DEUTSCHES ELEKTRONEN-SYNCHROTRON DESY

DESY 86-090
August 1986



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by

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ISSN 0418-9833

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DESY 86-090
August 1986

ISSN 0418-9833

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Invited talk given at the International Symposium on Weak and Electromagnetic Interactions in Nuclei, Heidelberg, July 1986, to appear in the Proceedings of the Symposium



Quasi Standard Model Physics

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## Abstract

Possible small extensions of the standard model are considered, which are motivated by the strong CP problem and by the baryon asymmetry of the Universe. Phenomenological arguments are given which suggest that imposing a PQ symmetry to solve the strong CP problem is only tenable if the scale of the PQ breakdown is much above $M_W$. Furthermore, an attempt is made to connect the scale of the PQ breakdown to that of the breakdown of lepton number. It is argued that in these theories the same intermediate scale may be responsible for the baryon number of the Universe, provided the Kuzmin Rubakov Shaposhnikov (B+L) erasing mechanism is operative.

## 1. Big and Little Excursions from the Standard Model

The standard SU(3) x SU(2) x U(1) model of the strong and electroweak interactions works extremely well phenomenologically. Particle theorists, however, are unhappy because they do not understand the deep reasons behind some of the structural aspects of the standard model. Putting it succinctly /1/, theorists would like to know:

i) why these are the forces we see in nature?
ii) why the matter we see are quarks and leptons?
iii) what fixes the dynamics which generates masses for all the elementary excitations?

Elaborate theoretical constructs exist which try to address these deep structural queries. Composite models, technicolor, supersymmetry, GUTs, supergravity and superstrings are some of the key concepts employed to try to provide an answer to the above deep questions. However, it is not my intention here to speak of any of these beautiful theoretical ideas (whose common link, alas, is that of having as yet no evidence for their validity!) Rather than looking at these rather large extrapolations beyond the standard model, I want to concentrate on two points which require only modest excursions beyond the standard model and for which one can adduce some experimental/theoretical evidence in their favor.

The first of these little excursions concerns the strong CP problem. Due to the structure of the QCD vacuum /2/ and the presence of an ABJ anomaly for chiral rotations /3/, one has an effective CP violating term in the standard model Lagrangian:

$$\mathcal{L}_{CP\,viol.} = \frac{\alpha_s}{4\pi}\left(\theta + \mathrm{Arg}\det M\right) F_a^{\mu\nu}\tilde{F}_{a\mu\nu} = \frac{\alpha_s}{4\pi}\,\bar{\theta}\, F_a^{\mu\nu}\tilde{F}_{a\mu\nu} \tag{1}$$

Here $\theta$ is the QCD vacuum angle and M is the quark mass matrix. However, the parameter $\bar{\theta}$ is very strongly bounded by the absence of a neutron electric dipole moment /4/

$$\bar{\theta} \lesssim 10^{-8} - 10^{-9} \tag{2}$$

It is totally ununderstandable theoretically why $\bar{\theta} \simeq 0$, unless some new physics forces a cancellation between the SU(3) and SU(2) x U(1) pieces in $\bar{\theta}$. Augmenting the standard model by an extra global $U(1)_{PQ}$ chiral symmetry locks automatically the phase of the quark mass matrix to the vacuum angle giving $\bar{\theta} = 0$ /5/. However, such a global symmetry also implies the existence of a pseudo Goldstone boson, the axion /6/.

The question of axions, as a price to pay to solve the strong CP problem, will be discussed in the next two sections. In Sec. II I will review the most recent bounds on visible axions, particularly those for the recently proposed variant axions /7/. The conclusion which will emerge is that no window is left for axions to exist, if the scale of the $U(1)_{PQ}$ breakdown is connected to that of the weak scale. In Sec. III, the astrophysical and cosmological bounds on invisible axions will be discussed, narrowing the range for an allowed scale of the $U(1)_{PQ}$ breakdown to a window from $10^8$ to $10^{12}$ GeV. Physical arguments will be presented in this section which will connect the scale of the $U(1)_{PQ}$ breakdown to that of lepton number. If this connection really obtains then light neutrinos, such as those needed to solve the solar neutrino puzzle, may indeed point to the same dynamical scale as that needed to solve the strong CP puzzle! /8/

