Origin of Large Extensive Air Showers of Cosmic Rays

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Some difficulties are pointed out for the models of exotic primary cosmic rays introduced to get rid of the difficulty of the cutoff at $\sim 10^{20}$ eV in the spectrum of primary cosmic rays. In place of these models, urbaryons are considered as primary cosmic rays of ultra-high energies.

§ 1. Introduction

Primary cosmic rays of ultra-high energies are usually considered to be of cosmological origin. It will be understood, for example, from the fact that there appears to be no anisotropy of these cosmic rays in terms of the observation of extensive air showers, although the radius of gyration for protons of energies above $\sim 10^{18}$ eV is beyond the thickness of the disk of the Galaxy if the magnetic field in the galactic space is $\sim 10^{-6}$ oerstead. Primary protons of cosmological origin will lose most of the energies due to the pion production by the collision with the cosmic blackbody radiation and the spectrum of primary cosmic rays will have a cut-off at $\sim 10^{20}$ eV. Cosmic nuclei will also disintegrate by the collision with the intergalactic optical radiation. On the other hand, the observed spectrum of shower producing primaries seems not to contain an abrupt steepening at $\sim 10^{20}$ eV, and a recent paper reports a discovery of a cosmic ray with energy of the order of $10^{21}$ eV.

In order to get rid of this difficulty, the following ideas have been proposed. One of them is to introduce an assumption which is incompatible with the relativity, and the other is to assume that shower producing cosmic rays are neither protons nor nuclei. We are interested in the latter case and shall discuss the models of various exotic agencies of extensive air showers which have been proposed till now. We shall give some comments on the neutrino model in § 2, the $\gamma$-ray in § 3 and the dust grain in § 4. The urbaryon model for primary cosmic rays will be proposed in § 5 and concluding remarks will be given in § 6.

§ 2. Neutrino model

In order not to give rise to a cut-off in the spectrum of primary cosmic rays at $\sim 10^{20}$ eV, various exotic primaries (neutrinos, $\gamma$-rays and dust grains) have been assumed. However, these exotic primaries will encounter other dif-
Firstly we discuss the neutrino model as follows: Shower-producing particles are neutrinos originated in decays of pions that are generated in collisions of ultra-high energy protons with the blackbody radiation at high redshifts. This model may, however, encounter the following difficulty: In order to produce air showers at $\geq 10^{20}$ eV, the cross section for the neutrino reaction would have to be as large as the geometrical one of the nucleon at these energies, and this would be possible if the cross section increases linearly with the neutrino energy up to $\sim 10^{20}$ eV in the rest frame of the nucleon. The linearly rising property of the cross section for the neutrino reaction is a direct consequence of the scaling; but there are some reasons to expect the breakdown of the scaling property at very high energies. The presence of the intermediate weak boson will lead to the result that the cross section increases at most logarithmically.

§ 3. $\gamma$-ray model

Wdowczyk et al. pointed out that interactions of cosmic ray protons with the blackbody radiation can lead to the transference of a relatively high fraction of the incident energy into $\gamma$-rays that may be responsible for extensive air showers. The energy spectrum of $\gamma$-rays at the earth was calculated taking into account the interactions of $\gamma$-rays and their ensuing cascade electrons with the blackbody radiation in the framework of the steady-state model of the universe. Arai also gave a detailed calculation of the energy spectrum of $\gamma$-rays taking into account the following interactions of $\gamma$-rays with the blackbody radiation without neglecting the evolutionary effects of the universe; the energy loss due to $e^+e^-$ pair creation and the gain due to the inverse Compton scattering by high-energy electrons arising from the pair creation and the $\pi\mu\nu$ decay. Further he showed that the flux of $\gamma$-rays is remarkably lower than the case of the steady-state model. In these calculations, however, productions of hadrons in the collisions of high-energy $\gamma$-rays with the blackbody radiation, which will be possible at energies $\geq 2 \times 10^{19}$ eV, has not been considered.

