# $He^3$ NUCLEI IN THE LOW ENERGY PRIMARY COSMIC RADIATION

By S. Biswas, P. J. Lavakare, S. Ramadurai and N. Sreenivasan

*(Tata Institute of Fundamental Research, Bombay-5, India)*

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## Abstract

The flux of $He^3$ nuclei and the ratio $He^3/(He^3 + He^4)$ in the low energy primary cosmic radiation have been determined using a stack of nuclear emulsions exposed at 3·1 g. cm.$^{-2}$ of atmospheric depth from Fort Churchill, Canada, in June 1963. The grain-density *versus* residual range method was used to determine the masses of the helium nuclei. Using a sample of 146 helium nuclei whose masses could be identified, the ratio $He^3/(He^3 + He^4)$ is obtained as $0 \cdot 14 \pm 0 \cdot 04$ for the kinetic energy interval 115–210 MeV per nucleon and $0 \cdot 43 \pm 0 \cdot 11$ for the rigidity interval 0·85–1·05 BV. The differential fluxes of $He^3$ nuclei are determined as $0 \cdot 017 \pm 0 \cdot 006$, $0 \cdot 045 \pm 0 \cdot 015$, and $0 \cdot 054 \pm 0 \cdot 017$ particles/$M^2$. Sr. Sec. MeV/nucleon, in the kinetic energy intervals of 117–183, 183–217, and 217–250 MeV/nucleon respectively. These results are compared with those of other investigators. From the results of the present work the amount of matter traversed in space by the primary cosmic ray helium nuclei of energy 115–210 MeV/nucleon is obtained as $4 \cdot 7 \pm 1 \cdot 8$ gm. cm.$^{-2}$ of hydrogen.

## 1. Introduction

The present knowledge on the abundance of helium isotopes in stellar objects indicates that $He^3$ is almost absent in a large majority of astronomical bodies (Aller, 1961); and it is also known that $He^4$ and heavier nuclei in the primary cosmic rays would produce $He^3$ and $H^3$ ($H^3$ having a half-life of 12·5 years decays to $He^3$) by collisions with hydrogen atoms during their traversal through source region and interstellar space. Thus the study of the isotopic composition of helium nuclei in the primary cosmic rays is of considerable importance in understanding the origin and the propagation of cosmic rays. If one assumes that $He^3$ is absent in the source region, as seems likely, the determinations of the ratio $\Gamma(E/N) = He^3/(He^3 + He^4)$ defining the relative flux of these nuclei near the earth in the energy per nucleon interval (E/N) and the relevant cross-sections for the production of $He^3$ and $H^3$ nuclei, enable us to obtain the amount of matter traversed in space by the primary cosmic ray nuclei. It is well known that the path length of the primary cosmic rays in space can also be obtained from the determination of the relative abundance of Li, Be and B nuclei in the primary cosmic rays. Thus the study of $He^3$ nuclei provides an independent means of investigating the properties of propagation of cosmic rays, particularly in the low energy region. Further, as the mass to charge ratios of the two isotopes are different, the determination of this ratio $\Gamma$ at different periods of solar activity may give some information regarding the propagation characteristics in the interplanetary space.

The earliest measurements of this ratio were made by Apparao (1961, 1962) using nuclear emulsions as detectors and these gave considerably high values of $\Gamma$(E/N). Subsequent measurements (Foster and Mulvey, 1963; Hildebrand *et al.*, 1963; Aizu *et al.*, 1964; Dahanayake *et al.*, 1964) confirmed the existence of $He^3$ nuclei in the primary cosmic radiation but the values of $\Gamma$ were considerably smaller and were in disagreement with earlier results. The flux of $He^3$ nuclei was not determined in any of these experiments. The present experiment was undertaken in 1963 to determine the ratio $\Gamma$ and the flux of $He^3$ nuclei in an energy interval of 115–210 MeV/nucleon during the period of low solar activity. In this paper we present the final results of this investigation, the preliminary results of which were reported earlier (Biswas *et al.*, 1965). Recently direct studies of $He^3$ nuclei have been made in 1963–65 by O'Dell *et al.* (1965), Hofmann and Winckler (1966) and Fan *et al.* (1966) who measured the ratios $\Gamma$(E/N) in the energy intervals of 215–370, 80–150 and 40–115 MeV/nucleon respectively. The results of the present experiment have been compared with these obtained during this period of low solar activity (1963–65), and by combining these observations, the energy spectrum of $He^3$ nuclei and the variation of the ratio $\Gamma$(E/N) with energy in the energy interval 40–300 MeV/nucleon have been studied. This is of much interest in determining the path length of low energy helium nuclei in space and its variation with energy when the appropriate values of the cross-sections for the production of $He^3$ nuclei and its energy dependence are available.

