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Isotopic Composition of the Low-Energy Helium Nuclei in the Primary Cosmic Radiation*

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The isotopic composition of low-energy helium nuclei in the primary cosmic radiation has been determined by using the "constant sagitta" scattering method on tracks of helium nuclei stopping in a nuclear-emulsion stack flown at a geomagnetic latitude $\lambda=55°$N and at a mean atmospheric depth of 8.5 g/cm^2; tracks with zenith angles less than 30° were accepted. The ratio of $He^3/(He^3+He^4)$ for the same energy per nucleon (between 200 and 400 Mev) is found to be 0.41 ± 0.09 at flight altitude. The correction for production of secondary He^3 in the residual atmosphere is calculated to be 4%. If one assumes that no He^3 nuclei are present at the source, the observed ratio corresponds to a traversal of 14 ± 3 g of interstellar matter by the low-energy helium nuclei. The value of $He^3/(He^3+He^4)$ corresponding to the same magnetic rigidity (between 1.3 and 1.6 Bv) is found to be 0.36 ± 0.11 which corresponds to a traversal of 12.2 ± 3.5 g of interstellar matter. The observed ratio may indicate the presence of He^3 at the source of cosmic rays, or may be a reflection of local production within the solar system.

1. INTRODUCTION

THE chemical composition of cosmic radiation as observed at the earth gives us information about the relative abundance of elements at the source together with the history of the traversal of cosmic radiation through interstellar space. In particular, as has been pointed out by Bradt and Peters,[1,2] the abundance of the elements Li, Be, and B is of importance. These elements have a negligibly low abundance in the universe compared to other elements[3]; as such, any cosmic-ray source will presumably have a low abundance of Li, Be, and B and any amount of these elements observed at the earth should be residues from collisions of elements of higher charge with the hydrogen of the interstellar space. Thus, a knowledge of the abundance of the light elements Li, Be, and B in the cosmic radiation, together with a knowledge of the probabilities of production of these residues in collisions of elements of higher charge with protons, gives a measure of the average amount of interstellar matter traversed by cosmic rays since their injection into the interstellar medium.

Many experiments have been performed to determine the abundance of Li, Be, B in comparison with the elements C, N, O, and F. However, due to the long time of exposure of the apparatus needed to observe sufficient numbers of these nuclei, and due to inherent limitations of balloon techniques, one is forced to observe these elements under a finite amount of residual atmosphere. Thus, besides the low statistical accuracy of these measurements and the difficulties in identification of the charge, one has the problem of correcting these observations for the finite production of the light elements in collisions of elements of higher charge with nuclei of the residual atmosphere. After a controversy over the past 10 years, during which time values of the ratio of Li, Be, and B to C, N, O, F at the top of the atmosphere varying from 0 to 1 were claimed, experimenters at present seem to be converging to a ratio of 0.25 (at the geomagnetic latitude $\lambda=41°$) with an uncertainty of about 0.1. In view of these difficulties, one seeks other ways of determining the amount of interstellar matter traversed by cosmic rays, where one is not beset with the above problems.

Several authors[4,5] have suggested the measurement of the abundance of helium 3 nuclei as compared to helium 4 nuclei. Present astronomical knowledge about the presence or absence of He^3 in the atmosphere of stars and in interstellar matter is extremely meager, although present opinion is that it is probably present in negligible quantities in most stars. (This point will be discussed later.) If we assume that He^3 does not exist at the source of cosmic rays, as with the Li, Be, and B, the determination of the abundance of He^3 gives us again a measure of the interstellar matter traversed by cosmic rays. It will be shown later that this measurement has the advantage that the correction for secondary production of He^3 in collisions of He^4 and other heavy nuclei with the nuclei of the residual atmosphere is negligible. However, the observation of He^3 in cosmic rays is interesting by itself.

2. EXPERIMENTAL DETAILS

(i) *The cosmic ray stack.* The nuclear-emulsion stack used in this experiment was exposed to cosmic rays by means of a stratospheric balloon launched from Minneapolis, Minnesota (geomagnetic latitude 55°N) on July 30, 1957. This stack is the same in which the energy

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[1] H. L. Bradt and B. Peters, Phys. Rev. **77**, 54 (1950).

