Reactor experiments of a new type to detect neutrino oscillations

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(Submitted 27 March 1992)
Pis'ma Zh. Eksp. Teor. Fiz. **55**, No. 10, 544–547 (25 May 1992)

A search for $\tilde{\nu}_e$ oscillations has been carried out with two detectors of the reaction $\tilde{\nu}_e + p \rightarrow n + e^+$, at distances of 12.15 and 18.34 m from a reactor of the Rovno nuclear power plant. The detectors were of the same type and operated simulataneously. This experimental approach eliminates the errors in the data on the reactor characteristics (its power and the isotopic composition of the fission fuel). The results lend further support to the conclusion that there are no $\tilde{\nu}_e$ oscillations.

A fission reactor is an intense source of electron antineutrinos $\tilde{\nu}_e$, with energies $E_{\tilde{\nu}_e}$ up to 10 MeV. These antineutrinos are produced in β decays of the fission fragments of the four major components of the nuclear fuel: ^{235}U, ^{239}Pu, ^{238}U, and ^{241}Pu. The hypothesized mixing of massive neutrinos has stimulated experiments to search for $\tilde{\nu}_e$ oscillations at reactors.[1–4] The $\tilde{\nu}_e - \tilde{\nu}_x$ oscillations might be manifested in a deformation of the spectrum and a change in the $\tilde{\nu}_e$ flux at distances R from the reactor comparable to the oscillation length $L(M) = 2.5E_\nu/\Delta m^2$, where Δm^2 is the difference between the squared masses of the neutrinos, expressed in units of eV^2, and E_ν is in MeV.

In particular, several studies have taken the approach of measuring the count rates ($N_{\tilde{\nu}_e}$) of events of the inverse β decay

$$\tilde{\nu}_e + p \rightarrow n + e^+ \tag{1}$$

by a detector at two fixed distances from the reactor. The results have then been compared. If there are no $\tilde{\nu}_e$ oscillations, the detector count rate in each measurement can be written as follows:[5]

$$N_{\tilde{\nu}_e} = \frac{W}{4\pi \bar{R}^2} \frac{(\Sigma \alpha_i \sigma_i)}{(\Sigma \alpha_i E_i)} (\epsilon N_p), \tag{2}$$

where W is the thermal power of the reactor; R^2 is the mean square distance from the center of the reactor to the detector; α_i are the relative contributions of the isotopes ^{235}U, ^{238}U, ^{239}Pu, and ^{241}Pu to the total number of fission events (these figures vary over the operating run of the reactor, as the nuclear fuel is burned); σ_i are the cross sections for reaction (1) per fission, averaged over the spectra of the antineutrinos emitted during the fission of the specified isotopes;[5] E_i are the average energies evolved during the fission of the isotopes; and ϵN_p is the product of the efficiency with which events of reaction (1) are detected by a detector and the number of hydrogen atoms in the target.

When the $\tilde{\nu}_e$ count rates at the two distances are compared, it is thus necessary to correct for the changes that occur in W and $(\Sigma\alpha_i E_i)$ in each experiment, and the related errors, in addition to dealing with the geometric factor. In measurements taken at comparatively short distances from a reactor by the high-luminosity detectors of reaction (1) which have recently been developed,[4–6] the number of events is extremely high, reaching tens of thousands over a few months of measurements. Consequently, the primary sources of error are the uncertainties in the reactor power and the isotopic composition of the nuclear fuel. For example, the error associated with the reactor characteristics in Ref. 3 was 2.2% and was the predominant component of the systematic measurement error.

In an effort to improve the accuracy of experiments to search for $\tilde{\nu}_e$ oscillations, we have proposed a new formulation of the experiment, which completely eliminates all errors associated with the working characteristics of the reactor. For this purpose, the $\tilde{\nu}_e$'s are detected by two detectors of identical construction which operate simulataneously. Since the measurements by the two detectors are carried out simultaneously, in the same $\tilde{\nu}_e$ flux, the ratio of the count rates of these detectors, which contains information on the oscillations, is essentially independent of the characteristics of the reactor itself. (All that is left to do is correct for the spatial distribution of the energy evolution over the reactor core, which is 0.7% in our case and is incorporated with an error of 0.2%.)

To detect the $\tilde{\nu}_e$'s, we selected the VIND integral detector,[6] designed for precise measurements of the cross section for reaction (1). The detector was placed in an underground neutrino laboratory at a distance of 18.34 m from the center of the VVÉR-440 reactor of the Rovno nuclear power plant. A scaled-down copy of the VIND detector was placed in a technological room of the reactor, at a distance of 12.15 m from its center[7] (Fig. 1). A consideration in the choice of these distances was that indications of an oscillation effect had been seen previously at these distances, as reported in Ref. 8. Later, after our own study had begun, those other authors revised their results.[3]

The detectors are described in detail in Ref. 9. Distilled water doubles as the target for the antineutrinos and as the moderator for the neutrons produced in reaction (1). Some ^{3}He neutron counters about 1 m long are placed in the water, in a square matrix with a step of 70 mm. In the VIND detector, at 18 m, the matrix consists of 16×16 counters, while in the smaller detector it consists of 12×12 counters. The neutrons are detected only in the central counters; the outer layer of counters is used to compensate for the leakage of neutrons produced in reaction (1) and to fix the working volume of the detector. The useful events are selected on the basis of an amplitude corresponding to the peak representing total absorption of the products of the reaction $n+{}^3\mathrm{He}\rightarrow{}^3\mathrm{He}+p$ and also on the basis of the multiplicity of neutron events in a time window $T=400\,\mu\mathrm{s}$ (only single events—events not accompanied by pulses over the time T—are analyzed; events with a multiplicity of 2 or more are detected to monitor the stability of the detectors). Anticoincidence shielding reduces the cosmic-ray neutron background.

