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NONEQUILIBRIUM DECAYS OF LIGHT PARTICLES AND THE PRIMORDIAL NUCLEOSYNTHESIS

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1. Introduction

The observed abundances of the light elements ^2H, ^3He, ^4He, ^7Li are well explained by the primordial nucleosynthesis theory /1,2/. When in the process of its expansion the Universe reached temperatures 1 - 0.1 MeV, nuclear reactions leading to light element production took place. The premordial abundances of these elements are good indicators of the conditions in the early Universe at the time of nucleosynthesis ($t \in 10^{-2} - 10^{2}$sec).

The output of the light elements depends primarily on the neutron-to-proton ratio at the freeze-out $(n/p)_F = \exp[(m_p - m_n)T_F^{-1}]$ which in turn is determined by the relation between the universe cooling rate and the rate of the weak processes $n + \nu \leftrightarrow p + e$ and $n + e^+ \leftrightarrow p + \bar{\nu}$. The cross-section of these reactions depends on the not very well-known value of the nucleon acial-vector coupling constant. The latter is defined through measuring the neutron half life-time $\tau_{1/2}$. The universe cooling rate $\dot{T}(t)/T(t)$ depends on the number of particle species in the primeval plasma k. Respectively $(n/p)_F$ and the calculated abundances of the light elements are functions of these two parameters.

After $(n-p)$- freeze-out the formation of nuclei in the primeval plasma proceeds through two-body baryonic fusion reactions with a rate depending upon nucleon density n_N. Thus, the amount of the produced light elements can be expressed through the following three parameters: k, $\tau_{1/2}$ and n/n_γ where n_γ is the photon density. In particular, ^{4}He-abundance is especially sensitive to the neutron-to-proton freezing ratio because nearly all neutrons ultimately bind into ^{4}He.

Theoretically calculated abundances of the light elements are in good agreement with observations. This allows one to put rather stringent restrictions on the physical conditions in the early Universe. The well-known limits on the number of neutrino flavours k_ν were obtained in such a way /3,4,5/. The recent analysis of observational data, made in ref. 2,5-7, leads to the conclusion that $k_\nu < 4$. This result is rather disturbing because in the fashionable elementary particle models there is a number of new light particles which can contribute to k. Superstring theories, for example, predict a whole shadow world connected with ours only gravitationally.

Concerning this, we reexamined the standard model trying to find possible modifications which may result in weakening the upper limit on k_ν. Putting aside serious alterations of the hot Universe scenario, such as those connected with time variation of the fundamental constant, we dwelled on a simple case of new quasistable particles.

The influence of new elementary particles on the primordial nucleosynthesis was investigated in refs. /7-14/. The corresponding changes in n/n_γ and in the effective number degrees of freedom k were considered. The presence of additional stable particles through nucleosynthesis leads to an increase in the total energy density ρ_{tot} at a given temperature, thus increasing the Universe expansion rate. This results in an increase of T_F and overproduction of ^4He. The effect of eventual equilibrium decays of massive particles after nucleosynthesis was also systematically studied /9-11/. Entropy produced by massive particle decays, changes the time-temperature relation and dilutes the ratio $n/n_\gamma=\eta$ thus requiring a larger initial η leading to overproduction of ^4He again. The influence of particles decaying before or during nucleosynthesis on the light element production has been studied only recently /12-14/. Mainly, the above discussed effects, i.e. the change in n/n_γ and ρ at the nucleosynthesis era by the immediately thermalizing decay products, have been considered.

We discuss the case of nonequilibrium decays of massive particles X during or before $(n-p)$ freezing. There have been studied the nonequilibrium interactions of the decay products with nucleons and their effect on ^4He production. The total effect of the eventual existence of these particles includes both the increase of the expansion rate and respectively T_F, and the direct influence on the kinetics of $(n-p)$ -transition by the interaction of the decay products with nucleons. The neutron-to-proton ratio can be shifted into either direction depending upon the decaying particle mass m_X its life time τ_X, the ratio of X -particle number density to that of photons prior to the decay and the decay channels of X --particle.

