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INTERNATIONAL CONFERENCE ON COSMIC RAYS AND THE EARTH STORM Part III

III-1-20. Present State of Knowledge of the Composition of the Primary Cosmic Radiation

C. J. WADDINGTON*

NASA Goddard Space Flight Center, Maryland, U.S.A.

This article summarizes the data on the composition of the primary cosmic radiation reported at this meeting and relates it to that available previously. It is mainly on a more detailed summary of the earlier data presented at the 1961 Varenna Summer School, Waddington (1961a).

Before considering the experimental data we should discuss, in the most general terms, the significance of the composition to our present concepts of the origins and modes of propagation of the particles of the primary radiation. It is consistent with the experimental evidence to state that among those particles arriving in the vicinity of the earth are examples of all the stable isotopes up to iron, and probably those of the heavier elements as well, see, for example, the results reported by Alvial at this conference. The relative abundances of these isotopes are not, in general, well known at this time, and only the crude features of the charge distribution can be discussed with any degree of confidence. However, some attempts have been made to investigate isotopic adundances of a few of the represented elements, and these are discussed by Kaplon in this Conference.

The most significant of the general features of the charge distribution appears to be the marked divergence of that observed from that assumed to be typical of the universe as a whole. The reasons for the divergence are thought to be twofold. Firstly, it is assumed that the nuclei which are accelerated in cosmic ray sources are not a representative sample, though whether this is due to a preferential acceleration mechanism, or to a singularity in the composition of the source themselves is not clear. Secondly, the nuclei emitted by the sources, from the moment they receive any appreciable suprathermal energies, have to pass through interstellar and source material before they can reach the earth. Consequently, because of nuclear interactions, the observed charge distribution is degraded from that existing at or near the source. It is thus of considerable interest to be able to estimate the amount of material traversed and the effect this has had on the original charge distribution. Such an estimate can in principle be made by looking in the primary cosmic radiation for isotopes or elements which are believed to be extremely rare in the sources. Possible examples are H^2, He^3, and L-nuclei, Li, Be and B; and F. Notice though that Burbidge and Burbidge discussed at this conference evidence that some stars contain an appreciable concentration of He^3 in their atmospheres.

The charge distribution observed in the vicinity of the earth is thus a reflection of the composition of the sources, the mechanism of acceleration, and the traversal of the interstellar and source material.

The Charge Distribution Above 4.5 BV.

We shall start by considering the experimental data on the charge distribution of those particles with a rigidity sufficient to permit them to be observed over Texas or Northern Italy, where there the geomagnetic threshold is 4.5 BV.

1) *Hydrogen Nuclei*

Intensities of these nuclei have been measured with counters, McDonald and Webber (1959) and emulsions, Waddington (1960a, and at this Conference) and lead to consistent results. These experiments give a value of the intensity at a time of low solar activity of:

$$J_p{}^0 = 610 \pm 30 \text{ hydrogen-nuclei/m}^2\text{.ster.sec.}$$

There is little or no experimental data on the isotopic composition of the hydrogen nuclei, although experiments to investigate this problem have been discussed in the literature e.g. Daniel *et al.* (1960).

2) *Helium Nuclei*

The intensity of helium-nuclei with $R \geq 4.5$ BV has been measured by many investigators

* National Aeronautics and Space Administration Research Associate.

and the mean value during solar minimum has been calculated to be, Waddington (1960b)

$J_{\alpha^0}=88\pm2$ helium nuclei/m². ster. sec.

It is found, e.g. Webber (1961) that the ratio of the intensities of hydrogen and helium nuclei above a given rigidity, $\Gamma_{p\alpha}(R)$ is constant down to at least 1.0 BV, with a value of 7.0±0.2. It is a result of this constancy of $\Gamma_{p\alpha}(R)$ that the ratio above a given energy per nucleon $\Gamma_{o\alpha}(E)$, varies unless $E\gg m_0 c^2$, decreasing with decreasing E. When $E\gg m^0c^2$, $\Gamma_{p\alpha}(E)=19.8\pm1.2$, and this is an upper limit to this ratio at any energy.

The ratio above a given *total* kinetic energy, $\Gamma_{p\alpha}(U)$, is derived from $\Gamma_{p\alpha}(E)$, and when $E\gg m_0 c^2$ has a value 2.48±0.15.