Attempts have been made to determine this ratio $\Gamma$ at high energies (Balasubrahmanyam *et al.*, 1963; Agrawal *et al.*, 1965) but the results obtained so far have large statistical uncertainties and hence are rather inconclusive.

## 2. EXPERIMENTAL PROCEDURE

(i) *Emulsion Stack and Exposure.*—A stack of nuclear emulsions consisting of 120 Ilford pellicles each of size $20 \times 10 \times 0 \cdot 06$ cm. was exposed at a mean atmospheric depth of 3·1 gm. $\text{cm.}^{-2}$ for 11·2 hours in a balloon flight from Fort Churchill, Manitoba, Canada, on June 15, 1963. During the ascent of the balloon, the plane of the emulsion was kept horizontal and the stack was flipped by 90° on reaching the ceiling altitude so that the 10 cm. side was vertical. The packing material above the top edge of the emulsions consisted of a light substance of thickness of only 0·02 g. $\text{cm.}^{-2}$ The middle 90 emulsions of the stack consisted of G-5, G-2 and G-0 emulsions of different sensitivities arranged in a sequence of G5-G2-G5-G2-G5-G0, which was repeated 15 times. These were flanked by 15 G-5 emulsions on either side.

(ii) *Scanning and Acceptance Criteria.*—The line scan procedure was adopted to pick up nuclei producing ionization greater than or equal to eight times that of a minimum ionizing singly charged particle. The scan line was 5 mm. below the top edge of the stack. The projected length per plate was $\geqslant$ 3 mm. and the projected zenith angle was $\leqslant$ 45°. Of the tracks of particles obtained from this scan those which came from outside the stack were followed into the stack, and only those stopping with a total residual range R in the stack such that $1 \cdot 0 \leqslant R \leqslant 10 \cdot 0$ cm. were used for analysis. From the given sample doubly charged nuclei were separated by using the ionization *vs.* residual range method, and 205 helium nuclei were obtained for further analysis.

Scanning efficiency was determined by rescanning about 45% of the emulsions of the original scan by different observers. The scanning efficiency was found to be 94%, 96% and 100% for helium nuclei of residual ranges 10–5·7 cm., 5·7–2·9 cm., and 2·9–0·5 cm. respectively.

(iii) *Measurements and Analysis.*—Only those tracks with total residual range in the stack, R, such that $1 \cdot 5 \leqslant R \leqslant 10 \cdot 0$ cm., and on which ionization measurements could be made in a G-2 emulsion at a residual range $\geqslant 0 \cdot 5$ cm. were used for mass measurements. Using these additional criteria, 146 helium nuclei were selected for mass measurements. The method of grain density *vs.* residual range was used to determine the mass of the particle. On an average about 350 to 450 grains were counted on each track. A second ionization measurement was made at a different residual range on all those tracks where such a measurement was possible. Thus a second independent measurement of mass could be made on 66 particles. The relation between the mass M (in units of proton mass) and ionization as given by grain density

I (Grains/100 $\mu$) at a residual range $R_r$ (in cm.) is given by (Powell *et al.*, 1959)

$$M^Y = \bar{K}.I.R_r^Y \tag{1}$$

where $\bar{K}$ is the average value of the normalization constant which varies from plate to plate. The exponent Y is a constant for the particular plate.

The variation of grain density within the entire thickness of the emulsion was studied by making measurements on very flat tracks of relativistic particles passing through the given emulsion. It was found that there was little or no variation of grain density with depth in the region 0·2–0·7 of the total thickness. All grain density measurements were made in this region.

Only those plates in which grain density measurements could be made on nine or more tracks have been used to determine $\bar{K}$ and Y and hence the mass of the particle. The exponent Y was obtained by visual fitting of a straight line to the I *vs.* $R_r$ plot for each plate. The particles which appeared to belong to the $He^3$ group were neglected in obtaining the value of Y. In the first approximation, the constant K was obtained for each nucleus by assuming all the nuclei were $He^4$. In order to remove the possible contamination due to $He^3$ nuclei, the following procedure was adopted. The mean and the standard deviation for all the K values were determined for each plate separately. Using this mean value of K we separated out those individual values of K which were above one standard deviation and from the remaining sample we determined the final mean value $\bar{K}$ for each plate. Further iteration was found to be unnecessary. The value of Y is same for both $He^3$ and $He^4$ nuclei. After thus determining $\bar{K}$ and Y for each plate, the masses of all the nuclei are determined using the relation (1). Using a weighted mean value of Y from all the plates a combined $M^Y$ distribution is obtained which is shown in Fig. 1. It is necessary to use the parameter $M^Y$ for plotting the distribution, instead of M, because only the distribution of $M^Y$ is gaussian and not that of M. A similar procedure was adopted to find out the masses of nuclei from the second independent measurement of ionization and residual range. The cross-plot of the masses obtained by the two measurements is shown in Fig. 2. Since the resolution is not very good, we adopted the statistical method (Hildebrand *et al.*, 1963) to identify the track as due to either $He^3$ or $He^4$ nucleus. For the purpose of fitting a best gaussian, the experimental mean of $M^Y$ of $He^4$ is taken at 1·70, which is close to the theoretical mean value of 1·72. The sample to the right of this value was used