In what follows we shall consider in some detail the case of the dominant decay mode $X\to\nu\bar\nu$ with nonthermalized neutrinos participating in the weak $(n-p)$ -transitions.

The dependence of (n/p) -frozen ratio on the energy spectrum of nonequilibrium neutrinos can be understood as follows. Symbolically the kinetic equation governing the neutron number density can be written as

$$\frac{\partial n_n}{\partial t} = -n_\nu n_n \Gamma(\nu n\to pe) + n_p n_{\bar\nu}\Gamma(p\bar\nu\to e^+n) + n_p n_e \Gamma(pe\to\nu n) - n_{e^+} n_n \Gamma(ne^+\to p\bar\nu). \quad (1)$$

Here n_i is the number density of particles i, Γ is the probability of the corresponding reaction. The exact equation, with the universe expansion taken into account, is written below.

Contribution of nonequilibrium neutrinos changes the first two terms in this equation. Now note that equilibrium density of neutrons is smaller than that of protons, $n_n/n_p = \exp(-\Delta/T)$. Correspondingly for high energy neutrinos, when $\Gamma(\nu n\to pe) = \Gamma(\bar\nu p\to e^+n)$, the second term is larger than the first one. This results in an increase of neutron density. On the contrary, for low energy neutrinos $\Gamma(p\bar\nu\to e^+n)$ could be much smaller than $\Gamma(\nu n\to pe)$ due to energy threshold in reaction $p\bar\nu\to e^+n$. Thus, extra low energy neutrinos can lead to a smaller neutron density. So, one could expect that for a large mass of X -particles the frozen value of (n/p) -ratio should increase whereas for sufficiently small m_X it should decrease.

The presence of the additional massive particles slightly changes the thermal history of the Universe. The qualitative effect of this is a raise of the $(n-p)$ -freezing temperature T_F, which leads to an increase of the (n/p) -freezing ratio, and a corresponding increase of ^4He in comparison with that obtained in the standard model.

The estimates of the two competitive effects, i.e. the increase in the freezing temperature T_F and the change in the kinetics of the $(n-p)$- transition by the neutrinos from X -decays, shows a great predominance of the second one. As a result, the total effect of a possible presence of low energy neutrinos is an underproduction of neutrons, and in turn of ^4He, in the primordial nucleosynthesis. That means that the cosmological restriction on the number of light neutrino types can be weakened.

In the standard scenario more than 4 neutrino types k_ν, where $k_\nu = \sum_F \frac{g_F}{2}\left(T_F/T_\nu\right)^4 + \frac{8}{7}\sum_B \frac{g_B}{2}\left(T_B/T_\nu\right)^4$ (sums are taken over relativistic bosonic-B and fermionic-F helicity states without e^+, e^-, γ), lead to ^4He production inconsistent with recent analysis /2,5-7/. In the presence of decaying X -particles the stringent bound $k_\nu < 4$ fails and a larger number of neutrino flavours is permitted.

In the following section we briefly review the standard calculations of n/p -ratio. In section 3 our model is more profoundly treated, the calculations and the results are discussed. Some speculations concerning possible physical candidates for the role of the decaying particles are made in section 4.

2. Neutron freezing in the standard model

The simplest model of an isotropic and homogeneous expanding Universe is used. In the early Universe the energy density is dominated by relativistic matter (as $\rho_{rel} \sim R^{-4} \sim T^4$, $\rho_{nonrel} \sim R^{-3} \sim T^3$ the curvature and the vacuum energy term are negligibly small).

$$\rho \sim \rho_{rel} = \frac{1}{2} g_* \rho_\gamma = \frac{\pi^2}{30} g_* T^4. \tag{2}$$

So that
$$H \equiv \frac{\dot R}{R} = -\frac{\dot T}{T} \approx 1.66\, g_*^{1/2} M_{PL}^{-1} T^2, \tag{3}$$

where g_* is the effective number of relativistic degrees of freedom $g_* = \sum_B g_B (T_B/T)^4 + \frac{7}{8} \sum_F g_F (T_F/T)^4$.
Sums are taken over all relativistic bosonic (B) and fermionic (F) helicity states. M_{PL} is the Planck mass.

