Reactor neutrino experiments

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Neutrino experiments in powerful nuclear reactors are described and the characteristics of the neutrino radiation of fission fragments and the experiments made in recent years by the group of Reines, including study of the inverse β decay of the proton and the deuteron, searches for neutral currents, and $\tilde{\nu}_e e^-$ scattering, are considered. Planned experiments and the possibility of practical use of neutrinos for diagnosis of intrareactor processes are discussed.

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INTRODUCTION

The first sources of neutrinos were naturally radioactive substances. Thus, in 1935 Nahmias investigated the ionization power of $\tilde{\nu}_e$ by means of a source containing 5 g of radium and obtained the upper bound $\sigma \leq 10^{-31}$ cm^2/electron on the cross section for interaction of this particle with matter.[1]

The development of nuclear reactors made it possible to use the incomparably stronger fluxes of electron antineutrinos emitted during the β decay of fission fragments. In the period 1953–1960, Reines and Cowan[2-5] observed for the first time neutrino–matter interaction near a powerful reactor, after which Pauli's hypothetical particle acquired the right to be called a "true" particle. The difficulty of setting up reactor neutrino experiments is very great. This explains why hitherto only Reines' group has made a series of such experiments. They studied inverse β decay,[6,7] scattering of antineutrinos by electrons,[8,9] and neutral currents.[10]

From 1962, neutrino investigations were made with high-energy accelerators, which are basically sources of muon neutrinos. These experiments were associated with very important discoveries in the physics of weak interactions, including the proof of a difference between electron and muon neutrinos,[11] the discovery of neutral currents,[12] etc. In recent years, neutrino experiments have been prepared in high-current proton accelerators (meson factories) with proton energy up to 1 GeV. It is proposed to use stopped μ^+ as a source of ν_e with energy up to 53 MeV. The energy of the muon neutrinos is below the threshold of muon production, and the branch $\pi^- \rightarrow \mu^- \rightarrow \tilde{\nu}_e$ is suppressed by capture of the negative particles in a thick target.[13] The mean energy of the ν_e spectrum for the meson factories is ten times higher than the energy of the $\tilde{\nu}_e$ emitted by fission fragments in nuclear reactors. This is important, since the cross section of neutrino–matter interaction increases rapidly with the ν_e energy, and the intensity of the background radiations falls with increasing detection energy threshold. On the other hand, the flux of reactor $\tilde{\nu}_e$ at the detector position exceeds the design intensity of the neutrino flux in meson factories by a factor 10^5–10^6.

The successes of experimental neutrino physics are based on the development of new methods of detection and the creation of unique detectors. A good example is provided by the investigation of natural neutrino sources: Davis' experiments to observe solar neutrinos, the detection of neutrinos from cosmic rays, etc.

Considering the prospects of reactor neutrino investigations, it must be said that the purposeful development of atomic technology and the methods of detection make it possible to plan new experiments (for example, experiments to study neutrino oscillations[14,15]) as well as exact quantitative estimates of already measured ν_e interaction cross sections (see Ref. 16 and below). Consideration has been given[17] to the practical use of neutrinos associated with the atomic fuel cycle and problems of international guarantees.

In the present review, we shall consider reactors as $\tilde{\nu}_e$ sources and the specific features of neutrino experiments using modern powerful facilities. We shall briefly characterize the background sources and the methods for dealing with them. We analyze the latest completed experiments and some planned experiments and describe neutrino detectors. We consider possible ways of developing the neutrino diagnostics of intrareactor processes.

1. CHARACTERISTICS OF THE ANTINEUTRINO RADIATION OF FISSION FRAGMENTS

Intensity of the $\tilde{\nu}_e$ flux from a reactor. After the emission of prompt neutrons and γ rays, the majority of fission fragments are still overenriched with neutrons and are far from the region of β-stable nuclei. The mean number of β^- decays undergone by both ^{235}U fission fragments is $\bar{n} \approx 6$ according to the data of various authors.[1)] Thus, the total antineutrino flux $\Phi(\nu_e/$sec) produced in the core of the reactor is more than twice the neutron flux. At a thermal power of the facility equal to W MW,

$$\Phi = \bar{n}\,(W/\bar{E})\,10^6\ \tilde{\nu}/ \approx 1.85 \cdot 10^{17} W\ \tilde{\nu}/\mathrm{sec}\,, \tag{1}$$

where $\bar{E}$ is the mean energy released in a ^{235}U fission event. For modern industrial reactors, W excees 10^3 MW, and the antineutrino flux f at 10–15 m from the center of the core is about $10^{13} \tilde{\nu}/(\mathrm{cm}^2 \cdot \mathrm{sec})$. The dependence of f on the distance to the center of the core for two power-station reactors, VVÉR-440 and VVÉR-1000, with thermal powers of 1300 and 3000 MW, is shown in Fig. 1.

[1)] $\bar{n} = 6.9 \pm 0.4$ (Ref. 18), $\bar{n} = 5.9 \pm 0.2$ (Ref. 19), $\bar{n} = 5.8 \pm 0.3$ (Ref. 20), $\bar{n} = 6.0 \pm 0.1$ (Ref. 21) [for ^{239}Pu, we take $\bar{n} = 5.2 \pm 0.5$ (Ref. 23)].

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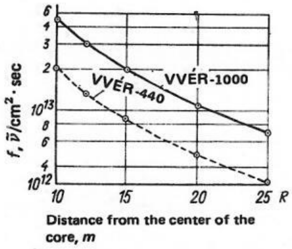

FIG. 1. Antineutrino flux from power-station reactors.

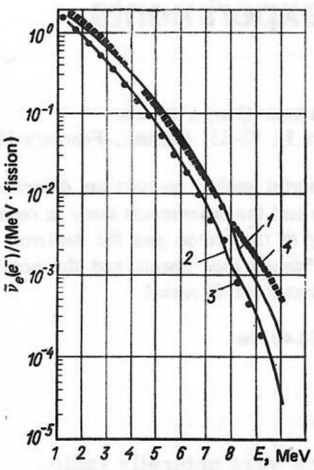

FIG. 2. Calculated energy spectra of antineutrinos and electrons from fragments of ^{235}U fission induced by thermal neutrons.

Energy spectra of antineutrinos from fission fragments. It is impossible to interpret reactor neutrino experiments without knowledge of the energy spectrum of the ν_e emitted by the fission fragments. The accuracy with which this spectrum must be determined increases on the transition from qualitative experiments to the elucidation of the quantitative relationships that are important for choosing between different variants of the theory of the weak interaction.

We begin our discussion of ways of finding the antineutrino spectrum with the computational method employed in Refs. 21–23. In them, it is assumed that the fission products are in a state of secular equilibrium, and the antineutrino spectra from individual fragments are summed. The contribution of isotope j with given Z and A is determined by its cumulative yield $Y_j(Z,A)$, i.e., the probability of production of the given isotope both directly in the fission process and through the β decay of other fragments. Thus, the number of antineutrinos emitted in the energy range from $E_{\tilde{\nu}}$ to $E_{\tilde{\nu}} + dE_{\tilde{\nu}}$ per fission event is determined by

$$dN(E_{\tilde{\nu}}) = \sum_{j,k} Y_j(Z, A)\, b_{jK} P_{Kj}(E_{\tilde{\nu}})\, dE_{\tilde{\nu}}, \qquad (2)$$

where b_jK is the probability of decay of isotope j through the K branch, and $P_{Kj}(E_{\tilde{\nu}})$ is a spectral factor that takes into account the Coulomb correction (the transitions are assumed to be allowed). The cumulative yield of each isotope was calculated by summing the probabilities of the independent yields[2)] $P(Z)$ of the isotope itself as well as of the parent isotopes and multiplying this sum by the total yield $Y(A)$ of fragments with mass number A. The sum of the probabilities of all independent yields with given A is normalized to unity, and $\Sigma Y(A)$ is taken equal to 2. According to modern ideas, the $P(Z)$ values are distributed on a Gaussian curve about the most probable charge value Z_p, so that

$$P(Z) = \exp[-(Z-Z_p)^2/c]/\sqrt{c\pi}, \qquad (3)$$

where the parameter c is related to the standard deviation σ of the distribution by $c = 2(\sigma^2 + 1/12)$.

In Ref. 21[3)] the sum (2) included 548 β^--unstable nuclei, among which there were 260 nuclei with studied decay schemes. For the remainder, depending on the parity of the parent and daughter nuclei, one of four schemes obtained by averaging known data was used. The value of c was taken to be 0.84 for all values of A.

[2)]The independent yield is the probability of production of the given isotope directly in the fission process.

[3)]This is a refinement of the earlier work of Ref. 22.

In Ref. 21, the antineutrino spectrum from ^{235}U fission fragments is given in the energy range from 0 to 10 MeV at every 0.5 MeV. According to the estimates of Avignone,[21] the error for each of the points of the spectrum does not exceed 10% (Fig. 2 and Table I).

From the latest data, in particular from numerous investigations that have considered the different dependences of Z_p and c on A (see, for example, the reviews of Ref. 24), it appeared interesting to repeat calculations of the antineutrino spectrum and also, using this method, to calculate the electron spectrum in order to make a comparison of it with the experimental spectrum.[25] This was done in Ref. 23. For each value of A, individual values of c were chosen. Data on decay schemes were taken from journals published up to June 1975.

When experimental data on the decay scheme were not available, use was made of one of three schemes obtained by averaging the transition probabilities and the energies of the excited levels in the investigated nuclei. These schemes differed from the ones adopted in Ref. 21. The results of the calculations of Ref. 21 (curve 4), the antineutrino (curve 1) and electron (curve 2) spectra obtained in Ref. 23, and the experimental electron spectrum (curve 3) are shown in Fig. 2. The latter agrees well with the calculated spectrum. The antineutrino spectra calculated in Refs. 21 and 23 are very similar up to 8 MeV. At higher $E_{\tilde{\nu}}$, a discrepancy is observed, this increasing with the energy. This is due to a number of factors, including the use of different decay schemes for uninvestigated nuclei, differences in the calculations of $P(Z)$, etc. However, the

TABLE I.

Energy $E_{\tilde{\nu}}$, MeV	Number of antineutrinos (MeV · fission)$^{-1}$* ^{235}U (Ref. 21)	^{235}U (Ref. 23)	^{239}Pu (Ref. 23)	Energy $E_{\tilde{\nu}}$, MeV	Number of antineutrinos (MeV · fission)$^{-1}$* ^{235}U (Ref. 21)	^{235}U (Ref. 23)	^{239}Pu (Ref. 23)
0.5	2.58 (0)	–	–	5.5	7.31 (–2)	7.93 (–2)	5.26 (–2)
1	2.18 (0)	–	–	6	4.47 (–2)	4.89 (–2)	3.01 (–2)
1.5	1.67 (0)	1.60 (0)	1.41 (0)	6.5	2.74 (–2)	3.03 (–2)	1.75 (–2)
2	1.35 (0)	1.26 (0)	1.09 (0)	7	1.55 (–2)	1.74 (–2)	9.87 (–3)
2.5	9.63 (–1)	8.82 (–1)	7.63 (–1)	7.5	8.75 (–3)	9.51 (–3)	5.04 (–3)
3	6.82 (–1)	6.61 (–1)	5.66 (–1)	8	4.77 (–3)	4.35 (–3)	2.07 (–3)
3.5	4.65 (–1)	4.65 (–1)	3.80 (–1)	8.5	2.70 (–3)	1.65 (–3)	7.66 (–4)
4	3.06 (–1)	3.22 (–1)	2.52 (–1)	9	1.73 (–3)	8.23 (–4)	3.98 (–4)
4.5	1.94 (–1)	2.04 (–1)	1.48 (–1)	9.5	1.01 (–3)	4.35 (–4)	2.16 (–4)
5	1.17 (–1)	1.30 (–1)	8.97 (–2)	10	5.00 (–4)	1.61 (–4)	8.17 (–5)

*The power of 10 is indicated in the brackets.

