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On the search for neutrino oscillations using an artificial neutrino source

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Abstract. In this paper the possibility of searching for neutrino oscillations with an artificial neutrino source is discussed and a comparison with reactor experiments is carried out.

1. Introduction

The hypothesis of neutrino oscillations was proposed by Pontecorvo in 1957 [1] and it allows one to explain the Solar neutrino problem. The full theory of the neutrino oscillation processes is available in many books; therefore, in the following we recall only the well known expression which describes the neutrino oscillation between two neutrino species:

$$P(\nu_i \to \nu_j) = \sin^2 2\theta \sin^2[1.27\Delta m^2 L/E_\nu] \qquad (1)$$

where $P(\nu_i \to \nu_j)$ is the probability of finding at a distance L, given in metres, an initial ν_i as ν_j; Δm^2 is the two neutrinos squared mass difference, given in eV^2, and E_ν is the ν_i energy, given in MeV.

Since this scenario has been proposed, much experimental effort has been carried out to search for this process, with various neutrino sources: at reactors, at accelerators and in cosmic rays. As is well known, the hypothesis of neutrino oscillations is at present the most credited solution for the solar neutrino problem [2], while some experimental indications for neutrino oscillations have been found for $\bar{\nu}_\mu \to \bar{\nu}_e$ in LSND [3] and for $\nu_\mu \to \nu_\tau$ in Kamiokande, in

SuperKamiokande, in MACRO, in IMB and in Soudan-2 [4]. We have to remark that these experiments are very difficult to carry out, especially when exploring marginal regions of the plane (Δm^2, $\sin^2 2\theta$). Here a search for oscillations is very interesting and confirmations from other independent experiments are very desirable.

In this paper—for a direct comparison—we will only consider the experiments on $\bar{\nu}_e$ disappearance performed at reactors. These kinds of experiments offer the possibility of investigating the $\bar{\nu}_e$ conversion into all neutrino species, including sterile neutrinos. Since the average reactor neutrino energy is about 4 MeV, a small Δm^2 can be investigated by this approach only when using the largest possible L distance (up to several kilometres at present).

We discuss here an alternative approach to investigate small Δm^2 by using neutrinos with as low an energy as possible; the effectiveness of this approach can be easily derived from equation (1). However, this has only become feasible recently when the creation of artificial neutrino sources with very large activities (of the order of a few MCi) has become realistic. We recall the ^{51}Cr neutrino sources with large activities which have been successfully produced and used for the calibration of the Ga radiochemical solar neutrino detectors: twice in the GALLEX [5] and once in the SAGE [6] experiments.

To exploit such a new possibility of using neutrinos with as low an energy as possible, an underground experimental site and a low background set-up of suitable mass and with low energy threshold are needed.

In the following, we will discuss the relevance of a search for neutrino oscillations by using an artificial neutrino source based on the ^{147}Pm isotope. The same isotope has been previously proposed with the aim of searching for a large neutrino magnetic moment [7] and some other processes [8]; in [7] details on the choice of source can be found.

2. The experimental approach

The principle of the experiment is similar to that of reactor experiments, but neutrinos from an artificial neutrino source (ANS) realized on the basis of the ^{147}Pm isotope are used instead of reactor neutrinos; this allows some limitations of the reactor experiments to be overcome. In fact, the neutrino flux from the ANS source can be at least ten times higher than that from a reactor (which typically offers a flux $\ll 10^{13}$ cm^{-2} s^{-1}) and can be known with an accuracy of 1% or better. Moreover, an underground laboratory and the environment with well reduced background also ensures the absence of continuous activation of the set-up materials by neutrons and cosmic rays present in a sea-level reactor experiment.

The ^{147}Pm isotope is an optimal candidate for an ANS both because of its physical parameters (low enough neutrino energy, absence of gamma rays, long enough lifetime) and the possibility to produce an ANS with sufficiently large radioactivity. The decay scheme of ^{147}Pm is presented in figure 1.

A relevant point in the realization of an ANS is the purity of the used material; in particular, the ^{147}Pm isotope has been produced with high purity by the Russian Nuclear Plant 'Mayak' since 1980 by using extraction from used reactor fuel and purification by a chromotographic technique. By this procedure the admixture of other radioactive rare earth elements (REEs) was less than 10^{-9} in the ^{147}Pm produced and it could be further lowered, if necessary. In [7] a 5 MCi source was considered as a first step; it can be produced by the same Russian Nuclear Plant 'Mayak' in 3–4 months after a small technological improvement. A source with higher radioactivity (up to 15 MCi) could still be achieved in a reasonable period of time.

