Is radiative decay of neutral leptons the mechanism for stripping of supernova envelopes?

G. T. Zatsepin and A. Yu. Smirnov

Institute of Nuclear Research, USSR Academy of Sciences

(Submitted 25 July 1978)
Pis'ma Zh. Eksp. Teor. Fiz. **28**, No. 6, 379–381 (20 September 1978)

The production of a neutral lepton L^0 with a mass on the order of several MeV in the core of a supernova and its radiative decay $L^0 \to L^{0'}\gamma$ in the envelope can lead to a stripping of the latter. L^0 can be identified with the τ neutrino, and $L^{0'}$ with ν_e or ν_μ.

PACS numbers: 97.60.Bw, 97.10.Cv, 95.30.Cq, 14.60. – z

1. *Mechanism.* The explanation of the stripping of supernova envelopes encounters difficulties (see, e.g., Refs. 1 and 2 and the bibliography therein). They are due primarily to an insufficiently effective transfer of energy and momentum from the collapsing core to the envelope, even though the total collapse energy released in the form of neutrinos ($W_0 \sim 5\times10^{53}$ erg) exceeds greatly the stripping energy ($\lesssim 10^{52}$ erg). We therefore discuss the following possible mechanism:

During the later stages of the evolution of massive stars ($M \gtrsim 8M_\odot$), the photodisintegration of the nuclei and the neutronization of the matter cause a collapse of the Fe–Ni core of the star. The radius of the core (with mass $\sim 1.4\,M_\odot$) changes from 10^8 to 10^6 cm, thereby increasing its density and temperature, and the core becomes opaque to the neutrinos, with $T_n \sim 5\times10^{10}$ K on the boundary of the opacity region. We assume the following: a) A neutral lepton L^0 exists with a mass of several MeV ($m_L \lesssim 3kT \approx 15$ MeV), so that generation of L^0 in the nucleus becomes possible during the above-described evolution stage ($e^+e^- \to \overline{L^0} L^0$; plasmon$\to L^0 L^0$, etc.) b) The leptons L^0 that leave the core undergo radiative decay $L^0 \to L^{0'}\gamma$ in the internal layers of the envelope ($L^{0'}$ is a lighter, possibly massless lepton). The practically instantaneous absorption of the decay gamma quanta is in fact the mechanism of the effective release of the collapse energy in the envelope and of the momentum transfer. The total energy $W(L^0)$ carried away from the core by the L^0 leptons, depends on m_L, and in the case $m_L \ll 3kT$ the approximate equality $W(L^0) \approx W(\nu_e) \approx W(\nu_\mu) \approx \ldots$ is possible.[1,2] That is to say, the energy released in the envelope is equal to $W(\gamma) \lesssim W_0/2n$, where $W_0 \approx 5\times10^{53}$ erg, n is the number of types of neutrino and the factor 2 takes into account the fact that approximately half the L^0 energy goes to the gamma quantum. For $n = 3$ and $m_L = (1\text{–}2)$ MeV we have $W(\gamma) \approx 8\times10^{52}$ erg, which is much higher than the stripping energy.

2. *Is the existence of such an L^0 allowed?* From the condition that the L^0 leaving the core with average energy ~ 10 MeV must decay in the internal layers of the envelope, i.e., $l_{\text{decay}} \approx 10^8$ cm, we obtain for the lifetime (τ):

$$\frac{\tau}{m_L\ (\text{in MeV})} \approx 3\times10^{-4}\ \text{sec}\,. \tag{1}$$

The existence of L^0 with such parameters ($m_L \sim$ nsec-MeV) is not forbidden by cosmological[3-5] and astrophysical[6] restrictions; in particular, the flux of the radiation from the L^0 decays will be practically completely absorbed in the outer layers of the envelope, and the contribution to the isotropic gamma background in the universe will be negligibly small ($\sim 10^{-12}$ cm^3 sec-sr^{-1}). The $L^0 \to L^{0\prime}\gamma$ decay is described by a vertex that takes the form of the interaction of a photon with an off-diagonal magnetic moment (f) of the pair $L^0 L^{0\prime}$ (Refs. 7,8), and the decay amplitude is $A \approx ef/2m_e \bar{u}_{L'} k_\nu \sigma^{\mu\nu} u_L \epsilon_\mu$, where f is in Bohr magnetons, m_e is the electron mass, and ϵ^μ and k^μ are the polarization vector and 4-momentum of the photon, respectively. Calculating the probability of the decay ($\Gamma \sim f^2 m_L^3$) and substituting it in (1), we obtain the condition

