New experimental limits on radiative neutrino decay

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(presented by M. SPIRO)

Abstract

We have searched for radiative decays of $\bar{\nu}_e$'s produced by a nuclear reactor giving photons with wavelengths in the sensitivity range of a photomultiplier. The absence of signal puts stringent limits on such a decay, and excludes it as an explanation for the solar neutrino problem, even for nearly degenerate mass eigenstates, provided that $\Delta m/m > 3\,10^{-7}$. No previous limits, including those coming from SN1987A, could exclude such an explanation for small values of $\Delta m/m$.

1 Introduction

Many explanations have been searched for to explain the deficit by a factor around 3 observed by Davis [1] and confirmed by Kamioka [2] in the solar neutrino flux. If not a problem with the sun standard model [3], the explanation must come from neutrino properties. Among these, neutrino oscillations in vacuum or in matter (the MSW effect) [4] are the most popular. Effects due to a magnetic dipole moment of the neutrino have been suggested [5], but might be already excluded [6]. Another possibility is that neutrinos are unstable and decay on their path to the Earth [7]. In the case of a radiative decay of heavy neutrinos to lighter ones, this implies a rather large coupling of ν_e's to heavier mass eigenstates to get the expected reduction factor. But, contrary to naive expectations, as shown below, the observation of neutrinos coming from the supernova SN1987A [8] does not rule out such an explanation.

Many constraints exist on such decays, coming from astrophysics and cosmology [9], experiments near nuclear reactors [10], from limits on X-ray and γ emission by the Sun [11] , and from the absence of γ emission during the supernova burst [12]. But these constraints are no longer valid if one assumes that neutrino mass eigenstates are nearly degenerate ($\Delta m/m \ll 1$): in this case, the average photon energy is only $\Delta m/m$ times the neutrino energy, so that it is below threshold for measuring devices [10,11,12], and too low to be of any consequence for cosmology [9].

We shall focus in the following on the possible radiative decays between nearly degenerate mass eigenstates. We are aware that the standard model rules out completely such a scenario for solar neutrinos, since lifetimes are too big by orders of magnitude [13]. But other models, existing or to come, could give much shorter lifetimes [9].

2 Formalism of neutrino radiative decay

Let us consider the decay of a heavy neutrino ν_2 of mass m_2 and of laboratory energy $E \gg m_2$ into a lighter neutrino ν_1 of mass m_1 and a photon. The photon energy in the lab frame ranges from 0 to $E(1 - m_1^2/m_2^2) \simeq 2E\Delta m/m$ for $m_2 - m_1 \ll m_1$. This decay can be described by two helicity amplitudes A and B shown in figure 1.

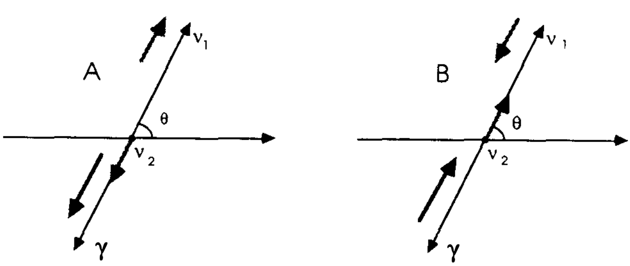

Figure 1: The 2 helicity amplitudes A and B describing the decay

If ν_2 is produced relativistically by V-A currents, it is purely left-handed so that the decay distribution is proportional to

$$| A |^2 \cos^2 \theta/2 + | B |^2 \sin^2 \theta/2 \propto (1 + \alpha \cos \theta)$$

where θ is the emission angle of ν_1 in ν_2 rest frame with respect to the laboratory line of flight of ν_2.

We need to know how the final-state neutrino acts in the laboratory frame. If $\Delta m/m \ll 1$, the ν_1 is nearly at rest in the decay rest frame and its polarisation in the lab, after integrating over θ, is found to be 1/3, independent of A and B: ν_1 will act as a left-handed neutrino 1/3 of the time, and as a right-handed one (that is a sterile neutrino if a Dirac particle or an antineutrino if a Majorana particle) 2/3 of the time. This model-independent property for nearly mass-degenerate neutrinos will be used in the following section.

