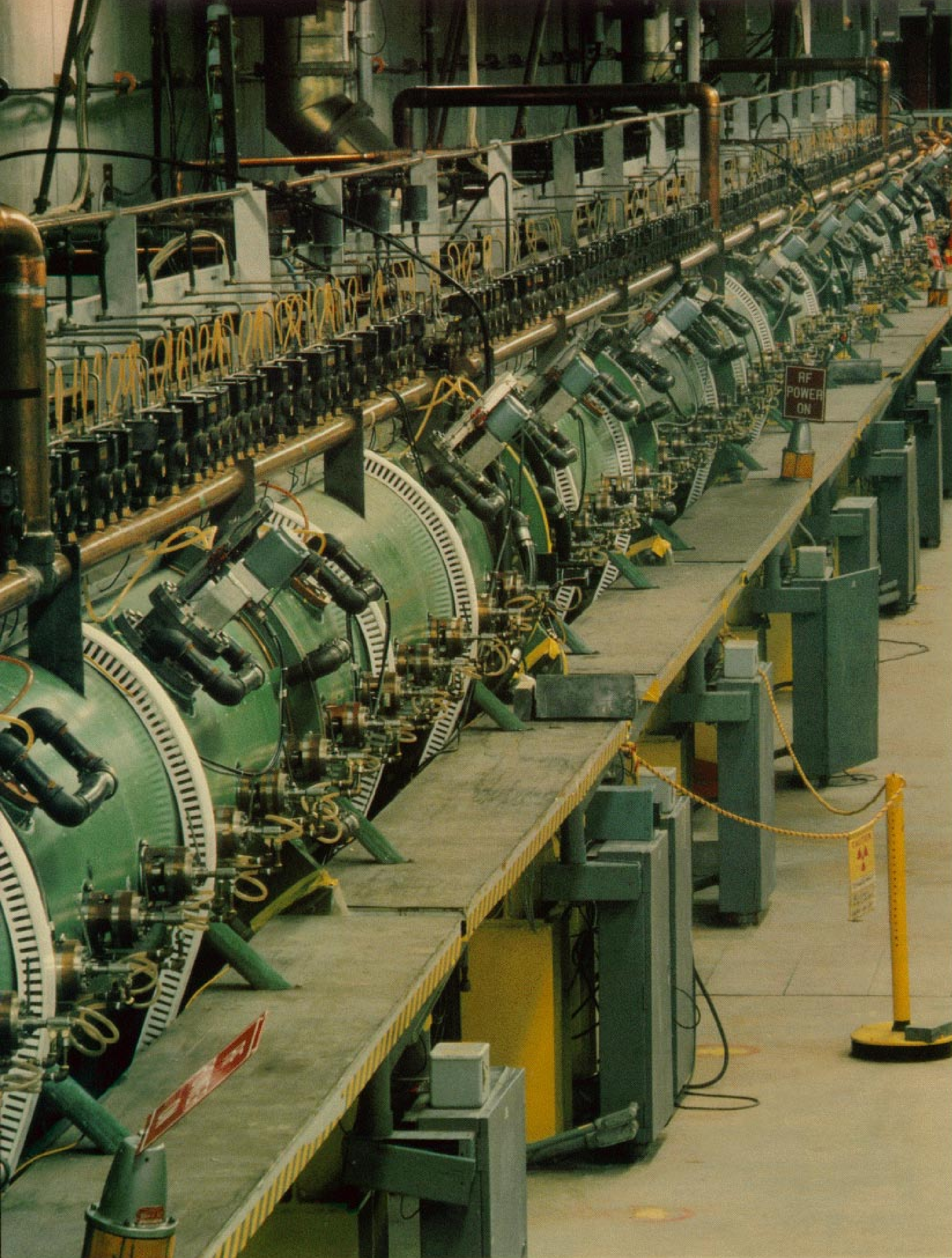
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the Neutrino in 1980

Neutrino experiments planned at the Los Alamos Meson Physics Facility and at the Nevada Test Site may hold the key to many advances in particle physics and cosmology.

by Thomas J. Bowles and Margaret L. Silbar

Fifty years ago scientists postulated the existence of the neutrino, a neutral, massless, spinning particle traveling at the speed of light, passing unimpeded through the whole earth and filling the universe in copious numbers. After numerous experiments and reformulations, the properties and behavior of the neutrino still challenge our theories about the forces and symmetries of nature.

The present puzzle concerns the results of a recent and controversial experiment, which indicate that neutrinos oscillate or spontaneously change their "flavor" as they travel through "empty" space—almost as if the apple falling from Newton's tree transformed itself into an orange before it struck him on the head. If this result is proved correct, it will mean that the neutrino, long assumed to be a massless particle, does have a nonzero rest mass. It will also mean that some of the conservation laws, which have been so successful in describing the phenomenology of weak interactions, will no longer apply to all physical processes.

Experiments are now being designed at Los Alamos and elsewhere to search further for evidence of a finite neutrino mass.

The Los Alamos Meson Physics Facility (LAMPF) provides the best testing ground for certain classes of ideas about neutrino oscillation, for it produces neutrino fluxes of uniquely high intensity and special composition and time structure. At the Nevada Test Site, the extremely high instantaneous neutrino fluxes available when nuclear devices are detonated provide other unequalled capabilities to test concepts of weak interactions,

The Laboratory has played a central role in the development of neutrino physics, for it was a Los Alamos team—Frederick Reines and the late Clyde Cowan, Jr.,—who first observed the neutrino in reactor experiments. This role will continue as experiments on neutrino oscillation and neutrino masses help test grand unified theories of fundamental particles. New data from these experiments may indicate the existence of totally new interactions in nature. They may even suggest that our expanding universe will come to a halt and finally contract.

Is the Neutrino Massless?

The possibility of a nonzero rest mass for the neutrino has been considered since 1930 when Wolfgang Pauli postulated its existence to save the laws of energy and momentum conservation in beta decay of radioactive nuclei. Originally beta decay was thought to be a two-body process in which a nucleus, such as RaE, changes to a unique final state, in this case RaF, and emits an electron (e-):

$$\mathrm{RaE}\ ({}^{210}_{83}\mathrm{Bi}) \rightarrow \mathrm{RaF}\ ({}^{210}_{84}\mathrm{Po}) + e^- \ .$$

Conservation of energy and momentum implies that all electrons in such a two-body decay reaction come out with the same energy. Instead, the emitted electrons have a wide spectrum of energies, as shown in Fig. 1. Pauli suggested that the missing energy was carried away by a highly penetrating (and hence, undetected) particle with no charge and little or no rest mass. He also noted that, to conserve angular momentum and to preserve the "law of spin and statistics," this neutral particle must be a fermion, a particle with an intrinsic spin of $^1/_2\hbar$.

In 1934, two years after the discovery of the neutron, Enrico Fermi used the neutrino hypothesis to formulate a theory of beta decay. This theory correctly predicted the shape of the electron spectrum and provided the central ideas for what was to become the theory of all weak interactions.

The basic process in nuclear beta decay is the change of a neutron (n) into a proton (p) with the emission of an electron and an antineutrino (ν):

$$n \rightarrow p + e^- + \bar{\nu}\ .$$

Fermi postulated that this process takes place through the direct interaction of these four particles, which are all fermiens. He assumed that the neutrino, like the other fermions, has a particle and an antiparticle form, but since the neutrino has no charge, and perhaps no magnetic moment, the distinction between neutrino and antineutrino was not then known.

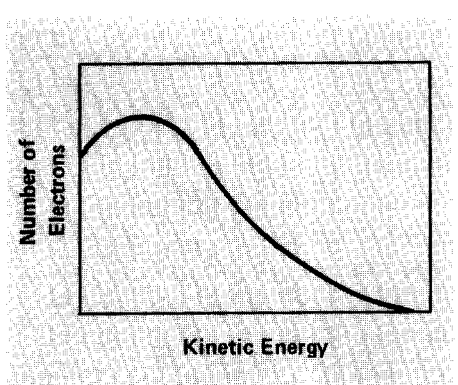


Fig. 1. Typical energy spectrum of electrons emitted in beta decay.

However, the mathematical form of the interaction dictated that fermion number (the number of fermions minus the number of antifermions) be conserved in the reaction. Since the neutron, the proton, and the electron are particles, and by convention are assigned a fermion number of + 1, the neutral, undetected particle emitted in beta decay must be the antineutrino with a fermion number of —1. Then the total fermion number is + 1 before and after the reaction. (As we will see, this and other number-conservation laws have played an important role in understanding and predicting weak-interaction processes.) But the question of whether or not the neutrino has a mass remained open.