$$f m_L^2 \text{ (MeV)} = 7 \times 10^{-8} . \tag{2}$$

Thus, all the additional interactions that result from the existence of the $L^0 \to L^{0\prime}\gamma$ decay will be proportional to $f^2 \approx 5 \times 10^{-15} m_L^{-4}$. The ratio of the probability σ_{LL} of the radiative production of the $\overline{L^0} L^{0\prime}$ pair to the corresponding probability of the e^+e^- production in an arbitrary process is

$$\frac{\sigma_{LL}}{\sigma_{e^+e^-}} \sim \frac{f^2}{4m_e^2} S \tag{3}$$

where S is the square of the total energy of the pair in the c.m.s. For $e^+e^- \to \gamma \to \overline{L^0} L^{0\prime}$ and $S \sim (5\text{ MeV})^2$, for example, we have $\sigma_{LL}/\sigma_{e^+e^-} \approx 10^{-7} m_l^{-4}$ (in MeV), which is much less than the experimentally observed values. At these values of S, the more probable process is $e^+e^- \to \overline{L^0} L^{0\prime}$ and is due to weak neutral currents. The existence of the $\overline{L^0} L^{0\prime}\gamma$ vertex presupposes also scattering of L^0 and $L^{0\prime}$ by charged particles as a result of photon exchange: $L^0 e \to L^{0\prime} e$, $L^0 p \to L^{0\prime} p$, etc. The cross sections (σ_{em}) of these processes vary logarithmically with energy and can exceed the cross sections of the weak interactions ($\sigma_{\text{n.h.}}$) at low values of S. For scattering by an electron with $S \sim (20$ MeV$)^2$ we get $\sigma_{\text{em}} \approx 10^{-40}$ cm$^2/m_L^4$ (in MeV) and $\sigma_{\text{em}} > \sigma_{\text{n.h.}}$ at $m_L \lesssim 2$ MeV. For scattering of L^0 having $E \sim 10$ MeV by a immobile proton we get $\sigma_{\text{em}} \sim 10^{-40}$ cm$^2/m_L^4$ (in MeV) and $\sigma_{\text{em}} > \sigma_{\text{n.h.}}$ at $m_L \lesssim 1.5$ MeV. It follows for this, in particular, that electromagnetic scattering by e and p does not make the core of the supernova additionally opaque to L^0, if $m_L \gtrsim 2$ MeV.

Can so rapid a decay $L^0 \to L^{0\prime}\gamma$(1) be decribed in gauge theories? The highest probabilities of such decays are predicted in schemes with RL (or LR) transitions[7,8]: $L_R^0 \to W^+M^- \to L_L^{0\prime}$ (the right-hand component of L^0 goes over here into the left-hand component $L^{0\prime}$; m^- is a new heavy lepton). In the $SU_2 \times U_1$ with doublets $(L^{0\prime},\ \cos\alpha M^- + \ldots)_L$, $(L^0, M)_R$ we get $f = G_F 2m_e 2m_M/(2\pi^2)^{1/2}$ and from (2) we have $m_M \cos\alpha \approx 40$ GeV$/m_L^2$ (in MeV).

3. *Can L^0 and $L^{0\prime}$ be identified with the known neutrino types*? Judging from the mass $m_L \gtrsim 2$ MeV, L^0 can be only the τ neutrino. $L^{0\prime}$ can be identified with ν_e or ν_μ: the additional contributions of the reactions $\nu_e e \to L^0 e$ or $\nu_\mu e \to L^0 e$ to the scattering processes $\bar{\nu}_e e$ (Ref. 9) and $\nu_\mu e$ (Ref. (10) respectively will not contradict the experimental data at $m_L > 3$ MeV.

The authors thank G.V. Domogatskiĭ and Yu. S. Kopysov for a discussion of the work.

[1] G.V. Domogatsky, V.S. Imshennik, and D.K. Nadyozhin, Proc. of Neutrino-77, Moscow, Nauka, vol. 1, 1978, p. 85.
[2] D.N. Schramm, ibid., p. 131.
[3] M.I. Vysotskiĭ, A.D. Dolgov, and Ya. B. Zel'dovich, Pis'ma Zh. Eksp. Teor. Fiz. **26**, 200 (1977) [JETP Lett. **26**, 188 (1977)].
[4] B.W. Lee and S. Weinberg, Phys Rev. Lett. **39**, 165 (1977).
[5] D.A. Dicus *et al.*, Phys. Rev. Lett. **39**, 169 (1977).
[6] R. Cowsik, Phys. Rev. Lett. **39**, 784 (1977).
[7] J.E. Kim, Phys. Rev. D **14**, 3000 (1976).
[8] T. Goldman and G.I. Stephenson, Phys. Rev. D **16**, 2256 (1977).
[9] F. Reines, H.S. Gurr, and H.W.Sobel, Phys. Rev. Lett. **37**, 315 (1976).
[10] J. Blietschau *et al.*, Phys. Lett. B **73**, 232 (1978).