NEUTRINO DECAY AND THE PRIMORDIAL MAGNETIC FIELD*

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ABSTRACT. The author's neutrino decay theory leads to a definite value of $10^{-14}\mu_B$ for the transition magnetic moment between τ and μ neutrinos. It also limits the present number density of right-handed τ neutrinos to 10 per cent of the left-handed ones, if these are Dirac particles. The spin flavour precession of left-handed τ neutrinos in a primordial magnetic field is then used to constrain this field. One obtains an upper limit for the present value of this field of 10^{-13} G in vacuo and about 3×10^{-12} G when allowance is made for the presence of matter. These limits are much stronger than that derived from observations of Faraday rotation ($\sim 10^{-8}$ - 10^{-9} G) but would still permit a dynamo origin for galactic magnetic fields.

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1. Introduction

It gives me great pleasure to participate in this meeting in honour of my old friend Leon Mestel. Over the years his work on cosmic magnetic fields has done much to illuminate a difficult area of astrophysics. I hope I may be forgiven if I present a more speculative discussion of this topic than Leon himself usually likes to do. My excuse is that I am trying to relate apparently disparate parts of physics, astronomy and cosmology, on the grounds that Nature does not recognise our compartmentalisation of her. In this talk I want to point out that if the neutrino decay theory for the ionisation of the interstellar medium (Sciama 1990) is correct, and if neutrinos are Dirac particles, then one can add two things to existing discussions of constraints on the primordial magnetic field which arise from the induced spin precession of cosmological neutrinos. Firstly, one can impose a new constraint on the number density of right-handed cosmological τ neutrinos at the present time. Secondly, the neutrino decay theory leads to a specific value for the transition magnetic moment between τ and μ neutrinos (this quantity will be explained below). Using this information one arrives at a constraint on the present value of the primordial magnetic field (assuming flux-freezing) which is several orders of magnitude stronger than can be derived from consideration of the Faraday rotation of the polarised radio emission from distant sources.

2. The Present Density of Thermally Excited Right-Handed Neutrinos

It is well known that, if neutrinos are Dirac particles, their right-handed states would be thermally excited in the very early universe. This would lead to the effective number of neutrino flavours N_ν being equal to 6 at that time. However, we know from considerations of primordial nucleosynthesis that at $T \sim 1$ MeV

$$N_\nu \leq 3.3$$

(Walker *et al* 1991), essentially corresponding to the known states $\nu_{eL}, \nu_{\mu L}$ and $\nu_{\tau L}$.

This problem was solved by Shapiro *et al* (1980) and by Dolgov and Zeldovich (1981), who pointed out that, while left-handed neutrinos decouple from the cosmological heat bath at $T \sim 1$ MeV, right-handed neutrinos would be expected to decouple at $T > 200$ MeV. In the vicinity of this latter temperature quarks become hadrons, and pions and muons annihilate permanently. This leads to a boost in the number density of the remaining coupled species – γ, e and ν_L, while the ν_R would be unboosted.

The resulting suppression of n_{ν_R} relative to n_{ν_L} has been calculated by Olive *et al* (1981). They find a suppression factor lying between 10 and 20, depending on the decoupling temperature of ν_R. This is nicely consistent with the constraint $N_\nu \leq 3.3$. If this constraint can be reliably reduced in the future, one might be able either to detect the right-handed neutrinos or to show that neutrinos are Majorana particles and so do not possess additional right-handed degrees of freedom.

3. Neutrino Magnetic Moments

If neutrinos have a magnetic moment μ their spin axis would precess in a magnetic field B at a rate

$$\mu B_{\perp}/h,$$

where h is Planck's constant, and left-handed neutrinos would become right-handed when the precession angle $\sim \pi/2$. This process could be important in both the Sun and in supernovae for plausible values of their magnetic fields if

$$\mu \sim 10^{-11} - 10^{-12}\mu_B,$$

where μ_B is a Bohr magneton.

In the standard electroweak model one has

$$\mu_\nu = 3 \times 10^{-19} \frac{m_\nu}{1eV}\ \mu_B,$$

but it can be much greater in other models.

Various astrophysical constraints lead to

$$\mu_\nu \leq 10^{-12}\mu_B,$$

whereas, typically, laboratory measurements lead only to

$$\mu_\nu \leq 10^{-10}\mu_B.$$

We now consider transition magnetic moments. These involve two neutrino flavours, say 1 and 2. Then in the presence of a magnetic field μ_{12} leads to spin flavour precession. For example ν_{1L} would rotate into ν_{2R}. The rate of this precession is governed by the quantity

$$\mu_{12}B_{\perp}/h.$$

From a formal point of view μ_{12} is the non-diagonal component of the magnetic moment matrix, and the flavour conversion is closely analogous to the phenomenon of neutrino oscillations.

Since we shall require that $n_{\nu_{rR}} < \sim 0.1 n_{\nu_{LR}}$, I note here the expression for the probability P_{L-R} that starting with the state ν_L one finds that it has become ν_R in a time Δt:

$$P_{L\to R} = \sin^2 \mu_{12} B \Delta t/h.$$

This expression holds in the collision-free case. Resonance phenomena can also occur in the presence of a medium, as in the MSW effect. In fact, resonantly enhanced spin flavour precession might solve the solar neutrino problem (Ahkmedov *et al* 1993).

