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Novel way to search for sterile neutrinos

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We show that the existence of a new massive sterile neutrino can be manifested employing a novel experimental method of neutrino oscillations, namely, neutrino oscillometry. With a judicious monochromatic neutrino source the relevant oscillation length is expected to be shorter than 1.5 m. Thus the needed measurements can be implemented with a gaseous spherical time projection chamber of modest dimensions having a very good energy and position resolution. The best candidates for oscillometry are discussed. The expected sensitivity to the mixing angle θ_{14} has been estimated: $\sin^2(2\theta_{14}) = 0.05$ (99%) with only two months of data handling with ^{51}Cr.

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A recent analysis of the low energy neutrino anomaly [1,2] led to a challenging claim that this anomaly can be explained in terms of a new fourth neutrino with a much larger mass squared difference. Assuming that the neutrino mass eigenstates are nondegenerate one finds [1,2]:

$$\begin{aligned}\Delta m^2_{31} &\approx \Delta m^2_{32} = |m^2_3 - m^2_2|,\\ \Delta m^2_{41} &\approx \Delta m^2_{42} = |m^2_4 - m^2_2| > 1.5\ (\text{eV})^2\end{aligned} \tag{1}$$

with a mixing angle:

$$\sin^2 2\theta_{14} = 0.14 \pm 0.08(95\%). \tag{2}$$

Even though this new neutrino is sterile, i.e., it does not participate in week interaction, it should contribute to the oscillation, since it will tend to decrease the electron neutrino flux.

In the present paper we will show that the observation of such an oscillation will establish beyond a doubt the existence of such an exotic neutrino and provide a more accurate determination of the above parameters.

In all the previous standard experiments the oscillation length is much larger than the size of the detector. So one is able to see the effect only if the detector is placed in the correct distance from the source. It is, however, possible to design an experiment with an oscillation length of the order of the size of the detector, as was proposed in [3,4]. Indeed, "short wavelength" experiments have recently been proposed, see [1,4] and the LENA Collaboration white paper [5]. A similar proposal has also been announced by the Borexino group [6]. The last two projects, however, deal with the liquid scintillator (LS) detectors. The main disadvantage of the LS is a much higher energy threshold for the recoil electron detection in the charged channel (about 200 keV), to be compared with that of the gaseous spherical time projection chamber (STPC) [7] (of 0.1 keV) proposed in our work. Consequently, the gaseous STPC can alternatively be used.

The experiment of the type we propose [3,4] can be best described as neutrino oscillometry. The main requirements are as follows [4]:

(i) The neutrinos should have as low as possible energy, so that the oscillation length can be minimized. At the same time it should not be too low, so that the neutrino-electron cross section is sizable.

(ii) A monoenergetic neutrino source has the advantage that some of the features of the oscillation pattern are not washed out by the averaging over a continuous neutrino spectrum. The continuous antineutrino spectrum offers the possibility to get an L/E (source-detector distance/neutrino energy) oscillation pattern. This L- pattern, however, is washed out because the antineutrinos are not monoenergetic, whereas the case of monoenergetic neutrinos leads to precise single L-values. Furthermore the use of both neutrinos and antineutrinos has already been discussed in connection with the neutral current scattering in our recent work [8].

(iii) The lifetime of the source should be suitable for the experiment to be performed. If it is too short, the time available will not be adequate for the execution of the experiment. If it is too long, the number of counts during the data taking will be too small. Then one will face formidable backgrounds and/or large experimental uncertainties.

(iv) The source should be cheaply available in large quantities. Clearly a compromise has to be made in the selection of the source.

At low energies the only neutrino detector, which is sensitive to neutrino oscillations, is one, which is capable of detecting recoiling electrons [3] or nuclei [8]. Thus we will show that the existence of a new fourth neutrino can be verified experimentally by the direct measurements of the oscillation curves for the monoenergetic neutrino-electron scattering. It can be done point by point within the dimensions of the detector, thus providing what we call neutrino oscillometry [4,9].

