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Neutron Oscillation and the Primordial Magnetic Field

C. SIVARAM and V. KRISHAN *Indian Institute of Astrophysics, Bangalore-560 034, India*

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The phenomenon of neutron-antineutron oscillations has been recently proposed as a novel consequence of grand unified theories. The sensitivity of the oscillations to the existence of a magnetic field and the presence of a large neutron population in the nucleosynthetic era of the big bang provides a lower limit on the strength of any ordered primordial magnetic field. This would supplement recent attempts to fix upper limits on the primordial field by considerations such as neutrino oscillations and helium production.

I. INTRODUCTION

Recently the phenomenon of neutron oscillations which is of great current interest for if observed it would provide an additional evidence of the unification of strong, weak and electromagnetic interactions has been invoked to account for sub-Gev antiproton cosmic rays. (Kuzmin (1978), Glashow (1979) and Mohapatra and Marshak (1980)).

Neutron-antineutron oscillations ($n\bar{n}$ oscillations) involve a change in baryon number of 2. The time period of the oscillations have been estimated in the context of GUT's to be $\geq 10^5 - 10^7$ secs, involving a transition energy 10^{-32} to 10^{-34} ergs. The beta decay of the antineutron so formed results in an antiproton and the fact that this can take place at low energies has been recently exploited to explain the sub-Gev excess of cosmic ray antiprotons. Thus Sawada, *et al.*, 1981, consider $n\bar{n}$ oscillations of neutrons produced by spallation of cosmic ray nuclei to generate antiprotons while Krishan and Sivaram (1982) apply the phenomenon to the large neutron flux produced in supernova explosions. These low energy neutrons then go into antineutrons by oscillation, the antineutrons subsequently decaying into antiprotons. A few supernova explosions could thus account for the galactic low energy antiproton flux. (Sivaram and Krishan, 1982).

In the presence of the magnetic field the $n\bar{n}$ oscillations are inhibited because of the magnetic splitting of the neutron energy levels $\Delta E = \mu g B$, where g is the anomalous gyromagnetic ratio of the neutrons, $\mu = e\hbar/2M_n c$ and B is the magnetic field strength. Writing the Hamiltonian in the presence of the magnetic field the usual Schrodinger perturbation theory then gives for the transition rate $\bar{n}/n$ as (Sawada *et al.*, 1981, Krishan and Sivaram 1982):

$$\frac{\bar{n}}{n} \simeq \frac{1}{2}\left[\frac{\Delta e}{\Delta E}\right]^2 \tag{1}$$

where $\Delta e \simeq (\hbar/\tau) \leq 10^{-32}$ ergs for an oscillation time $\tau \geq 10^5$ seconds, and $\Delta E = 9 \times 10^{-24} B$ ergs where B is in gauss. We see thus that the ratio $\bar{n}/n$ is inversely proportional to $1/B^2$. It is apparent that the phenomenon of neutron oscillations would be important wherever large fluxes of neutrons and low magnetic fields are present. As will be seen subsequently this would enable us to put a lower limit on any primordial field present especially during the initial stage of the big bang, ie. the nucleosynthetic stage, the epoch during which deuterium and helium were synthesized. The problem of the intensity of any primordial pregalactic magnetic field present since the beginning of the universe is of both observational and theoretical interest. Various estimates have been made in the literature. For instance Harrison (1969) by considering the relative motion between ions and electrons ends up with a seed field of 10^{-15} gauss. Equipartition with the microwave background field would give a strength for the primordial field of $B \sim (8\pi a)^{1/2} T^2 \sim 10^{-6}$ gauss.

In the next section we shall describe further limits obtained on the primordial field strength.

