On the Origin of Primary Cosmic Radiation

Tokuji MATSUMOTO and Masao SUGAWARA

Department of Physics, Hokkaido University

(Received December 4, 1952)

At first it is illustrated that two important empirical facts concerning primary cosmic radiation, i.e., (i) the similarity of energy spectra expressed with respect to kinetic energy per nucleon of various nuclei independent of their charge numbers and (ii) fairly abundant existences of heavier nuclei, will not be able to be explained by any acceleration mechanisms. And it is shown that (i) and (ii) can be understood only if one assumes a new type of element formation, according to which, from the nucleon gas of extremely high temperature ($\sim 10^9\times 10^5$) and pressure, various atomic nuclei are created with energy spectra $N(\varepsilon) \sim C \exp\left\{-(1+\varepsilon)/kT\right\}$ ($\varepsilon$ : kinetic energy per nucleon) and with ratio $C_{\text{P}} : C_{\text{A}} : C_{\text{NO}} : C_{\text{A}>10} = 10 : 1 : 1/20 : 1/60$. Physical inevitability with which this assumption is introduced and its physical significance are discussed. The theory itself of element formation of such a type, however, is not touched but only it is pointed out that the introduction of such an assumption is strongly required from present knowledges concerning primary cosmic ray particles.

§ 1. Introductory discussions

The theory on the origin of primary cosmic radiation should explain the following two important results of observation: (i) The energy spectra of primary cosmic radiation, which are expressed with respect to the kinetic energy per nucleon, have the same form for all nuclei. (ii) As to the chemical composition, the cosmic abundance is the same with that in primary cosmic radiation for the nuclei with rather small $Z$ ($Z < 6$), but for heavier nuclei the abundance in primary cosmic radiation exceeds that in the universe and indeed the nuclei of $Z \geq 10$ are about ten times more abundant in primary cosmic radiation than in the universe. Moreover, in order to understand the isotropy of primary radiation, it seems to be necessary to consider that the primary particles incident upon the earth have travelled through the universe for a long time after their origination. At the present time, these observational facts have been obtained fairly in detail in the kinetic energy region between 0.3 and 10 Bev per nucleon$^1$.

Owing to the empirical fact (ii), especially because of the fact that there exist few, or else none of, nuclei of Li$^3$, Be$^4$, and B$^5$ in primary cosmic radiation$^2$, we must conclude as follows: primary particles reach to the earth without too much collisions with the interstellar hydrogen gas, and therefore their chemical composition changes scarcely from that at the time of origination. From this point of view, it seems to be inadequate to assume some acceleration process in order to explain the problem of primary cosmic radiation as was done, for instance, by Fermi$^3$, because by any acceleration mechanism heavier particles are not so easily accelerated as lighter ones and it would, therefore, be difficult
within the energy range (kinetic energy per nucleon in Bev) $0.3 \lesssim \varepsilon \lesssim 10$ are well established by the following empirical formulae:

$$N(\varepsilon) = \frac{4000}{(1 + \varepsilon)^{1.07}} \quad \text{for protons,} \quad (1)$$

and

$$N(\varepsilon) = K(1 + \varepsilon)^{1.06} \quad \text{for other nuclei.} \quad (2)$$

Now we must emphasize that $(1 + \varepsilon)$ is the total energy per nucleon because the rest energy of a nucleon is 1 Bev. Therefore, the integral spectra (1) and (2) are the simple functions only of the total energy per nucleon. From this point also, Fermi's theory, according to which the forms of the energy spectra depend on the species of nuclei, must be considered to be unsatisfactory. If, furthermore, one refers again to the fact that primary cosmic radiation seems to reach the earth after few collisions and therefore to experience acceleration process not so much as its chemical composition appreciably changes, it can be concluded that the energy spectra given by (1) and (2) are those of primary cosmic radiation at the time of their origination. Thus the energy spectra and chemical composition of primary cosmic radiation observed on the earth must be the same as those at the time of their origination. Then one should assume that, at some time after the origination of our universe, and from somewhere in our universe, various bare nuclei had been created with energy spectra given by (1) and (2). Although only for energy range (kinetic energy per nucleon in Bev) $0.3 \lesssim \varepsilon \lesssim 10$ above mentioned results of observation (i) and (ii) are well established, there is some evidence that (i) and (ii) seem to hold at higher energies. At least it is certain that there are many primary particles of much higher energies than 10 Bev per nucleon. Now we refer to Cocconi's interesting discussion about the origin (solar origin or galactic one) of cosmic primary radiation. According to Cocconi's discussion, cosmic ray particles of moderate energy ($1 \sim 10$ Bev) are those which were created locally near the sun and have been trapped in the closed orbits by the solar magnetic field, and reach the earth with relatively short lifetimes ($\approx 10^4$ years), thus passing through the matter layer less than 1 gram. The lifetime of this order of magnitude is sufficient to account for the isotropy of cosmic ray and selective absorption of electronic components. Thus these particles of moderate energies can be considered to be incident upon the earth with energy spectra and chemical composition at their times of origination. On the other hand, particles of higher energies have the orbits with curvatures that are comparable with the size of solar system and, therefore, these particles cannot be confined only within the solar system but are distributed in the whole galaxy. That is, higher energy particles are those that were created at some star and leaked out of its trapping field and have travelled through the whole galaxy, being accelerated repeatedly for many years. Owing to the fact that its life time may have order of magnitude about $10^8$ years, the chemical composition and energy spectra for these components of cosmic primary radiation must be changed entirely from those at the time of their origination.
§ 2. Our hypothesis concerning element formation and related discussions