[2] H. L. Bradt and B. Peters, Phys. Rev. **80**, 943 (1950).

[3] H. E. Suess and H. C. Urey, Revs. Modern Phys. **28**, 53 (1956).

[4] S. F. Singer, *Progress in Cosmic-Ray and Elementary Particle Physics* (North-Holland Publishing Company, Amsterdam, The Netherlands, 1958), Vol. 4, and references therein.

[5] B. Hildebrand (private communication to Dr. E. M. Hafner).

spectra of helium[6] and nuclei of higher charges[7] have been determined. The ratio of (Li,Be,B)/(C,N,O,F) with energies greater than 1 Bev/nucleon has also been determined in reference 7. The flight curve is given in reference 6. The plane of the emulsions was held horizontal until after the balloon had reached its floating altitude and then rotated through 90° such that it became vertical. The effective collection time for cosmic-ray tracks was 8 hr, 51 min, with the average amount of air above the stack being 8.5 g/cm^2. To this must be added approximately 0.3 g/cm^2 for the packing material and the $\frac{1}{4}$-in. Fiberglas dome in which the emulsions and the rotating mechanism where housed. The trajectory of the balloon was almost straight west from Minneapolis and deviated from the latitude of the launch site by less than half a degree.

The emulsion stack consisted of 150 Ilford G5 nuclear emulsions, 30 cm×25 cm and 400-μ thick. They were exposed with the 25-cm edge horizontal. They were developed in the usual way.

(ii) *Scanning procedure.* A line scan was performed in each plate one cm from the top edge and the scan was adjusted such that a track with the accepted zenith angle of 30° had a potential range of 30 cm. Tracks with grain density of 5.4 times minimum and having a length >5 mm in the scanned plate are accepted. The grain density of 5.4 times minimum corresponds to that of He^4 nuclei with a residual range ~30 cm. Only tracks with range >4.5 cm were used in this experiment.

(iii) *Method of identification.* All the stopping tracks obtained in the scan were first grain counted in the scan plate. The grain densities are plotted against the residual range; this graph is displayed in Fig. 1. As can be seen, the doubly charged particles group at upper right are clearly differentiated from the singly charged particles. The solid line corresponds to a triton; a triton would fall closest on such a plot to the doubly-charged group.

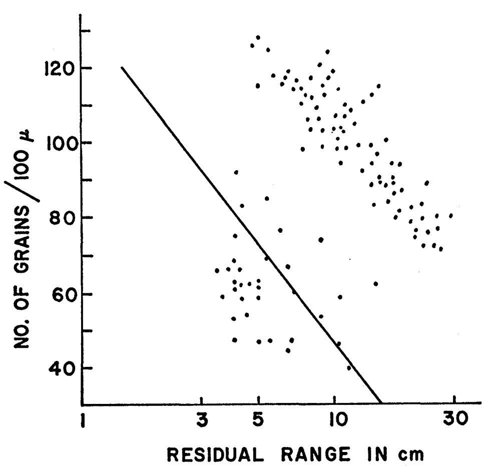

FIG. 1. Plot of grain density vs residual range for cosmic-ray particles obtained with the criteria mentioned in the text. The group at upper right corresponds to doubly-charged particles. The solid line corresponds to a triton.

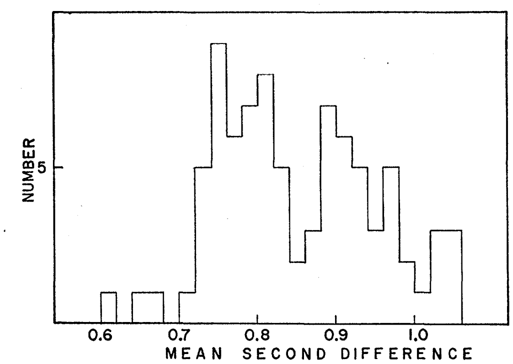

FIG. 2. Plot of the scattering parameter $\bar{D}_2$ vs number for cosmic-ray alpha particles.