The second little excursion from the standard model which I would like to discuss concerns the Universe baryon asymmetry. The observed ratio /9/

$$(n_B - n_{\bar{B}})/n_\gamma \simeq 10^{-10} \tag{3}$$



could be a peculiar initial condition. However, if the Universe started in a symmetric way, to obtain (3) it is necessary that there should be baryon number violating interactions at some level. Baryon number, classically, is a global symmetry of the standard model and so it is natural to presume that for the Universe's asymmetry to obtain it is necessary to go beyond the standard model. However, at the quantum level, baryon number is violated in the standard model /2/ because the baryon number current has an ABJ anomaly /3/. Thus one must check first that these effects are irrelevant, before invoking physics beyond the standard model to explain the ratio in (3).

The physics of baryon number violation in the standard model is quite analogous to that of the strong CP problem. For baryon number violation what is relevant also is the presence of a non trivial vacuum structure, connected with the appearance of an electroweak vacuum angle $\theta_{EW}$. However, under normal circumstances, baryon violating processes are suppressed by a factor of $\exp(-4\pi\sin^2\theta_W/\alpha)$ and are totally negligible. However, as pointed out by Kuzmin, Rubakov and Shaposhnikov /10/, and as discussed in Sec. IV, in the early Universe the non trivial electroweak vacuum structure may lead to significant baryon number violation. Indeed if the KRS mechanism is operative it is quite possible that any previously produced baryon number (more precisely B+L) could get erased at temperatures of order of $M_W$. Thus, there exist the exciting possibility that a lepton asymmetry in the Universe, generated at temperatures of the order of the $U(1)_{PQ}$ symmetry breaking, may ultimately be responsible for the observed ratio (3). In this way, the strong CP problem, light neutrinos and the baryon asymmetry of the Universe are mutually interconnected phenomena.

## 2. The Last Hurrah for Visible Axions

Technically to solve the strong CP problem, by imposing an additional global $U(1)_{PQ}$ symmetry /5/, requires at least two doublets of Higgs in the theory. When these doublets $\phi_i$ get vacuum expectation value not only does SU(2) x U(1) break down to $U(1)_{em}$, but also $U(1)_{PQ}$ is broken down. Fortunately, the resulting Goldstone boson - the axion /6/ - is not totally massless because the $U(1)_{PQ}$ symmetry is anomalous. However, the axion is still very light with a mass of order $m_\pi f_\pi/V$, with V being the scale of the electroweak symmetry breaking ( $V \sim \langle\phi_i\rangle$ ) and hence ought to be visible.

Two classes of axion models have been invented: standard and variant. In the standard axion model /5/ /6/ all quark flavors are treated in a symmetric fashion under $U(1)_{PQ}$, while in variant models /7/ /11/ the quarks are treated asymmetrically under $U(1)_{PQ}$ (For instance, only the first generation of quarks effectively have PQ charges). In terms of the couplings to the Higgs field $\phi_i$, the distinction between standard and variant models is that in the standard axion case all charge 2/3 (all charge -1/3) right handed quark fields couple to $\phi_1$ ($\phi_2$), while in the variant case some charge 2/3 right handed quark fields couple to $\tilde{\phi}_2$ rather than $\phi_1$.

Standard axions have been ruled out experimentally already a number of years ago by a combination of experiments, including quarkonia radiative decays ($\psi \to \gamma a$; $\Upsilon \to \gamma a$), beam dump experiments and a variety of nuclear deexcitation experiments /12/. Variant axion models were (re)invented this year to try to explain the positron peaks and $e^+e^-$ correlated signals seen at GSI /13/. Since these phenomena require kinematically that the axion mass be near 1.7 - 1.8 MeV it follows that one of the Higgs expectation values is much greater than the other (see below). Because of this, unless one has asymmetric couplings to quarks of different families, either the rate for $\psi \to \gamma a$ or that for $\Upsilon \to \gamma a$ is very enhanced. Variant axion models, very neatly avoid this problem /7/. Furthermore, these models also have a very short lifetime for a $\to e^+e^-$ and can avoid in this way the old beam dump and nuclear deexcitation bounds. Hence the GSI signals raised the exciting possibility that perhaps some kind of visible variant axion might really exist.

