CERN-TH/95–299
OUTP-95-45P

hep-ph/9511357

# A Supersymmetric Resolution of the KARMEN Anomaly

**Debajyoti Choudhury***

*Theory Division, CERN, CH–1211 Geneva 23, Switzerland*

and

**Subir Sarkar**†

*Theoretical Physics, University of Oxford, 1 Keble Road, Oxford OX1 3NP, UK*

hep-ph/9511357 v2 20 Mar 1996

## ABSTRACT

We consider the hypothesis that the recently reported anomaly in the time structure of signals in the KARMEN experiment is due to the production of a light photino (or Zino) which decays radiatively due to violation of $R$-parity. Such a particle is shown to be consistent with all experimental data and with cosmological nucleosynthesis. There are difficulties with constraints from SN 1987A but these may be evaded if squarks are non-degenerate in mass.

*Physics Letters B (in press)*

*debchou@surya11.cern.ch
†PPARC Advanced Fellow

Recently, the KARMEN collaboration has reported an anomaly [1] in the time distribution of charged and neutral current events induced by neutrinos emanating from $\pi^+ \rightarrow \mu^+\nu_\mu \rightarrow e^+\nu_e\bar{\nu_\mu}$ decays at rest. After all the $\pi^+$s have decayed in the beam stop, one expects to see an exponential distribution characterized by the muon lifetime, but the data reveal an additional 'bump' containing $125 \pm 23$ events [2] which arrive 3.6 $\mu$s after beam-on-target. The KARMEN collaboration have suggested that this may be due to a new massive slow-moving ($\beta_x \sim 0.02$) particle $x$, which is produced through $\pi^+ \rightarrow \mu^+ x$. The mean flight path between the beam stop and detector is 17.5 m (including over 7 m of steel shielding) and no anomaly is observed in the visible energy deposition in the detector, which is consistent with that of ordinary neutrino events which have $\langle E_{\text{visible}} \rangle \sim 11 - 35$ MeV. Thus this hypothetical particle $x$ must be neutral and weakly interacting with a mass $m_x = 33.9$ MeV, and decay (producing electromagnetic energy) with a lifetime $\tau_x$ exceeding 0.3 $\mu$s.

The possibility that $x$ is a neutrino has been examined in some detail [3]. While $x$ *cannot* be a doublet neutrino, in particular the $\nu_\tau$, it can consistently be interpreted as an isosinglet (sterile) neutrino produced through its mixing with the $\nu_\mu$ and decaying through its mixing with all three doublet neutrinos. The dominant (visible) decay modes, $x \rightarrow e^+e^-\nu$, $\nu\gamma$, proceed faster than usual due to the absence of GIM suppression, with a combined width [3]

$$\Gamma_{\text{visible}} = K \left[920|U_{ex}|^2 + 210|U_{\mu x}|^2 + 210|U_{\tau x}|^2\right] \text{ s}^{-1}, \tag{1}$$

where $K = 1$ (2) for Dirac (Majorana) $x$. The KARMEN event rate [1] determines the product

$$B\ (\pi^+ \rightarrow \mu^+ x)\ \Gamma_{\text{visible}} \simeq 3 \times 10^{-11} \text{s}^{-1} \tag{2}$$

with the branching ratio $B = 0.0285|U_{\mu x}|^2$ [3]. An ingenious experiment at PSI [4] has recently imposed the stringent upper limit

$$B\ (\pi^+ \rightarrow \mu^+ x) < 2.6 \times 10^{-8}\ (95\%\ \text{c.l.}), \tag{3}$$

implying that $\Gamma_{\text{visible}} > 1.1 \times 10^{-3}$. This can still be satisfied, given present experimental limits, for a reasonably large region in the $|U_{ex}|^2 - |U_{\mu x}|^2 - |U_{\tau x}|^2$ parameter space. The favoured solutions require $|U_{\tau x}|^2$ to dominate $\Gamma_{\text{visible}}$ since this allows a short lifetime $\tau_x \sim 0.001 - 150$ s, whereas when $|U_{ex}|^2$ or $|U_{\mu x}|^2$ dominate, the lifetime is $\tau_x \sim 150 - 300$ s [3]. Such short lifetimes are necessary to evade constraints coming from cosmological and astrophysical considerations, viz. that $x$ neutrinos produced (through matter-enhanced mixing) in the early universe should decay before the nucleosynthesis era and that $x$ particles produced (by nucleon bremsstrahlung) in the core of SN 1987A should decay within the core itself.