In this case of radiation dominated Universe $\rho = \frac{3}{32} \pi M_{PL}^2 t^{-2}$.
So, the temperature-time relation is:

$$\frac{t}{1\,\mathrm{sec}} = 2.42\, g_*^{-\frac{1}{2}} \left(\frac{1\,\mathrm{Mev}}{T}\right)^2. \tag{4}$$

The temperature falls with the expansion of the Universe. Up to 1 MeV the nucleons p and n are in equilibrium through the reactions:

$$\begin{aligned} p + e &\leftrightarrow n + \nu_e \\ n + e^+ &\leftrightarrow p + \bar\nu_e \\ n &\leftrightarrow p + e + \bar\nu_e . \end{aligned} \tag{5}$$

At the temperatures of interest, i.e. $T \sim 1\,\mathrm{Mev}$, the characteristic time scale is of an order of 1 sec and so the last reaction can be neglected. The corresponding corrections can easily be taken into account afterwards.

The evolution of the number density of neutrons participating in reactions (5) in the expanding Universe can be traced by the Boltzmann kinetic equation:

$$\frac{\partial n_n}{\partial t} = H p_n \frac{\partial n_n}{\partial p_n} - \frac{(2\pi)^4}{2E} \sum_{Z,Y} \int d\nu_Z\, d\nu_Y\, \delta^4(p_n + p_Y - p_Z) \times$$
$$\times \left[|A(n_n + Y \to Z)|^2 n_n \prod_Y n - |A(Z \to Y + n_n)|^2 \prod_Z n \right]. \tag{6}$$

Here, n is the particle occupation number in the phase space, Y, Z denote many-particle states, $\prod_Y n$ means a product of particle densities forming the Y -state. In our case Y is a one-particle state, $Y = e^+$ or $Y = \nu_e$ and no product is taken, $\prod_Z n$ means a product of particle densities forming the Z -state ($Z = p, e^+$ or $Z = p, \bar\nu_e$), $d\nu_Z = \prod_Z d^3p \frac{1}{2E(2\pi)^3}$ denotes a product over all particles in the Z-state. $A(n + Y \to Z)$ is the amplitude of the transition from the $(n + Y)$ -state into the Z -state.

The first term on the right-hand side describes the effects of the Universe expansion.

In the calculations the following relations are throughout used $N_n + N_p = \mathrm{const}$, $n_\nu(p) = e^{-x}(1 + e^{-x})^{-1}$, $n_e = e^{-z}(1 + e^{-z})^{-1}$, where $x = E_\nu/T$, $z = E_e/T$, $\Delta = m_n - m_p$, $N_{n,p}$ are particle number densities. The neutrino and the electron number densities are assumed an equilibrium ones, whereas nucleon number densities $n_n(p)$, $n_p(p)$ (respectively $N_n(x)$ and $N_p(x)$ in X-space) deviate from equilibrium because of the universe expansion and slowing down the rates of the reactions ($\nu + n \leftrightarrow p + e$ and $e^+ + n \leftrightarrow p + \bar\nu$). The corresponding nonequilibrium neutron density can be found through numerical integration of the kinetic equation (6). The calculations are performed with the equilibrium number densities for neutrons and protons as an initial condition at high temperatures, $T > 3$ MeV: $n_n/n_p = \exp(-\Delta/T)$. Particle number densities, i.e. the number of particles in a unit volume can be expressed through $n(p)$ as $N(x) = (2\pi)^{-3} \int d^3p\, n(p)$. Performing integration in the r.h.s of eq.(6), one can obtain the following equation for the time evolution of the neutron number density:

$$\frac{\partial N_n}{\partial t} = -3HN_n - G_F^2 \frac{(1+3\alpha^2)}{\pi^3} \left(N_n - N_p e^{-\frac{\Delta}{T}}\right) T^5 I, \tag{7}$$

where
$$I = \int_0^x dx\, x^2 e^{-x} (1 + e^{-x})^{-1} (1 + e^{-x-y})^{-1} (y + x) \sqrt{(y+x)^2 - \mu^2 y^2} +$$
$$+ \int_{\mu y}^{\infty} dx\, x\, e^{-x} (1 + e^{-x})^{-1} (1 + e^{-x-y})^{-1} (y + x) \sqrt{x^2 - \mu^2 y^2},$$
$$\mu = \frac{m_e}{\Delta}, \quad x = \frac{E_\nu}{T}, \quad y = \frac{\Delta}{T}, \quad \Delta = 1.293\ \mathrm{Mev}$$

The first term in the right-hand side of eq.(7) describes the Universe expansion ($H \equiv \Gamma_{exp} \sim M_{PL}^{-1} \rho^{1/2} \sim M_{PL}^{-1} T^2 \sim 1/2t$, the next two terms describe the processes $n + \nu \leftrightarrow p + e$ and $n + e^+ \leftrightarrow p + \bar{\nu}$, respectively ($\Gamma_{wk} \sim G_F^2 T^5$).

The series expansion $(1+e^{-x})^{-1} = \sum_k (-1)^k \exp(-kx)$ makes possible to do integral I analytically. The resultant equations can be numerically integrated for the temperature range of interest.

Our numerical calculations include the interval 5 MeV - 0.3 MeV. The results well coincide with those previously obtained /2, 2a, 2b/ and they are in accordance with the observed abundance of ^4He.

3. Neutron density with nonequilibrium neutrinos

The essential point in the standard approach is the assumption about the equilibrium occupation number of leptons. In what follows we reject this assumption and consider a modification of the standard approach due to nonequilibrium neutrinos in the primeval plasma. Physically, these neutrinos could arise from the decay of a new long-lived particle $X \to \nu\bar{\nu}, \tau_x \sim 1\,\mathrm{sec}$. Electrons and photons, if produced in the decay, quickly thermalize, but weakly interacting neutrinos can be long enough (or even for ever) out of equilibrium.

To calculate the modified (n/p)-ratio we start from the equation defining the evolution of decaying X-particles in the expanding Universe:

$$\frac{\partial n_x}{\partial t} = Hp\frac{\partial n_x}{\partial p} - \frac{m_x}{E_x}\Gamma n_x . \tag{8}$$

Here E_x is the total energy of X-particle, $\Gamma_x \equiv \tau_x^{-1}$ is the decay width. The first term describes the expansion, and the second one is due to the decays.

We assume that X-particle interaction with the primeval plasma is sufficiently weak, so, they are out of a thermal contact with the plasma at temperatures $T < T_F^x$ and $T_F^x > 1$ MeV. We solved eq.(8) for two different possibilities for the mass-to-freezing temperature ratio: $m_x/T_F^x > 1$ and $m_x/T_F^x \leq 1$ i.e. for different initial conditions for n_x . The second case is deserving a special attention as it allows the underproduction of ^4He.

The evolution of the decay products of X-particles is described by the equation:

$$\frac{\partial n_\nu}{\partial t} = Hp_\nu \frac{\partial n_\nu}{\partial p_\nu} + \frac{m_x \Gamma_x}{E_\nu^2}\int_{E^x_{min}}^{\infty} dE_x\, n_x(p_x) , \tag{9}$$

where $E^x_{min} = \dfrac{m_x^2 + 4E_\nu^2}{4E_\nu}$.