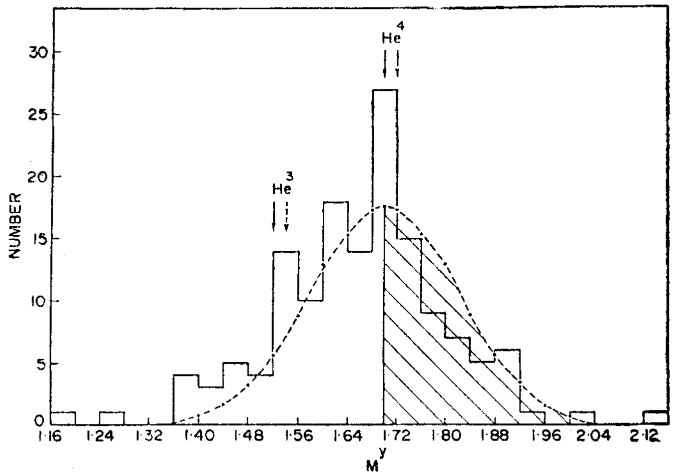

FIG. 1. The observed distribution of $M^Y$ for the mean $Y = 0 \cdot 392$. Dashed curve indicates the gaussian fitted for the He$^4$ sample. The slight asymmetry on the left-hand side of the observed distribution is due to the presence of He$^3$ nuclei.

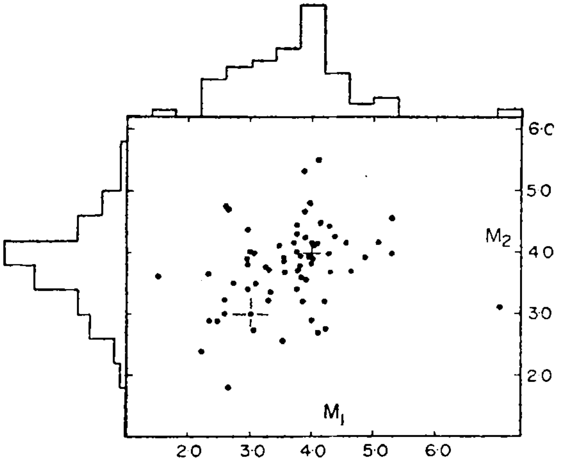

FIG. 2. The cross-plot of mass estimates $M_1$ and $M_2$, made by two independent mass measurements. The histograms of mass estimates from each set of measurements are also shown. The mass $M_1$ is obtained from measurements made at a residual range $R_1$ which is smaller than $R_2$ at which measurements were made to obtain the mass $M_2$.

to fit a gaussian for He$^4$ nuclei, as shown in Fig. 1. (Whenever second measurements were made, a gaussian was fitted separately for this $M^Y$ plot.) The corresponding experimental mean value of $M^Y$ for He$^3$ is $1 \cdot 52$. Assuming the same standard deviation for the sample of both He$^3$ and He$^4$ nuclei we have computed the probability that a particular track is either He$^3$ or He$^4$.

Since the nuclei which we have picked up can only be $He^3$ or $He^4$ nuclei, we normalise the sum of the probabilities $P_{He}^{3}$ and $P_{He}^{4}$ of each track to one. In all those cases where a second measurement was made we computed the $P_{He}^{4'}$ and $P_{He}^{3'}$ separately for this sample as above and the combined probability that a track is $He^4$ or $He^3$ is computed as $P_{He}^{4} \times P_{He}^{4'}$ or $P_{He}^{3} \times P_{He}^{3'}$. Again we normalise the sum of the combined probabilities to one for the same reason as above. The probability of a particular track being $He^4$, $P_{He}^{4}$ is shown in Fig. 3 for the entire sample. As can be seen from the figure majority of the tracks have the probabilities very close to one. Only very few tracks have probabilities around 0·5. We classify a particle as a $He^4$ nucleus if $P_{He}^{4} \geqslant 0 \cdot 5$. The rest of the particles in the sample have to be necessarily $He^3$ nuclei.

