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Coherence Condition for Resonant Neutrino Oscillation

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1. Introduction

Walker and Schramm[1] pointed out, prior to the observation of SN1987A, that the ν_e burst generated at the core of the supernova would be converted to another type of neutrino, owing to MSW effect, in passing through the outer region and the neutronization ν_e burst becomes unobservable. After the detection of neutrinos from SN1987A, many arguments have been presented on the MSW effect connected with the interpretation of the first one or two events in KamiokandeII. However the neutrino coherence which holds the key for matter oscillation has not been mentioned in relation to the MSW effect until now.

We study the coherence condition for a neutrino to keep coherence between the effective mass eigenstates in the presence of matter and, according to this condition, investigate whether or not the MSW effect happens in the cases of solar and supernova neutrinos. If the propagating neutrino loses the coherence between its effective mass eigenstates before arriving at the resonant density region, the resonant amplification of neutrino oscillations will no longer occur. That is, the MSW mechanism can not work in that case.

Besides the resonance and adiabatic conditions[2], there is, for the occurrence of RNO, an important condition which originated in the existence of a coherent wave length.

2. Coherence Condition

According to the studies about the width of spectral lines, the emitted ν_e really has a wave packet of width d along the propagating direction[3]. Within a very dense and hot medium, d is limited by collisions between the ν_e emitter and neighboring particles because of the random-phase change of ν_e wave trains emitted before and after collision. Such an effect is called collision (or pressure) broadening. Using the coherence time τ_0 which is the effective time to emit an uninterrupted train of waves, we can expect

$$d \simeq c\tau_c . \quad (1)$$

On the other hand, ν_e is superposition of effective mass eigenstates ν_1, ν_2 if we assume for simplicity that only two types of neutrino ν_e, ν_μ are relevant to oscillation effects. Here effective mass eigenstates mean the mass ones which received the contribution due to the weak current interaction in matter. The velocities of ν_1, ν_2 components are nearly the speed of light but slightly different each other owing to the difference of their masses. So they separate by ΔL during the propagation of a distance L through matter.

When a neutrino falls into $\Delta L > d$, the ν_1, ν_2 components no longer overlap and cannot interfere to produce oscillations in ν_e, ν_μ. And if this happens before the neutrino arrives at the resonant density region, RNO also never comes about. Then we call the relation

$$\Delta L < d \quad (2)$$

coherence condition. While ν_1, ν_2 go from emitting point to resonance region with energy E, they separate by

$$\Delta L = \frac{1}{2E^2}\int_{R_{core}}^{R_{res}} \Delta\tilde{m}^2 \, dx$$

$$\frac{1}{2E^2}\int_{R_{core}}^{R_{res}} \{(\Delta m^2 \cos 2\Theta - 2\sqrt{2}G_F E n_e)^2 + (\Delta m^2)^2 \sin^2 2\Theta\}^{1/2} , \quad (3)$$

where $\Delta m^2 = m_2{}^2 - m_1{}^2$. In the following sentences we explain d in detail.

Charged particles $e^\pm$, p(or nuclei) are included in ν_e emissions. Therefore, throughout these reactions, the emissions of ν_e are interrupted by the electromagnetic interactions between those particles(or nuclei) and neighboring ones on time scales much shorter than those of the above weak interactions.

To estimate d under such circumstances in a simple way[4], we consider Coulomb scatterings of charged particles(or nuclei) which take part in ν_e emission with neighboring electrons or protons. τ_c can be determined from

$$\tau_c = \frac{\ell}{v} , \quad (4)$$

where v and ℓ are the thermal mean velocity and the mean free path of e^- or p, respectively. ℓ can be estimated from the number density n of the charged particles(or nuclei) and the distance a which satisfies

$$\frac{1}{2}kT \simeq \frac{Ze^2}{a} . \tag{5}$$

Eq.(5) guaranties that the courses are greatly changed when e^-, p come to within the distance a of the charged particles(or nuclei)[5]. Then

$$\ell \simeq \frac{1}{\pi a^2 n} \simeq \frac{(kT)^2}{4\pi Z^2 e^4 n} \simeq 2.4 \times 10^{22} \times \frac{[T(MeV)]^2}{Z^2 n(cm^{-3})} \text{ cm.} \tag{6}$$

Setting Eq. (4) into Eq. (1), we find

$$d \simeq c \frac{\ell}{v} . \tag{7}$$

Here, we note that the neutrino which created near the center of the sun (or near the core of supernova) keeps the value of d unchanged while propagating outward. It is because almost all of the created neutrinos go through the star without scattering and absorption by the surrounding matter.