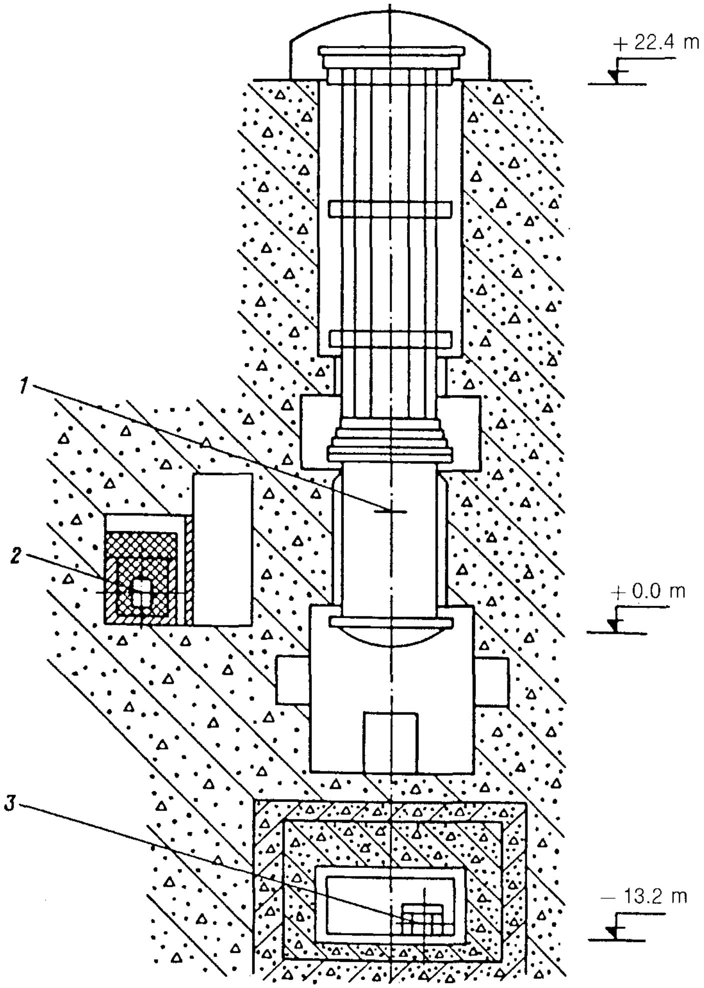

FIG. 1. 1—Center of the core of the VVÉR-440 reactor; 2—the small integral detector (12×12 counters); 3—the VIND detector (16×16 counters).

To interpret the results of the measurements, we introduce a reduced ratio of the intensities detected by the detectors, corrected for the geometry and the characteristics of the detectors:

$$I(R_1/R_2)=\frac{(N_{\bar{\nu}})_1}{(N_{\bar{\nu}})_2}\frac{R_1^2}{R_2^2}\frac{(\epsilon N_p)_2}{(\epsilon N_p)_1}. \qquad (3)$$

In the absence of oscillations, this ratio should be one. The subscripts 1 and 2 in (3) refer to the distances of 12.15 and 18.34 m, respectively.

To measure the relative characteristics of the detectors, $(\epsilon N_p)_1/(\epsilon N_p)_2$, in (3),

TABLE I.

$\frac{(N_{\bar{\nu}})_1}{(N_{\bar{\nu}})_2}$	$\frac{(R^2)_1}{(R^2)_2}$	$\frac{(\epsilon N_p)_1}{(\epsilon N_p)_2}$
$\frac{1338 \text{ events over } 10^5 \text{ s}}{1161 \text{ events over } 10^5 \text{ s}} \pm 2.1\%$	$\frac{(12.15)^2}{(18.34)^2} \pm 1.0\%$	$0.518 \pm 0.5\%$

we carried out some special control experiments with a Pu-Li source of low-energy neutrons ($\epsilon_n \simeq 200$ keV). For each detector we studied the spatial variation of the neutron count rate from the Pu-Li source. We calculated a ratio $(\epsilon N_p)_1/(\epsilon N_p)_2 = 0.518 \pm 0.5\%$.

The Rovno measurements were carried out in the standard way: while the reactor was shut down for refueling (these were background measurements) and while it was operating at 100% power. The count rates of background events in the detectors while the reactor was shut down were 2101 events over 10^5 s (12 m) and 2931 events over 10^5 s (18 m).

Table I shows data from the measurements of the neutrino effect, along with the relative characteristics of the detectors. In calculating the geometric factor we incorporated the distribution of the energy evolution over the volume of the reactor core and the circumstance that the detectors are not point detectors.

The error due to instability in the operation of the detectors was found from an analysis of the experimental data and of control counts; the error was no worse than 1%.

The measured ratio of the rates of $\tilde{\nu}_e$ interactions turned out to be

$$I(12.15/18.34) = 0.976 \pm 0.020(\text{stat}) \pm 0.015(\text{syst}).$$

Thus no $\tilde{\nu}_e$ oscillation effect was found.

This result agrees with the data from recent measurements at a reactor in Byuzhe,[3]

$$I(13.6/18.3) = 1.007 \pm 0.021(\text{stat}) \pm 0.021(\text{syst}),$$

and it finally resolves the question of whether neutrino oscillations are observed at these distances from a reactor.

We wish to thank our colleagues in the laboratory and the staff at the Rovno nuclear power plant for assistance in the experiments.

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Translated by D. Parsons