In this Letter, we investigate a different possibility, viz. that $x$ is the lightest neutralino in the minimal supersymmetric standard model (MSSM) [5]. We shall assume that this is the lightest supersymmetric particle (LSP), which is either the photino ($\tilde{\gamma}$) or the Zino ($\widetilde{Z}$). We show that this hypothesis too is consistent with all experimental data and fares no worse with regard to the cosmological and astrophysical constraints.

It is obvious that a straightforward supersymmetrization of the SM Lagrangian does not lead to the process

$$\pi^+ \to \mu^+ + \tilde{\gamma}\ (\tilde{Z})\ , \tag{4}$$

since this does not conserve lepton number. However, the most general gauge-invariant superpotential contains, apart from the usual terms, pieces such as [6]

$$\mathcal{W}_{R\!\!\!/} = \lambda_{ijk} L_i L_j E^c_k + \lambda'_{ijk} L_i Q_j D^c_k + \lambda''_{ijk} U^c_i D^c_j D^c_k\ , \tag{5}$$

where $L_i$ and $Q_i$ are the $SU(2)$-doublet lepton and quark superfields, and $E^c_i, U^c_i, D^c_i$ are the singlet superfields. Clearly $\lambda_{ijk}$ is antisymmetric under the interchange of the first two indices, while $\lambda''_{ijk}$ is antisymmetric under the interchange of the last two. To avoid the potential embarrassment that the introduction of such terms may cause (e.g. the $\lambda$ and $\lambda'$ couplings violate lepton number conservation, while $\lambda''$ couplings violate baryon number), a discrete symmetry termed $R$-parity is introduced. Representable as $R = (-1)^{3B+L+2S}$ [7], where $B, L, S$ are the baryon number, lepton number and the intrinsic spin of the field respectively, this symmetry rules out each of the terms in eq.(5), with the additional important consequence that the LSP is required to be absolutely stable.

Although an exact $R$-parity may be phenomenologically desirable, it is not essential from a theoretical point of view. Thus we may allow for $R$-parity–violating ($R\!\!\!/_p$) couplings as long as they are not inconsistent with experimental data [8, 9]; for example, rapid proton decay can be simply prevented by requiring that all the $\lambda''_{ijk}$ be zero. This is in fact well motivated theoretically [10]; moreover such a scenario has interesting cosmological implications, e.g. for baryogenesis [11]. It has been argued that the presence of other $R\!\!\!/_p$ terms may wash out the baryon asymmetry of the universe [12]; however this is model-dependent and can be evaded, for example through lepton mass effects which allow a baryon asymmetry to be regenerated at the electroweak scale through sphaleron processes if there is a primordial flavour-dependent lepton asymmetry [13]. Moreover, there are other ways in which a primordial asymmetry may be protected or regenerated [14].

The presence of $R\!\!\!/_p$ couplings makes it possible for the LSP to decay, thus allowing the $\tilde{\gamma}\ (\tilde{Z})$ to deposit visible energy in the KARMEN detector in our model. The preferred mode of decay is, of course, determined by both the spectrum of the theory and the relative sizes of the possible $R\!\!\!/_p$ couplings. For the process in eq.(4) to operate, $\lambda'_{211}$ must be non-zero. The strongest constraint on this coupling comes from charged-current universality [15]:

$$\lambda'_{211} \leq 0.09\ \left(\frac{m_{\tilde{q}}}{100\ \mathrm{GeV}}\right)\ . \tag{6}$$

Bounds on the other couplings are obtained from both low-energy measurements such as meson decays [15, 16] and limits on $\Delta L = 2$ operators [17], as well as the LEP measurements at the $Z$–peak [18]. Except for the bound on $\lambda'_{111}$ (which is required to be $\lesssim 10^{-4}$ [19]), the other bounds are similar to that shown in eq.(6) or weaker. Constraints on products of couplings can however be obtained from the data on flavour-changing neutral-current (FCNC) processes, and these are much more severe [20].

