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BOSE CONDENSATES, BIG BANG NUCLEOSYNTHESIS AND COSMOLOGICAL DECAY OF A 17 KEV NEUTRINO

Jes Madsen

Abstract

Early Universe decay of 17 keV neutrinos is likely to happen in equilibrium for lifetime $t_{free} < 10^5$ sec. For 3×10^{-4} sec $< t_{free} < 1 \times 10^{-2}$ sec the primordial ^4He mass-fraction Y_p may be *reduced* by up to 0.028 relative to the standard model. Bosons from the decay can form a Bose condensate, with interesting consequences for galaxy formation and the dark matter problem. The effects are generic to early Universe decay of fermions; not just of relevance for 17 keV neutrinos.

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Bose condensates, Big Bang nucleosynthesis and cosmological decay of a 17 keV neutrino

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Early Universe decay of 17 keV neutrinos is likely to happen in equilibrium for lifetime $t_{free} < 10^5$ sec. For 3×10^{-4} sec $< t_{free} < 1 \times 10^{-2}$ sec the primordial ^4He mass-fraction Y_p may be *reduced* by up to 0.028 relative to the standard model. Bosons from the decay can form a Bose condensate, with interesting consequences for galaxy formation and the dark matter problem. The effects are generic to early Universe decay of fermions; not just of relevance for 17 keV neutrinos.

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Recent experimental evidence [1] for a 17 keV neutrino mass eigenstate with 0.8% mixing to ν_e , while still disputed, has led to extensive theoretical investigations because it is very difficult to reconcile a particle with these properties with standard particle theories, not to mention cosmology and astrophysics [2]. In particular the 17 keV neutrino (henceforth assumed to be ν_τ) must be unstable to prevent the Universe from being “overclosed” by a factor of almost 200 today.

This Letter points out that the generically simplest decay pattern

$$\nu_\tau \rightarrow B + F, \quad \bar{\nu}_\tau \rightarrow \bar{B} + \bar{F}, \quad (1)$$

where B and F denote bosons and fermions with antiparticles $\bar{B}$ and $\bar{F}$, is severely constrained by saturation of the final state levels, leading to an equilibrium with effective lifetime approaching 10^5 sec irrespective of the free-particle lifetime, t_{free} , provided 3×10^{-4} sec $< t_{free} < 10^5$ sec.

Two scenarios are studied, both assuming B and F to be stable, with masses m_B and m_F less than 100 eV to avoid an “overclosure” contribution from the decay products : 1. $F \neq \nu_e$. 2. $F = \nu_e$. Both scenarios arrive in two variants, depending on B (assumed to have one internal degree of freedom) being its own antiparticle or not. Assuming a symmetric behavior of particles and antiparticles, and no other reactions than decays and the corresponding inverse reactions, *similar distributions are predicted for the particles and antiparticles, with the same sign for particle and antiparticle chemical potentials*. This leads to interesting consequences for Big Bang nucleosynthesis in scenario 2 if 3×10^{-4} sec $< t_{free} < 1 \times 10^{-2}$ sec; a *reduction* of Y_p of 0.02–0.03 may occur relative to standard Big Bang nucleosynthesis (SBBN).

Scenario 1 (and 2 for a limited range of t_{free}) leads to formation of a Bose condensate. This can have very interesting consequences for galaxy formation and the dark matter problem. The possibility of nonzero chemical potentials also changes the

hot dark matter scenario for galaxy formation, and the Tremaine-Gunn phase-space limit on the mass of dark matter particles [3, 4] is significantly altered.

The generic two-particle decay of a 17 keV neutrino is simply described in the center-of-momentum frame, where both of the relativistic decay-products carry 8.5 keV of energy. By application of Lorentz-transformations [5] one may calculate the momentum-distribution of the decay-products in the cosmic frame assuming instant isotropic decay in the rest frame at temperature T_ν , taking into account the thermal Fermi-Dirac distribution of the decaying ν_τ . An example is shown in Fig. 1, for $T_\nu = 1\text{MeV}$. The distribution function of the decay-products derived in this purely kinematical fashion exceeds the thermal distributions for momenta $p < 1\text{MeV}$. The “oversaturation” of levels proceeds down to temperatures of a few keV, corresponding to lifetimes $t_{free} \approx 10^5 \text{ sec}$ [6]. This demonstrates that “free decay” of a ν_τ with lifetime less than 10^5 sec is impossible. The inverse reaction is crucial, and an equilibrium description is more appropriate.

