Propagation of Ultra-High Energy Nucleus in the Intergalactic Photon Field

T.Yamamoto[1], M.Ave[1], K.Mase[2], M.Takeda[3], N.Sakaki[3], M.Teshima[4]
(1) Center for Cosmological Physics, University of Chicago, Chicago, IL 60637, USA
(2) Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, Chiba 277-8582, Japan
(3) RIKEN, Saitama, 351-0198, Japan
(4) Max-Planck-Institute fddotur Physik, Fddotoringer Ring 6, 80805, Mddotunchen, Cermany

Abstract

We present a calculation of nuclei propagation with energyes above 10^{18} eV in the intergalactic photon field. The calculation is based on a Monte Carlo approach for the nucleus-photon interaction as well as intergalactic magnetic field. We assume that the Ultra-High Energy Cosmic Rays (UHECR) are nuclei which are emitted from extra-galactic point sources. Four bumps are found in the energy spectrum of UHECR which make clusters in the distribution of its arrival directions. Based on this calculation, the energy distribution of the cluster events is discussed.

1. Introduction

The arrivale direction of Ultra-High Energy Cosmic Ray (UHECR) inform us their origin. Clusters in the distribution of the arrival direction of the cosmic rays above an energy of 4×10^{19} eV have been reported by AGASA [1,2]. The cluster events correlated with Galactic magnetic field and the energy spectrum is harder than isotropic cosmic ray. AGASA results suggests to us an interesting possiblilty that UHECR might be nuclei. We investigate the energy distribution of the UHE nuclei which are observed as cluster events on the earth using Monte Carlo simulation. In this calculation, we assume that UHE nuclei are emitted from extra-galactic point sources. The detail of this simulation and the result will be reported.

2. Interaction of Nuclei with background photons

The UHE nuclei should interact with Intergalctic Background Radiation and lose energy. The energy loss is mainly caused by pair-production of e^+e^- and photo-disintegration. The pair-production process can occur if the energy of the

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background photon is larger than 1 MeV in the rest system of the nucleus. If the Lorentz factor of the nucleus is more than 10^9, it will interact with CMBR effectively. The photo-disintegration prosess is important for the propagation of UHE nuleus. The nucleus interacts with the background photon and is disintegrated to a lighter nucleus with emission of nucleons. In this paper, we calculate this process by Monte-Carlo method according to the reference of (Puget et al. 1976; Stecker & Salamon 1999 [3,4]). They parametrized the total cross section $\sigma(\epsilon)$ as a function of photon energy in the rest frame of the nucleus. Then the probability of the photo-disintegration per unit length R is calculated as a function of the nucleus energy depending on its mass. The effect of CMBR becomes the largest when the Lorentz factor γ is around 10^{10}. In case of Fe, this value corresponds to an energy of 10^{21} eV, yielding a value of $\tau = 2 \times 10^{14}$s (2Mpc) where τ is energy loss time. Because the IIBR density is much lower than CMBR, τ increases rapidly at lower energy. τ of Fe with 10^{20} eV is about 2.5×10^{17}s (2.5Gpc). In general, one or a few nucleons and a single lighter nucleus are emitted by this interaction. The Lorentz factor is conserved at each photo-disintegration interaction, though it is reduced by the pair-production. Finally, UHE particles will pile up at a Lorentz factor below 10^{10}. When ^9Be is disintegrated, one proton and two He are emitted. Therefore no nucleus is created with a mass number between 5 and 8.

The interaction probability is calculated for every possible photo-disintegration process involving the emission of one or more nucleons for all nuclei lighter than Fe. Based on these probabilities, the propagation of the nucleus is simulated by the Monte-Carlo method. The effect of the pair production, the adiabatic expansion, and photo-pion production for proton are taken into account in this simulation analytically.

3. Scattering by the intergalactic magnetic field

The effect of magnetic field is described by the rigidity ($= E/Z$). Particles with small rigidity are deflected by the magnetic field and cannot be observed as a cluster. As the deflection of magnetic field increases the propagation time, particles that come from distant sources may not be observable. We calculate effect of the intergalactic magnetic field based on Monte Carlo method.

To simulate the scattering by the intergalactic magnetic field, we assume a Kolmogorov spectrum for the random magnetic field that is 1 nG in average with a 1 Mpc correlation length according to the reference of (Stanev et. al. 2000 [5]).

In our simulation, source energy spectrum $dN(E)/dE$ is assumed to have a power low dependence E^{-2} and have a cut off at the energy of $Z \times 2 \times 10^{19}$ eV, where Z is charge of each primary nucleus. We treat the composition as 4 components, ^2_4He, $^7_{14}N$, $^{12}_{24}Mg$, and $^{26}_{56}Fe$. The fraction of these nuclear abundances in the UHE region are unknown. Therefore we assume the fraction relative to He

are 1 at the source. 20000 particles are created for each nucleus.