We can now consider two possibilities :

1. $\lambda'_{211}$ is the *only* $\not{R}_p$ coupling in the theory, so the neutralino may decay only radiatively.

2. $\not{R}_p$ couplings other than $\lambda'_{211}$ are non-zero, so that the neutralino may decay (at tree level) into $e^+e^-\nu$ etc.

Examination of FCNC processes demonstrate that bounds from such data on the products of $\not{R}_p$ couplings are least restrictive when only one flavour is nonconserved [20]. Hence, for the second possibility above, this implies that the second non-zero $\not{R}_p$ coupling should be $\lambda_{211}$. Since electron flavour is then a good quantum number, bounds from $\mu \to e\gamma$ and $\mu \to 3e$ are inoperative while constraints from other muon-number-violating processes are comparatively weaker. Thus the situation is analogous to that in ref.[3], albeit with relatively more freedom in the parameter space.[1] We shall not discuss this any further.

Returning to the first possibility, we shall limit our discussion to the photino case; for the $\widetilde{Z}$, one obtains analogous results. The dominant decay mode of the photino is the radiative one,

$$\widetilde{\gamma} \to \nu_\mu + \gamma \ , \tag{7}$$

proceeding through a one-loop diagram involving the $d$-quark and the $\tilde{d}_{L,R}$-squarks. The relevant $\pi$-decay (see eq.4) branching fraction is then

$$\begin{aligned} \mathcal{P} \equiv \frac{\Gamma(\pi^+ \to \mu^+ \widetilde{\gamma})}{\Gamma(\pi^+ \to \mu^+ \nu_\mu)} \ = \ & \frac{8\pi}{9\alpha} \left( \frac{\lambda'_{211} \sin^2\theta_W m_\pi^3}{m_u + m_d} \right)^2 \frac{m_\pi^2 - m_\mu^2 - m_{\widetilde{\gamma}}^2}{m_\mu^2 (m_\pi^2 - m_\mu^2)^2} \\ & \mathcal{C}\left(1, \frac{m_{\widetilde{\gamma}}^2}{m_\pi^2}, \frac{m_\mu^2}{m_\pi^2}\right) \ m_W^4 \left[ \frac{1}{m_{\tilde{d}R}^2} + \frac{2}{m_{\tilde{u}L}^2} - \frac{6}{m_{\tilde{\mu}L}^2} \right]^2 \end{aligned} \tag{8}$$

where $\mathcal{C}(a,b,c) \equiv \left[(a-b-c)^2 - 4bc\right]^{1/2}$ is the usual Callan function. Henceforth, we shall assume a common sfermion mass $m_{\rm sf} \equiv m_{\tilde{u}_L} = m_{\tilde{d}_L} = m_{\tilde{d}_R} = m_{\tilde{\mu}L}$. Using the constituent quark masses, we have

$$\mathcal{P} \simeq 8.9 \times 10^{-4} \ \lambda'^2_{211} \left( \frac{100 \ \mathrm{GeV}}{m_{\rm sf}} \right)^4 . \tag{9}$$

On the other hand, the photino decay width is

$$\Gamma \equiv \Gamma(\widetilde{\gamma} \to \nu_\mu \gamma) = \frac{\alpha^2 \lambda'^2_{211}}{2592\pi^3} \frac{m_{\widetilde{\gamma}}^3}{m_{\rm sf}^2} \ f\!\left( \frac{m_d^2}{m_{\rm sf}^2} \right) \ , \tag{10}$$

where

$$f(x) = x \left[ 1 + \frac{3 - 4x + x^2 + 2\ln x}{(1-x)^3} \right]^2 . \tag{11}$$

[1] Such a phenomenology also arises if there is mixing between the neutrinos with the gauginos/Higgsinos which gives rise to a non-zero sneutrino vev (as in spontaneous $\not{R}_p$ models [9]); the neutralino decay to $e^+e^-\nu$ may then explain the KARMEN anomaly but this requires the Higgs mixing term $\mu H_1 H_2$ in the superpotential to be bounded by $\mu \lesssim 30$ MeV [21] which would further exacerbate the well-known $\mu$ hierarchy problem [22]. This scenario also implies a massive $\nu_\tau$ which is severely constrained by many cosmological and astrophysical arguments, in particular those concerning SN1987A [23].