Unfortunately variant axion models are now also ruled out experimentally. First of all, the appearance of a second correlated peak in the EPOS experiment /13/, plus the failure of finding any convincing production mechanism /14/ have considerably weakened the axion interpretation for the GSI phenomena. Most importantly, however, new experiments contradict the expectations of the most general variant axion models and thus, independently of the GSI observations, eliminate this remaining option for an axion model, where the scale of breaking of $U(1)_{PQ}$ is the same as that of the electroweak theory.

Variant axion models have essentially two free parameters: the ratio $x = \langle\phi_2\rangle/\langle\phi_1\rangle$ of Higgs vacuum expectation values and the number, $N_{PQ}$, of quark doublets which have a PQ symmetry. The axion mass fixes, however, one combination of these parameters. One has /11/

$$m_a \simeq \frac{m_\pi f_\pi}{v} \frac{(m_u m_d)^{1/2}}{(m_u + m_d)} N_{PQ}\left(x + \frac{1}{x}\right) \simeq 25\, N_{PQ}\left(x + \frac{1}{x}\right) \mathrm{KeV} \tag{4}$$

If $m_a \simeq 1.7$ MeV, $N_{PQ}(x + \frac{1}{x})$ must be large. Further, to avoid the quarkonia bounds, x not $x^{-1}$ must be large. Hence the GSI identification implies $N_{PQ}x \simeq 70$. Since one can measure experimentally three characteristics of variant axions, as a function of



the remaining free parameter: the axion coupling to electrons, the isovector content of the axion and the isoscalar content of the axion, these models are testable.

Electron beam dump experiments, recently performed at KEK /15/ and Orsay /16/, rule out any coupling of variant axions to $e^+e^-$ which are consistent with the g-2 bound on this coupling. In particular, values of $x \lesssim 70$ are clearly excluded. Experiments measuring axion deexcitation in hadronic transitions also rule out variant axions /1/. Isovector transitions like $np \to da$ /17/, $\pi^+ \to a\, e^+ \nu_e$ /18/ or the decay of the $2^+1$ 9.17 MeV state in $^{14}N$ to its $1^+0$ ground state /19/ measure the mixing parameter

$$\lambda_3 \simeq \frac{x}{2}\left[1 - N_{PQ}\frac{(m_d - m_u)}{(m_d + m_u)}\right] \simeq \frac{x}{8}(4 - N_{PQ}) \tag{5}$$

The most stringent bound comes from the $\pi^+$ decay experiment where one predicts /20/ /21/

$$B(\pi^+ \to a\, e^+ \nu_e) \simeq 3 \times 10^{-9} (\lambda_3)^2 \tag{6}$$

to be compared to the SIN bound /18/

$$B(\pi^+ \to a\, e^+ \nu_e) \lesssim (1\text{-}2) \times 10^{-10} \tag{7}$$

yielding $|\lambda_3| \lesssim 0.25$. Such a value is only compatible with (5) and $xN_{PQ} \simeq 70$ if $N_{PQ} = 4$. However, such a value is in conflict with the recent result of an isoscalar, axion induced, nuclear deexcitation experiment in $^{10}B$. The axion to photon rate for the 3.59 MeV $2^+0 \to 3^+0$ transition is predicted to be /1/ /20/

$$\frac{\Gamma_a}{\Gamma_\gamma} = 7.9 \times 10^{-4} (\lambda_s)^2 \tag{8}$$

while experimentally /22/ one observes

$$\frac{\Gamma_a}{\Gamma_\gamma} \lesssim 7.2 \times 10^{-3} \tag{9}$$

implying a bound for the isoscalar mixing: $|\lambda_s| \lesssim 3$. However, in variant axion models one has a constraint

$$\lambda_3 - \lambda_s \simeq \frac{3}{8} x N_{PQ} \simeq 26 \tag{10}$$

which is clearly violated by the above bounds.

