Proposed Search for a Fourth Neutrino with a PBq Antineutrino Source

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Several observed anomalies in neutrino oscillation data can be explained by a hypothetical fourth neutrino separated from the three standard neutrinos by a squared mass difference of a few eV^2. We show that this hypothesis can be tested with a PBq (ten kilocurie scale) ^{144}Ce or ^{106}Ru antineutrino beta source deployed at the center of a large low background liquid scintillator detector. In particular, the compact size of such a source could yield an energy-dependent oscillating pattern in event spatial distribution that would unambiguously determine neutrino mass differences and mixing angles.

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Most results from neutrino experiments over the last 20 years can be quite accurately described by a model of oscillations between three ν flavors (ν_e, ν_μ, ν_τ) that are mixtures of three massive neutrinos (ν_1, ν_2, ν_3) separated by squared mass differences of $\Delta m^2_{21} = 8 \times 10^{-5}$ eV^2 and $\Delta m^2_{31} = 2.4 \times 10^{-3}$ eV^2 [1]. In the past the LSND experiment suggested the existence of a fourth massive neutrino with a mass of ~ 1 eV^2 [2]. This evidence has been confirmed by the MiniBoone experiment in the antineutrino sector [3]. Recently the hypothetical existence of a fourth ν has been revived by a new calculation [4] of the rate of $\bar{\nu}_e$ production by nuclear reactors that yields a ν flux about 3% higher than previously predicted. This calculation then implies [5] that the measured event rates for all reactor $\bar{\nu}_e$ experiments within 100 meters of the reactor are about 6% too low. The deficit can also be explained by a hypothetical fourth massive ν separated from the three others by $|\Delta m^2_{\rm new}| > 0.1$ eV^2. This mixing can explain a similar deficit in the rate of ν interactions in gallium solar-ν detectors when exposed to artificial ^{51}Cr and ^{37}Ar MCi sources [6]. The combination of [5,6] deficits is significant at the 99.8% C.L., though no conclusive model can explain all data [7]. In this Letter we propose an unambiguous search for this fourth neutrino by using a 1.85 PBq (50 kCi) antineutrino source deployed at the center of a kiloton scale detector such as Borexino [8], KamLAND [9], or SNO+ [10]. Antineutrino detection will be made via the inverse beta-decay (IBD) reaction $\bar{\nu}_e + p \rightarrow e^+ + n$. The delayed coincidence between detection of the positron and the neutron capture gamma rays will allow for a nearly background-free experiment. The small size (~ 10 g) of the source compared to the size a nuclear reactor core may allow the observation of the characteristic ν-oscillation pattern of event positions.

Large liquid scintillator (LS) detectors, called LLSD hereafter, share key features well suited to search for an eV-scale fourth ν ($\bar{\nu}$) state mixing with ν_e ($\bar{\nu}_e$). The active mass is composed of about a thousand tons of ultrapure LS contained in a nylon or acrylic vessel. The scintillation light is detected via thousands of photomultipliers uniformly distributed on a stainless steel spherical vessel. In Borexino and KamLAND the target is surrounded by mineral oil or scintillator contained in a stainless steel vessel. This buffer is enclosed in a water tank instrumented by photomultipliers detecting the Cherenkov light radiated by cosmic muons. In the following we study the deployment of a ν source of energy spectrum $\mathcal{S}(E_\nu)$, mean lifetime τ, and initial activity $\mathcal{A}_0$, encapsulated inside a thick tungsten (W) and copper (Cu) shielding sphere, at the center of a LLSD. We consider a running time t_e with a fully efficient detector. The theoretical expected number of interactions at a radius R and energy E_ν can be written

$$\frac{d^2N(R, E_\nu)}{dRdE_\nu} = \mathcal{A}_0 n \sigma(E_\nu) \mathcal{S}(E_\nu) \mathcal{P}(R, E_\nu) \int_0^{t_e} e^{-t/\tau} dt, \quad (1)$$

where n is the density of free protons in the target for inverse beta decay, σ is the cross section. $\mathcal{P}(R, E_\nu)$ is the 2-ν oscillation survival probability, defined as

$$\mathcal{P}(R, E_\nu) = 1 - \sin^2(2\theta_{\rm new}) \sin^2\left(1.27 \frac{\Delta m^2_{\rm new}[{\rm eV}^2] R[{\rm m}]}{E_\nu[{\rm MeV}]}\right), \quad (2)$$