In fig. 1, we show the correlation between $\mathcal{P}$ and lifetime $\tau \equiv \Gamma^{-1}$ required to reproduce the experimental result, with the part consistent with our hypothesis highlighted. The latter information is also presented in fig. 2 in the form of a dark band in the $m_{\rm sf}$–$\lambda'_{211}$ plane. For parameter values in this region, the quantities $\mathcal{P}$ and $\Gamma$ would obey the correlation of fig. 1. We now proceed to examine the consistency of this hypothesis *vis a vis* cosmological and astrophysical bounds.

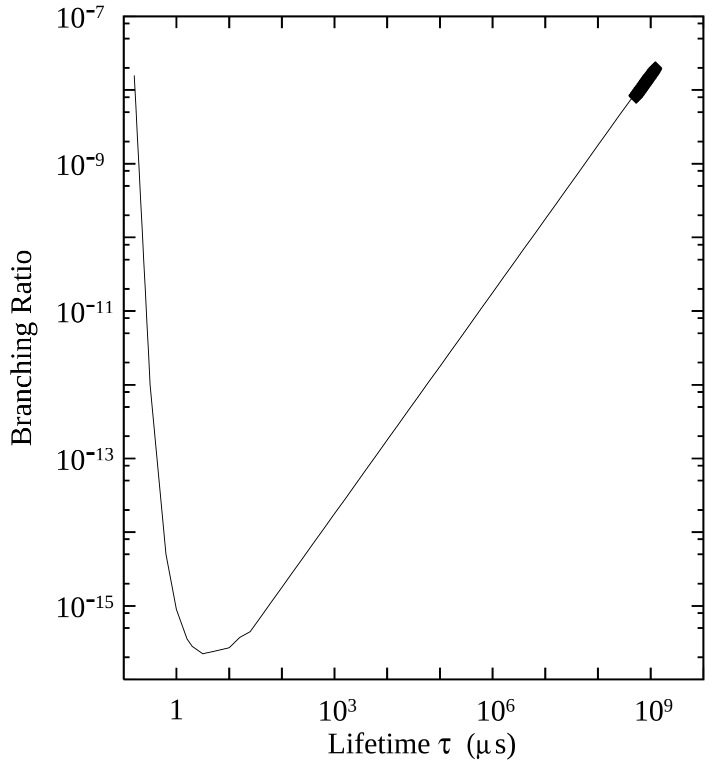


Figure 1: The correlation between the mean lifetime and the production branching ratio required to explain the KARMEN anomaly. The part consistent with the decaying photino hypothesis (assuming degenerate squarks) is emphasized in bold.

A potential problem with the production of a massive unstable particle in the early universe is that this can disrupt the standard cosmology which is in good agreement with observations [24]. For example, the mass density of a non-relativistic particle can speed up the expansion rate during nucleosynthesis, while the electromagnetic energy generated through its subsequent decays can dilute the nucleon-to-photon ratio, resulting in the synthesis of too much $^4$He. Decays that create high energy photons can also alter the elemental abundances through photofission processes or distort the blackbody spectrum of the relic 2.73 K radiation. Such considerations enable stringent bounds to be placed on the relic abundance of the decaying particle as a function of its lifetime [25]. Using the standard freeze-out formalism [24], we find the relic abundance of the hypothetical photino to be

$$m_{\tilde\gamma}\left(\frac{n_{\tilde\gamma}}{n_\gamma}\right) \sim 2.4\times 10^{-3}\ \mathrm{GeV}\left(\frac{\mathrm{m}_{\tilde\gamma}}{34\ \mathrm{MeV}}\right)^{-2}\left(\frac{\mathrm{m}_{\tilde{\mathrm{q}},\tilde{\mathrm{l}}}}{100\ \mathrm{GeV}}\right)^{4}\ . \qquad (12)$$

