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Abstract

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MULTIPLE PRODUCTION OF NUCLEON PAIRS AND SUPERNOVA OUTBURSTS

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It is known (1) that a body with a mass exceeding the stability limit, after exhaustion of its nuclear sources of energy, must enter a nonstationary state of hydrostatically unbounded gravitational contraction. However, the literature (2–4) has not considered all the physical processes possible in this case. On approaching the gravitational radius, the kinetic (and consequently also the thermal) energy becomes comparable with the rest energy, which should lead to processes of multiple particle production. In this connection, alongside the production of hyperons and mesons already considered (5–8), special importance should be acquired by the multiple production of nucleon pairs by π^0-mesons, which for some reason has not been taken into account up to now. From general thermodynamic considerations it follows that this process is sharply facilitated in the presence of strong gravitational fields.

We shall proceed from the principle of detailed equilibrium. The known annihilation process

$$\mathrm{N} + \widetilde{\mathrm{N}} \to m\pi^0 \tag{1}$$

must correspond to the reverse process of formation of nucleon pairs by neutral π-mesons:

$$m\pi^0 \rightleftarrows \mathrm{N} + \widetilde{\mathrm{N}}. \tag{2}$$

Let us find the condition of equilibrium of this reaction. Since π^0-mesons are their own antiparticles, their number is conserved neither in the arithmetic nor in the algebraic sense, and consequently the chemical potential is equal to zero (1). In this case the equilibrium condition does not depend on the number m of participating π^0-mesons and has the form

$$\mu + \tilde{\mu} + 2m_n c^2 \varphi = 0, \tag{3}$$

where μ and $\tilde{\mu}$ are the chemical potentials of the nucleon and antinucleon in the absence of a field, and φ is the gravitational potential. Inside a spherical mass of radius R and uniform density ρ, at a distance r from the center,

$$\varphi = \frac{2}{3}\pi G\rho\,(r^2 - 3R^2). \tag{4}$$

Condition (3) is based on two assumptions. First, upon annihilation there need not necessarily be direct formation of particles other than π^0. Second, we have assumed that the gravitational field acts identically on particles and antiparticles. The latter has long since received direct experimental confirmation, since during solar eclipses the deflection in the gravitational field has been observed of the photon, which is its own antiparticle.

Let us now see in what approximation the chemical potential should be calculated. The energy of degeneracy of nucleons is

$$E_n = m_n c^2 \sqrt{1 + \nu_n^{2/3}}, \tag{5}$$

where the dimensionless density ν_n is related to the number of particles per unit volume n, or to the ordinary density ρ, by

$$\nu_n = 3\pi^2 \lambda_n^3 n = 1.4 \cdot 10^{-16} \rho. \tag{6}$$

Here $\lambda_n = \hbar / m_n c$ is the Compton wavelength of the nucleon.

Thus, the relativistic expression for nucleons would become applicable only at densities two orders of magnitude greater than nuclear density. Limiti-

Taking densities not exceeding nuclear density, we may assume that the degeneracy energy is small in comparison with the rest energy. But the processes of multiple production that interest us require thermal energies comparable with the rest energy. Therefore we may regard the nucleons as nondegenerate. Under the conditions of interest to us the matter is, of course, already in the neutron state, and at densities below nuclear density the interaction may be neglected. Then, for the equilibrium of pair formation in an ideal neutron gas, (3) gives:

$$n\tilde{n} = 4\left(\frac{m_n kT}{2\pi\hbar^2}\right)^3 e^{-2m_n(\varphi + c^2)/kT}. \tag{7}$$

Since the gravitational potential φ is negative, the gravitational field facilitates pair production.

Let us consider the course of the process of interest to us under hydrostatically unconstrained compression of a sphere of uniform density with mass M, equal to $\mathfrak{M}$ solar masses. As is known (^{2}), the hydrodynamics of general relativity without taking pressure forces into account leads to the conclusion that the radius of the sphere tends to the gravitational radius

$$R_g = \frac{2GM}{c^2} \tag{8}$$

and, correspondingly, the density—to the gravitational density

$$\rho_g = \frac{3}{32\pi}\frac{c^6}{G^3M^2} = \frac{2\cdot 10^{16}}{\mathfrak{M}^2}. \tag{9}$$