The assumption of equilibrium breaks down when the relevant reaction rates, depending on the actual couplings in the model, become small relative to the cosmic expansion rate. I shall assume that equilibrium is a good approximation as long as a significant fraction of the kinematically preferred phase-space for the decay products is inaccessible; that is, for $T_\nu > \text{a few keV}$ [7]. To avoid a complicated reaction network, I shall limit discussion to $t_{free} > 3 \times 10^{-4} \text{ sec}$, so that the decay process is unimportant prior to freeze-out of the weak interactions that keep neutrinos and antineutrinos in equilibrium at $T > 2.3\text{MeV}$, $t < 0.13 \text{ sec}$.

The occupation number distributions in equilibrium are

$$f_i(E_i) = [\exp((E_i - \mu_i)/T) \pm 1]^{-1}, \quad (2)$$

with chemical potentials constrained by

$$\mu_{\nu_\tau} = \mu_B + \mu_F, \quad \mu_{\bar{\nu}_\tau} = \mu_B + \mu_F. \quad (3)$$

Equation (3) assumes that no reactions apart from decay and inverse decay take place. The total number of fermions (ν_τ plus $\bar{\nu}_\tau$) must be conserved by the decay, and the number of bosons shall equal the number of ν_τ that have decayed (twice the number of ν_τ decaying if $B = \bar{B}$). Finally, the energy density must be conserved in the decay. For $F = \nu_e$, $B = \bar{B}$ this leads to the conservation equations:

$$n_{17}(T_D, 0) = n_{\nu_\tau}(T_A, \mu_{\nu_\tau}) + \frac{1}{2}n_B(T_A, \mu_B) \quad (4)$$

$$n_{17}(T_D, 0) + n_{\nu_e}(T_D, 0) = n_{\nu_\tau}(T_A, \mu_{\nu_\tau}) + n_{\nu_e}(T_A, \mu_{\nu_e}) \quad (5)$$

$$\rho_{17}(T_D, 0) + \rho_{\nu_e}(T_D, 0) = \rho_{\nu_\tau}(T_A, \mu_{\nu_\tau}) + \rho_{\nu_e}(T_A, \mu_{\nu_e}) + \frac{1}{2}\rho_B(T_A, \mu_B), \quad (6)$$

where $n_i(T, \mu_i)$, $\rho_i(T, \mu_i)$ are number- and energy densities, T_D is the neutrino temperature at decay (assumed to be instant), and T_A is the temperature immediately after decay. The distribution function of 17 keV neutrinos prior to decay is that of Eq. (2) with $\mu_{17} = 0$, $E_{17} = p_{17}$ because of the relativistic decoupling. Similar conservation laws hold for the other 3 cases. For $\mu_B = 0$ Eqs. (3), (5) and (6) describe the equilibrium, and a critical temperature $T_c = (\pi^2 n_B / \zeta(3))^{1/3}$ (with n_B calculated from Eq. (4)) is established. Below T_c a fraction $[1 - (T_A/T_c)^3]$ of the bosons are in a Bose condensate with zero momentum [8]. Figure 2 shows the evolution of chemical potentials required to satisfy Eqs. (3)–(6), and Fig. 3 illustrates how ν_τ survives until it becomes nonrelativistic. This property is *independent* of the nature of the decay products [9].

A 17 keV ν_τ with a lifetime longer than 10^{-2} sec acts like a normal third neutrino in SBBN calculations. For lifetimes between $3 \times 10^{-4} \text{ sec}$ and 10^{-2} sec the nucleosynthesis changes if $F = \nu_e$, the yields depending on whether B is its own antiparticle.

