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The Production of Radio Isotopes in Collisions of Cosmic Ray Nuclei with Hydrogen in Space and the Effect of Their Decay on the Composition of the Radiation Observed near the Earth

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The effects arising from the decay of radio isotopes produced in collisions of cosmic-ray nuclei with hydrogen in space, on the composition of the radiation observed in the neighbourhood of the earth have been investigated. The production cross sections for all the individual isotopes resulting from such collisions have been deduced using the available experimental data and an empirical relation due to Rudstam. The calculations show that: (a) The cosmic radiation should have traversed an amount of 2.5 ± 0.5 g/cm^2 of hydrogen between the source region and the earth; (b) the calculated relative intensities of Li, Be and B nuclei, produced in collisions of heavy nuclei with hydrogen, after taking decay effects into account, agree well with the observed relative intensities of these nuclei in the primary cosmic radiation in the vicinity of the earth; (c) nuclei with $Z=16$–19 are very rare near the source region compared to nuclei with $Z=10$–15 and $Z=20$–28; (d) the decay effects of radio isotopes give rise to pronounced even-odd effects for nuclei with $Z=10$–19 and (e) with the available experimental data on the composition of the primary cosmic radiation at the top of the earth's atmosphere and the partial cross sections deduced in this investigation, it is impossible to start with a pure Fe-source for the cosmic radiation and obtain the chemical composition near the earth by spallation processes.

§ 1. Introduction

A number of careful investigations have been carried out in recent years on the chemical composition of the cosmic radiation at the top of the atmosphere. In particular, O'Dell et al.[1] have used nuclear emulsions exposed at an atmospheric depth of 2.7 g/cm^2 of air on a balloon flight from Texas, U.S.A., ($\lambda=41°$N) and obtained good charge resolution in the case of nuclei with charge Z between 3 and 9; Daniel and Durgaprasad[2] have made a detailed study of nuclei with $Z\geq10$ at the same latitude. With this knowledge of the chemical composition of the cosmic radiation in the vicinity of the earth, one can ask the question as to what the composition at the source might be. For this it is necessary to allow for charge transformations suffered by the radiation during the time of acceleration and transit from the source to the earth. The charge transformations arise from collisions suffered by cosmic ray nuclei in the source region and with interstellar matter which is mainly hydrogen. Thus one requires to know the fragmentation parameters, (P_{ij}), associated with collisions of heavy nuclei with hydrogen nuclei (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). The results obtained will not be seriously in error even if helium atoms account for about 20% of the interstellar gas, because the P_{ij} values for hydrogen and helium targets are expected to be not very different. Experiments for determining P_{ij} values in hydrogen are now being carried out using subtraction methods; Evans et al.[3] are investigating the differences in the collisions of heavy primary nuclei in teflon and polyethylene whilst Badhwar et al.[4] have been studying such differences in graphite and paraffin targets. Attempts are also being made to estimate these parameters from hydrogen-like collisions in emulsions.

In the case of such laboratory experiments, the secondary nuclei and fragment products are studied close to their production point; thus if radioactive isotopes are produced they will not have a chance to decay unless they have lifetimes $\lesssim 10^{-11}$ sec. On the other hand, in the case of collisions in distant space the secondary radioactive products, which have lifetimes up to cosmic ray traversal times (of $\sim 10^7$ years), can decay; the daughter product arising in the decay can possess a charge or belong to a charge group*) different from that of the nucleus which emerged from the collision. As a result, the fragmentation parameters obtained from laboratory experiments of the type mentioned above will not be applicable to the cosmic ray situation. Corrections are required to take into account radioactive isotopes which change their charge number on decay. In order to do this it is essential to know the cross sections for the production of individual isotopes in collisions of cosmic ray nuclei with protons or for the identical but inverse process, the collision of protons with different target nuclei. The experimental data available at present for this is quite meagre. The production cross sections of individual isotopes can, however, be deduced indirectly by making use of some empirical relations. One such relation is due to Rudstam.[5] To use the Rudstam formula, one needs to know for each element either the cross section for the production of at least one of its isotopes or the total cross section for the production of all isotopes. The difficulties in using this relation are:

(i) The experimental cross sections are available only for a few targets and a few radioactive isotopes for incident protons of energies $\gtrsim 100$ Mev;

(ii) Even the available cross sections have sometimes large errors;

(iii) The Rudstam relation is energy dependent to some extent and is known to be applicable well only for heavy fragments.

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*) At present the heavy nuclei in the primary cosmic radiation are grouped by charge as follows: (i) the L-group consisting of Li, Be and B nuclei, (ii) the M-group consisting of C, N, O and F nuclei and (iii) the H-group consisting of nuclei with $Z \gtrsim 10$; the H-group is further divided into three sub-groups, H_3, H_2 and H_1, consisting of nuclei with $Z=10$–15, 16–19 and 20–28 respectively. Nuclei with $Z \gtrsim 6$ are also referred to as the S-group.