Introduce the compression parameter

$$\xi = \frac{R}{R_g} = \left(\frac{\rho_g}{\rho}\right)^{1/3} \tag{10}$$

and the thermalization coefficient

$$\beta = \frac{E_T}{E_g} = \frac{RkT}{m_{nGM}}. \tag{11}$$

As long as the relative concentration of nucleon pairs is small, it is expressed from (7) as

$$\frac{\tilde{n}}{n} = \frac{9}{16}\pi\frac{\beta^3}{\nu^2\xi^3}\exp\left(\frac{A-4\xi}{\beta}\right), \tag{12}$$

where A is a number varying from 3 at the center of the sphere to 2 at its surface. It is convenient to express from (6) the dimensionless density ν through the gravitational density ρ_g and the parameter ξ:

$$\nu = 1.4\cdot 10^{-16}\frac{\rho_g}{\xi^3} = \frac{2.8}{\mathfrak{M}^2\xi^3}, \tag{13}$$

after which

$$\frac{\tilde{n}}{n} = 0.22\,\beta^3\mathfrak{M}^4\xi^3\exp\left(\frac{A-4\xi}{\beta}\right). \tag{14}$$

As ξ approaches unity, the very concept of gravitational energy loses its meaning. If $\tilde{n}/n$ is large, then one must take into account the increase of mass due to pair production, which will rapidly lead to values of ξ for which the derived formulas are inapplicable. But formula (14) makes it possible to draw quite definite qualitative conclusions. The sphere of uniform density considered corresponds to the burnt-out core of a heterogeneous star. If its mass is of the order of the solar mass, then, according to (14), the concentration of nucleon pairs is negligible. For a mass of the order of 10 solar masses, formula (14) is quantitatively inapplicable, but the qualitative conclusion is obvious: already in the region where Newton' s theory of gravitation is applicable, practically all the matter must pass into the state of nucleon pairs.

We shall call the phenomena of nucleon-pair formation under gravitational compression, as well as all phenomena in which gravitation and nuclear forces act simultaneously, **gravitational phenomena**. Matter consisting of nucleon pairs stabilized

by a gravitational field and a high temperature, is a variety of plasma of charged particles, which we shall call epigravitational plasma, or epiplasma.

The formation of epiplasma in the final stages of stellar contraction before a supernova outburst may have important astrophysical consequences. The difference in the character of the explosion in supernovae of types I and II receives a natural explanation (^{4,5}). In type-I supernovae with a mass of about 1.5 solar masses (^{4}), the gravitational density is considerably higher than nuclear density. Here the contraction is stopped by repulsive forces between nucleons long before the gravitational radius is reached. The fraction of matter passing into the state of nucleon pairs is small. In this case the processes involving leptons are of primary importance: electron degeneracy and the formation of lepton pairs, which lead to large gradients of electron pressure and to the electric fields associated with them. The energy of contraction is transformed first into electrostatic energy, then into magnetic energy, and subsequently into the energy of superthermal particles emitting nonthermal radiation in magnetic fields (^{9,10}). By contrast, in type-II supernovae with masses of order 10 solar masses and higher (^{4,5}), the gravitational density is lower than nuclear density. Here, even before nuclear density is reached, nucleon pairs are formed in quantities many times exceeding the initial amount of matter. In this case the ejected matter must consist mainly of epiplasma. The principal process during its expansion becomes the annihilation of nucleon pairs, in which only a small fraction of the energy is converted into light. The annihilation process also continues later in the regions of interstellar gas surrounding the site of the outburst and leads to hard radiation from these regions.

Taking epigravitational phenomena into account forces a reconsideration of ideas about the remnants of supernova explosions. These should be not simply stars of high density (white dwarfs or hypothetical neutron stars), but stars containing epiplasma within them. Their capture of interstellar gas should lead to a gradual replacement of antimatter by matter, with subsequent annihilation of the liberated antimatter in the outer layers of the star. It is natural to assume that such annihilation processes should lead to instability and proceed in a nonstationary manner. In this case relativistic particles should be formed, emitting nonthermal radiation in magnetic fields. The diffusive character of the process of exchange of antimatter for matter will lead to the formation, around the dense epiplasma core, of a comparatively cold envelope. From this point of view, the remnants of outbursts should be, for type-I supernovae, nonstationary red dwarfs (flare stars) of the UV Ceti type, and for type-II supernovae, stars of the T Tauri type. It is natural for the latter to tend to form associations, since, owing to the short evolutionary path of massive stars, type-II supernovae exploding in the present epoch are young stars of the flat component. Let us note that epiplasma possesses many of the properties which V. A. Ambartsumian (11) ascribed to the hypothetical "protostellar matter."

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