The decay angular distribution determines the photon energy spectrum in the laboratory. CPT conservation implies $| A |=| B |$ for Majorana neutrinos [14], so that the decay distribution is flat ($\alpha_{Majorana} = 0$). For Dirac neutrinos, no constraints exist so that α_{Dirac} may range from -1 to +1. For the most general (effective) coupling given by

$$\bar{\psi}(\nu_1)\sigma_{\mu\nu}(a + b\gamma_5)\psi(\nu_2)\partial^\mu A^\nu$$

A and B are found proportional respectively to $(a - b)$ and $(a + b)$, implying:

$$\alpha_{Dirac} = -2Re(a^* b)/(| a |^2 + | b |^2)$$

In the standard model [13], $b/a = (m_2 - ml)/(m_2 + m_1)$, so that

$$\alpha_{Dirac}^{SM} = (m_1^2 - m_2^2)/(m_1^2 + m_2^2)$$

goes to zero when $m_2 - m_1 \ll m_1$. (The often quoted value $\alpha = -1$ is only valid for $m_2 \gg m_1$).

3 Solar neutrinos and the Supernova

From the preceding analysis, one can deduce in a model independent way the detected flux of solar ν_e's and supernova $\bar{\nu}_e$'s detected on earth, assuming that all the heavy mass components have decayed to the lightest one, and that the mass eigenvalues are nearly equal. It will depend only upon the couplings $| U_{ei} |^2$ of the electron neutrino to the mass eigenstates ($m_3 > m_2 > m_1$) and upon the branching ratio r of $\nu_3 \to \nu_1$, $1 - r$ being the branching ratio for the cascade $\nu_3 \to \nu_2 \to \nu_1$.

For solar neutrinos, the detected flux (assuming $\gamma c\tau \ll 1A.U$) normalised to the initial flux will be, for Dirac as well as for Majorana neutrinos:

$$f =| U_{e1} |^2 \{| U_{e1} |^2 + \frac{1}{3} | U_{e2} |^2 + (\frac{5 - 2r}{9}) | U_{e3} |^2\}$$

As a function of $|U_{e1}|^2$, f will be minimum for $r = 1$, maximum for $r = 0$ and $|U_{e2}|^2 = 0$. This formula is valid even in the case of vacuum oscillations between neutrino flavors, since these oscillations conserve $|U_{xi}|^2$ values during the propagation of neutrinos before their decay. Only the MSW driving effect in the Sun, implying $|U_{e1}|^2 > 0.5$ and specific values of Δm^2, would lead to a modification of the formula.

For supernova antineutrinos, one must also consider the antineutrinos of other flavors which, through their decay to the lightest antineutrino, acquire a $\bar{\nu}_e$ component, as well as neutrinos of all flavors in the Majorana case, which through helicity flip in their decay become antineutrinos. The resulting flux is, assuming an equal initial population of ν_e, ν_μ, ν_τ, $\bar{\nu}_e$, $\bar{\nu}_\mu$, $\bar{\nu}_\tau$:

$$f_{Dirac} = |U_{e1}|^2 \left(\frac{17 - 2r}{9}\right)$$

and

$$f_{Majorana} = 3\,|U_{e1}|^2$$

These formulae are again valid in the case of neutrino oscillations, even when the MSW driving effect is present, since we have assumed an equal production of all flavors.

All these fluxes are shown on figure 2. It is clear that there exists a large window in $|U_{e1}|^2$ for which solar neutrinos are substantially suppressed while the Supernova

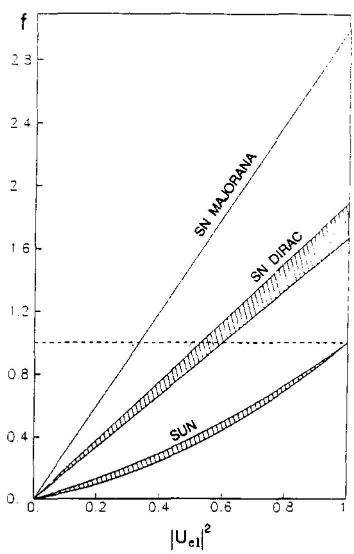

Figure 2: Expected flux of observed neutrinos from Sun and Supernova for 3 families and nearly degenerate masses as a function of the coupling of ν_e to the lightest neutrino. The shaded zones show the range of values as r is varied from 0 to 1 (see text).