In order to estimate the value of the $\gamma\gamma$ hadronic total cross section, the vector meson dominance and the additive quark model will be assumed. These assumptions seem to be useful to describe the rough aspect of the electromagnetic property and the high-energy scattering of hadrons. Under these assumptions, the $\gamma\gamma$ hadronic total cross section is approximately constant ($\sim 0.3 \mu b$) at energies $\geq 3$ GeV in the c.m. system. The presence of the resonant states expected in the energy region $\sim 0.4$ to $\sim 3$ GeV will lead to the result that the $\gamma\gamma$ hadronic cross section at the resonant energies is fairly higher than the asymptotic one. Since the density of the blackbody radiation is $\sim 500$ cm$^{-3}$, the mean free path for the absorption of $\gamma$-rays of energies $\geq 3 \times 10^{21}$ eV is $\sim 1/2$ of the Hubble radius and those for the resonant energies are far shorter than it. Thus the flux
of γ-rays of energies $\sim 2 \times 10^{19}$ to $\sim 3 \times 10^{21}$ eV will be remarkably lower than the case of Wdowczyk et al. and it seems to be difficult that the shower producing primaries escape the abrupt steepening at $\sim 10^{20}$ eV.

§ 4. Dust grain model

Finally we make a comment on the dust grain model.\textsuperscript{19} In this model, shower producing primaries of ultra-high energies consist of dust grains such as the mass, radius and density are $\sim 10^{-16}$ g, $\sim 3 \times 10^{-6}$ cm and $\sim 3$ g/cm$^3$, respectively. It is, however, questionable whether they are stable against the optical radiation in the intergalactic space. In fact, the energy of the optical photon is $\sim 10$ keV in the rest frame of the grain and higher than the ionization energy for K-shell of atoms of the atomic number $Z \leq 25$. To begin with, we examine whether the electrons recoiled by photons can run away from the dust grain. The range for the ionization loss of a low-energy electron is empirically given by

$$ R = 0.407 \times E^{1.58}, \quad 0.15 \text{ MeV} \leq E \leq 0.7 \text{ MeV} $$

(1)

for Al, but is close for all the other substances,\textsuperscript{16} where $R$ is the range in g/cm$^3$ and $E$ is the energy in MeV. The energy of $\sim 0.7$ keV will correspond to the range equal to the diameter of the dust grain, although the value may receive a little change in practice. Thus the electrons of energies above several keV will easily pass through the grain. Next, the photoelectric effect is considered. Under the Born approximation the cross section for a K-electron\textsuperscript{10} is given by

$$ \sigma_K = \sigma_T 2 \sqrt{2} Z^3 \alpha^4 \left( \mu/k \right)^2 $$

(2)

for the nonrelativistic energies, where $\sigma_T$ is the cross section for the Thomson scattering, $\alpha$ is the fine structure constant, $\mu$ is the electron mass and $k$ is the energy of the incident photon in the rest frame of the atom. If we imagine, for simplicity, a dust grain composed of atoms of $Z=14$ corresponding to a most familiar element Si on the earth, then the cross section for photoelectric effect by a photon of $\sim 10$ keV is $\sim 2.3 \times 10^{-21}$ cm$^2$. Due to the breakdown of the Born approximation, the real cross section will be smaller by several factors than the above value. Since the density of the optical photon is presumed to be $\sim 10^{-8}$ cm$^{-3}$ in the intergalactic space, the mean free path is of the order of $10^{14}$ cm. As we can neglect the time needed for transition to K-shell from higher levels, we may well consider that all the electrons bounded in atoms are recoiled as K-electrons. Thus the mean free path for the disintegration of a dust grain by losing all the electrons will be approximately equal to that for a K-electron. If the grains are composed of lighter atoms, the recoil of electrons will be expressed as the Compton scattering rather than the photoelectric effect. The cross section for the Compton scattering is equal to that of the Thomson scattering for the nonrelativistic energies, and the mean free path is $\sim 1.5 \times 10^{27}$ cm for the intergalactic photons. Therefore, even if the grains can be accelerated at quasars of cosmological dis-
tance ($\sim10^{29}$ cm), they will be disintegrated by losing all the electrons before they arrive at the earth.

§ 5. Urbaryons as primary cosmic rays

As is shown in the previous sections, the models of exotic primaries which have been proposed till now seem difficult to keep away from other difficulties. It may be suggested that we need to introduce a highly massive and stable "matter" as a cosmic ray$^{16}$ if the relativity is valid.

The heaviest stable particle that is thought of will be an urbaryon (constituent of hadrons), although it is hypothetical as yet. In fact, the fundamental triplet has been considered as a set of highly massive particles in the non-relativistic triplet model which is successful in the classification of hadron mass levels.$^{17}$ We take the value of the urbaryon mass $\sim10$ GeV/$c^2$, as this value seems to be favourable to explain the mass levels of boson resonances.$^{18}$ The lightest component of the triplet will not be able to decay into usual particles but may well be considered as stable.