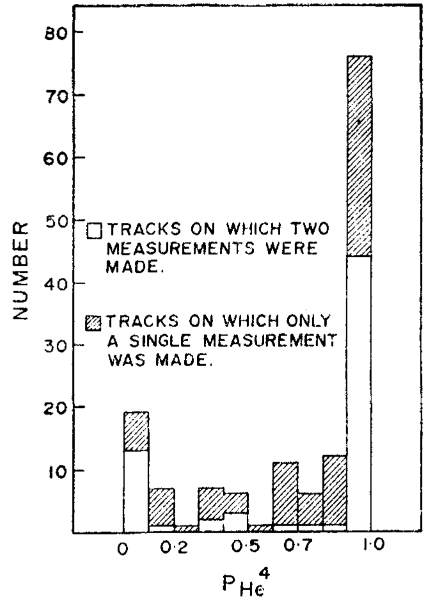

FIG. 3. The distribution of tracks as a function of $P_{He}^{4}$, the probability of a track being $He^4$. The combined probability, $P_{He}^{4} + P_{He}^{3}$ was normalised to unity (*see* text).

Using the above criteria for separating $He^3$ and $He^4$ nuclei, we have in our sample of 146 helium nuclei, 38 $He^3$ nuclei and 108 $He^4$ nuclei. Using the range-energy relation, the energy and rigidity at the top of the atmosphere for each of the nucleus were calculated.

## 3. RESULTS AND DISCUSSIONS

(*a*) *Flux, Energy Spectra and Rigidity Spectra of $He^3$ and $He^4$ nuclei.*— Using the criteria for scanning and selection of particle tracks described earlier, we have a sample of 205 helium nuclei. Out of these 146 tracks could be further identified as due to either $He^3$ or $He^4$ from the mass measurements. The fluxes of $He^3$ and $He^4$ nuclei and the ratio $\Gamma = He^3/(He^3 + He^4)$ have been determined from these mass-identified particles.

Before finding the fluxes at the top of the stack we made the following corrections: (i) the loss of particles due to scanning inefficiency as given previously, (ii) loss of particles due to additional acceptance criteria for mass measurements (this correction factor, which is an average over the entire energy interval, is $205/146 = 1{\cdot}40$, and is applicable to fluxes of $He^4$ and $He^3$ nuclei); (iii) loss of particles due to interactions in the stack. For this purpose each particle track is given a weight factor, $e^{R/\lambda}$, where R is the total range of the particle in the stack and $\lambda$ is the interaction mean-free path of helium nuclei in emulsion. We have taken $\lambda = 18$ cm. for both $He^3$ and $He^4$.

Having obtained the fluxes of $He^3$ and $He^4$ nuclei at effective flight altitude of 3·4 g. cm.$^{-2}$ these were extrapolated to the top of the atmosphere using the absorption mean-free path of helium nuclei in air as 45 g. cm.$^{-2}$ Contribution of secondary helium nuclei arising from the interactions of heavier nuclei in air is only 1·2% and hence is neglected. The differential fluxes of helium, $He^4$ and $He^3$ nuclei are shown in Table I.

TABLE I

*Differential fluxes of $He^3$ and $He^4$ nuclei at the top of the atmosphere*

| | Kinetic energy, MeV/nucleon | $\frac{dJ}{dE}$ particles/ $M^2$. Sr. Sec. MeV per nucleon | Rigidity Bv | $\frac{dJ}{dR}$ particles/ $M^2$. Sr. Sec. MV |
|---|---|---|---|---|
| He—Nuclei (All treated as $He^4$) | 82–100 | 0·13 ±0·02 | 0·80–0·89 | 0·026 ±0·005 |
| | 100–135 | 0·13 ±0·02 | 0·89–1·04 | 0·030 ±0·004 |
| | 135–165 | 0·18 ±0·02 | 1·04–1·15 | 0·051 ±0·006 |
| | 165–190 | 0·18 ±0·02 | 1·15–1·25 | 0·046 ±0·007 |
| $He^4$ | 100–125 | 0·12 ±0·02 | 0·89–1·00 | 0·027 ±0·005 |
| | 125–150 | 0·15 ±0·03 | 1·00–1·10 | 0·037 ±0·005 |
| | 150–188 | 0·12 ±0·02 | 1·10–1·24 | 0·032 ±0·005 |
| | 188–200 | 0·12 ±0·04 | 1·24–1·28 | 0·038 ±0·013 |
| $He^3$ | 117–183 | 0·017±0·006 | 0·72–0·93 | 0·0056±0·0015 |
| | 183–217 | 0·045±0·015 | 0·93–1·02 | 0·0157±0·0050 |
| | 217–250 | 0·054±0·017 | 1·02–1·10 | 0·0226±0·0068 |

For comparison with other data, we have plotted in Fig. 4 the differential fluxes *vs.* kinetic energy/nucleon of helium nuclei (all treated as He$^4$) as obtained from experiments made during the middle of 1963. There is good agreement between these results. We have also shown in this figure the results of the experiments made during the middle of 1965 by Fan *et al.* (1966), Balasubrahmanyan *et al.* (1966) and Hofmann and Winckler (1966). These fluxes of helium nuclei show good agreement with one another. The best fitting lines are drawn through the two sets of data in Fig. 4 and these represent the differential energy spectrum of helium nuclei during mid-1963 and mid-1965. The difference between the two spectra represents the effect of the variation of the solar modulation during this period.

