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1965

SovietRxiv

Abstract

Full Text

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NEUTRONIZATION OF MATTER DURING COLLAPSE AND THE NEUTRINO SPECTRUM

At present the question of collapse as the final stage in the evolution of stars (with M greater than the mass of a white dwarf, $1.42\,M_\odot$) is being intensively developed. As is known, upon compression to densities above 10^6–10^{11} g/cm^3, any stable nuclei are transformed into neutrons ([1]). In this process high-energy neutrinos are emitted, unlike the thermal neutrinos and antineutrinos emitted in the course of the slow evolution of stars. It may be possible to detect high-energy neutrinos experimentally. Since the time of collapse is short, of the order of a second, the neutronization process will be nonequilibrium, and its kinetics must be studied.

Let us turn to the kinetics of neutronization, the first step in the study of which was made by D. A. Frank-Kamenetskii ([2]). As the simplest example, let us consider the neutronization of cold hydrogen under compression according to the law of free fall and without taking subsequent reactions into account. Thus, consider a homogeneous cloud of cold hydrogen whose compression is not affected by the pressure gradient. In this case the density varies according to the law

$$\rho = \frac{1}{6\pi G(t_0 - t)^2} = \frac{7.96 \cdot 10^5}{(t_0 - t)^2}; \qquad dt = 4.46 \cdot 10^2 \rho^{-3/2}\, d\rho, \tag{1}$$

where t is time, and t_0 is the moment at which collapse ends. Let the ratio of protons to the total number of nucleons be denoted by x, so that the mean molecular weight of the electron gas will be $\mu_e = \frac{1}{x} m_n$. In this case the Fermi momentum of the electrons has the form

$$p_F = 3.09\hbar(\rho x/m_n)^{1/3}, \tag{2}$$

and for $p_F > m_{ec}$, i.e., for a relativistic degenerate gas, the limiting Fermi energy is

$$E_F = cp_F = 3.09c\hbar(\rho x/m_n)^{1/3} \tag{3}$$

or, numerically,

$$E_F = m_{ec}^2 \left(\frac{\rho x}{10^6 \text{ g/cm}^3} \right)^{1/3}; \qquad E_F = 5.12 \cdot 10^{-3} (\rho x)^{1/3} \text{ MeV}. \tag{3a}$$

The kinetic equation for the transformation of protons into neutrons in the reaction $e^- + p = n + \nu$, in the limit of large energies E_F, has the form

$$\frac{dx}{dt} = -x \frac{\frac{1}{5}\left(\frac{E_F}{m_{ec}^2}\right)^5 \ln 2}{f\tau}. \tag{4}$$

The product $f\tau$ in the denominator consists of τ, the lifetime of β-decay of a free neutron, and $f = f(Q)$, the Fermi function for this decay, where Q is the neutron-proton energy difference; $f\tau = 790$ s. Thus, the experimental data on neutron decay are used to obtain information about the inverse reaction converting a proton into a neutron. Substituting the expression for dt in terms of $d\rho$ and E_F in terms of ρ, x, we obtain

$$dx/d\rho = -8.1 \cdot 10^{-12} \rho^{1/6} x^{8/3}. \tag{5}$$

We integrate this equation, taking $x = 1$ at $\rho = 0$, and find

$$x^{-5/3} - 1 = 1.16 \cdot 10^{-11} \rho^{7/6}. \tag{6}$$

Let us find the moment when the transformation has occurred halfway, $x = 0.5$, $\rho = 4.57 \cdot 10^9$; in this case $E_F = 6.74$ MeV, $t_0 - t = 1.32 \cdot 10^{-2}$ sec. This rough calculation leads to an important qualitative conclusion*: the transformation essentially occurs in a short time $\sim 10^{-2}$ sec, at a Fermi energy $E_F \gg m_{ec}^2$ and many times exceeding the threshold energy of the reaction $Q = 2.53 m_{ec}^2$, which justifies the use of the asymptotic formula for the probability of neutronization, which is not applicable near threshold. Almost all the excess energy $E_F - Q$ is transferred to the neutrino energy. More precisely, we find

$$\overline{E_\nu} = \int_0^{E_F - Q} E^3 (E+Q)^2 \, dE \Big/ \int_0^{E_F - Q} E^2 (E+Q)^2 \, dE =$$

$$= \frac{5}{6}(E_F - Q) = 4.56 \text{ MeV}. \tag{7}$$

In reality, apparently, compression of cold hydrogen according to the law of free fall to such densities does not occur, since the collapse of stars takes place after the stage of thermonuclear reactions, during which helium, carbon, and heavier elements up to iron are accumulated. The calculation given was intended to show the order of magnitude of the electron Fermi energy and of the neutrino energy. An exact calculation must follow from consideration of the complete problem of stellar evolution.