These results have dashed all hopes to prove experimentally that the solution of the strong CP problem is due to having an extra $U(1)_{PQ}$ in the theory, which then begets a visible axion. That is not to say, however, that this may not be still the solution to the strong CP problem. If the scale of the breakdown of $U(1)_{PQ}$, $V_{PQ}$, is much greater than the weak interaction scale $V \sim 250$ GeV, then the concomitant axion is superlight ($m_a \sim \frac{1}{V_{PQ}}$) and very weakly coupled ($\sim \frac{1}{V_{PQ}}$) and hence essentially invisible.

## 3. Invisible Axions and Elusive Neutrinos - is there a Connection?

Invisible axion models /23/ make use of an additional $SU(2) \times U(1)$ singlet Higgs field $\sigma$ which carries $U(1)_{PQ}$ charge and which has a very large vacuum expectation value

$$\langle\sigma\rangle = V_{PQ} \gg V \tag{11}$$

Because of the extra $U(1)_{PQ}$ symmetry, the strong CP problem is solved ($\bar{\theta} = 0$). However, now there are no experimental problems (or tests!) for the resulting axion because it is very light, very weakly coupled and extremely long lived. The real question then becomes how can one tell that this is right? Remarkably, invisible axions have some astrophysical and cosmological constraints and, under certain circumstances, can even be searched for experimentally.

Astrophysics gives a lower bound on the symmetry breaking scale $V_{PQ}$. This bound follows because invisible axions can efficiently cool stars by a Compton-like process $\gamma + e \to e + a$, with the resulting axions escaping from the star because they are so weakly coupled. The energy loss due to axions is proportional to the cross section for the above process and thus is inversely proportional to $V_{PQ}^2$. Only if $V_{PQ}$ is sufficiently big, axions would not have affected the known life cycle of stars. Detailed investigations /24/ give a bound for $V_{PQ}$

$$V_{PQ} \gtrsim 10^8 \text{ GeV} \tag{12}$$

Cosmology gives actually an upper bound for $V_{PQ}$. This comes about because in the early Universe, at temperatures below those of the scale of the $U(1)_{PQ}$ breakdown but much above the scale of QCD, the locking mechanism which fixed the phase of the quark mass matrix is not operative. In this temperature regime this phase is arbitrary and not fixed to be $-\theta$. This unrestricted Yukawa phase corresponds to a coherent axion field of magnitude of order $V_{PQ}$ (i.e. a phase of $O(1)$):

$$a(x) \sim V_{PQ} \tag{13}$$

As the temperature decreases locking takes place and the phase oscillates about its final value $-\theta$. These phase oscillations (axion oscillations) contribute to the



Universe energy density and one finds /25/ that if $V_{PQ}$ is too big, the energy density today in the oscillating axion field exceeds the critical density needed to close the Universe. This gives an upper bound for $V_{PQ}$ of order /25/:

$$V_{PQ} \lesssim 10^{12} \text{ GeV} \tag{14}$$

We see that the strong CP problem can be solved by having an extra $U(1)_{PQ}$ symmetry in the theory only if the scale of the breakdown lies between:

$$10^8 \text{ GeV} \lesssim V_{PQ} \lesssim 10^{12} \text{ GeV} \tag{15}$$

In particular, if $V_{PQ}$ is near the upper end of the above range then the Universe's energy density is dominated by axions! The axion mass, if $V_{PQ} \sim 10^{12}$ GeV, is $m_a \sim 10^{-5}$ ev which corresponds to a gigahertz frequency. Such axions, because they would permeate our galaxy, may be amenable to direct detection /26/. Since an axion has a coupling to two photons, axions in the Milky Way halo would give a tiny, but perhaps measurable, Q shift in an appropriate electromagnetic cavity.