The electron neutrino, produced in weak interactions, can be expressed in terms of the standard mass eigenstates as follows:

$$\nu_e = \cos\theta_{14}[\cos\theta_{12}\cos\theta_{13}\nu_1 + \sin\theta_{12}\cos\theta_{13}\nu_2 + \sin\theta_{13}e^{i\delta}\nu_3] + \sin\theta_{14}e^{i\delta_4}\nu_4, \tag{3}$$

where $\sin\theta_{13}$ is a small quantity constrained by the T2K and MINOS experiments and $\sin\theta_{14}$ is the small mixing angle proposed for the resolution of the low energy neutrino anomaly [1,2]. We can apply a four neutrino oscillation analysis to write the (ν_e, e) cross section, proportional to the ν_e disappearance oscillation probability. The latter, under the approximations of Eq. (1), can be written as

$$P(\nu_e \rightarrow \nu_e) \approx 1 - \chi[E_\nu]\left[\sin^2 2\theta_{12}\sin^2\left(\pi\frac{L}{L_{21}}\right) + \sin^2 2\theta_{13}\sin^2\left(\pi\frac{L}{L_{31}}\right)\right] - \sin^2 2\theta_{14}\sin^2\left(\pi\frac{L}{L_{41}}\right) \tag{4}$$

with

$$L_{ij} = \frac{4\pi E_\nu}{m_i^2 - m_j^2}. \tag{5}$$

The function $\chi(E_\nu)$ of Eq. (4) appears, since, as we have already mentioned in connection with the NOSTOS project [3,8], in the experiment involving neutrino-electron scattering, unlike the case of a hadronic target, not only electron neutrinos but the other two neutrino flavors interact with electrons with a different cross section, which depends on the energy [8]. These flavors are generated via the appearance oscillation. Since, however, the oscillation lengths are very different, $L_{42} \ll L_{32} \ll L_{21}$, one may judiciously select the energy of the neutrino source and place it at the center of our spherical detector, so that, within our detector, one observes only one mode of oscillation, e.g., that due to the sterile neutrino. Thus

$$P(\nu_e \rightarrow \nu_e) \approx 1 - \left[\sin^2 2\theta_{14}\sin^2\left(\pi\frac{L}{L_{41}}\right)\right]. \tag{6}$$

Thus the number of the scattered electrons, which bear this rather unusual oscillation pattern, is proportional to the (ν_e, e^-) scattering cross section, which can be cast in the form:

$$\sigma(L, x, y_{\rm th}) = \sigma(0, x, y_{\rm th})(1 - p(L, x)) \tag{7}$$

with $x = E_\nu/m_e$ and $y_{\rm th} = (T_e)_{\rm th}/m_e$, $(T_e)_{\rm th}$ being the threshold electron energy imposed by the detector. The oscillation part due to the sterile neutrino takes the form:

$$p(L, x) = \sin^2[2.48((\Delta m_{41}^2/1\ {\rm eV}^2)(L/m))/x]\sin^2(2\theta_{14}) \tag{8}$$

with L the source-detector distance (in meters). The total cross section in the absence of oscillations can be written in the form:

$$\sigma(0, x, y_{\rm th}) = \frac{G_F^2 m_e^2}{2\pi}(h(x) - h(y_{\rm th})), \quad h(x) = \frac{x^2(17.7x^2 + 15.3x + 3.36)}{(2x+1)^3} \tag{9}$$

with $h(y_{\rm th}) \rightarrow 0$, since the threshold effect is negligible in the case of the STPC [7].

We will consider a spherical detector with the source at the origin and will assume that the volume of the source is much smaller than the volume of the detector. The number of events between L and $L + dL$ is given by

$$dN = N_\nu n_e \frac{4\pi L^2 dL}{4\pi L^2}\sigma(L, x, y_{\rm th}) = N_\nu n_e dL \sigma(L, x, y_{\rm th}) \tag{10}$$

or

$$\frac{dN}{dL} = N_\nu n_e \sigma(L, x, y_{\rm th}) \tag{11}$$

with N_ν being the number of neutrinos emitted by the source and n_e the density of electrons in the target, which is proportional to the atomic number Z.

One can ask whether the relevant candidates for small length oscillation measurements exist in reality. A detailed analysis shows that there exist many cases of nuclei, which can undergo orbital electron capture yielding monochromatic neutrinos with low energy.

Since this process has the two-body mechanism, the total neutrino energy is equal to the difference of the total capture energy $Q_{\rm EC}$ (which is the atomic mass difference) and binding energy of captured electron B_i and the energy of the final nuclear excited state E^*, that is,

$$E_\nu = Q_{\rm EC} - B_i - E^*. \tag{12}$$

This value can be easily determined because the capture energies are usually known (or can be measured very precisely by the ion-trap spectrometry [10]) and the electron binding energies as well as the excited nuclear energies are tabulated [11,12]. The main feature of the electron capture process is the monochromaticity of neutrino. This paves the way for the neutrino oscillometry [4]. Since $\Delta m_{41}^2 > 1.5\ ({\rm eV})^2$ [1], i.e., very large by neutrino mass standards, the oscillation length can be quite small even for quite energetic neutrinos.