The stopping doubly charged particles are subjected to the constant sagitta-scattering method.[8] The scattering scheme was made to obtain an average second difference $\bar{D}_2=0.75\ \mu$ for He^4, assuming a scattering constant $K=27.0$[9] and using the range-energy curves of Willis and Stableford[10] and Atkinson and Willis.[11] This corresponds to $\bar{D}_2=0.85\ \mu$ for He^3 as obtained from the usual formula,[12]

$$\bar{D}_2=0.00348KR^{-0.58}Z^{-0.16}M^{-0.42}t^{\frac{3}{2}},$$

where K is the scattering constant, R is the residual range, Z is the charge, M the mass, and t the cell length. This formula assumes the nonrelativistic approximation $p\beta=2E$; if we use the correct relativistic relation, for the present scattering scheme, $\bar{D}_2=0.88\ \mu$ for He^3. The $\bar{D}_2$ for measured tracks is obtained first by computing the average third difference $\bar{D}_3$, during which all D_3 values greater than $4\bar{D}_3$ are replaced by $4\bar{D}_3$, and then reducing $\bar{D}_3$ by the usual factor of $(\frac{2}{3})^{\frac{1}{2}}$ and also by the "adjustment factor"[13] of 0.94.

(iv) *The machine stack.* For calibration purposes, a stack of 25 pellicles of G-5 emulsions 20 cm×10 cm ×600 μ was exposed to the 925-Mev alpha particles (He^4) accelerated by the synchrocyclotron at Berkeley, California,[14] with the 20 cm side parallel to the beam.

[6] A. Engler, M. F. Kaplon, A. Kernan, J. Klarmann, C. E. Fichtel, and M. W. Friedlander, Nuovo cimento (to be published).

[7] C. E. Fichtel, Nuovo cimento (to be published).

[8] Tracks which were steep (length <2 mm/emulsion in the last 1 cm) were not used.

[9] The scattering constant has been measured directly and found to be $K=26.9\pm0.6$ for He^4 and $K=27.3\pm1.3$ for He^3 [M. V. K. Appa Rao and T. Yamanouchi (to be published)].

[10] B. H. Willis and C. V. Stableford, University of California Radiation Laboratory Report UCRL-2426, November, 1956 (unpublished), Vol. I.

[11] J. H. Atkinson and B. H. Willis, University of California Radiation Laboratory Report UCRL-2426, June, 1957 (unpublished), Vol. II.

[12] C. Dilworth, S. J. Goldsack, and L. Hirschberg, Nuovo cimento **11**, 113 (1954).

[13] S. Biswas, E. C. George, and B. Peters, Proc. Indian Acad. Sci. **38A**, 418 (1953).

[14] We thank Dr. Burton J. Moyer, Professor Walter Barkas, and Dr. T. F. Hoang for kindly exposing the stack.

These particles have a range of 13.1 cm, so that all of them which did not interact stopped in the stack.

The scanning procedure in this stack consisted in picking up a track at 1 cm from the entering edge and following it until it stopped or interacted. The tracks which stopped were used for calibration of the constant sagitta method. Tracks with the range of 13.1 cm are due to He^4 of 925 Mev and we call these "normal tracks."

An area scan was also performed for interactions produced by He^4 particles of the incident beam and in which there was a track of nearly the same grain density as the incoming particle and which made an angle less than 20°. This outgoing particle was followed until it stopped. These interactions are the (He nucleus-in)-(He nucleus-out) type of interactions observed earlier.[15] In the present experiment, only those interactions with range of the outgoing helium nucleus track greater than 3 cm, the range necessary for the application of the scattering method, are used.

3. RESULTS

The $\bar{D}_2$ distribution, obtained by the application of the constant sagitta method to 84 stopping cosmic-ray helium nuclei is displayed in Fig. 2; about 110 cells were obtained for each track. It is seen from Fig. 4 that there is a separation of the particles into two groups. In order to make sure of the separation, the constant-sagitta scattering method has been applied to 50 stopping tracks in the 'machine stack' having the normal range of 13.1 cm. The $\bar{D}_2$ distribution is given in Fig. 3. It is seen that only three particles occur with $\bar{D}_2$ beyond 0.85 μ. These could be due to contamination in the beam.

