CAN LSND AND SUPERKAMIOKANDE BE EXPLAINED BY RADIATIVE DECAYS OF $\nu_\mu$'S?

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The radiative decay of $\nu_\mu$'s in matter with a scheme of mass-degenerate neutrinos could be the common origin of the appearance of $\bar{\nu}_e$’s at LSND and the disappearance of $\nu_\mu$’s at SuperKamiokande. With the decay probability fixed by the LSND signal, the deficit of atmospheric neutrinos can be satisfactorily reproduced.

1 Introduction

There are several puzzles in neutrino physics:

- the appearance of $\bar{\nu}_e$’s in the LSND experiment, not confirmed by the very similar experiment Karmen.
- the disappearance of atmospheric $\nu_\mu$’s at SuperKamiokande over distances of the order of the earth’s diameter.

These two findings have been interpreted as evidence of neutrino oscillations. Together with the solar deficit also interpreted as a sign of oscillations, it is difficult to build a coherent scenario with the only three neutrinos which are known to exist.

Another possibility is considered here, namely the radiative decays of $\nu_\mu$’s in the context of mass-degenerate neutrinos, for example neutrinos having masses of a few eV for cosmological purposes and related by a $\delta m^2$ fixed by the solar deficit. This could explain both the LSND and SuperKamiokande signals.

Decays of neutrinos have been advocated and rejected as a solution for the atmospheric deficit. We consider here the radiative mode which is hugely amplified by matter effects.

This process differs from the simple case of decays in vacuum considered up to now in two aspects: antineutrinos may not be affected (the refraction index is different for neutrinos and antineutrinos), and the decay probability varies rapidly with the density of the traversed medium.

2 Interpretation of the LSND signal

The radiative decay of neutrinos consists of the process:

$$\nu_2 \rightarrow \nu_1 + \gamma$$

where $\nu_2$ and $\nu_1$ are mass eigenstates, $\nu_2$ being the heaviest one. In a simple scheme, $\nu_2$ is predominantly $\nu_\mu$ and $\nu_1$ predominantly $\nu_e$. As a consequence of the helicity flip in the
transition, the final neutrino is right-handed. If neutrinos are Dirac particles, the emerging neutrino is sterile. If, on the other hand, neutrinos are Majorana particles, the right-handed final neutrino is active and the process can be written:

\[ \nu_\mu \rightarrow \bar{\nu}_e + \gamma \]

This is the decay mode which will be assumed for the present argument. Similar considerations of stimulated conversion between mass-degenerate neutrinos have been discussed.\(^8\)

Radiative decays of \(\nu_\mu\)'s have been searched for experimentally.\(^9\) The result is \(\tau/m \geq 15.4\ \text{s/eV}\), where \(m\) is the mass of the decaying neutrino. This result seems to exclude the considerations which are developed below. However this limit only applies to neutrinos with very different masses, when the emitted photon takes half of the incident neutrino energy. With mass-degenerate neutrinos, the limit does not apply, and the \(\bar{\nu}_e\) takes up most of the incident energy. This process could therefore be at the origin of the LSND signal.

The LSND beam is composed of \(\nu_\mu\), \(\bar{\nu}_\mu\) and \(\nu_e\) at equal level, but contains almost no \(\bar{\nu}_e\). A signal of \(\bar{\nu}_e\) is claimed and the favoured interpretation is the oscillation of \(\bar{\nu}_\mu\) into \(\bar{\nu}_e\). The decay discussed above would be equally satisfactory. In fact, it would explain why the Karmen experiment does not see a signal. With Karmen, the beam is better time-defined, the \(\nu_\mu\)'s and \(\bar{\nu}_\mu\)'s are well separated, and the oscillation is specifically searched from the \(\bar{\nu}_\mu\) component.

If this is the correct interpretation of the LSND signal, it gives a decay probability of \(3 \times 10^{-3}\) for 30 MeV neutrinos, over a decay path of about 30 m (distance between the beam stop and the centre of the detector). With these parameters the lifetime is: \(\tau/m \simeq 10^{-12}\ \text{s/eV}\).

Such a short lifetime is not a priori excluded by laboratory limits, which only apply to non-degenerated neutrino masses.

### 3 Consequences for atmospheric neutrinos

Let us now consider a 1 GeV \(\nu_\mu\) travelling along a flight path of 13000 km (diameter of the earth). This is the typical situation encountered with atmospheric neutrinos. The lifetime inferred from LSND gives a \(\gamma c \tau\) of \(3 \times 10^5\) m. This is more than an order of magnitude too small to give a decay probability corresponding to the level of disappearance seen by the SuperKamiokande experiment for upward going neutrinos.