However, in view of the fact that there seems to be no better way at present, we have deduced a set of partial cross sections for all isotopes from different target nuclei. These calculations yield results which have a certain amount of internal consistency. They are the following:

(i) In the case of oxygen targets, measured cross sections are available for two residual nuclei, N^{13} and C^{11}, as also the total cross sections $\sigma_{O\to N}$ and $\sigma_{O\to C}$ for the production of elements N and C respectively. In these cases it is found that the cross sections for the production of N^{13} and C^{11} predicted by the Rudstam relation (using $\sigma_{O\to N}$ and $\sigma_{O\to C}$ as input) agree well with those measured (Table I). This seems to indicate that the Rudstam relation may be used with reasonable confidence for fragment nuclei up to carbon.

(ii) In the case of C, N and O targets bombarded by protons one can calculate, using the Rudstam relation, the difference between the total inelastic cross section and the cross section for all reactions which result in the production of a fragment at least as heavy as or heavier than lithium. This difference will be the cross section for reactions in which only α-particles, protons and neutrons are present as spallation products and can be directly compared with the complete disruption of an incident medium group nucleus into α-particles and protons in hydrogen-like collisions.[6] There appears to be good agreement. (In the calculations one has to exclude reactions which result in the production of Be^8 since it decays into 2α-particles with a lifetime of $\sim 10^{-15}$ sec.)

(iii) Using the calculated cross sections and an assumed composition at the source, we have estimated the composion at the top of the earth's atmosphere for a traversal of 2.5 g/cm^2 of hydrogen such that the value obtained for the ratio Γ_{LS}, of the number of L-nuclei to that of S-nuclei, is that experimentally observed. (The ratio of the abundance or intensity of nuclei of species A to that of species B is denoted by Γ_{AB}.) It is then found that the relative intensities of Li, Be and B nuclei corrected for decay agree well with that observed by O'Dell etal.[1]; the uncorrected values agree well with that got from hydrogen-like collisions of cosmic ray heavy nuclei in emulsion.

Even considering the various uncertainties involved, the values obtained from these calculations for the source composition and the amount of matter traversed are unlikely to be in error by more than 20 – 30%; it should be emphasized that for these calculations we have considered only cross sections at energies of a few hundred Mev and greater and assumed that the cross sections remain constant throughout (for energies >100 Mev).

Attempts have been made in the past to take into account effects due to the decay of unstable isotopes.[6),7),8] In all of these calculations, however, the principal aim was to estimate the amount of hydrogen traversed by the radiation and only the broad features of the fragmentation process were taken into account. No importance was attached to the detailed features of the chemical composition in the vicinity of the earth, such as the relative intensities of Li, Be and B nuclei, etc., which turn out to be sensitive to such decay effects.

The present calculations have been made as a result of a remark by Prof. B. Peters at the International Conference on Earth Storm and Cosmic Rays (Kyoto, Japan, Sept. 1961). He pointed out that the fragmentation parameters obtained by laboratory experiments (of the subtraction type) for collisions of cosmic ray nuclei with hydrogen may have to be modified to take into account decay effects before they can be used to determine the transformations suffered by the cosmic radiation during its lifetime.

We have in this work first obtained a complete set of cross sections using the available experimental data and the Rudstam relation; these are listed in Table I. We have then used these to deduce P_{ij} values applicable to the cosmic radiation. We have then obtained the source composition assuming that the radiation had no Li, Be and B nuclei to start with.

§ 2. Procedure

The first step is to obtain *the total inelastic cross sections and the partial cross sections for the production of individual isotopes* in collisions of protons with different target nuclei ($Z=6$—26). For this we have estimated these quantities separately for target nuclei of carbon, nitrogen and oxygen. (Fluorine, which is very rare compared to oxygen, has been included in oxygen.) Nuclei of H_3-group ($Z=10-15$) have been replaced by one nucleus of charge 13, and nuclei of H_1-group ($Z=20-28$) by a single nucleus of charge 26. (In view of the near absence in the vicinity of the earth of H_2-group of nuclei with $Z=16-19$, they have not been taken into consideration.) Partial cross sections have been estimated for the production, in the collisions, of isotopes right from Li up to the target element; these are given in Table I. The method of obtaining the cross sections is as follows:

(i) *Total inelastic cross sections*

It has been found that all experimental inelastic cross sections[9] for collisions of high energy protons with various target nuclei are consistent with an effective nuclear radius $r_0=1.20\times10^{-13}$cm. Therefore we have calculated the total inelastic cross sections assuming a relation $\sigma=\pi(r_0\times A^{1/3})^2$ cm^2 for various values of A, the mass number.

