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Determination of CP violation parameter using neutrino pair beam

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ABSTRACT

Neutrino oscillation experiments under neutrino pair beam from circulating excited heavy ions are studied. It is found that detection of double weak events has a good sensitivity to measure CP violating parameter and distinguish mass hierarchy patterns in short baseline experiments in which the earth-induced matter effect is minimized.

1. Introduction

As is pointed out in our previous paper [1], when excited ions with a high coherence are circulated, neutrino pair emission rates become large with neutrino energies extending to the GeV region. Produced neutrino beam is a coherent mixture of all pairs of neutrinos, $\nu_e\bar{\nu}_e$, $\nu_\mu\bar{\nu}_\mu$, $\nu_\tau\bar{\nu}_\tau$. This gives a CP-even neutrino beam, providing an ideal setting to test fundamental symmetries of particle physics [2], in particular, to measure the CP violating (CPV) phase in the neutrino sector [3].

In the present work, a sequel to the previous one, we investigate observable quantities at detection sites away from heavy ion synchrotron, including the location of the facility.

Our main physics objectives are

(1) CPV δ phase measurement (excluding the ones intrinsic to the Majorana neutrino),
(2) NH vs IH distinction.

We shall demonstrate that double neutrino detection is necessary to achieve these objectives. Furthermore, in order to avoid possible contamination of earth-induced effects that mimic CPV parameter dependence, it is wise to conduct oscillation experiments at a short baseline. Our results show that a location within ∼50 km away from the synchrotron can do an excellent job.

The rest of this paper is organized as follows. In Section 2 we explain special features of neutrino oscillation experiments under CP-even neutrino pair beam after a brief summary of neutrino pair emission at synchrotron. The conclusion on experimental means is that one should measure double weak events at detector for CPV parameter determination. The neutrino pair beam is found insensitive to CPV phases intrinsic to the Majorana neutrino. In Section 3 we discuss short baseline experiments in which the earth-induced matter effect is neglected. We demonstrate that both CP-even and CP-odd quantities can provide a sensitive measurement of CPV parameter with high precision. Distinction of normal and inverted hierarchical mass patterns is shown to be possible in short baseline experiments of the pair beam. In Section 4 the earth matter effect is discussed and shown to give large influence on determination of CPV parameter.

Although it is not the purpose of the present work to present a concrete accelerator and experimental scheme using a specific ion beam for CPV parameter measurements, we give in Appendix A a concrete example of accelerator and detector system using He-like Th ion and calculate event rates.

Throughout this work we use the natural unit of $\hbar = c = 1$.

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2. Neutrino experiments under coherent pair beam

We consider measurements of neutrinos at a distance L under the coherent neutrino pair beam of all mixtures of $\nu_a\bar{\nu}_a$, $a = e, \mu, \tau$ produced at a heavy ion synchrotron. It is important to calculate detection rates by treating the whole event quantum mechanically, since produced neutrino pairs are not detected at the synchrotron site.

We shall first recapitulate main features of the coherent neutrino pair beam proposed in our previous paper [1]. The neutrino pairs are produced from excited heavy ions of a boost factor γ circulating in a ring of radius ρ. Its production rates are enormous, given by

$$\Gamma_{2\nu} \sim 3.1 \times 10^{21}\ \mathrm{Hz} \frac{N|\rho_{eg}|^2}{10^8} (\frac{\rho}{4\ \mathrm{km}})^{1/2} (\frac{\gamma}{10^4})^4 (\frac{\epsilon_{eg}}{50\ \mathrm{keV}})^{11/2}, \quad (1)$$

ignoring the ion spin factor of order unity. The ionic coherence ρ_{eg} between the excited and the ground levels of spacing ϵ_{eg} is required to be substantial, and we assumed in this estimate a number 10^8 when it is multiplied by the total available ion number N. Relation between the pair production amplitude $\mathcal{P}_{\bar{b}b}(1,2)$ of a neutrino pair $\bar{\nu}_b\nu_b$, $b = e, \mu, \tau$ with kinematical variables collectively denoted by 1, 2 (angles measured from the ion tangential direction), and its rate $R_{\bar{b}b}(1,2)$ is [1]