That same year Hans Bethe and Rudolf Peierls pointed out that Fermi's theory allowed the neutrino to induce inverse beta decay:

$$\nu + p \rightarrow n + e^+\ .$$

This reaction provided a means for verifying the existence of the neutrino by observing the emitted neutron and positron. However, the probability for inverse beta decay is so low (the cross section is about $10^{-44}\ \mathrm{cm}^2$) that neutrino detection was not pursued until almost 20 years later when an intense source of antineutrinos became available from fission reactors.

In 1953. Frederick Reines and Clyde Cowan, Jr., reported results consistent

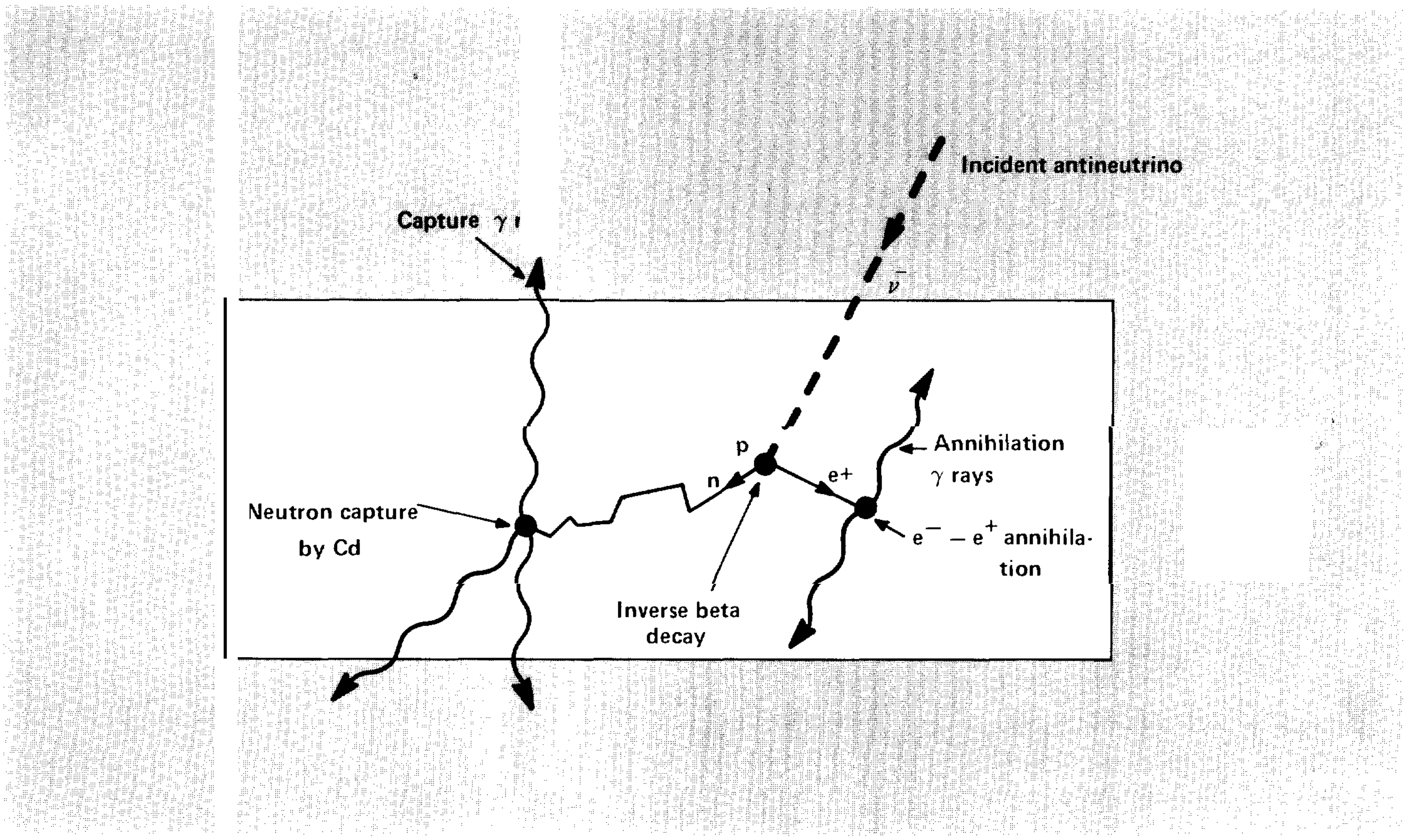


Fig. 2. Neutrinos can be detected by observing the events associated with inverse beta decay, the interaction of an antineutrino with a proton to produce a neutron and a positron. The positron annihilates with an electron to produce two gamma rays. The neutron eventually interacts with a nucleus with a high neutron-capture cross section, such as cadmium, to produce capture gamma rays. The positrons and/or the gamma rays are observed by their interactions with a detecting medium, such as a liquid scintillator.

with the occurrence of inverse beta decay in an experiment at the Hanford reactor. Incontrovertible proof of the neutrinos existence came three years later when Reines and Cowan. together with F. B. Harrison, Herald W. Kruse, and Austin D. McGuire, repeated the experiment at the Savannah River reactor. Figure 2 shows how neutrino-induced inverse beta decay can be observed.

By this time other weak processes were known, in particular the decay of the pion (π) into the muon (μ),

$$\pi \rightarrow \mu + \nu ,$$

and the decay of the muon,

$$\mu \rightarrow e + \nu + \bar{\nu} .$$

Although the neutrinos were not observed, their existence was assumed, this time to preserve lepton-number conservation, a special case of fermien-number conservation. A lepton is a fermion that does not participate in the strong interactions. Each lepton (e^-, μ^-, and ν) is assigned a lepton number of+ 1 and each antilepton (e^+, μ^+, and $\bar{\nu}$) a lepton number of –1. With these assigned numbers, the law of lepton-number conservation says that total lepton number remains constant in weak processes. This law, which emerges naturally from the assumed mathematical form of weak interactions, is consistent with all observed weak processes and explains the nonoccurrence of processes that would violate it.

Then, in 1957, the startling discovery that parity is not conserved in beta decay led to a major breakthrough in our conception of the neutrino and of weak interactions in general, At the suggestion of T. D. Lee and C. N. Yang, C. S. Wu and her collaborators measured the direction of electrons emitted in the beta decay of polarized Co^{60}. They found that 40% more electrons were emitted along the Co^{60} spin axis than opposite it. This near-maximum violation of parity, or right-left symmetry, could be explained if the antineutrinos emitted in beta decay exist only in a longitudinally polarized form, that is. with spin vector pointing either along or opposite the direction of motion (right- or left-polarized, respectively), but not both.

The property of longitudinal polarization led to a new and very appealing theory of the neutrino. Unlike other known fermions, whose wave functions have four components corresponding to particle and antiparticle in both right- and left-polarized states, the neutrino has only two components: the neutrino is *always* left-polarized, or more precisely. left-handed, and the antineutrino is *always* right-handed.* The other two components (right-handed neutrino and left-handed antineutrino) are missing. Such a two-component theory in which neutrino and antineutrino are distinguished by their handedness implies that the neutrino travels at the speed of light and is therefore a massless particle (see Fig. 3).