Irrespective of whether invisible axions will ever be seen experimentally, there remains the theoretical questions of why $V_{PQ}$ should lie in the range (15). With Langacker and Yanagida /27/, I have recently put forward the suggestion that this scale could be the same as the scale at which lepton number breaks. If a Majorana mass for right handed neutrinos indeed has a scale $V_{PQ}$, then the numerology of neutrino masses is quite nice. Using the standard see-saw mechanism /28/, one expects

$$m_{\nu_\ell} \sim \frac{m_\ell^2}{M_{\nu_R}} \sim \frac{m_\ell^2}{V_{PQ}} \tag{16}$$

which for $V_{PQ} \sim 10^{10}$ GeV gives $m_{\nu_\tau} \sim 0.1$ ev, $m_{\nu_\mu} \sim 10^{-3}$ ev, $m_{\nu_e} \sim 10^{-7}$ ev. One sees therefore that the mass difference $\delta(m^2_{\nu_\mu} - m^2_{\nu_e})$ is of the right order of magnitude to appeal to the Mikheyev Smirnov Wolfenstein /29/ $\nu_e \to \nu_\mu$ conversion mechanism in the sun to understand the solar neutrino puzzle.

Can one argue for this connection between $V_{PQ}$ and the scale of breakdown of lepton number theoretically? The answer is yes, if one demands that the breakdown of the $U(1)_{PQ}$ augmented standard model leads to axions as the <u>only</u> approximate Goldstone bosons /27/. With $\phi_1$, $\phi_2$ and $\sigma$ one can write down 5 possible Yukawa couplings (per family)

$$\bar{Q}_L \phi_1 u_R \; ; \; \bar{Q}_L \phi_2 d_R \; ; \; \bar{L}_L \phi_1 \nu_R \; ; \; \bar{L}_L \phi_2 e_R \; ; \; \nu_R^T C \sigma \nu_R \tag{17}$$

These preserve 9 - 5 = 4 U(1) symmetries, corresponding to weak hypercharge, baryon number, lepton number and $U(1)_{PQ}$. When $\sigma$ and $\phi_i$ acquire vacuum expectation value, B remains unbroken but the other U(1) quantum numbers break down. Hypercharge is gauged, so its Goldstone boson is eaten, but there remain two other Goldstone excitations. One is the axion and the other, corresponding to the breakdown of L, is a Majoron /30/. To avoid this extra Goldstone boson one must break one of the above four U(1)'s explicitly in the Higgs potential via, for example, a term like

$$V = K\, \phi_1 \phi_2\, \sigma \tag{18}$$

In this case the Majoron acquires a mass proportional to K $\langle\sigma\rangle$ and one is left with an invisible axion model where the scale of the $U(1)_{PQ}$ breaking $\langle\sigma\rangle$ is precisely the same as that which gives the right handed neutrino a large Majorana mass. Of course, one must ultimately argue for the reason for the appearance of (18) and the necessary fine tuning needed to keep $\langle\sigma\rangle \gg \langle\phi_i\rangle$, which requires K to be very small.

## 4. The KRS catastrophe and the great L $\leftrightarrow$ B switch

I would like to discuss finally another, quite speculative, reason for having an intermediate scale of lepton number violation of the order of $V_{PQ}$, connected to baryon number violation in the standard model. Although baryon number is a classical global symmetry of the standard model, the baryon number current has an ABJ anomaly:

$$\partial^\mu B_\mu = \frac{2 n_f \alpha}{\pi \sin^2\theta_W} W_a^{\mu\nu} \tilde{W}_{a\mu\nu} \tag{19}$$

Here $W_a^{\mu\nu}$ is the SU(2) field strength and $n_f$ is the number of families. Eq. (19) implies that there exist baryon number violating Green's functions in the theory /2/. The real vacuum state for the electroweak theory $|\theta_{EW}\rangle$ is a superposition of distinct gauge variant vacua $|n\rangle$

$$|\theta_{EW}\rangle = \sum_m e^{i m \theta_{EW}} |m\rangle \tag{20}$$

As a result of this the vacuum amplitude, from which all Green's functions are generated, contains a superposition of terms involving transitions which change $|n\rangle$

$${}_+\langle\theta_{EW}|\theta_{EW}\rangle_- = \sum_\nu e^{i\nu\theta_{EW}} \left\{ \sum_m {}_+\langle m+\nu | m\rangle_- \right\} \tag{21}$$

One can show that terms of non zero $\nu$ involve a change in B /2/. However, $\nu \neq 0$ amplitudes are ridiculously small, of order $\exp - \frac{2\pi \sin^2\theta_W\, \nu}{\alpha}$, where the exponential factor is essentially the probability for tunnelling between different $|n\rangle$ vacua. Although there exists baryon number violation in the standard model, it appears to be of no practical importance.