(ii) *Partial cross sections*

An adequate experimental data is not available at present to estimate the partial cross sections for the production of individual isotopes. It was therefore found necessary to make use of the relation due to Rudstam[5] which gives the relative cross sections for the production of isotopes of a given fragment element. If, therefore, the absolute value for one or more isotopes is known experimentally, the production of all the other isotopes of that fragment element can be estimated. According to Rudstam's formula,

$$\sigma(A_f, Z_f) = \exp\{P\cdot A_f - Q - R(Z_f - S\cdot A_f)^2\};$$

$\sigma(A_f, Z_f)$ is the cross section for the production of fragment isotope of mass number A_f and atomic number Z_f and P, Q, R and S are constants. P, Q and R are further related as follows:

$$e^{-Q} = P\cdot\sigma_{A_t}(t)\cdot(R/\pi)^{1/2}\{\exp(P\cdot A_t) - \exp(P\cdot A_t/2)\}^{-1},$$

where $\sigma_{A_t}(t)$ is the total inelastic cross section for a target of mass number A_t. The value of P has been determined by Barr[10] for an incident proton energy of 5.7 Gev and found to be 0.053. This value has been used in all our calculations. P is thought to be energy dependent to some extent but in the absence of precise information on this point, it has been assumed to be constant by us.

Table I. Proton-Carbon.
$\sigma_C(t) = 225.0$ mb
$P_{CX} = 0.35$

Isotopes	Decay mode	Cross section (mb) used	Experimental cross section (mb)
C^{11}	β^+	23.4	23.4,[16),17),18)] 26.6,[19)] 27.9±2.0,[20)] 21.7[28)]
C^{10}	β^+	0.67	0.67±0.5,[11)] 2.67[18)]
Totol (C)	—	24.1	
B^{11}, B^{10}, B^9?	Stable	48.4	118±13.0[11)]
B^8	$\beta^+\to 2\alpha$	0.67	≤1.0[11)]
Total (B)	—	49.1	
Be^{10}	β^-	6.8	6.8±1.6[11)]
Be^9	Stable	15.0	15.0±3.5[11)]
Be^8	2α	26.0	26.0±4.0[11)]
Be^7	EC	10.6	10.6,[16)] 14.5±4.3,[11)] 11.1,[21)] 11.0,[22)] 8.8±1.0[23)]
Total (Be)	—	58.4	
Li^9	β^-	0.20	0.20±0.20[11)]
Li^8	$\beta^-\to 2\alpha$	0.70	0.70±0.20,[18)] 0.82±0.42[11)]
Li^7, Li^6, Li^4?	Stable	40.0	40.0±7.0[11)]
Total (Li)		40.9	
He^6	β^-	0.60	0.60[24)] 2.54 ±0.96[11)]

Table I (cont'd). Proton-Nitrogen.
$\sigma_N(t) = 262.0$ mb
$P_{NX} = 0.13$

Isotopes	Decay mode	Cross-section (mb) used	Experimental cross section (mb)
N^{13}	β^+	10.9	10.9[16),18),25)]
N^{12}	β^+	7.5	7.5[22], 7.3,[27] 7.0,[26] 5.0,[26] 3.1[28]
Total (N)		18.4	
C^{13} }	Stable	46.8	
C^{12} }			
C^{11} }	β^+	13.0	13.0,*[22] 9.4,[27] 9.5,[7] 8.8,[24] 20.6[16]
C^{10}	β^+	1.92	
Total (C)	—	61.7	
B^{13}	β^-	2.7	
B^{12}	β^-	10.0	
B^{11} }			
B^{10} }	Stable	34.4	
B^{9}? }			
B^{8}	$\beta^+ \to 2\alpha$	1.5	
Total (B)	—	48.6	
Be^{10}	β^-	6.7	
Be^{9}	Stable	14.8	
Be^{8}	2α	25.8	
Be^{7}	EC	10.5	10.5,*[25] 11.0,[25] 14.0[22]
Total (Be)	—	57.8	
Li^{9}	β^-	0.20	
Li^{8}	$\beta^- \to 2\alpha$	0.63	0.55 ± 0.16[18]
Li^{7} }			
Li^{6} }	Stable	39.6	
Li^{4} }			
Total (Li)	—	40.5	
He^{6}	β^-	0.70	

Table I (cont'd). Proton-Oxygen.
$\sigma_O(t) = 287.0$ mb
$P_{OX} = 0.20$

Isotopes	Decay mode	Cross-section (mb) used	Experimental cross-section (mb)
O^{15}	β^+	37.0	37.0,*[16),18)] 21.06,[27] 22.0,[27] 33.0[22]
O^{14}	β^+	6.4	
Total (O)	—	43.4	
N^{15} }			
N^{14} }	Stable	52.3	
N^{13}	β^+	8.2	6.0,[22] 2.8,[27] 1.5[22]
N^{12}	β^+	1.9	

Table I. Proton-Oxygen (cont'd).