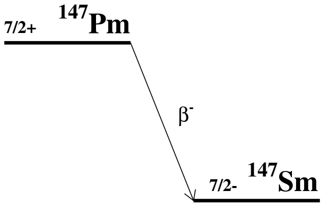

Figure 1. The decay scheme of ^{147}Pm.

Here we will discuss the possibility of using a large mass, low radioactive set-up (similar to the one considered in [7, 8]) in order to search for neutrino oscillations. The more important advantages of this approach are: (1) a source activity and, therefore, a neutrino flux known with high accuracy (0.3%) [9]; (2) a ^{147}Pm neutrino energy distribution which corresponds to an allowed and well known transition, assuring therefore a substantial reduction of the systematic errors.

As a target for the search of neutrino oscillations with ANS, we consider here an ultimate radiopure NaI(Tl) set-up taking into account the work already done by the DAMA collaboration to develop the $\simeq$100 kg NaI(Tl) DAMA set-up installed in the Gran Sasso National Laboratory of INFN [10–12] and the new developments in progress. The NaI(Tl) scintillation set-up is ideal for this kind of experiment since: (i) the exposed mass can be large enough with relatively low cost; (ii) a software threshold of about 2 keV can be effectively used; (iii) the methods of NaI(Tl) purification from main sources of background (U, Th and K) are well worked out and efforts are still in progress. The mass of the detector is at present $\simeq$100 kg and it is to be scaled up to 250 kg. Therefore, the feasibility of a set-up with mass scaled up to 1 t in the near future becomes realistic.

The ^{147}Pm neutrino source will be surrounded by a passive shielding of W (20 cm) and Cu (5 cm) to deal with the unavoidable admixture of ^{146}Pm ($\simeq 10^{-8}$), giving a 750 keV γ line, and other possible REE γ isotopes [7]. The heating of the source will be $\simeq$400 W/MCi and it is not expected to be a serious problem considering both the contact with the massive W/Cu shield and the possibility of realizing refrigeration system [7]. The possibility of decreasing the shielding could also be considered after careful measurements of γ admixture in commercial ^{147}Pm samples.

In the following section we will discuss the results achievable in a search for neutrino oscillations by means of this approach.

3. The expected results for the neutrino oscillation search

As is known well known, the only reaction due to standard electroweak theory which can be observed in the NaI(Tl) target at low neutrino energies available for the present study ($E_\nu(\max) = 240\,\mathrm{keV}$) is neutrino–electron scattering. To verify the effectiveness of the approach proposed here even at the first possible step of the experiment, the expected number of $(\bar{\nu}, \mathrm{e})$ reaction events has been calculated by considering a spherical form for a 5 MCi ^{147}Pm source (1.06 l of Pm_2O_3) and a 100 kg NaI(Tl) target homogeneously distributed around the shield of 25 cm. For a running time equal to the half-life of ^{147}Pm (2.6 year) the expected number of $(\bar{\nu}, \mathrm{e})$ events is thought to be 1.17×10^4, which ensures a statistical accuracy of better than 1%. The number of expected events has been calculated taking into account the scattering of $\bar{\nu}_\mu$

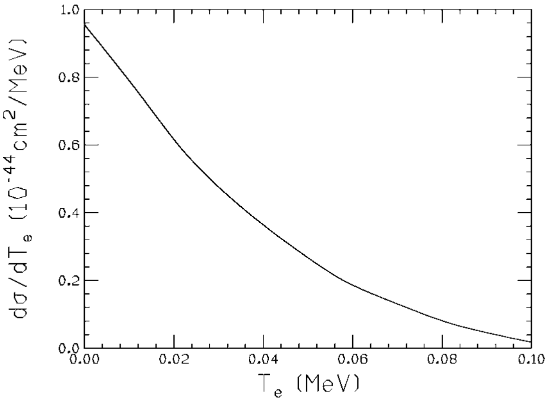

Figure 2. Differential cross section for the antineutrino–e$^-$ scattering integrated over the ^{147}Pm spectrum.

(produced as a result of oscillations) via neutral current. The cross section of $(\bar{\nu}_\mu, \mathrm{e})$ scattering is approximately 25% of $(\bar{\nu}_e, \mathrm{e})$ scattering in this energy region. The differential cross section is shown in figure 2; the shape of the energy distribution of the events is analogous since it is proportional to the differential cross section.