To confirm the separation further, the outgoing tracks in the (He nucleus-in)–(He nucleus-out) interactions are used. It was shown earlier[15] that the outgoing He nucleus from a (He nucleus-in)–(He nucleus-

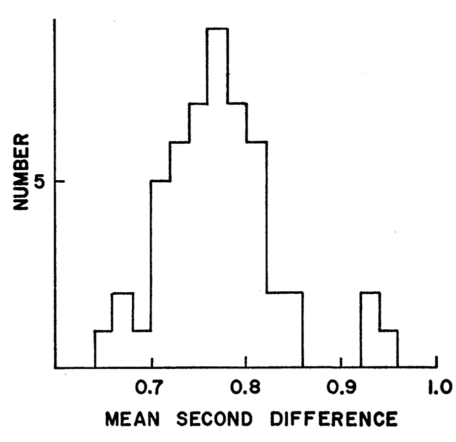

FIG. 3. Plot of the scattering parameter $\bar{D}_2$ vs number for machine-accelerated He^4 nuclei.

[15] M. V. K. Appa Rao, R. R. Daniel, and K. A. Neelakantan, Proc. Indian Acad. Sci. **43**, 181 (1956).

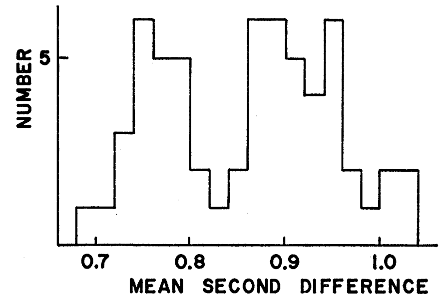

FIG. 4. Plot of the scattering parameter $\bar{D}_2$ vs number for outgoing He nuclei tracks from (He nucleus-in)-(He nucleus-out) interactions.

out) interaction is most probably a He^3 at energies greater than 6 Bev/nucleon. However, at the energies dealt with here, 150–200 Mev/nucleon, there may be some He^4 in the outgoing He nuclei tracks.

The $\bar{D}_2$ distribution obtained by the application of the constant sagitta method to 60 He nuclei tracks coming out of (He nucleus-in)–(He nucleus-out) interactions is displayed in Fig. 4. This distribution clearly shows the separation between the groups and these can be intrepreted as due to He^4 and He^3.

The $\bar{D}_2$ distribution of the "normal tracks" which are tracks due to He^4 particles, and the $\bar{D}_2$ distribution of the "He nucleus-out" tracks, which are a mixture of He^4 and He^3 particles, show that tracks with $\bar{D}_2$ less than 0.85 μ are those due to He^4 particles and those with $\bar{D}_2$ greater than 0.85 μ are those due to He^3 particles. Thus with the cutoff at 0.85 μ, out of the 84 particles there are 46 He^4 and 38 He^3 particles.

The average of the $\bar{D}_2$ of the group of tracks below 0.85 μ is 0.76 μ with an error on the average of ± 0.15, and the average $\bar{D}_2$ of these tracks above 0.85 μ is 0.92 with an error on the average of ± 0.18. The mean $\bar{D}_2$ for He^4 tracks agrees very well with the expected $\bar{D}_2$ of 0.75. However, the average for He^3 tracks seems to be about 2 standard deviations away from the value expected. This fact of course does not affect our analysis, because we have a direct calibration from the 'machine stack'.

However, we have to remember now that we pick up tracks at a certain grain density, and follow the tracks into the stack until they stop. This corresponds to picking up the helium nuclei at the same velocities, which correspond to different total energies for He^4 and He^3. With the same energy/nucleon, He^3 has a shorter range than He^4; but the stack has fixed dimensions. Thus, there is bias against He^4, if one considers energy/nucleon as the criterion, and one has to remove those He^3 corresponding to He^4 which do not stop in the stack in order to get a ratio for the same energy/nucleon. We remove two He^4 with zenith angles larger than 30°, which were included in the histogram of $\bar{D}_2$ distribution. The distribution of the particles is given in Table I. Thus, the ratio He^3/He^4 (correspond-

TABLE I. Breakdown of He^4 and He^3 data into two energy-per-nucleon ranges (see text).