The interval of interest corresponds to decay after ν - $\bar{\nu}$ freeze-out at $T = 2.3\text{MeV}$ but prior to freeze-out of the neutron-to-proton ratio at $T \approx 0.7\text{MeV}$, which defines the main properties of the SBBN outcome.

In scenario 1 the nucleosynthesis yields are identical to SBBN—the particles involved in the decay affect nucleosynthesis only through their energy density, and this is merely redistributed between the species (this expectation was confirmed to 0.1% accuracy by numerical nucleosynthesis calculations).

In scenario 2 the energy is again redistributed without changing the cosmic expansion rate. But now the weak interactions giving the neutron-to-proton ratio at freeze-out are pushed to the proton side since *both* μ_{ν_e} and $\mu_{\bar{\nu}_e}$ take identical positive values of $+0.899$ for $B \neq \bar{B}$ ($+0.657$ for $B = \bar{B}$) in units of T_A (which is 0.844 (0.884) times T_D). While the reduction in neutrino temperature alone increases the helium yield by nearly 0.02 due to earlier freeze-out of the neutron-to-proton ratio, this is more than compensated by an opposite effect of nearly -0.05 due to the positive chemical potentials. This results in a total *reduction* of 0.028 (0.021) in Y_p as illustrated in Fig. 4. The results in Fig. 4 were calculated using Kawano’s [10] version of the Wagoner-code [11], modified to accommodate equal instead of opposite values for the chemical potentials of ν_e and $\bar{\nu}_e$, as well as $T_A < T_D$ [12]. Minor, but observationally indistinguishable changes resulted for D, ^3He and ^7Li (a 10–15% reduction in ^7Li being the only potentially observable exception). The neutron half-life was taken to be 10.3 minutes.

Fitting the observed abundances of D, ^3He and ^7Li [13] leads to an allowed range of $2.8 \leq \eta_{10} \leq 4.0$ ($\eta_{10} = 10^{10} n_{\text{bar}}/n_{\text{ph}}$, where n_{bar} and n_{ph} are the baryon and photon number densities), with a corresponding ^4He production of $0.236 \leq Y_p \leq 0.241$ in SBBN. This is marginally consistent with the primordial production deduced from observations: $Y_p = 0.228 \pm 0.010$ [14]. Scenario 2 predicts $0.208 \leq Y_p \leq 0.212$ for

$B \neq \bar{B}$, and $0.215 \leq Y_p \leq 0.219$ for $B = \bar{B}$. The latter is marginally consistent with observations. For lifetimes very close to 3×10^{-4} or 1×10^{-2} sec the ^4He -yield approaches that of SBBN. There has been a tendency of reducing observational estimates of Y_p in recent years. Should this tendency continue, it is worth noting, that the scenario presented here is one of the only mechanisms known that leads to a reduction in the primordial ^4He -production without noticeable effects on the other light elements.

In the low-temperature limit the end-products of the equilibrium decay in scenario 1 are a new fermion (and its antiparticle), plus a boson (and its antiparticle, assuming $B \neq \bar{B}$), all with $\mu \rightarrow -\infty$. More likely, equilibrium is broken in the Bose condensate regime, leaving as many as 36% of the bosons in the zero-momentum ground state. The final number-densities of F and B each equal that of a relativistic zero chemical potential neutrino flavor. In scenario 2 one again gets $\mu \rightarrow -\infty$ in the low- T limit, with a more likely loss of equilibrium when the chemical potentials are $-1 < \mu/T_A < 1$. For $B = \bar{B}$ and T_D near 5 keV there is a chance of pushing up to 26% of the bosons into a condensate.