where $\Delta m^2_{\rm new}$ and $\theta_{\rm new}$ are the new oscillation parameters relating ν_e to the fourth ν. In our simulations we assume a 15 cm vertex resolution and a 5% energy resolution. In the no-oscillation scenario we expect a constant ν rate in concentric shells of equal thickness [see Eq. (1)]. At 2 MeV the oscillation length is 2.5 m for $\Delta m^2_{\rm new} = 2$ eV^2, proportional to $1/\Delta m^2_{\rm new}$ [see Eq. (2)]. A definitive test of the reactor antineutrino anomaly, independent of the knowledge of the source activity, would be the observation of the oscillation pattern as a function of the ν interaction radius and possibly the ν energy.

Intense man-made ν sources were used for the calibration of solar-ν experiments. In the nineties, ^{51}Cr (~ 750 keV, $\mathcal{A}_0 \sim$ MCi) and ^{37}Ar (814 keV, $\mathcal{A}_0 = 0.4$ MCi) were used as a check of the radiochemical experiments Gallex and Sage [11]. There are two options for deploying ν sources in LS: monochromatic ν_e emitters, like ^{51}Cr or ^{37}Ar, or $\bar{\nu}_e$ emitters with a continuous β spectrum. In the first case, the signature is provided by ν_e elastic scattering off electrons in the LS molecules. This signature can be mimicked by Compton scattering induced by radioactive and cosmogenic background, or by solar-ν interactions. The constraints of an experiment with ν_e impose the use of a very high activity source (5–10 MCi) outside of the detector target. In the second option, $\bar{\nu}_e$ are detected via inverse beta decay. Its signature, provided by the e^+-n delayed coincidence, offers an efficient rejection of the mentioned background. For this reason, we focus our studies on $\bar{\nu}_e$ sources.

A suitable $\bar{\nu}_e$ source must have $Q_\beta > 1.8$ MeV (the IBD threshold) and a lifetime that is long enough ($\gtrsim 1$ month) to allow for production and transportation to the detector. For individual nuclei, these two requirements are contradictory so we expect candidate sources to involve a long-lived low-Q nucleus that decays to a short-lived high-Q nucleus. We identified four such pairs ^{144}Ce-^{144}Pr [$Q_\beta(\mathrm{Pr}) = 2.996$ MeV], ^{106}Ru-^{106}Rh [$Q_\beta(Rh) = 3.54$ MeV], $^{90}\mathrm{Sr} - {}^{90}\mathrm{Y}$ [$Q_\beta(Y) = 2.28$ MeV], and $^{42}\mathrm{Ar} - {}^{42}\mathrm{K}$ [$Q_\beta(K) = 3.52$ MeV], some of them also reported in [12]. The first three are common fission products from nuclear reactors that can be extracted from spent fuel rods. While not minimizing the difficulty of doing this, the nuclear industry does have the technology to produce sources of the appropriate intensity, at the ppm purity level. In fact, 10 kCi ^{90}Sr sources have been produced and used industrially for heat generation. Delays obtaining authorizations for transportation and deployment of the source into an underground laboratory should be addressed at the start of the project.

For this Letter, we concentrate on the ^{144}Ce source (Fig. 1) because its Q_β is greater than that of ^{90}Sr and because it is easier to extract chemically than ^{106}Ru. We note also that it has a very low production rate of high-energy γ rays (> 1 MeV) from which the $\bar{\nu}_e$ detector must be shielded to limit background events. Finally, cerium is present in fission products of uranium and plutonium at the level of a few percent.

We now focus on the unique oscillation signature induced by an eV-scale sterile ν at the center of a LLSD. For ^{144}Ce-^{144}Pr, 1.85 PBq (50 kCi) source is needed to reach 40 000 interactions in 1 yr in a LLSD, between 1.5 and 6 m away from the source ($n_H = 5.3 \times 10^{28}$ m^{-3}). This is realized with 14 g of ^{144}Ce, whereas the total mass of all cerium isotopes is $\sim$1.5 kg, for an extraction from selected fission products. The compactness of the source, $<$4 cm, is small enough to be considered as a pointlike source for $\Delta m^2_{\mathrm{new}}$ eV^2 oscillation searches. This source initially releases $\sim$300 W, and it could be cooled either by convective exchanges with the LS, or via conduction though an ultrapure copper cold finger connecting the massive passive shield to a low temperature bath. β^--decay induced $\bar{\nu}_e$ are detected through IBD. The cross section is $\sigma(E_e) = 0.956 \times 10^{-43} \times p_e E_e \mathrm{cm}^2$, where p_e and E_e are the momentum and energy (MeV) of the detected e^+, neglecting recoil, weak magnetism, and radiative corrections (percent-level correction). The e^+ promptly deposits its kinetic energy in the LS and annihilates emitting two 511 keV γ rays, yielding a prompt event, with a visible energy of $E_e = E_\nu - (m_n - m_p)$ MeV; the emitted keV neutron is captured on a free proton with a mean time of a few hundred microseconds, followed by the emission of a 2.2 MeV deexcitation γ ray providing a delayed coincidence event. The expected oscillation signal for $\Delta m^2_{\mathrm{new}} = 2$ eV^2 and $\sin^2(2\theta_{\mathrm{new}}) = 0.1$, is shown on Fig. 2. LLSD are thus well suited to search for an eV-scale fourth ν state.