$$R_{\bar{b}b}(1,2) = 2\frac{|\mathcal{P}_{\bar{b}b}(1,2)|^2}{T}, \qquad T = \frac{\sqrt{\pi}}{2^{1/4}}\sqrt{\rho}F^{-1/4}, \quad (2)$$

$$F = (E_1+E_2)(\frac{\epsilon_{eg}}{\gamma} - \frac{E_1+E_2}{2\gamma^2}) - \frac{1}{2}(E_1^2\psi_1^2 + E_2^2\psi_2^2) - \frac{E_1E_2}{2}(\theta_1-\theta_2)^2 - \frac{\epsilon_{eg}}{2\gamma}(E_1\theta_1^2 + E_2\theta_2^2). \quad (3)$$

$T/2$ typically of order 10 ps is the effective time of neutrino pair emission, which is more precisely a function of neutrino energies and their emission angles. Vertical emission angles ψ_i, $i = 1, 2$ and the opening angle of a pair, $\sin^{-1}(\cos\psi_1\cos\psi_2\cos(\theta_1-\theta_2))$, are both limited by the boost factor $1/\gamma$. These angles are of order 100 μradian $10^4/\gamma$.

The probability amplitude of the entire process consists of three parts: the production, the propagation, and the detection due to charged current (CC) interaction, each to be multiplied at the amplitude level. Thus, one may write the amplitude for double neutrino quasi-elastic scattering (with J the nucleon weak current) as

$$\sum_b (\frac{G_F}{\sqrt{2}})^2 \bar{\nu}_a\gamma_\alpha(1-\gamma_5)l_a J^\alpha \bar{l}_c\gamma_\beta(1-\gamma_5)\nu_c(J^\beta)^\dagger \times \langle\bar{a}|e^{-iHL}|\bar{b}\rangle\langle c|e^{-iHL}|b\rangle\mathcal{P}_{\bar{b}b}(1,2), \quad (4)$$

where H is the hamiltonian for propagation including earth-induced matter effect [4–6], which is in the flavor basis

$$H = U\begin{pmatrix} \frac{m_1^2}{2E} & 0 & 0 \\ 0 & \frac{m_2^2}{2E} & 0 \\ 0 & 0 & \frac{m_3^2}{2E}\end{pmatrix}U^\dagger \mp \sqrt{2}G_F n_e \begin{pmatrix}1&0&0\\0&0&0\\0&0&0\end{pmatrix}, \quad (5)$$

with $U = (U_{ai})$, $a = e, \mu, \tau$, $i = 1, 2, 3$ the neutrino mixing matrix. The sign $\mp$ refers to neutrino $(-)$ and anti-neutrino $(+)$.

Let V and $\bar{V}$ be unitary 3×3 matrices that diagonalize the hamiltonian H for neutrino and $\bar{H}$ for anti-neutrino, including the earth matter effect. We shall denote three eigenvalues by λ_i for neutrinos, and $\bar{\lambda}_i$ for anti-neutrinos. The propagation amplitude is then

$$\langle c|e^{-iHL}|b\rangle = \sum_i V_{ci}^* V_{bi} e^{-i\lambda_i L},$$

$$\langle\bar{a}|e^{-iHL}|\bar{b}\rangle = \sum_i \bar{V}_{ai}^* \bar{V}_{bi} e^{-i\bar{\lambda}_i L}, \quad (6)$$

$$\sum_b \langle\bar{a}|e^{-iHL}|\bar{b}\rangle\langle c|e^{-iHL}|b\rangle c_b = \frac{1}{2}\sum_{ij} V_{ci}^*\bar{V}_{aj}^*\xi_{ij} e(\bar{\lambda}_j, \lambda_i),$$

$$(c_b) = \frac{1}{2}(1,-1,-1), \quad (7)$$

$$\xi_{ij} = \bar{V}_{ej}V_{ei} - \bar{V}_{\mu j}V_{\mu i} - \bar{V}_{\tau j}V_{\tau i},$$

$$e(\bar{\lambda}_j, \lambda_i) = \exp[-iL(\lambda_i + \bar{\lambda}_j)]. \quad (8)$$