These distributions may change the hot dark matter galaxy formation scenarios with eV-mass fermions [15] or bosons [16]. If $F = \nu_e$, half the usual ν_e -mass is needed to account for a given value of the density parameter, Ω . This improves the possibilities for ν_e to be the dark matter if the mass is close to experimental upper bounds of 10 eV, but it also doubles the free-streaming scale, if $\mu_{\nu_e} \approx 0$, which may intensify the problems in fitting simulations of structure formation. For $T_D < 5\text{keV}$ free-streaming is further increased due to heating of the ν_e -distribution. The lower mass-limit for neutrino dark matter from the simplest applications of the Tremaine-Gunn phase-space constraint [3, 4] is strengthened by a significant factor for low μ_{ν_e} since the maximum occupation number, f_{max} , is increased from 0.5 to $1/(\exp((m_{\nu_e} -$

$\mu_{\nu_e}/T_\nu) + 1)$, and the mass-limit is proportional to $f_{max}^{-1/4} \approx \exp(-\mu_{\nu_e}/4T_A)$. Thus ν_e cannot cluster in galaxies for very negative μ_{ν_e} .

If the bosons are massive, they will contribute like one light neutrino flavor to the density but have more power on small scales due to higher occupation numbers at low momenta. For small negative chemical potential the distribution will be somewhat intermediate between the zero-chemical potential neutrino and boson spectra shown in Fig. 2 of Ref. [16]. The Tremaine-Gunn limit for the boson masses [4] are strengthened by a factor approaching $\exp(-\mu_B/4T_A)$ for very negative μ_B . If a fraction of the bosons form a condensate, one has the fascinating possibility of a dark matter candidate which at the *same* time acts as hot dark matter [16] (the $\approx 65\%$ of particles not in the condensate) *and* cold dark matter (the $\approx 35\%$ of particles in the condensate). Such hybrid models have been shown to work well with massive neutrinos plus an unknown cold dark matter component [17]. The boson model will be rather similar, but with only one particle involved.

In summary, two-particle decay of a 17 keV ν_τ in the early Universe is forced into equilibrium with the inverse decay. The effective lifetime is thereby extended to 10^5 sec for free-particle lifetimes 3×10^{-4} – 10^5 sec. If the fermion produced in the decay is ν_e and the lifetime is 3×10^{-4} – 10^{-2} sec, this may give one of the only known mechanisms to reduce primordial ${}^4\text{He}$ without significantly changing the production of other elements [18]. If either of the decay-products have eV-masses, galaxy formation may proceed via a variant of the hot dark matter model, or (in the case of Bose condensation) like a hybrid hot + cold dark matter model, with the *same* particle responsible for both components. Phase-space constraints on the masses of dark matter particles in galaxy halos are strengthened significantly due to the non-zero chemical potentials (except in the hybrid case).

I have attempted to keep the discussion very general without reference to specific

models for the 17 keV neutrino or its decay properties. Details may change in particular models, but the main inferences seem to be generic, and will prevail even for decays into three or more particles, for models identifying the 17 keV neutrino with a fermion distinct from ν_τ , and for other fermion decays in the early Universe.

