CERN-TH/2002-193

Cosmological Sign of Neutrino CP Violation

P.H. Frampton$^{(1,2\dagger)}$, S.L. Glashow$^{(3)}$ and T. Yanagida$^{(1,4\dagger)}$
(1) TH Division, CERN, CH 1211 Geneve, 23, Switzerland
(2) Department of Physics and Astronomy, University of North Carolina, Chapel Hill, NC27599, USA.
(3) Department of Physics, Boston University, Boston, MA 02215, USA.
(4) Department of Physics, University of Tokyo, Tokyo 113-0033, Japan.
† *permanent address*

It is shown how, in a class of models, the sign of the baryon number of the universe can be related to CP violation in neutrino oscillation experiments.

One of the most profound ideas is [1] that baryon number asymmetry arises in the early universe because of processes which violate CP symmetry and that terrestrial experiments on CP violation could therefore inform us of the details of such cosmological baryogenesis.

The early discussions of baryogenesis focused on the violation of baryon number and its possible relation to proton decay. In the light of present evidence for neutrino masses and oscillations it is more fruitful to associate the baryon number of the universe with violation of lepton number [2]. In the present Letter we shall show how, in one class of models, the sign of the baryon number of the universe correlates with the results of CP violation in neutrino oscillation experiments which will be performed in the forseeable future.

Present data on atmospheric and solar neutrinos suggest that there are respective squared mass differences $\Delta_a \simeq 3\times10^{-3}eV^2$ and $\Delta_s \simeq 5\times10^{-5}eV^2$. The corresponding mixing angles θ_1 and θ_3 satisfy $tan^2\theta_1 \simeq 1$ and $0.6 \leq sin^2 2\theta_3 \leq 0.96$ with $sin^2\theta_3 = 0.8$ as the best fit. The third mixing angle is much smaller than the other two, since the data require $sin^2 2\theta_2 \leq 0.1$.

A first requirement is that our model accommodate these experimental facts at low energy.

In the minimal standard model, neutrinos are massless. The most economical addition to the standard model which accommodates both neutrino masses and allows the violation of lepton number to underly the cosmological baryon asymmetry is two right-handed neutrinos $N_{1,2}$. This gives rise to a more constrained see-saw mechanism than envisioned in [3].

These lead to new terms in the lagrangian:

$$\mathcal{L} = \frac{1}{2}(N_1, N_2)\begin{pmatrix} M_1 & 0 \\ 0 & M_2 \end{pmatrix}\begin{pmatrix} N_1 \\ N_2 \end{pmatrix} +$$

$$+ (N_1, N_2)\begin{pmatrix} a & a^{'} & 0 \\ 0 & b & b^{'} \end{pmatrix}\begin{pmatrix} l_1 \\ l_2 \\ l_3 \end{pmatrix} H + h.c. \qquad (1)$$

where we shall denote the rectangular Dirac mass matrix by D_{ij}. We have assumed a texture for D_{ij} in which the upper right and lower left entries vanish. The remaining parameters in our model are both necessary and sufficient to account for the data. The texture zeroes of Eq(1) can be achieved with supersymmetry by imposing a complicated global symmetry.

For the light neutrinos, the see-saw mechanism leads to the mass matrix [3]

$$\begin{aligned} \hat{L} &= D^T M^{-1} D \\ &= \begin{pmatrix} \frac{a^2}{M_1} & \frac{aa^{'}}{M_1} & 0 \\ \frac{aa^{'}}{M_1} & \frac{(a^{'})^2}{M_1} + \frac{b^2}{M_2} & \frac{bb^{'}}{M_2} \\ 0 & \frac{bb^{'}}{M_2} & \frac{(b^{'})^2}{M_2} \end{pmatrix} \end{aligned} \qquad (2)$$

We take a basis where $a, b, b^{'}$ are real and where $a^{'}$ is complex $a^{'} \equiv |a^{'}|e^{i\delta}$. To check consistency with low-energy phenomenology we temporarily take the specific values (these will be loosened later) $b^{'} = b$ and $a^{'} = \sqrt{2}a$ and all parameters real. In that case:

$$\hat{L} = \begin{pmatrix} \frac{a^2}{M_1} & \frac{\sqrt{2}a^2}{M_1} & 0 \\ \frac{\sqrt{2}a^2}{M_1} & \frac{2a^2}{M_1} + \frac{b^2}{M_2} & \frac{b^2}{M_2} \\ 0 & \frac{b^2}{M_2} & \frac{b^2}{M_2} \end{pmatrix} \qquad (3)$$

We now diagonalize to the mass basis by writing:

$$\mathcal{L} = \frac{1}{2}\nu^T \hat{L} \nu = \frac{1}{2}\nu^{'T} U^T \hat{L} U \nu^{'} \qquad (4)$$

where

$$U = \begin{pmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 0 \\ -1/2 & 1/2 & 1/\sqrt{2} \\ 1/2 & -1/2 & 1/\sqrt{2} \end{pmatrix} \times$$

$$\times \begin{pmatrix} 1 & 0 & 0 \\ 0 & cos\theta & sin\theta \\ 0 & -sin\theta & cos\theta \end{pmatrix} \qquad (5)$$

We deduce that the mass eigenvalues and θ are given by

$$m(\nu_3^{'}) \simeq 2b^2/M_2; \quad m(\nu_2^{'}) \simeq 2a^2/M_1; \quad m(\nu_1^{'}) = 0 \qquad (6)$$

and

$$\theta \simeq m(\nu_2^{'})/(\sqrt{2}m(\nu_3^{'})) \qquad (7)$$

in which it was assumed that $a^2/M_1 \ll b^2/M_2$.