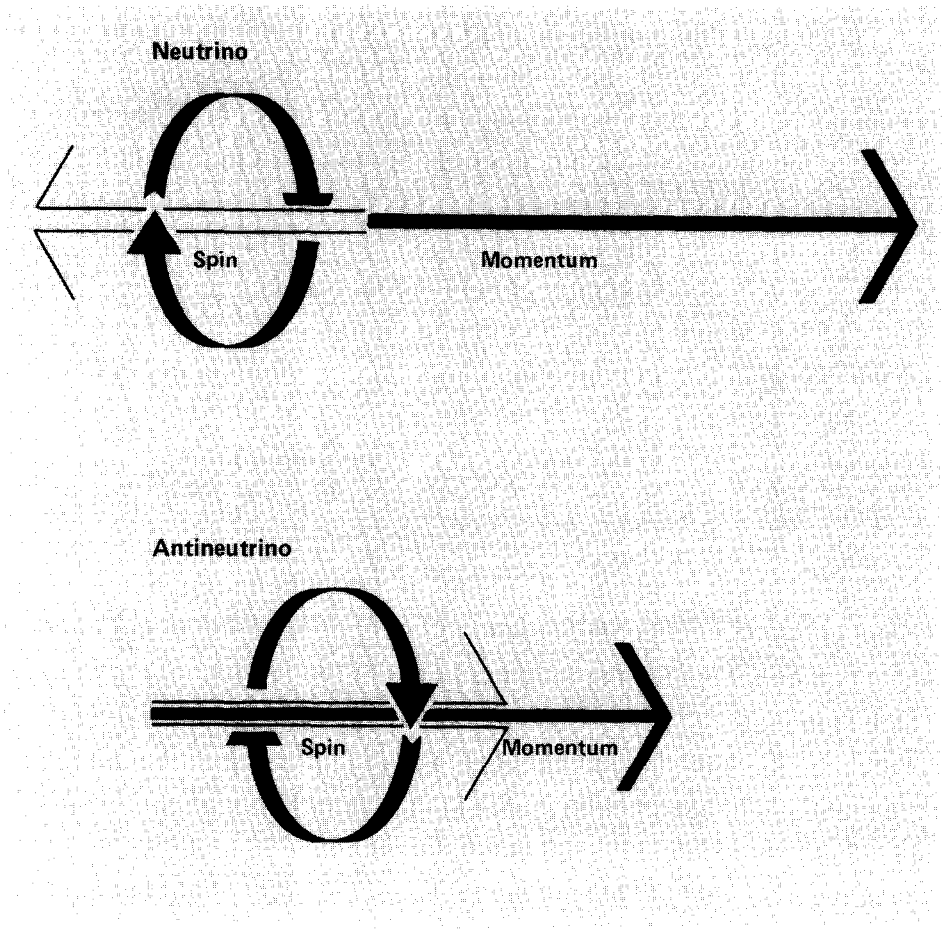


Fig. 3. In the standard two-component neutrino theory, the neutrino is a massless particle with intrinsic spin, or angular momentum, of $^1/_2\hbar$. The neutrino is always left-handed, that is, tile direction of its spin vector is opposite that of its momentum; the antineutrino is always right-handed with the direction of its spin vector the same as that of its momentum. This distinction between particle and antiparticle impossible only if the neutrino is traveling at the speed of light (and is therefore massless). Otherwise, transformation to a reference frame moving faster than the neutrino would reverse the momentum and cause the neutrino to appear to be an antineutrino.

The massless two-component neutrino theory had two important consequences for weak interactions. First, since the neutrino and its antiparticle were not the same, $\nu \neq \bar{\nu}$, it was possible to retain the lepton number assignments of + 1 and –1, respectively. Thus lepton-number conservation remained an exact law for weak interactions. Second, the left-handed character of the neutrino helped to establish a universal left-handed mathematical form for all weak-interaction processes, thus explaining why even massive particles emerging from such processes are partially polarized.

**Right- or left-handed is not exactly the same as right- or left-polarized except for massless particles, but for this discussion we will ignore the difference.*

We must emphasize that although the standard two-component theory implies that the neutrino is massless, it does not prove this as fact, It is possible to formulate a two-component theory for a massive neutrino consistent with the observed polarizations of participants in weak interactions. However, this alternative formulation (in which the two components correspond to the right- and left-handed neutrino) does not produce a lepton-number conservation law because the neutrino and the antineutrino are the same particle, that is, $\nu = \bar{\nu}$. The physics community favored the massless two-component theory. It was simple. It was aesthetically appealing. And, most important, it preserved lepton-number conservation.

This simple picture of the neutrino became more complex when, in 1963, experiments showed that neutrinos come in two "flavors." The quantum number flavor was postulated to explain the fact that antineutrinos from beta decay never produce positive muons. That is, if we call the antineutrino from beta decay $\bar{\nu}_e$, then

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

but

$$\nu_e + p \not\rightarrow n + \mu^+ \ .$$

Thus weak interactions separate the leptons into two families, the muon family consisting of the muon, the muon neutrino, and their antiparticles, and the electron family consisting of the electron, the electron neutrino, and their antiparticles. Further these two families are not "mixed" by weak interactions: a member of the muon family cannot by itself change into a member of the electron family. For example, a negative muon cannot decay into an electron unless a muon neutrino is emitted in the decay. Thus the decay $\mu^- \rightarrow \nu_\mu + e^- + \bar{\nu}_e$ does occur, but the decay $\mu^- \rightarrow e^- +$ y does not.

Lepton-number conservation was thus separated into muon-number conservation and electron-number conservation. Again, these conservation laws reflect the observed occurrence or nonoccurrence of various weak interactions. * Evidence for a third lepton family, the tau and the tau neutrino, has now produced a tau-number conservation law. The existence of three neutrino flavors did not, however, change the notion that each one was a massless, two-component particle.

That brings us to the present status of theories and observations about the neutrino. The hypotheses of a massless two-component neutrino and lepton-number conservation appear correct for all observed weak interactions and are incorporated into the Glashow-Weinberg-Salam model that unifies the electromagnetic and the weak forces.

Although all experiments to date support this simple picture of the neutrino, there is no fundamental reason why the neutrino should be massless. In fact, modern views of fundamental forces which incorporate the Glashow-Weinberg-Salam model into a larger model suggest that neutrinos have a small rest mass and that effects of this rest mass can be observed through the phenomenon of neutrino oscillation between members of different lepton families.

Neutrino Oscillation—A Recurring Idea

The first suggestion that neutrinos might oscillate—periodically change from one form to another—came from Bruno Pontecorvo in 1957. He noted that if the massless two-component neutrino theory was wrong, that is, if neutrinos were massive and lepton-number conservation was violated, then the neutrino, like the neutral K meson, might oscillate between its particle and antiparticle forms. This possibility was not explored because at that time the physics community was just beginning to accept the massless two-component theory of the neutrino.

In 1963, as a result of the discovery of the muon neutrino, the idea of oscillation surfaced again—this time between the electron neutrino and the muon neutrino—and in 1969 gained some respectability as a possible explanation for the solar neutrino puzzle. (See Kolb's commentary, "Neutrinos in Cosmology and Astrophysics.") It nonetheless remained on the fringes of theoretical physics because it violated the empirically established conservation laws of muon number and electron number.

Only in the last few years has the possibility of neutrino oscillation been taken more seriously, Indeed, this phenomenon is a natural result of radically new schemes that attempt a unified description of all fundamental interactions. (See Goldman's commentary, "Neutrinos and Grand Unified Theories.") To achieve unification, these theories must postulate that at least some of

Experiments to search for reactions that violate muon-number conservation are discussed by Cy Hoffman and Minh Duong-Van in Los Alamos Science, I, No. 1,62-67 (1980).

the empirical number-conservation laws are not exact. The theories suggest that, at very high energies (or, equivalently, at very small distances), neutrinos and the other leptons become indistinguishable from the quarks, which are the constituents of those particles (such as the proton and the pion) that interact through the strong force. In this framework neutrinos acquire a nonzero rest mass just as do all the other fundamental constituents of matter. Thus, the major philosophical objections to oscillation have been swept away.

In fact, the structure of unified theories suggests that neutrino oscillation does occur. The terms in these theories that could give the neutrino its mass are not likely to have the same symmetry as those describing weak interactions; these mass terms might mix members of the different lepton families and thereby produce oscillations between different neutrino flavors ($\nu_e \leftrightarrow \nu_\mu$) or they might produce oscillations between particle and antiparticle forms ($\nu_{e,\mu} \leftrightarrow \bar{\nu}_{e,\mu}$) as originally suggested by Pontecorvo. Further, if the neutrino is massive, it might actually be a four-component fermion whose two unseen components take part in "superweak" interactions that have yet to be observed. Thus the discovery of massive neutrinos through oscillation experiments or direct measurements would open up a Pandora's box of new possibilities for the elusive and still puzzling neutrino.

New Results and New Plans

We can now understand the excitement created by the announcement in 1980 of the controversial experiment mentioned at the beginning of this article. The experiment, performed at the Savannah River reactor by a group from the University of California at Irvine, provided evidence for neutrino oscillation, evidence that implies a nonzero rest mass for at least one neutrino type. Oscillation experiments determine not a value for the mass of a neutrino, but rather a value for $m_1^2 - m_2^2$, where m_1 and m_2 are the eigenmasses of the neutrino mass eigenstates defined by the lepton-mixing mass terms referred to above. This difference is said by the Irvine group to be about 1 $(eV)^2$.