II. LIMITS ON THE PRIMORDIAL FIELD

Upper limits on the primordial magnetic field have been obtained from a variety of considerations. For instance requiring that $B_i^2/8\pi a T^4 \leq 1$ all the way back to Planck time $t_p \sim (\hbar G/c^5)^{1/2} \sim 10^{-43}$ sec. (Zeldovich 1970), gives the present value of the magnetic field to be $B < (1\text{–}3) \times 10^{-7} G$. Other constraints are based on the consideration that the primordial field should not affect helium production. A recent attempt in this direction (Shapiro and Wasserman, 1981) points out that if the neutrinos have a small non-zero rest mass they would acquire a magnetic moment and would undergo spin precession in the primordial field. The rate at which the neutrinos flip helicities is proportional to the strength of the field and for a sufficiently large field this rate can exceed the rate of the neutrino-Fermion interactions which thermalize the left-handed neutrinos. However if the flipping is too rapid, an equilibrium population of right-handed neutrinos can also result, doubling the number of thermal (Dirac) neutrino types from $N_\gamma \geq 3$ to $N_{\gamma'} = 2N_\gamma \geq 6$. This would violate the constraint (Yang. J. *et al.*, 1979) of $N_{\gamma'} \leq 4$ imposed on the standard big-bang model by the observed ^{4}He abundance, $Y \leq 0.25$. Satisfying the constraint $N_{\gamma'} \leq 4$ by requiring that the rate of spin precession is comparable to the rate of thermalizing neutrino-fermion interactions, Shapiro and Wasserman (1981) obtain a stringent limit on the strength B of any relic magnetic field present today. The constraint is placed on the field at the decoupling time of the neutrinos corresponding to a temperature $T_D \sim 1$ Mev. Assuming flux conservation $BR^2 =$ constant, and $RT =$ constant for the adiabatic expansion of the universe would imply a present day primordial field of $B = B_D (To/T_D)^2$, where To is the present background radiation temperature. The limit on the present value of the relic field turns out to be: $B \leq (0.2 - 1.0) \times 10^{-9}\, G$, for the range of neutrino masses $4 \leq m_\gamma(ev) \leq 20$, B being inversely proportional to m_γ. Since the rate of spin flipping and production of right handed neutrinos is directly proportional to the magnetic field, the limit thus obtained is an upper limit. We will now show that the phenomenon of n–$\bar{n}$ oscillations by its sensitive dependence on the magnetic field as implied by equation (1), would place an equally stringent lower limit as the oscillation rate is inversely proportional to the square of the magnetic field. The presence of vast numbers of neutrons at the beginning of nucleosynthesis is crucial for the formation of helium as the first step in the reaction is the production of deuterium through the fusion of neutrons and protons, ie. $n + p \rightarrow D + \gamma$, virtually all the neutrons present when $T \sim 0.1$ Mev are incorporated in the helium formed. The number of neutrons (relative to protons) available for necleosynthesis depends on the freeze out temperature through the competition between the weak interaction rate (proportional to T^5) and the expansion rate of the universe (Proportional to T^2). The neutron to proton ratio "freezes out" when the weak interaction rate and the expansion rate become comparable and thus the amount of helium produced is sensitive to the expansion rate and the number of neutrons present. (Peebles, 1971, Steigman *et al.*, 1977). Hitherto it has been assumed that baryon violating processes are entirely negligible at $T \sim 1$ Mev, and that the total number of nucleons are conserved. However if neutron oscillations occur, a portion of the large number of neutrons present at this stage could get converted into antineutrons thus depleting the neutron population available for helium production via the weak interaction $\nu + n \to p + e^-$ etc. In order not to affect the helium production we could impose the constraint that the rate of conversion of neutrons via the weak interaction process be greater than or equal to the oscillation rate of neutrons to antineutrons, at temperature $T \sim 0.1$ Mev. For the nucleosynthesis, the weak interaction rate is given by:

$$\gamma_w = G_F^2 \hbar^{-7} (kT)^5 c^{-6} \tag{2}$$

where G_F is the universal Fermi interaction constant,

$$(G_F = 1.5 \times 10^{-49}\ \text{ergs cm}^3)$$

The expansion rate of the universe at this time is $\left(\frac{\dot{R}}{R}\right) \propto (g(T))^{1/2}\ T^2$ where $g(T)$ is the number of degrees of freedom. It turns out that the two rates are comparable at the epoch of nucleosynthesis. If $\bar{n}$ is the density of antineutrons produced, (by oscillations) annihilation rate of $n\bar{n}$ (into pions) is given as:

$$\gamma_a \simeq (\hbar/m_\pi c)^2\, \bar{n} c \tag{3}$$

where m_π is the pion mass.