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REFERENCES

- lack of $B\bar{B}$ pair production.
- [9] Slightly different chemical potentials are found if B is the photon or if F is ν_μ . However, decays into photons seem excluded by astrophysical constraints.
- [10] L. Kawano, FERMILAB-PUB-88/34-A (1988) (unpublished).
- [11] R.V. Wagoner, *Astrophys.J.Suppl.* **18**, 247 (1969).
- [12] Radiative, Coulomb, and finite-temperature corrections were taken into account by subtracting 0.0025 from Y_p . These effects are described by D.A. Dicus *et al.*, *Phys.Rev.* **D26**, 2694 (1982), for $\mu_\nu = 0$. Minor errors may occur in applying this subtraction for nonzero chemical potentials.
- [13] T.P. Walker *et al.*, *Astrophys.J.* **376**, 51 (1991).
- [14] B.E.J. Pagel *et al.*, *Mon.Not.Roy.Astron.Soc.* **255**, 325 (1992), deduce $Y_p = 0.228 \pm 0.005$ from extragalactic HII-regions. This is marginally inconsistent with SBBN as well as scenario 2. The authors argue that systematic errors may be an additional ± 0.005 , making SBBN as well as scenario 2 fit marginally.
- [15] See for instance C.S. Frenk, *Phys.Scr.* **T36**, 70 (1991), for a recent review.
- [16] J. Madsen, *Astrophys.J.Lett.* **371**, L47 (1991).
- [17] A. van Dalen and R.K. Schaefer (to be published).
- [18] Another model reducing primordial ${}^4\text{He}$ production via decay of an inert 17 keV neutrino has recently been published; K. Enqvist, K. Kainulainen and M. Thomson, *Phys.Rev.Lett.* **68**, 744 (1992).
- [1] J.J. Simpson, *Phys.Rev.Lett.* **54**, 1891 (1985). J.J. Simpson and A. Hime, *Phys.Rev.* **D39**, 1825 (1989). A. Hime and J.J. Simpson, *Phys.Rev.* **D39**, 1837 (1989). A. Hime and N.A. Jelley, *Phys.Lett.* **B257**, 441 (1991). B. Sur *et al.*, *Phys.Rev.Lett.* **66**, 2444 (1991). I. Žiljmen *et al.*, *Phys.Rev.Lett.* **67**, 560 (1991).
- [2] See for instance L.M. Krauss, *Phys.Lett.* **B263**, 441 (1991). E.W. Kolb and M.S. Turner, *Phys.Rev.Lett.* **67**, 5 (1991). D.O. Caldwell and P. Langacker, *Phys.Rev.* **D44**, 823 (1991).
- [3] S. Tremaine and J.E. Gunn, *Phys.Rev.Lett.* **42**, 407 (1979).
- [4] J. Madsen, *Phys.Rev.Lett.* **64**, 2744 (1990); *Phys.Rev.* **D44**, 999 (1991).
- [5] Inspired by J.D. Jackson: *Classical Electrodynamics* (John Wiley & Sons, New York, 1975), p. 523.
- [6] Prior to decay, time and neutrino temperature is to good approximation related by $t \approx 0.7 \text{ sec} (1 \text{ MeV} / T_\nu)^2$, where T_ν equals the photon temperature, T , for $T > 0.5 \text{ MeV}$, $T_\nu = (4/11)^{1/3} T$ for $T < 0.5 \text{ MeV}$. The mean energy of thermal fermions is $3.151 T_\nu$, so relativistic time-dilation increases the neutrino lifetime roughly by a factor $3.151 T_\nu / 17 \text{ keV}$ when $T_\nu \gg 17 \text{ keV}$.
- [7] For $T_\nu = 10 \text{ keV}$ 26% of the decay products have occupation numbers exceeding 1 in the kinematical approach.
- [8] H.E. Haber and H.A. Weldon, *Phys.Rev.Lett.* **46**, 1497 (1981) argue for a T^2 -dependence for relativistic Bose-condensates, but the present case differs by the

FIGURES

FIG. 1. Occupation number distribution for low-mass B and F if decay was purely kinematic, instantaneous and isotropic in the rest-frame at $T_\nu = 1\text{MeV}$ (full line). Dotted and dash-dotted curves are thermal Fermi- and Bose-distributions at the same temperature. Dashed curve is the fraction of decay products with momentum below p .

FIG. 2. Chemical potentials for decay in equilibrium. (a) $F \neq \nu_e, B \neq \bar{B}$; (b) $F \neq \nu_e, B = \bar{B}$; (c) $F = \nu_e, B \neq \bar{B}$; (d) $F = \nu_e, B = \bar{B}$. Full lines are for B, dotted lines for F, and dashed lines for ν_τ . Dash-dotted curves are T_A/T_D , and dash-triple-dot curves T_A/T_c .

FIG. 3. Full and dotted curves are the occupation number distributions for B and F at $T_D = 1\text{keV}$. Dashed curves from top to bottom show the evolution for ν_τ at $T_D = 100, 10, 5, 3$ and 1keV for $F \neq \nu_e, B \neq \bar{B}$. The other scenarios are similar; ν_τ disappears after 10^5 sec, at temperatures of a few keV.

FIG. 4. Primordial mass-fraction of ^4He as a function of baryon-to-photon ratio. Full curve is the standard model. Dashed and dotted curves correspond to Fig. 2 (c) and (d). The box is allowed by observations.

FIG. 1

Fig. 2a

Fig. 2b

Fig. 3

Fig. 4

Fig. 2c

Fig. 2d