nonlinearity. Thus for a differential spectrum falling towards lower energies of the type observed, the change in ΔE will tend to compensate the change in E leaving the corrected spectrum only slightly different than that derived without the correction.

The only remaining alternative seems to be now to assume that the difference in cutoff effects between protons and helium nuclei is due to the presence of He^3 nuclei. If this is done we can calculate the shape of the measured helium cutoff relative to that of protons under the assumptions that (1) the transmission factor is the same for protons and the different isotopes of helium of the same rigidity (2) R is constant as a function of energy/nucleon $R(E)$, and (3) R is a constant as a function of rigidity $R(P)$. The results are shown in Figs. 4(a) and 4(b). Notice that for a value of R constant with rigidity, the differences in the measured cutoffs for protons and helium nuclei are small for the value of $R(P)=0.3$ used in the calculation. The difference is not large even for values of $R(P)$ approaching one (corresponding to all He^3 at low rigidities). This is a direct consequence of the steeply falling helium spectrum below 1 BV and the fact that for the same kinetic energy/nucleon, He^3 has a lower rigidity than He^4. Our measurements give a best value of $R=0.30\pm0.07$ constant with energy over the range 120–300 MeV/nucleon, although we cannot exclude the possibility that there is a slight increase in $R(E)$ with decreasing energy.

It appears that it should be possible in a series of flights to use the geomagnetic cutoff over the range 0.8–2.0 BV to measure the spectrum of He^3 nuclei from 100–800 MeV/nucleon.

Our results further suggest that the values of R of 0.38, 0.06, and 0.10 reported in Refs. 1, 2, and 4, respectively, may not represent the ratio of primary He^3 and He^4 outside of the earth's magnetic field in equivalent energy/nucleon intervals. These measurements were made at 55° (Minneapolis) and 53.5° (Sioux Falls) geomagnetic latitude, respectively, and as a consequence of the energy intervals over which R was obtained, the He^3 nuclei would be partially cut off relative to the He^4 nuclei if the geomagnetic cutoff had the values and transmission characteristics suggested by our measurements at the time of the above determinations.

The remaining measurements in Table I are directly comparable with ours since they are made at locations where He^3 is not cut off by the earth's field and also cover approximately the same energy/nucleon range. They give values of R from 0.15 to 0.31, and all results seem to be consistent with a value ~0.20–0.30. Assuming He^3 is absent from cosmic-ray sources, the above ratio suggests a path length in interstellar hydrogen of from 5–10 g/cm^2, depending upon the diffusion model and fragmentation cross sections chosen. The best estimates of the ratio of the light (Li, Be, B) to all heavier nuclei at the top of the atmosphere of[12] 0.21±0.05 (above 1.5 BeV/nucleon) gives a path length of only 3–4 g/cm^2. There is some evidence, however, that this ratio is ~0.35–0.45 at energies comparable to those at which the helium isotope ratio is obtained.[13,14] This corresponds to a path length of 5–8 g/cm^2 at these energies and points to a consistent interpretation of the secondary origin for both the He^3 and light nuclei at these energies. It also strongly suggests a common mechanism for the increase in path length with decreasing energy that is apparently observed.

The fragmentation hypothesis for the origin of He^3 nuclei is further strengthened by our measurement that the value of R is more nearly a constant as a function of energy/nucleon than rigidity. Calculations on the expected dependence of R if He^3 were all due to collision in interstellar hydrogen (mainly resulting from He^4 collisions), and neglecting any other process or energy gain or loss, suggest that energy/nucleon is the basic quantity rather than rigidity.[15] In fact these calculations show that R should remain approximately constant down to ~200 MeV/nucleon slowly increasing at lower energies and becoming a factor of 2 larger at ~60 MeV/nucleon. This is a result of the increasing cross section for the production of He^3.

Our results are not capable of clearly discerning such an increase, although as noted before, they do give some suggestion that it occurs. We hope to examine this point further and other details of the He^3 component in subsequent flights.

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