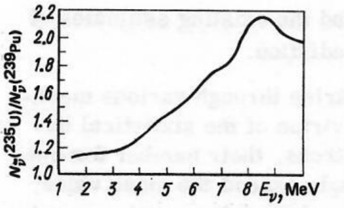

FIG. 3. Calculated ratio of the number of antineutrinos emitted by the fragments from the fission of ^{235}U and ^{239}Pu induced by thermal neutrons as a function of the antineutrino energy.

discrepancy between the spectra does not lead to appreciable differences in the cross sections of neutrino reactions, since the absolute intensity of hard neutrinos is low.[4)]

In Ref. 23, attention was first drawn to the fact that as a result of accumulation in the reactor core of ^{239}Pu the energy spectrum of the obtained antineutrinos may change with the time. Indeed, a calculation of the $\tilde{\nu}_e$ and electron spectra from ^{239}Pu fission fragments showed that they are significantly softer than the analogous spectra for ^{235}U. The dependence of the ratio of the number of antineutrinos with given energy $E_{\tilde\nu}$ emitted by U and Pu $[N_{\tilde\nu}(^{235}\mathrm{U})/N_{\tilde\nu}(^{239}\mathrm{Pu})]$ on $E_{\tilde\nu}$ is shown in Fig. 3. This reveals that the ratio increases with the energy of the antineutrinos from 1.1 at $E_{\tilde\nu} = 1.5$ MeV to 2–2.1 in the region $E_{\tilde\nu} \geq 8$ MeV. The energy dependence of this ratio was also calculated under the assumption that for nuclei with independent decay modes the schemes proposed in Ref. 21 are valid. This dependence virtually coincided with the curve shown in Fig. 3. The accumulation of Pu in a reactor core naturally depends on the type of reactor, the initial composition of the fuel, the regime of operation, etc. For power-station thermal reactors the accumulated Pu can reach 50% of the amount of ^{235}U in the core two years after the start of operation. This means that one must take into account the distortion of the antineutrino spectrum due to the presence of the Pu when one is making precise quantitative experiments.

To conclude our review of Refs. 21 and 23, we give Table I, in which we have summarized the information on the calculated antineutrino spectra.

An attempt to reconstruct the antineutrino spectrum from the experimentally measured spectrum of electrons from fission fragments was made by Carter *et al.*[26] The source of β^- particles was a ^{235}U foil placed in a flux of thermal neutrons. The electrons were detected by a plastic scintillator, in front of which a proportional counter with narrow windows was placed. Such a detection scheme (of coincidence between dT/dx and T) makes it possible to lower appreciably the γ-ray background. The obtained β spectrum was approximated

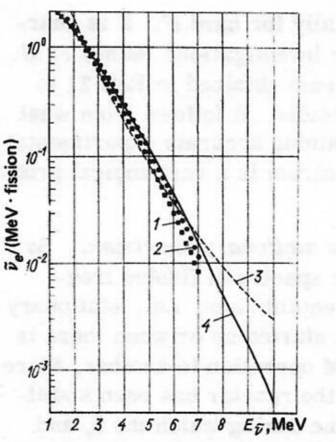

FIG. 4. Reconstruction of antineutrino spectrum. 1) and 2) are from Ref. 8; 3) is from Ref. 6; and 4) is the calculated spectrum of Ref. 21.

by the dependence

$$N(T) = 3.88\exp(-0.575T - 0.055T^2)\ \text{electron/(MeV}\cdot\text{fission)}, \quad (4)$$

where T is the electron energy measured in MeV.

The function (4) is the superposition of many spectra of electrons emitted by isotopes with different Z. The antineutrino spectrum was reconstructed under two extreme assumptions about the atomic number of the fragments (either $Z = 32$ or $Z = 60$ for all β^- emitters). Both the obtained energy dependences of the number of $\tilde{\nu}_e$ on $E_{\tilde\nu}$ are given in Fig. 4, which shows that they differ, the difference increasing with increasing antineutrino energy. The real spectrum must lie between the calculated curves. The theoretical cross section of $\tilde{\nu}_e$ interaction with the proton calculated by means of these spectra, $(6.1 \pm 1) \times 10^{-43}$ cm^2/fission, had a smaller uncertainty than the one measured in the experiment[4] of Reines and Cowan in 1959: $(6.7 \pm 1.5) \times 10^{-43}$ cm^2/fission. From this point of view, the reconstruction of the spectrum was fairly good.

In the experiment[6] of Nezrick and Reines, the antineutrino spectrum was obtained from the measured spectrum of positrons in the inverse β-decay reaction:

$$\tilde{\nu}_e + p \to n + e^+. \quad (5)$$

The neutron kinetic energy was low (of order 10 keV), and virtually all the energy of the incident antineutrino, after subtraction of the reaction threshold (1.8 MeV), is carried away by the light particle, the positron. The cross section of the direct process, the neutron decay, is known, and this makes it possible to calculate the cross section of the reaction (5) for given antineutrino energy and to reconstruct the spectrum. The accuracy of the obtained results is determined by the accuracy in the measurement of the energy and the efficiency of positron detection. The obtained energy dependence of the intensity $N(E_{\tilde\nu})$ was approximated by the function

$$N(E_{\tilde\nu}) = 19.4\exp(-1.28E_{\tilde\nu} + 0.04E_{\tilde\nu}^2)\ \text{electron/(MeV}\cdot\text{fission)}. \quad (6)$$

For the range of $\tilde{\nu}_e$ energies from 1.8 to 10 MeV, these results are presented in the form of curve 4 in Fig. 4. It can be seen that at high energies the values of $N_{\tilde\nu}$ obtained by Nezrick and Reines differ strongly from the calculated values. Preference must be given to the latter, since the positron spectrum was measured in Ref.

[4)]After this review had been written, Avignone and Greenwood published their paper of Ref. 78, in which they again calculated the antineutrino spectrum from ^{235}U fission fragments on the basis of the latest data. Up to energies $E_{\tilde\nu} \leq 7$ MeV, it virtually coincides with the spectrum of Ref. 23. The method of the calculation is similar to that described earlier.

6 with large errors, especially for hard e^+. It is characteristic that in their later investigations Reines *et al.* used the calculated $\tilde{\nu}_e$ spectrum obtained in Ref. 21 to analyze the experimental results. It follows from what we have said above that obtaining accurate experimental data on the antineutrino spectrum is a very topical problem.

Time of establishment of a stationary spectrum. So far, we have considered the spectra of fission fragments in a state of secular equilibrium, i.e., stationary spectra. When a reactor is started up or when there is a change from one regime of operation to another, there is, even after the power of the reactor has been stabilized, a certain period of time during which the $\tilde{\nu}_e$ and β^- spectra cannot be regarded as stationary. An idea of the time lag (it depends strongly on the chosen interval of $\tilde{\nu}_e$ values) can be obtained from numerous experimental and theoretical studies (see, for example, Refs. 20, 25, and 28). Thus, in Refs. 20 and 25 measurements were made of the spectrum and intensity of electrons as a function of the time t since the start of irradiation of a ^{235}U target in a flux of thermal neutrons. The evaluated results are given in Table II [$t(0.9)$ is the time from the start of irradiation until the establishment of 90% of the stationary radiation intensity; T is the electron energy].

From the same papers one can obtain data on the growth of the total intensity of the electron or antineutrino radiation: after 10 sec, 20%; after 60 sec, 50%; and after 1 hour, 80% of the stationary flux. Information on the nonstationary spectra of antineutrinos is especially important if, as has been proposed on a number of occasions, a pulsed nuclear reactor is used as the $\tilde{\nu}_e$ source (see below). These questions are investigated in Ref. 28.

Do fission fragments emit neutrinos? After fission, the majority of fragments are overenriched with neutrons and appreciable yields (say, greater than 10^{-3} nuclei/fission) of proton-rich isotopes, and, as a consequence, neutrino-active isotopes cannot be expected. Hitherto, reactor neutrino experiments have been qualitative in nature, and a small admixture of ν_e in the $\tilde{\nu}_e$ flux could not have influenced the results. The transition to quantitative estimates and the achievement of an accuracy of a few percent may change the situation. This can be seen in the example of antineutrino scattering by electrons. If it is assumed that among the fission fragments there exists a neutrino emitter with $E_{\text{lim}} \approx 13$ MeV, then at 3 MeV electron detection threshold $\bar{\sigma}_{\nu e^-}$ exceeds $\bar{\sigma}_{\tilde{\nu} e^-}$ for the fragment spectrum by two orders of magnitude. Experiments to study the difference between ν_e and $\tilde{\nu}_e$ (of the type of Davis' experiment) are also sensitive to a neutrino admixture. We therefore consider possible causes of production of neutrino-active isotopes in fission and the existing estimates of the intensity (N_ν) of their radiation.

Neutrino emitters could arise through various mechanisms. For example, by virtue of the statistical nature of the emission of neutrons, their number for one of the fragments may strongly exceed the mean value, and it becomes proton-rich. A neutrino emitter may be produced in triple fission. Finally, one of the fragments may be superenriched with neutrons—an "unusual" nucleus. In this case, the second fragment, which is deficient in neutrons, will emit positrons or capture electrons (possibly, emit protons). Unfortunately, the currently developed theory of "unusual" nuclei, in particular, superdense or neutron nuclei (see, for example, Refs. 29 and 30), has not yet yielded any predictions on the possible production of such nuclei in fission.

For binary fission, an estimate of N_ν can be made on the basis of the method described above. It was found in Ref. 31 that $N_\nu \leq 1.5 \times 10^{-7}$ ν_e/fission. This value is very uncertain. The charges of nuclei that undergo β^+ decay or electron capture exceed Z_p for the given isobar chain by three to five units. This leads to a strong dependence of the calculated yields on the parameters of the Gaussian curve. In addition, it may be invalid to extrapolate ideas about the normal nature of the charge distribution to the region $Z - Z_p > 3$.

In radiochemical experiments, a systematic search for fission fragments capable of being neutrino sources has not been made. In addition, the method does not permit detection of short-lived (high-energy) emitters with relatively small yields.

An investigation of the positron (neutrino) activity of products from the decay of ^{252}Cf, covering the complete spectrum of fragments and a large range of energies and lifetimes, was made in experiments[31,32] using the spectrometer Positron-20. The results of the measurements are given in Fig. 5. Along the abscissa we have plotted the limiting energy of the assumed positron spectrum, and along the ordinate the upper bound for the intensity of β^+ particles. It was assumed in the calculations that the β^+ transition proceeds directly to the ground state of the daughter nucleus. It can be seen from the graph that if the neutrino activities of the fission fragments of ^{252}Cf, ^{235}U, and ^{239}Pu have the same order of magnitude, the contribution of this radiation to the investigated processes can be ignored.

TABLE II.

T, MeV	0.5	1.1	1.5	1.9	2.5	3.5	Complete spectrum
$t(0.9)$, min	180	110	60	35	20	18	180

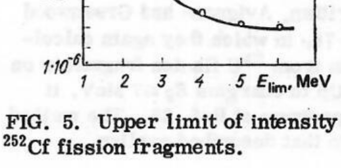

FIG. 5. Upper limit of intensity of the positron radiation of ^{252}Cf fission fragments.