In other words, unlike the case involving θ_{13} previously discussed [3,4,9], one can now choose much higher neutrino energy sources and thus achieve much higher cross sections. Thus our best candidates, see in Table I, are nuclides, which emit monoenergetic neutrinos with

TABLE I. Proposed candidates for a new neutrino oscillometry at the spherical gaseous TPC. Tabulated nuclear data have been taken from [12,13], other data have been calculated in this work (see the text for details. The mass of the source was assumed to be 0.1 Kg).

Nuclide	$T_{1/2}$ (d)	$Q_{\rm EC}$ (keV)	E_ν (keV)	L_{31} (m)	L_{41} (m)	$\sigma(0, x, y_{\rm th})$ 10^{-45} cm^2	N_ν (s^{-1})
^{37}Ar	35	814	811	842	1.35	5.69	3.7×10^{17}
^{51}Cr	27.7	753	747	742	1.23	5.12	3.1×10^{17}
^{65}Zn	244	1352	1343	1330	2.22	10.5	1.5×10^{16}

energies higher than many hundreds of keV. Columns 2 and 3 show the decay characteristics of the corresponding nuclides [12,13]. The neutrino energies in column 4 have been calculated by using Eq. (12) taking $Q_{\rm EC}$ from [12] and B_i from [11]. Columns 5 and 6 give the oscillation lengths for the third and the fourth neutrino states. One can see that L_{31} and L_{41} are very different and, thus, the two oscillation curves can be disentangled. The maximum energy of the recoiling electron can be calculated by use of Eq. (2.4) in [4]. Column 7 shows the neutrino-electron cross sections calculated by the use of formula (9). The last column presents the neutrino source intensities which can be reasonably produced by irradiation of the corresponding targets of stable nuclides in high flux nuclear reactors. In principle, the strong intensity sources for the oscillometry with the STPC can be produced in such reactors. The performed estimations have been done with the use of a neutron flux of 5×10^{14} n/(cm^{2}s)). For completeness we mention that the ^{51}Cr source for GALLEX with a neutrino intensity of about 1.7 MCi was produced at the Siloe reactor in Grenoble with the neutron flux of 5.5×10^{13} n/cm^{2}s. Our estimated value for the ^{51}Cr intensity in the last column of Table I (8.3 MCi) is about 5 times higher than that used by GALLEX. It can be provided, e.g., by the higher neutron flux of modern reactors (5×10^{14}) and after 30 days irradiation of about 17.8 kg of Cr, i.e., half of that used by GALLEX (35.5 kg of Cr enriched in ^{50}Cr with 38.6% [14]).

The sources we are concerned with in this paper (see Table I) are not free of problems. The chromium source actually has several monochromatic neutrino lines and an associated gamma ray (320 keV). The ^{65}Zn source was originally proposed by Alvarez and has both a 1.3 MeV line as well as a 0.24 MeV line with roughly equal strength. ^{65}Zn will also give intense 1.115 MeV gammas. The production of the necessary amount of ^{37}Ar from Table I, which is 25 times higher than obtained in the SAGE project [15], needs the invention of an ingenious method. That is why we did not further consider ^{37}Ar. So, at this point, let us elaborate further on the source ^{51}Cr:

(i) There are two monoenergetic neutrino branches in this nuclide. Their energies are 747 and 428 keV. The intensity of the former is 90%, whereas for the latter it is 10%. The neutrino-electron scattering cross section for the 428 keV is 2.5 times less than for 747 keV. It means that the number of $\nu - e$ events associated with the 747 keV branch contain 96% of total events. The 4% events from the 428 keV branch can be fitted and considered as a background. Incidentally similar considerations can be applied in the case of ^{65}Zn, whereby the $\nu - e$ cross section for the low energy branch of 0.24 MeV is more than 10 times less than for the 1.34 MeV.