The data of [11] taken over several years of running time have shown a less than 1% stability in the energy region of interest here (2–100 keV). Assuming that a 2% lower counting rate will be obtained when comparing the measured rate with the expected one, the limit sensitivity for the oscillation parameters given in figure 3 (from [13]) will be obtained. Comparing the latter with the best reactor results [13], one can see that additional information will be obtained for the region $\Delta m^2 = 0.3$–1.0 eV^2; moreover, the reactor results will be significantly improved in the region $\Delta m^2 = 1$–10 eV^2, $\sin^2 2\theta = 0.025$–0.100 even at the current stage of the experiment. Neutrino oscillations in this region are foreseen by some theoretical models for the $(\nu_e \rightarrow \nu_\tau)$ channel of oscillations [14].

Considering a mass scaling up to 1 t of NaI(Tl) with further improvement of the background parameters, distances of the order of 1–3 m would be achievable with the same statistical accuracy depending on the source activity. In figure 3 the curves 2 and 3 show the limit sensitivities which can be obtained with a detector mass of 1 t and a source activity of 10 MCi at distances of 1.5 m and 3 m (statistical accuracy $\simeq$2% for the 3 m distance). The reactor results will be significantly improved in the region $\Delta m^2 = 0.04$–0.20 eV^2 and $\sin^2 2\theta = 0.025$–0.050; further improvements will also be present in the region $\Delta m^2 = 0.02$–0.04 eV^2 and $\sin^2 2\theta = 0.05$–0.10.

Extending our consideration to future possibilities of a set-up with a mass of $\simeq$10 t with ultralow background specifications (as to search for various rare event processes is now considered a future step) distances of up to 30 m can be considered in the search for neutrino oscillations with ANS; the results will be obtained by comparing the counting rates measured at different distances. In particular, in the case of an exposed mass of 10 t of radiopure NaI(Tl) and of a source activity of 15 MCi a different strategy can be pursued; see figure 4. In fact, a distance of 6 m (curve 1) gives the possibility of obtaining high statistical accuracy and investigating the region of $\sin^2 2\theta = 0.025$–0.080 and $\Delta m^2 = 0.01$–0.08 eV^2, while larger distances of 12–24 m (curves 2 and 3) can offer the possibility of investigating the region $\Delta m^2 = 0.002$–0.080 eV^2. Moreover, as can be seen from figure 4, a new wide region $\Delta m^2 = 0.002$–0.080 eV^2 and $\sin^2 2\theta = 0.025$–0.100 can be investigated in addition to those already explored by reactor experiments.

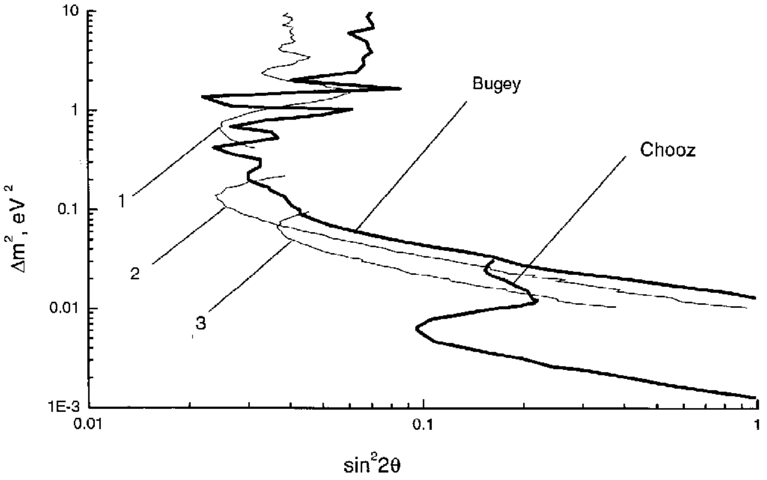

Figure 3. Expected limit sensitivity at 1 σ confidence level for the oscillation parameters when assuming a 2% lower measured counting rate with respect to the expected one. The contour number 1 corresponds to the case of an ANS activity of 5 MCi, a detector mass of 100 kg and a distance of 0.25 m; the contour number 2 corresponds to an ANS activity of 10 MCi, a detector mass of 1 t and a distance of 1.5 m; the contour number 3 corresponds to an ANS activity of 10 MCi, a detector mass of 1 t and a distance of 3 m.