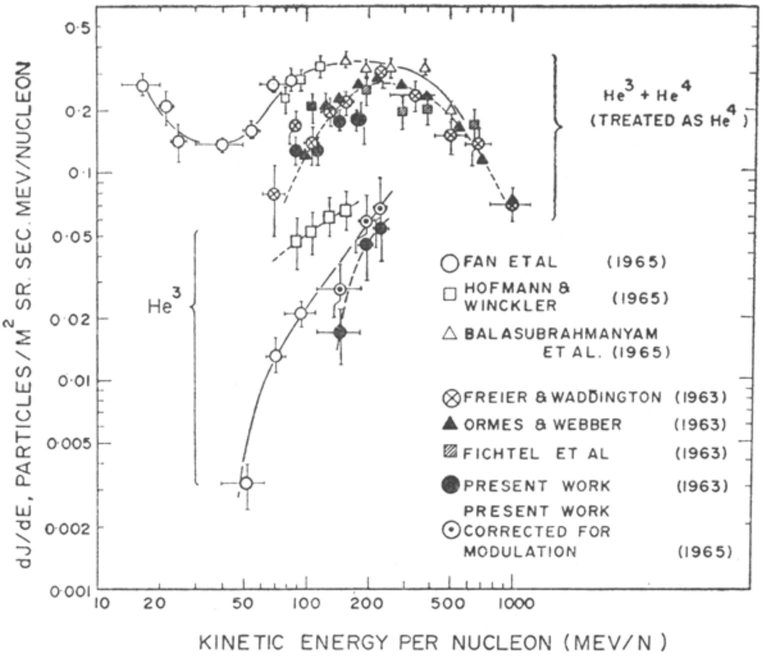

FIG. 4. Differential energy spectra as a function of kinetic energy/nucleon of helium nuclei (all treated as He$^4$) and He$^3$ nuclei measured during mid-1963 and mid-1965. The solid line through He$^3$ data represents the differential energy spectrum during mid-1965. The Mount Washington Neutron monitor rates corresponding to these experiments were: Mid-1963—Freier and Waddington, 2325; Ormes and Webber, 2310; Fichtel, *et al.*, 2330; Present work, 2330. Mid-1965—Fan *et al.*, 2477–2380; Balasubrahmanyan *et al.*, 2472; Hofmann and Winckler, 2520.

In the same figure we have shown the differential fluxes of He$^3$ nuclei as measured in the present experiment in 1963 and those measured in 1965 by Fan *et al.* (1966) and Hofmann and Winckler (1966). In order to obtain the He$^3$ spectrum over a wider energy interval in 1965, it is necessary to correct for the relative modulation between mid-1963 and mid-1965. Assuming that the solar modulation is mainly velocity-dependent at low energies as suggested by Fan *et al.* (1965) and Gloeckler (1965), we obtained the relative modulation factor as a function of kinetic energy/nucleon from the ratios of the helium fluxes as given by the best fitting spectra of 1963 and 1965 shown in Fig. 4. Using these relative modulation factors we estimated the $He^3$ fluxes for mid-1965 from the fluxes measured by us in mid-1963 and are shown in Fig. 4. The results obtained in the above three investigations show an increase in the flux of $He^3$ nuclei with energy. However, at 150 MeV/nucleon the flux of $He^3$ given by Hofmann and Winckler (1966) is higher than our value by a factor of about two. At 90 MeV/nucleon also the result of Hofmann and Winckler (1966) is higher than that of Fan *et al.* (1966) by a factor of about two, which according to Fan *et al.*, cannot be accounted by modulation effect. The solid line drawn through the points of Fan *et al.* (1966) and of the present work, hence represents, according to us, the $He^3$ spectrum in mid-1965 in the energy interval 40–300 MeV/nucleon on the basis of velocity-dependent solar modulation. If, on the other hand, we assume that the solar modulation is dependent on $R\beta$ (*i.e.*, rigidity × velocity) as suggested by Gloeckler and Jokipii (1966), the fluxes of $He^3$ nuclei in 1965 as deduced from our results in 1963 in the energy intervals of 117–183, 183–217 and 217–250 MeV/nucleon would be $0{\cdot}031 \pm 0{\cdot}010$, $0{\cdot}072 \pm 0{\cdot}023$ and $0{\cdot}081 \pm 0{\cdot}025$ respectively. These values are only about 12% higher than those shown in the figure for 1965. This spectrum of $He^3$ nuclei is much steeper than that of He nuclei in mid-1965 in the corresponding energy per nucleon interval as shown in Fig. 4, indicating the energy dependence of the ratio $\Gamma$. This is examined in the following section.