2. ARRANGEMENT OF REACTOR NEUTRINO EXPERIMENTS. BACKGROUND SOURCES

Signal–background ratio. Because of the small antineutrino–matter interaction cross section (for the fragment spectrum, the characteristic value of the cross section is in the range $10^{-43}-10^{-45}$ cm^2), a central problem of reactor experiments is the signal–background ratio.

In a detector with a sensitive volume ~1 m^3 at the flux $f=(2-5)\times10^{13}\ \tilde{\nu}/(\text{cm}^2\cdot\text{sec})$ there are hundreds or thousands of antineutrino interactions per day, i.e., apparently quite a lot. However, the characteristic value of the ratio $k=N_{\text{sig}}/N_{\text{back}}$ for an ordinary detector of this volume is in the range $10^{-2}-10^{-4}$. The effect can be separated if measurements of it and of the background are alternated sufficiently often, but as a rule such a procedure is not possible in the case of industrial facilities. The continuous operation of a reactor lasts for months, and the achievable stability of the apparatus permits quantitative measurement of an effect if it exceeds ~0.1 of the background. For this, in the completed and planned neutrino experiments detectors with a comparatively small sensitive volume (10–100 liters) are chosen; they can be readily shielded from external radiation and made of especially pure materials. Simultaneously, the energy threshold for the detection of the reaction products is raised and all possible criteria for selecting useful events are employed. In this way one can separate the effect, but at the price of reducing its absolute value to a few counts per day. At the present time, it is only for the process $\tilde{\nu}_e+p\to n+e^+$, which (for neutrino physics) has a large cross section (10^{-43} cm^2), and for a well-shielded detector with active volume 250 liters that one can expect to obtain $k=3-5$ without significant loss in the detection efficiency of useful events (see Ref. 33 and Sec. 7 in the present review).

Some years ago it was suggested that a pulsed nuclear reactor, a neutrino generator, should be used for neutrino investigations.[34,35] The main idea was to achieve a significant improvement in the signal–background ratio. This is achieved by creating short but very intense $\tilde{\nu}_e$ fluxes from the β decay of fission fragments. The pulsed regime of operation (with a 0.5-sec duration of the neutron pulse it was anticipated that the effective duration of the antineutrino pulse from the decay of the fragments would be 10–20 sec, the repetition frequency of the pulses would be ten per day, and the integrated flux of antineutrinos per pulse at the detector would be $J=2\times10^{16}\ \tilde{\nu}/\text{cm}^2$) gives two further advantages:

1) the effect and background are measured with a very small separation in time, so that the requirements on the stability of the apparatus are greatly reduced;

2) the measurements can be made when the reactor is effectively off because of the difference in time between the neutron and neutrino pulses.

References 34 and 35 also contain the suggestion that the facility should be loaded with the isotope ^{7}Li, which by capturing some of the neutrons, becomes a source of hard antineutrinos (the limiting energy of the spectrum is 13 MeV). The pulse characteristics of the generator are also improved (the half-life of ^{8}Li is 0.8 sec). The profile of the β spectrum of Li is, in contrast to the spectrum of reactor antineutrinos, well known. There is no doubt that the practical realization of this idea would lead to a significant advance in the study of the physics of electron neutrinos.

Background associated with the operation of the reactor. According to the nature of the sources, the background can be conveniently divided into a number of components:

1) the background associated with the operation of the reactor;

2) the background due to cosmic rays;

3) the background from the natural radioactivity of the materials of the facility.

We shall restrict ourselves here to a brief description of these components and ways by which they can be suppressed in neutrino experiments. The successful development of such methods made it possible to advance significantly in the solution of other problems of nuclear physics and related fields when low-background measurements are involved.

In $\tilde{\nu}_e$ experiments, reduction of the background of neutrons and gamma rays emitted by the working reactor requires extra shielding in addition to the biological installation. If we assume that in the room where the neutrino experiment is made the fast-neutron (≈1 MeV) radiation dose for the service personnel is 100 times below the maximal permitted dose, i.e., is 0.05 rem/year, the product of the interaction cross section σ_{np} of these neutrons with hydrogen and their flux f_n still exceeds $\bar{\sigma}_{\tilde{\nu}p}f_{\tilde{\nu}}$ by a factor 10^5-10^6 despite the appreciable antineutrino flux $(1-5)\times10^{13}\ \tilde{\nu}/(\text{cm}^2\cdot\text{sec})$. These several orders of magnitude must be compensated by additional shielding.

The choice of such shielding has been described in detail by Nezrick and Reines.[6] The background was monitored by a scintillation spectrometer with a large sodium iodide crystal. With the reactor on, the spectrum of γ rays in the range of energies from 0.2 to 8 MeV was measured as a function of the thickness l of the lead shield surrounding the crystal. It was found that a significant suppression of the background is achieved for $0\leq l\leq20$ cm. A further increase in the thickness had little influence on the γ-ray intensity. It was therefore decided to stop at $l=30-40$ cm and use an additional neutron shield—boron and paraffin. The energy spectrum of the γ rays measured by the NaI(Tl) crystal (of volume ~5 liter) with the reactor on and off and with different compositions of the shield is shown in Fig. 6.

The construction of a shielding house made it possible to reduce the intensity of the sodium iodide count at low energies (≤1 MeV) by a factor ~400, and at energies higher than 6.5 MeV by a factor 44×10^3. Starting up the reactor increased the number of pulses from γ rays with $E_\gamma<3$ MeV by approximately 10%. As a result of the adopted measures, the component of the background

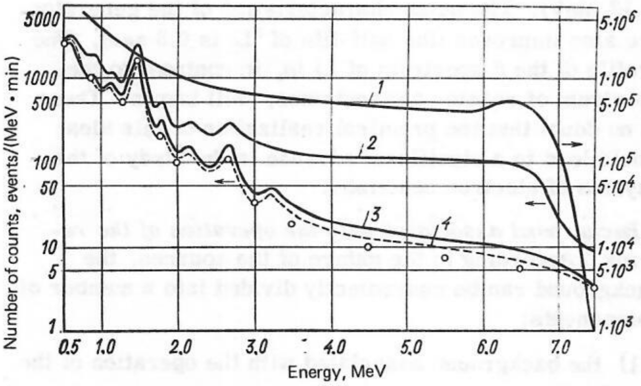

FIG. 6. Background spectrum of sodium iodide crystal near a reactor. 1) Reactor on, no special shielding (right-hand scale); 2) reactor on, detector shielded by lead (l = 30–40 cm); 3) reactor on, lead and neutron shield; 4) reactor off, lead shield; the open circles are when the reactor is off and there is complete shielding.

associated with the operation of the reactor became smaller than the other components. In the region $E_\gamma > 3$ MeV, the background was determined by the natural radioactivity of the materials of the facility, and at higher energies by the cosmic rays. A significant fraction of the background of the neutrino detector in the case of particle detection with energy above 3 MeV can be attributed to the last component.

Background due to cosmic rays.[5)] The primary cosmic rays that reach the top of the Earth's atmosphere from space are rapidly absorbed in the air and produce secondary particles in interactions. It is convenient to separate three groups of such particles:

1) electrons and γ rays (soft component);

2) nuclear-active particles (nucleon component);

3) positive and negative muons (hard component).

The soft component is absorbed in relatively small thicknesses of a passive shield (10–15 cm of Pb). To absorb nuclear-active particles, one requires a depth of 15–20 m water equivalent (the mean range of this component in the ground is 200 g/cm², and in lead 300 g/cm²). Therefore, if possible, the neutrino detector should be deep underground, for example, under the reactor. At sea level, the main neutron flux (about 90%) is associated with the nucleon component. Neutrons can arrive in the apparatus from the ambient medium or can be produced directly in the detector, the shield, or construction materials. Under usual conditions, the flux of neutrons of cosmic-ray origin at the surface of the Earth is $(1-5)\times10^{-3}$ neutrons/(cm² • sec), which is several times greater than the flux associated with the natural radioactivity of terrestrial rocks.

To reduce the neutron background, one uses materials that slow down neutrons effectively (water, paraffin, polyethylene, etc.) and materials that absorb them actively (lithium, boron, cadmium). A layer of paraffin of thickness 0.5 m attenuates the flux of cosmic-ray neutrons at sea level by almost a factor of 5.[37]

5)For more details, see Ref. 36.

The main method used to suppress the meson background is an anticoincidence system that is an active shield. The detectors generally used in the system are Geiger counters and Cherenkov and scintillation counters. With the development of the scintillation method, wide use has been made of tanks of liquid scintillator in anticoincidence systems. The possibility of suppressing the cosmic-ray background by an anticoincidence system with a liquid scintillator has been studied in detail by Reines' group.[38] The intention was to use the results for constructing detectors of high-energy neutrinos.

The main scintillation counter of volume 50 liters, surrounded by a 10-cm lead shield, was placed on the bottom of a tank containing 1500 liters of liquid scintillator. A passive shield was placed at the top. Particles leaving an energy greater than 10 MeV in the counter were detected. This eliminated effects associated with natural radioactivity. The total background suppression coefficient at a thickness of the passive shield of about 0.6 kg/cm² was 10^4, which corresponded to a background count in 1 liter of the main detector of 4.4×10^{-5} event/sec.

It is interesting to compare this value with the counting rate of useful events in the detection of $\tilde{\nu}_e e^-$ scattering. For $T > 3$ MeV in 1 kg of plastic scintillator the number of recoil electrons is 10^{-6} sec^{-1}. Therefore, detection of the effect in the experiments of Ref. 9 required mobilization of literally all the possible means of background suppression.

Interacting with the material of the detector, the meson component produces neutrons (the fraction of these neutrons is small and at sea level constitutes 5–7% of the total number of cosmic-ray neutrons). Their lifetime in the apparatus may reach hundreds of microseconds, and for sufficiently large detectors a simple lengthening of the blocking pulse may lead to a significant loss of efficiency. If all the neutrons must be eliminated, then for a ground-based laboratory one can use the circumstance that 80% of them are produced by the capture of stopped μ^- mesons.[39] The separation of such mesons with respect to the past is achieved by the introduction of additional anticoincidences between the lower and upper shielding counters. The electronic circuit blocks the detector for a significant time when a stopped meson is detected. This measure renders the detector insensitive to quanta of the $n\gamma$ reaction, but does not protect one from the background associated with the production of radioactive nuclei resulting from the capture of neutrons and μ^- mesons.

In the high-energy region of the background, contributions may be made by the ionizing particles themselves as well as by cascades of γ rays produced by the passage of the mesons through the matter. They can be generated in layers of the shield close to the detector or in the construction materials, giving rise to an "internal" soft component of the cosmic rays. Such cascades are especially dangerous for experiments in which coincident events are detected. For example, in Ref. 40 an investigation was made of the possibility of detecting the inverse β-decay reaction $\tilde{\nu}_e + A(Z,N) \to \beta^+$

$+A(Z-1,N+1)$ in the case when a free neutron is not produced. It was suggested that useful events should be selected on the basis of triple coincidences between pulses from the positron detector and two counters of annihilation γ rays. The experiments, which were intended for an industrial reactor, were not carried out. This was because of the large background of triple coincidences not associated with the operation of the reactor. Investigations and calculations showed that almost all the $(89 \pm 13)\%$ background events occur sooner than 0.2 μsec after the cosmic-ray muon has passed through the apparatus. The events were attributed to cascades of γ rays produced in the passive shield (20 cm of lead and 10 cm of borated paraffin) by the passage of a μ meson. It was concluded that only a highly efficient anticoincidence system completely surrounding the passive shield could suppress this background, which prevents observation of the reaction.

