How can effects masking possible neutrino oscillations be minimized?

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(Submitted 4 October 1988)
Pis'ma Zh. Eksp. Teor Fiz. **48**, No. 9, 477–479 (10 November 1988)

The influence of factors which hinder observation of neutrino oscillations in the experiments which have been carried out is discussed. An underground low-background radiochemical experiment with a source of monoenergetic neutrinos (K capture) is proposed. This approach would eliminate the disruption of the coherence of a neutrino beam caused by the continuous nature of the neutrino spectrum. Other factors masking an oscillation effect would also be minimized.

Observation of the neutrino oscillations discussed by Pontecorvo[1,2] would be of fundamental importance for reaching an understanding of the nature of these particles and would be unambiguous evidence that they have a rest mass. It is accordingly important to understand whether the lack of success in searches for oscillations in reactor and accelerator experiments is a consequence of a disruption of the conditions which would be required for an observation of the effect (and which were pointed out in Refs. 1 and 2). In particular, the following inequalities must hold:

$$R \gtrsim L > d, \tag{1}$$

where R, L, and d are the baseline, the length of the oscillations, and the sum of the sizes of the sources (d_1) and the detector (d_2).

In the simplified case with two types of neutrinos, which is the case usually discussed, the oscillation length is given in meters by

$$L = 2.47\, E_\nu / \Delta m^2 , \tag{2}$$

where E_ν is the neutrino energy, in MeV, and $\Delta m^2 = m_1^2 - m_2^2$ is the difference between the square masses, in eV^2, of neutrinos ν_1 and ν_2. A superposition of these neutrinos with weights determined by the mixing angle θ gives the neutrinos an observable flavor (ν_e, ν_μ, ν_τ).

The condition $R \gtrsim L$ follows from the expressions for the probability for observing neutrinos of a certain type e.g., ν_μ, at a distance R from a source in which neutrinos of another type, e.g., ν_e, are produced:

$$W_{\nu_\mu \nu_e}(R) = \sin^2 2\theta \sin^2 \frac{1.27\, \Delta m^2 R}{E_\nu} = \sin^2 \frac{\pi R}{L} . \tag{3}$$

The corresponding expression for the case in which the neutrinos produced in the sources are of the same type is

$$W_{\nu_\mu \nu_\mu}(R) = 1 - \sin^2 2\theta \sin^2 \frac{1{,}27 \Delta m^2 R}{L} . \quad (4)$$

This inequality, however, must be refined. If the ratio R/L is small and approximately equal to an integer $n = 0, 1, 2, 3, \ldots$, the oscillations would evidently be unobservable. If R/L is approximately a half-integer $n = 1/2, 3/2, 5/2, \ldots$, the oscillations would be observable, but the $R/L = 1/2$ the condition $R \gtrsim L$ would be violated.

The condition $d < L$ follows from the requirement that the neutrino beam be coherent.

Coherence is also disrupted because of the continuous nature of the energy spectrum of the neutrinos which have been used in all previous experiments carried out to search for oscillations.

These requirements loom particularly large if nature has assigned a small value to the mixing angle for the eigenvalues ν_1 and ν_2 of a given pair of types of neutrinos.

A unique possibility for completely eliminating that disruption of coherence which stems from the continuous nature of the spectrum of neutrinos and for minimizing the violation of the requirements which follow from conditions (1) would be presented by an intense radioactive source whose nuclei emit monoenergetic neutrinos as they undergo K capture in an underground laboratory. The source with the most appropriate decay half-life is $^{65}Zn(T_{1/2} = 245$ days), which can be produced in the reaction $n + {}^{64}Zn \rightarrow {}^{65}Zn$ by bombarding the isotope ^{64}Zn (preferably enriched from 49% to 90%) in the core of a modern research reactor with a neutron flux density of $(3\text{–}4) \times 10^{15}\ cm^{-2} \cdot s^{-1}$. A ^{65}Zn source emits neutrinos with an energy of 1.35 MeV; the activity at saturation for a sample with a mass of 7 kg could be close to a megacurie. The most favorable reaction for detection is $\nu_e + {}^7Li \rightarrow {}^7Be + e^-$, for which the cross section is $\sigma = 4.9 \times 10^{-44}\ cm^2$, and the threshold is 0.86 MeV. After several metric tons of metallic lithium are bombarded, the ^7Be atoms (K capture, $T_{1/2} = 53$ days) can be extracted from the dissolved lithium target by known radiochemical methods (by adding small amounts of a carrier) and can be put in low-background proportional counter. Under the assumption that the distance from a one-metric-ton lithium target to a ^{65}Zn source with an activity of 1 MCi is 1 m, we would expect the count rate of ^7Be K-capture events (Auger electrons) to be on the order of 100 counts/day.

At the count rates expected, none of the sources of background which were important in Davis's radiochemical experiment, where the count rate per metric ton of C_2Cl_4 was 0.0026 count/day, would play a role here. The primary source of background would be solar neutrinos (if indeed solar neutrinos are what is detected in the Davis apparatus): The background expected from solar neutrinos is 0.3 count/day per metric ton in a lithium detector (in the calculation of this background, the neutrinos from all reactions at the sun were taken into account). The background of the counter can be lowered by using extremely selective methods of laser ionization spectroscopy in combination with a position-sensitive counter.