Energy/nucleon in Mev	No. of He^4	No. of He^3
200–400	44	31
400–480	(will not stop in the emulsion stack)	7

ing to 200–400 Mev/nucleon at the top of the atmosphere) is 31/44, and the ratio

$$He^3/(He^3+He^4)=0.41\pm0.09.$$

If one considers the total magnetic rigidity as the criterion, our selection at the same grain density for all helium nuclei corresponds to different rigidities for He^4 and He^3. In fact, we have a bias against He^3 at the high-rigidity end due to the finite dimensions of the stack and we have a bias against He^4 at the low-energy end, since we use only those tracks with total range greater than 4.5 cm. (This corresponds to a total rigidity of 1.25 Bv for He^4.) The breaking up of particles with different magnetic rigidity ranges is shown in Table II. The ratio $He^3/(He^3+He^4)$ for the same magnetic rigidity (between 1.3 and 1.6 Bv) is seen from Table II to be 0.36 ± 0.11.

The total flux of helium nuclei and the energy spectra as observed in this stack may be found in reference 6.

For obtaining the ratio at the top of the atmosphere, we have to calculate the secondary production of He^3 in the residual atmosphere. The interaction mean free paths for He^4 and medium nuclei (C,N,O,F) in air are well known and are $\lambda_{He^4}{}^{(air)}=45$ g/cm^2 and $\lambda_M{}^{(air)}=26.5$ g/cm^2, respectively. The probability of production of He^3 in a single collision of He^4 and an air nucleus $P_{4-3}{}^{(air)}$ is estimated to be 0.1 and the corresponding value for medium nuclei is $P_{M-3}{}^{(air)}=0.5$ (see Appendix). The contribution of nuclei with $Z>10$ to the secondary production of He^3 is negligible (see following section). With the above values, the correction to the ratio $He^3/(He^3+He^4)$ due to secondary production of He^3 within the atmosphere is calculated to be less than 4%. Since the correction is small, in view of our large statistical uncertainty, we do not apply this correction and the value of the ratio of $He^3/(He^3+He^4)$ at the top of the atmosphere is 0.41 ± 0.09 for the same energy/nucleon and the ratio for the same magnetic rigidity range is 0.36 ± 0.11.

TABLE II. Breakdown of He^4 and He^3 data into three rigidity ranges (see text).

Rigidity in Bv	No. of He^4	No. of He^3
0.98–1.3	(we do not pick up due to minimum total range criterion)	22
1.3 –1.6	28	16
1.6 –1.9	16	(will not stop in the emulsion stack)

Calculation of the Interstellar Matter Traversal

We assume that there are no He^3 nuclei at the source of cosmic rays. We also assume that the abundance of medium nuclei at the source is 8% of the abundance of α nuclei.[3,16] The mean free path of He^4 nuclei and medium nuclei in hydrogen are $\lambda_{He^4}{}^{(p)}=14.6$ g/cm^2 and $\lambda_M{}^{(p)}=6$ g/cm^2 (see Appendix). We also have to know the probabilities of production of He^3 in collisions of He^4 nuclei and medium nuclei with hydrogen. However, in these collisions, tritons are also produced; and since the lifetime of tritons is only 12.3 years, we assume that these nuclei decay completely into He^3. Thus, it is sufficient if we know the combined probability of production of H^3 and He^3 in collisions of He^4 and medium nuclei with hydrogen. There is no direct experiment to our knowledge to determine these probabilities for production of H^3 and He^3 in collisions of He^4 with protons $P_{4-3t}{}^{(p)}$, and we obtain this from an experiment in which He^4 is bombarded with neutrons. The correctness of our estimate is seen from other considerations (see Appendix). The values of $P_{4-3t}{}^{(p)}$ and $P_{M-3t}{}^{(p)}$ are taken to be 0.4 and 0.2, respectively. Again, we neglect the contribution due to H-nuclei ($Z\geqslant10$) since their abundance is a third of M nuclei and $P_{H-3t}{}^{(p)}=0.15$.