3) $Z\geq3$ *Nuclei*

a) Γ_{LS}

It at last appears that essential agreement has been reached among all major groups working on this problem that there is a finite intensity of L-nuclei in the primary cosmic radiation. The values found in a number of recent experiments performed near the top of the atmosphere for the ratio of L-nuclei to all heavier nuclei, S-nuclei, $\Gamma_{LS}(R, x)$, are shown in Fig. 1 as a function of the depth of overlying atmosphere. Included here are the results of Shapiro *et al.*, reported at this Conference. It can be seen that all these experimental results are consistent with a unique growth curve through the atmosphere.

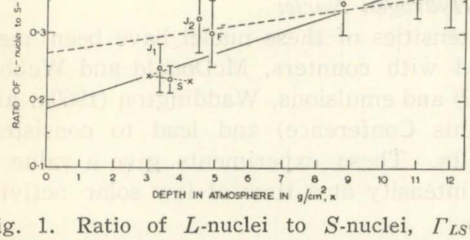

Fig. 1. Ratio of L-nuclei to S-nuclei, $\Gamma_{LS}(x)$, plotted as a function of x, the depth in the atmosphere, in g/cm². Points are: W, Waddington (1957); K, Koshiba *et al.* (1958); G, Garelli *et al.* (1960); F, Freier *et al.* (1959); J, Van Heerden and Judek (1960), J_1 $\theta\leq35°$, J_2 $30°<\theta\leq60°$; and S, O'Dell *et al.* (1961); crosses show $\theta\leq30°$ and $30°<\theta\leq60°$. Dotted straight line shows diffusion extrapolation to top of atmosphere, normalized to point W, while solid straight line is the least squares fit.

This growth curve may be constructed theoretically by using the somewhat uncertain experimental parameters which describe the absorption and production of nuclei in the atmosphere, or directly from the experimental values of $\Gamma_{LS^{(x)}}$. The first approach is shown on Fig. 1 as the dashed curve constructed from the parameters given previously, Waddington, (1960b) and arbitrarily normalized to the point, W, at $x=12$ g/cm². This leads to $\Gamma_{LS^{(0)}}=0.27$. The second approach consists of fitting a straight line by the method of least squares and produces the solid line shown in Fig. 1. This gives $\Gamma_{LS^{(0)}}=0.19\pm0.2$. It may be noticed that the difference between these two curves is almost entirely due to one experimental result, that of Shapiro *et al.* (1961), and it is therefore entirely reasonable to take as the best value $\Gamma_{LS^{(0)}}=0.21\pm0.05$, where this error is a 90% confidence limit rather than a standard deviation. Results reported by Daniel and Durga Prasad of the Tata Institute at this Conference agree with this conclusion and show that this group also now accept the existence of a finite intensity of L-nuclei.

Other experiments bearing on this problem have been reported at this Conference by Zhdanov *et al*, who used emulsions exposed under 8–10 g/cm² of material in a Sputnik and by McDonald and Webber, who flew cerenkov-scintillator arrays at ~6 g/cm². In both cases values of $\Gamma_{LS}(x)\sim0.3$ were reported for $R\geq4.5$ BV, which, after correction for overlying material, would be quite consistent with the value given above for $\Gamma_{LS^{(0)}}$.

b) Γ_{HM}

Fig. 2 shows results similar to those Fig.

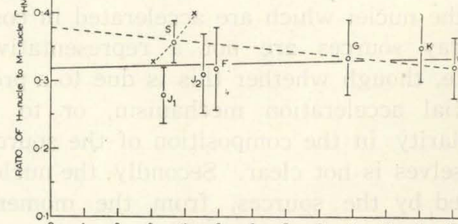

Fig. 2. Ratio of H-nuclei to M-nuclei, $\Gamma_{HM}(x)$ plotted as a function of x, the depth in the atmosphere. Experimental points and lines have similar significance as in Fig. 1.

