search & discovery

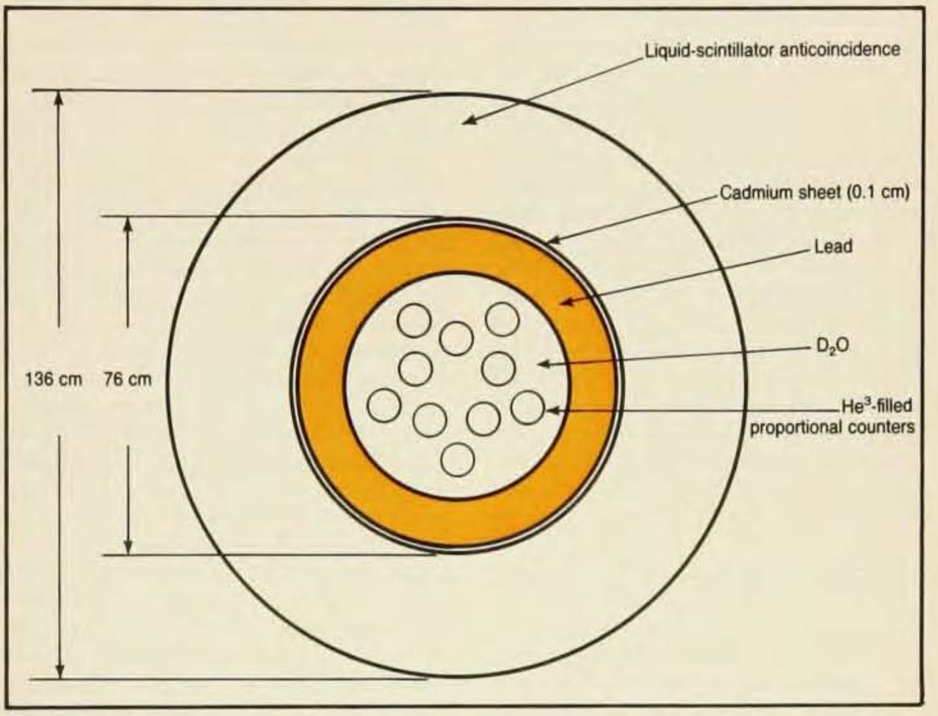
Do neutrinos oscillate from one variety to another?

As the concept of the neutrino has developed since the early 1930's, it has developed a split personality and put on weight. The neutrino is now thought to come in three varieties—electron neutrino, muon neutrino and tau neutrino. And a number of experiments are showing hints that a neutrino has a small mass and that it can oscillate from one variety to another. Taken alone, however, any individual experiment cannot be considered strong evidence of neutrino oscillations.

At the APS meeting in Washington at the end of April, Frederick Reines announced that he, Henry W. Sobel and Elaine Pasierb (all of the University of California at Irvine) had three-standard-deviation evidence for an electron anti-neutrino changing its type as it traveled from the Savannah River reactor to a detector 11.2 meters away from the center of the core. Assuming two types of neutrinos, they found a mass-squared difference of about 1 $(\mathrm{eV})^2$ and a mixing angle between 22 and 32 deg.

Late in June, at Neutrino 80, the international conference held in Erice (where the 50th anniversary of the neutrino was to be celebrated), a Caltech, Grenoble, Munich collaboration was planning to report they found no evidence for neutrino oscillations in an experiment at the Laue–Langevin reactor, in which the detector was placed 8.7 meters from the core.

A group at the Institute of Theoretical and Experimental Physics in Moscow has submitted a paper to *Yadernaya Fizika* (Nuclear Physics)reporting that the endpoint of the tritium beta-decay spectrum indicates the electron neutrino has a mass between 14 and 46 eV (with a 99% confidence level).



Irvine detector system (top view) to study charged- and neutral-current reactions of $\bar{\nu}_e$ on deuterons. Not shown here is the massive lead, concrete and water shielding surrounding the anticoincidence detector. The detector is 11.2 meters from the Savannah River reactor.