(*b*) *Determination of the Ratio* $\Gamma = He^3/(He^3 + He^4)$.—Since the propagation characteristics of the cosmic radiation may be velocity (*i.e.*, energy/nucleon) or rigidity-dependent, it is necessary to group the particles in equal energy/nucleon or equal rigidity intervals. Owing to the relative biases involved in scanning and the acceptance criteria, careful grouping of the helium nuclei into appropriate energy/nucleon or rigidity intervals is necessary. For the same energy/nucleon at the top of atmosphere, $He^3$ and $He^4$ have different residual ranges in the emulsion stack. Similar is the case when we select the same rigidity interval groups. The acceptable ranges in the stack for the two different groups are summarized in Table II.

In order to determine the ratio at the top of the atmosphere for different intervals we made the following two corrections: (i) the loss of particles due to interactions in the stack as described previously, (ii) the contribution due to the atmospheric secondaries. This is estimated to be only 1·6% using the parameters given by Dahanayake *et al.* (1964).

TABLE II

*Acceptable ranges and observed number of $He^3$ and $He^4$ nuclei for different grouping intervals*

| | $He^3$ | | $He^4$ | |
|---|---|---|---|---|
| | Acceptable R in cm. | No. of tracks | Acceptable R in cm. | No. of tracks |
| Kinetic energy interval 115–210 MeV/N. | $1{\cdot}5 \leqslant R \leqslant 7{\cdot}5$ | 17 | $2{\cdot}0 \leqslant R \leqslant 10{\cdot}0$ | 85 |
| Rigidity interval 0·85–1·05 Bv | $2{\cdot}7 \leqslant R \leqslant 8{\cdot}0$ | 24 | $1{\cdot}5 \leqslant R \leqslant 4{\cdot}0$ | 36 |

The final values of $\Gamma$ at the top of the atmosphere are obtained as $\Gamma$(E/N) $= 0{\cdot}14 \pm 0{\cdot}04$ for kinetic energy interval, 115–210 MeV/nucleon and $\Gamma$(R) $= 0{\cdot}43 \pm 0{\cdot}11$ for rigidity interval, 0·85–1·05 Bv.

We wish to mention here that these values are in agreement with the $\Gamma$(E/N) and $\Gamma$(R) values of $0{\cdot}10 \pm 0{\cdot}04$ and $0{\cdot}62 \pm 0{\cdot}25$ respectively obtained by us if we take only those particles identified by two mass measurements. The latter ratios are, however, of poor statistical weight.

In Table III we have shown all the results obtained so far on the ratios $\Gamma$(E/N) and $\Gamma$(R). From this table it is seen that in the energy interval 100–370 MeV/nucleon, most of the values of $\Gamma$(E/N), including that of the present experiment, lie between 0·1 and 0·2. The values of $\Gamma$(R) obtained by different investigators, however, show larger variation which may be partly due to the velocity-dependent solar modulation. The only two measurements of $\Gamma$ (R) made in 1963 by O'Dell *et al.* (1965) and by us, however, show a large variation. This could partly arise from the fact that O'Dell *et al.* measured the ratio at a rigidity higher than that of the present investigation and the differential spectrum of helium nuclei at these rigidities (1·2–1·5 Bv) is nearly flat (Ormes and Webber, 1965) so that the values of $\Gamma$(E/N) and $\Gamma$ (R) are nearly the same for the experiment of O'Dell *et al.* (1965). Using detectors borne in satellite, Fan *et al.* (1966) recently measured the ratios $\Gamma$ (E/N) in the energy interval 40–110 MeV/nucleon and obtained the energy dependence of the ratio in this energy interval. In Fig. 5 we have