The two terms in the r.h.s. represent the diluting effect of the expansion and the effect of creation of n_ν from X-decays. We do not take into account the inverse decay $\nu\bar{\nu} \to X$ because the nonequilibrium neutrino density is assumed to be small.

The influence of thus produced ν and $\bar{\nu}$ on the neutron density is determined by the evolution equation for neutrons:

$$\frac{\partial}{\partial t}\Delta N_n = -\frac{G_F^2}{2\pi^3}(1+3\alpha^3)T^5(N_n - N_p)\int_0^\infty d\lambda \left(\lambda + \frac{\Delta}{T}\right)^2 \lambda^2 n_\nu , \tag{10}$$

where ΔN_n represents the alteration in the number density of neutrons due to the reactions of the decay products with nucleons.

We have solved these equations for masses $m_x > 1$ MeV, and particle life time $\tau_x \sim 1$ sec. The constraint on the life-time is based on the requirement for nonthermalization of the decay products. We found it convenient for analytical calculations to study separately the cases: $m_x/T_F^x > 1$ and $m_x/T_F^x \leq 1$.

In the first case , $m_x/T_F^x > 1$, X particles become nonrelativistic ($T_{NONREL} \sim m_x$) while still in thermal equilibrium. Their concentration for the period $t_{NONREL} < t < t_F$ is strongly suppressed by the Boltzmann factor $\exp(-m_x/T)$. X-particles decouple from the primeval plasma at temperature T_F^x (freezing temperature) with the equilibrium concentration: $N_x \sim \exp(-m_x/T_F^x) \cdot N_\gamma$. Further on, their density changes due to the expansion diluting effect and their decays.

We follow the earlier described procedure (eqs. 8-10) to find the evolution of neutrons number density in the presence of the decaying X-particles. The initial condition for eq.(8), i.e. number densities at T_F^x is $n_x^F = \exp(-E_x/T_F^x)$. For the evolution of neutrons number density in this case we obtain:

$$\frac{\partial N_n}{\partial t} = \frac{\partial N_n}{\partial t}^{standard} + \frac{\partial}{\partial t}\Delta N_n^X = -3HN_n - \frac{G_F^2(1+3\alpha^2)}{2\pi^3}\left(N_n - N_p e^{-\frac{\Delta}{T}}\right)T^5 I - \frac{G_F^2}{2\pi^3}(1+3\alpha^2)(N_n - N_p)T^5 J , \tag{11}$$

where
$$\mathcal{J} = (\gamma_F^{-2} + \gamma_F^{-1})\exp(-\gamma_F) - \left[\gamma_F^{-2} + \left(\frac{T_F^X}{T}\right)^2 \gamma_F^{-1}\right]\exp\left[-\gamma_F\left(\frac{T_F}{T}\right)^2\right]$$
$$\gamma_F = \Gamma_X t_F .$$

The last term in eq.(11) describes the effect of the $\nu + n \to p + e$ and $\bar{\nu} + p \to n + e^+$ nonequilibrium reactions with ν and $\bar{\nu}$ from X-decays. Numerical calculations have been performed for $T_F^X > 2$ MeV, $m_X > 2(\Delta + m_e)$, $\Gamma \in [1 \div 500]\ sec^{-1}$. In this case an increase in the ^4He production can be achieved. There exists also a range of values of m_X, Γ_X and T_F^X, for which the effect is negligible, e.g. the model reduces to the standard one concerning the ^4He abundance. An underproduction of ^4He is not possible in this case. More attractive in this sence is the second case: $m_X / T_F^X < 1$, where the possibility of a ^4He underproduction exists.

