Physics Letters B 719 (2013) 154–163

Contents lists available at SciVerse ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Observables in neutrino mass spectroscopy using atoms

D.N. Dinh [a,b,*], S.T. Petcov [a,c,1], N. Sasao [d], M. Tanaka [e], M. Yoshimura [f]

[a] *SISSA and INFN – Sezione di Trieste, Via Bonomea 265, 34136 Trieste, Italy*
[b] *Institute of Physics, Vietnam Academy of Science and Technology, 10 Dao Tan, Hanoi, Vietnam*
[c] *Kavli IPMU, University of Tokyo (WPI), Tokyo, Japan*
[d] *Research Core for Extreme Quantum World, Okayama University, Okayama 700-8530, Japan*
[e] *Department of Physics, Graduate School of Science, Osaka University, Toyonaka, Osaka 560-0043, Japan*
[f] *Center of Quantum Universe, Faculty of Science, Okayama University, Okayama 700-8530, Japan*

ARTICLE INFO

Article history:
Received 9 October 2012
Received in revised form 7 January 2013
Accepted 8 January 2013
Available online 11 January 2013
Editor: T. Yanagida

Keywords:
Neutrino mass matrix
Majorana neutrino
Radiative neutrino pair emission
Leptonic CP violation

ABSTRACT

The process of collective de-excitation of atoms in a metastable level into emission mode of a single photon plus a neutrino pair, called radiative emission of neutrino pair (RENP), is sensitive to the absolute neutrino mass scale, to the neutrino mass hierarchy and to the nature (Dirac or Majorana) of massive neutrinos. We investigate how the indicated neutrino mass and mixing observables can be determined from the measurement of the corresponding continuous photon spectrum taking the example of a transition between specific levels of the Yb atom. The possibility of determining the nature of massive neutrinos and, if neutrinos are Majorana fermions, of obtaining information about the Majorana phases in the neutrino mixing matrix, is analyzed in the cases of normal hierarchical, inverted hierarchical and quasi-degenerate types of neutrino mass spectrum. We find, in particular, that the sensitivity to the nature of massive neutrinos depends critically on the atomic level energy difference relevant in the RENP.

1. Introduction

Determining the absolute scale of neutrino masses, the type of neutrino mass spectrum, which can be either with normal or inverted ordering[2] (NO or IO), the nature (Dirac or Majorana) of massive neutrinos, and getting information about the Dirac and Majorana CP violation phases in the neutrino mixing matrix, are the most pressing and challenging problems of the future research in the field of neutrino physics (see, e.g., [1]). At present we have compelling evidence for existence of mixing of three massive neutrinos ν_i, $i = 1, 2, 3$, in the weak charged lepton current (see, e.g., [2]). The masses $m_i \geqslant 0$ of the three light neutrinos ν_i do not exceed a value approximately 1 eV, $m_i \lesssim 1$ eV. The three neutrino mixing scheme is described (to a good approximation) by the Pontecorvo, Maki, Nakagawa, Sakata (PMNS) 3×3 unitary mixing matrix, $U_{\rm PMNS}$. In the widely used standard parametrization [1], $U_{\rm PMNS}$ is expressed in terms of the solar, atmospheric and reactor neutrino mixing angles θ_{12}, θ_{23} and θ_{13}, respectively, and one Dirac (δ), and two Majorana [3,4] (α and β) CP violation (CPV) phases. In this parametrization, the elements of the first row of the PMNS matrix, U_{ei}, $i = 1, 2, 3$, which play important role in our further discussion, are given by

$$U_{e1} = c_{12}c_{13}, \qquad U_{e2} = s_{12}c_{13}e^{i\alpha}, \qquad U_{e3} = s_{13}e^{i(\beta-\delta)}, \tag{1}$$

where we have used the standard notation $c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$ with $0 \leqslant \theta_{ij} \leqslant \pi/2$, $0 \leqslant \delta \leqslant 2\pi$ and, in the case of interest for our analysis,[3] $0 \leqslant \alpha, \beta \leqslant \pi$ (see, however, [5]). If CP invariance holds, we have $\delta = 0, \pi$, and [6] $\alpha, \beta = 0, \pi/2, \pi$.