## TABLE III

*Summary of various values of* $\Gamma = He^3/(He^3 + He^4)$

| No. | Observer | λ Geomag. Lat. | Date | Altitude g. cm.$^{-2}$ | (K. energy) Interval (MeV./N) | $\Gamma$(E/N) | Rigidity Interval BV | $\Gamma$(R) | Detector |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Apparao .. | 55° N | 30-6-1957 | 8·5 | 200-400 | 0·38 ±0·09 | 1·3 -1·6 | 0·41±0·11 | Emulsion |
| 2 | Apparao .. | 61° N | 3-8-1958 | 3·8 | 160-355 | 0·31 ±0·08 | 1·05-1·48 | 0·33±0·08 | do. |
| 3 | Foster and Mulvey .. | 61° N | 3-8-1958 | 3·8 | 202-291 | 0·14 ±0·04 | 1·20-1·37 | 0·15±0·07 | do. |
| 4 | Aizu *et al.* .. | 53·5° N | 4-9-1959 | 2·0 | 155-320 | 0·10 ±0·03 | 1·0 -1·4 | 0·25±0·13 | do. |
| 5 | Hildebrand *et al.* .. | 55° N | 21-4-1961 | 3·8 | 255-360 | $0{\cdot}06\ ^{+0{\cdot}03}_{-0{\cdot}02}$ | 1·1 -1·4<br>1·1 -1·48 | $0{\cdot}20^{+0{\cdot}12}_{-0{\cdot}08}$<br>$0{\cdot}15^{+0{\cdot}09}_{-0{\cdot}06}$ | do. |
| 6 | Dahanayake *et al.* .. | 73° N | 4-8-1962 | 4·2 | 160-370 | 0·18 ±0·05 | 1·1 -1·4 | 0·24±0·08 | do. |
| 7 | Webber and Ormes | .. | 1963 | 6·0 | 120-300 | 0·30 ±0·10 | .. | .. | Cerenkov counter |
| 8 | O'Dell *et al.* .. | 73° N | 19-6-1963 | 4·0 | 215-368 | 0·10 ±0·03 | 1·2 -1·5 | 0·11±0·04 | Emulsion |
| 9 | Present experiment .. | 73° N | 15-6-1963 | 3·1 | 115-210 | 0·14 ±0·04 | 0·85-1·05 | 0·43±0·11 | do. |
| 10 | Hofmann and Winckler | 69·5° N | 12-5-1965 | 3·5-4·5 | 80-150 | 0·19 ±0·05 | ~0·8 | 0·39±0·09 | $dE/dx$ *vs.* E counters |
| 11 | Fan *et al.* .. | IMP—III | 29-5-1965<br>to<br>20-9-1965 | .. | (i) 40-65<br>(ii) 65-80<br>(iii) 80-115 | 0·025±0·006<br>0·05 ±0·01<br>0·068±0·012 | ..<br>..<br>.. | ..<br>..<br>.. | do. |
| 12 | Balasubrahmanyam *et al.* | 8° N | 1963 | ~10 | >9·97 BeV/*n* | 0·6 ±0·4 | >14·7 | 0·54±0·28 | Gas Cerenkov Counter |
| 13 | Agrawal *et al.* .. | 8° N | 1964 | 9·3 | >9·97 BeV/*n* | 0·54 ±0·26 | >14·7 | 0·43±0·26 | do. |

shown the values of $\Gamma$ (E/N) in the energy interval 40–400 MeV/nucleon as obtained in the four investigations made in 1963–65 during the period of low solar activity. As discussed earlier, the flux of $He^3$ measured by Hofmann and Winckler (1965) in the energy interval 80–100 MeV/nucleon is higher than that of Fan *et al.* (1966) by a factor of two and hence the ratio $\Gamma$ (E/N) obtained by the former is also higher. The ratio $\Gamma$ (E/N) would not be affected by change of solar modulation between 1963 and 1965 if the modulation is velocity-dependent at these low energies (Fan *et al.*, 1965; Gloeckler, 1965) and these values would give us the energy dependence of this ratio over this energy interval. Thus the dashed line in Fig. 5 shows the approximate shape of the energy dependence of $\Gamma$ (E/N) in the interval 40–400 MeV/nucleon, obtained from the results of Fan *et al.* (1966), O'Dell *et al.* (1965) and the present work. (If the solar modulation is dependent on R$\beta$ (Gloeckler and Jokipii, 1966), the ratio $\Gamma$ (E/N) for 1965 deduced from our results in 1963 would be $\sim$ 15% higher).

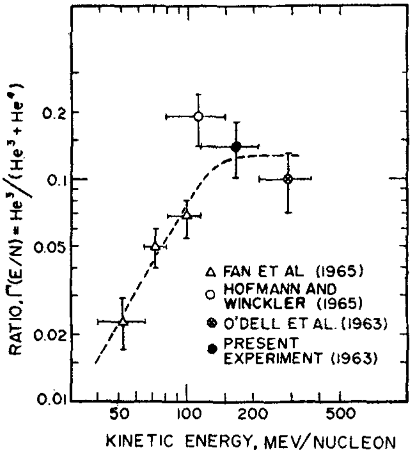

FIG. 5. The ratio of $He^3/(He^3 + He^4)$ as a function of kinetic energy per nucleon as measured during 1963–1965. The dashed line shows the approximate variation of the ratio, $\Gamma$ (E/N) with kinetic energy/nucleon.