Let us consider, very roughly and for orientation, the neutronization of helium. Neutronization of He^4 occurs with the formation of 3 particles: $e^- + He^4 = T + n + \nu$, which makes the calculation difficult. We hope to return to an exact calculation in a subsequent publication. In any case, the process proceeds at E_F above the threshold corresponding to 22 MeV, which corresponds to the density $\rho = 1.75 \cdot 10^{11}$. Taking $ft = 10^3$ and considering the kinetic energy of the neutron formed in the process to be small, we obtain $E_F \sim 32$–33 MeV; the neutrino energy will then be of the order of 10 MeV. The next step will be the reaction $e^- + T = 3n + \nu$, in which neutrinos with energy greater than 22 MeV will be formed. We note that such a mechanism for the formation of high-energy neutrinos also works under slow compression and ensures the production of half the neutrinos with energies of order 10-13 MeV.

Let us now consider the collapse of a star consisting of iron. When, as a result of compression, the electron energy reaches 3.3 MeV, neutronization of iron begins: $e^- + {}_{26}F^{56} = {}_{25}Mn^{56} + \nu$. This process starts a series of reactions of electron capture and neutron emission, as a consequence of which the nucleus will move through the region of isobars with a large excess of neutrons, ultimately passing through the stages He^6 and T. However, already in the example of hydrogen we saw that in the course of free fall neutronization occurs at electron energies substantially exceeding the reaction threshold, and the more so the smaller the reaction probability, i.e., the larger ft. Under these conditions, undoubtedly, neutronization of iron will proceed with the formation of excited levels of Mn, for which ft is smaller. To obtain information on the sum of the probabilities of transition of iron into all excited states of manganese, one can use data on the probability of the process $\mu^- + Fe = Mn + \nu_\mu$, just as for $e^- + He^4 = T + n + \nu$ –data on $\mu^- + He^4 = T + n + \nu_\mu$.

Simultaneously with the transformation Fe $\rightarrow$ Mn, the entire chain of subsequent processes Mn $\rightarrow$ Cr, Cr $\rightarrow$ V ... will also proceed. All these processes are also interconnected because μ_e and the number of electrons per gram of matter depend on the entire composition.

* A more accurate calculation under the same physical assumptions, but taking into account the dependence of the reaction rate also on Q, gives a close result: $E_F(x = 0.5) = 7.5$ MeV.

The examples presented show that neutronization during collapse may be a source of neutrinos with energies on the order of 10-30 MeV. In order for the reddening of the neutrinos leaving the star to be negligible, the mass of the star must be of the order of no more than $150 M_\odot = 3 \cdot 10^{35}$ g. For a rough estimate of their flux, let us assume that the total density of collapsed and neutronized matter in the Universe is of the order of 10^{-29} g/cm^3, which amounts to $\sim 10^{-5}$ nucleons/cm^3 and, consequently, will give the same mean density of neutrinos.

The corresponding flux is $c \cdot 10^{-5} = 3 \cdot 10^5$ neutrinos/cm^2·sec. An estimate under the assumption of the collapse of $5 \div 10$ stars per year with $M \sim 2 \div 3 M_\odot$ in our Galaxy gives the same order of magnitude. It should be compared with the flux of solar neutrinos from the decay of B^8, $3 \cdot 10^7 \nu/\text{cm}^2$·sec, with a limiting energy of 14 MeV. However, the energy of cosmic neutrinos may be higher than 14 MeV, which will increase their count rate. Taking into account new experimental ideas ([4]), the detection of cosmic neutrinos cannot be considered excluded. Earlier, one of the authors, together with Ya. A. Smorodinsky, noted that cosmological considerations make it possible to limit the neutrino density by a bound quite unattainable for measurement by nuclear methods ([3]). The apparent contradiction between the work mentioned and the present note is due to the fact that there neutrinos of low energies, ~ 0.5 MeV and below, were considered, whereas now we turn to the consideration of high-energy neutrinos. On Earth, the total flux of all neutrinos from stars is related to the flux of neutrinos from the Sun approximately in the same way as the corresponding light fluxes, i.e., it amounts to $2 \cdot 10^{-8}$ of the solar flux. Consequently, hopes for the possibility of detecting stellar neutrinos are entirely connected with the possibility that, during neutronization in collapsing stars, such energetic neutrinos arise as are absent from the spectrum of the Sun. The very rough calculations presented above indicate two possible causes of such a situation: 1) rapid compression, 2) a stepwise reaction with a difficult first step ($He^4 \to T \to 3n$).

Received
12 III 1964

CITED LITERATURE

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