Some Remarks concerning the Energy Dependence of the Intensities of Nuclei of Helium-3, Lithium, Beryllium and Boron in the Galactic Cosmic Radiation

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Available experimental data on the energy dependence of the production cross sections of some favourable light nuclei from spallation reactions of protons with typical cosmic ray nuclei, have been examined. The analysis focuses attention on the necessity of determining accurately cross sections for the production of isotopes of light nuclei from various targets at low bombarding energies; this is necessary for the proper understanding and interpretation of the primary cosmic radiation. The calculations show that in the galactic cosmic radiation (i) the deuterons produced from spallations constitute only a very small proportion of singly charged particles, whereas the proportion of He\(^3\) among doubly charged particles is large enough to be detected experimentally with techniques in use at present, (ii) the production rate of He\(^3\) is energy dependent and can be employed to deduce information on the history of the radiation and (iii) the amount of matter traversed by the radiation during the time of its acceleration from about 20 MeV/n to about 100 MeV/n is much less than 2.5 g/cm\(^2\) of hydrogen.

§ 1. Introduction

It has been well recognised by cosmic ray physicists that a detailed knowledge of the chemical and isotopic composition of the galactic cosmic radiation and its dependence on energy will permit one to deduce information regarding its history. In particular, a determination of the intensities, in the vicinity of the earth, of the nuclei of H\(^2\), He\(^3\), Li, Be and B, all of which are known to be almost absent in average astro-physical bodies,\(^{1,2}\) and hence probably in the source of the cosmic radiation, can be usefully employed to obtain such information. (Since the lifetime of H\(^3\) is very small compared to the cosmic ray time scale, all H\(^3\) will transform into He\(^4\)). At present the only well determined quantity is \(I_{LS}\), the ratio\(^3\) of the flux of nuclei of Li, Be and B (the L-nuclei) to that of nuclei with charge \(Z\geq6\) (the S-nuclei) in the primary radiation vertically incident at the top of the atmosphere over Texas, U.S.A.\(^3\) (\(\chi=41^\circ\)N and vertical geomagnetic cutoff energy = 1.5 GeV/nucleon). In a recent investigation, Badhwar et al.,\(^4\) (hereafter referred to as Paper I), using the available experimental data on spallation and on the basis of some empirical relations

\(^{1}\) The ratio of the intensity of nuclei belonging to group A to that of any other group B is represented as \(I_{AB}\).
have deduced the production cross sections for all individual isotopes with $Z \geq 3$ resulting from collisions of cosmic ray nuclei at relativistic energies with hydrogen in space; they then allowed for the decay of radioactive isotopes with half lives $< \text{cosmic ray lifetimes}$ and obtained information on the mean amount of matter traversed by the radiation as also its chemical composition near the source region. In these calculations it was assumed that (a) all spallations took place at energies $\geq 300 \text{MeV}/n$, and (b) the fragmentation parameters, $P_{ij}$, do not vary with energy for values $\geq 300 \text{MeV}/n$; ($P_{ij}$ is the ratio of the number of secondary $j$ nuclei produced by $i$ type primary nuclei to the total number of interactions of $i$ nuclei).

Though the acceleration of nuclei starts right from thermal energies, spallation processes remain unimportant up to energies $\sim 15 \text{MeV}/n$ which is the threshold in the case of nuclei with $Z \geq 6$ for inelastic process involving protons and nuclei. This necessarily implies that, in principle, a study of cosmic ray nuclei which are rare in the universe cannot yield information regarding the amount of matter traversed by the radiation before it attained about 15 MeV/n. (Reactions induced by neutrons and $\gamma$-rays have not been considered here). Thereafter the processes will be quite complex and spallation products characteristic of the energies involved and proportional to the amount of hydrogen traversed at that energy will go on adding up. The cumulative effect of these processes is seen in the radiation observed in the vicinity of the earth and it is this complex situation which has to be unravelled. There is one practical difficulty which bears on the range of energies which can be studied and this stems from the fact that nuclei with energies $\leq 150 \text{MeV}/n$ are almost absent in the galactic cosmic radiation observed in the neighbourhood of the earth. (The reason for this effect is still not well understood).