Recently, however, Kuzmin, Rubakov and Shaposhnikov (KRS) /10/ pointed out that the electroweak vacuum structure may in fact be important in the early Universe. Their idea is very simple. If $T \neq 0$ one can imagine going over from an $|n\rangle$ vacuum to an $|n+1\rangle$ vacuum by thermal fluctuations instead of tunnelling, thereby bypassing perhaps the exponential suppression factor discussed above. KRS specifically made use of a saddle point solution for the free energy, found by Klinkhamer and Manton /31/, which allows one to connect an $|n\rangle$ to an $|n+1\rangle$ vacuum. The rate for this transition, near the temperature $T_c$ where the electroweak phase transition takes place, computed by KRS is not exponentially damped and can in fact exceed the Universe expansion rate. As a result, it may be possible for this phenomena to erase all previously accumulated (B+L) asymmetry in the Universe at a very low temperature (since (B-L) has no anomaly in the standard model only (B+L) really gets affected). Furthermore, when these B+L violating processes finally go out of equilibrium, it is too late to reestablish any significant baryon asymmetry /10/.

The KRS result is somewhat of a catastrophe, if true. If it is effective, it means that the baryon number asymmetry after KRS is just

$$B = \frac{1}{2}\,(B-L)_{\text{early Univ.}} \tag{22}$$

Thus for any GUTs where (B-L) is conserved, like SU(5), one is left with no final asymmetry! It is of course possible that the KRS estimate for the baryon violating transition rate is a gross overestimate. This could be because the Klinkhamer Manton path is only a very particular path /32/ or, more likely, because near $T_c$ the whole vacuum structure itself begins to lose meaning altogether. In this case there would be no low temperature erasure of any baryon number established at high temperature. More interesting, however, is to suppose that the KRS mechanism does work and that the final baryon asymmetry is a reflection of an earlier established (B-L) asymmetry. An obvious candidate for this latter asymmetry would be a lepton number asymmetry established at some intermediate scale /33/. Clearly having the possibility of breaking lepton number at a scale $V_{PQ}$ would be very interesting in this connection /27/. Out of equilibrium decays of $\nu_R$ at $T \sim V_{PQ}$ would create an initial lepton number asymmetry which, by the KRS mechanism, would then at $T \sim T_c \sim V$ be turned into a baryon number asymmetry /27/ /33/. So a simple extension of the standard model which incorporates a $U(1)_{PQ}$ symmetry plus a singlet Higgs field could interrelate invisible axions with light neutrinos and, at the same time, be the trigger for the baryon asymmetry of the Universe!

## 5. Conclusions

I hope to have given you an impression that small excursions from the standard model are well worth exploring. Although certainly not compelling, it is possible to envisage models where apparently disconnected phenomena, like small neutrino masses, invisible axions and the Universe's baryon asymmetry, in fact have a common origin. These theoretical musing suggests, if nothing else, that besides exploring the high energy frontier experimentally it is very worthwhile to look for subtle effects in low energy experiments.

## Acknowledgements

I would like to thank W. Bardeen, P. Langacker and T. Yanagida for some of their insights.

## References

1 For a somewhat more extended discussion, see for example R.D. Peccei in the Proceedings of the 12th International Conference on Neutrino Physics and Astrophysics, Sendai, Japan, June 1986

2 G. 't Hooft: Phys. Rev. Lett. 37 8 (1976); Phys. Rev. D14 3432 (1976)

3 S.L. Adler: Phys. Rev. 177 2426 (1969); J.S. Bell and R. Jackiw: Nuovo Cimento 60A 49 (1969); W.A. Bardeen: Phys. Rev. 184 1848 (1969)