For the effective suppression of the soft and hard components, it was suggested in a number of papers that a shield should be constructed as follows. An outer layer of a passive shield, which absorbs the soft component, surrounds the active shield. The latter must have the greatest possible efficiency. Then follows a second layer of passive shield, which is immediately next to the detector. The γ-ray cascades produced by the muons in the inner passive shield are eliminated by an anticoincidence system that has detected the meson. Cascades produced by muons that pass outside the active shield are stopped by the second layer of passive shield.

The arrangement used in Ref. 9 to study $\bar{\nu}_e e^-$ scattering is shown in Fig. 7. The inner part of the detector, which consists of plastic and NaI(Tl), is surrounded by layers of lead (7.6–10.8 cm) and cadmium and is placed in a tank containing 2200 liters of liquid scintillator, which serves as the active shield. Then follows a lead shield, concrete, and water—the outer layer of the passive shield.

Backgrounds associated with natural radioactivity of materials. Natural radioactive elements are dispersed throughout all the materials of the detector, the shield, in the air, etc. Among them, ^{40}K and members of the ^{238}U and ^{232}Th family make the largest contribution in the energy range of background radiation in which we are interested. One gram of natural potassium emits in 1 sec 3.5 γ rays with energy 1.46 MeV and about 28 β particles with maximal energy 1.3 MeV as a result of the decay of the ^{40}K contained in it. On the transition of ^{238}U into ^{206}Pb, a total energy of 52 MeV is released, this being carried away by eight α particles, six β particles, and γ rays emitted successively with them. It is only on the decay of one of the members of the chain ^{214}Bi–^{214}Po that γ rays with energy exceeding 1 MeV are emitted. The most intense lines of this transition are at 1120, 1764, and 2204 keV. In the decay chain that begins with ^{232}Th and ends with the stable ^{208}Pb, an energy of 43 MeV is released and six α particles and four β particles are emitted. The most intense γ-ray lines with energy greater than 1 MeV are at 1620 keV and 2614+583 keV (^{212}Bi→^{212}Po and ^{208}Tl→^{208}Pb).

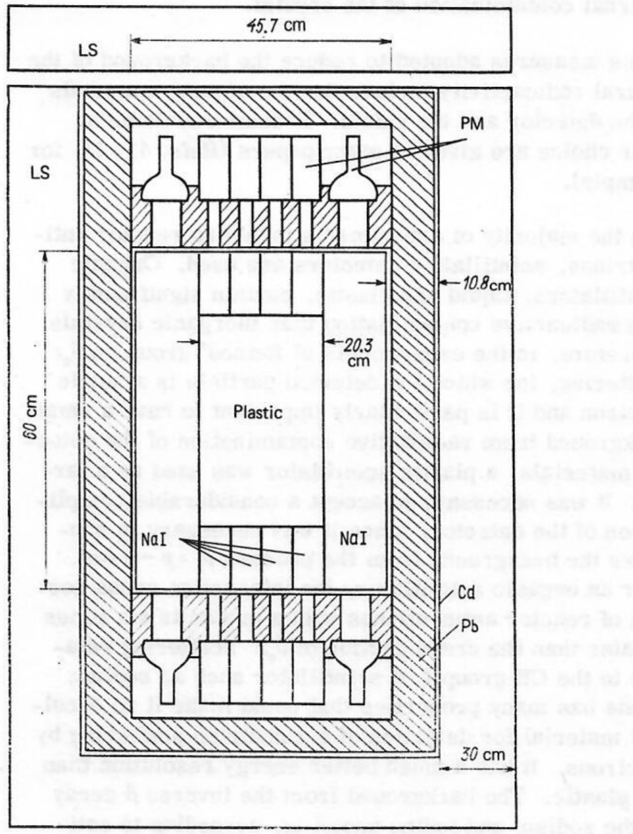

FIG. 7. Schematic arrangement of the detector of Ref. 9.

The background spectrum of a well-shielded (passive and active shield) NaI(Tl) crystal and the spectra of the individual components contributing to this background—cosmic-ray muons and the natural radioactivity of ^{40}K, ^{232}Th, and ^{238}U—is shown in Fig. 8. In the range from 4 to 8.8 MeV, one observes peaks from α particles of

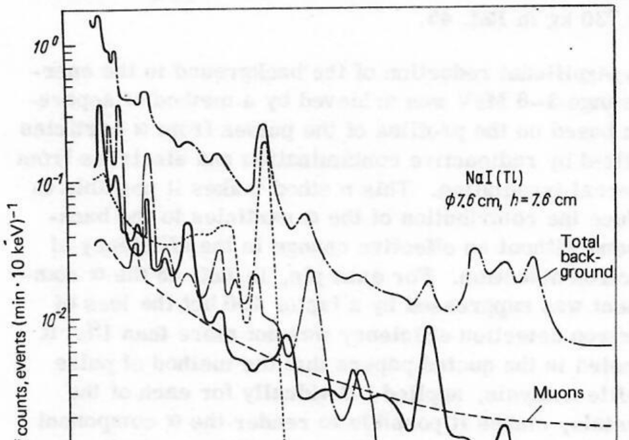

FIG. 8. Energy spectrum of individual components and total background of sodium iodide crystal.

internal contamination of the crystal.

The measures adopted to reduce the background of the natural radioactivity include the use of pure materials in the detector and the shield. Recommendations on their choice are given in many papers (Refs. 41–43, for example).

In the majority of experiments involving reactor antineutrinos, scintillation detectors are used. Organic scintillators, liquid and plastic, contain significantly less radioactive contamination than inorganic crystals. Therefore, in the experiments of Reines' group on $\tilde{\nu}_e e^-$ scattering, for which the detected particle is a single electron and it is particularly important to have a small background from radioactive contamination of the detector materials, a plastic scintillator was used as a target. It was necessary to accept a considerable complication of the detector, since it was necessary to suppress the background from the process $\tilde{\nu}_e + p \to n + e^+$. (For an organic scintillator, the interaction cross section of reactor antineutrinos with a proton is six times greater than the cross section of $\tilde{\nu}_e e^-$ scattering relative to the CH group.) A scintillator such as sodium iodide has many properties that could make it an excellent material for detection of antineutrino scattering by electrons. It has a much better energy resolution than the plastic. The background from the inverse β decay on the sodium and iodine nuclei is, according to estimates, appreciably smaller than the effect.

The possibilities of reducing the background from radioactive contamination of the NaI(Tl) crystals and the possibility of using them to detect $\tilde{\nu}_e e^-$ scattering are discussed in Refs. 44 and 45. These studies investigated the background characteristics of a spectrometer consisting of cylindrical sodium iodide crystals (diameter 70 mm, length 400 mm). The total mass of the sensitive material of the detector was 200 kg in Ref. 44 and 730 kg in Ref. 45.

A significant reduction of the background in the energy range 3–8 MeV was achieved by a method of separation based on the profiles of the pulses from α particles emitted by radioactive contamination and electrons from external irradiation. This method makes it possible to reduce the contribution of the α particles to the background without an effective change in the efficiency of electron detection. For example, in Ref. 45 the α component was suppressed by a factor 100 but the loss of electron detection efficiency was not more than 1%. It is noted in the quoted papers that the method of pulse profile analysis, applied individually for each of the crystals, makes it possible to render the α component of the background essentially insignificant. Studies to perfect the spectrometer will be continued.

One further type of scintillator for studying antineutrino scattering by electrons currently under development contains hexafluorobenzene (C_6F_6) as a solvent (see Refs. 46 and 47). From the point of view of radioactivity, this is one of the purest of materials,[48] and in it the inverse β-decay background can be due only to scintillating additives if they contain hydrogen.

3. INVERSE β PROCESSES

General questions. We begin our discussion of reactions induced by antineutrinos with processes that are inverse to β decay. We have inverse β^- decay

$$\tilde{\nu}_e + A(Z,\ N) \to e^+ + A(Z-1,\ N+1); \tag{7}$$

the direct reaction

$$A(Z-1,\ N+1) \to A(Z,\ N) + e^- + \tilde{\nu}_e \tag{8}$$

and induced capture of an orbital electron:

$$\tilde{\nu}_e + e^- + A(Z,\ N) \to A(Z-1,\ N+1). \tag{9}$$

For monoenergetic $\tilde{\nu}_e$, the cross section of the process (7) is given by

$$\sigma(T,\ Z) = S\frac{2\pi^2 \ln 2}{(ft)\,c}\left(\frac{\hbar}{mc}\right)^3 F(T,\ Z)(T+1)\sqrt{(T+1)^2-1}$$
$$= S\frac{2.63\cdot 10^{-41}}{(ft)} F(T,\ Z)(T+1)\sqrt{(T+1)^2-1}. \tag{10}$$

Here, S is the spin statistical factor, equal to $(2I_f+1)/(2I_{in}+1)$, where I_{in} and I_f are the spins of the initial and the final nucleus; T is the kinetic energy of the emitted positron, which is related to $E_{\tilde{\nu}}$ and the reaction threshold Δ by $T = E_{\tilde{\nu}} - \Delta$, and, in its turn, $\Delta = (M_{in} - M_f) + 1$, in which M_{in} and M_f are the masses of the initial and final nuclei, respectively; the energies and masses are given in units of $m_e c^2$; $F(T, Z)$ is a function that takes into account the Coulomb interaction in the final state. Its values are tabulated in Ref. 49; (ft) is the reduced half-life of the direct reaction.

As an illustration of the $\sigma(T, Z)$ values obtained in a reactor antineutrino spectrum, Fig. 9a shows graphs taken from Ref. 50. The calculations were made for nuclei with Z from 20 to 90. The reduced cross section $[\sigma(T, Z)(ft)]/S$ is plotted along the ordinate, and the limiting kinetic energy T_0 of the β^- particles from the $A(Z-1, N+1) \to A(Z, N)$ transition along the abscissa. In the calculations, the antineutrino spectrum was taken from Ref. 6.

Induced electron capture, the possibility of which was first noted by Fermi,[51] was considered in detail in Ref. 50. It is distinguished by a number of features. A stable atom absorbs an incident antineutrino plus an electron from one of the shells and is transformed into an atom with a vacancy in the corresponding shell. The process can take place only under the influence of antineutrinos with a definite resonance energy $E_{\tilde{\nu}}^{(res)}$, since

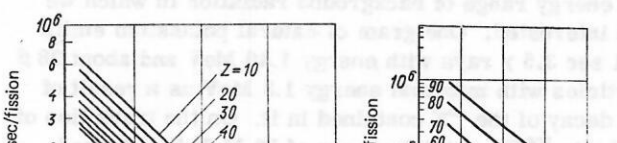

FIG. 9. Reduced cross sections of inverse β decay of nuclei (a) and induced electron capture (b).

it occurs between atomic states in the discrete spectrum. If the nucleus $A(Z-1, N+1)$ is produced in the ground state, then $E_{\tilde{\nu}}^{(\mathrm{res})} = T_0 + E_i$, where T_0 is the limiting energy of the β spectrum in the decay (8) of the nucleus, and E_i is the electron binding energy. A transition can also take place to excited levels of the final nucleus, and the $E_{\tilde{\nu}}^{(\mathrm{res})}$ is increased by E_γ, the energy of the excited level.

It can be seen from comparison of the reactions (7) and (9) that the energy threshold for induced electron capture is $2m_ec^2$ lower than for the inverse β^- decay process.