A number of investigations have recently been carried out to determine the flux of $H^1$, $H^2$, $H^3$, $He^3$, and $He^4$ in different energy regions of the primary radiation. In the case of $H^1$, it has only been possible to place upper limits on the flux, while for $He^3$ the results from the different investigations at energies in the region of 200 MeV/n are in serious contradiction with one another. Hence, no reliable quantitative estimates can at present be attributed to the flux of $H^1$ or $He^3$ in any energy region.

In this paper an attempt has been made to investigate the dependence on energy of the production cross sections for some favourable isotopes of light nuclei.\(^*1\) In §2, the fragmentation parameters for the production of $H^1$, $H^2$, $H^3$, $He^3$, and $He^4$ by proton bombardment of different target nuclei at an energy of about 200 MeV have been calculated; these values are then employed to deduce the intensities of these isotopes in the neighbourhood of the earth assuming that the cosmic radiation traversed a total of 2.5 g/cm$^2$ of hydrogen at this energy.

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\(^*1\) In all these calculations the effect of collisions of cosmic ray nuclei with the small amount of He present in interstellar matter has been neglected.
In the later sections we have attempted to study the energy dependence of the production of He$^3$ and $L$-nuclei in the energy region down to about 20 MeV/n. The conclusions obtained here are semi-quantitative and sometimes speculative in nature but indicate that with more experimental determinations of cross sections, more definite deductions can be made; they also focus attention on the wealth of information that can be derived about the origin of cosmic radiation from a study of the energy dependence of the intensities of some favourable nuclei in the galactic cosmic radiation.

§ 2. Fragmentation parameters for the production of isotopes of nuclei with $Z=1$ and 2 at about 200 MeV

From a survey of the literature on star production by low energy nucleons in different target materials, it is found that there is sufficient data available in the region of 200 MeV to permit us to deduce a set of fragmentation parameters for the production of isotopes of hydrogen and helium in collisions of cosmic ray nuclei with hydrogen in space. In order to do this one requires a knowledge of the production frequencies of these isotopes in the bombardment of different target elements by protons of energy about 200 MeV, and the mean number of heavy prongs, $N_h$, associated with them; these have been obtained as described below.

(i) The production frequencies of the isotopes of hydrogen and helium

![Graph](https://academic.oup.com/ptp/article-abstract/30/5/615/1851246)
from spallations in various targets were obtained from the following investigations:

<table>
<thead>
<tr>
<th>Authors</th>
<th>Bombarding energy</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Innes</td>
<td>300 MeV</td>
<td>Helium-4</td>
</tr>
<tr>
<td>Fuller</td>
<td>300 MeV</td>
<td>Oxygen</td>
</tr>
<tr>
<td>Bailey</td>
<td>190 MeV</td>
<td>Carbon, Aluminium and Nickel</td>
</tr>
</tbody>
</table>

The values obtained from these investigations have been assumed to be representative of a bombarding energy of 200 MeV.

(ii) It has been found from a number of investigations that (a) for targets in the range of atomic weights from 16 to 60, the value of $N$, including one pronged stars, for stars produced by neutrons of 190 MeV does not show any detectable change and that (b) for a given target, as in the case of emulsions, (Fig. 1), the value of $N$ is found to increase by only about 15% when the bombarding proton energy increases from 200 to 300 MeV. Also it is known that in these spallations the contribution of fragments, (as distinct from residues), of $Z \geq 3$ is less than 2%. These observations were used to estimate the values of $N$ at 200 MeV for different target elements.

Table I. Fragmentation parameters in hydrogen at $\sim 200$ MeV.