Isotopes	Decay mode	Cross section (mb) used	Experimental cross section (mb)
Total (N)	—	63.7	63.7*[29]
C^{15}	β^-	4.2	
C^{14}	β^-	12.6	
C^{13} } C^{12} }	Stable	37.2	
C^{11}	β^+	10.3	12.0,[22] 7.25,[27] 6.8,[27] 5.4[22]
C^{10}	β^+	1.6	
Total (C)	—	65.8	65.8*[29]
B^{13}	β^-	0.80	
B^{12}	β^-	2.5	
B^{11} } B^{10} } B^9? }	Stable	24.4	
B^8	$\beta^+\to 2\alpha$	0.34	
Total (B)	—	28.0	28.0*[29]
Be^{10}	β^-	3.0	
Be^9	Stable	6.3	
Be^8	2α	11.3	
Be^7	EC	4.7	
Total (Be)	—	25.2	(13.95*[29] + 11.3) = 25.2
Li^9	β^-	0.08	
Li^8	$\beta^-\to 2\alpha$	0.27	
Li^7 } Li^6 } Li^4 }	Stable	15.7	
Total (Li)	—	16.0	16.0*[29]
He^6	β^-	0.80	

Table I (cont'd). Proton-Aluminium.

$\sigma_{Al}(t) = 407.0$ mb

$P_{AlX} = 0.13$

Isotopes	Decay mode	Cross section (mb) used	Experimental cross section (mb)
$\sigma_{Al\to H_3}$	—	109.6	
F^{20}	β^-	5.9	
F^{19}	Stable	8.1	
F^{18}	β^+	5.3	(5.3, 6.3, 8.0, 8.4),[30] 7.7,[22] 6.5,[27] 4.7[27]
F^{17}	β^+	1.8	
Total (F)	—	21.1	

Table I (cont'd). Proton-Aluminium.

Isotopes	Decay mode	Cross section (mb) used	Experimental cross section (mb)
O^{19}	β^-	5.7	
O^{18}, O^{17}, O^{16}	Stable	54.8	
O^{15}	β^+	5.7	(5.7, 7.0),[30] 4.5[22]
O^{14}	β^+	0.88	
Total (O)	—	66.3	
N^{17}	β^-	0.71	
N^{16}	β^-	2.24	
N^{15}, N^{14}	Stable	6.08	
N^{13}	β^+	0.97	0.97, 1.1,[20] 1.7[22]
N^{12}	β^+	0.20	
Total (N)	—	10.9	
C^{15}	β^-	0.74	
C^{14}	β^-	2.06	
C^{13}, C^{12}	Stable	29.5	
C^{11}	β^+	4.9	4.9,[30] 2.4, 2.8,[31),32] 7.3,[33] 6.1,[30] 6.0[22]
C^{10}	β^+	1.2	
Total (C)	—	38.3	
B^{13}	β^-	1.2	
B^{12}	β^-	3.5	
B^{11}, B^{10}, B^9?	Stable	34.0	
B^8	$\beta^+ \rightarrow 2\alpha$	0.50	
Total (B)	—	39.2	
Be^{10}	β^-	5.5	
Be^9	Stable	12.0	
Be^8	2α	20.8	
Be^7	EC	8.5	(8.5, 8.2, 10.8)[30], 0.9[22], 1.4[31,32]
Total (Be)	—	46.8	
Li^9	β^-	0.21	
Li^8	$\beta^- \rightarrow 2\alpha$	0.74	
Li^7, Li^6, Li^4?	Stable	42.1	
Total (Li)	—	43.1	
He^6	β^-	1.3	1.3[24]

Table I (cont'd). Proton-Iron.
$\sigma_{Fe}(t) = 662.0$ mb
$P_{FeX} = 0.06$ (only Be^8)