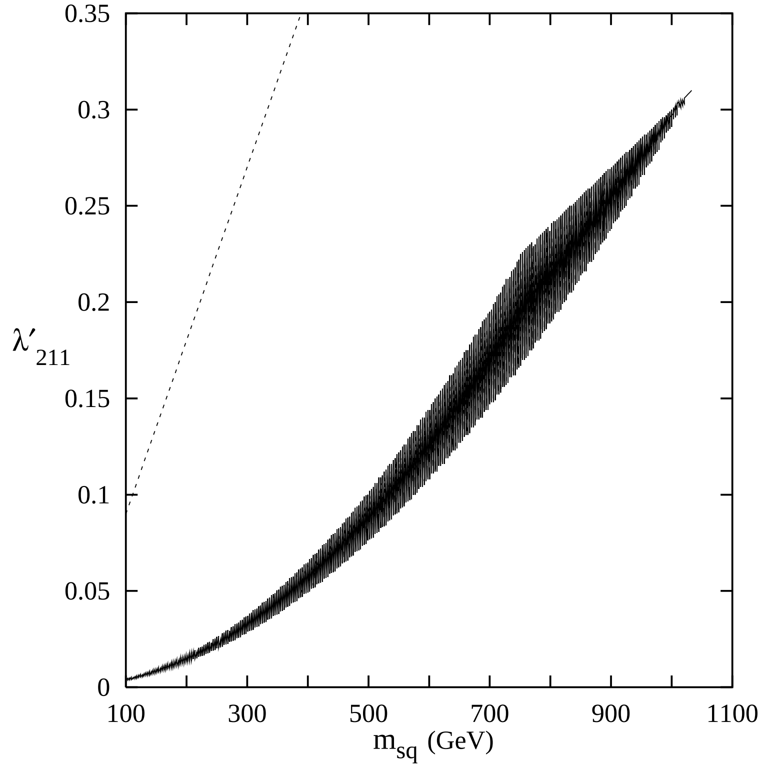


Figure 2: The region in parameter space (dark band) which admits the decaying photino solution to the KARMEN anomaly. The dashed line shows the experimental upper bound ($1\sigma$) on the $R\!\!\!/_p$ coupling as a function of the (assumed common) squark mass.

This is rather high[2] because the self-annihilation cross-section is (s-wave) suppressed for a Majorana particle [26]. We see from ref. [25] that the decay lifetime is then required to be less than a few hundred seconds in order that the synthesised $^4$He mass fraction not exceed the conservative upper limit of 25%. This constraint is satisfied for $\lambda'_{211}$ close to its highest permissible value consistent with the KARMEN event rate.

Light photinos can also be produced through nucleon bremsstrahlung and $e^+e^-$ annihilation in supernovae such as SN 1987A [27]. If the squark and selectron masses are comparable to $m_W$ then the photinos are trapped in the dense core by photino-nucleon and photino–electron elastic scatterings and diffuse out to be emitted from a 'photinosphere' with a thermal spectrum, like an additional species of neutrino. The temperature of the photinosphere increases, thus increasing the photino luminosity, as the elastic scattering cross-section is decreased by increasing the squark/slepton mass. Thus an *upper* bound on the latter follows by considerations of the total energy loss permitted. However, as the slepton/squark mass is further increased, photino interactions with matter eventually become so weak that they begin to escape freely. At this point the photino luminosity

[2]The relic abundance of a singlet neutrino [3] is also high since the (matter-enhanced) oscillation processes that create it go out of equilibrium at a temperature of $\mathcal{O}($ GeV), when it is still relativistic. Although its number density relative to doublet neutrinos is thus diluted by a factor of $\sim 10$ during the subsequent quark–hadron transition, its energy density during nucleosynthesis is very large since by this time the singlet neutrinos have turned non-relativistic, thus $m_{\nu_s} n_{\nu_s}/n_\gamma \sim 1.9 \times 10^{-3}$ GeV ($m_{\nu_s}$/34 MeV).

peaks and then begins to decrease, and so can be made phenomenologically acceptable for a sufficiently large slepton/squark mass. It has been argued that consistency with observations of SN 1987A is not possible for any squark mass which is allowed by experiment or 'naturalness' arguments, and that a stable light photino is therefore ruled out altogether [28].[3] To evade this constraint one must invoke $\not{R}_p$ violation to make the photino unstable as in the present case, but other constraints then come into play.

