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PHYSICS

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Abstract

Full Text

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ON THE POSSIBILITY OF PREFERENTIAL ACCELERATION OF HEAVY ELEMENTS IN SOURCES OF COSMIC RAYS

(Presented by Academician M. A. Leontovich on 2 VI 1958)

In the primary component of cosmic rays the abundance of nuclei with atomic number $Z_0 > 2$, relative to protons and α-particles, is on the average 5-10 times greater than the cosmic abundance ([1]), despite the fact that heavy nuclei apparently drop out of the composition of cosmic rays more rapidly because of nuclear collisions with atoms of the medium. This peculiarity of the composition may be explained either by an enhanced content of elements with $Z_0 > 2$ in cosmic-ray sources, or by their more effective acceleration. Below, using the example of Fermi' s statistical acceleration mechanism ([2]), the second possibility is investigated. It will be shown that in cosmic-ray sources there may exist conditions favorable to the preferential acceleration of heavy elements.

In statistical acceleration the mean increase of the total energy E of a particle with time is determined by the expression:

$$\frac{dE}{dt} = \left(\frac{u^2}{c^2 l}\right) vE = \alpha\sqrt{E^2 - (Mc^2)^2}, \qquad (1)$$

where $\alpha = u^2/cl$; l and u are the mean scale and velocity of the inhomogeneities of the magnetic field associated with the moving medium; M and v are the mass and velocity of the particle.

Along with acceleration, the particle undergoes energy losses in collisions with atoms and electrons of the medium. Under the condition that the velocity of the particle exceeds the velocity of the electrons of the medium v_e, the energy losses are

$$-\frac{dE}{dt} = \frac{4\pi e^4 Z^2 nL}{mv}; \qquad (2)$$

where Z is the charge of the particle; n is the concentration of electrons in the medium; m is the electron mass; L is a factor weakly dependent on the particle velocity. For nonrelativistic energies, when a heavy particle moves in neutral and

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completely ionized hydrogen, the factor L is equal respectively to $\ln(2mv^2/I)$ and $\ln(2.25\,mv^2/\hbar\omega_0)$, where I is the ionization potential of hydrogen and $\omega_0 = (4\pi ne^2/m)^{1/2}$ is the plasma frequency.

Whether a particle will be accelerated or not depends on the ratio of losses to energy gain. Equating (1) and (2), it is easy to find the threshold energy, usually called the injection energy, above which the energy gain exceeds the losses. Neglecting the logarithmic dependence of L on velocity, the injection energy is

$$E_i = \gamma + \sqrt{\gamma^2 + (Mc^2)^2}, \tag{3}$$

where $\gamma = 2\pi e^4 Z^2 nL/mc\alpha$. For large α the kinetic energy lies in the nonrelativistic region and is

$$E_{ki} = \gamma = \frac{2\pi e^4 Z^2 nL}{mc\alpha}. \tag{4}$$

The presence of Z^2 in expression (4) shows that the injection energy for multiply charged ions is higher, and therefore the acceleration conditions for them are less favorable. Hence, it would seem to follow that the occurrence of an excess of heavy elements in the acceleration process is impossible. However, such a conclusion is incorrect, since expression (2), and consequently also (4), is valid only for $v \gg v_e$; for $v \ll v_e$ the losses are small and increase linearly with the energy ([3,4]), reaching a maximum in the region $v \sim v_e$. Therefore the injection energy (4) has meaning only in the case when it exceeds the energy at which the losses are maximal, i.e. if $E_{\mathrm{ki}} > \frac{1}{2}Mv_e^2$; otherwise α, which determines the acceleration rate, is so large that the energy gain at the maximum exceeds the losses. From the condition $E_{\mathrm{ki}} = \frac{1}{2}Mv_e^{2*}$ the critical value of the parameter α is determined, above which there is no injection threshold, i.e. the particles are accelerated independently of their energies. This value is evidently equal to:

$$\alpha_{\mathrm{k}}(A, Z) = \frac{4\pi e^4 Z^2 nL}{mcMv_e^2} = \frac{\alpha_{\mathrm{k}}(\mathrm{p}) Z^2}{A}, \tag{5}$$

where $\alpha_{\mathrm{k}}(\mathrm{p}) = 4\pi e^4 nL/mcM_{pv}e^2$ is the critical value of α for protons; M_p is the proton mass.

From expression (5) follows the possibility of more effective acceleration of heavy elements. Indeed, it is natural to suppose that the particles begin to be accelerated while having a charge $Z_i = 1 \div 2$, corresponding to the predominant degree of ionization in sources of cosmic rays (nebulae, stellar atmospheres, etc.). In particular, for initial double ionization for $A > 4$, $\alpha_{\mathrm{k}}(A) = 4\alpha_{\mathrm{k}}(\mathrm{p})/A$, and therefore such an α is possible that particles with atomic number greater than a certain value will be accelerated independently of their energy, while the acceleration of all lighter particles is hindered by the presence of an injection threshold.