Isotopes	Decay mode	Half life	Cross section (mb) used	Experimental cross section (mb)
$\sigma_{Fe \to H_1}$	—	—	299.1	
$\sigma_{Fe \to (H_2, H_3)}$	—	—	205.3	
F^{20}	β^-	11.0m	4.20	
F^{19}	Stable	—	5.60	
F^{18}	β^+	112.0m	3.50	3.4,[21] 1.0[30].
F^{17}	β^+	66.0s	2.00	
Total (F)	—	—	15.3	
O^{19}	β^-	29.0s	1.8	
O^{18}, O^{17}, O^{16}	Stable	—	17.2	
O^{15}	β^+	124.0s	1.8	
O^{14}	β^+	72.0s	0.30	
Total (O)	—	—	21.0	
N^{17}	β^-		1.6	
N^{16}	β^-	7.40s	5.2	
N^{15}, N^{14}	Stable	—	14.0	
N^{13}	β^+	10.0m	2.2	
N^{12}	β^+	—	0.40	
Total (N)	—	—	23.3	
C^{15}	β^-	—	0.10	
C^{14}	β^-	5.6×10^3y	0.30	
C^{13}, C^{12}	Stable	—	4.2	
C^{11}	β^+	20.0m	0.70	≤ 0.65,[34] ≤ 3.1[21]
C^{10}	β^+	19.0s	0.16	
Total (C)	—	—	5.3	
B^{13}	β^-	—	—	
B^{12}	β^-	0.02s	2.5	
B^{11}, B^{10}, B^9?	Stable	—	24.4	
B^8	$\beta^+ \to 2\alpha$	0.80s	0.33	
Total (B)	—	—	27.2	
Be^{10}	β^-	2.6×10^6y	4.0	
Be^9	Stable	—	8.6	
Be^8	2α	$1.4 \times 10^{-16} < t < 4 \times 10^{-15}$s	15.0	
Be^7	EC	53d	6.1	10.0,[29),31] 11.0,[34] 11.9,[19] 16.5,[21] 2.9[23]

Table I. Proton-Iron (cont'd)

Isotopes	Decay mode	Half life	Cross section (mb) used	Experimental cross section (mb)
Total (Be)	–	–	33.8	
Li^9	β^-	–	0.05	
Li^8	$\beta^- \to 2\alpha$	0.08s	0.53	
Li^7 } Li^6 } Li^4? }	Stable	–	30.3	
Total (Li)	–	–	30.9	
He^6	β^-	0.80s	4.2	4.0[24]

Q is dependent on A_t and has a value -0.017 for Cu. R and S are constants and the values used for these are 1.47 and 0.47 respectively. The Rudstam formula is well applicable in the case of heavy fragments; however, we have used it in the case of fragments as light as carbon; some justification has been given for this in the previous section.

In Table I we have summarized the various cross sections; we have also indicated in this table the available experimental data. Cross sections obtained at energies greater than about 300 Mev have been used wherever available. The values marked with asterisks are those which have been used in the Rudstam formula. Since the usefulness of our calculations regarding the effect of the decay of radio-isotopes on the charge composition of the cosmic radiation depends solely on the correctness of the cross sections, we will now critically examine the different sets of values used by us.

a) *Proton-carbon collisions*

This is a well-studied reaction and experimental partial cross sections are available for all isotopes. There is, however, an unreliable value for the $(B^{11}+B^{10})$ cross section which is far too large to be correct. This large value probably arises because of the fact that the experiment was made by neutron bombardment of carbon and under certain assumptions.[11] We have therefore assigned a reasonable value of 48 mb for the $(B^{11}+B^{10})$ cross section from a consideration of the cross section for C^{11}. This arbitrary assignment is justified by the fact that the ratio of the cross section $(\sigma_{C\to Be^8}+\sigma_{C\to\alpha,p})$, for the complete breakup of carbon into α-particles and singly charged particles, to the total cross section, $\sigma_C(t)$, is equal to 0.35, which is in agreement with the value of P_{CX} given by Aizu et al. for hydrogen-like collisions. (The above ratio is of course the same as P_{CX}, the fragmentation parameter corresponding to complete breakup of carbon, which includes the cross section for the production of Be^8 since in laboratory experiments the nucleus will decay before traversing any measurable distance.)

b) *Proton-nitrogen collisions*

The partial cross sections for nitrogen and carbon isotopes were estimated from the measured cross sections for N^{13} and C^{11} and using Rudstam's relation. The partial cross sections of the Be isotopes were obtained using the measured absolute cross section for Be^7 and the relative cross sections for the production of Be isotopes in the bombardment of carbon. The cross sections for the boron and lithium isotopes were then obtained using the relative total cross sections for B, Be and Li fragments and the relative cross-sections for the isotopes of B, Be and Li obtained in the case of carbon targets. That this method gives reasonable cross sections for individual isotopes can be seen from the fact that the cross section of 0.63 mb for Li^8 deduced by this method agrees well with the experimental value of 0.55 ± 0.16 mb.

c) *Proton-oxygen collisions*

Partial cross sections for the isotopes of O, N and C were obtained using the measured cross sections of O^{15}, the measured total cross sections of N and C isotopes[11] and the Rudstam relation. The use of the Rudstam relation for isotopes of even carbon is justified from the fact that the calculated values of 8.2 mb and 10.3 mb for N^{13} and C^{11} respectively are consistent with the experimental values given in Table I. The partial cross sections for the Li, Be and B isotopes were obtained by making use of the experimental total cross sections for Li, Be and B and the relative cross sections for their isotopes in the case of carbon targets. The value of P_{OX} obtained by subtraction is 0.20.