For an allowed transition, the cross section of the process (9) can be written as

$$\sigma = 4.18 \cdot 10^{-41} g_0^2 \frac{\rho(E_{\tilde{\nu}}^{\mathrm{res}})}{ft}\ \mathrm{cm}^2, \qquad (11)$$

where $\rho(E_{\tilde{\nu}}^{\mathrm{res}})$ is the number of $\tilde{\nu}_e$ in the region of the resonance per 1 MeV energy interval and normalized such that $\int_0^\infty \rho(E)dE = 1$; g_0^2 for heavy nuclei is with good accuracy equal to $4(Z/137)^3$.

The cross sections for the fragment antineutrino spectrum[6] and various nuclei ($Z = 20$–90) are given in Fig. 9b, from which it can be seen that with increasing Z the probability of induced electron capture increases rapidly and in the region $Z \geqslant 60$ begins to exceed the probability of inverse β decay. It is possible that this process could be helpful in investigating soft $\tilde{\nu}_e$. Davis[52] has pointed out that the reaction $\tilde{\nu}_e + {}^{209}\mathrm{Bi} + e \rightarrow {}^{209}\mathrm{Pb}$ of this type, which has a very low threshold (0.64 MeV), will be particularly interesting for searches of antineutrino activity of the Earth.

At the present time, the technical difficulties of observing the process (9) are very great, since the occurrence of resonance capture can be deduced only from the emission of x rays in $A(Z-1)$ and from the γ rays for the production of the final nucleus in the excited state.

Antineutrino–proton interaction. Among the neutrino processes, a particular position is occupied by the reaction

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

which is the inverse of β^- decay of the neutron and in which the neutrino was first observed. In the investigations of Reines and Cowan and their collaborators, and then Nezrick and Reines, the value of $\bar{\sigma}_{\tilde{\nu}p}$ in the antineutrino flux from a powerful reactor was determined with successively increasing accuracy:

1953: detection of the process (5);

1959–60: first quantitative results:

$$\bar{\sigma}_{\tilde{\nu}p} = (1.2^{+0.7}_{-0.4}) \cdot 10^{-43}\ \mathrm{cm}^2;\ \bar{\sigma}_{\tilde{\nu}p} = (1.1 \pm 0.26) \cdot 10^{-43}\ \mathrm{cm}^2;$$

1966: $\bar{\sigma}_{\tilde{\nu}p} = (0.94 \pm 0.13) \times 10^{-43}\ \mathrm{cm}^2$.

The investigations during the period 1953–1960 have been frequently described and we shall discuss in detail only the investigation of 1966 (Ref. 6).

The arrangement of this experiment is shown schematically in Fig. 10. In the central part we have a cylinder containing 3.2 liters of liquid scintillator (LS) based on decalin loaded with a gadolinium compound (24 g/liter). The cylinder was scanned by 30 photomultipliers situated along its sides. At the ends of the cylinder, two NaI(Tl) cylinders of diameter 29 cm and height 7.6 cm were attached. Each of these was scanned by seven photomultipliers. We have already described the passive shield for this experiment. Under the influence of the antineutrinos, inverse β decay occurs on the protons of the liquid scintillator and a neutron and positron are formed. The positron is annihilated almost instantaneously into two γ rays ($E_\gamma = 510$ keV), which can be detected in the sodium iodide crystals. The energy of the positron itself is detected in the liquid scintillator. After a certain time during which it is slowed down and diffuses, the neutron, which has not left the liquid scintillator, is captured by the gadolinium. As a result of the (n, γ) reaction, there are emitted on the average four γ rays, each with an energy of 2 MeV. They can also interact in the scintillators.

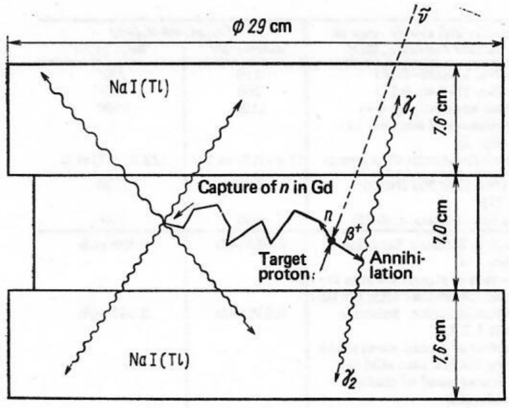

FIG. 10. Schematic arrangement of the experiment of Ref. 6.

The useful events were selected on the basis of the following criteria:

1) the energy of the first particle detected by the liquid scintillator must exceed 0.5 MeV;

2) this signal must coincide with signals from two NaI crystals of appropriate energies (0.51 MeV ± the resolution of the crystal);

3) the energy from the particles of the second event lost in all the scintillation counters must exceed 0.75 MeV;

4) the second event must occur in the interval between 2.8 and 50 μsec after the first. The mean lifetime of the neutrons in the scintillator was ~8 μsec. Therefore, the overwhelming majority of them (92 ± 1%) were captured in a time less than 50 μsec after their production. In the experiment, the time interval 2.8–100 μsec after the first event was divided into two groups of 50 μsec. Pulses in the second group made it possible to estimate the background of random coincidences;

5) for the final selection, the signals were displayed on an oscilloscope screen. Events in which more than one candidate for the "neutrons" or "positrons" was detected were rejected.

TABLE III.

Useful event	Detector and energy range of particle detection, MeV	Count, events/min	
		Reactor off	Reactor on
First event (positron-like)	NaI (No. 1) (0.46–0.56)	210	250
	NaI (No. 2) (0.46–0.56)	200	250
	Organic scintillator (>0.4)	1100	1300
	Coincidences of NaI (No. 1) NaI (No. 2)		1
	Triple coincidences (first event)	(5.6 ± 0.3) ev/h	(28.2 ± 0.7) ev/h
Second event (neutron-like)	NaI (No. 1) or NaI (No.2) (>0.75)	850	1000
	Organic scintillator (>0.75)	650	760
First and second events	Complete detector. Selection criteria 1–5 Detection of second event in the interval 2.8–50 μsec after the first	0.073 ev/h	0.308 ev/h
	Complete detector. Selection criteria 1,2,3,5 Detection of second event in the interval 50–100 μsec after the first (background of random coincidences)	0.039 ev/h	0.087 ev/h
	Complete detector. Selection criteria 1–5 Correlated events	0.034 ev/h (background)	0.221 ev/h (effect + background)
		Effect (0.187 ± 0.021) ev/h	

The use of these criteria made it possible to reduce the background significantly (Table III). It can be seen from the table that random and correlated (first and second events genetically related) coincidences contribute to the background. When the reactor was off, the latter constituted 18% of the effect and the random coincidences 21%.

The cross section of $\tilde{\nu}_e$ interaction with a proton, averaged over the spectrum of the reactor antineutrinos, was obtained from the relation

$$\bar{\sigma}_{\exp} = R/(3600 f N \bar{\xi}),$$

where R is the counting rate of the useful events, equal to $0.187 \pm 0.021\ \mathrm{h}^{-1}$, f is the antineutrino flux, equal to $7.2 \times 10^{13}\ \tilde{\nu}/(\mathrm{cm}^2 \cdot \mathrm{sec})$, N is the total number of protons in the target, equal to 2.56×10^{26}, and ξ is the mean detection efficiency, equal to 0.030 ± 0.002.

The obtained result was $\sigma_{\exp} = (0.94 \pm 0.13) \times 10^{-43}\ \mathrm{cm}^2$. We now turn to an estimation of this cross section, using Eq. (10). In a flux of monoenergetic antineutrinos

$$\sigma_{\tilde{\nu} p} = \frac{2.63 \cdot 10^{-41}}{(ft)_n} (T+1) \sqrt{(T+1)^2 - 1}. \quad (12)$$

To obtain $\bar{\sigma}_{\text{theor}}$ and compare it with the experiment, it is necessary to average this cross section over the spectrum $N(E_{\tilde{\nu}})$ of the incident antineutrinos.[6)] Thus, $\bar{\sigma}_{\text{theor}}$ contains two experimental parameters—the neutron half-life and $N(E_{\tilde{\nu}})$.

In the experiment of Nezrick and Reines, the antineutrino spectrum was obtained from the measured positron spectrum (see above), and the half-life $t_n = (11.7 \pm 0.3)$ min was taken from Ref. 53. To good accuracy, the calculated cross section was equal to the experimental one: $\bar{\sigma}_{\text{theor}} = (1.07 \pm 0.07) \times 10^{-43}\ \mathrm{cm}^2$ and $\alpha = \bar{\sigma}_{\exp}/\bar{\sigma}_{\text{theor}} = 0.88 \pm 0.13$.

During the past decade, the value of t_n has been determined more accurately. For example, in the studies of Cristensen *et al.* to determine the neutron half-life the following values were obtained: in 1967, $t_n = (10.78 \pm 0.16)$ min (Ref. 54) (preliminary result) and in 1972, $t_n = (10.61 \pm 0.16)$ min (Ref. 55) (corrected result). The reduced neutron half-life $(ft)_n$ can also be estimated independently on the basis of measurements of the angular correlations in the decay of polarized neutrons[56] and the value of (ft) for $0 \to 0$ transitions. The obtained values $t_n = (10.35 - 10.45)$ min are shorter than in Ref. 55.

We have already said that subsequently Reines' group used, as the most accurate, the spectrum $N(E_{\tilde{\nu}})$ from Ref. 21 to evaluate data in neutrino experiments. If $\bar{\sigma}_{\text{theor}}$ is calculated for the two calculated spectra and $t_n = 10.6$ min, the results $\bar{\sigma}_{\text{theor}} = 1.25 \times 10^{-43}\ \mathrm{cm}^2$ (spectrum taken from Ref. 21) and $\bar{\sigma}_{\text{theor}} = 1.27 \pm 10^{-43}\ \mathrm{cm}^2$ (spectrum taken from Ref. 23) are obtained. Taking $\bar{\sigma}_{\text{theor}} = 1.26 \pm 0.02$, we get $\alpha = 0.75 \pm 0.11$.

It can be seen from this that the use of the latest data destroys the good agreement between $\bar{\sigma}_{\exp}$ and $\bar{\sigma}_{\text{theor}}$. Their difference exceeds twice the experimental error. This fact is most probably explained by a statistical fluctuation or ignored errors of a methodological nature. However, $\bar{\sigma}_{\exp}$ could be decreased by a number of physical factors such as accumulation of plutonium in the reactor, the existence of neutrino oscillations, etc. (see Ref. 57). The inverse β-decay reaction of the proton is of fundamental importance for neutrino physics and the entire theory of weak interactions. It is therefore obvious that further experiments must be made to obtain a more accurate value of $\bar{\sigma}_{\exp}$ and the antineutrino spectra from fission fragments.

Inverse β decay of the deuteron. The reaction

$$\nu_e + d \to n + n + e^{+} \quad (13)$$

was observed for the first time in 1969 in an experiment of Jenkins, Kinard, and Reines.[7] It has some characteristic features. First, the corresponding direct process, in which two neutrons are transformed into a deuteron, an electron, and an antineutrino, is not amenable to study. Second, in contrast to the process (5), the transition matrix element in the reaction (13) contains only an axial-vector part, since the produced neutrons have antiparallel spins on account of the Pauli principle, and the deuteron spin is equal to unity. Third, the reaction cross section depends on the interaction of the neutrons produced in the final state.