flux is equal to or even bigger than the expectation in the absence of decay. A more refined analysis should take into account the differences in flux and energy spectrum between neutrino flavors emitted by the Supernova, but this will not change our conclusion. We would like to emphasize here that as no photon detector was looking at the Large Magellanic Cloud at the time of collapse, any hypothetical luminous flash accompanying the neutrino burst has been missed. Furthermore, if neutrinos decay fast enough, the decay light could also have been absorbed by the star itself, whose dimension was of the order of the Sun-to-Earth distance.

4 Experimental Set-up

As nuclear reactors are intense sources of MeV $\bar{\nu}_e$'s, one should detect decay photons in the visible energy range (1-3 eV) with high efficiency for small $\Delta m/m$. The detector used is very simple and is shown on figure 3. It consists of a 2" photomultiplier (XP2233) whose single photoelectron rate is only 90 Hz when cooled at $-20°$C. This photomultiplier looks at a light-tight cylinder, 50 cm long and 15 cm in diameter, that is used as a decay volume for neutrinos. A lens focusses decay photons produced in the cylinder onto the photocathode, giving an angular acceptance falling nearly linearly from 1. to 0. between 0 and 3 degrees. The quantum efficiency $\epsilon(E_\gamma)$ of the photocathode rises nearly linearly from 0. to 0.24 between 1.5 and 3 eV. A shutter placed in front of the photocathode allows us to measure and substract the PM thermal noise (which may vary slowly with time) by running with the shutter closed.

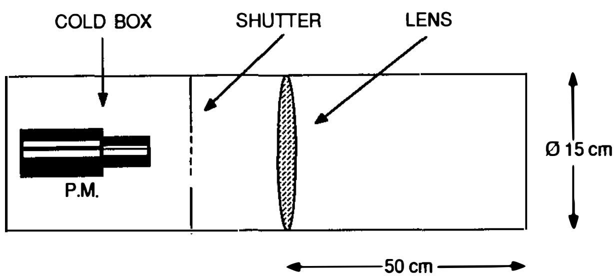

Figure 3: Experimental set-up

5 Results

The apparatus was located at Le Bugey Nuclear Plant, 32 meters from the reactor. The core is a cylinder 3.6 meters high and 3 meters in diameter. Our absolute pointing accuracy is estimated to be better than 1 degree. The reactor emits 5.2 10^{20} antineutrinos per second when running at 2800 MW thermal power.

18 runs of roughly 10 hours each were taken with the detector pointing at different angles, towards and away from the reactor core. During each run, the shutter was switched every 10 seconds, counting rates and spectra being recorded separately for shutter on and shutter off. The equality of on and off counting times was found to be better than 10^{-6} using a high frequency pulse generator. The signal rate (shutter open - shutter closed) was, on average, $3Hz$, and is explained by Cerenkov light generated by cosmic rays passing through the lens.

The results are summarized in Table 1. (Note that the first runs were taken while the reactor was stopped). No variation other than statistical fluctuations can be seen on the signal. A fit to a constant rate gives $\chi^2/N = 15.88/17$ giving 0.53 probability. These data allow us to put an upper limit on a signal due to neutrino decays of 0.3 Hz at 95% CL, assuming a misalignment of the detector not bigger than 2° (which we consider a safe limit).

Table 1: Measured shutter open - shutter closed rates for different orientations of the detector (0° is towards the center of the core, tilts are in the horizontal plane). P is the ratio of the actual reactor power to its nominal value (2800 MW).