If $\alpha < \alpha_{\text{k}}$, then in acceleration from a thermal distribution the fraction of accelerated particles is determined by the expression

$$\frac{N}{N_0} = \frac{2}{\sqrt{\pi}(kT)^{3/2}} \int_{E_{\text{ki}}}^{\infty} E_{\text{k}}^{1/2} e^{-E_{\text{k}}/kT}\, dE_{\text{k}} = \frac{2}{\sqrt{\pi}} \int_{E_{\text{ki}}/kT}^{\infty} e^{-y} y^{1/2}\, dy, \tag{6}$$

where N_0 is the total number of particles of the given kind; T is the temperature of the medium. Since, according to (4) and (5), $E_{\text{ki}}/kT = \alpha_{\text{k}}(\text{p}) M_p v_e^2/2\alpha kT > M_p v_e^2/2kT$, and for an ionized medium $v_e = (3kT/m)^{1/2}$, the relative number of accelerated particles is negligibly small (of order $(M_p/m)^{1/2}\exp(-3M_p/2m)$). This means that, in acceleration from a thermal distribution, particles for which an injection threshold exists are practically not accelerated.

Thus, for equal initial ionization there exist conditions for preferential acceleration of heavy elements. Will these conditions be preserved under further ionization of the particle in the process of its acceleration? To clarify this question, following Bohr ([5]), we shall assume that the loss by an ion of the next, least-bound electron occurs when the ion velocity reaches the orbital velocity of this electron. In this case the charge of the ion is a function of its velocity and is equal to:

$$Z_v = \frac{Z_0^{1/3} v}{v_0}, \tag{7}$$

where $v_0 = e^2/\hbar$. This expression is valid within the velocity interval

* Extrapolating (2) all the way to $v = v_e$, we somewhat overestimate the losses at the maximum. Comparison with the available data for atomic hydrogen shows that this difference is small.

$v_0 < v < v_0 Z_0^{1/3}$ and, obviously, gives an overestimated value of the charge outside this interval, since at $v \sim v_0$ the atom is only beginning to ionize and its charge cannot be greater than the initial Z_i; complete ionization occurs at $v \sim Z_0 v_0$, i.e., at a higher velocity than follows from (7). It must also be emphasized that the establishment of the equilibrium charge (7) presupposes a sufficiently large number of collisions; under real astrophysical conditions, at low density and a high rate of acceleration, the ion may carry a charge smaller than the equilibrium one. Thus, by using expression (7) over the entire range of velocities, we can only overestimate the charge of the particle; therefore our estimate of the electron-loss effect will correspond to the most stringent conditions.

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Using (1), (2), and (7), it is easy to obtain, by analogy with the preceding case, an expression for the critical value of the acceleration parameter with allowance for the indicated effect:

$$\alpha_k'(A) = \alpha_k(\mathrm{p}) \left(\frac{v_e}{v_0}\right)^2 \frac{Z_0^{2/3}}{A}. \tag{8}$$

For the reasons indicated above, this expression gives an upper estimate of the critical value of α for $v_e > v_0 Z_0^{-1/3} Z_i$; in the region $v_e < v_0 Z^{-1/3} Z_i$, which corresponds to a medium temperature $T \lesssim 10^5 Z^{-2/3} Z_i^2$, $\alpha_k'(A)$ is smaller than $\alpha_k(A, Z_i)$ from (5) and must be replaced by the latter.

As follows from expressions (5) and (8), the ranges of values of the parameter α for which preferential acceleration of heavy elements takes place are comparatively narrow, and therefore, under real conditions, a chance establishment of the required α would be unlikely. However, in a system that includes the gas-magnetic medium and the accelerated particles, there must exist a process of self-regulation, as a result of which α necessarily falls within these limits. Indeed, if at the beginning of the acceleration process $\alpha > \alpha_k(\mathrm{p})$, all particles in the region under consideration will be accelerated. In this case one can speak of acceleration only conditionally: in practice, heating of the medium and rapid damping of the turbulent motions of the gas must occur. This process will continue until α becomes so small that only heavy elements will be accelerated; their relative abundance is small, and the turbulent energy is sufficient to accelerate them to relativistic energies.

The possibility, considered using the example of the statistical mechanism, of preferential acceleration of heavy elements is retained also for a number of other acceleration mechanisms, in particular for induction acceleration under exponential growth of the magnetic field. This makes it possible to pose in a new way the problem of the formation of the primary component of cosmic rays, if its composition is regarded as the result of the transformation of heavy elements supplied by sources in nuclear collisions with atoms of the medium.

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CITED LITERATURE

1. V. L. Ginzburg, *Uspekhi fizicheskikh nauk*, **62**, 37 (1957).

2. E. Fermi, *Phys. Rev.*, **75**, 1169 (1949).

3. E. Fermi, E. Teller, *Phys. Rev.*, **72**, 399 (1949).

4. J. Neufield, R. H. Ritchie, *Phys. Rev.*, **98**, 1632 (1955).

5. N. Bohr, *The Passage of Atomic Particles Through Matter*, IL, 1950.

Note: Figure translations are in progress. See original paper for figures.

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