Nuclei with Lorentz factor above 10^9 interact with CMBR comparatively rapidly. A small pile-up is induced below this energy and the maximum energy of the particle is reduced after 1 Mpc propagation. Since we assume a cut off energy on the source spectrum, protons are emitted with energies below $Z/A \times 2 \times 10^{19} (\sim 10^{19})$ eV where A is mass number of the primary nucleus.

4. Results and discussion

The rigidity is proportional to Z^{-1} and E, and Z is approximately proportional to its mass number A while Lorentz factor is proportional to A^{-1} and E. This means the Lorentz factor of a particle is approximately proportional to the rigidity. Therefore, if the Lorentz factor of the nucleus is large, the energy is reduced by the photo-disintegration. If the Lorentz factor is small, the particle is deflected by the magnetic field due to its small rigidity. However particles with Lorentz factor of about 10^9 remain with small deflection angle. As a result, the bumps appear in the energy distribution of the small deflection angle particles depending on its mass number. The combination of the photodisintegration and the magnetic field is like a “filter” for $\gamma = 10^9$ particles.

Figure 5. shows result of expected energy distribution under the assumption that the sources are distributed uniformly in the Universe. The solid line shows the expected energy distribution of all of the particles which reach the earth. Above $10^{20.2}$ eV, the energy spectrum is getting steeper and maximum energy is about $10^{20.4}$ eV in our model. The exact details of the upper end of the spectrum will depend on exactly how the source spectrum cuts off.

The dashed lines in Figure 5. show the expected energy distribution as a function of the deflection angle cut. Particles which are deflected by the magnetic field larger than a certain angle would not be identified as being part of a cluster.

Four bumps appear in this figure. The bump just below 10^{19} eV is composed of protons and strongly depends on the cut off energy in each source. The bump around $10^{19.3}$ eV is composed of *Deuterons* and He. Every nucleus with Lorentz factor around 10^9 contributes to the He bump after propagation. The bump between $10^{19.6}$ eV and 10^{20} eV is composed of nuclei with mass between Be and Mg. The bump above $10^{20.1}$ eV is composed of Fe and nuclei of nearby atomic number.

This total spectral structure bears a striking resemblance to the result of AGASA [6].

In the simulation, we assumed an intergalactic magnetic field, cut off energy and composition of primary nucleus at the source, and maximum deflection angle. The deflection angle depends on the strength and the correlation length of the magnetic field.

This result suggests that if we detect few hundred of events above 10^{20} eV

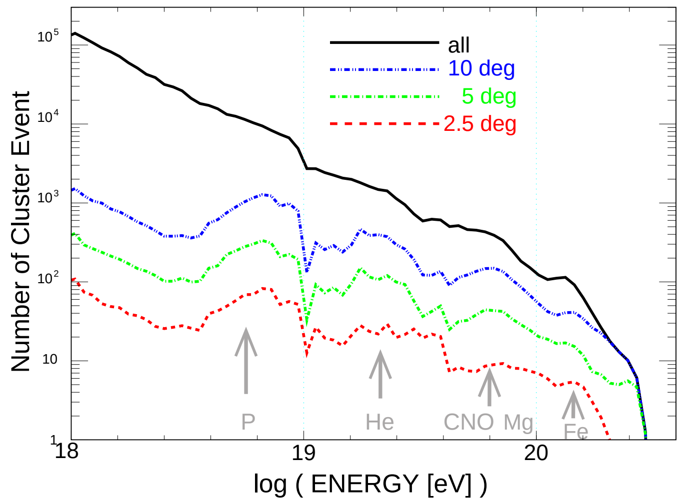

Fig. 1. Expected energy distribution of the cluster events under the assumption that point sources distribute uniformly in the universe. Solid line shows energy distribution of all of the particles which reach the earth. Dashed dotted lines show the energy distribution of the particles with smaller deflection angle than indicated value in the figure.

by future experiments, we should be able to extract the structure of the bumps in the energy distribution of cluster events. The Pierre Auger Observatory is quite sufficient for this purpose and may confirm the nuclei signature in the spectrum in the near future.

Acknowledgments

We thank Angela Olinto, Alan Watson, James W. Cronin, and Medina Tanco for useful discussions. This research was supported by grant NSF PHY-0114422 to the Center for Cosmological Physics, University of Chicago, and grant NSF PHY0103717.

5. References

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