With the above values of mean free paths and fragmentation probabilities, the values of the ratio $He^3/(He^3+He^4)$ for different values of the amount of interstellar matter traversed, are calculated using the usual solution of the one-dimensional diffusion equation. Figure 5 gives the plot of the ratio $He^3/(He^4+He^3)$ vs the number of grams of hydrogen traveled by the low-energy helium nuclei. The figure also includes the curve obtained from the estimation of Hayakawa, Ito, and Terashima.[16] The number of grams corresponding to the ratio 0.41 ± 0.09 is seen from Fig. 5 to be 14 ± 3 g and the number of grams corresponding to the ratio for the same magnetic rigidity is seen to be 12.2 ± 3.5 g.

Discussion

We do not know at present whether the value of the amount of matter traversed corresponding to the same energy/nucleon is significant or the value corresponding to the same magnetic rigidity is significant, though the expectation is that the latter most probably is. Both the values obtained in this experiment are seen to be much higher than usually expected; however, one must remember that this corresponds to very low energies (200–400 Mev/nucleon). It may be remarked here that there was no unusual solar activity at the time our

[16] S. Hayakawa, K. Ito, and Y. Terashima, Progr. Theoret. Phys. (Kyoto) Suppl. 6, 2 (1958).

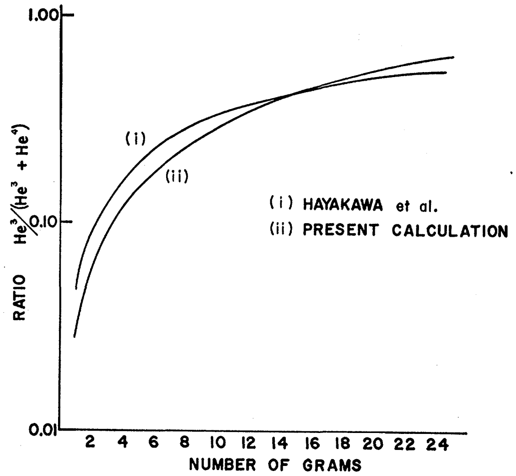

FIG. 5. The growth of the ratio $He^3/(He^3+He^4)$ with the number of grams of interstellar matter traversed by cosmic rays. Curve (i) is the estimation of Hayakawa *et al.*[16] Curve (ii) refers to present calculation.

emulsion stack was exposed to cosmic rays.[17] In contrast to the high value of interstellar matter traversal obtained above, one has the value of 3 ± 1 g obtained from the (Li,Be,B)/(C,N,O,F) ratio corresponding to an average energy of 3 Bev/nucleon. [The uncertainty as given above is due to the controversy in the extrapolation of the observed values of the ratio (Li,Be,B)/(C,N,O,F) to the top of the atmosphere.] From the above data, one can make the following remarks under the assumption that our observations do not represent a strongly time-dependent phenomenon (similar observations are underway on a different exposure at a different time):

(i) The source of cosmic rays may contain a finite abundance of He^3.

(ii) Low-energy nuclei travel through a larger amount of matter than high-energy nuclei.

(iii) Helium nuclei travel through a larger amount of matter than nuclei of higher charges (C, N, O, and F).

We will discuss these three remarks below.

(i) The observation by Greenstein[18] shows that He^3 exists, if at all, with low abundance in the sun (<5%). On the other hand, the possibility of a high abundance is arrived at by Burbidge and Burbidge[19] from the spectroscopic observations of the magnetic star Aquilae 21; these results are somewhat uncertain because it is difficult to estimate the extent of the effect of Stark effect on the isotopic shift observed. Observations thus being meager, the opinion of the astronomers at present is that He^3 most probably does not occur in stars. If the cosmic rays observed at the earth represent an average of the cosmic rays produced by various sources, then, even conceding Burbidge and Burbidge's results, the type of stars named above are not numerous enough to produce the bulk of cosmic rays.