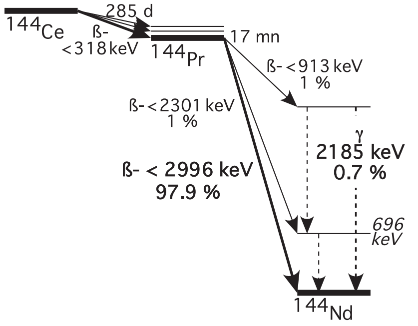

FIG. 1. Simplified decay scheme of the pair ^{144}Ce-^{144}Pr.

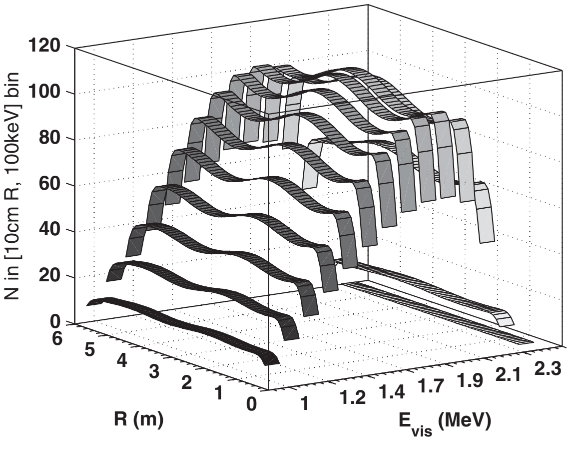

FIG. 2. Advantage of $\bar{\nu}_e$ sources providing both R and E_{vis} oscillation patterns. IBD rate for a 50 kCi ^{144}Ce source deployed at a center of a LLSD, in 10 cm radius bins and 100 keV bins of visible energy, $E_{\mathrm{vis}} = E_e + 2\ \mathrm{m}_e$. In one year, 38 000 $\bar{\nu}_e$ interact between 1.5 and 6 m radius, for $\Delta m^2_{\mathrm{new}} = 2$ eV^2 and $\sin^2(2\theta_{\mathrm{new}}) = 0.1$.

TABLE I. Features of ^{144}Ce-^{144}Pr and ^{106}Ru-^{106}Rh pairs, extracted from spent nuclear fuel. F.Y. are the fission yields of ^{144}Ce and ^{106}Ru, $t_{1/2}$, their half-lives. β end points are given for the first and second nucleus of each pair. The I_γ's are the branching ratio of γ rays per beta decay above 1 and 2 MeV. The two last columns are the heat produced/kCi and the activity required to get 40 000 events/year.

Source	F.Y. ^{235}U/^{239}Pu	$t_{1/2}$	1st β^- (keV)	2nd β^- (keV)	$I_{\gamma>1\ \mathrm{MeV}}$	$I_{\gamma>2\ \mathrm{MeV}}$	W/kCi	kCi/4×10^4 int/y
^{144}Ce-^{144}Pr	5.2%/3.7%	285 d	318 (76%) 184 (20%) 238 (4%)	2996 (99%) 810 (1%)	1380 (0.007%) 1489 (0.28%)	2185 (0.7%)	7.47	43.7
^{106}Ru-^{106}Rh	0.5%/4.3%	373 d	39.4 (100%)	3540 (78%) 3050 (8%) 2410 (10%) 2000 (2%)	1050 (1.6%) 1128–1194 (0.47%) 1496–1562 (0.19%) 1766–1988 (0.09%)	2112 (0.04%) 2366 (0.03%) 3400 (0.016%)	8.40	23.0

Note that a study of signals of a ^{90}Sr MCi source external of a LLSD was done in [13].