The implied existence of massive neutrinos is supported by another recent experiment. A group at the Institute of Theoretical and Experimental Physics in Moscow measured the neutrino mass directly from a careful analysis of the spectrum of electrons emitted in the beta decay of tritium, $H^3 \rightarrow He^3 + e^- + \bar{\nu}_e$. The deviation between their experimentally determined spectrum and that expected for a massless neutrino indicates a value for the rest mass of the electron antineutrino of at least 14 eV, with a most probable value of $\sim$35 eV. (The rest mass of the electron is 511 keV.) Although no one has yet found fault with this experiment, there is concern that the observed deviation may be due to interactions of the electrons as they leave the sample, which in this case was solid (tritium in an amino acid deposited on an aluminum backing).

To eliminate this uncertainty, a Michigan State University-Los Alamos group is planning a similar experiment at Los Alamos, in which the source consists of a cold (10 K), monatomic tritium beam. As the beam passes through a l-m long decay region, the spectrum of electrons from beta decay of tritium will be measured with a magnetic spectrometer and analyzed for evidence of a nonzero neutrino mass. Recent work by solid-state physicists at the University of Amsterdam and at the Massachusetts Institute of Technology promises atomic beams in the near future of sufficient intensity to permit verification of the Moscow result.

Physicists at Los Alamos National Laboratory also plan to address the question of neutrino mass by searching for evidence of neutrino oscillation both at LAMPF and at the Nevada Test Site.

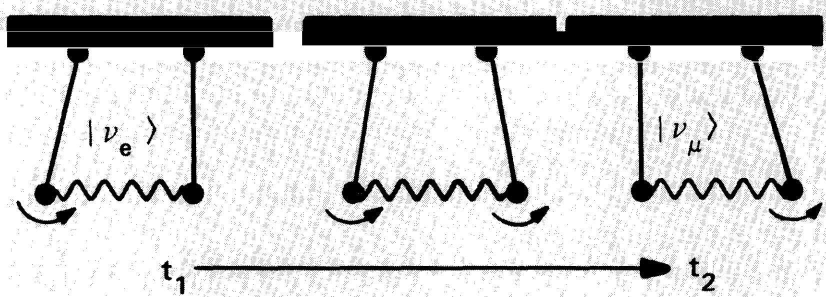
The Mechanism of Oscillation

Oscillation of one neutrino flavor into another and back again seems very mysterious because it conjures up the image of matter suddenly disappearing and just as suddenly reappearing. But this quantum-mechanical phenomenon becomes more intelligible when we realize that it is analogous in many ways to the classical phenomenon of energy transfer between the two (identical) bobs of a double pendulum system (see Fig. 4).

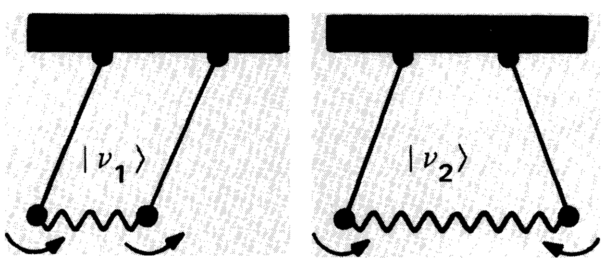
We know that if we start the pendulum by swinging only one bob, after some time the second bob will be swinging and the first will be stationary; still later the second bob will be stationary and the first bob will again be swinging. The change of an electron neutrino into a muon neutrino and back again is analogous to this periodic transfer of energy between the two bobs.

Why does this transfer occur? In the case of the double pendulum it occurs because the pendulums are coupled by a spring between the bobs. In the case of massive neutrinos it would occur if different neutrino flavors are coupled by

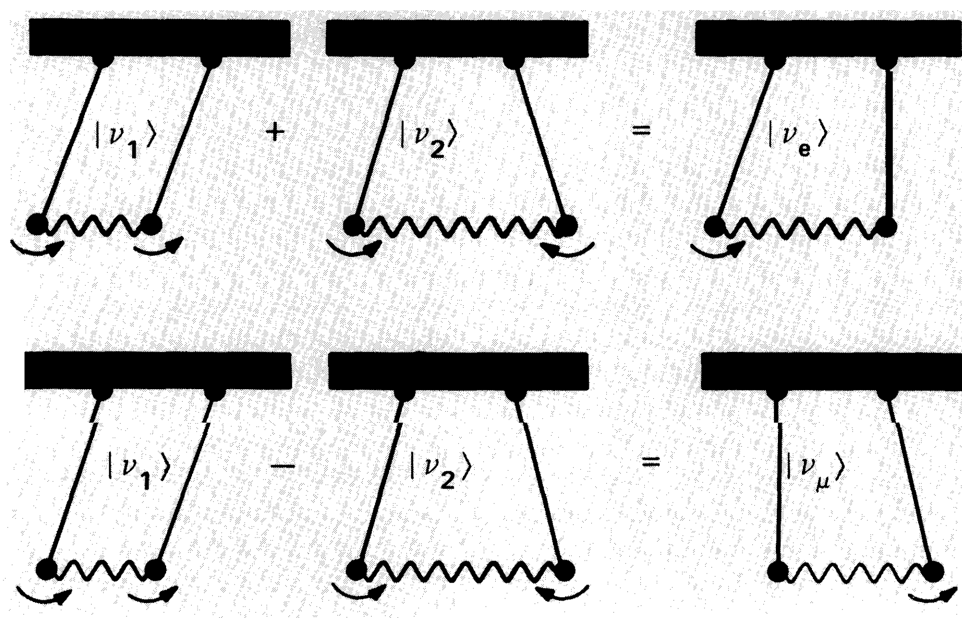
Fig. 4. An analogy between neutrino oscillation and periodic energy transfer in a coupled double pendulum.



At time t_1, the left pendulum swings alone. Coupling of the two pendulums by a spring between the bobs causes energy to be transferred until, at some time t_2, all the energy has been transferred to the right pendulum. Then the process reverses. This periodic energy transfer is analogous to the quantum-mechanical oscillation between an electron neutrino and a muon neutrino in which the probability of finding an electron neutrino gradually decreases from unity to a minimum (determined by the mixing angle θ) and then increases again to unity.



The coupled double pendulum has two stationary states, or normal modes. The mode in which the two pendulums swing in phase has a lower oscillation frequency than the mode in which the pendulums swing completely (180°) out of phase.



Addition and substraction of the normal modes (with appropriate normalizing factors) yield motion of the right pendulum and motion of the left pendulum, respectively.

***In this normal mode description, energy transfers from the left to the right pendulum because the different oscillation frequencies of the normal modes cause the relative phase between them to change with time. Similarly the mass difference between the neutrino** mass eigenstates causes the combination of mass eigenstates representing the electron neutrino to evolve with time into that representing the muon neutrino.*

the proposed lepton-mixing mass terms.

The time it takes for energy to transfer from one pendulum bob to the other depends on the frequency difference between the double pendulum's two normal modes of oscillation; similarly, the time it takes for one neutrino flavor to oscillate into another depends on the difference between the squares of the two neutrino eigenmasses $(m_1^2 - m_2^2)$.

To understand this dependence we must continue our analogy on a mathematical level. Consider the possibility that the electron and muon neutrinos produced in weak processes acquire mass as a result of new interactions that mix members of the muon and electron families.* Then although these neutrinos do not have definite masses, their wave functions $|\nu_e\rangle$ and $|\nu_\mu\rangle$ can be described by linear combinations of two other neutrino wave functions $|\nu_1\rangle$ and $|\nu_2\rangle$ that do have definite eigenmasses m_1 and m_2, respectively.

$$|\nu_e\rangle = \cos\theta\,|\nu_1\rangle + \sin\theta\,|\nu_2\rangle \qquad (1)$$

and

$$|\nu_\mu\rangle = -\sin\theta\,|\nu_1\rangle + \cos\theta\,|\nu_2\rangle\ , \qquad (2)$$

where θ, the mixing angle, describes the extent to which ν_e, and ν_μ are mixed by the new interaction. If m_1 does not equal m_2, oscillation between ν_e and ν_μ will occur. That is, as the state $|\nu_e\rangle$ produced at t = O propagates in time, the relative phase between its $|\nu_1\rangle$ and $|\nu_2\rangle$ components will change so that the state $|\nu_e\rangle$ will begin to disappear and the state $|\nu_\mu\rangle$ will begin to appear.

This is exactly analogous to the time evolution of the double pendulum. We can identify $|\nu_e\rangle$ and $|\nu_\mu\rangle$ with the states describing the swing of one or the other pendulum bob, and $|\nu_1\rangle$ and $|\nu_2\rangle$ with the normal modes, or stationary states, of the pendulum corresponding to the two bobs swinging exactly in phase and exactly out of phase, respectively. The swing of one bob or the other corresponds to addition or subtraction of equal parts of the two normal modes, respectively [Eqs. (1) and (2) with $\theta = \pi/4$]. But the two normal modes have different frequencies. (The mode in which the bobs swing in opposite directions has a higher frequency because the spring restricts the separating motion.) Consequently the relative phase between the two normal modes changes with time so that the additive combination describing the swing of one bob [Eq. (l)] eventually changes into the subtractive combination describing the swing of the second bob [Eq. (2)].