Finally, by studying the process (13), one can obtain information on the cross section of the reaction

$$p + p \to d + e^{+} + \nu_e,$$

which is very important in astrophysics.

All the listed features emphasize the importance of studying the inverse β decay of the deuteron, although the detection of this process in a reactor antineutrino flux involves much greater difficulties than the detection of the $\tilde{\nu}_e p$ interaction.

The threshold of the reaction (13) is about 4 MeV. Calculations of its cross section for the antineutrino spectrum of ^{235}U fission fragments gives the value $\bar{\sigma}_{\text{theor}} = 3 \times 10^{-45}\ \mathrm{cm}^2$ and $\bar{\sigma}_{\text{theor}} = 2.0 \times 10^{-45}\ \mathrm{cm}^2$ for ^{239}Pu (Ref. 58), i.e., almost two orders of magnitude smaller than $\bar{\sigma}_{\text{theor}}(\tilde{\nu}_e p)$. Only exploitation of all the specific features

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6) $\sigma_{\text{theor}} = \left(\int_{1.8}^{\infty} \sigma_{\tilde{\nu}_p} N(E_{\tilde{\nu}})\, dE_{\tilde{\nu}}\right) / \left(\int_{0}^{\infty} N(E_{\tilde{\nu}})\, dE_{\tilde{\nu}}\right).$

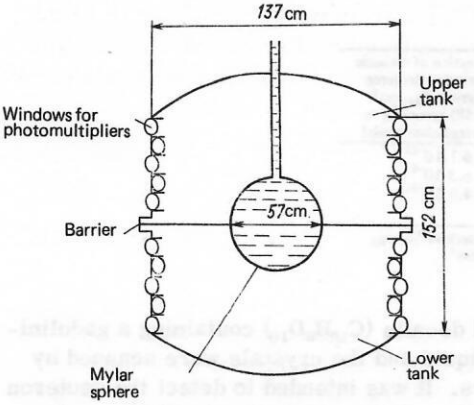

FIG. 11. Arrangement of the experiment in Ref. 13.

of the reaction products made it possible to detect the process (13) in the experiments of Reines' group. The arrangement of the experiment is shown schematically in Fig. 11. A tank containing 2240 liters of scintillator based on a mineral oil was divided by a horizontal barrier. At its center, there was a transparent mylar sphere containing 97 liters of deuterated decalin ($C_{10}H_8D_{10}$) containing scintillation additives and 2.6 g/liter of gadolinium in the form of gadolinium octoate. The tank was scanned by 132 photomultipliers through windows of transparent plastic. The complete detector was placed in a massive lead shield.

The principle of separating useful signals consisted of using delayed coincidences between the positron and two neutrons slowed down and trapped in the gadolinium. The first event was assumed to be positron-like if the total energy left by the particles (the positron and the annihilation γ rays) lay in the interval 1.75–6 MeV. Two neutron pulses were then expected during an interval of 60 μsec. The capture γ rays were detected on the basis of coincidences between the upper and lower tanks. The detection threshold for each of the events was 1.5 MeV. The total energy released in the entire scintillator had to lie in the interval between 5.5 and 10 MeV. The pulses from the upper and lower tanks, and also the total pulse, were displayed on an oscilloscope and photographed. The experiments were made with the reactor on and off, and also when the deuterated scintillator was replaced by a mineral-oil scintillator.

In all the experiments, events were also detected in which a positron-like pulse was accompanied by only one neutron-like pulse. Subsequently, after allowance for the background, they were attributed to the reaction $\tilde{\nu}_e + p \rightarrow e^+ + n$ on protons of the inner scintillator. This made it possible to determine the efficiency of detection of the inverse β decay of the deuteron in a relative manner by using the cross section $\overline{\sigma}_{\tilde{\nu}p} = (1.07 \pm 0.07) \times 10^{-43}$ cm^2 and a number of calculated coefficients. Finally,

$$\overline{\sigma}_{\exp}(\tilde{\nu}d) = R/(N_d F \overline{\xi}),$$

where R, the total number of selected events, is equal to 121 ± 47; N_d, the number of deuterons in the target, is equal to 3.82×10^{27}; F, the integrated neutrino flux during the time of the experiment, was equal to $1.08 \times 10^{20}\ \tilde{\nu}/\mathrm{cm}^2$ [flux intensity $f = 2.8 \times 10^{13}\ \tilde{\nu}/(\mathrm{cm}^2 \cdot \mathrm{sec})$]; and $\overline{\xi}$, the detection efficiency of the process (13), was 0.10 ± 0.034.

Substitution of these values gives for $\overline{\sigma}_{\exp}(\tilde{\nu}d)$ the value $(3.0 \pm 1.5) \times 10^{-45}$ cm^2, in good agreement with the theoretical predictions. The appreciable error of the experiment rules out the drawing of quantitative conclusions, and it can be regarded only as proof of the existence of the process (13).[7)]

Some comments. Further progress in the investigation of inverse β decay requires an increase in the antineutrino fluxes, improvement of the detectors, and shielding of the apparatus from the background. On the one hand, this would make it possible to make exact quantitative measurements of the cross sections of processes such as $\tilde{\nu}p$ and $\tilde{\nu}d$ and, on the other, it would extend the range of possible experiments. For example, in studying the antineutrino–proton interaction it is above all necessary to establish the reasons for the existing discrepancy between $\overline{\sigma}_{\exp}$ and $\overline{\sigma}_{\text{theor}}$. For the reaction $\tilde{\nu}_e = d \rightarrow n + n + e^+$, we have already pointed out the large amount of information that could be obtained if the cross section of this process were determined with high accuracy. These experiments could become the first steps in a new field—neutrino nuclear physics.

Among other experiments, one can consider the study of superallowed inverse β processes for, for example, light nuclei: $\tilde{\nu}_e + {}^6\mathrm{Li} \rightarrow {}^6\mathrm{He} + e^+$ [(ft) of the transition is $<10^3$, and the theoretical reaction cross section is $\overline{\sigma}_{\text{theor}} \approx 6 \times 10^{-45}$ cm^2 (Ref. 28)].

Great interest attaches to observation of transitions to excited states of a neighboring nucleus having a structure of the neutron–proton hole type. Such levels, situated just above the ground state, are expected in nuclei with a medium value of the atomic number.[60] These transitions have a realtively high probability, and they can be identified on the basis of the positron and the γ-ray cascade.

4. NEUTRAL CURRENTS

New types of neutrino reaction. The existence of neutral currents in weak interactions [they were detected for the first time in experiments at CERN in 1973 (Ref. 12)][8)] significantly extends the reactions in which neutrinos can participate. Their further study is very important for the construction of a unified theory of the weak and electromagnetic interactions. Although neutral currents can be introduced phenomenologically into the $V-A$ model of the weak interaction, it is well known that this has numerous shortcomings. The main one of these is the nonrenormalizability of the theory: Finite values of the amplitudes of processes are obtained only in the lowest order of perturbation theory and the contribution of the virtual particles is infinite, the degree of divergence increasing with the order of the diagram. The problem is not resolved either by introducing a massive intermediate boson into the theory.

The unified theories of the electromagnetic and weak

[7)]See the footnote 10.

[8)]See also Refs. 59 and 60.

interactions proposed in recent years, for example, the Weinberg–Salam model, do not have this shortcoming. In the Weinberg–Salam model, which does not contradict the available experimental data, neutral currents with a coupling constant of the order of the Fermi constant occur organically. They can be manifested not only through new processes, as mentioned above, but also in the measurement of the differential and total cross sections of reactions allowed by the $V-A$ theory. As an example we can take $\tilde{\nu}_e e^-$ scattering, which will be considered in the following section. Here, we shall consider only inelastic scattering of antineutrinos by nuclei. Such a process will exist if the interaction Hamiltonian includes a product of the neutral leptonic current $(\bar{\nu}_e \nu_e)$ and the neutral current of the nucleons, i.e., $(\bar{p}p)$ or $(\bar{n}n)$. The incident antineutrino loses some of its energy and carries the nucleus into an excited state. The process can be identified by means of the γ rays or, if the excitation energy is sufficiently high, from the neutrons and charged particles emitted by the nucleus.

Several proposals have been published for investigating inelastic scattering of $\tilde{\nu}_e$ by nuclei, but experimental results have been obtained only for deuteron disintegration reactions:

$$\tilde{\nu}_e + d \to p + n + \tilde{\nu}_e'. \qquad (14)$$

Inelastic scattering of antineutrinos by deuterons. The first theoretical estimates of the cross section $\sigma_{\bar{\nu}d}^{\rm inel}$ of the process (14) were made by Gaponov and Tyutin.[62] An interesting feature of this reaction is the circumstance that the $\tilde{\nu}_e$ interacts simultaneously with both the nucleons forming the deuteron, and the cross section of the process in the employed model depends on the relative phases of the scattering by these particles.

For allowed transitions $\sigma_{\bar{\nu}d}^{\rm inel} \sim (\lambda_n - \lambda_p)^2$, where λ_n and λ_p are the coupling constants for the interaction of the antineutrino with the neutron and proton, respectively. If $\lambda_n = -\lambda_p$, the cross section is maximal; if $\lambda_n = \lambda_p$, it is necessary to consider forbidden transitions, and $\sigma_{\bar{\nu}d}^{\rm inel}$ is reduced by almost two orders of magnitude.

Calculations of the cross section of this process, made in Ref. 58 on the basis of the Weinberg–Salam model for various spectra of fragment antineutrinos, are given in the second column of Table IV.[9)]

Experimental attempts to detect the reaction and to estimate the cross section of inelastic scattering of antineutrinos by deuterons have hitherto yielded only upper bounds on $\bar{\sigma}_{\bar{\nu}d}^{\rm inel}$. For example, the bound $\bar{\sigma}_{\bar{\nu}d}^{\rm inel} \leq 10^{-40}$ cm^2 was obtained in the 1965 experiment of Cowan, Jenkins, and Reines.

The 1969 experiment of Munsee and Reines[63] reduced this limit considerably. The detector used in the experiment consisted of two large NaI(Tl) crystals, between which there was a volume with a liquid scintillator, deuterated decalin ($C_{10}H_8D_{10}$) containing a gadolinium salt. The liquid and the crystals were scanned by photomultipliers. It was intended to detect the deuteron disintegration process by means of scintillation pulses produced by the proton and neutron from the reaction. Initially, both nucleons are detected in the liquid scintillator (the neutron by means of the recoil protons resulting from its slowing down). After a certain time t the neutron, if it has not left the liquid, is captured by the gadolinium. The resulting γ rays can reach the NaI(Tl) crystals and can be detected. These two events are subjected to selection with respect to the energy left by the nucleons in the liquid scintillator and the γ rays in the sodium iodide and with respect to the time $t = 0.5-30$ μsec.

TABLE IV.

Form of antineutrino spectrum	Cross section of inelastic antineutrino-deuteron scattering, $\bar{\sigma}_{\bar{\nu}d}$, cm^2 (Ref. 58) according to Weinberg-Salam model
^{232}U (Ref. 21)*	$6.1 \cdot 10^{-45}$
^{235}U (Ref. 23)	$6.3 \cdot 10^{-45}$
^{239}Pu (Ref. 23)	$4.9 \cdot 10^{-45}$

*Recently published calculations[78] of $\bar{\sigma}_{\bar{\nu}d}$ give the value 7.4×10^{-45} cm^2.