The factor c_b arises from the production amplitude $\mathcal{P}_{\bar{b}b}(1,2)$. The precise relation between neutrino and anti-neutrino eigenvalue problem is given by

$$\bar{\lambda}(G_F) = \lambda(-G_F), \qquad \bar{V}_{ai}^*(G_F) = V_{ai}(-G_F). \quad (9)$$

An important question of the Majorana CPV phase (MP) dependence of the neutrino propagation amplitude $\langle a|e^{-iHL}|b\rangle$ and its anti-neutrino counterpart is worked out as follows, using the parametrization.[1] First, the eigenvalue equation $\det(\lambda - H) = 0$, when explicitly written out, indicates that $\lambda_i, \bar{\lambda}_i$ are independent of MP, α, β. Define MP-independent mixing matrix by $\tilde{U} = UP^\dagger$, $P = (1, e^{i\alpha}, e^{i\beta})$. The hamiltonian in the mass eigen-state basis $U^\dagger HU$ has a simple MP phase dependence $P^\dagger\tilde{H}P$, $\tilde{H}$ being MP-independent. Diagonalization of $\tilde{H}$ can be done, $\tilde{H} = \tilde{V}^\dagger H_D\tilde{V}$ by MP-independent matrix $\tilde{V}$. The unitary matrix V for H diagonalization is then MP-independent, since $V = \tilde{V}PU^\dagger = \tilde{V}PP^\dagger\tilde{U}^\dagger = \tilde{V}\tilde{U}^\dagger$. This proves that $\langle a|e^{-iHL}|b\rangle$ is MP-independent.

More general formulas relating these to re-phasing invariant quantities are given in [6].

We now discuss prospects of single neutrino events in which one of pair neutrinos goes undetected. The rate of neutrino ν_c undetected (and $\bar{\nu}_\mu$ detected) contains the squared propagation factor,

$$\sum_c |\sum_{ij} V_{ci}^*\bar{V}_{\mu j}^*\xi_{ij}e(\bar{\lambda}_j,\lambda_i)|^2 = \sum_{ijkl}\sum_c V_{ci}^*V_{ck}\bar{V}_{\mu j}\bar{V}_{\mu l}^*\xi_{ij}\xi_{kl}^* e(\bar{\lambda}_j,\lambda_i)e^*(\bar{\lambda}_l,\lambda_k) = \sum_{jl}\bar{V}_{\mu j}\bar{V}_{\mu l}^* e(\bar{\lambda}_j,\lambda_i)e^*(\bar{\lambda}_l,\lambda_i)\sum_i \xi_{ij}\xi_{il}^* = \sum_{jl}\bar{V}_{\mu j}\bar{V}_{\mu l}^* e(\bar{\lambda}_j,\lambda_i)e^*(\bar{\lambda}_l,\lambda_i)\delta_{jl} = 1, \quad (10)$$

since $e(\bar{\lambda}_j,\lambda_i)e^*(\bar{\lambda}_l,\lambda_i)$ is i-independent. This result relies on the unitarity of mixing matrices alone.

[1] For numerical analysis we use $s_{12}^2 = 0.307$, $s_{23}^2 = 0.386$, $s_{13}^2 = 0.0241$, $\delta m_{21}^2 = 7.54 \times 10^{-5}\ \mathrm{eV}^2$, $\delta m_{31}^2 = 2.43 \times 10^{-3}\ \mathrm{eV}^2$ as determined by [7]. We use the parametrization as given by

$$(U_{ai}) = \begin{pmatrix}1&0&0\\0&c_{23}&s_{23}\\0&-s_{23}&c_{23}\end{pmatrix}\begin{pmatrix}c_{13}&0&s_{13}e^{-i\delta}\\0&1&0\\-s_{13}e^{i\delta}&0&c_{13}\end{pmatrix}\begin{pmatrix}c_{12}&s_{12}&0\\-s_{12}&c_{12}&0\\0&0&1\end{pmatrix}P,$$

$$P = \begin{pmatrix}1&0&0\\0&e^{i\alpha}&0\\0&0&e^{i\beta}\end{pmatrix}, \qquad a = e,\mu,\tau,\ i = 1,2,3,$$

where $s_{ij} = \sin\theta_{ij}$ and $c_{ij} = \cos\theta_{ij}$.