Run	P	Angle (degrees)	Signal rate (Hz)
1	0.	0.	3.01±0.17
2	0.1	-2.	2.68±0.22
3	0.2	+2.	2.87±0.23
4	0.5	0.	2.80±0.15
5	0.8	+6.	3.04±0.23
6	0.9	+6.	2.74±0.15
7	0.9	+4.	3.10±0.17
8	0.9	+2.	2.94±0.14
9	0.9	0.	3.00±0.14
10	0.9	-2.	2.88±0.14
11	1.0	-6.	3.12±0.15
12	1.0	-8.	3.11±0.14
13	1.0	-3.	2.99±0.15
14	1.0	0.	2.79±0.14
15	1.0	+3.	3.28±0.15
16	1.0	+6.	2.89±0.15
17	1.0	+8.	2.86±0.15
18	1.0	0.	2.84±0.15

To transform this limit into a lifetime, one has to compute the proper time T during which heavy neutrinos are observed for 1 second data taking. T is given by:

$$T = kN \int_0^\infty dE f(E) \frac{m}{E} t_0 \int_0^{2E\frac{\Delta m}{m}} \epsilon(E_\gamma) g(E_\gamma) dE_\gamma$$

where $N = 2.5\,10^{14} Hz$ is the flux of neutrinos whose decay photon produced in the cylinder would hit the photocathode
$k = 1 - \mid U_{e1} \mid^2$ is the fraction of heavy neutrinos in the beam
m is the heavy neutrino mass, E is the neutrino energy with a normalised spectrum f(E), $\frac{m}{E} t_0$ is the proper time spent by a heavy neutrino in the cylinder with $t_0 = 50 cm/c$
the integral over the photon energy E_γ gives the probability for the decay photon to give a photoelectron
$\epsilon(E_\gamma)$ is the quantum efficiency of the PM
$g(E_\gamma)$ is the normalized energy distribution of the photon

$$g(E_\gamma) = \frac{1}{2E\Delta m/m}\{1 + \alpha(1 - \frac{E_\gamma}{E\Delta m/m})\}$$

(α is 0 in the Majorana case, between -1 and +1 in the Dirac case)

$I = T/(km)$ was computed as a function of $\Delta m/m$ and α using the neutrino spectrum given by [15]. As the neutrino spectrum was not available below 200 keV, we took $f(E)/E^2$ constant below this energy, which is a pessimistic lower limit since, for each contributing isotope i, $f_i(E)/E^2$ is a constant near threshold and then decreases.

If the proper lifetime of the heavy neutrino is τ_H, the expected number of observed decays per second is T/τ_H. Our experimental limit translates to

$$\frac{\tau_H}{km} > \frac{I(\Delta m/m, \alpha)}{0.3}$$

These limits are shown on figure 4 for $\alpha = 0$ (Majorana case), +1 and −1 (Dirac case limits). On the same figure are shown limits from other relevant experiments. The reactor experiments [10] gave a limit assuming $\Delta m/m = 1$, but are actually sensitive to smaller $\Delta m/m$ values (curve 1) as long as the source produces a significant flux of neutrinos of energies greater than $m/(2\Delta m)E_{Threshold}$. Other results coming from Sun emission [11] put stringent limits on the X-ray flux coming from the Sun (between flares) which forbid decays of neutrinos with X-ray emission *outside* the Sun (curve 2) on their path to the Earth. (If neutrinos decay *inside* the Sun, any produced X-rays are thermalized and become undetectable). One should note however that below $\Delta m/m = 10^{-2}$, this limit relies on the ^8B neutrino flux predicted by the standard solar model, while our limit is solar-model independent.

Let us now assume that the standard solar model is correct: the vertical scale at right of figure 4 gives laboratory lifetime limits for 5 MeV neutrinos (the lifetime in the lab of a neutrino with energy E is just $E\tau_H/m$ and 5 MeV is a lower bound for the mean energy of neutrinos detected by Davis) assuming $\mid U_{e1} \mid^2 = 0.5$, a value which would explain both solar and supernova observations, as shown on figure 2 (a lower value for $\mid U_{e1} \mid^2$ would give better limits). The time of flight between Sun and Earth being 500 seconds, one sees that the radiative decay of neutrinos is now totally excluded as an explanation for the solar neutrino deficit, as long as $\frac{\Delta m}{m} > 3.10^{-7}$.