d) *Proton-aluminium collisions*

Since it is now known that nuclei with $Z=16-19$ are almost absent in the primary radiation,[2] we have replaced the group of nuclei with $Z=10-19$ by the aluminium nucleus. In the absence of experimental values for any Al isotope we have tried to make a reasonable guess for this cross section. Cross sections for the isotopes of Mg, Na, Ne, F, O, N and C were calculated using the measured cross sections for Mg^{27}, Na^{24}, Ne^{24}, F^{18}, O^{15}, N^{13} and C^{11} and Rudstam's relation.

The cross sections for the Be isotopes were calculated using the measured cross section for Be^7 and the relative values obtained in the case of carbon. The total cross section for Li, Be and B fragments were then calculated using the relative values (81 : 88 : 71) obtained in the case of Cu targets by Barr[10]; the values for the Li and B isotopes can then be assigned using the relative values obtained in the case of carbon. By subtraction the value of P_{AlX} is found to be 0.13.

e) *Proton-iron collisions*

The very heavy nuclei ($Z=20-28$) have been replaced by iron. Since the measurements are available only for copper, we made use of them after reducing the measured values by the ratio of the total cross sections $\sigma_{Fe}(t)/\sigma_{Cu}(t)$. We then made use of measured cross sections (mainly due to Barr[10]) for various isotopes and Rudstam's relation and calculated all the necessary cross sections of interest up to carbon. We next assumed that the cross section $\sigma_{Fe\to\alpha,p}=0$ and obtained the cross section $\sigma_{Fe\to(Li,Be,B)}$ which was divided in the ratio of 81 : 88 : 71 among Li, Be and B nuclei respectively. The partial cross sections were then distributed as obtained for carbon targets.

Remarks

The following remarks regarding the cross sections given in Table I are necessary: (i) In the absence of measured cross sections for the production of individual isotopes of Li, Be and B nuclei and the inapplicability of Rudstam's relation to these nuclei, it was necessary to make use of the relative cross sections for the isotopes of these nuclei obtained with carbon targets. However, except in nitrogen (which is known to be much rarer than C and O), in all other targets the total cross sections for Li, Be and B nuclei have been obtained by other methods described earlier. Even in the case of nitrogen the cross section calculated for Li^8 agrees very well with the experimental value as has been pointed out in § 2, (ii) b. (ii) In all these calculations, the possibility of ejection of two isotopes both with $Z\geq 3$ has not been taken into account. This effect is negligible for the medium group of nuclei while even for Fe it is not more than about 2%.[12] However, the effect of this on our final calculations is small compared to other uncertainties. (iii) In the absence of experimental measurements for B^{13} and B^{12} isotopes, "reasonable" estimates of their cross sections have been made. These cross sections are expected to be very small compared to that of stable isotopes and hence cannot seriously affect the final results.

§ 3. Results

(a) *Calculated fragmentation parameters in hydrogen*

We have made use of the cross sections given in Table I to determine the fragmentation parameters in hydrogen for the various groups of nuclei of the primary radiation; these are summarized in Table II. These values have been deduced with and without correction for the decay of unstable isotopes and compared with the values obtained for hydrogen-like collisions in nuclear emulsions. It can be seen from this table that the fragmentation parameters attributed to groups of nuclei are not very sensitive to the decay effects of radioactive isotopes. However, as will be seen in the next section, the relative frequency of Li, Be and B nuclei among the L-group depends quite critically on the decay effects. Therefore, a comparison of the relative frequency of Li, Be and B nuclei expected on the basis of our calculations with that observed experimentally will constitute a check of the dependability of the derived cross sections.

(b) *The composition of the cosmic radiation*

In Table III, column 4, is summarized the chemical composition observed near the top of the atmosphere from balloon flights made from Texas, U.S.A. ($\lambda=41°$N). The intensities of elements with $Z\leq 9$ were obtained from the investigation of O'Dell et al.[1] and for heavier elements from that of Daniel and Durgaprasad.[2] All abundances are given with respect to carbon which has been taken as 100. The value of Γ_{LS} on the basis of this table is 0.185 which may be compared with the experimental value of 0.18 according to O'Dell et al.[1]

i) *Amount of matter traversed and the ratio Γ_{LS} near the earth*

We have adjusted the composition at the source region and the total amount of matter (hydrogen) traversed such that using the partial cross sections derived earlier and allowing for decay effects (including complete decay of Be^{10}) we

Table II.
Fragmentation parameters in hydrogen.