As a result of the preceding considerations, we have enough evidence for the following important fact: That is, cosmic ray particles of energy less than 10 Bev, which can hardly be accounted for by any acceleration process, were created directly inside the solar system or else near it with the same chemical composition and energy spectra as observed on the earth concerning primary cosmic radiation. And, above in all, it should be noted that heavier nuclei must have been created much more abundantly than is predicted by the presently accepted theory of element formation.

According to G. Gamow7), our universe has the age of $10^6 \sim 10^{10}$ years and in the early times it was in a gaseous state that consisted of nucleons with extremely high temperature and pressure, and its temperature, averaged over whole universe, was given by the following expression:

$$T = 1.5 \times 10^{10} / \sqrt{t} \cdot 9 K,$$

where $t$ is the age of universe after its origination in second. It is believed also that the present universe with well known chemical composition was established through an element formation process that happened at the time when $T \approx 10^{6.5} K$ or $kT \approx 1$ Mev ($k =$ Boltzmann’s constant). It must be, however, denied owing to the above mentioned reasons, especially on account of marked predominance of heavier nuclei, to consider that after above process of element formation various nuclei were accelerated to cosmic ray energies under the operation of some acceleration mechanism. On the other hand, even if one assumes that the various nuclei with a certain kinetic energy were created directly from nucleon gas of extremely high temperature and pressure through the above element formation process, the emission of nuclei of kinetic energy $\approx 1$ Bev could hardly be understood because $kT \approx 1$ Mev corresponding to temperature $T \approx 10^{6.5} K$ and the nuclear binding energies are of the same order.

In this paper, therefore, we wish to point out that, according to the discussions we have given above, our present knowledges with primary cosmic radiation give a strong evidence that there must be some new mechanism of element formation which is of quite different type from those considered and accepted up to the present. This new mechanism of element formation should be such that allows marked predominance of heavier nuclei and energy distribution of emitted nuclei agreeable with (1) and (2) in kinetic energy range per nucleon $0.3 \lesssim \epsilon \lesssim 10$ Bev.

From these considerations we seek an expression that approximates (1) and (2) most closely in kinetic energy range $0.3 \sim 10$ Bev. For instance it is the following one:

$$N(\epsilon) = C \exp \left\{ - (1 + \epsilon)/kT \right\},$$

where $kT \approx 2.12$ Bev, or $T \approx 2.46 \times 10^{10} K.$

Above expressions are plotted in Figure by solid curves while dashed ones are empirical spectra (1) and (2). The agreements of these curves are fairly good in this energy range. It should be noted that the exponent of the energy distribution (4) is not
\(-A(1+\epsilon)/kT\) \((A:\text{mass number})\) but \(-(1+\epsilon)/kT\)
the physical significance of which is discussed later and the former exponent cannot reproduce the empirical curves entirely.