<table>
<thead>
<tr>
<th>Secondary</th>
<th>Protons</th>
<th>Deuterons</th>
<th>Tritons</th>
<th>Helium-3</th>
<th>Tritons + Helium-3</th>
<th>Helium-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Helium-4</td>
<td>1.78</td>
<td>0.482</td>
<td>0.034</td>
<td>0.565</td>
<td>0.599</td>
<td>-</td>
</tr>
<tr>
<td>Carbon</td>
<td>2.68</td>
<td>0.302</td>
<td>0.107</td>
<td>0.180</td>
<td>0.287</td>
<td>0.676</td>
</tr>
<tr>
<td>Oxygen</td>
<td>2.06</td>
<td>0.473</td>
<td>0.052</td>
<td>0.087</td>
<td>0.139</td>
<td>0.564</td>
</tr>
<tr>
<td>Aluminium</td>
<td>2.18</td>
<td>0.308</td>
<td>0.055</td>
<td>0.067</td>
<td>0.122</td>
<td>0.795</td>
</tr>
<tr>
<td>Nickel</td>
<td>2.16</td>
<td>0.245</td>
<td>0.052</td>
<td>0.061</td>
<td>0.113</td>
<td>0.598</td>
</tr>
</tbody>
</table>

The fragmentation parameters were then calculated for typical cosmic ray nuclei and are summarised in Table I. In these calculations it has been assumed that (a) equal numbers of protons and neutrons are emitted in spallations, (and all neutrons decay into protons) and that (b) the production cross section of $H^3$ from proton bombardment is equal to that of $He^3$ from neutron bombardment and vice versa.

It has been shown in Paper I that the value of $\Gamma_{LS} = 0.18 \pm 0.04$ obtained for cosmic radiation possessing energies $\geq 1.5 \text{ GeV/n}$ can be accounted for by allowing the radiation to traverse $2.5 \pm 0.5 \text{ g/cm}^2$ of hydrogen; from these calculations it was also possible to deduce the chemical composition of the radiation near the source region assuming that all the transformations due to spallations took place at energies $\geq 300 \text{ MeV/n}$. An attempt has been made now to calculate the relative intensities of the various light stable nuclei in the cosmic radiation using the source composition and the value of $2.5 \text{ g/cm}^2$ for the traversal...
of matter estimated in Paper I, the fragmentation parameters given in Table I and assuming that all spallations occurred at an energy of about 200 MeV/n. The results are summarised in Table II. From this table it is found that $\Gamma_{\text{H}^3}$ \approx 0.01 and $\Gamma_{\text{He}^3(\text{He}^3+\text{He}^4)}$ \approx 0.07. These values have also been estimated by Hayakawa et al.\(^3\) for relativistic energies and they find that $\Gamma_{\text{H}^3}$ \approx 3 \times 10^{-3}\,x and $\Gamma_{\text{He}^3(\text{He}^3+\text{He}^4)}$ \approx 5 \times 10^{-3}\,x where $x$ is the amount of matter traversed in grams. These are in good agreement with our calculations and indicate that while estimates of the intensity of deuterons produced in spallations is too small to be observable experimentally, the He$^3$ production is large enough to be detected with techniques in use at present.

§ 3. Energy dependence of $\Gamma_{\text{He}^3(\text{He}^3+\text{He}^4)}$

Unlike the light nuclei Li, Be and B of the primary cosmic radiation which arise only from spallations of the $S$-nuclei, the He$^3$ nuclei (including the H$^3$ nuclei which subsequently transform into the He$^3$ nuclei) arise predominantly from collisions of He$^4$ with hydrogen. In fact, as can be seen from Fig. 3, when the radiation traverses a few g/cm$^2$ of hydrogen at 200 MeV/n, only about 10% of the He$^3$ nuclei and a few percent of He$^4$ nuclei originate from collisions of carbon and heavier nuclei. Therefore, the energy dependence of $\Gamma_{\text{He}^3(\text{He}^3+\text{He}^4)}$ will depend to a very great extent on the energy dependence of the sum of the cross sections for reactions which give rise to He$^3$ and H$^3$ from He$^4$.