The initial condition to start the calculating procedure described by eqs. (8-10) is the number density of the X-particle n_X at the moment of decay. The interaction rate of X-particles with the thermal background drops below the expansion rate at temperature T_F^X while X are still relativistic: $T_F^X > m_X$. The particles freeze out at the equilibrium concentrations: $n_F^X \sim \exp(-P/T_F^X)$ (m_X / T_F^X is neglected). It is the initial condition for eq.(8) in this case. The equations can be analytically integrated for the case $\Gamma_X t \leq 1$ at $t \sim 1sec$.

The resultant equation has the form:

$$\frac{\partial N_n}{\partial t} = \frac{\partial N_n}{\partial t}^{standard} + \frac{\partial}{\partial t}\Delta N_n^X = -3HN_n - G_F^2\,\frac{(1+3\alpha^2)}{2\pi^3}\left(N_n - N_p e^{-\frac{\Delta}{T}}\right)T^5 I +$$
$$+ G^2(1+3\alpha^2)\frac{N_n \Gamma_X T m_X^2}{8\pi^3 B \sum_{k=0}^{\infty}(k+1)^3}\cdot\left[1-\gamma^4 + \frac{8}{3}\beta(1-\gamma^3) + 2\beta^2(1-\gamma^2)\right] -$$
$$- \frac{3G^2(1+3\alpha^2)}{8\pi^3 B\sum_{k=0}^{\infty}(k+1)^4}\cdot N_n \Gamma_X m_X T^2 \exp(-\Gamma_X t)\cdot(1+\beta)^2 \qquad (12)$$
$$\gamma = 2\,\frac{\Delta + m_e}{m_X}, \quad \beta = \frac{2\Delta}{m_X}, \quad B = 3.32\, g_*^{1/2} \cdot M_{PL}^{-1} .$$

The results of the numerical integration of (12) for $\Gamma_X = 1\ s^{-1}$, and for $m_X \in (2 \div 14)$ MeV, are plotted in figs. 1 and 2.