Cosmic urbaryons of ultra-high energies will lose their energies dominantly by collisions with the cosmic blackbody radiation. The production of hadrons will be possible at energies above $\sim10^{20}$ eV if the mass of an urbaryon is $\sim10$ GeV/$c^2$. At energies $\lesssim10^{21}$ eV, the main energy loss of a cosmic urbaryon may be caused by $e^+e^-$ pair creations due to the interaction with the thermal radiation. However, the radiation length for pair production which is estimated by analogy with the proton$^{19}$ is much longer than the Hubble radius, and therefore a pair creation seems not to cause a significant energy loss for a cosmic urbaryon.

An urbaryon will emit one pion by a collision with the blackbody radiation when the energy is over $\sim10^{21}$ eV and various channels will be successively open as the energy increases. Although it is not known how we should treat the hadron production on an urbaryon by a photon, we may be able to make a rough estimate of the cross section for the photo-pion production on an urbaryon by means of the Born approximation. Then we will use the value of the pion-urbaryon coupling constant which can be easily obtained under the static approximation. If we imagine an urbaryon of integral charge which is possible in the modified triplet model,$^{20}$ the calculated cross section for one-pion production under these assumptions increases rapidly as the energy of an urbaryon increases, has the value $\sim37\,\mu$b at the energy of the threshold of two-pion production ($\sim2\times10^{21}$ eV) and reaches a maximum $\sim40\,\mu$b in the vicinity of $5\times10^{21}$ eV. When the energy of an urbaryon is over $\sim2\times10^{21}$ eV, the photon-urbaryon total hadronic cross section may be larger than the above estimate because other channels will be open. Thus the distance scale for energy loss of a cosmic urbaryon at $\sim2\times10^{21}$ eV is $\sim2\times10^{27}$ cm and seems to become much shorter than the value as the energy of an urbaryon increases. The result suggests that a steepening or a cutoff in the spectrum of shower producing primaries will occur at an energy of the order
of $10^{21}$ eV, if they are urbaryons of $\sim 10 \text{ GeV}/c^2$.

§ 6. Concluding remarks

In the previous sections, we have pointed out some difficulties of various models of the origin of extensive air showers and proposed another model of exotic particle, i.e., urbaryon. Even if the urbaryons are of fractional charge like quarks, our result does not receive essential changes. It should be noted that our result is strongly dependent on the assumed value of urbaryon mass rather than the charge. The most important characteristic of constituents of hadrons in the non-relativistic triplet model is that they are highly massive. If the heavy particle which has been observed in China is of fractional baryon number, the incident particle, too, will be of fractional one. This may suggest that urbaryons form a part of primary cosmic rays.

Finally, we make a short comment on another way to get rid of the cutoff problem, which contains assumptions incompatible with the relativity. Sato and Tati showed that the spectrum of ultra-high energy cosmic rays does not give rise to a cutoff under the following assumptions: (i) All inertial systems are not equivalent and there exists an universal time-like unit vector $N$. Our laboratory system is not very different from the $N$-system in which $N_\mu = (1, 0, 0, 0)$. (ii) The production of hadrons at high-energy collisions is suppressed when their momenta in the $N$-system become larger than some critical value $P_c$. If the critical momentum of pion is $\sim 10^{18}$ eV/c in the $N$-system, then productions of pions of energies above $\sim 10^{18}$ eV will be suppressed, and the energy spectrum of $\gamma$-rays produced in $\pi^0 \rightarrow 2\gamma$ decays will decrease rapidly at the energy $\sim 10^{18}$ eV. However, the observed spectrum of $\gamma$-rays in high-energy jet phenomena is smooth over $\sim 10^{18}$ eV. This suggests that the $\pi^0$ production is not suppressed at this energy. Most of the muons in cosmic rays will be produced by $\mu$-decays of $\pi$- and $K$-mesons. The energy of muons produced in $\mu$-decays is of the order of that of parent mesons. If the critical momentum for $K$-mesons is also of the order of $10^{18}$ eV/c, the energy spectrum of cosmic ray $\mu$-mesons will give rise to a steepening at the energy of the order of $10^{18}$ eV. On the other hand, the spectrum of the parents of horizontal air showers, which are possibly muons, seems to be smooth in the region $10^{13} \sim 10^{14}$ eV.

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