The available data on the bombardment of He$^4$ are due to (i) Wickersham\(^3\) who used 28 MeV protons, (ii) Tenneswald\(^3\) who used 90 MeV neutrons, (iii) Innes\(^3\) who used 300 MeV neutrons, and (iv) Kozodaev at al.\(^4\) who used 630 MeV protons; all these experiments were conducted with He$^4$ filled cloud chambers. The total cross sections for reactions which lead to the production of He$^3$ and H$^3$ in these experiments are 64 mb, 75 \pm 7 mb, 42 \pm 4 mb and \approx 75 mb respectively. (We have assumed that the total cross section for the production of H$^3$ and He$^3$ in neutron bombardment of He$^4$ is equal to that in proton bombardment at the
Fig. 2 The production cross sections of H³ as a function of the bombarding proton energy for C, N, O, Al and Fe targets.

Fig. 3 Plot of $J_i \cdot \sigma_f$, the product of, $J_i$, the intensity of the incident nucleus or group of nuclei $i$ (He⁴ and S nuclei with $Z \geq 6$) of the cosmic radiation near the source region and, $\sigma_f$, the cross section for the production of the fragment, $f$, under consideration against bombarding energy.
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same energy). It can be seen from these results that while the first two experiments at 28 MeV and 90 MeV give cross sections of about 70 mb for the production of $^3\text{He}+^3\text{H}$, the third measurement at 300 MeV shows a decrease of almost 50 %; the last value at 630 MeV again shows an increase of about 100 % with respect to that at 300 MeV. Since the apparent increase of cross section at 630 MeV is inconsistent with the general trend in the dependence of such cross sections with energy and since the total inelastic cross section at this energy is only about 80 mb, we feel inclined to believe that this determination is seriously in error. We have, therefore, attempted to get additional information from some indirect observations. There exist two investigations, one by Appa Rao and Lavakare$^{25}$ and the other by Appa Rao et al.$^{26}$ in which interactions in nuclear emulsions produced by $^4\text{He}$ nuclei of energy 225 MeV/$\text{n}$ and $\geq 5$ GeV/$\text{n}$ respectively have been investigated. From these two experiments it is found that the fraction of inelastic events which give rise to $^3\text{He}$ fragments are $0.073 \pm 0.016$ and $0.075 \pm 0.02$ at these two energies respectively. These values indicate that there could be no large increase in the cross sections over the range 225 MeV to a few GeV per nucleon. If it turns out, (as it seems likely), that the cross sections determined at 90 MeV and 300 MeV are correct and that the cross sections at energies $\geq 300$ MeV do not change, it would mean that when the energy increases from about 100 MeV to 300 MeV, the production rate of $^3\text{He}$ from $^4\text{He}$ in the cosmic radiation would decrease by as much as a factor of two.

The situation regarding the availability of experimental data at energies $> 200$ MeV for the production of $^3\text{H}$ in the proton bombardment of heavy targets is quite encouraging; these are summarised in Fig. 2.$^{27-34}$ It is seen that for all targets the production cross section increases beyond the threshold and reaches a constant value at high energies; the increase from about 200 MeV to 2 GeV is found to be a factor of 2 and 5 for carbon and iron targets respectively. It is also known that in such targets $\sigma_{^4\text{He}} \approx 1.2 \sigma_{^3\text{He}}$ and hence it becomes possible to estimate the total production rate of $^3\text{He}$ assuming all the $^3\text{H}$ decays into $^7\text{He}$. We have plotted in Fig. 3, as a function of incident energy, the quantity $J_i \cdot \sigma_f$, the product of $J_i$, the intensity of the incident nucleus or group of nuclei $i$ of the cosmic radiation near the source region, (as given in Table III of Paper I and Table II of this Paper), and $\sigma_f$, the cross section for the production of the fragment, $f$, under consideration. This figure clearly demonstrates the relation between incident energy and the production rate of $^3\text{H} + ^3\text{He}$ from $^4\text{He}$ and from $S$-nuclei; the following observations can be made from it: (i) for energies $\approx 300$ MeV, almost the entire amount of $^3\text{H} + ^3\text{He}$ results from collisions of $^4\text{He}$; and (ii) at energies above a GeV, about 20 % of $^3\text{H} + ^3\text{He}$ arises from collisions of $S$-nuclei.