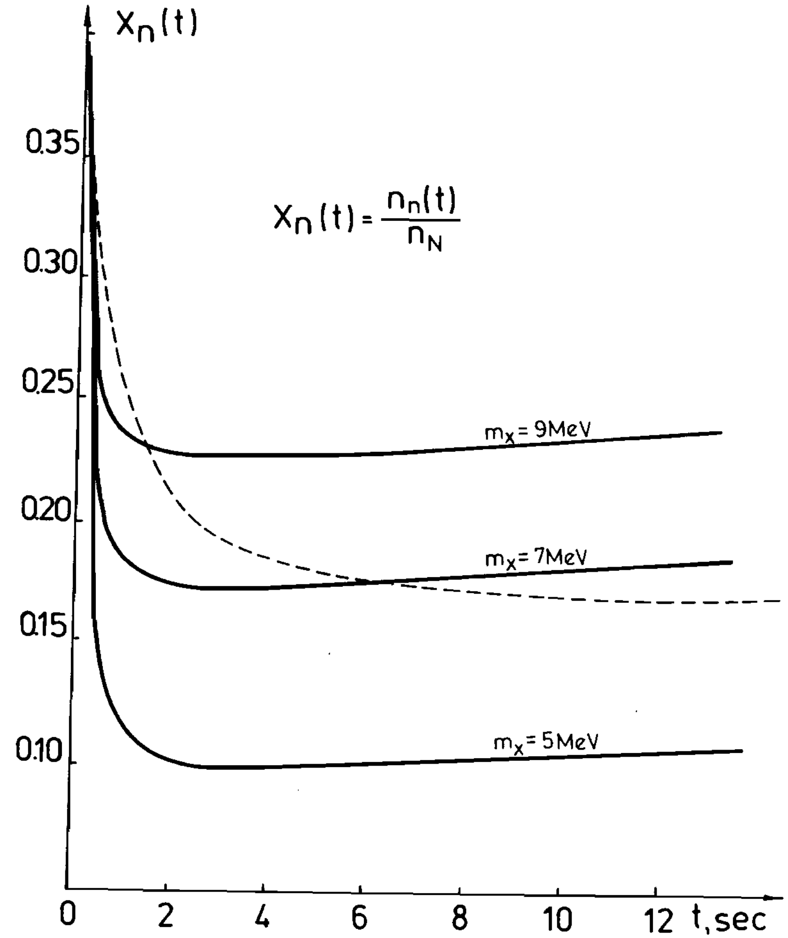

Fig.1. Solid lines give the evolution of the number density of neutrons relative to nucleons $X_n = \frac{n_n}{n_N} \approx \frac{n_n}{n_n + n_p}$ for the models with decaying X-particles with a lifetime $\tau_X \sim 1$ sec and masses m_X = 5 MeV, 7 MeV and 9 MeV. The dashed line gives the evolution of the relative neutron number density for the standard model of primordial nucleosynthesis.

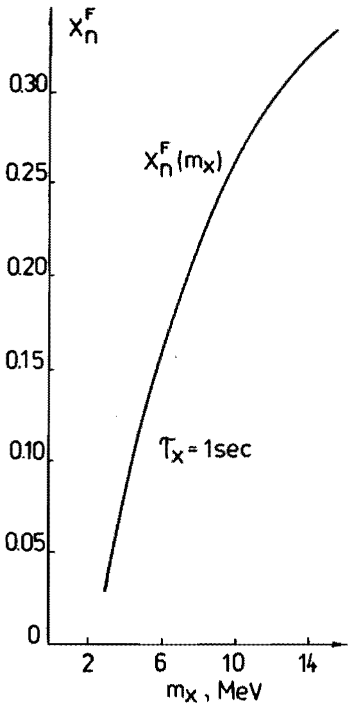

Fig.2. Neutron number density relative to nucleons at freezing temperature as a function of the particle mass m_X at $\tau_X = 1 sec.$

The relationship of the n abundance to m_X reveals the possibility for the ^4He underproduction at a sertain mass interval $m_X < 7$ MeV. $(Y_p(^4He) \sim 2X_n^F \sim 2\frac{n_n}{n_N})$

It is evident that the curves reflect the expected physical picture: below definite energies of the neutrinos $E_\nu \sim \delta + m_e$ e.g. $m_X \sim 2(\Delta + m_e)$, the p-producing reaction becomes predominant and a decrease of n and the final ^4He can be achieved.

The possibility for the ^4He underproduction can be used to weaken the stringent constraints on the number of light neutrino flavors /5-7/.

The increase of the latter leads to an overproduction of ^4He. A hybrid model with more ligh neutrinos and decaying X-particles may lead to the standard abundance of ^4He provided that the two effects compensate each other.

4. Particle physics candidates for sources of nonequilibrium neutrinos

We have shown that the comological bound on the number of neutrino species would be weaker if there existed a light quasistable particle X decaying into neutrinos. These particles must be out of equilibrium, when they decay, to produce nonequilibrium neutrinos. The characteristic time scale is of an order of 1 sec and the energy or mass scale is of an order of several MeV. An important question is whether such particles are predicted by the theory or at least do not contradict the existing experimental data. The answer to the first part of this question is unfortunately negative. No definite prediction exists for particles with such ranges of mass and life-time.

One natural candidate for X is a massive neutrino ν_X with mass of an order of 10 MeV, which drops from equilibrium at $T \sim m_X$. As for life-time of such a neutrino, the simple rescaling of muon life-time, $\tau_{\nu_X} = \tau_\mu (m_\mu / m_{\nu_X})^5$, results in $\tau_X \sim 1 sec$, see, which is of the right order of magnitude, if there is no extra suppression of the decay, which seems to be most unlikely, however.