Analysis of the electron neutrinos time evolution is similar and is given in the accompanying note "Derivation of Neutrino Oscillation Length." Here we simply state the results. As an electron neutrino produced at t = O travels through space at almost the speed of light, c, it will periodically disappear and reappear over a characteristic length $L \cong cT$ where T is the period of neutrino oscillation. L is called the oscillation length. Thus the probability $P_{ee}(x)$ that an electron neutrino has not oscillated into another type of neutrino at a distance x from the source is given by

$$P_{ee}(x) = 1 - (\tfrac{1}{2}\sin^2 2\theta)\,[1 - \cos(2\pi x/L)]\ ,$$

where θ, the mixing angle that appears in Eqs. (1) and (2), determines the amplitude of the oscillation. The oscillation length L in meters is given by

$$L = 2.5\ E_\nu/\delta m^2\ ,$$

where E_ν is the neutrino energy in MeV and δm^2 is $m_1^2 - m_2^2$ in $(\mathrm{eV})^2$.

Designing Oscillation Experiments

The equation for $P_{ee}(x)$ says that oscillation effects are maximum at half-integer multiples of L. Therefore, to detect oscillation the distance between the neutrino source and the detector must be at least the same order of magnitude as L. However, δm^2 and hence L are unknown.

Theoretical considerations suggest that δm^2 may be very small and hence L may be very large. Consequently, to be sensitive to low values of δm^2, detectors should be placed at the farthest distance from the source consistent with obtaining a measurable signal. In addition, to minimize the oscillation length as much as possible, experiments should exploit sources of low-energy neutrinos. The most convincing experiments will be those that demonstrate, by changes in the source-detector distance, the variation with distance of the number of neutrinos of a particular type.

Neutrinos of a particular type are detected by observing the reactions they induce in a detecting medium. For example, if protons are the medium and electron antineutrinos from beta decay

**In actuality, we may be dealing with the mixing of more than just two neutrino types. The formalism, however, remains the same. Ultimately, the question of which neutrinos mix with which no doubt depends on how many different neutrinos exist.*

are the source, a reaction to observe is inverse beta decay, $\bar{\nu}_e + p \rightarrow n + e^+$. The signature of this reaction is the delayed coincidence of photons from annihilation of the positron and from capture of the neutron. A decrease in the rate of this reaction from that predicted for massless neutrinos would be evidence for neutrino oscillation. (An experiment of this kind is known as a disappearance experiment.)

To determine such a change in an already low reaction rate is a tremendous challenge. The experiments require extensive shielding to minimize background events and sophisticated detectors to differentiate background from events of interest. Detectors are similar in concept to that used by Reines and Cowan, but they are more sensitive. Made up of multiple units monitored by modern electronics, these detectors obtain fine-grained information about the sources of the measured signals.

Despite the size of present detectors, the expected count rates are still quite low. For example, at LAMPF with a typical neutrino flux of 10^{10} neutrinos per second incident on a 50-ton detector (a not abnormally large size) located 100 m from the LAMPF beam stop, one can expect to observe an interaction of interest in the detector only once every three or four hours.

As diffiicult as these experiments may be, their implications for grand unified theories and cosmology provide a compelling motive to attempt them.

Oscillation Experiments So Far

The Irvine group, who have claimed positive results, used neutrinos from the Savannah River reactor to search for the

Derivation of Neutrino Oscillation Length

Some simple algebra can show how neutrino oscillation effects depend on the mass difference of the neutrino mass eigenstates. We express the quantum-mechanical wave function for an electron neutrino produced at t = O as a mixture of the mass eigenstates $|\nu_1\rangle$ and $|\nu_2\rangle$ with masses m_1 and m_2.

$$|\nu(0)\rangle = |\nu_e\rangle = \cos\theta\,|\nu_1\rangle + \sin\theta\,|\nu_2\rangle ,$$

where 0, the mixing angle, characterizes the extent of mixing of the mass eigenstates in the weak-interaction eigenstate. At a later time t, the wave function is

$$|\nu(t)\rangle = \cos\theta\,\exp(-iE_1t)\,|\nu_1\rangle + \sin\theta\,\exp(-iE_2t)|\nu_2\rangle ,$$

where E_1 and E_2 are the energies of $|\nu_1\rangle$ and $|\nu_2\rangle$. For relativistic neutrinos ($E_\nu \gg m$), we can approximate E_1 and E_2 by

$$E_k = (p^2 + m_k^2)^{1/2} \cong p + m_k^2/2p .$$

After substituting these energies, $|\nu(t)\rangle$ becomes

$$|\nu(t)\rangle = \exp[-it\,(p + m_1^2/2E_\nu)][\cos\theta\,|\nu_1\rangle + \sin\theta|\nu_2\rangle\,\exp(i\delta m^2t/2E_\nu] ,$$

where $\delta m^2 = m_1^2 - m_2^2$ and $E_\nu \cong p$. Since these neutrinos are traveling almost at the speed of light, we can replace t by x/c, where x is the distance from the source of electron neutrinos. Then we calculate $P_{ee}(x)$, the probability of finding an electron neutrino at x.

$$\begin{aligned} P_{ee}(x) &= |\langle\nu(0)|\nu(t = x/c)\rangle|^2 \\ &= |\cos^2\theta + \sin^2\theta\,\exp(i\delta m^2x/2E_\nu c)|^2 \\ &= \cos^4\theta + \sin^4\theta + 2\cos^2\theta\,\sin^2\theta\,\cos(\delta m^2x/2E_\nu c) . \end{aligned}$$

Adding and substracting $2\cos^2\theta\,\sin^2\theta = \frac{1}{2}\sin^2 2\theta$ and setting $L = 2\pi cE_\nu/\delta m^2$, we obtain

$$P_{ee}(x) = 1 - (\tfrac{1}{2}\sin^2 2\theta)\,[1 - \cos(2\pi x/L)] .$$

Thus the probability oscillates with distance and the oscillation length L is given in meters by

$$L = 2.5\,E_\nu/\delta m^2 ,$$

where E_ν is in MeV and δm^2 is in $(eV)^2$ ■

transition $\bar{\nu}_e \rightarrow$ anything. They measured the cross sections for both a "charged current" and a "neutral current" reaction* induced by an electron antineutrino on a deuteron:

$$\bar{\nu}_e + d \begin{cases} \nearrow n + n + e^+ \text{ (charged current reaction).} \\ \searrow n + p + \bar{\nu}_e \text{ (neutral current reaction).} \end{cases}$$

The detecting medium, located 11,2 m from the reactor core, consisted of 268 kg of heavy water in which were placed 10 ^{3}He-filled proportional counters for measuring coincident and single neutron counts. Liquid-scintillator anti-coincidence counters surrounded the detector, which was enclosed in a lead and cadmium shield.

The cross section for the neutral current reaction is independent of the type of neutrino that initiates the reaction. The charged current reaction, in contrast, can be induced only by the electron antineutrino. If neutrino oscillation occurs, the count rate for two-neutron events will be reduced relative to the count rate for one-neutron events.

From their data, the Irvine group derived a "ratio of ratios" (the ratio of the experimental cross sections for the two reactions divided by the ratio of the theoretical cross sections). For massless neutrinos this ratio of ratios should be unity. The Irvine group's currently reported value of 0.38 ± 0.21 led them to claim that neutrino oscillation does occur.

The controversy associated with this experiment is due to the fact that its results are not confirmed by another experiment performed in Grenoble at the Laue-Langevin Institute's reactor. A group from the California Institute of Technology, the Nuclear Sciences Institute (Grenoble), and the Technical University of Munich also searched for the transition $\bar{\nu}_e \rightarrow$ anything by determining the rate of inverse beta decay. The detecting medium, located 8.7 m from the reactor core, consisted of 375 liters of proton-rich liquid scintillator for photon detection and neutron moderation and ^{3}He-filled proportional counters for neutron detection. Using a neutrino energy spectrum calculated by Davis and Vogel, the group found no deviation from the expected rate of inverse beta decay and therefore concluded that oscillation at the level seen by the Irvine group does not occur. For maximum mixing ($\theta = \pi/4$), the Grenoble experiment set* an upper limit on δm^2 of 0.16 (eV)^2. The Irvine group claims** $\delta m^2 = 1$ (eV)^2 and $\sin^2 2\theta = 0.5$ ($2\theta = \pi/4$).

