INFLUENCE OF THE NUCLEAR PHOTOEFFECT ON THE PRIMARY COSMIC RAY SPECTRUM

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The effect of the nuclear photoeffect on the energy spectrum of high-energy primary cosmic rays is investigated. An estimate indicates that it is very improbable for very high-energy ($\sim 10^{18}$ ev) heavy nuclei of intergalactic origin to appear in the galaxy.

HIGH energy cosmic-ray nuclei disintegrate in the galaxy as a result of the nuclear photoeffect on stellar photons. The nuclear photoeffect on photons from the sun was considered earlier.[1,2] Assuming that the radiation spectrum of most stars is similar to the solar spectrum, let us estimate the effective energy of the nuclei subject to photodisintegration. The photoeffect occurs at a photon energy on the order of 10^7 ev in the system moving with the nucleus. The mean energy of the photons radiated by the stars in the galaxy is about 1 ev. Going over to the frame moving with the nucleus, we find that the nuclei of interest to us should have a Lorentz factor

$$\gamma \approx \varepsilon / 2\varepsilon_0 \cos^2(\alpha/2) \approx 10^7. \qquad (1)$$

Here ε and ε_0 are the photon energies in the coordinate systems moving with the nucleus and with the galaxy, respectively; α is the angle between the directions of motion of the nucleus and the photon. Consequently the effective energy for the photodisintegration will be

$$E \approx \gamma Mc^2 A \approx 10^{16} A. \qquad (2)$$

Thus, the photoeffect on heavy nuclei can change the spectrum of cosmic radiation only at very high energies.

We shall assume henceforth, in accordance with one of the prevalent notions,[3] that the highest energy in cosmic radiation is possessed by the heavy nuclei; to be specific, we shall assume these to be iron nuclei. The time variation of the number N(E) of iron nuclei of given energy is

$$\partial N(E)/\partial t = Q(E) - N(E)/T_{\text{nuc}} - N(E)/T_{\text{ph}}(E). \qquad (3)$$

The first term in the right side is the energy spectrum of the cosmic rays at their source, while the second and third terms represent the decrease of the number of nuclei in a given energy interval, due to respective interactions with interstellar matter and with the photons, the mean interaction times being T_{nuc} and T_{ph}.

Since we assume the processes occuring in the galaxy to be stationary, i.e.,

$$\partial N/\partial t = 0, \qquad (4)$$

we have

$$N(E) = T_{\text{nuc}} Q(E)\,[1 + T_{\text{nuc}}/T_{\text{ph}}(E)]^{-1}. \qquad (5)$$

Let us assume that the differential energy spectrum of the cosmic rays, without account of the photoeffect (i.e., $T_{ph} \to \infty$), is given by the power function

$$T_{\text{nuc}} Q(E) \approx KE^{-\beta}. \qquad (6)$$

The modified spectrum will have the following form:

$$N(E)\,dE = KE^{-\beta}\,dE\,[1 + T_{\text{nuc}}/T_{\text{ph}}(E)]^{-1}. \qquad (7)$$

The ratio T_{nuc}/T_{ph} (E) is equal to

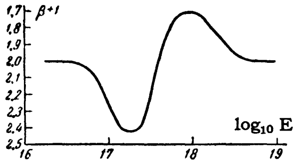
$$T_{\text{nuc}}/T_{\text{ph}}(E) = cT_{\text{nuc}} \int_{\varepsilon_{0min}}^{\infty} \sigma_{\text{ph}}(\varepsilon)\, n(\varepsilon_0)\, d\varepsilon_0, \qquad (8)$$

where $\sigma_{ph}(\varepsilon)$ is the photodisintegration cross section of the nucleus; $n(\varepsilon_0)\,d\varepsilon_0$ is the spectrum of the stellar photons, and ε and ε_0 are related by Eq. (1). The function $\sigma_{ph}(\varepsilon)$ has already been defined earlier.[2]

The photon spectrum was specified in terms of the Planck function for black-body radiation at T = 5800°K (kT = 0.5 ev). After suitable integration (with some simplification which does not appreciably alter the results) and averaging over the angles, assuming isotropic distribution of the photons in the galaxy, we obtain

$$\frac{T_{\text{nuc}}}{T_{\text{ph}}(E)} \approx \frac{cT_{\text{nuc}} c_g \bar{n}_G}{1.2}\left(\frac{\varepsilon_g}{2\gamma kT}\right)^2 \frac{\exp(-\varepsilon_g/2\gamma kT)}{(a_g + \varepsilon_g/2\gamma kT)^2}\left[1 + \frac{2}{a_g + \varepsilon_g/2\gamma kT}\right]. \qquad (9)$$

Here c_g, a_g, and ε_g are parameters in the photoeffect cross section, which are given in the nota-



tion of[2] (for iron $c_g = 570$ mb, $a_g = 2.8$, and $\varepsilon_g = 13 \times 10^6$ ev), while $\bar{n}_G$ is the average photon density in the galaxy.