Primary \ Secondary		H: H_1 ($Z=20-28$)	H: H_2 ($Z=16-19$)	H: H_3 ($Z=10-15$)	M ($Z=6-9$)	L ($Z=3-5$)
Fe ($Z=26$)	1	0.45	0.15	0.15	0.10	0.14
	2	0.44	0.16	0.14	0.09	0.12
	3	0.40	0.55 (H_2+H_3)		0.05	0.00
Al ($Z=13$)	1			0.27	0.34	0.32
	2			0.28	0.32	0.27
H_3+H_2 ($Z=10-19$)	3			0.50	0.30	0.15
M ($Z=6-9$)	1				0.25	0.48
	2				0.32	0.48
	3				0.15	0.40

1. P_{ij} values uncorrected for decay.
2. P_{ij} values corrected for decay.
3. P_{ij} values in hydrogen-like collisions.[6]

obtain the chemical composition observed experimentally. The abundances of the H_3, H_1 and C, N, O nuclei at the source are adjusted to give the right composition at the earth. (In our calculations isotopes undergoing electron capture have been assumed to be stable.) Because of the small amount of matter traversed we have considered only the first generation of isotopes arising in

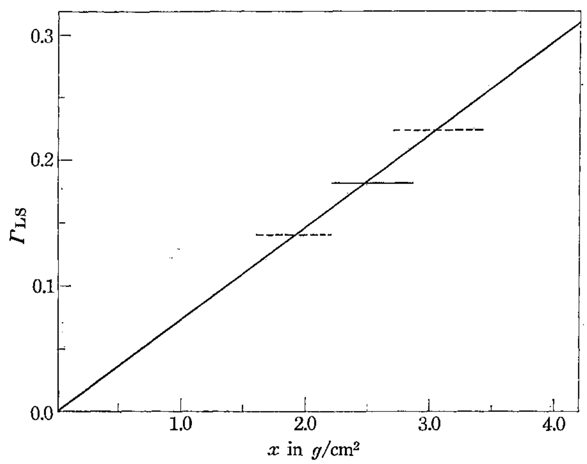

Fig. 1. The dependence of the ratio Γ_{LS} on the amount of hydrogen traversed by the cosmic radiation using the cross sections deduced in this paper. The experimental value of $\Gamma_{LS}=0.18\pm0.04$ according to O'Dell et al.[1] at the top of the atmosphere is also shown in the figure.

collisions and the decays. A more precise calculation may be made when the cross sections and the chemical composition of the cosmic radiation are known better. However, since the quantity P_{ML} is the decisive factor in determining the secondary production of L-nuclei, the amount of matter traversed, x, is very insensitive to the detailed composition assumed at the source. The values given in Table III were obtained for 2.5 g/cm² of hydrogen. In Fig. 1 we have plotted the calculated ratio Γ_{LS} as a function of x and also indicated the experimental value of 0.18 ± 0.04 according to O'Dell et al.[1] From this it can be seen that the amount of hydrogen traversed by the cosmic radiation is 2.5 ± 0.5 g/cm².

Table III.
Assumed amount of hydrogen traversed=2.5 g/cm²

Element (1)	Universal abundance (Suess & Urey) (2)	Calculated source composition (3)	Experimentally observed composition at top of the atmosphere (4)	Calculated composition at the top of the atmosphere	
				Corrected for decay (5)	Uncorrected for decay (6)
H_1 ($Z=20-28$)	19.0	23.0	19.4	19.5	18.3
H_2 ($Z=16-19$)	15.3	0.0	$\leq$3.1	3.2	3.0
H_3 ($Z=10-15$)	328.6	41.0	39.1	38.6	36.1
Oxygen + Flourine	614.2	75.0	72.6	69.1	70.0
Nitrogen	188.6	19.0	32.3	31.9	24.7
Carbon	100.0	100.0	100.0	100.0	100.0
Boron	6.85×10^{-4}	0.0	24.6	24.7	16.0
Beryllium	5.72×10^{-4}	0.0	7.7	8.5	9.8
Lithium	2.86×10^{-5}	0.0	17.1	14.3	13.3

ii) *The relative intensity of Li, Be and B nuclei*

Having adjusted the ratio Γ_{LS} by a suitable choice of x, we can now examine the relative intensity of Li, Be and B nuclei among the L-group allowing for and without allowing for decay effects. The relative intensity after allowing for decay effects should be compared with that in the cosmic radiation in the neighbourhood of the earth. It is seen from Table III, columns 4 and 5, that this agreement is remarkably good. (It must be emphasized that the adjustment of the source composition was carried out only to account for the ratio Γ_{LS} and not the relative proportion of Li, Be and B nuclei.) The calculated relative proportions of Li, Be and B nuclei without allowing for decay effects (Table III, column 6) can be compared with that seen in the case of laboratory experiments. For this we selected hydrogen-like collision events observed by Rajopadhye and Waddington[13] and Cester et al.[14] in nuclear emulsions; the actual number of Li, Be and B fragments observed are 11, 10 and 10 respectively. This should be compared with 11.0 : 8.1 : 13.2 (from column 6, Table III) predicted from the calculated values. There is reasonable agreement between the calculated and observed values of the relative intensities of Li : Be : and B nuclei, on the one hand where the calculations allow for decay effects and the comparison is with the cosmic radiation at the top of the atmosphere and on the other hand where no decay effects are taken into account and the comparison is with the fragmentation of heavy nuclei in condensed media (hydrogen-like collisions in emulsion). This gives some confidence in the correctness of the partial cross sections used.