The experiments were made at a Savannah River reactor in an antineutrino flux $f = 8 \times 10^{13}$ $\bar{\nu}/(\text{cm}^2 \cdot \text{sec})$. During 55 h of measurements, 396 double events were detected. Despite the introduced selection criteria, which reduced the efficiency of detection of true events to 0.5%, and the measures adopted to shield the apparatus from the background, the number of random coincidences during this time was 369. The upper limit of the cross section determined in this experiment is still far from the value predicted by theory: $\bar{\sigma}_{\bar{\nu}d}^{\rm inel} \leq (1.4 \pm 1.4) \times 10^{-42}$ cm^2.

In the experiment of 1974, this limit was lowered by almost two orders of magnitude, and it was found that the cross section of inelastic antineutrino scattering by deuterons does not exceed 2.6×10^{-44} cm^2 with an accuracy of three standard deviations.[10]

The measurements were made by means of counters filled with BF_3 and immersed in heavy water. As a control, the heavy water was replaced by ordinary water. The sensitive region was surrounded by a layer of lead and cadmium, followed by an active shield, a liquid scintillator. The outer part of the passive shield consisted of lead, water, and concrete. The authors assumed that a further increase in the sensitivity could be achieved by using high-pressure counters filled with ^{3}He. These have the best spectrometric properties, which makes it possible to reduce the intrinsic background of such counters (Ref. 64).[10)]

Other possibilities for observing neutral currents. In 1962, Gershteĭn *et al.*[65] suggested that the inelastic

9)The deuteron disintegration reaction produced by the neutrino neutral current occurs only on account of the axial current, which in the framework of this model makes it possible to calculate its cross section unambiguously without knowledge of the mixing angle θ_W.

10)The results of an experiment with ^{3}He counters were published in 1969: $\bar{\sigma}^{\rm inel} = (3.8 \pm 0.9) \times 10^{-45}$ cm^2 and for inverse β decay of the deuteron $\sigma_{\rm exp} = (1.5 \pm 0.4) \times 10^{-45}$. The authors were E. Pasierd, H. S. Gurr, J. Lathrop, F. Reines, and W. Sobel.

scattering of antineutrinos by the isotope ^{7}Li,

$$\tilde{\nu}_e + {}^7\text{Li} \rightarrow {}^7\text{Li}^* + \tilde{\nu}'_e, \qquad (15)$$

could be used to look for neutral currents. It can be detected through 478-keV γ rays emitted when ^{7}Li* goes over to the ground state. This reaction is attractive in that the transition matrix element is large, and the ^{7}Li content in the natural mixture of isotopes is 92.5%. The cross section of the process (15) in the fragment antineutrino spectrum was estimated in Ref. 66 on the basis of the Weinberg–Salam model. The value obtained for $\bar{\sigma}_{\bar{\nu},\text{Li}}^{\text{inel}}$ was 2.5×10^{-44} cm^2. Thus, in 1 kg of Li and in the antineutrino flux 2×10^{13} $\tilde{\nu}_e/(\text{cm}^2 \cdot \text{sec})$ four 478-keV γ rays will be produced in a day. At the present time, the detection of such an effect by scintillation methods appears impossible. For example, if one uses LiI(Eu) (total mass 50 kg) crystals to detect (15) and assumes that the background of such a detector is close to the background of NaI(Tl) crystals of the same mass and well shielded from external radiation and specially purified of radioactive contamination, the signal–background ratio is 10^{-4} in the energy range 420–520 keV at detection efficiency ~50% of the useful events.

In Ref. 66, the possibility of detecting the inelastic scattering of antineutrinos in the reaction (15) by means of Ge(Li) detectors is discussed. The proposal is to take ten crystals, each with a volume of 25 cm^3, surrounded by an Li layer. The background is estimated on the basis of Fiorini's experiments[67] on neutrinoless double β decay. The authors assume that it will be possible to achieve a signal–background ratio equal to 1/20, one or two useful events per day being detected. [The antineutrino flux is $f = 2 \times 10^{13}$ $\tilde{\nu}/(\text{cm}^2 \cdot \text{sec})$.] They also discuss the possibility of detecting the process

$$\tilde{\nu}_e + {}^{19}\text{F} \rightarrow \tilde{\nu}'_e + {}^{19}\text{F}^*.$$

5. ANTINEUTRINO–ELECTRON SCATTERING

Features of the process. Estimate of the cross section. The elastic scattering of antineutrinos by electrons

$$\tilde{\nu}_e + e^- \rightarrow \tilde{\nu}'_e + e^- \qquad (16)$$

could take place under very different assumptions concerning the nature of the interaction of these particles. For example, it could be attributed to the $\tilde{\nu}_e$ having "anomalous"[11)] electromagnetic properties such as a magnetic moment[12)] $\mu_{\tilde{\nu}}$ or an electric radius r. In the first case, the differential cross section of $\tilde{\nu}_e e^-$ scattering for monoenergetic antineutrinos with energy $E_{\tilde{\nu}}$ is described by the expression

$$d\sigma/dT = \mu_{\tilde{\nu}}^2 \pi r_0^2 (1/E_{\tilde{\nu}})(E_{\tilde{\nu}}/T - 1) \ \text{cm}^2/\text{MeV}, \qquad (17)$$

where T is the kinetic energy of the recoil electrons, r_0 is the classical electron radius, and $\mu_{\tilde{\nu}}$ is measured in Bohr magnetons. If the antineutrino has an electric radius, then $d\sigma/dT \sim r^2$. It was shown in Ref. 68 that the existence of a magnetic moment of $\tilde{\nu}_e$ would lead to a much softer spectrum of the recoil electrons compared with the case when the reaction (16) is due to an electric radius of the antineutrino. Thus, these mechanisms are in principle distinguishable.

11)I.e., not associated with virtual weak processes.

12)In the two-component theory, $\mu_{\tilde{\nu}} \equiv 0$.

TABLE V.

Detection threshold T_d, MeV	Spectrum of $\tilde{\nu}_e$					
	V-A theory			Weinberg–Salam model		
	^{235}U (Ref. 21)	^{235}U (Ref. 23)	^{239}Pu (Ref. 23)	^{235}U (Ref. 21)	^{235}U (Ref. 23)	^{239}Pu (Ref. 23)
1.5	9.3 (0)	9.5 (0)	8.0 (0)	1.1 (1)	1.1 (1)	9.5 (0)
2	5 (0)	4.8 (0)	4.0 (0)	6.2 (0)	6.4 (0)	5.0 (0)
3	1.2 (0)	1.2 (0)	9.0 (−1)	2.1 (0)	2.2 (0)	1.7 (0)
4	3.1 (−1)	2.9 (−1)	2.0 (−1)	7.0 (−1)	7.2 (−1)	5.0 (−1)
5	7.9 (−2)	6.4 (−2)	4.0 (−2)	2.3 (−1)	2.2 (−1)	1.5 (−1)

In the framework of the weak interaction, the scattering process is of particular interest, since it enables one to draw conclusions about the nature of the "diagonal" terms of the Hamiltonian determined by the squares of the currents [in our case, $(\bar{e}\nu_e)(\bar{\nu}_e e)$]. The difficulties of studying such reactions until very recently have left wide scope for the most varied assumptions. For example, Gell-Mann *et al.*[69] advanced the hypothesis that processes like $\tilde{\nu}_e e^-$ scattering are different in their nature from other weak interactions. The experimental data obtained in recent years do not require for their explanation such radical suggestions, and we shall restrict ourselves here to considering two possibilities: a) the $V-A$ theory is valid; b) the Weinberg–Salam (W–S) model holds. The difference between the natures of the interactions for these cases is due to the fact that in the $V-A$ theory the reaction (16) is described by a single diagram with exchange of a charged vector boson W, whereas in the Weinberg–Salam model there is besides this mechanism the possibility of scattering through the exchange of the neutral vector boson Z_0. When $\tilde{\nu}_e e^-$ scattering is described in terms of vector and axial-vector couplings with constants g_V and g_A, the cross section of the process (16) has the form

$$\frac{d\sigma}{dT} = \frac{G^2 m_e}{2\pi\hbar^4 c^2}\left[(g_V + g_A)^2 + (g_V - g_A)^2\left(1 - \frac{T}{E_{\tilde{\nu}}}\right)^2 + \frac{m_e c^2 T}{E_{\tilde{\nu}}^2}(g_A^2 - g_V^2)\right], \qquad (18)$$

where $G^2 m_e/(2\pi\hbar^4 c^2) = 4.28 \times 10^{-45}$ cm^2/MeV. The parameters g_V and g_A have the values

$$(V-A)\ g_V = 1, \quad g_A = -1;$$
$$(W\text{-}S)\ g_V = 1/2 + 2e^2/g^2 = 1/2 + 2\sin^2\theta_W, \ g_A = -1/2,$$

where θ_W is the Weinberg angle.

Using the results of the calculations of Ref. 21 and 58, we give the values of the integrated cross section for the production of recoil electrons as a function of the lower detection threshold T_d:

$$\sigma(T > T_d) = \int_{T_d}^{\infty} dT \int_{E_{\tilde{\nu}}^{\min}}^{\infty} \frac{d\sigma}{dT}\rho(E_{\tilde{\nu}})\,dE_{\tilde{\nu}},$$

where $E_{\tilde{\nu}}^{\min}$ is the minimal energy of the incident antineutrino needed for production of recoil electrons with given energy T, and $E_{\tilde{\nu}}^{\min} = (T + \sqrt{T^2 + 2mc^2 T})/2$. In the calculations, the value $\sin^2\theta_W = 0.3$ was taken (Table V).[13)]

13)The integrated cross section is given in units of 10^{-46} cm^2. The power of 10 is given in the brackets.

The possibility of making a choice between the theoretical variants makes investigation of the process (16) especially interesting. Here, we should also mention the important astrophysical consequences associated with the discovery of $\tilde{\nu}_e e^-$ scattering (see, for example, Ref. 70).

Experimental results. As can be seen from Table V, the predicted cross sections for $\tilde{\nu}_e e^-$ scattering are much less than $\bar{\sigma}_{\tilde{\nu}p}$. The difficulties of detecting the reaction (16) are aggravated by the fact that the useful events cannot be identified by means of coincidences. The history of searches for this process in $\tilde{\nu}_e$ fluxes from reactors stretches over several decades. The results of the first investigations, in which the upper bound for $\bar{\sigma}_{\tilde{\nu}_e}$ was still very far from the region 10^{-45} cm^2, were usually interpreted in terms of a magnetic moment of the antineutrino (17). Thus, from the 1947 experiments of Wollan[71] it followed that $\mu_{\tilde{\nu}} < 10^{-6}\,\mu_0$. The results of Reines and Cowan's experiments in 1953–1960 on the inverse β decay of the proton made it possible to estimate the cross section of antineutrino-electron interaction. The value of $\mu_{\tilde{\nu}}$ was found to be less than $10^{-9}\mu_0$. In a review published in 1960, considering the immediate program of $\tilde{\nu}_e$ investigations at reactors, Reines proposed that a scintillation detector made of individual sections should be used to detect $\tilde{\nu}_e e^-$ scattering. In this case, the γ rays of the background should be detected with a high probability in several of them, while the true events (recoil electrons) would give a scintillation pulse in one section and could thus be separated.