The largest uncertainty in the results of both these experiments lies in the energy spectra of neutrinos from the reactors, which for the original analyses were calculated theoretically. The Irvine group claims that its ratio of ratios is insensitive to both experimental and theoretical uncertainties, but both groups are now performing experiments to check calculations of the neutrino spectra. Preliminary data from a direct measurement by the Grenoble group support their calculated spectrum. This group has since moved its experiment to a reactor in Gösgen, Switzerland, where they plan to obtain data at source-detector distances of 35-80 m. The Irvine group, in turn, has begun direct spectrum measurements at the Savannah River reactor and is obtaining further oscillation data at distances of 11-38 m.

Other information on oscillation exists from an experiment performed at LAMPF by a group primarily from Yale University and Los Alamos. This experiment set an upper limit on δm^2 of 0.9 (eV)^2 for the transition $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ and 3.0 (eV)^2 for the transition $\nu_e \rightarrow$ anything.*

Figure 5 shows the limits on δm^2 set by these experiments.

Whether the evidence for neutrino oscillation is confirmed or eventually refuted, these experiments have stimulated tremendous interest in the scientific community and many experimental groups are planning even more sensitive experiments to determine neutrino masses and mixing angles.

Neutrinos at LAMPF

As a source of neutrinos, LAMPF offers two great advantages: neutrino fluxes much greater than those of any other accelerator facility, and low neutrino energies (20-53 MeV) particularly suited to oscillation experiments. It also offers a unique opportunity to study muon neutrino oscillations at low

Charged current or neutral current refers to the charge of the hypothetical intermediate vector boson that mediates the reaction.

As reported (at the 90% confidence level) by F. Boehm et al. in "Neutrino Oscillation Experiment at the ILL Reactor at Grenoble," presentation at the International Conference on Neutrino Physics and Astrophysics: Neutrino 80, Erice, Sicily, June 23-27, 1980 (to be published).

**As reported (at the 68% confidence level) by F. Reines *et al.* in "Evidence for Neutrino Instability," presentation at the Spring Meeting of the American Physical Society, Washington, D. C., April 28-May 1, 1980 and submitted to Physical Review Letters.

**Unless otherwise noted, all upper limits on* δm^2 are at the 90% confidence level.

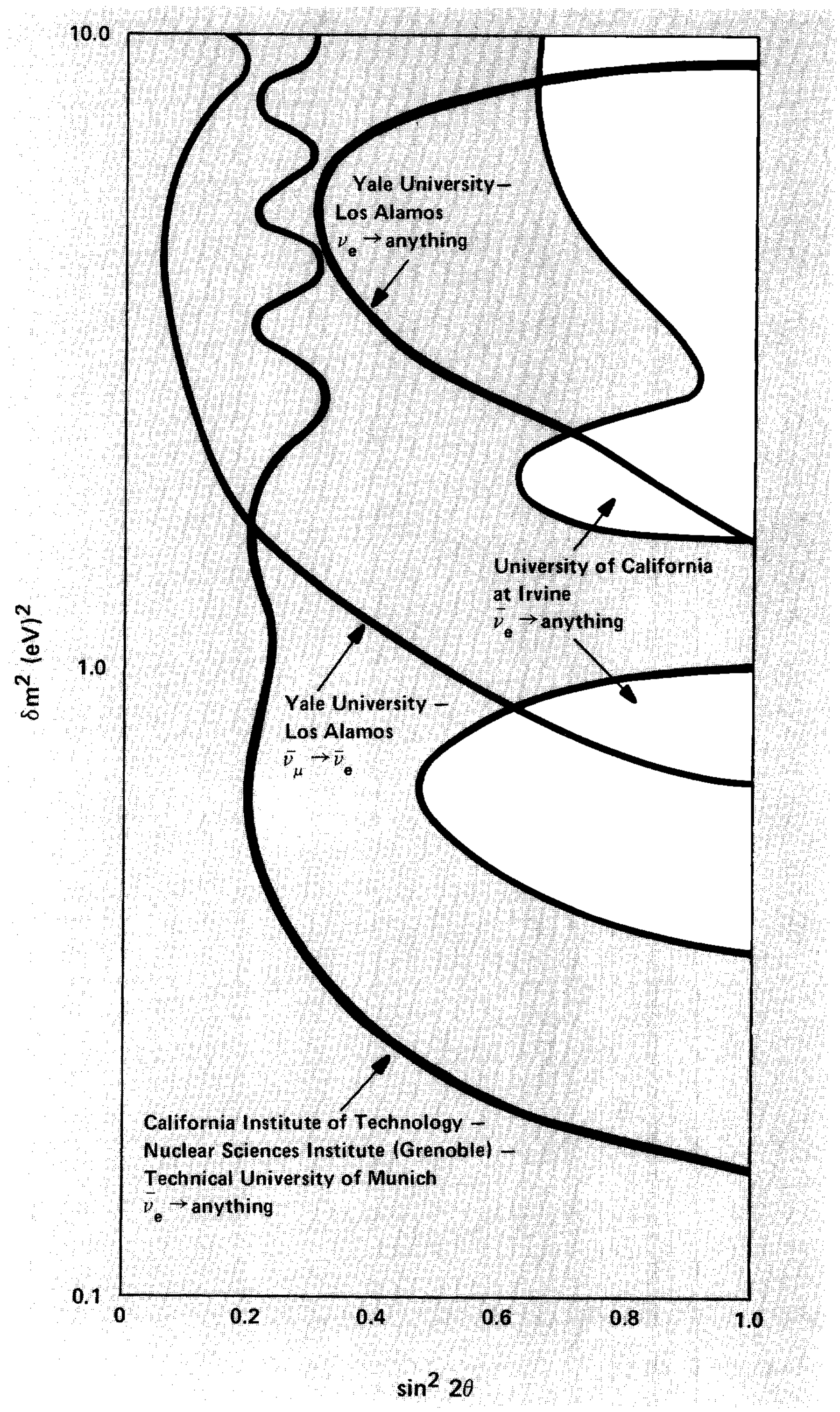


Fig. 5. Results of completed neutrino experiments appear to be contradictory. The Irvine group's positive results for δm^2 *as a function of mixing angle* θ *(claimed at the 68% confidence level are shown by the unshaded region. Negative results from other experiments established upper limit curves for* δm^2 *as a function of 0, shown here at the 90% confidence level. According to these later experiments, possible values of* δm^2 *and* $\sin^2\theta$ *lie to the left and below these upper limit curves.*

Aerial view of the Clinton P. Anderson Meson Physics Facility (LAMPF). The beam stop and neutrino facility, dwarfed by other experimental areas, are located at the far right.

energies.

Neutrinos at LAMPF are produced by the decay of pions and muons. Protons that remain after passing through the upstream targets are brought to rest in the beam stop at the end of the accelerator. In the process, they collide with atoms in the beam stop to produce the three charge states of the pion: π^+, π^0, and π^-. The neutral pions decay into photons and the negative pions are almost completely absorbed in nuclear reactions. The positive pions come to rest and decay by the reaction $\pi^+ \rightarrow \mu^+ + \nu_\mu$. The positive muon in turn decays by the reaction $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$. Note that these two decays yield no electron antineutrinos.

The two oscillation experiments scheduled to begin at LAMPF' in early 1981 take advantage of this fact. Both are designed to search for the transition $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ by determining the rate of inverse beta decay. Occurrence of this reaction at a rate significantly higher than expected from background events will be clear evidence of neutrino oscillation. (Such experiments are called appearance experiments because electron antineutrinos appear in a beam that originally had none.)

One experiment, an Irvine-Los Alamos collaboration, is an outgrowth of a long-planned study of the elastic scattering of electron neutrinos by electrons. The heart of this experiment is a 14-ton "sandwich" detector to be located inside the neutrino facility, an "iron house" about 10 m from the beam stop. The detector, which contains 10 tons of plastic scintillator and 4 tons of polypropylene flash chambers, will measure the energy, position, and direction of motion of the recoil electrons

Marilyn Barlett is shown assembling several of the 600 d@ tube modules to be used in the anticoincidence counter of the Irvine-Los A lames neutrino oscillation experiment at LAMPF.