By examining the relation between the three mass eigenstates and the corresponding flavor eigenstates we find that for the unitary matrix relevant to neutrino oscillations that

$$U_{e3} \simeq sin\theta/\sqrt{2} \simeq m(\nu_2)/(2m(\nu_3)) \qquad (8)$$

Thus the assumptions $a^{'}\ \sqrt{2}a$, $b^{'} = b$ adequately fit the experimental data, but $a^{'}$ and $b^{'}$ could be varied around $\sqrt{2}a$ and b respectively to achieve better fits.

But we may conclude that

$$\begin{aligned} 2b^2/M_2 &\simeq 0.05eV = \sqrt{\Delta_a} \\ 2a^2/M_1 &\simeq 7 \times 10^{-3}eV = \sqrt{\Delta_s} \end{aligned} \qquad (9)$$

It follows from these values, taking into account that the L asymmetry for N_2 decay is suppressed due to the washing-out effect, also by a factor $(hh^{\dagger})^2/(hh^{\dagger})_{22}$, that the mass M_2 for N_2 must be larger than 10^{12} GeV [4] if N_2 decay is responsible for the present baryon asymmetry.

This would mean that the reheating temperature is higher than 10^{12} GeV which would lead to a serious problem with cosmological production of gravitinos of mass O(TeV) in the supersymmetric standard model.

Therefore we consider it more likely that N_1 decay produces the baryon asymmetry, since the mass M_1 of N_1 can be $\sim 10^{10}$ GeV.

Making this choice enables us to compute from the sign (known from cosmological B) of the high-energy CP violating parameter (ξ_H) appearing in leptogenesis the sign of the CP violation parameter which will be measured in low-energy ν oscillations (ξ_L).

We find the baryon number B of the universe produced by N_1 decay proportional to [5]

$$\begin{aligned} B \propto \xi_H = (ImDD^{\dagger})^2_{12} &= Im(a^{'}b)^2 \\ &= +Y^2a^2b^2sin2\delta \end{aligned} \qquad (10)$$

in which B is positive by observation of the universe. Here we have loosened our assumption about $a^{'}$ to $a^{'} = Yae^{i\delta}$.

At low energy the CP violation in neutrino oscillations is governed by the quantity [7]

$$\xi_L = Im(h_{12}h_{23}h_{31}) \qquad (11)$$

where $h = \hat{L}\hat{L}^{\dagger}$.

Using Eq.(2) we find:

$$\begin{aligned} h_{12} &= \left(\frac{a^3a^{'}}{M_1^2} + \frac{a|a^{'}|^2a^{'*}}{M_1^2}\right) + \frac{aa^{'}b^2}{M_1M_2} \\ h_{23} &= \left(\frac{bb^{'}a^{'2}}{M_1M_2}\right) + \left(\frac{b^3b^{'}}{M_2^2} + \frac{bb^{'3}}{M_2^2}\right) \\ h_{31} &= \left(\frac{aa^{'*}bb^{'}}{M_1M_2}\right) \end{aligned} \qquad (12)$$

from which it follows that

$$\xi_L = -\frac{a^6b^6}{M_1^3M_2^3}sin2\delta[Y^2(2+Y^2)] \qquad (13)$$

Here we have taken $b = b^{'}$ because the mixing for the atmospheric neutrinos is almost maximal.

Neutrinoless double beta decay $(\beta\beta)_{0\nu}$ is predicted at a rate corresponding to $\hat{L}_{ee} \simeq 3\times 10^{-3}eV$.

The comparison between Eq.(10) and Eq.(13) now gives a unique relation between the signs of ξ_L and ξ_H.

As a check of this assertion we consider the equally viable alternative model

$$D = \begin{pmatrix} a & 0 & a^{'} \\ 0 & b & b^{'} \end{pmatrix} \qquad (14)$$

in Eq.(1) where ξ_L reverses sign but the signs of ξ_H and ξ_L are still uniquely correlated once the $\hat{L}$ textures arising from the D textures of Eq.(1)

and Eq.(14) are distinguished by low-energy phenomenology. Note that such models have five parameters including a phase and that cases B1 and B2 in [6] are unphysical limits of (1) and (14) respectively.

This fulfils in such a class of models the idea of [1] with only the small change that baryon number violation is replaced by lepton number violation.

The work of P.H.F. was supported in part by the Department of Energy under Grant Number DE-FG02-97ER-410236; that of S.L.G. by the National Science Foundation under Grant Number NSF-PHY-0099529; and that of T.Y. by Grant-in-Aid for Scientific Research (S)14102004.

---

[1] A.D. Sakharov, Pis'ma Zh. Eksp. Teor. Fiz. **5,** 32 (1967) [JETP Lett. **5,** 24 (1967)]

[2] M. Fukugita and Y. Yanagida, Phys. Lett. **B174,** 45 (1986).

[3] T. Yanagida, in *Proceedings of the Workshop on Unified Theories and Baryon Number of the Universe* Editors:O.Sawada and A. Sugamoto, (Tsukuba, Japan, 1979), KEK Report KEK-79-18, page 95.
M. Gell-Mann, P. Ramond and R. Slansky, in *Supergravity* Editors: D.Z. Freedman and P. Van Nieuwenhuizen, (North-Holland, Amsterdam, 1979).

[4] W. Buchmüller, P. Di Bari and M. Plumacher. `hep-ph/0209301`.

[5] See *e.g.* W. Buchmüller and M. Plumacher, Phys. Reps. **320,** 329 (1999), and references therein.

[6] P.H. Frampton, S.L. Glashow and D. Marfatia, Phys. Lett. **B536,** 79 (2002).

[7] G.C. Branco, T. Morozumi, B.M. Nobre and M.N. Rebelo. `hep-ph/0204189`; M. Rebelo. `hep-ph/0207236`.