Many years devoted to the construction and perfection of such a detector made it possible first to improve the values for $\bar{\sigma}_{\tilde{\nu}_e}$ and $\mu_{\tilde{\nu}}$ [in 1970, $\mu_{\tilde{\nu}} \leqslant 5.5\times10^{-10}$, $\bar{\sigma}_{\tilde{\nu}_e} \leqslant 4\bar{\sigma}(V-A)$ (Ref. 72); in 1972, $\mu_{\tilde{\nu}} \leqslant 3.6\times10^{-10}$, $\bar{\sigma}_{\tilde{\nu}_e} \leqslant 1.7\bar{\sigma}(V-A)$ (Ref. 8); and in 1974, $\bar{\sigma}_{\tilde{\nu}_e} = (1.1\pm0.8)\bar{\sigma}(V-A)$], and then to detect the process.[9]

The detector used in the last experiment is shown schematically in Fig. 7. The target was a plastic scintillator (PS) divided into 16 optically insulated sections of mass 15.9 kg. Each of the sections was scanned by photomultipliers through a NaI(Tl) light tube. Identification of the scintillation pulses by means of their profiles made it possible to determine whether a particle had been detected in the plastic scintillator or in the sodium iodide. The plastic was additionally surrounded by a ring of NaI(Tl) crystals. The complete detector was placed in a tank of liquid scintillator (the shielding has been discussed above). The scintillation pulses produced in the sections of the plastic scintillator were assumed to be due to $\tilde{\nu}_e e^-$ scattering if they were not accompanied by the detection of particles in the neighboring plastic scintillator blocks, the NaI, or the liquid scintillator. The pulses were displayed on an oscilloscope screen and photographed. The chosen delay time made it possible to detect as well γ rays produced by neutron capture if the reaction $\tilde{\nu}_e + p \to n + e^+$ took place in the plastic.

The recoil electrons were detected in the energy range from 1.5 to 4.5 MeV. The time of the measurements with the reactor on was 64.6 days, and the background was measured for 60.7 days. Such lengthy measurements required a constant check on the stability of the apparatus. Energy calibrations were therefore made periodically and the efficiency and stability of the detector was tested.

TABLE VI.

Energy range, MeV	Count with reactor on, events/day	Count with reactor off, events/day	Error associated with instability of the apparatus, events/day	Value of the effect, events/day
1.5–3	45.1±1.0	39.2±0.9	±0.6	5.9±1.4
3–4.5	2.4±0.19	1.2±0.14	±0.08	1.2±0.25

One of the methods of testing consisted of detecting the β activity of ^{214}Bi (the limiting energy of the spectrum is 3.2 MeV) contained in the elements of the detector (natural radioactivity). The pulses from ^{214}Bi were identified by introducing delayed coincidences between the β particle and the α decay of the daughter isotope ^{214}Po that follows it after $t_{1/2} = 164$ μsec.

Table VI gives data from this investigation that characterize the magnitude of the effect and the background and also the stability of the detector in different energy ranges.

Among the various forms of background, the most dangerous for the experiment was inverse β decay on the proton, since it is genetically related to the antineutrino. The total number of such events in the plastic scintillator was about 200 per day. However, by virtue of the high coefficient of suppression of them in the sectioned detector, the contribution of the inverse β decay was estimated by the authors to be 2% and 3% for the energy detection intervals 1.5–3 and 3–4.5 MeV, respectively.

A whole series of control experiments also showed that the γ and neutron backgrounds associated with the reactor did not make an appreciable contribution to the detected events. The results of the experiment are

$$\bar{\sigma}_{\exp} = (0.87\pm0.25)\,\bar{\sigma}_{\text{theor}}(V-A),\ 1.5\ \text{MeV} \leqslant T \leqslant 3.0\ \text{MeV},$$
$$\bar{\sigma}_{\exp} = (1.70\pm0.44)\,\bar{\sigma}_{\text{theor}}(V-A),\ 3.0\ \text{MeV} \leqslant T \leqslant 4.5\ \text{MeV}.$$

They agree with the Weinberg–Salam model if $\sin^2\theta_W = 0.29\pm0.05$.

On the basis of these data one can not only speak of the detection of the key process of $\tilde{\nu}_e e^-$ scattering but also point out that the value of $\bar{\sigma}_{\tilde{\nu}_e}$ can be fully explained in the framework of the weak interaction. Further steps in the study of the reaction (16) must aim to increase the accuracy in the determination of $\bar{\sigma}_{\tilde{\nu}_e}$ (to a few percent) and find the form of the recoil electron spectrum in order to choose between different variants of the theory. Without significant improvements in the detector, this appears impossible. It is necessary to increase significantly the counting rate of the useful events and to improve the signal–background ratio. The fundamental nature of this process means that it must be investigated by other independent groups. In recent years (1970–1978) a number of projects for measuring the $\tilde{\nu}_e e^-$ or $\nu_e e^-$ scattering cross sections with high accuracy has been made in the literature. We have already mentioned the proposal to use a pulsed reactor for neutrino experiments, and we have also mentioned work on improving detectors based on sodium iodide and fluorobenzene.

The possibilities of investigating the process $\nu_e + e^- \to \nu_e' + e^-$ in meson factories have been considered by a group of physicists at the University of California[13] and by Lobashov and Serduk.[73,74] The former proposed that μ^+ neutrinos stopped in a thick target (mean value $E_\nu \approx 30$ MeV) should be used as source. According to the calculations, the count of useful events in a detector consisting of plates of scintillation plastic and flat spark chambers with total mass 3.7 tons at $f = 2.7 \times 10^7$ ν/(cm$^2 \cdot$sec) and efficiency ~0.4 is 0.5 events/day. (The background evidently exceeds the effect.) In Ref. 74, it was proposed that π and μ mesons produced by the proton beam of an accelerator should be trapped in a superconducting magnetic trap. The decay of these particles in flight makes it possible to increase the mean energy of the ν_e to 100 MeV, which results in an increase in $\bar{\sigma}_{\nu e}$ and creates a concentration of neutrinos in the orbital plane. According to the estimates, the expected counting rate of useful signals in a scintillation detector of 6 tons will be 11 events/day with a background of 2 events/day. It can be seen from this that precise quantitative investigations of $\nu_e e^-$ scattering will still be a difficult problem even with high-current proton accelerators.

6. NEUTRINO DIAGNOSTICS OF INTRAREACTOR PROCESSES

Neutrino investigations, especially in the last decade, have influenced the most varied fields of physics and experimental technology, although they have not had a direct spin-off in applied problems. Now that the purposeful development of atomic energy has led to the construction of power stations with reactors whose power is steadily increasing, the conditions have been created for the direct use of neutrino fluxes in technology. For example, Refs. 17 and 33 discuss the problem of monitoring a powerful reactor by means of antineutrino radiation—neutrino diagnostics of intrareactor processes. The antineutrino flux carries information of two kinds: a) the number N of $\tilde{\nu}_e$ detected in the detector is proportional to the energy release W of the reactor,

$$N = A\xi W, \tag{19}$$

where ξ is the efficiency of detection of useful events in the detector, and A is a coefficient that takes into account the geometrical situation of the detector, its volume, and so forth; b) the energy spectrum of the antineutrinos characterizes the fissioning substance.

Antineutrinos can be detected through the reaction (6) in a hydrogen-bearing liquid or a plastic scintillator through the positrons and γ rays from neutron capture by the method of "shifted coincidences." In this case, one measures the number and spectrum of the $\tilde{\nu}_e$. To determine the energy release, one can use a simpler detector that detects the antineutrinos through the neutrons of the reaction (6) by means of gas counters penetrating a hydrogen-bearing material.

In a detector with a useful volume of about 1 m^3 of organic material (in Ref. 33, four sections of 250 liters of liquid scintillator containing a gadolinium compound were considered) at a distance 15 m from the center of the core of the VVÉR-440 reactor the total number of events exceeds 10^4 events/day. If the detection efficiency is sufficiently good, this makes it possible to achieve an accuracy of relative measurements of the energy release of about 1% in a few days. To determine the efficiency of the detector sections, Monte Carlo calculations were made in Ref. 33. They showed that at a gadolinium concentration of 3 g/liter, and at the detection threshold for 1.5-MeV positrons and 3-MeV capture γ rays and expected time interval of the second event after the first of 20–40 μsec, the value of ξ lies in the range 0.35–0.5.

The introduction of delayed coincidences appreciably reduces the background, though in the room containing the detector it is necessary to put into effect numerous other measures to reduce the background from the reactor, cosmic rays, and the natural radioactivity of the surrounding materials. In the quoted studies, it was suggested that the facility should be placed under the reactor, that it should have a special shield of heavy concrete, and so forth. If these requirements are satisfied, the signal–background ratio can be raised to values 3–5.

Let us now consider some effects that could destroy the linear dependence (19):

1) The time delay between the measurements of the power level and the flux intensity. Such delay has already been discussed (see above). It is obvious that fluctuations in the reactor power will not affect the correctness of measurements of the energy release in an interval of measurements of the order of days.

2) "Extraneous" antineutrinos. They could arise as a result of neutron capture in various materials of the reactor with subsequent β decay of the neutrons. However, capture in typical materials (water, graphite, steel, boron, ^{238}U, ^{235}U, fuel element casings, concrete, etc.) either does not lead to the formation of β emitters at all, or the number and energy of the resulting $\tilde{\nu}_e$ is such that the effect is virtually negligible in the detector. What we have said above also applies to fission fragments that accumulate during the operation of the reactor.

3) If several fissioning isotopes contribute to the energy release, for example, ^{235}U and ^{239}Pu, the expression (19) must be modified to

$$N = A\xi_5 \left[1 + (\xi_9/\xi_5 - 1)(W_9/W)\right] W, \tag{20}$$

where ξ_5 and ξ_9 are the efficiencies of detection of the $\tilde{\nu}_e$ arising from the fission fragments of these isotopes, and W_9 is the contribution of Pu to the total energy release.

It can be seen from (20) that deviations from a linear dependence arise if the apparatus has different sensitivities for the U and Pu radiations, i.e., if $\xi_9/\xi_5 \neq 1$.

An estimate for power-station reactors of the type VVÉR and RBMK shows that for the detection of posi-

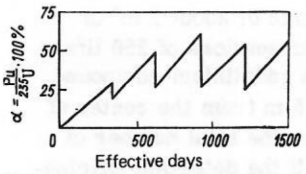

FIG. 12. Accumulation of ^{239}Pu in the core of the VVÉR-440 reactor.

trons in a wide energy range the correction term in the square brackets of (20) is very small (0.03–0.06) and, in addition, can be calculated on the basis of independent data, so that the corresponding error is less than 1%.

The dependence of the ratio α of the numbers of Pu and ^{235}U in the core on the effective days of operation of a reactor in the VVÉR-440 series is shown in Fig. 12. Fuel reloading occurred after 250, 600, 900, etc., effective days. At the end of the first year of operation, α reached 0.3, and after several years of operation 0.6–0.65. As ^{239}Pu accumulates in the reactor, the $\tilde{\nu}_e$ spectrum, and therefore the positron spectrum of the reaction (6), is deformed, especially in its hard region (see Table I). Comparison of it with the initial spectrum when the only antineutrino source was ^{235}U fission opens up the possibility of a direct determination of the amount of ^{239}Pu.

Successful development of methods of neutrino diagnostics would make it possible to create instruments for remote determination of the composition of fissioning materials in reactor cores, which would have great importance for the control of nuclear materials.

CONCLUSIONS

The restricted volume of the present review has not enabled us to describe the experiments to distinguish ν_e and $\tilde{\nu}_e$ proposed by Pontecorvo[75] and carried out by Davis.[76,77]

Important questions such as conservation of the lepton charge and neutrino oscillations have been considered in detail in the review of Bilen'kiĭ and Pontecorvo.[15] Also, we have not considered a number of proposals for using artificial radioactive elements obtained in reactors as $\tilde{\nu}_e$ sources.

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