In the above, we have attempted to investigate the production rate of $^3\text{He}$ in the cosmic radiation as a function of energy. It has been shown in the earlier
section that if the original radiation traverses an amount of matter \( x = 2.5 \text{ g/cm}^2 \) of hydrogen at 200 MeV/n, \( I_{\text{He}^8(\text{He}^+ + \text{He}^+)} \approx 0.07 \). This ratio is, however, strongly dependent on \( x \) and, therefore, to detect experimentally any effect due to the energy dependence of this ratio, it is also essential to fix the value of \( x \) from other observations such as \( I_{\text{LS}} \).

**§ 4. Production of \( L \)-nuclei as a function of energy**

In the calculations in Paper I, the value of \( I_{\text{LS}} \) observed for primary energies \( \geq 1.5 \text{ GeV/n} \) was used to estimate the amount of matter traversed by the radiation assuming that all fragmentations occurred at energies \( \geq 300 \text{ MeV/n} \). We have here examined the available literature on the production of the Li, Be and B nuclei from spallations at energies \( < 300 \text{ MeV} \). Here again the available data are very limited and hence only deductions of a qualitative or semi-quantitative nature are possible.

In Fig. 4 is summarised the experimental data available on the production cross section of \( \text{C}^{11} \) and \( \text{Be}^7 \) from the bombardment of various targets by protons of energy varying from about 20 MeV up to about 28 GeV.\(^{35,40} \) (\( \text{C}^{11} \) decays into \( \text{B}^{11} \) with a half life of 20 m and \( \text{Be}^7 \) which undergoes electron capture will be considered stable for cosmic ray purposes). The following conclusions can be drawn from Fig. 4 regarding the cross sections between about 20 and 300 MeV:

![Fig. 4 Energy dependence for the production cross section of \( \text{Be}^7 \) and \( \text{C}^{11} \) from C, N, F and Al targets.](image-url)
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(a) for any bombarding energy in this energy region, the cross section for the production of $^{11}\text{Li}$ decreases rapidly with target mass and is almost negligible for an Fe target compared to a C target, (b) the cross section for $^{12}\text{C} \rightarrow ^{11}\text{Li}$ has a very pronounced maximum at about 30–50 MeV and because of the abundance of $^{12}\text{C}$ in the primary radiation it is by far the most important individual source of $^{11}\text{Li}$, and (c) the cross section for $^{7}\text{Be}$ production is more or less constant in this energy region and rapidly decreases with increasing target mass.\(^{44}\)

Table III. Calculated and observed relative intensities of Li, Be and B nuclei.\(^{43}\)

<table>
<thead>
<tr>
<th>Energy region</th>
<th>Lithium</th>
<th>Beryllium</th>
<th>Boron</th>
</tr>
</thead>
<tbody>
<tr>
<td>20–100 MeV/n (calculated)</td>
<td>0.0</td>
<td>1.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Present work</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>300 MeV/n (calculated)</td>
<td>1.7</td>
<td>1.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Paper I</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.5 BeV/n in cosmic rays</td>
<td>2.1</td>
<td>0.94</td>
<td>3.0</td>
</tr>
<tr>
<td>O’Dell et al. (^{9})</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^{43}\) In these calculations all Be\(^{10}\) produced in spallations has been assumed to have decayed.