If the lifetime is longer than $\sim 10^3$s, the escaping photinos would decay outside the supernova. This would have resulted in a gamma-ray flash which was not seen from SN 1987A by satellite-based detectors [30]. For shorter lifetimes, the decays would have occurred within the progenitor, and the decay photons would have been thermalized leading to distortions of the lightcurve. Since the observed lightcurve of SN 1987A appears to be well understood in terms of energy input from $^{56}$Co decay (but see ref.[31]), this would appear to rule out such decays unless the lifetime is so short than decays occur within the core [32]. This requirement, viewed in conjunction with fig. 2, apparently excludes the hypothesis under consideration, but there are possible loopholes. For example, we have assumed throughout that all three relevant squarks as well as the smuon are mass-degenerate. While the excellent agreement found at LEP between the $\rho$-parameter and its SM value demands that $m_{\tilde{u}_L} \approx m_{\tilde{d}_L}$, the mass of the $\tilde{d}_R$ need not satisfy this constraint. In fact only $\tilde{d}_{L,R}$ contributes to the photino lifetime. On the other hand, the branching ratio receives contributions from both $\tilde{u}_L$ and $\tilde{d}_R$; for identical squark masses, the $\tilde{u}_L$ contribution is *larger*. Assuming that $m_{\tilde{d}_R} < m_{\tilde{u}_L} \approx m_{\tilde{d}_L}$ thus allows us to significantly lower the photino lifetime while still being in agreement with the correlation of fig. 1 and consistent with the weak lower limit to the photino lifetime from the VENUS experiment [33]. This can also be effected (to a greater degree) if the smuon mass were to be somewhat larger than the common squark mass. One should also reconsider the production rate of photinos with a mass as large as 34 MeV, since this is of the same order as the core temperature.

To summarize, the KARMEN anomaly can be interpreted as due to the production and decay of photinos in a supersymmetric theory with $R$-parity violation. Just *one* non-zero $\not{R}_p$ coupling suffices for this purpose, while non-zero values for more than one $\not{R}_p$ coupling makes the phenomenology similar to that of an unstable sterile neutrino. The lifetime for radiative decays is consistent with bounds from cosmological nucleosynthesis. The only problematic constraint comes from the light curve of SN 1987A, but this may possibly be evaded by assuming a hierarchy in squark masses. An experimental test of this hypothesis would be look for the monoenergetic decay photons with $E_\gamma \simeq 17$ MeV which distinguishes this from the singlet neutrino scenario (as well as the $\not{R}_p$ scenario with more than one $\not{R}_p$ coupling) where the decay electrons are expected [3] to have a characteristic broader spread in energy.

**Acknowledgements:** DC wishes to thank G. Bhattacharyya, M. Neubert and F. Vissani for discussions and SS would like to thank H. Dreiner, A. Pilaftsis, R.J.N. Phillips and B. Seligmann. SS is a PPARC Advanced Fellow and acknowledges support from the EC Theoretical Astroparticle Network.

[3]This conclusion may be evaded only if selectrons are significantly lighter than squarks [29].

## References


[1] KARMEN collab.: B. Armbruster *et al.*, Phys. Lett. B348 (1995) 19.

[2] B. Seligmann (KARMEN collab.), Proc. Intern. EPS Conf. on High Energy Physics, Brussels (1995), in press.

[3] V. Barger, R.J.N. Phillips and S. Sarkar, Phys. Lett. B352 (1995) 365 (erratum B356 (1995) 617).

[4] M. Daum *et al.*, Phys. Lett. B361 (1995) 179;
see also R. Bilger *et al.*, Phys. Lett. B363 (1995) 41;
D.A. Bryman and T.Numao, Phys. Rev. D53 (1996) 558.

[5] H.P. Nilles, Phys. Rep. 110 (1984) 1.

[6] S. Weinberg, Phys.Rev. D26 (1982) 287;
N. Sakai and T. Yanagida, Nucl. Phys. B197 (1982) 83.

[7] G. Farrar and P. Fayet, Phys. Lett. B76 (1978) 575.

[8] L. J. Hall and M. Suzuki, Nucl. Phys. B231 (1984) 419;
F. Zwirner, Phys. Lett. B246 (1985) 120;
R. Mohapatra, Phys. Rev. D34 (1986) 3457;
R. Barbieri and A. Masiero, Nucl. Phys. B267 (1986) 679;
S. Dimopoulos and L. Hall, Phys. Lett. B207 (1987) 210.