4 V. Baluni: Phys. Rev. D19 2227 (1979); R. Crewther, P. di Vecchia, G. Veneziano and E. Witten: Phys. Lett. 89B 123 (1979)

5 R.D. Peccei and H.R. Quinn: Phys. Rev. Lett. 38 1440 (1977); Phys. Rev. D16 1791 (1977)

6 S. Weinberg: Phys. Rev. Lett. 40 223 (1978); F. Wilczek: Phys. Rev. Lett. 40 279 (1978)

7 R.D. Peccei, T.T. Wu and T. Yanagida: Phys. Lett. 172B 435 (1986); L.M. Krauss and F. Wilczek: Phys. Lett. 173B 189 (1986)

8 For somewhat different arguments for this connection see M.S. Turner and B.J. Carr: Fermilab-Pub-86/66-A (May 1986)

9 J. Yang, M.S. Turner, G. Steigman, D.N. Schramm and K. Olive: Ap. J. 281 493 (1982)

10 V.A. Kuzmin, V.A. Rubakov and M.E. Shaposhnikov: Phys. Lett. 155B 36 (1985)

11 W.A. Bardeen and S.-H.H. Tye, Phys. Lett. 74B 229 (1978)

12 For a review see A. Zehnder, Proceedings of the 1982 Gif-sur-Yvette Summer School

13 J. Greenberg, these proceedings



14 A. Schäfer et al.: J. Phys. G, Nucl. Phys. 11 L69 (1985); A. Chodos and L.C.R. Wijewardhana: Phys. Rev. Lett. 56 302 (1986); J. Reinhardt et al.: Phys. Rev. 33C 194 (1986)

15 A. Konaka et al.: KEK preprint 86-9 May 1986

16 M. Davier, private communication

17 S.J. Freedman, these proceedings

18 R. Eichler et al: SIN preprint PR 86-07 May 1986

19 M.J. Savage et al.: Phys. Rev. Lett. 57 178 (1986)

20 W.A. Bardeen, R.D. Peccei and T. Yanagida: DESY 86-054, Nucl. Phys. B to be published

21 L.M. Krauss and M.B. Wise: Yale preprint YTP 86-13 May 1986

22 F.W.N. de Boer et al.: Groningen preprint, Phys. Lett. B to be published

23 J.E. Kim: Phys. Rev. Lett. 43 103 (1979); M.A. Shifman, A.I. Vainshtein and V.I. Zakharov, Nucl. Phys. B166 493 (1980); M. Dine, W. Fischler and M. Srednicki: Phys. Lett. 104B (1981) 99

24 D.A. Dicus et al.: Phys. Rev. D18 1829; D22 839 (1980); M. Fukugita, S. Watamura and M. Yoshimura: Phys. Rev. D26 1840 (1982); N. Iwamoto: Phys. Rev. Lett. 53 1198 (1984)

25 J. Preskill, M.B. Wise and F. Wilczek: Phys. Lett. 120B 127 (1983); L.F. Abbott and P. Sikivie: Phys. Lett. 120B 133 (1983); M. Dine and W. Fischler, Phys. Lett. 120B (1983) 137

26 P. Sikivie: Phys. Rev. Lett. 51 1415 (1983); L.M. Krauss, J. Moody, F. Wilczek and D. Morris: Phys. Rev. Lett. 55 1797 (1985)

27 P. Langacker, R.D. Peccei and T. Yanagida, in preparation

28 T. Yanagida in Proceedings of the Workshop on Unified Theory and Baryon Number of the Universe KEK Japan 1979; M. Gell-Mann, P. Ramond and R. Slansky in Supergravity (North Holland 1979)

29 L. Wolfenstein: Phys. Rev. D16 2369 (1978); S.P. Mikheyev and A. Smirnov, Nuovo Cimento 9C (1986) 17

30 Y. Chikashige, R.M. Mohapatra and R.D. Peccei: Phys. Lett. 98B 265 (1981)

31 R.F. Klinkhamer and N.S. Manton: Phys. Rev. D30 2212 (1984)

32 E.W. Kolb and M.S. Turner, private communication

33 M. Fukugita and T. Yanagida: Phys. Lett. 174B 45 (1986)