Also in order to get the best agreement with empirical curves it is necessary to use the following ratio of abundance:

\[
C_p : C_\alpha : C_{\text{CNO}} : C_{\text{Fe} >10} = 10 : 1 : 20 : 60,
\]

which must be compared with the known chemical abundance of the whole universe given at present as follows:

\[
\begin{array}{c|c|c|c|c}
\text{Element} & \text{Abundance} \\
\hline
\text{Hydrogen} & 74.952 \\
\text{Helium} & 24.762 \\
\text{Carbon} & 0.550 \\
\text{氮 (N)} & 0.001 \\
\end{array}
\]

Figure: Integral energy spectrum of primary cosmic radiation. The dashed curves drawn for the heavy nuclei are represented by \(N(\epsilon) = N_0/(1+\epsilon)^{1.15}\) and for the protons by \(N(\epsilon) = 4000/(1+\epsilon)^{1.07}\), where \(\epsilon\) is kinetic energy in Bev per nucleon. The solid ones are obtained from the formulae assumed in this paper: \(N(\epsilon) = C \exp\{-(1+\epsilon)/kT\}\). The dots, crosses and vertical bars represent the results of observation.
On the Origin of Primary Cosmic Radiation

\[ C_p : C_a : C_{0/10} : C_{>10} = 10 : 1 : 1/75 : 1/500, \]

which show quantitatively how the heavier elements are much more abundant in primary cosmic ray particles than in the present universe. Now, as the final step of our consideration, we wish to set up the following assumption: That is, somewhere in our universe, presumably in such places as inside the star, there existed, or exists, place or places of extremely high temperature \( (T \approx 10^{15} K) \) and there, as a matter of course, atomic nuclei were not yet formed and all the nucleons existed separately, forming a gaseous state of extremely high temperature and pressure, in which the Maxwell’s energy distribution of nucleons of type \( (4) \), \( (1 + \epsilon) \) being the total energy per nucleon, was maintained. In addition to these, we assume that from above gas of nucleons of high temperature and pressure various nuclei were created according to some new type of mechanism with the chemical composition given by \( (6) \) and since nuclear binding energy \( \approx 1 \) Mev is negligible compared with thermal kinetic energy \( \approx 1 \) Bev, atomic nuclei still have the same kinetic energy per nucleon as before they are formed. Hence we may say that the emitted nuclei have the same energy distribution with regard to kinetic energy per nucleon as \( (4) \). Without introducing such an assumption, it seems very difficult to understand the empirical fact that cosmic ray components of any \( Z \) have the same energy spectra with respect to kinetic energy per nucleon. It should be remarked that even if one assumes Maxwell’s distribution for the gas of extremely high temperature and pressure, if various atomic nuclei were formed already, the Maxwell’s distribution in this case would be \( \sim \exp \left[-A(1 + \epsilon)/kT\right] \) \( (A: \text{mass number of each nucleus}) \), which quite disagree with the empirical fact mentioned just above. Therefore, the cosmic ray data requires evidences not merely for high temperature but also for a possible existence of a new type of element formation which takes place at extremely high temperature. Regarding this new type of element formation, of course, the possibility of it must be studied in detail but, since such a problem is out of lines of present authors, we will discontinue further discussions with this point. The authors wish merely to note that our present knowledge concerning primary cosmic radiation could be scarcely understood without introducing such an assumption and that our assumption is not necessarily unreasonable physically.

It is clear from our discussions that above considerations do not exclude any acceleration mechanism at all. Indeed it is certainly necessary to introduce some acceleration process in order to explain the existences of particles of energy \( \gtrsim 10 \) Bev. If, for instance, one adopts Fermi’s assumption\(^9\) in addition to our one, the heavier nuclei will also be accelerated because according to our assumption there exist already various nuclei having kinetic energy of order of magnitude of 1 Bev which far exceeds Fermi’s minimum injection energy. Hence it will not be the case that, as in Fermi’s theory, only protons can be accelerated on account of which one can not understand the abundant existence of heavier nuclei in primary radiations. We do not continue, however, to discuss the acceleration mechanism in detail theoretically, but only point out the possibility that the better agreement may be gained between solid curves and empirical dashed ones in Figure by considering some acceleration processes.
Finally, with respect to latitude effect, there appears a knee at $\lambda \approx 50^\circ$ in the numbers of counts of primary particles versus latitude curve, which has been considered as an evidence against the existence of particles of energy less than 2 Bev ($\approx$ magnetic cut-off momentum at $\lambda \approx 50^\circ$). According to our assumption, however, $kT \approx 2$ Bev and therefore the appearance of knee in latitude effect seems to be understood naturally.

The authors wish to express their appreciation for the valuable and stimulating discussions to Dr. Y. Ôno and Dr. S. Hayakawa (Osaka City University) throughout the course of this work. They also wish to thank Professor S. Tomonaga for his kind and helpful advices.

References

3) E. Fermi, Phys. Rev. 75 (1949), 1169.
6) T. M. Donahue, Phys. Rev. 84 (1951), 972.
8) H. Brown, Rev. Mod. Phys. 21 (1949), 625.