We now require that (3) should not exceed (2), (as neutrons should not be depleted enough to effect helium production) thereby giving a limit for $\bar{n}$ as:

$$\bar{n} \leq G_F^2\, m_\pi^2\, \hbar^{-9} (kT)^5 c^{-5} \tag{4}$$

The photon density at a temperature T is given by: $n_\gamma = 480\pi^3 (kT/\hbar c)^3$ and the ratio of number of photons to baryons is given by

$$\frac{n_\gamma}{n_B} = \left(\frac{\hbar c}{G M_p^2}\right)^{1/4}$$

(Zeldovich and Novikov, 1967, Rees 1978) where M_p is the mass of proton. This would give roughly the density of neutrons at the temperature T:

$$n = 480\pi^3 \left(\frac{kT}{\hbar c}\right)^3 \left(\frac{\hbar c}{G M_p^2}\right)^{-(1/4)} \tag{5}$$

Combining (4) and (5) would give for the ratio $\bar{n}/n$ *as:*

$$\frac{\bar{n}}{n} \leq \frac{G_F^2 (kT)^2\, m_\pi^2}{480\pi^3\, M_p^{1/2}} \left(\frac{1}{\hbar^{23} c^7 G}\right)^{1/4} \tag{6}$$

This would give the limiting ratio of $\bar{n}/n$.

To bring in the magnetic field, we equate $\bar{n}/n$ as given by equation (6) to that in equation (1) giving:

$$\frac{G_F^2(kT)^2 m_\pi^2}{480\pi^3 M_p^{1/2}}\left(\frac{1}{\hbar^{23} c^7 G}\right)^{1/4} \geq \left(\frac{\Delta e}{\Delta E}\right)^2 = \left(\frac{\Delta e}{g\mu B}\right)^2 \tag{7}$$

Δe and ΔE are as defined before.

Using $\mu = e\hbar/2m_n c$ and $\Delta e = \hbar/\tau$, we finally get the limit on the primordial field as:

$$B \geq \left(\frac{m_n}{m_\pi}\right)\frac{(480\pi^3 m_p^{1/2})^{1/2}}{g\tau e G_F kT}\hbar^3 c^3 \left(\frac{G}{\hbar c}\right)^{1/8} \tag{8}$$

Equation (8) would give the value of the relic field at $T \sim 0.1$ Mev. For a present microwave background temperature, $T_o = 3\,°\mathrm{K}$, we would have the present value for the strength of the relic magnetic field as

$$B_o = B(T_o/T)^2$$

Apart from τ all the other quantities on the right hand side of the inequality (8) are fundamental physical constants. The theoretical lower limit on τ, as predicted by the grand unified theories is 10^6 secs (corresponding to a proton decay time of 10^{31} yrs.). There are a number of experiments being planned in order to determine τ, which are expected to be sensitive to $\tau \sim 5 \times 10^6$ secs. Green (1981) and Florini (1982). Using the lower limit on τ i.e. $\tau \sim 10^6$ secs gives $B_o \geq 10^{-10}$ gauss. An accurate determination of τ will fix the lower limit on the primordial magnetic field through equation (8). Table 1 shows the limits on B_o for several values of τ.

Table I

τ secs	B_o Gauss
10^6	$\geq 10^{-10}$
10^7	$\geq 10^{-11}$
10^9	$\geq 10^{-13}$
10^{11}	$\geq 10^{-15}$
10^{13}	$\geq 10^{-17}$

CONCLUSION

We have seen that the recently postulated phenomenon of neutron oscillations, with its sensitivity to the ambient magnetic field would, when applied to the neutron rich environment of the nucleo-synthetic stage of the big bang, impose a lower limit on the strength of the primordial magnetic field. The conversion rate is inversely proportional to the square of the magnetic field so that one would arrive at a lower limit on the strength of the field so as not to deplete the availability of neutrons for helium production.

In contrast the estimate of Shapiro and Wasserman, (1981) involves the phenomenon of helicity flipping of massive neutrinos the rate of which is directly proportional to the magnetic field strength which would then give an upper limit to the strength of the primordial field.

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