1 but for $\Gamma_{HM^{(x)}}$, and a similar approach to the determination of $\Gamma_{HM^{(0)}}$ suggests a best value of 0.34±0.04. This may be compared with the value of 0.30±0.02 reported by Daniel and Durga Prasad at this Conference.

c) *Individual Nuclei*

The intensities of the individual nuclei are not too well determined at this time, due to the uncertain corrections that must be made for the overlying material. By using a similar approach to that employed to determine Γ_{LS} and Γ_{HM} least mean square fits can be obtained for the percentage abundance of individual nuclei, Γ_{ix} values, where x represents all nuclei with $Z \geq 3$. These values are shown in Table I, and must have standard errors of between 20 and 30%. Also shown in this table are the values reported by McDonald and Webber at this Conference for $R \gtrsim 2$ BV and $x \sim 6$ g/cm². Apart from the large difference for Be-nuclei, which may be due to a rapid production of these nuclei in the atmosphere, as is suggested by the least mean squares analysis, the agreement between these two sets of figures is very reasonable. Both illustrate the interesting feature that nitrogen appears to be significantly less abundant than either carbon or oxygen.

Table I. Intensities of individual nuclei.

	From emulsion data 20-30% percentages	McDonald and Webber percentages
Li	3.9	—
Be	1.7	6.7
B	11.6	10.1
C	26.0	28.6
N	12.4	13.3
O	17.9	17.9
F	2.6	—
$Z \geq 10$	23.9	16.6

For the H-nuclei the relative abundances given in my review article Waddington (1960b), while not particularly reliable, do not appear to have been improved on. At this Conference the Bombay group have again directed attention to the apparent paucity of elements with $15 \leq Z \leq 19$ which was shown in that review.

It thus appears that there begins to be significant evidence for detailed structure in the charge distribution which is hardly compatible with the suggestion that this distribution is the result of fragmentation after a preferential acceleration of heavy nuclei.

d) *Intensities*

In order to compare these results with those on the hydrogen and helium nuclei it is necessary to determine the absolute intensities of the various groups. This is made rather difficult by the fact that neither of the two experiments on $Z \geq 3$ nuclei of high statistical weight performed at $x < 5$ g/cm² can be used, due to an uncertainty in the flight time, while the other experiments were performed during different levels of solar activity. However, by using neutron monitor data to establish this level, the published intensity values can be scaled up or down to a standard level. Such a procedure results in values* typical of a period of low solar activity.

$J_L{}^0 = 1.60 \pm 0.40$ nuclei/m²ster. sec.

$J_M{}^0 = 5.70 \pm 0.28$ nuclei/m²ster. sec.

$J_H{}^0 = 1.94 \pm 0.25$ nuclei/m²ster. sec.

From these intensities, and those given previously for $J_p{}^0$ and $J_\alpha{}^0$, the various values of $\Gamma_{i\alpha}$ and Γ_{ip} have been calculated and are given in Table II.

These ratios have been compared in Table III with the similar ratios derived for the so called cosmic abundances of elements in the universe, Φ_{ij}, derived by Suess and Urey (1956), and by Cameron (1959).

Charge Distribution at Low Rigidities.

At rigidities below 4.5 BV solar modulation of the galactic radiation and solar injection of particles becomes progressively more important. However, if injection effects are neglected, then it appears that $\Gamma_{p\alpha}(R)$ values probably remain constant down to at least $R > 1$ BV. Thus, a knowledge of the energy spectrum, and hence the rigidity spectrum, of one of these components, permits the calculation of the other. In practice, the energy spectrum of the helium nuclei is the best known experimentally. It should be noticed however, that Pomerantz and Witten, this Conference, find that the energy spectrum of the high energy, $E > 3.0$ BeV per nucleon, S-nuclei varies quite rapidly over periods of a few weeks. It is not yet established whether the other components show a similar variation, but this observation suggests that it is

* See Varenna Summer School report for details of this calculation.

Table II

	$\Gamma_{i\alpha}$ (R, o)	$\Gamma_{i\alpha}$ (E, o)	$\Gamma_{i\alpha}$ (U, o)*	A
P	7.0±0.2	19.8±1.2*	2.48±0.15	1
L	0.018±0.005	0.018±0.005	0.070±0.02	9.9
M	0.065±0.004	0.065±0.004	0.425±0.026	14.0
H	0.022±0.003	0.022±0.003	0.46±0.06	30.5
	Γ_{ip} (R, o)	Γ_{ip} (E, o)	Γ_{ip} (U, o)*	
α	0.143±0.004	0.050±0.002	0.45±0.02	4
L	0.0026±0.0007	0.00090±0.00003	0.029±0.008	9.9
M	0.0093±0.0006	0.0033±0.0002	0.17±0.01	14.0
H	0.0031±0.0004	0.0011±0.0002	0.19±0.03	30.5