(ii) The gamma-ray background is a very severe problem.
For the 320 keV gamma transition we propose to use lead shielding. Calculations of the total absorption thickness made by the program FLUKA [16] give for this energy the value of 15 cm in the case of lead. Thus the neutrino source should be surrounded by a lead sphere with this surface width.
In a recent work [17] its authors noted the possibility of using tungsten as a shielding material with an external layer of ultra pure copper. This suggestion can solve some problems with U and Th abundance in the shielding material and can also diminish the shielding thickness. For ^{65}Zn the shielding should be much thicker and this is one of the reasons why this nuclide, in spite of its more favorable neutrino energy, is less preferable than the ^{51}Cr or ^{55}Fe and ^{71}Ge sources discussed in our previous work [4].

(iii) The values of the rates in Table I for ^{51}Cr and ^{65}Zn include the branching ratios and the change of rates because of radioactive decay of nuclides during the measurement time.

The goal of the experiment is to scan the monoenergetic neutrino-electron scattering events by measuring the electron recoil counts as a function of the distance from the neutrino source, which has been prepared in advance at the appropriate reactor. This scan means point-by-point determination of scattering events along the detector dimensions within its position resolution.

In the best cases these events can be observed as a smooth curve, which reproduces the neutrino disappearance probability. It is worthwhile to note again that the oscillometry is suitable for monoenergetic neutrino, since it deals with a single oscillation length L_{31} or L_{41}. This is obviously not the case for antineutrino, since, in this instance, one extracts only an effective oscillation length. Thus some information may be lost due to the folding with the continuous neutrino energy spectrum.

We emphasize again that Table I clearly shows that the oscillation lengths for a new neutrino proposed in [1,2] are much smaller compared to those previously considered [9] in connection with θ_{13}. They can, thus, be directly measured within the dimensions of detector of reasonable sizes. One of the very promising options could be the STPC proposed in [3].

In this spherical chamber with a modest radius of a few meters the shielded neutrino source can be situated in the center of the sphere. The electron detector is also placed around the center of the smaller sphere with radius $r \approx 1$ m. The sphere volume out of the detector position is filled with a gas (a noble gas such as Ar or preferably Xe, which has a higher number of electrons). The recoil electrons are guided by the strong electrostatic field towards the Micromegas-detector [7,18]. A prototype with a diameter of 1.3 m is already operating at LSM (Laboratoire Souterrain de Modane). It has been tested up to a pressure of 5 bars. The actual detector, which is under development using KET, Kapton Etching Technology, has the advantage of precise position determination (better than 0.1 m), in the detection of very low energy electron recoils (down to a few hundreds of eV), with 4π geometry, well suited to the nuclides of Table I.

Assuming that we have a gas target under pressure P and temperature T_0, the number of electrons in STPC can be determined by formula:

$$n_e = Z\frac{P}{kT_0} = 4.4 \times 10^{27} m^{-3}\frac{P}{10\text{ Atm}}\frac{Z}{18}\frac{300}{T_0}, \qquad (13)$$

where Z is the atomic number, while P and T_0 stand for a gas pressure and temperature.

Since in the resolution of neutrino anomaly one can employ sources with quite high energy neutrinos of hundreds of keV, one expects large cross sections. Therefore a modest size source, so that it can easily fit inside the inner sphere of the detector, and a modest size Ar detector say of radius of 4 m and pressure of 10 bar can be adequate. We will thus employ these parameters in this calculation and assume a running time equal to the life time of the source. The result obtained for one of the candidates, nuclide ^{51}Cr, is shown in Fig. 1. This nuclide has previously been considered for oscillation measurements [1,2,4].

As can be seen from this figure the oscillometry curves are well disentangled for different values of mixing angle θ_{14}, which shows the feasibility of this method for identification of the new neutrino existence as such.

The sensitivity for determination of θ_{14} can be deduced also from the total number of events in the fiducial volume of detector. After integration of Eq. (11) over L from 0 to 4 m it can be written in the form:

$$N_0 = A + B\sin^2(2\theta_{14}), \qquad A = N_\nu n_e R_0 \sigma(0, x),$$
$$\frac{B}{A} = -\left[\frac{1}{2} - \frac{0.067}{R_0} x \sin\left(\frac{7.45 R_0}{x}\right)\right]. \qquad (14)$$

Thus for 55 days of measurements with ^{51}Cr we find: $A = 1.59 \times 10^4$ and $B = -7.56 \times 10^3$. Then the total number of events is 1.6×10^4.

Adopting these values we have determined the sensitivity of $\sin^2(2\theta_{14}) = 0.05$ within 99% of confidence level reachable after two months of data handling in the STPC. This value is good enough to access the validity of the existence of a new neutrino.

