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Abstract

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PHYSICS

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MULTIPLE PRODUCTION OF NUCLEON PAIRS BY THERMAL PHOTONS IN AN OPEN COSMOLOGICAL MODEL

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According to the principle of detailed balance, the theoretically known (1) process of two-photon annihilation of nucleons and antinucleons must correspond to the inverse process of production of nucleon pairs by above-threshold photons:

$$\mathrm{N} + \widetilde{\mathrm{N}} \rightleftarrows 2\gamma.$$

In an unbounded space filled with thermal radiation, the presence of an exponentially small number of above-threshold photons in the "tail" of the Planck distribution may lead to multiple production of nucleon pairs in the form of fluctuations of very large scale.

We shall find the probability density W_1 for the formation of one nucleon pair by thermal photons in a volume V per unit time from the principle of detailed balance. It is equal to the probability density of the inverse annihilation process at equilibrium concentrations of nucleons and antinucleons:

$$W_1 = \sigma[\mathrm{n}][\tilde{\mathrm{n}}]vV. \tag{1}$$

Here σ is the cross section for two-photon annihilation, calculated in (1):

$$\sigma = 38.5\pi\left(\frac{e^2}{mc^2}\right)^2\frac{c}{v} = 3\cdot 10^{-30}\frac{c}{v}\ \mathrm{cm}^2;$$

[n], [ñ] are the equilibrium concentrations of nucleons and antinucleons; v is their relative velocity. The equilibrium concentrations are found from the Fermi distribution with chemical potential equal to zero:

$$d[\mathrm{n}] = d[\tilde{\mathrm{n}}] = \frac{8\pi}{(2\pi\hbar)^3}\frac{p^2dp}{e^{\varepsilon/kT}+1}, \tag{2}$$

where ε is the total energy of a nucleon with momentum p, including the rest energy ε_0. For $\varepsilon_0 \gg kT$, with accuracy sufficient for an estimate,

$$[\mathrm{n}] = [\tilde{\mathrm{n}}] \approx \frac{1}{\lambda_T^3}e^{-\varepsilon_0/kT}, \tag{3}$$

where

$$\lambda_T = \frac{\hbar}{m\bar{v}} \tag{4}$$

is the wavelength of a nucleon at the mean thermal velocity $\bar{v} \approx \sqrt{kT/m}$. Hence

$$W_1 \approx \frac{\sigma\bar{v}V}{\lambda_T^6}e^{-2\varepsilon_0/kT}. \tag{5}$$

In the absence of gravitational interaction, $\varepsilon_0 = mc^2$. In the multiple production of a very large number of pairs, the gravitational interaction between them may become significant. Then under ε_0 one should understand···

take the relativistic energy of the nucleon in the comoving coordinate system. For a not too strong gravitational interaction we may resort to a classical estimate, assuming

$$\varepsilon_0 = m(c^2 + \varphi), \tag{6}$$

where $\varphi < 0$ is the gravitational potential. The probability that the next pair is created in a volume V before the preceding one has time to annihilate is

$$\Omega_1 = 1 - e^{-W_1/\sigma n\tilde{n}V} = 1 - e^{-[n][\tilde{n}]/n\tilde{n}}, \tag{7}$$

where n and $\tilde{n}$ are the concentrations of the already existing nucleons and antinucleons. Since we are interested in super-equilibrium fluctuations, the exponent is small, and one may use the approximation

$$\Omega_1 \simeq \frac{[n][\tilde{n}]}{n\tilde{n}}. \tag{8}$$

Passing from concentrations to the total numbers N and $\tilde{N}$ in the volume V, substituting (3) and (6), and taking into account $N = \tilde{N}$, we obtain:

$$\Omega_1 = \frac{1}{\lambda_T^6}\frac{V^2}{N^2}\,e^{-2m(c^2+\varphi)/kT}. \tag{9}$$

The probability that the creation of N subsequent pairs will follow the creation of the first pair is

$$\Omega_N = \prod_{\nu=1}^{N}\Omega_\nu. \tag{10}$$

The probability density of multiple creation of N pairs in the volume V per unit time is

$$W_N = W_1\Omega_N = \frac{\bar{\sigma}N^2}{V}\left(\frac{V}{N\lambda_T^3}\right)^{2N} e^{-2\eta Nmc^2/kT}, \tag{11}$$

where $\eta < 1$ is a factor depending on the gravitational energy.