iii) *Even-odd effect in the heavy group of nuclei*

We have also tried to evaluate the effect of the decay of radioactive isotopes with $Z=10-19$ arising from collisions of Fe nuclei with hydrogen. It is seen that the relative intensities of K, A, Cl, S, P, Si, Al, Mg, Na and Ne arising out of Fe interactions after allowing for decay effects are 5.3, 9.1, 2.9, 7.7, 2.9, 6.9, 2.4, 6.1, 2.1 and 6.0 respectively while without decay effects they are 7.7, 7.5, 5.7, 4.9, 4.7, 4.5, 4.2, 4.1, 3.9 and 4.3. Thus it is seen that, on the average, in the case of stable isotopes, the ratio of elements with even charge to those with odd charge is about 3 while according to Suess and Urey[15] it is about 10 in the universal abundance. Thus it can be seen that the even-odd effect persists to a great extent even among elements which arise from fragmentation of heavy nuclei of the primary radiation; a similar effect is also seen in the case of fragmentation of Al; this principally arises from decay effects.

iv) *The near absence of H_2 − nuclei ($Z=16-19$)*

The value of the ratio $\Gamma_{H_2H_3}=0.083$ predicted near the earth assuming that there are no H_2-nuclei near the source region agrees well with the value $\Gamma_{H_2H_3}=0.08\pm0.08$ obtained by Daniel and Durgaprasad.[2] From this it would appear that H_2-nuclei are almost absent near the source region, the upper limit for its abundance being one third of the H_1-group.

v) *The Fe-source model*

It is now certainly impossible to start only with Fe-nuclei at the source and allow them to undergo sufficient amount of spallation to explain the observed chemical composition at the top of the atmosphere. This conclusion can now be made with confidence because of the near absence of H_2-nuclei and the low intensity of L-nuclei compared with H_3 and M-nuclei as given in Table III, column 4. If all nuclei with $Z<20$ resulted from the spallation of Fe-nuclei, then it can be seen from Table II that it is not possible to obtain the chemical composition as observed at the top of the atmosphere.

vi) *Universal abundance and the calculated source composition*

The universal abundance according to Suess and Urey[15] is given in Table III, column 2. It is found that the only similarity between this and the calculated source composition given in column 3 is the ratio of the H_1 nuclei to carbon nuclei which is found to be about 0.2 for both. The importance of this observation, if any, is not clear at present.

§ 4. Conclusions

The important conclusions which follow from the calculations may be summarized as follows:

(i) A complete set of partial cross sections for all isotopes with $Z\geq 3$ resulting from the collisions of high energy protons with C, N, O, Al and Fe targets has been derived by making use of all available measured cross sections and the empirical relation given by Rudstam. These calculated values are to some extent uncertain but they have an internal consistency amongst themselves and also in relation to allied cross sections.

(ii) The cross sections derived as above have been used to determine the amount of hydrogen traversed by the cosmic radiation between the source region and the earth ensuring at the same time that the total flux of Li, Be and B nuclei observed experimentally can be acounted for; this assumes that there is no Li, Be and B near the source. The amount of matter traversed is found to be 2.5 g/cm^2 of hydrogen and almost certainly between 2 and 3 g/cm^2. This value is very insensitive to the composition attributed to the radiation in the source region.

(iii) The relative intensities of Li, Be and B nuclei produced in the collisions of heavy nuclei with hydrogen have been calculated. The calculated values after taking decay effects into account agree well with the observed relative intensities in the primary cosmic radiation in the vicinity of the earth. The values calculated without accounting for decay effects agree with observations in the case of hydrogen-like collisions in nuclear emulsions.

(iv) It is found that nuclei with $Z=16-19$ are very rare near the source region compared to nuclei with $Z=10-15$ and $20-28$.

(v) The decay effects of radio isotopes give rise to a pronounced even-odd effect for nuclei with $Z=10-19$ and thus account for observations in the cosmic radiation.

(vi) It is now certain that it is not possible to start with a pure Fe-source and obtain the chemical composition of the cosmic radiation near the earth by spallation processes.

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