Most of the astrophysical constraints on μ apply also to μ_{12}. One therefore expects that

$$\mu_{12} \leq 10^{-12}\mu_B.$$

There is no accepted particle physics model leading to the value of μ_{12}. However, there is a model-independent relation between μ_{12} and τ_{12}, the lifetime for the radiative decay

$$\nu_1 \to \gamma + \nu_2.$$

For $m_{\nu_2} << m_{\nu_1}$ (which would hold both for the MSW explanation of the solar neutrino problem, and for the see-saw model of neutrino masses (Bahcall 1989)) one has

$$\mu_{12}^2 \sim \left(10^{-14}\mu_B\right)^2 \left(\frac{30eV}{m_{\nu_1}}\right)^3 \frac{10^{23}sec}{\tau_{12}}.$$

A general relation of this kind arises because both μ_{12} and τ_{12} are determined in perturbation theory by the same Feynman diagrams.

According to the neutrino decay theory (Sciama 1990) the interstellar medium is ionised by decay photons from dark matter neutrinos in the Galaxy. This requires that $m_{\nu_\tau} \sim 30$ eV and $\tau_{\tau\mu} \sim 10^{23}$ secs. Hence according to this theory

$$\mu_{\tau\mu} \sim 10^{-14}\mu_B.$$

This satisfies the astrophysical constraint that $\mu_{12} \leq 10^{-12}\mu_B$.

It may be interesting for the future to note that $\mu_{e\mu}$ might be appreciably larger than $\mu_{\tau\mu}$, and could even come close to the upper limit of $10^{-12}\mu_B$. This might lead to observable effects, for example in the Sun and in supernovae. This question depends on presently uncertain aspects of the particle physics models.

4. A Constraint on $n_{\nu_{\tau R}}$ From The Neutrino Decay Theory

In the neutrino decay theory the mass m_{ν_τ} is determined in terms of the energy E_γ of the decay photons ($m_{\nu_\tau} \sim 2E_\gamma$). This energy is itself determined by parameters derived from atomic and molecular physics and from the inferred intergalactic flux of ionising photons (Sciama 1993). Thus m_{ν_τ} is independent of $n_{\nu_{\tau R}}$. It follows that if $n_{\nu_{\tau R}}$ increases the density of the universe also increases.

This increase can be constrained if we adopt our preferred values of $\Omega = 1$ and $\lambda = 0$ as well as our derived value of $m_{\nu_\tau} \sim 30$ eV. Then we find that if $n_{\nu_{\tau R}} = 0, H \sim 56$ km sec^{-1} Mpc^{-1} and the age of the universe $\sim 12 \times 10^9$ yrs, which is low but acceptable. If $n_{\nu_{\tau R}} > 0$, H must increase and the age of the universe must decrease. If we allow at most a 5 per cent decrease in the age we find that

$$n_{\nu_{\tau R}} \leq 0.1 n_{\nu_{\tau L}}.$$

It is interesting that this is the same constraint as follows from $N_\nu \leq 3.3$, if this excess over 3 is equally divided between the different neutrino flavours.

5. A Constraint On The Primordial Magnetic Field From Spin Flavour Precession

A constraint on the primordial magnetic field from the ordinary spin precession of neutrinos was derived some years ago (Shapiro and Wasserman 1981, Lynn 1981). They used the standard model value for the magnetic moment, and assumed that $N_\nu \lesssim 4$. It is straightforward to update their discussion by using spin flavour precession with $\mu_{\tau\mu} \sim 10^{-14}\mu_B$ and by requiring that $n_{\nu_{\tau R}} \leq 0.1 n_{\nu_{LR}}$. Following the earlier discussions we note that the spin flip rate $\sim \mu_{\mu\tau}B/h \sim T^2$ if flux freezing is assumed for the magnetic field. The expansion rate H also $\sim T^2$. However the collision rate of ν_L with the heat bath $\sim T^5$ and equals the expansion rate at the decoupling temperature $T_D \sim 1\text{MeV}$.

Since collisions would disturb the spin flavour precession we apply the constraint

$$P_{L-R} \leq 0.1$$

at the epoch of decoupling T_D. (Any later $L-R$ conversion would not change the total number density of neutrinos). We then find that the present value B_o of the primordial magnetic field must satisfy

$$B_o \ < \ 10^{-13} \ G,$$

if the field is aligned over a distance ct_D at t_D (corresponding to a scale $\sim$ 30 pc to-day).

However, matter effects are important and have been considered by Fukugita *et al* (1988) and Enqvist *et al* (1992), with somewhat model dependent results. Using our estimates for $\mu_{\tau\mu}$ and $n_{\nu_{\tau R}}$ we find, typically, that

$$B_o \ <\sim \ 3 \times 10^{-12} \ G.$$

If other moments $\sim \ 10^{-12} \ \mu_B$ we would have

$$B_o \ <\sim \ 3 \times 10^{-14} \ G.$$

These limits, which are of course speculative, would be much stronger than the Faraday rotation limit of $10^{-8} - 10^{-9}$ G. They would probably still permit the galactic magnetic field to be generated from an intergalactic field by dynamo action, but other possible consequences of a primordial magnetic field might be constrained.

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