TABLE I

NEUTRINO OSCILLATION EXPERIMENTS

Experiment	E_ν (MeV)	Source-Detector Distance (m)	δm^2 for $\sin^2 2\theta = 1$[a] $(eV)^2$	Transition	Observed Reaction
University of California at Irvine SITE: Reactor, Savannah River Plant STATUS: Completed	1-8	11.2	~1[b]	$\bar{\nu}_e \rightarrow$ anything	$\bar{\nu}_e + d \rightarrow n + n + e^+$ $\bar{\nu}_e + d \rightarrow n + p + \bar{\nu}_e$
California Institute of Technology Nuclear Sciences Institute (Grenoble) Technical University of Munich SITE: Reactor, Laue-Langevin Institute STATUS: Completed	1-8	8.7	<0.16	$\bar{\nu}_e \rightarrow$ anything	$\bar{\nu}_e + p \rightarrow n + e^+$
Yale University Los Alamos National Laboratory SITE: LAMPF STATUS: Completed	20-53	9	<0.9 <3.0	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ $\nu_e \rightarrow$ anything	$\bar{\nu}_e + p \rightarrow n + e^+$ $\nu_e + d \rightarrow p + p + e^-$
University of California at Irvine SITE: Reactor, Savannah River Plant STATUS: In progress	1-8	11-38[c]	<0.1	$\bar{\nu}_e \rightarrow$ anything	$\bar{\nu}_e + p \rightarrow n + e^+$
California Institute of Technology Nuclear Sciences Institute (Grenoble) Technical University of Munich SITE: Reactor, Gösgen, Switzerland STATUS: In progress	1-8	35-80[c]	<0.1	$\bar{\nu}_e \rightarrow$ anything	$\bar{\nu}_e + p \rightarrow n + e^+$
University of California at Irvine Los Alamos National Laboratory SITE: LAMPF STATUS: Approved for 1981	20-53	10	<0.4	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	$\bar{\nu}_e + p \rightarrow n + e^+$
Los Alamos National Laboratory SITE: LAMPF STATUS: Approved for 1981	20-53	33[d]	<0.15	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	$\bar{\nu}_e + p \rightarrow n + e^+$
Los Alamos National Laboratory SITE: Nevada Test Site STATUS: Approved for 1981-82	1.8-8	200-1200[c]	<0.0005, <0.005[e]	$\bar{\nu}_e \rightarrow$ anything	$\bar{\nu}_e + p \rightarrow n + e^+$
Rice University University of Houston Los Alamos National Laboratory SITE: LAMPF STATUS: Proposed	20-53	50-75[c]	<0.06, <0.12[f]	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	$\bar{\nu}_e + p \rightarrow n + e^+$
Ohio State University Argonne National Laboratory Louisiana State University California Institute of Technology SITE: LAMPF STATUS: Proposed	20-53	25-60[c]	<0.2	$\nu_e \rightarrow$ anything	$\nu_e + d \rightarrow p + p + e^-$
Los Alamos National Laboratory SITE: LAMPF STATUS: Proposed	60-250	40-300[c]	<0.025 <0.2	$\left\{ \begin{array}{c} \nu_\mu \rightarrow \nu_e \\ \text{plus } \bar{\nu}_\mu \rightarrow \bar{\nu}_e \end{array} \right\}$ $\left\{ \begin{array}{c} \nu_\mu \rightarrow \text{anything} \\ \text{plus } \bar{\nu}_\mu \rightarrow \text{anything} \end{array} \right\}$	$\nu_e + n \rightarrow p + e^-$ $\bar{\nu}_e + p \rightarrow n + e^+$ $\nu_\mu + n \rightarrow p + \mu^-$ $\bar{\nu}_\mu + p \rightarrow n + \mu^+$

[a] *Unless otherwise noted, all δm^2 values are at the 90% confidence level.*

[b] *The Irvine group claimed $\delta m^2 = 1\ (eV)^2$ for $\sin^2 2\theta = 0.5$ (at the 68% confidence level).*

[c] *Several source-detector distances in this range will be investigated.*

[d] *If positive results are observed at this distance, the detector will be moved.*

[e] *The smaller upper limit on δm^2 is that projected for use of several detectors on each of several weapon tests.*

[f] *The smaller and larger upper limits on δm^2 are those projected with and without neutron detection, respectively.*

from elastic neutrino-electron scattering. In the search for neutrino oscillation, the same quantities will be measured for the positrons from inverse beta decay reactions. The Irvine-Los Alamos group expects to place an upper limit on δm^2 of 0.4 $(eV)^2$, assuming maximum neutrino mixing.

The other scheduled experiment, a Los Alamos effort, is in some sense a preliminary experiment: its first objective is to test a 5-ton detector being assembled at LAMPF but planned for eventual use in neutrino oscillation experiments at the Nevada Test Site where tests of fission weapons provide an extremely brief but extremely intense pulse of neutrinos. The detector, containing 4470 liters (-5 ton) of gadolinium-loaded liquid scintillator and surrounded by an anticoincidence shield, will be located 33 m from the LAMPF beam stop in a hole drilled in tuff and will be covered with about 8 m of sand and iron for shielding. If cosmic-ray backgrounds are found to be sufficiently low, the group will search for the transition $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$. Both the positrons and the neutrons from inverse beta decay will be detected. During a 110-day run with one detector (the possibility of more detectors is being considered), the group hopes to set an upper limit on δm^2 of 0.15 $(eV)^2$. If warranted by observation of positive results, the detector can, with modest effort, be relocated at other source-detector distances. Background information garnered by the group will also be used by later experiments.

The group also believes that it may be possible to search for the transition $\nu_e \rightarrow$ anything by determining the rate of the reaction $\nu_e + Pb \rightarrow (Bi^* \rightarrow Bi + n) + e^-$. If so, then their experiment would be simultaneously an appearance and a disappearance experiment (and could thus serve to refute or verify the Irvine group's results).

Neither of these experiments in their currently approved forms constitutes what has been called the definitive test: detection of the same transition at the same neutrino energy but at varying source-detector distances. However, when the 5-ton Los Alamos detector is moved to the Nevada Test Site, it will, again if warranted by observation of positive results, be positioned at various source-detector distances.

Three new proposals for experiments at LAMPF involve the search for oscillation effects as a function of distance. We will briefly discuss the Nevada Test Site experiment and three proposed LAMPF experiments.

Table I summarizes the status and basic parameters of all the neutrino oscillation experiments discussed.

Neutrinos at the Nevada Test Site

The Los Alamos experiment at the Nevada Test Site, a disappearance experiment like those performed at reactors, will be a search for a rate of the reaction $\bar{\nu}_e + p \rightarrow n + e^+$ that is lower than expected in the absence of oscillation. Here, sensitivity to small values of δm^2 will be greater than at reactors because of the larger source-detector distances (200-1200 m). Test of a fission weapon produces a short but very intense pulse of electron antineutrinos. Signal-to-noise ratios will therefore be high. On the other hand, ground motion from the blast creates huge problems and the total number of counts expected from each test is quite small. It may be necessary to use several detectors on each of several tests. The return for such extra effort, however, is the possibility of setting an upper limit on δm^2 of 0.0005-0.005 $(eV)^2$, values that may not be achieved in other ways.

The Next Generation Experiments

The high interest in oscillation phenomena and the need to explore all channels of neutrino mixing have focused continuing attention on LAMPF, where an intense source of muon neutrinos as well as electron neutrinos will enable experimentalists to search for oscillation with increased sensitivity. At this writing, three such proposals have been submitted to and reviewed by the Program Advisory Committee, and its recommendations are awaiting review by Louis Rosen, Director of LAMPF,

Two of these experiments are representative of neutrino experiments that can be done at the LAMPF beam stop. One proposal is by a group from Rice University, the University of Houston, and Los Alamos; the other is by a group from Ohio State University, Argonne National Laboratory, Louisiana State University, and the California Institute of Technology. In both experiments, detectors will be placed at distances from the source that are variable and greater than those to be investigated by the Irvine-Los Alamos group. Variable distance helps to eliminate uncertainties due to beam-associated backgrounds and neutrino flux magnitudes,

The Rice-Houston-Los Alamos group proposes an appearance experiment.

They will search for the transition $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ by determining if the rate of inverse beta decay, $\bar{\nu}_e + p \rightarrow n + e^+$, is greater than expected from background events. For positron tracking and energy measurement, the group will use a 40-ton array of liquid scintillator modules and drift chambers. Detector-source distances will be in the range 50-75 m with the detector placed in a deep tunnel for cosmic-ray shielding. The projected upper limit on δm^2 is 0.12 $(eV)^2$ if only positrons are detected, and 0.06 $(eV)^2$ if, as is hoped, both neutrons and positrons are detected simultaneously.