If one assumes that all cosmic rays (H, He, C, N, O, F, etc.) travel through the same amount of interstellar matter, 3 ± 1 g/cm², as obtained from the Li, Be, B results, then the present observation of the $He^3/(He^3+He^4)$ ratio indicates that the abundance of He^3 at the source is about one-half of the abundance of He^4 nuclei.

(ii) This remark seems unlikely, since this would lead to serious consequences regarding the abundance at injection and propagation of nuclei $Z>10$. However, an estimate of the ratio of (Li,Be,B)/(C,N,O,F) at low energies can be made from the data of Tamai[20] who performed his experiment at the geomagnetic latitude $\lambda=55°$N. From the histogram of the charge spectrum given in his paper, one obtains a ratio of (Li,Be,B)/(C,N,O,F)=1.12 under 8.5 g/cm² of atmosphere. Extrapolation to the top of the atomsphere using the fragmentation probabilities of Kaplon *et al.*[21] yields a ratio of (Li,Be,B)/(C,N,O,F)$\sim$1. This corresponds to about 10 g of interstellar matter traversal by cosmic rays. Thus, it is possible that low-energy nuclei travel a larger amount of matter than high-energy nuclei; it may be remarked that if this proposition is accepted seriously, the amount of material traversed seems to be approximately proportional to the inverse of the total momentum.

(iii) This observation seems unlikely in the light of present beliefs, since this would require different sources for helium and medium nuclei. However, if one looks at the low-energy end of the energy spectra of helium and nuclei of higher charges, one finds that the maximum occurs at about the same energy/nucleon.[22] The occurrence of this maximum is tentatively explained as a magnetic effect,[23] even though it is not fully understood. If we interpret this effect as due to 'ionization loss' the occurrence of the maximum at the same energy/nucleon for helium and medium nuclei shows that they must have traveled through different amounts of matter.[24] A similar explanation may be proposed for the dissimilarity of helium and proton spectra below 1 Bv.

However, all the three possibilities mentioned above may operate at the same time to different degrees.

Conclusions

The ratio of $He^3/(He^3+He^4)$ at the top of the atmosphere in cosmic rays for the same energy/nucleon

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[17] We are grateful to Dr. Gordon Newkirk, High Altitude Observatory, Boulder, Colorado, for providing information regarding this point.

[18] J. L. Greenstein, Astrophys. J. **113**, 531 (1952).

[19] E. M. Burbidge and G. R. Burbidge, Astrophys. J. **124**, 655 (1956).

[20] E. Tamai, Phys. Rev. **117**, 1345 (1960).

[21] M. F. Kaplon, J. H. Noon, and G. W. Racette, Phys. Rev. **96**, 1408 (1954).

[22] K. Yokoi (to be published).

[23] S. F. Singer, Suppl. Nuovo cimento **8**, 342 (1958).

[24] M. V. K. Appa Rao (to be published).

(between 200 and 400 Mev) is 0.41 ± 0.09 on July 30, 1957. If we assume that no He^3 exists at the source of cosmic rays, and that our observations represent a steady-state situation, this tells us that low-energy helium nuclei travel through 14 ± 3 g/cm^2 of interstellar matter. The same ratio for the same magnetic rigidity is 0.36 ± 0.11 and it corresponds to 12.2 ± 3.5 g/cm^2 of interstellar matter.

However, in order to draw more definitive conclusions, (i) the abundance of Li, Be, and B should be determined at low energies; (ii) the isotopic composition of helium nuclei should be determined at higher energies; (iii) the abundance of He^3 in stars should be known; (iv) the abundance of tritons in cosmic radiation should be determined to obtain the amount of interstellar matter traversed in the immediate vicinity of the earth and to investigate whether the observed abundance is a "local" phenomenon.