However, the case to be considered is more complex, as the neutrinos are travelling through matter. It has been shown that radiative decays of neutrinos are hugely amplified in dense media. The lifetime \(\tau_m\) in matter is related to the lifetime in vacuum \(\tau_0\) by the expression:

\[
\frac{\tau_0}{\tau_m} = 8.6 \times 10^{23} F(v) \left( \frac{N_e}{10^{24}\text{cm}^{-3}} \right)^2 \left( \frac{1\text{eV}}{m} \right)^4
\]

where \(N_e\) is the electron density of the medium. This formula applies for neutrinos with a mass hierarchy. For mass-degenerate neutrinos, it becomes:

\[
\frac{\tau_0}{\tau_m} = 8.6 \times 10^{23} F(v) \left( \frac{N_e}{10^{24}\text{cm}^{-3}} \right)^2 \left( \frac{1\text{eV}}{m} \right)^4 \left( \frac{m^2}{\delta m^2} \right)^2
\]

The value of \(F(v)\) has not been completely elucidated. For relativistic neutrinos the term \(F(v)\) tends to 4 \(m/E\) according to some authors,\(^6\) whilst it is about 1 according to others.\(^7\) The issue needs further calculations, and we have adopted the naive approach, with an amplification proportional to the square of \(N_e\), and inversely proportional to the neutrino energy. Taking into account these factors, let us reconsider the cases of LSND and SuperKamiokande.

In the LSND beam, the neutrinos cross about 10 m of copper and steel. This corresponds to a path weighed by the square electron density of the traversed matter of approximately 130 m...
(gcm\(^{-3}\))^2. In a simplified description, the earth is composed of a central core of radius 3500 km and density 11.5 gcm\(^{-3}\), surrounded by a mantel of 3000 km thickness and density 4.5 gcm\(^{-3}\). This gives, for a neutrino crossing the whole diameter of the earth, a weighed path of about 160000 km(gcm\(^{-3}\))^2. We keep the simple formula for the decay probability:

\[ P = \exp(-lm/E\tau_m) \]

where \(l\) is the actual length, and \(\tau_m\) includes the matter effect. Note that, in principle, the mass of a neutrino is affected by matter effects and thus can vary depending on the medium. We take here a well defined mass \(m\) which may or may not be the vacuum value.

Scaling from the LSND result, the probability for a 1 GeV \(\nu_\mu\) to decay through the earth is 0.80. The disappearance seen by SuperKamiokande is about 0.50. The model seems to give an excessive deficit, but the enhancement in matter comes from a coherent interaction on atomic electrons, and is different for neutrinos and antineutrinos. Atmospheric neutrinos at low energy have equal populations of \(\nu_\mu\) and \(\bar{\nu}_\mu\). Because of the reduced cross-section of \(\bar{\nu}_\mu\), 1/4 of the events coming from this source are unaffected. Furthermore, the weighed path decreases very rapidly with the zenith angle, as the dense matter is concentrated in the core. For a \(\cos \theta = -0.8\) (the last bin in the SuperKamiokande notation) the probability of decay goes down to 0.30.

With the angular resolution of SuperKamiokande, and considering the unaffected contribution of antineutrinos, the deficit obtained for contained events (sub-GeV as well as multi-GeV) is satisfactory.

The decay results in \(\bar{\nu}_e\) and gives an excess of e-like events. However because of the reduced cross-section of antineutrinos, this excess is small, and can be seen in the data.

The difficulty may arise with up-going muons. Here the direction is well reconstructed and the model predicts a deficit of 0.07 for 5 GeV \(\nu_\mu\) and 0.02 for 10 GeV \(\nu_\mu\) between horizontal and vertical directions. This seems low compared with the observations.

4 Conclusion

The conjecture of a common origin for the LSND and SuperKamiokande findings is suggested. It is surprising that both experiments can be interpreted by the radiative decay:

\[ \nu_\mu \rightarrow \bar{\nu}_e + \gamma \]

with degenerated neutrino masses. Within this hypothesis, LSND sees the appearance of \(\bar{\nu}_e\), while SuperKamiokande sees the disappearance of \(\nu_\mu\). Taking into account the amplification in matter, one finds that the lifetime inferred from LSND reproduces adequately the size of the effect seen in atmospheric neutrinos, at least for the contained event sample. This lifetime is not in contradiction with other experimental results. A careful \(\chi^2\) analysis would probably prefer the oscillation interpretation, but the present observation has the advantage of explaining both LSND and SuperKamiokande with the same phenomenon.

If the energy term in the amplification factor is the one found in Ref.[6], the effect would be very small in the MiniBoone and I216 experiments proposed to check the LSND signal, and also in the high energy long base-line projects. On the other hand, other experimental tests are possible and are being studied.

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