The solid line in Fig. 1 shows a calculated curve in the $\sin^2 2\theta$, Δm^2 plane which separates the forbidden region (at the right) from the allowed region under the as-

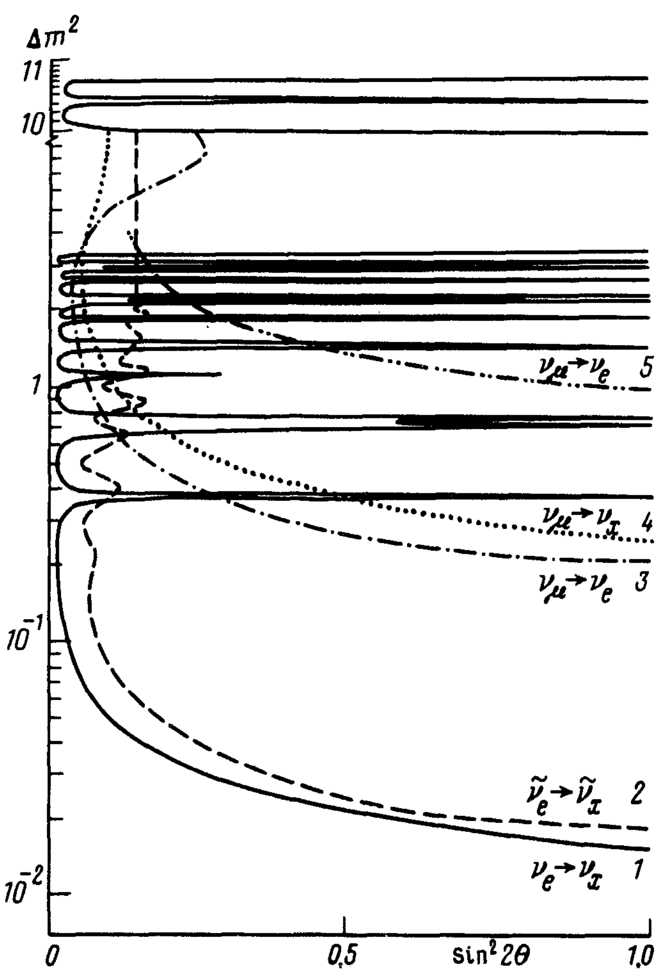

FIG. 1. Comparison of curves which bound the forbidden regions (at the right) in the Δm^2, $\sin^2 2\theta$ parameter plane in various experiments. 1—Proposed experiment; 2—Ref. 3; 3—Ref. 4; 4—Ref. 5; 5—Ref. 6.

sumption that the ratio of the numbers of events detected in two thin detectors (with a thickness of 0.1–0.15 m) of spherical shape, positioned 2 and 7 m from the center of a spherical source (0.1 m in diameter), i.e., at a baseline of 5 m, would differ from unity by less than 0.5%. The narrow dips seen on this curve stem from the monoenergetic nature of the neutrino spectrum. The curve spans the region of small mixing angles ($\sin^2 2\theta = 0.01$).

Using inequality (1), we see that the actual sensitivity region of this method is $0.7 < \Delta m^2 < 20$ eV^2. Since the neutrinos are monoenergetic, this region is fairly definite. A comparison of these numbers with the data in Fig. 1 shows that low values of the quantity Δm^2 at large mixing angles, shown on curve 1, lie far outside the sensitivity region. The same conclusion applies to all other curves in this figure. For example, for the best curve (with the smallest value of the parameter Δm^2), obtained at a reactor in Gesgen[3] (curve 2), with $R=64.7$ m, $d=d_1+d_2=4$ m, and $E_\nu=3.5$ MeV, the sensitive interval is $0.13<\Delta m^2<2.2$ eV^2. For experiments carried out on the CERN proton synchrotron, the corresponding limits are $10<\Delta m^2<140$ eV^2 in the case of the CDHSW group[4] ($R=755$ m, $d=52$ m, $E_\nu=3\times 10^3$ MeV) (cf. curve 3) and $4.2<\Delta m^2<78$ eV^2 in case of the CHARM group[5] ($R=890$ m, $d=48$ m, $E_\nu=1.5\times 10^3$ MeV) (cf. curve 4).

We recall that in all of the studies which have been carried out the pattern of oscillations must have been smeared by the continuous nature of the spectrum, and it would have been considerably more difficult to detect an effect in each part of the spectrum than in the case of a monoenergetic neutrino beam.

I wish to thank Ya. I. Azimov, L.A. Mikaélyan, and L. B. Okun' for reading the manuscript and for useful comments.

[1]B. M. Pontecorvo, Zh. Eksp. Teor. Fiz. **53**, 1717 (1967) [Sov. Phys. JETP **26**, 984 (1967)]; Zh. Eksp. Teor. Fiz. **33**, 549 (1957) [Sov. Phys. JETP **6**, 429 (1958)]; Zh. Eksp. Teor. Fiz. **34**, 247 (1958) [Sov. Phys. JETP **6**, 429 (1958)].
[2]S. M. Bilen'kiĭ and B. M. Pontecorvo, Usp. Fiz. Nauk **123**, 181 (1977) [Sov. Phys. Usp. **20**, 776 (1977)].
[3]V. Zacek *et al.*, Phys. Lett. **164B**, 193 (1985).
[4]F. Bergsma *et al.*, Phys. Lett. **142B**, 103 (1984).
[5]F. Dydak *et al.*, Phys. Lett. **134B**, 281 (1984).
[6]P. Nemethy *et al.*, Phys. Lett. **D23**, 262 (1981).

Translated by Dave Parsons