The space-time coincidence signature of IBD events ensures an almost background-free detection. Backgrounds are of two types, those induced by the environment or detector, and those due to the source and its shielding.

The main concern is accidental coincidences between prompt ($E > 0.9$ MeV) and delayed energy depositions ($E > 2.0$ MeV) occurring within a time window taken as three neutron capture lifetimes on hydrogen (equivalent to about 772 μs), and within a volume of 10 m^3 (both positions are reconstructed, this last cut leading to a background rejection of a factor 100). The main source of detector backgrounds originates from accidental coincidences, fast neutrons, and the long-lived muon induced isotopes ^{9}Li/^{8}He and scales with R^2 when using concentric R bins. These components have been measured *in situ* for the Borexino geo-ν searches [14], at 0.14 ± 0.02 counts/day/100 tons. Being conservative we increase it to 10 counts/day/100 tons in our simulation.

Geologic $\bar{\nu}_e$ arising from the decay of radioactive isotopes of uranium or thorium in Earth have been measured at a rate of a few events/(100 ton · yr) in KamLAND [15] and Borexino [14]. Reactor $\bar{\nu}_e$ emitted by the β decays of the fission products in the nuclear cores have been measured in KamLAND at a rate of ~10 events/(100 ton · yr) in the energy range of interest [15]. We use a rate of 20 events/(100 ton · yr), which is negligible with respect to the $\bar{\nu}_e$ rate from a kCi source.

The most dangerous source background originates from the energetic γ produced by the decay through excited states of ^{144}Pr (Table I). We approximate γ ray attenuation in a shield of 33 cm of W and 2 cm of Cu with an exponential attenuation law accounting for Compton scattering and photoelectric effect. The intensity of 2185 keV γ rays is decreased by a factor $<10^{-12}$ ($\lambda_W \sim 1.2$ cm) [16], to reach a tolerable rate.

The energy spectrum of external bremsstrahlung photons in the cerium is estimated with a simulation using the cross section of [17]. Results were confirmed with a GEANT4 [18] simulation. The number of photons above a prompt signal threshold of 0.9 MeV is 6.5×10^{-3} photons per β decay, and 10^{-4} photon per β decay >2.0 MeV.

An important remaining background source could be the W shield itself. Activities at the level of ten to hundreds of mBq/kg have been reported. We anticipate the need of an external layer of ultrapure copper, set to 2 cm in our simulation. It allows one to achieve the radiopurity and material compatibility requirements. Assuming a ~4 ton shield we consider prompt and delayed event rates of 50 and 25 Hz, respectively. The escaping γ are attenuated in the LS, assuming a 20 cm attenuation length [16]. Beyond a distance of 1.5 m from the source the backgrounds become negligible. Any of the bremsstrahlung photons or shielding backgrounds can account for either the prompt or delayed event, depending on their energy. The sum of the backgrounds integrated over their energy spectrum is shown on Fig. 3, supporting the case of kCi $\bar{\nu}_e$ source

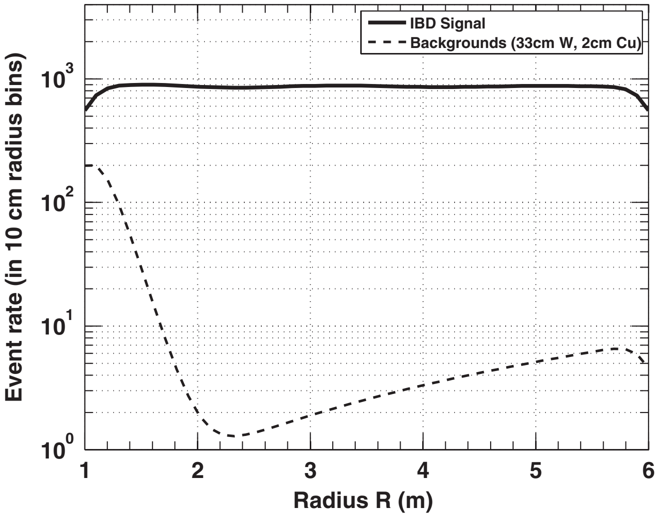

FIG. 3. Signal rate of a 50 kCi ^{144}Ce deployed for one year at a center of a LLSD (plain line), compared to the sum of all identified background rates (dashed line), as a function of the detector radius in 10 cm concentric bins. A shield made of 33 cm of W and 2 cm of Cu attenuates the backgrounds, dominated primarily by ^{144}Ce γ lines, then by external bremsstrahlung of the ^{144}Ce β-decay electrons slowing down in the cerium material.