(*c*) *Amount of Matter Traversed in Space.*—As $He^3$ nuclei are rare in most astronomical objects, it is reasonable to assume that they are absent in the beginning of the acceleration process in the source region and arise only from the fragmentations of $He^4$ and heavier nuclei in collision with hydrogen in the source region and in the interstellar space. Therefore, we now examine how the variation of the ratio $He^3/(He^3 + He^4)$ as a function of kinetic energy per nucleon, as shown in Fig. 5, is related to the amount of matter traversed by cosmic ray nuclei in space.

The first question is to decide the variation of $\Gamma$ (E/N) with kinetic energy per nucleon outside the solar system. If the solar modulation is velocity-dependent at low energies (E $<$ 500 MeV/nucleon) as indicated by the results obtained by Fan *et al.* (1965) and Gloeckler (1965), the curve $\Gamma$ (E/N) *vs.* E/N as shown in Fig. 5 should not be affected by the residual solar modulation and it would then represent the situation in the local interstellar space. If, on the other hand, there is some rigidity-dependent component of solar modulation at low energies (Gloeckler and Jokipii, 1966), the $\Gamma$ (E/N) *vs.* E/N curve will have less positive slope than the observed one. While this question is not yet completely resolved, we assume for the present the former situation on the basis of the results of Fan *et al.* (1965).

Next question that is to be considered is the variation of the cross-section for the production of $He^3$ nuclei by $He^4$ and heavier nuclei with interstellar (and source) material in the energy interval 40–400 MeV/nucleon and the effect of the ionization loss of low energy $He^3$ and $He^4$ nuclei neglecting acceleration in the interstellar space. This is not known completely at present. So far the growth curves of the ratio $\Gamma$ (E/N) as a function of the amount of interstellar neutral hydrogen have been calculated only for kinetic energy of about 200 MeV/nucleon neglecting ionization loss (Hayakawa *et al.*, 1958; Foster and Mulvey, 1963; Badhwar and Daniel, 1963; and Dahanayake *et al.*, 1964). Badhwar and Daniel (1963) discussed in detail the cross-sections for production of $He^3$ and $H^3$ nuclei at $\sim$200 MeV/nucleon and the predicted growth curve from these data agrees well with that of Dahanayake *et al.* (1964) for E $\sim$200 MeV/nucleon.

Therefore we use the $\Gamma$(E/N) $= 0 \cdot 14 \pm 0 \cdot 04$ at 115–210 MeV/nucleon obtained in the present experiment and the growth curve of Dahanayake *et al.* (1964) for $\sim$200 MeV/nucleon, to determine the amount of matter traversed in space. Thus we obtain the path length of $4 \cdot 7 \pm 1 \cdot 8$ g. cm.$^{-2}$ of hydrogen for helium nuclei of energy $\sim$150 MeV/nucleon. We wish to point out here that since the velocity of the secondary products in the fragmentation process is nearly the same as that of primary nucleus, whereas the rigidities are different for $He^3$ and $He^4$, it is considered more appropriate to evaluate the matter traversed from $\Gamma$ (E/N) rather than from $\Gamma$ (R).

The path length of primary cosmic ray heavy nuclei of energy 50–150 MeV/nucleon was determined as $5 \cdot 5 \pm 1 \cdot 4$ g. cm.$^{-2}$ of hydrogen from the ratio of Li to M-nuclei ($6 \leqslant Z \leqslant 9$) in the primary cosmic rays by Biswas *et al.* (1966) and this is consistent with that obtained for the primary $He^4$ nuclei in the present work from the ratio of $He^3$ to ($He^3$ + $He^4$) nuclei. But the low energy heavy nuclei of $Z \geqslant 6$ of energy of about 50–200 MeV/nucleon have strikingly different spectral shape as compared to He-nuclei in the same energy per nucleon interval as shown by Comstock *et al.* (1965). Because of the different features of low energy heavy nuclei ($Z \geqslant 6$) of energy 50–150 MeV/nucleon it has been suggested by Biswas *et al.* (1966) and Comstock, *et al.* (1966) that these heavy nuclei may come from a separate source or have different propagation path as compared to other heavy nuclei of higher energies. How the low energy helium nuclei fit in this hypothesis of two sources is yet an open question. This could be partly answered when the variation of the path length of both $He^4$ and heavy nuclei ($Z \geqslant 6$) in the energy interval 40–500 MeV/nucleon can be evaluated in detail.

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