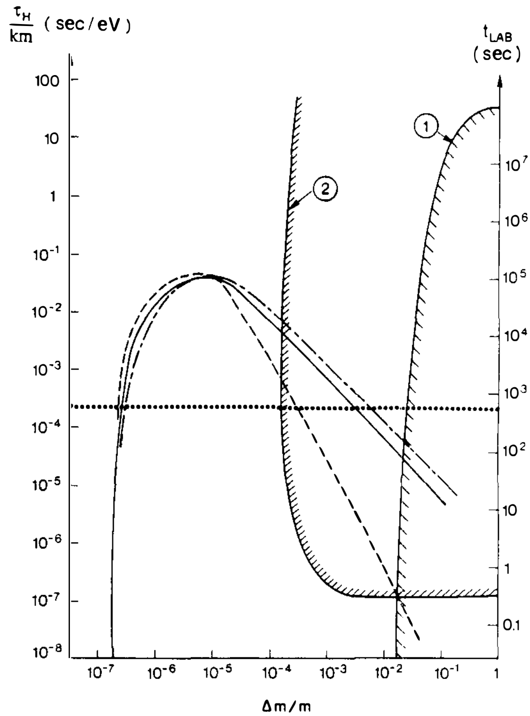

Figure 4: Exclusion plot for neutrino radiative decays. Continuous curve: $\alpha = 0$ (Majorana case). Dashed curve: $\alpha = -1$ and dot dashed curve: $\alpha = +1$ (Dirac case interval). The zone below these curves is excluded by our experiment. Curve 1: limit from other reactor experiments. Curve 2: limit from X-ray solar flux. The horizontal dotted line corresponds to the time of flight between Sun and Earth.

6 Conclusion

With a very simple experiment whose sensitivity can be easily improved by 1 to 2 orders of magnitude, we have been able to exclude one of the possible scenarios for the solar neutrino problem. We also exclude the possibility of supernova neutrinos decaying inside the stellar envelope. Our limits however cannot disprove the possibility of (soft) radiative decays on astronomical scales, and we would like to stress the importance of a permanent survey of the sky to see if Type 2 supernova explosions are accompanied by a strong luminous flash. For SN1987A, the evidence for X-ray or UV emission at the time of the burst is being looked for in ionospheric data [16], but no result has been published yet.

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References

[1] R.Davis, 7^{th} Workshop on Grand Unification, ICOBAN'86, Toyama, Japan (1986); J.N.Bahcall et al, Astrophys.J.Lett. 292 (1985) L79

[2] M.Koshiba, these proceedings.

[3] J.N.Bahcall et al, Rev.Mod.Phys. 54 (1982) 767;
J.N.Bahcall and R.K.Ulrich, Rev.Mod.Phys.,to be published;
S.Cahen, C.Doom and M.Cassé, 6^{th} Moriond Workshop on Massive Neutrinos, Tignes, France (1986) 83 (Editions Frontières)

[4] S.P.Mikheyev and A.Yu.Smirnov, Nuovo Cimento C9 (1986) 17;
L.Wolfenstein, Phys.Rev.D 17 (1978) 2369

[5] M.B.Voloshin et al, Sov.Phys.JETP 64 (1986) 446

[6] M.Fukugita ans S.Yazaki, Phys.Rev.D 36 (1987) 3817

[7] J.N.Bahcall et al, Phys.Rev.Lett.28 (1972) 316
J.N.Bahcall et al, Phys.Lett.B 181 (1986) 369

[8] K.Hirata et al, Phys.Rev.Lett.58 (1987) 1490;
R.M.Bionta et al, Phys.Rev.Lett. 58 (1987) 1494

[9] M.Roos, Research Institute for Theoretical Physics, University of Helsinki, Preprint 87-43 (1987)

[10] F.Reines et al, Phys.Rev.D 32 (1974) 180;
P.Vogel, Phys.Rev.D 30 (1984) 1505;
L.Oberauer et al, Phys.Lett.B 198 (1987) 113

[11] G.G.Raffelt, Phys.Rev.D 31 (1985) 3002

[12] F. von Feilitzsch and L.Oberauer, Phys.Lett.B 200 (1988) 580

[13] P.B.Pal and L.Wolfenstein, Phys.Rev.D 25 (1982) 766

[14] B.Kayser, private communication

[15] F.T.Avignone, Phys.Rev.D 2 (1970) 2609. More recent data exist, but none give the low energy part of the spectrum.

[16] H.Ogelman, MPI Garching, cited in New Scientist, 5 Nov 1987, page 54