According to the available data,[4,5] the radiation energy density in the galaxy is approximately 0.3 ev/cm^3. If it is assumed that the average photon energy in the radiation from stars is about 1 ev, we get $\bar{n}_G \sim 0.3$ cm^{-3}. The maximum value of the ratio T_{nuc}/T_{ph} (E) for iron, attainable at $E \approx 6 \times 10^{17}$ ev, amounts then to 0.8.

The diagram shows the variation of the exponent of the integral spectrum of the nuclei of a given isotope of iron, due to photodisintegration. It must be emphasized that inasmuch the reactions (γ, n) and (γ, 2n) predominate in the region of giant resonance, there is no complete breakup of the heavy nuclei if T_{nuc}/T_{ph} (E) $\lesssim 1$. All that changes is the isotopic composition of the primary component, which is of galactic origin.

Let us consider now the influence of the photoeffect on cosmic rays that move in intergalactic space.* The lifetime of the iron nucleus in the galaxy is $T_{nuc} \approx 1.4 \times 10^8$ years. Since the density in intergalactic space is three orders of magnitude lower than in the galaxy, the average lifetime between collisions is about 10^{11} years there. However, this is longer than the age of the galaxy ($\sim 10^{10}$ years). We must therefore assume that the nuclei practically do not collide with nuclei of matter in the metagalaxy.

In order to estimate the density of the photons in the intergalactic region, we assume that all galaxies radiate in a fashion similar to ours, and the total radiation is proportional to the number of galaxies in the visible part of the world. Then the ratio of the density of the number of photons $\bar{n}_i$ in the intergalactic space to the density $\bar{n}_G$ will be

$$\bar{n}_i/\bar{n}_G \approx 4\pi R_i R_G^2 \eta. \qquad (10)$$

Here $R_G \approx 5 \times 10^{22}$ cm is the radius of the galaxy; we assume R_i to be equal to one-quarter of the radius of the entire visible part of the universe,† i.e., about ($^1/_4 \times 10^{28}$ cm; finally, a is the distribution density of the galaxies. According to astrophysical data,* a volume 5 million parsec in radius contains on the average some 300 galaxies with $\sim 10^{10}$ stars and about 30 galaxies with $\sim 10^{11}$ stars like our own galaxy. Since we start from the radiation density in our own galaxy, we assume that the equivalent radiation will be produced by 60 galaxies with 10^{11} stars. Then $\eta \approx 4 \times 10^{-75}$ galaxies per cubic centimeter, and

$$\bar{n}_i/\bar{n}_G \approx {}^1/_3.$$

According to Allen[5] $n_i/n_G \approx 1/4$.

Estimating on the basis of these figures the lifetime of the nuclei for the photoeffect, we obtain $T_{ph} \sim 10^9$ years. Therefore, if nuclei with energy $\sim 10^{18}$ ev were formed in the intergalactic space $\sim 10^{10}$ years ago, they could not be conserved, owing to the photoeffect, and there is no intergalactic component of the cosmic radiation spectrum with this value of energy.

On the other hand, if the nuclei are being produced at the present time, these estimates enable us to establish the dimensions of that region in space, from which they arrive into the galaxy. Ginzburg and Syrovat-skii[3] give a figure of 1.5×10^{26} cm for the dimensions of this region. The effect considered here reduces this radius by another factor of three, since the lifetime of the nuclei of higher energies is decreased by the photoeffect by one order of magnitude. Inasmuch as there are few new stars or other objects capable of serving as powerful sources of cosmic rays in that region, this fact makes also probable the conclusion that the intergalactic component of the cosmic rays makes no contribution to the corresponding part of the spectrum observed on earth.

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†We do not consider the red shift in this part of the universe, and we neglect the contribution to the radiation from the remaining part. A more accurate account of the red shift can result in only an insignificant correction.

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