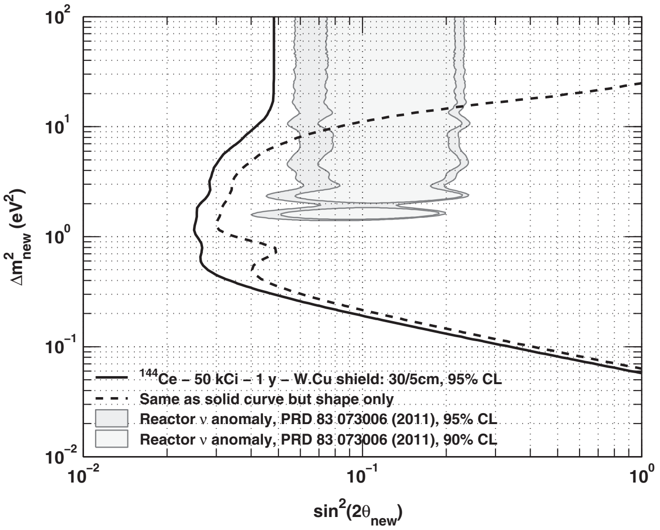

FIG. 4. 95% C.L. exclusion limit of the $50 \text{kCi} \cdot \text{y}$ ^{144}Ce experiment obtained in the Δm^2_{new} and $\sin^2(2\theta_{\text{new}})$ plane (2 dof). Our result (plain and dashed lines with and without knowledge of source activity) is compared to the 90% and 95% C.L. inclusion domains given by the combination of reactor neutrino experiments, Gallex and Sage calibration sources experiments, MiniBooNE as described in Fig. 8 of [5] (gray areas).

versus MCi ν_e source for which solar-ν's become an irreducible background. A light doping of the LS with gadolinium or an oil buffer surrounding the shielding would further suppress backgrounds; finally, nonsource backgrounds could be measured *in situ* during a blank run with an empty shielding.

We now assess the sensitivity of an experiment with a 50 kCi ^{144}Ce source running for 1 yr. With the shield described above and using events between 1.5 and 6 m, the background is negligible. With $\Delta m^2_{\text{new}} = 2$ eV^2 and $\sin^2(2\theta_{\text{new}}) = 0.1$, the interaction rate decreases from 40 000 to 38 000 per year. The 95% C.L. sensitivity is extracted through the following function:

$$\chi^2 = \sum_i \sum_j \frac{[N^{i,j}_{\text{obs}} - (1+\alpha)N^{i,j}_{\text{exp}}]^2}{N^{i,j}_{\text{exp}}(1+\sigma_b^2 N^{i,j}_{\text{exp}})} + \left(\frac{\alpha}{\sigma_N}\right)^2, \qquad (3)$$

where $N^{i,j}_{\text{obs}}$ are the simulated data in the no-oscillation case and $N^{i,j}_{\text{exp}}$ the expectations for a given oscillation scenario, in each energy E_i and radius R_j bin. σ_b is a 2% fully uncorrelated systematic error, accounting for a fiducial volume uncertainty of 1% in a calibrated detector, as well as for (e^+, n) space-time coincidence detection efficiencies uncertainties at the subpercent level. σ_N is a normalization error of 1%, describing for the source activity uncertainty (from calorimetric measurement, see [19]), and α is the associated nuisance parameter. Figure 4 clearly shows that 50 kCi of ^{144}Ce allows us to probe most of the reactor antineutrino anomaly parameter space [5] at 95% C.L. An analysis assuming no knowledge on the source activity shows that the oscillatory behavior can be established for $\Delta m^2_{\text{new}} < 10$ eV^2. We note that a 10 kCi source would be enough to test the anomaly at 90% C.L.

The reactor $\bar{\nu}_e$ anomaly and the hypothetical existence of a 4th ν state mixing with the ν_e could be efficiently tested by deploying a β source of about 10 grams of ^{144}Ce (or ^{106}Ru) at the center of a large low background liquid scintillator detector. The technical challenge lies in the production of the source itself, as well as in the realization of a thick ultrapure W/Cu shielding surrounding the Ce (Ru) material. Significant collaborative work would be needed to bring this idea to fruition.

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