[9] C.S. Aulakh and R. Mohapatra, Phys. Lett. B119 (1984) 136;
J. Ellis *et al.*, Phys. Lett. B150 (1985) 142;
S. Dawson, Nucl. Phys. B261 (1985) 297.

[10] G.G Ross and L.E. Ibanez, Nucl. Phys. B368 (1992) 3.

[11] A. Bouquet and P. Salati, Nucl. Phys. B284 (1987) 557;
A.E. Nelson and S.M. Barr, Phys. Lett. B246 (1990) 141;
W. Fischler, G. Giudice, R.G. Leigh and S. Paban, Phys. Lett. B258 (1991) 45.

[12] B.A. Campbell, S. Davidson, J. Ellis and K.A. Olive, Phys. Lett. B256 (1991) 457.

[13] V. Kuzmin, V. Rubakov and M. Shaposhnikov, Phys. Lett. B191 (1987) 171;
H. Dreiner and G.G. Ross, Nucl. Phys. B410 (1993) 188.

[14] B.A. Campbell, S. Davidson, J. Ellis and K.A. Olive, Phys. Lett. B297 (1992) 118;
A. Antaramian, L.J. Hall and A. Rasin, Phys. Rev. D49 (1994) 3881;
J.M. Cline, K. Kainulainen and K.A. Olive, Phys. Rev. D49 (1994) 6394.

[15] V. Barger, G.F. Giudice and T. Han, Phys. Rev. D40 (1989) 218.

[16] G. Bhattacharyya and D. Choudhury, Mod. Phys. Lett. A10 (1995) 1699.

[17] R.M. Godbole, P. Roy and X. Tata, Nucl. Phys. B401 (1993) 67.

[18] G. Bhattacharyya, J. Ellis and K. Sridhar, Mod. Phys. Lett. A10 (1995) 1583;
G. Bhattacharyya, D. Choudhury and K. Sridhar, Phys. Lett. B355 (1995) 193.

[19] M. Hirsch, H.V. Klapdor-Kleingrothaus and S.G. Kovalenko, Phys. Rev. Lett. 75 (1995) 17.

[20] D. Choudhury and P. Roy, preprint TIFR/TH/95-51.

[21] M. Nowakowski and A. Pilaftsis, preprint RAL-TRR/95-035, hep-ph/9508271.

[22] e.g., G. Giudice and A. Masiero, Phys. Lett. B206 (1988) 480.

[23] G. Gelmini and E. Roulet, Rep. Prog. Phys. 58 (1995) 1207.

[24] E.W. Kolb and M.S. Turner, The Early Universe (Addison Wesley, 1990).

[25] J. Ellis *et al.*, Nucl. Phys. B373 (1992) 399;
S. Sarkar, preprint OUTP-95-16P, hep-ph/9602260.

[26] H. Goldberg, Phys. Rev. Lett. 50 (1983) 1419;
J. Ellis *et al.*, Nucl. Phys. B238 (1984) 453.

[27] G. G. Raffelt, Mod. Phys. Lett. A5 (1990) 2581.

[28] J. Ellis, K.A. Olive, S. Sarkar and D.W. Sciama, Phys. Lett. B215 (1988) 404;
J.A. Grifols and E. Masso, Phys. Lett. B220 (1989) 591, Nucl. Phys. B331 (1990) 244.

[29] K. Lau, Phys. Rev. D47 (1993) 1087.

[30] A. Dar and S. Dado, Phys. Rev. Lett. 59 (1987) 2368;
L. Oberauer, C. Hagner, G. Raffelt and E. Rieger, Astropart. Phys. 1 (1993) 377;
R.N. Mohapatra, S. Nussinov and X. Zhang, Phys. Rev. D49 (1994) 3434.

[31] T. Hatsuda, C.S. Lim and M. Yoshimura, Phys. Lett. B203 (1988) 462.

[32] R. Cowsik, D.N. Schramm and P. Höflich, Phys. Lett. B218 (1989) 91;
G. Sigl and M.S. Turner, Phys. Rev. D51 (1994) 1499.

[33] K. Abe *et al.*, Z. Phys. C45 (1989) 175.