The neutrino oscillation data, accumulated over many years, allowed to determine the parameters which drive the solar and atmospheric neutrino oscillations, $\Delta m^2_{\odot} \equiv \Delta m^2_{21}$, θ_{12} and $|\Delta m^2_A| \equiv |\Delta m^2_{31}| \cong |\Delta m^2_{32}|$, θ_{23}, with a high precision (see, e.g., [2]). Furthermore, there were spectacular developments in the last year in what concerns the angle θ_{13} (see, e.g., [1]). They culminated in a high precision determination of $\sin^2 2\theta_{13}$ in the Daya Bay experiment using the reactor $\bar{\nu}_e$ [7]:

$$\sin^2 2\theta_{13} = 0.089 \pm 0.010 \pm 0.005. \tag{2}$$

Similarly, the RENO, Double Chooz, and T2K experiments reported, respectively, 4.9σ, 3.1σ and 3.2σ evidences for a non-zero value of θ_{13} [8], compatible with the Daya Bay result.

---

* Corresponding author at: SISSA and INFN – Sezione di Trieste, Via Bonomea 265, 34136 Trieste, Italy.

E-mail address: dngdinh@sissa.it (D.N. Dinh).

[1] Also at: Institute of Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, 1784 Sofia, Bulgaria.

[2] We use the convention adopted in [1].

[3] Note that the two Majorana phases α_{21} and α_{31} defined in [1] are twice the phases α and β: $\alpha_{21} = 2\alpha$, $\alpha_{31} = 2\beta$.

0370-2693/$ – see front matter
http://dx.doi.org/10.1016/j.physletb.2013.01.015

A global analysis of the latest neutrino oscillation data presented at the Neutrino 2012 International Conference [2] was performed in [9]. We give below the best fit values of Δm^2_{21}, $\sin^2\theta_{12}$, $|\Delta m^2_{31(32)}|$ and $\sin^2\theta_{13}$, obtained in [9], which will be relevant for our further discussion:

$$\Delta m^2_{21} = 7.54 \times 10^{-5}\ \text{eV}^2,$$

$$\left|\Delta m^2_{31(32)}\right| = 2.47\ (2.46) \times 10^{-3}\ \text{eV}^2, \qquad (3)$$

$$\sin^2\theta_{12} = 0.307,$$

$$\sin^2\theta_{13} = 0.0241\ (0.0244), \qquad (4)$$

where the values (the values in brackets) correspond to NO (IO) neutrino mass spectrum. We will neglect the small differences between the NO and IO values of $|\Delta m^2_{31(32)}|$ and $\sin^2\theta_{13}$ and will use $|\Delta m^2_{31(32)}| = 2.47 \times 10^{-3}$ eV^2, $\sin^2\theta_{13} = 0.024$ in our numerical analysis.

After the successful measurement of θ_{13}, the determination of the absolute neutrino mass scale, of the type of the neutrino mass spectrum, of the nature of massive neutrinos, as well as getting information about the status of CP violation in the lepton sector, remain the highest priority goals of the research in neutrino physics. Establishing whether CP is conserved or not in the lepton sector is of fundamental importance, in particular, for making progress in the understanding of the origin of the matter–antimatter asymmetry of the Universe (see, e.g., [10–12]).

Some time ago one of the present authors proposed to use atoms or molecules for systematic experimental determination of the neutrino mass matrix [13,14]. Atoms have a definite advantage over conventional target of nuclei: their available energies are much closer to neutrino masses. The process proposed is cooperative de-excitation of atoms in a metastable state. For the single atom the process is $|e\rangle \to |g\rangle + \gamma + (\nu_i + \nu_j)$, $i, j = 1, 2, 3$, where ν_i's are neutrino mass eigenstates. If ν_i are Dirac fermions, $(\nu_i + \nu_j)$ should be understood for $i = j$ as $(\nu_i + \bar\nu_i)$, and as either $(\nu_i + \bar\nu_j)$ or $(\nu_j + \bar\nu_i)$ when $i \neq j$, $\bar\nu_i$ being the antineutrino with mass m_i. If ν_i are Majorana particles, we have $\bar\nu_i \equiv \nu_i$ and $(\nu_i + \nu_j)$ are the Majorana neutrinos with masses m_i and m_j.

The proposed experimental method is to measure, under irradiation of two counter-propagating trigger lasers, the continuous photon (γ) energy spectrum below each of the six thresholds ω_{ij} corresponding to the production of the six different pairs of neutrinos, $\nu_1\nu_1, \nu_1\nu_2, \ldots, \nu_3\nu_3$: $\omega < \omega_{ij}, \omega$ being the photon energy, and [13,14]

$$\omega_{ij} = \omega_{ji} = \frac{\epsilon_{eg}}{2} - \frac{(m_i + m_j)^2}{2\epsilon_{eg}}, \quad i, j = 1, 2, 3,\ m_{1,2,3} \geqslant 0, \qquad (5)$$

where ϵ_{eg} is the energy difference between the two relevant atomic levels.