The results presented in Fig. 1 did not take into consideration the electron energy threshold of 0.1 keV, which is too small in comparison with the neutrino energy and the average electron recoil energy. This gives STPC a big advantage over the liquid scintillation detectors with a typical threshold of 200 keV or liquid Ar detectors with an even higher threshold. The advantage of a low energy threshold in experiments involving nuclear recoils [8] has been recognized, since, in this case, neither liquid scintillator nor liquid Ar can be employed for low neutrino energies. We neglected the Solar background of 2 counts per day derived from the measured Borexino results [19,20]. It is obvious that STPC should be installed in an underground laboratory surrounded with appropriate shield against rock radioactivity.

In conclusion, we propose to use the novel oscillometry method for direct observation of the recently proposed sterile neutrino. The calculations and the analysis involved show that neutrino oscillometry with the gaseous STPC is a powerful tool for identification of a new neutrino in neutrino-electron scattering. Since the expected mass difference for this neutrino is rather high, the corresponding oscillation length is going to be sufficiently small for a monochromatic neutrino source with energy of ≈ 1 MeV, so that it can be fitted into the dimensions of a spherical detector with the radius of a few meters. The neutrino oscillometry can be implemented in this detector with the use of the intense monochromatic neutrino sources, which

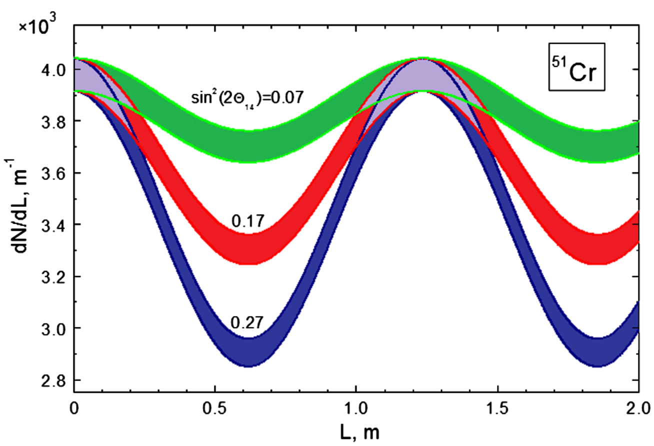

FIG. 1 (color online). Oscillation spectra with different values of $\sin^2(2\theta_{14}) = 0.07$, 0.17 and 0.27 on the corresponding curves with the statistical corridor of 1σ. The values on the y-axis are obtained for 55 days of measurement with a ^{51}Cr source and an Ar target under a pressure of 10 bar. In all cases we have included distances up to $1.5 \times L_{41}$. The pattern is repeated 2 times up to the radius of the sphere $R_0 = 4$ m.

can be placed at the origin of sphere and suitably shielded. The gaseous STPC with the Micromegas detection has a big advantage in the 4π geometry and in very good position resolution (better than 0.1 m) with a very low energy threshold ($\approx$ 100 eV). The most promising candidates for oscillometry have been considered. The sensitivity for one of them, e.g., ^{51}Cr, to the mixing angle θ_{14} is estimated as $\sin^2(2\theta_{14}) = 0.05$ with the 99% of confidence, which can be reached after only two months of data handling. This value can be pushed even further down by replacing the source many times, something that can be easily accomplished in a STPC. The observation of the point-by-point oscillometry curve suggested in this work will be a definite manifestation of the existence of a new type of neutrino, like the one recently proposed by the analysis of the low energy antineutrino anomaly.

Our analysis can be extended to apply in the case of two sterile neutrinos as suggested by the recent global analysis [21]. Instead of one mixing angle one has two, with the total strength essentially the same with the one employed here. The mass squared differences are a bit smaller, about 1 eV^2, i.e., the oscillation lengths will be longer. This, of course, may be accommodated by our set up, since even then the full oscillation can take place inside our detector (see Fig. 1). Anyway we are currently exploring this situation and we expect our proposal to resolve the issue of the number of sterile neutrinos, if the two square mass differences Δm^2_{42} and Δm^2_{52} are not nearly the same.

To summarize: The results of this work clearly show that oscillometry, i.e., the direct neutrino oscillation studies with a spherical TPC, is a very useful tool in exploring the challenging problem of the existence of new neutrinos beyond those of the standard model. It will also be complementary to other studies involving the large scale experiments, which are under way or planned.

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