* For $E \gg m_0c^2$

Table III. Comparison of Cosmic Abundances and Cosmic Ray Abundances

	P	L	M	H	VH
$\Phi_{i\alpha}$ (Suess and Urey)	13.0	4.7 10^{-8}	1.03 10^{-2}	3.6 10^{-3}	2.3 10^{-4}
$\Phi_{i\alpha}$ (Cameron)	6.6	3.8 10^{-8}	9.6 10^{-3}	8.9 10^{-4}	4.7 10^{-5}
$\Gamma_{i\alpha}$ (E)	19.8*	1.8 10^{-2}	6.5 10^{-2}	1.6 10^{-2}	6.0 10^{-3}
	α	L	M	H	VH
Φ_{ip} (Suess and Urey)	7.7 10^{-2}	3.6 10^{-9}	7.9 10^{-4}	2.8 10^{-4}	1.8 10^{-5}
Φ_{ip} (Cameron)	1.5 10^{-1}	5.7 10^{-9}	1.5 10^{-3}	1.3 10^{-4}	7.1 10^{-6}
Γ_{ip} (E)*	5.05 10^{-2}	9.0 10^{-4}	3.3 10^{-3}	8.0 10^{-4}	3.0 10^{-4}

* These values are somewhat doubtful due to the uncertain nature of the proton energy spectrum, and the composition of the α-particles, but have been calculated assuming $E \gg m_0c^2$.

very dangerous to compare results obtained from experiments made at different times.

At these low rigidities the determination of Γ_{ij} values for $Z \geq 3$ nuclei is experimentally more difficult than at higher rigidities, so that some care is necessary in assessing the value of those experimental results reported thus far. The most extensive results reported are those of the Japanese group, Aizu *et at* (1961) and the report by Koshiba at this Conference. These workers have performed two separate experiments in emulsions flown at very great altitudes, $\gtrsim 1.5$ g/cm², and find that $\Gamma_{LM}(E)$ increases by 20±7% for $1.3 \leq R \leq 2.7$ BV over the value at $R > 2.7$ BV, while $\Gamma_{HM}(E)$ shows an indication of a decrease, although it is hardly statistically significant. They also point out that if the *L* and *M* nuclei are assumed to have a distribution of isotopes similar to that in the cosmic abundances, an unlikely assumption, then Γ_{LM}(R) at low rigidities is similar to that at higher values.

These conclusions are supported by the results reported by Zhdanov *et al.* at this Conference, who also find an increase in Γ_{LM} at low rigidities. Further, they are not incompatible with those of McDonald and Webber, who find no difference between Γ_{LM} at $R > 4.5$ BV and Γ_{LM} for $2.0 \leq R \leq 4.5$ BV.

However, it should be noted that the positive evidence for an increase in $\Gamma_{LM}(E)$ at low energies rests mainly on the results of those experiments reported by Koshiba, and our experience of the controversy on the value of this quantity at higher energies shows that even apparently reliable emulsion experiments can be subjected to unsuspected errors. For this reason, it would appear desirable that some caution should be exercised in accepting these results until they have been cofirmed by other independent experiments.

Two other components have been detected at these low rigidities which have not been seen at higher rigidities. Meyer and Vogt (1961) and Earl (1961) have both detected evidence for a primary electron flux which is a few percent of the primary nucleon flux above about 0.5 BeV per nucleon. These results were discussed by Meyer at this Conference. Appa Rao (1961) has reported the presence of an appreciable He^3 abundance in the low energy helium nuclei component, finding $He^3/He^3+He^4=41\pm9\%$ for $0.2\leq E\leq0.4$ BeV per nucleon. Aizu, however, finds evidence that this ratio is only $8\pm8\%$. The presence of He^3 nuclei to the extent indicated by Appa Rao suggests a traversal of $\sim12\,g/cm^2$ of interstellar matter by the producing particles, c.f. the $5\,g/cm^2$ suggested by the abundance of L-nuclei. If this difference is confirmed by further experiments it will provide good evidence for the diffusion model of propagation in interstellar space, in which lighter particles would have a greater average 'age'.