History. After the first experimental observation of neutrinos in 1956 by the late Clyde Cowan and Reines (at the same Savannah River reactor), neutrinos were found to come in two varieties—one associated with electrons, the other with muons—by Leon Lederman, Melvin Schwartz and Jack Steinberger. Thus the possibility of neutrinos changing from ν_e to ν_μ or vice versa was at least conceivable. When the two-component neutrino theory was postulated, it was natural to assume that neutrinos had zero mass. In 1963 Masami Nakagawa, Hisaichiro Okonogi, Shoichi Sakata and Akiro Toyoda (then at the Institute for Theoretical Physics, Nagoya) proposed[1] that a neutrino might have mass. Four years later Bruno Pontecorvo (Joint Institute for Nuclear Research, Dubna, USSR), drawing an analogy with neutral kaon oscillations, qualitatively discussed[2] neutrino oscillations.

By 1977 it appeared likely that Martin Perl and his collaborators at SLAC had found a third lepton—the tau (PHYSICS TODAY, November 1977, page 17). Presumably there is also a tau neutrino, but attempts to observe it have not succeeded.

Meanwhile, after a decade of measurements with 610 tons of perchlorethylene almost a mile below the Earth's surface, Raymond Davis (Brookhaven) and his collaborators had found a limit on the electron-neutrino flux from the Sun one-third that predicted by the standard solar model (PHYSICS TODAY, December 1978, page 19). One possible explanation is that some fraction of the ν_e flux emitted by the Sun oscillates to another neutrino variety before reaching Earth.

Last year Alvaro de Rujula, Maurizio Lusignoli, Luciano Maiani, Sergio Petcov and Roberto Petronzio (CERN) analyzed[3] the present experimental information on neutrino oscillations in standard weak-interaction theory with three neutrinos, rather than the more popular two-neutrino analysis. More recently Vernon Barger, K. Whisnant and David Cline (University of Wisconsin) and Robert J. N. Phillips (Rutherford Laboratory, UK) have also done[4] such an analysis. The CERN group noted that because accelerator neutrino beams are mainly ν_μ beams, the best limit on neutrino oscillations is the absence of the transition $\nu_\mu \rightarrow \nu_e$. They noted that limits on $\nu_\mu \rightarrow \nu_\tau$ are also quite stringent.

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The difference of the squares of neutrino masses $\Delta_{ij} = m_i^2 - m_j^2$, and $\sin^2 2\theta_{ij}$, where θ is the mixing angle, are the relevant parameters to consider. Limits on the $\nu_\mu \rightarrow \nu_e$ oscillation were obtained in 1978 by a CERN Gargamelle group; at the Neutrino 80 conference a Los Alamos–Yale group was scheduled to report $\Delta_{ij} < 0.6\ (\mathrm{eV})^2$, assuming full mixing.

In their paper last year the CERN group said they felt the most stringent limits on these parameters are from a beam-dump experiment with the Big European Bubble Chamber and from the Reines reactor experiments. However, they cautioned that the interpretation of the beam-dump experiments in terms of neutrino oscillations "is speculative (and possibly incorrect)." They also noted that "knowledge of the neutrino flux is subject to uncertainties; the solar-neutrino flux in particular is not yet under the experimentalist's control." The CERN group feels that oscillations of ν_e into ν_τ may indeed exist. The indications, they say, are that mixing angles are "comfortably large, about 22 deg and that the relevant mass difference may be in the range of a few to a few tens of eV."

Barger and his collaborators, on the basis of old data from Reines and his collaborators, found three classes of solutions and in one, indications of neutrino oscillations with $\Delta_{ij} = 1\ (\mathrm{eV})^2$.

Irvine result. In mid-April Reines, Sobel and Pasierb submitted a paper to *Phys. Rev. Letters* reporting evidence for neutrino instability, and at the Washington APS meeting, Reines described their conclusions. Since the pioneering experiments Reines did with Cowan at Savannah River, he and his collaborators have continued working with the same 2000-MW reactor. Last year the Irvine group reported[5] results from a detector placed 11.2 meters from the core. It consists of 268 kg of D_2O in which He^3-filled neutron proportional counters are placed. They enclosed the target in a lead and cadmium shield and surrounded it with liquid-scintillator anticoincidence counters. The group measured the cross section for both a charged-current and neutral-current reaction:

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

Six weeks before the APS meeting, the Irvine group hit upon a new way of analyzing their results to look for oscillations. The neutral-current reaction will occur no matter what kind of neutrino hits the deuteron, but the charged-current reaction can only be induced by $\bar{\nu}_e$ because the threshold for other neutrinos is too high. Thus if the $\bar{\nu}_e$ changes its type on the way to the detector, the counting rate for two-neutron events will be reduced. They considered the "ratio of ratios,"

$$R = \frac{(\sigma_{cc}/\sigma_{nc})_{\mathrm{exp}}}{(\sigma_{cc}/\sigma_{nc})_{\mathrm{theor}}}$$

where σ_{cc} is the cross section for the charged-current reaction for the fission neutrino spectrum and σ_{nc} for the neutral-current reaction. If neutrino oscillations were not occurring, the ratio R should be unity. Unlike other reactor data, Reines pointed out, the ratio of ratios is remarkably insensitive to uncertainties, both experimental and theoretical. In the numerator, various geometrical and instrumental stability factors cancel, including the neutrino flux. The denominator is independent of the reactor neutrino absolute normalization and insensitive to the exact shape of the reactor neutrino spectrum.