The process occurs in the 3rd order (counting the four Fermi weak interaction as the 2nd order) of electroweak theory as a combined weak and QED process, as depicted in Fig. 1. Its effective amplitude has the form of

$$\langle g|\vec d|p\rangle \cdot \vec E \frac{G_F \sum_{ij} a_{ij} \nu_j^\dagger \vec\sigma \nu_i}{\epsilon_{pg} - \omega} \cdot \langle p|\vec S_e|e\rangle, \qquad (6)$$

$$a_{ij} = U^*_{ei} U_{ej} - \frac{1}{2}\delta_{ij}, \qquad (7)$$

where U_{ei}, $i = 1, 2, 3$, are the elements of the first row of the neutrino mixing matrix U_{PMNS}, given in Eq. (1). The atomic part of the probability amplitude involves three states $|e\rangle, |g\rangle, |p\rangle$, where the two states $|e\rangle, |p\rangle$, responsible for the neutrino pair emission, are connected by a magnetic dipole type operator, the electron spin $\vec S_e$. The $|g\rangle - |p\rangle$ transition involves a stronger electric dipole operator $\vec d$. From the point of selecting candidate atoms, E1×M1 type transition must be chosen between the initial and the final states ($|e\rangle$ and $|g\rangle$). The field $\vec E$ in Eq. (6) is the one stored in the target by the counter-propagating fields. The formula has some similarity to the case of stimulated emission. By utilizing the accuracy of trigger laser one can decompose, in principle, all six photon energy thresholds at ω_{ij}, thereby resolving the neutrino mass eigenstates instead of the flavor eigenstates. The spectrum rise below each threshold $\omega \leqslant \omega_{ij}$ depends, in particular, on $|a_{ij}|^2$ and is sensitive to the type of the neutrino mass spectrum, to the nature of massive neutrinos, and, in the case of emission of two different Majorana neutrinos, to the Majorana CPV phases in the neutrino mixing matrix (see further).

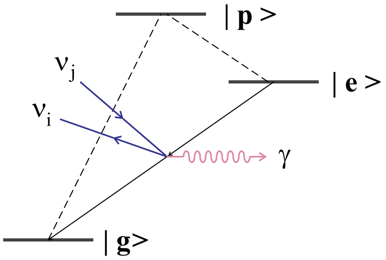

Fig. 1. Λ-type atomic level for RENP $|e\rangle \to |g\rangle + \gamma + \nu_i\nu_j$ with ν_i a neutrino mass eigenstate. Dipole forbidden transition $|e\rangle \to |g\rangle + \gamma + \gamma$ may also occur via weak E1× M1 couplings to $|p\rangle$.

The disadvantage of atomic targets is their smallness of rates which are very sensitive to available energy of order eV. This can be overcome by developing, with the aid of a trigger laser, macro-coherence of atomic polarization to which the relevant amplitude is proportional, as discussed in [16,17]. The macroscopic polarization supported by trigger field gives rise to enhanced rate $\propto n^2 V$, where n is the number density of excited atoms and V is the volume irradiated by the trigger laser. The proposed atomic process may be called radiative emission of neutrino pair, or RENP in short. The estimated rate roughly of order mHz or a little less makes it feasible to plan realistic RENP experiments for a target number of order of the Avogadro number, within a small region of order 1–10^2 cm^3, if the rate enhancement works as expected.

The new atomic process of RENP has a rich variety of neutrino phenomenology, since there are six independent thresholds for each target choice, having a strength proportional to different combinations of neutrino masses and mixing parameters. In the present work we shall correct the spectrum formula for the Majorana neutrino case given in [14] and also extend the discussion of the atomic spin factor.

In the numerical results presented here we show the sensitivity of the RENP related photon spectral shape to various observables; the absolute neutrino mass scale, the type of neutrino mass spectrum, the nature of massive of neutrinos and the Majorana CPV phases in the case of massive Majorana neutrinos. All these observables can be determined in one experiment, each observable with a different degree of difficulty, once the RENP process is experimentally established. For atomic energy available in the RENP process of the order of a fraction of eV, the observables of interest can be ranked in the order of increasing difficulty of their determination as follows:

(1) The absolute neutrino mass scale, which can be fixed by, e.g., measuring the smallest photon energy threshold $\min(\omega_{ij})$ near which the RENP rate is maximal: $\min(\omega_{ij})$ corresponds to the production of a pair of the heaviest neutrinos ($\max(m_j) \gtrsim$ 50 meV).