Charge Distribution at High Rigidities

Above 4.5 BV the experimental data on the chemical distribution is rather sparse, due principally to the difficulty of obtaining results of significant statistical weight. At $R>16$ BV Γ_{ij} values appear to be closely similar to those at $R>4.5$ BV; see, for example, the work of Neelakantan and Shukla, reported at this Conference; while $\Gamma_{p\alpha}(R)$ has been studied up to $R\geq5.10^3$ BV and still appears to be constant. Jain *et al.* (1959) find that the H and M-nuclei have the same rigidity spectra at 200 BV as at lower rigidities. Finally, at very high energies. $\geq10^{17}$eV there is the very interesting observation of the M.I.T. group reported here, that the primary particles, judged on a basis of their total K.E., are predominantly lighter or heavier than carbon nuclei; which suggests that the charge distribution has changed appreciably from that observed at lower energies.

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Discussion

Friedlander, M. W.: It should be pointed out that the balloon flight from Prince Albert, from which was deduced the variation of the L/M ratio rigidity, was made on the recovery after a Forbush decrease and may thus not be representative of the quiet galactic spectrum.

Waddington, C. J.: This is certainly true, and taken together with Pomerantz's evidences for rapid fluctuations in the intensity and energy spectrum of $Z\geq6$ nuclei shows that one must be extremely careful in attempting to compare results obtained at different times.

Menon, M. G. K.: I would like to make a comment concerning the so called H-nuclei in the primary radiation; this group involves all nuclei with charge $Z\geq10$. This is a definition which has come down over more than a decade and still persists. This group covers a wide range of nuclei and there have been suggestions that one should really subdivide it into smaller groups; the ideal situation would be to deal with the group, element by element, by charge but for reasons of difficulty in charge resolution and low flux this has not been possible yet. A subdivision is, however, possible and yields results of interest as has been shown by Daniel and Durga Prasad from Bombay. They have been able to carry out this subdivision because they have good statistics in their experiment (1200 tracks due to nuclei with $Z \geq 3$) as pointed out by Dr. Waddington. They divide the H-nuclei (which effectively lie from $Z=10$ to $Z=28$) into three subgroups: H_1, H_2, H_3 groups constituting $Z=20$-28, 16-19 and 10-15 respectively. With this subdivision they have been able to investigate the abundance of H_1, H_2, and H_3 nuclei at the top of the atmosphere using the experimentally determined growth curve in the atmosphere for extrapolation. They show that the H_2 group ($Z=16$-19) is much less abundant, and rather rare, in the primary radiation. This may be of interest to astrophysicists. If spallation reactions are important, one would expect to build up fairly smoothly lower species from higher species and whilst in the case of individual elements, as emphasised by Professor Peters, processes such as radio active decay may be important so that input is made by out put leading to effective small "reservoirs" this seems difficult in the case of a wide band of nuclei. The matter therefore appears to me to be an important one to pursue.

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III-1-21. Isotopic Composition

M. F. KAPLON
The University of Rochester, Rochester 20
New York, U.S.A

I will begin by repeating a comment made to me quite a few years ago—"most experimental papers in physics raise more questions than they answer". I am afraid such may be the case here, presuming of course that the new results to be presented are correct.

My principal task in this report is to summarize the papers presented on isotopic composition in the plenary session. This is a new and interesting field and I must apologize beforehand if I seem to take up most of the time with the work done by Appa Rao at Rochester on He^3-He^4 but it is so far the principal work in this field.

First we must consider the reason, apart from the always prevailing one, to satisfy one's inherent curiosity, why we are concerned with the isotopic composition of the cosmic radiation. The importance of a detailed knowledge of the chemical composition was pointed out a long time ago by Bradt and Peters with particular emphasis on the observation of the relative intensity of elements whose cosmic abundance is very low (*i.e.* the light element, Li, Be, and B problem). In this case, it was believed possible to infer crucial information on the history of cosmic rays by observation of their abundance relative to the heavier elements ($Z \geq 6$) if one made the reasonable assumption that they are produced by the nuclear reactions of heavier elements in their traversal of the interstellar gas from the sources to their observation at the top of our atmosphere. This is an example of what we may call a "cold" reaction which can contribute to the observed composition of the cosmic radiation. Ideally one seeks other cold reactions which contribute to the composition as observed of earth and thus obtain by a joint extrapolation information on both the history and source composition of cosmic rays.