In addition, this experiment may provide information about the muon neutrino lifetime, which is of relevance to detecting the neutrino background assumed to exist as a remnant of the Big Bang. If a muon neutrino decays to a lower-mass neutrino plus a monoenergetic photon, the decay could be detected by observing the electron-positron pairs produced by the photon. The group claims they can improve the limit on the muon neutrino lifetime from its present value, $(2.6 \times 10^4) m_{\nu_\mu}$ s/MeV, to $(2.7 \times 10^8) m_{\nu_\mu}$ s/MeV, where m_{ν_μ} is the muon neutrino mass.

The Rice-Houston-Los Alamos group may also perform a disappearance experiment. Replacement of liquid scintillator with heavy water would permit them to observe the reaction $\nu_e + d \rightarrow p + p + e^-$ and thus to search for the transition $\nu_e \rightarrow$ anything.

The Ohio State-Argonne-Louisiana-Cal Tech group proposes both disappearance and appearance experiments. The former will consist of a search for the transition $\nu_e \rightarrow$ anything by determining the rate of the reaction $\nu_e + d \rightarrow p + p + e^-$. Properties of the emitted electrons will be measured with a detector consisting of drift chambers in heavy water. With source-detector distances of 25-60 m, the group expects to set an upper limit on δm^2 of 0.2 $(eV)^2$. Substitution of ordinary water in the detector will permit the group to perform an appearance experiment by searching for the transition $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ by determining the rate of inverse beta decay. In addition, if the group's proposal to build a more energetic muon neutrino source at the LAMPF beam dump is approved, the group will search for disappearance of muon neutrinos by determining the rate of the reaction $\nu_\mu + d \rightarrow \mu^- + p + p$.

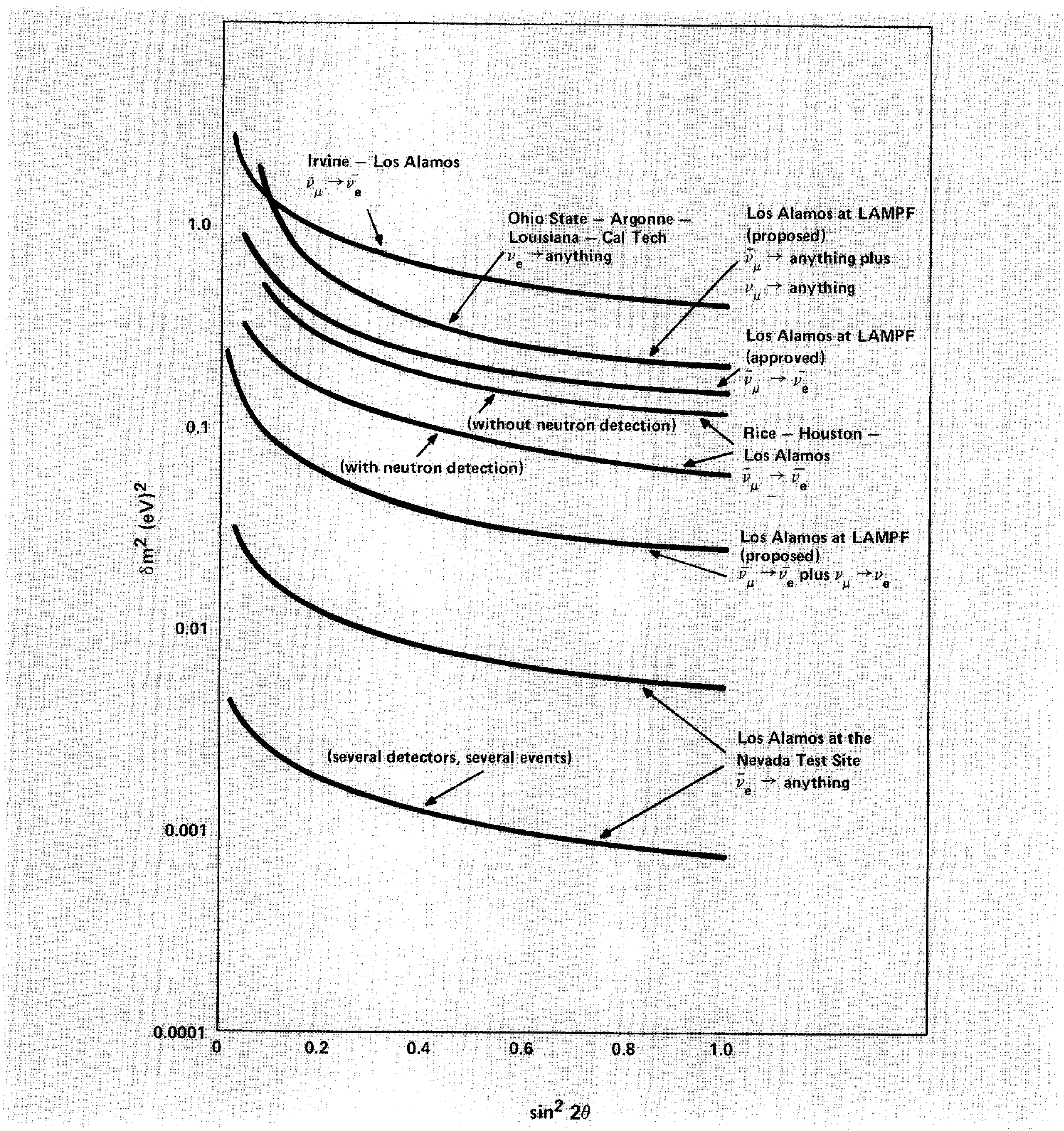
The third proposed experiment was conceived by a Los Alamos group and calls for the construction of a new beam line at LAMPF. Here pions, created by collision of part of the proton beam with a thin target, will decay in flight in a decay region to produce muon neutrinos and antineutrinos with average energies of 150 MeV. At such energies the reactions $\bar{\nu}_\mu + p \rightarrow n + \mu^+$ and $\nu_\mu + n \rightarrow p + \mu^-$ are possible. Observation of these reactions at rates lower than expected will indicate the occurrence of the transitions $\bar{\nu}_\mu, \nu_\mu \rightarrow$ anything. The group will also search for the transitions $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ and $\nu_\mu \rightarrow \nu_e$ by determining the rates of the inverse beta decay reactions $\nu_e + n \rightarrow p + e^-$ and $\bar{\nu}_e + p \rightarrow n + e^+$. The proposed 50-ton detector, to consist of liquid scintillator and drift chambers, will be positioned at source-detector distances of 40-300 m.

The projected limits on δm^2 for the various proposed experiments are shown in Fig. 6.

Conclusion

The neutrino has been one of the most successful inventions of theoretical physics. In the 50 years since its existence was first postulated, it has profoundly altered our theories of weak interactions and of astrophysical phenomena. Now we realize that if this particle has even a very small mass, it can influence our understanding of *all* fundamental interactions and the dynamics of the cosmos as well. The new experiments to measure neutrino masses and mixing angles will just begin to explore the many possibilities created by the existence of massive neutrinos ■

Fig. 6. The approved and proposed experiments at LAMPF and at the Nevada Test Site may not observe neutrino oscillation effects. Even so, they will establish upper limits on the neutrino mass difference δm^2 as functions of the mixing angle 0. The curves here are the upper limits (at the 90% confidence level) projected for the various experiments.



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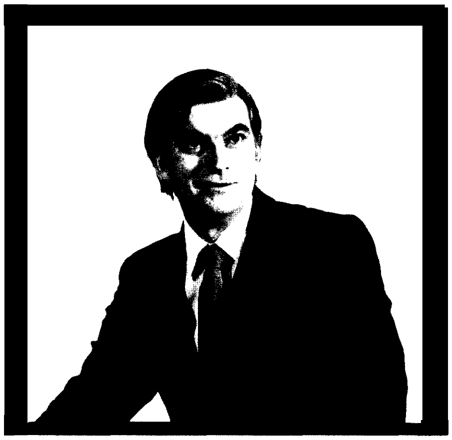

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Further Reading

"The Early Days of Experimental Neutrino Physics," F. Reines, Science, 203, No. 4375, 11-16 (1979).

"Lepton Mixing and Neutrino Oscillations," S. M. Bilenky and B. Pontecorvo, Physics Reports, 41, No. 4, 225-261 (1978).

"Is The Proton Stable?" M. Goldhaber, P. Langacker, and R. Slansky, Science, 210, No. 4472,851-860 (1980).

"Cosmology Confronts Particle Physics," G. Steigman, Annual Review of Nuclear and Particle Science, 29313-337 (1979).