3.Possibility of RNO in case of solar neutrino

We evaluate the d and ΔL of the ^{8}B neutrinos. Using these values, $kT \simeq 1.3$ KeV, $\rho \simeq 120$ $g \cdot cm^{-3}$, $m_p \simeq 938$MeV, Z=5(A=8) and $n=(\rho/A)N_A \, cm^{-3}$, we obtain from Eqs.(6),(7)

$$d \simeq 0.9 \times 10^{-7} \text{ cm.} \tag{8}$$

On the other hand, from Eq.(8),

$$\Delta L \simeq \frac{1}{2E^2} \cdot \frac{R_{sun}}{10.54} \Bigg[-\Delta m^2 \sin 2\Theta + \sqrt{D(n_B)} + \Delta m^2 LN\left[\frac{2\sqrt{2}G_F n_B E \sin 2\Theta (1 + \sin 2\Theta)}{\cos 2\Theta(\Delta m^2 - 2\sqrt{2}G_F n_B E\cos 2\Theta + \sqrt{D(n_B)})}\right] + \Delta m^2 \cos 2\Theta LN\left[\frac{\Delta m^2 \sin 2\Theta}{\sqrt{D(n_B)} + \sqrt{2}G_F n_B E - \Delta m^2 \cos 2\Theta}\right]\Bigg], \tag{9}$$

where $n_B = 245 N_A$ and

$$D(n_B) = (\Delta m^2 \cos 2\Theta - 2\sqrt{2}G_F n_B E)^2 + (\Delta m^2)^2 \sin^2 2\Theta .$$

The right hand side in Eq.(9) depends on two parameters Δm^2 and Θ. By numerical calculations on what is called MSW triangle in the (Δm^2, $\sin^2 2\Theta/\cos 2\Theta$) plane[2,6] that is restricted by the resonance and adiabatic conditions and $\sin^2 2\Theta \simeq 1/4$, we obtain

$$\Delta L \lesssim 0.1 \times 10^{-7} \text{ cm,} \tag{10}$$

for the ^{8}B neutrinos with $\langle E_\nu \rangle \sim 7$MeV[7].

From Eqs.(8) and (10), we find that $d > \Delta L$ and that there is the possibility of RNO.

As a result of the similar consideration of the ^{8}B neutrino case, we get

$d \simeq 0.5 \times 10^{-6}$ cm,

$\Delta L \lesssim 0.3 \times 10^{-6}$ cm.

for the pp neutrinos with $<E_\nu> \sim 0.3$MeV. So we are also allowed to expect RNO for this case.

4. Possibility of RNO in case of SN1987A neutrino

Using $m_p \simeq 938$MeV, $Z=1$, $n=10^{32}\,\mathrm{cm}^{-3}$, and $T \simeq 1$MeV(at $R \simeq 10^8$ cm), we obtain from Eqs.(6), (7)

$$d \simeq 4.2 \times 10^{-9} \text{ cm.} \tag{11}$$

On the other hand, from Eq.(3)

$$\Delta L = \frac{1}{2E^2}\int_R^{R_{res}} \Delta\tilde{m}^2\, dx \gtrsim \frac{1}{2E^2}\int_{10^8}^{10^9} \Delta\tilde{m}^2\, dx$$
$$\simeq \frac{1}{2E^2}\int_{10^8}^{10^9} 2\sqrt{2}G_F E n_e(x)\, dx, \tag{12}$$

because $2\sqrt{2}G_F E n_e(x) >> \Delta m^2$ in $x=10^8 \sim 10^9$ cm($<R_{res}$). By substituting Eq.(12) and $<E_\nu> \simeq 15$MeV leads to

$$\Delta L \gtrsim 4.2 \times 10^{-5} \text{ cm.} \tag{13}$$

From Eqs.(11) and (13), we find that $d << \Delta L$ (even at the point $x=10^9$ cm $< R_{res}$). This means that RNO does not happen in the case of SN1987A neutrino burst.

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Verification of the Quantum Electroweak Effects through the Weak Boson Mass Relation

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ABSTRACT

Recent studies of the M_W-M_Z relation using the new experimental data on the weak boson masses are reported. It is shown that those data clearly indicate the existence of the quantum effects of the electroweak interaction, and also give an upper bound on the top-quark mass.

The standard $SU(2) \times U(1)$ gauge theory of the electroweak interaction (the electroweak theory hereafter) has been so far very successful for describing a lot of weak interaction phenomena. It has been even crucial recently to take account of the radiative corrections (R.C.) in these analyses [1]. This fact gives a strong support to the validity of the electroweak theory beyond tree approximation.

Those analyses, however, have fully used the value of $\sin^2\theta_W$ extracted from the deep inelastic neutrino-nucleon scatterings. There, actual experimental conditions have to be incorporated, and also we are forced to use the parton model to describe the quarks in the target nucleons. Although these points must have been carefully taken into account, other precision tests independent of the ν experiments are therefore strongly desired. Based on my recent analysis [2], I wish to show here that new experimental data on the weak boson masses make actually such a "new-type"