We have considered a concrete case of aboson X decaying into $\nu\bar{\nu}$. We implicitly assumed that X was a vector particle so that it decayed into proper neutrino and antineutrino (i.e. left--handed ν_L and right-handed $\bar{\nu}_R$). For example, X could be the gauge boson connected with leptonic charge, the corresponding local symmetry being broken so that X becomes massive. The coupling constant of X is determined by the condition

$$\Gamma_X = \frac{1}{2}\frac{g_L^2}{4\pi} \cdot m_X \sim 1 \sec^{-1}$$

which gives $g_L^2/4\pi = 10^{-22}$ for $m_X = 5$ Mev. This value is safely far from the bound obtained, e.g. from electronic $(g-2)$ value. If X is indeed the leptonic gauge boson it decays not only into $\nu\bar{\nu}$ but also into e^+e^-. This decay channel was not taken into account in the preceding section; but if one notes that the electrons from the decay quickly thermalize, the effect of this extra channel amounts only to a change in the decay width.

More interesting is the case of X being a scalar boson. Now its coupling to neutrinos should not be so unnaturally tiny as for a vector particle. The point is that the decay of a scalar particle into a $\nu\bar{\nu}$ pair is forbidden by the helicity concervation if neutrino is massless. The decay amplitude is

$$A(X \to \nu\bar{\nu}) = g_S \frac{p_\mu}{m_S} \bar{\nu}\gamma_\mu (1+\gamma_5)\nu$$

and the corresponding life-time is:

$$\tau_S \equiv \Gamma_S^{-1} = \left[\frac{g_S^2}{2\pi} \cdot m_S \left(\frac{m_\nu}{m_S}\right)^2\right]^{-1} = \left(\frac{g_S^2}{2\pi}\right)^{-1} \cdot 10^{-10} \sec \cdot \left(\frac{10 eV}{m_\nu}\right)^2 \left(\frac{m_S}{10 MeV}\right).$$

We get the life-time of the right order of magnitude if $(g_S^2/2\pi) \sim 10^{-10}$. Thus, in fact an anomalously strong neutrino interaction mediated by X_S-boson change should exist. There are no experimental data which forbid such an interaction if X_S couples only to neutrinos. It is noteworthy that half of the neutrinos produced in $(X \to \nu\bar{\nu})$-decay have the wrong polarization and do not interact with nucleons.

Because of this, the calculation presented above should be modified and the final effect is to be smaller. In addition, the right-handed neutrinos contribute to ρ_{tot} , effectively increasing k_ν .

To conclude particle physics does not predict a particle with the peculiar properties we need, but at least the existence of such a particle is not forbidden and one can hope to find a room which is not squized by ^4He, ^2H, etc., for extra neutrinos or for a whole shadow world if the proposed hypothesis is true.

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Неравновесные распады легких частиц и первичный нуклеосинтез

Изучается возможность модификации стандартного сценария первичного нуклеосинтеза, которая позволила бы ослабить ограничение на число типов нейтрино. Рассмотрена конкретная модель с легкими $m_x \sim 1$ МэВ квазистабильными частицами $\tau_x \sim 1$ сек, распадающимися по каналу $X \to \nu\bar{\nu}$. В случае, когда продукты распада не успевают термализоваться, они меняют закаленное (n/p) -отношение и соответственно количество образовавшихся легких элементов. Увеличение или уменьшение этого отношения зависит от параметров модели, и, соответственно, ограничение на число сортов нейтрино может быть существенно ослаблено.

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Nonequilibrium Decays of Light Particles and the Primordial Nucleosynthesis

Possible modifications of the standard big-bang nucleosynthesis scenario, which would loosen the bound on the number of neutrino flavours, are examined. A concrete model with light (m = 0 (MeV)) quasistable particles decaying into $\nu\bar{\nu}$ is considered. If the decay products do not thermalize they shift the frozen (n/p)-ratio and respectively the abundances of the light elements produced primordially. The direction of this shift depends on the parameters of the model. Correspondingly, for the particular choice of these parameters the restrictions on the number of neutrino flavours may be considerably weakened.

The investigation has been performed at the Laboratory of Theoretical Physics, JINR.

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