ACKNOWLEDGMENTS

I thank Professor M. F. Kaplon for his continued encouragement throughout the project. I acknowledge the important preliminary work done at this laboratory on this problem by Dr. A. Engler and Dr. A. Kernan. I have been benefited by many useful discussions with Dr. Savedoff, Dr. Helfer, Dr. Hafner, Dr. Fazio, and Dr. Klarmann. Help in some measurements by Dr. Yamanouchi and Mr. Lavakare is deeply appreciated. My thanks are due to Mrs. V. Miller, Mrs. A. Vilks, Mrs. L. Hawrylak, Mrs. A. Izaks, and Mrs. Upelencis for carrying out a difficult scanning job patiently. My special thanks are to Miss Susanna Morin for her noteworthy assistance.

APPENDIX

Our information on the fragmentation probabilities comes mainly from Bailey[25] and Innes.[26]

Innes bombarded neutrons of energy 300 Mev (approximately the same energy in the center of mass corresponding to our α particles) on He^4 in a cloud chamber. He identifies the fragments from various interactions and obtains the cross sections for various processes of which the two processes in which we are interested, viz., $n(He^4,pn)H^3$ and $n(He^4,nn)He^3$, form a part. We invoke charge symmetry, and the two processes above correspond to $p(He^4,np)He^3$ and $p(He^4,pp)H^3$, and then we obtain for the probability for production of He^3 and H^3 in collisions of He^4 with hydrogen, $P_{4-3t}{}^{(p)}=0.4$. An upper limit for this probability can be obtained from the paper by Kozodev *et al.*[27] who bombarded 600-Mev protons on He^4 in a cloud chamber. However, their data are not explicit enough, so that we could only get an upper limit of $P_{4-3t}{}^{(p)}=0.5$. A lower limit can also be set from (α-in)–(α-out) interactions in nuclear emulsions,[12,27] from which $P_{4-3}=0.1$. If we give an equal value for P_{4-t}, we have $P_{4-3t}=0.2$. This is a lower limit, since emulsions contain heavier nuclei.

Bailey bombarded various elements (C, Al, etc.) with protons of energy 190 Mev. He uses a magnetic deflection technique to obtain the mass distribution of the fragments from the target nuclei. He gives cross sections for production of He^3 when protons are bombarded by carbon and aluminum. We calculate the total cross section in these interactions using the formula $\pi r_0^2(A_1^{1/3}+A_2^{1/3})^2$, where A_1 and A_2 are the atomic numbers of the target and incident nuclei, with $r_0=1.2\times10^{-13}$ cm. Using the two cross sections, we obtain $P_{M-3t}{}^{(p)}=0.2$ and $P_{H-3t}{}^{(p)}=0.15$. In contrast, one has the values for the probability of production of He^4 in collisions of M nuclei and H nuclei with hydrogen, $P_{M-4}{}^{(p)}=0.43$ and $P_{H-4}{}^{(p)}=0.78$.

The probabilities $P_{M-3}{}^{(\mathrm{air})}$ and $P_{4-3}{}^{(\mathrm{air})}$ are obtained from observations in nuclear emulsions.[12,28] The value of $P_{4-3}{}^{(\mathrm{air})}=0.1$. The value of $P_{M-\alpha}{}^{(\mathrm{air})}$ is found from the values given by Rajopadhye and Waddington[29] and Kaplon *et al.*[19] to be 1.0. If we assume He^3 and He^4 are equally probable, we obtain $P_{M-3}{}^{(\mathrm{air})}=0.5$. This value is large compared to $P_{M-3}{}^{(p)}$, but can be understood if we recognize that the destruction of a M nucleus is more complete in a collision with an air nucleus as compared to a collision with a proton. However, a variation in these probabilities by a factor of two increases the correction in the secondary production of He in the atmosphere to only 6%. The variation in $P_{M-3t}{}^{(p)}$ affects the matter traversed to a recognizable extent; an increase of $P_{M-3t}{}^{(p)}$ from 0.2 to 0.5 changes this by about 1 g.

The probabilities used in our analysis are

$$P_{4-3t}{}^{(p)}=0.4,\quad P_{M-3t}{}^{(p)}=0.2,\quad P_{H-3t}{}^{(p)}=0.15,$$
$$P_{4-3}{}^{(\mathrm{air})}=0.1,\quad P_{M-3}{}^{(\mathrm{air})}=0.5.$$

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