Let us consider a fluctuation whose gravitational energy is small in comparison with its rest energy, so that (6) may be used. We shall call such a fluctuation classical. Immediately after its creation it must undergo the usual gravitational contraction with a time scale

$$t_g \simeq (G\rho)^{-1/2},$$

where G is the gravitational constant. The contraction will lead to an acceleration of the annihilation process, and the overwhelming majority of pairs will again turn into photons. But in regions where there was even an insignificant excess of particles or antiparticles, statistically distributed clusters of matter and antimatter– "worlds" and "antiworlds" –will remain. In the course of contraction the density and pressure will reach values at which the curvature of space becomes substantial, after which Newtonian contraction will be replaced by local relativistic expansion.

As is evident from (11), the probability of a classical fluctuation with a given number of particles increases with volume. The most probable fluctuations are those of the greatest volume. But at too large a volume, i.e., at low density, the formation of the next fluctuation will occur before the contraction of the preceding one. Fluctuations of lower density will give only a homogeneous equilibrium background. Hence, for a given number of particles, the largest scale of a nonequilibrium fluctuation is found from

$$W_N t_g \simeq 1, \tag{12}$$

whence

$$W_{\max} = N\lambda_T^3\chi e^{\eta mc^2/kT}, \tag{13}$$

$$\rho_{\min} = \frac{m}{\lambda_T^3\chi}e^{-\eta mc^2/kT}, \tag{14}$$

where

$$\chi = \left(\frac{V\sqrt{G\rho}}{\sigma v N^2}\right)^{1/2N} \tag{15}$$

is a dimensionless number very close to unity. The characteristic time

$$t \sim \left(\frac{\lambda_T^3\chi}{Gm}\right)^{1/2}\eta e^{\frac{1}{2}\eta\frac{mc^2}{kT}} \tag{16}$$

is at the same time both the contraction time and the time of formation of the fluctuation.

As a result of the decrease of η due to the gravitational interaction of the pairs with one another, the most probable fluctuations should be those with a radius close to the gravitational one, i.e., with a very large number of particles.

The observed mass density $\rho \sim 10^{-29}$ g/cm^3 corresponds to an energy density $\varepsilon \sim 10^{-8}$ erg/cm^3 and to an equilibrium-radiation temperature $T = (\varepsilon/a)^{1/4} \simeq$ 30°K. At this temperature the quantity mc^2/kT standing in the exponent is $\simeq 10^{11}$.

The spatial and temporal scales considered are maximal. Below them extends a continuous spectrum of fluctuations. The maximal scales greatly exceed everything to which we are accustomed. But for a universe infinite in space and time, the scales are not in any fundamental way limited.

We have spoken of classical fluctuations. Relativistic fluctuations, for which the total energy in the comoving system is close to zero, may prove to be incomparably more probable ($\eta \ll 1$). But their consistent consideration requires a joint treatment of gravitation and the strong interaction. Phenomena in which both of these interactions manifest themselves simultaneously we propose to call **epigravitational**. The most important of them is the multiple production of nucleon pairs with the formation of a mixture of nucleons and antinucleons –**epiplasma**. Fluctuations with the formation of epiplasma we shall call **epifluctuations**. As a way of making Boltzmann' s fluctuation hypothesis more concrete, one may pose the question of the possibility of constructing a turbulent cosmology in the form of an open model, filled with equilibrium radiation, in which epifluctuations statistically occur, leading to local contractions and expansions of space. On scales large in comparison with an epifluctuation the model is stationary and reversible: the constant concentration of "worlds" and "antiworlds" is maintained by their fluctuation-born production and by annihilation in collisions. Within an individual epifluctuation, however, complete irreversibility takes place.

The parameter of the model is the radiation temperature. It is determined by the exceedingly large value of the dimensionless number mc^2/kT.

Epiplasma is unstable with respect to local expansion and contraction. Therefore the annihilation process must have a nonuniform, turbulent character. In separate places epiplasma may be preserved until a later epoch. Such remnants of epiplasma may serve as sources of energy on galactic scales. The release of energy in radio galaxies and during ejections of matter from galactic nuclei ([2]), as well as the peculiar phenomena observed in interacting galaxies ([3]), may be connected with the annihilation of remnants of epiplasma which has survived in a rarefied state and only at a later stage has undergone gravitational contraction.

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