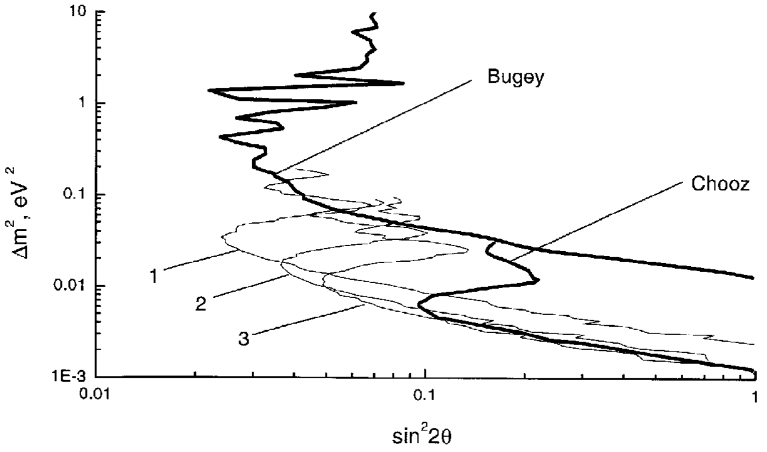

Figure 4. Expected limit sensitivities at 1 σ confidence level for the oscillation parameters with an ANS activity of 15 MCi, a detector mass of 10 t and a distance of (1) 6 m, (2) 12 m and (3) 24 m, respectively.

4. Background

The estimates quoted in the previous paragraph have been obtained by assuming–as is usual to give the reference point—no background contribution. Obviously this is an ideal condition and, therefore, in the following we will briefly comment on how to deal with background limitations.

The required background level in real conditions is determined by the fact that the statistical fluctuation of the number of events due to the background plus the number of events estimated from the standard electroweak model should be less than the expected effect. Considering the discussion carried out in the previous section, we can conclude that the background should be less than the effect expected in the standard model; therefore, the background rate due to residual radioactive contaminants should be less than 10^{-3} counts/day/kg. It is clear that the background requirements for this measurement are more stringent than for example, the ones satisfied at present by the NaI(Tl) set-up of [10]. However, the quantitative investigations of [10] on the radiopurity of the NaI(Tl) detectors and two independent analyses of the whole experimental energy spectra show that in the energy region of interest the residual internal standard contaminants (^{238}U, ^{232}Th and ^{40}K) should give rise to a counting rate much lower than the measured values, which points out the role of the nearby materials.

As discussed in [8], the lower background levels of interest here can be obtained by: (1) carefully selecting, with low background germanium detector deep underground, all the materials required to build the detectors; (2) further sorting the selected materials by using highly sensitive mass spectrometers and/or neutron activation procedures, paying attention to the more important non-standard contaminants (see [10]); (3) chemically purifying (in several purification cycles) the selected powders, by using specific additives for every radioactive element; (4) growing and assembling the detectors deep underground in a high-quality clean room under control of the proper operating conditions by experimentalists. This strategy will also minimize the casual pollution which can occur in an industrial environment and the material activation at sea-level.

Obviously the same care should be taken to avoid any casual pollution of the detectors during handling and the detectors and the nearby materials should never be exposed to the neutron source. As regards the background arising from surviving cosmic rays deep underground, the expected muon cosmic-ray intensity is $\simeq 1 \ \mathrm{h}^{-1} \ \mathrm{m}^{-2}$ which is small enough for the background requirements; in addition, it could be further decreased (even by four to five orders of magnitude) by introducing, if necessary, a suitable anti-coincidence system.

Other question closely connected with the background is the optimal choice of the detection energy region; in fact, the spectrum of recoil electrons (figure 2) drops steeply with increasing energy. The 2–30 keV energy interval gives the best results since it can offer a statistical accuracy only 10% lower than the full recoil electron energy range (0–100 keV), but the allowed background level can be three times higher. On the other hand, a suitable increase of the energy threshold will ensure the rejection of contributions from possible side processes (such as, e.g., WIMP–nucleus scatterings).

5. Conclusion

We have discussed here the competitiveness of an experiment searching for neutrino oscillations deep underground by using a ^{147}Pm artificial neutrino source and a very massive highly radiopure NaI(Tl) set-up.

With this approach a new large region of oscillation parameters—with respect to the regions explorable at reactors– can be investigated, depending on the source activity and on the target mass.

Further work to improve the background parameters of the present generation NaI(Tl) set-up is already in progress.

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