If, however, we restrict ourselves to energies in the region of 20–100 MeV, it can be said that the production of light nuclei from targets heavier than fluorine will be extremely small because of the high threshold energies involved for such targets. The most effective target will be carbon because of its proximity to the light nuclei in the periodic table while nitrogen and oxygen may also make some reasonable contributions. In the case of carbon targets at these bombarding energies, the total inelastic cross section is around 200 mb out of which the $^{12}\text{C} \rightarrow ^{11}\text{Li}$ process alone accounts for about 70–100 mb. From the work with 90 MeV neutrons\(^{45}\) it seems reasonable to say that all beryllium isotopes together can account for about 50 mb. Since at this energy all boron isotopes together could be expected to have a cross section comparable to that of $^{11}\text{Li}$ production, only a negligibly small cross section can be attributed to the production of lithium isotopes. This conclusion is also consistent with the general behaviour expected in nuclear reactions at such low energies. The situation in the case of nitrogen and oxygen targets is expected to be similar though the absolute values for the cross sections will be much lower. It, therefore, seems that in the energy region around 50 MeV the ratio of Li : Be : B should be about 0 : 1 : 3 after taking into account the decay of radioactive isotopes.

It is of interest to compare the relative frequencies of Li, Be and B isotopes produced at these energies with those calculated at energies $\geq 300$ MeV in Paper I and then examine the data obtained by O’Dell et al.\(^{9}\) for the cosmic radiation at energies greater than 1.5 GeV/n. The relevant values have been summarised in Table III. It is found that the experimental frequencies agree well with
those calculated for high energies. This observation, together with the fact that the value \( J_x \cdot \sigma \) for the process \( S_{\text{atm}}(p, x)C^{11} \) at energies \( \leq 100 \text{ MeV} \) in Fig. 3 is very high, strongly suggests that the amount of matter traversed by the radiation during the time of its acceleration from about 20 MeV/n to about 100 MeV/n should be very small compared to 2.5 \( \text{g/cm}^2 \) of hydrogen. If in future experiments the total and relative intensities of Li, Be and B nuclei in the primary radiation are determined at different energies between 200 MeV/n and 1.5 GeV/n, it will be possible to draw important and decisive conclusions of this nature regarding the acceleration of the radiation.

§ 5. Conclusions

From observations made in the earlier sections it is clear that while the study of the composition of the cosmic radiation can yield very interesting results, it requires for its proper understanding and interpretation many more reliable measurements than exist at present concerning the cross sections for the production of isotopes of light nuclei for various targets at various bombarding proton energies. Using the very restricted experimental data available at present, some conclusions have been derived here which are semi-quantitative and rather speculative in nature. They are however, presented because they already indicate interesting aspects which relate to galactic cosmic radiation and further focus attention on this type of work and its scope. The important results are as follows.

(i) Fragmentation parameters have been derived for the production of isotopes of nuclei with \( Z = 1 \) and 2 at an energy of about 200 MeV in the collision of typical cosmic ray nuclei with hydrogen in space. Using these values the composition of the cosmic radiation in the vicinity of the earth for nuclei of \( Z = 1 \) and 2 has been calculated assuming (a) the source composition obtained in paper I, (b) that the cosmic rays traversed a total of 2.5 \( \text{g/cm}^2 \) of hydrogen, and (c) all spallations occurred at an energy of about 200 MeV/n. The calculations indicate that while the proportion of H\(^3\) among singly charged particles is very small, that of He\(^3\) among doubly charged particles is large enough to be detected using experimental techniques available at present.

(ii) The production rate of He\(^3\) seems to be energy dependent and hence can be used to deduce information on the history of the cosmic radiation.

(iii) From the calculated relative production cross sections of Li, Be and B nuclei at energies between 20 and 100 MeV in the spallation of heavier nuclei and a comparison of these values with the corresponding figures observed experimentally at energies \( \geq 1.5 \text{ GeV/n} \) in the cosmic radiation in the vicinity of the earth, it seems highly probable that the amount of matter traversed by the radiation during the time of its acceleration from about 20 MeV/n to about 100 MeV/n is \( \leq 2.5 \text{ g/cm}^3 \) hydrogen.
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