The Irvine preprint to *Phys. Rev. Letters* compared their experimental values with theoretical calculations for the reactor neutrino spectrum. These theoretical calculations are difficult and uncertain above 5 or 6 MeV, where experimental data are much more incomplete and estimates are needed for level densities and decay schemes. The Irvine preprint compared their experiment with predictions based on spectral calculations by Frank T. Avignone III and Zeno D. Greenwood[6] (University of South Carolina) and by Brian R. Davis and Petr Vogel (Caltech), Fred M. Mann and Robert E. Schenter[7] (Hanford). (In their February 1980 preprint, Avignone and Greenwood pointed out an apparent paradoxical agreement of their calculated fission beta spectrum with experiment but a disagreement between quantities calculated with their fission neutrino spectrum and experimental values. Reines and his collaborators reported in their original preprint that $R = 0.43 \pm 0.17$ or 0.45 ± 0.17 (depending on which spectral calculation is used), a 3.2 to 3.4 standard-deviation departure from unity.

Interpreting their result for R in terms of two base states, the Irvine group determined the allowed values of $\sin^2 2\theta$ and $\Delta_{1,2} = m_1^2 - m_2^2$, where m_1 and m_2 are the masses associated with the two states. Using the Avignone spectrum, there is an overlapping region consistent with all the experiments, in which $22° < \theta < 32°$ and $0.8 < \Delta(\mathrm{eV})^2 < 1.0$. The Davis spectrum yields no overlap within one standard deviation.

Skepticism. The Irvine report was greeted with interest but skepticism. Among the skeptics were Richard Feynman (Caltech) and Vogel, who offered three reasons why they feel the Reines, Sobel and Pasierb data presented in the preprint "do not constitute clear evidence for neutrino oscillations." In earlier experiments Reines and his collaborators had studied the neutrino-induced reaction on the proton: $\bar{\nu}_e + p \rightarrow n + e^+$. This charged-current reaction is physically the same as the reaction $\bar{\nu}_e + d \rightarrow n + n + e^+$ except that the proton is bound in the deuteron. So from measuring the positron spectrum in the ccp reaction one can estimate the $\bar{\nu}_e$ spectrum. Whether or not there are neutrino oscillations, the ratio of the observed to predicted charged-current reaction should be unity, Feynman and Vogel point out. Instead, the Irvine group reported in their original preprint this ratio to be 0.64 ± 0.24. They recognized that this ratio was inconsistent; they believe that a conceivable explanation might lie in the normalization of the proton data.

A second concern of Feynman and Vogel was that the count rates measured at Savannah River were time dependent. By comparing data in the preprint with data in the Irvine group's paper last year, Feynman and Vogel found that the background rate had risen from last year to this. Instead of lumping all the data together as was done in the preprint, they argued that it should be grouped into smaller time intervals, in which case the ratio R increases to 0.62 ± 0.24. Following this suggestion, the Irvine group has reanalyzed its data and added further data from an additional 40 days (20 with the reactor on, 20 with it off). The previous runs had been with the reactor on for 74 days and off for 47. The new analysis divides the data into ten groups, each with the reactor both up and down. In addition, they no longer assumed a normal distribution. Instead they looked at the partial derivatives of each term in the cross section and calculated the propagation of errors. With their new error analysis the effect is reduced to a 3.0 to 2.7 standard deviation effect. The new value for R is 0.38 ± 0.21 or 0.40 ± 0.22.

Feynman and Vogel also note: "The crucial test of neutrino oscillation, independent of spectrum uncertainties, is that the same reaction measured at the same energy gives two different results at two different distances. There is one reaction, ccp (charged-current involving protons) at 4.0-MeV threshold [in an earlier reactor experiment], measured at two distances—11.2 and 6 meters, but it gives the same rate within errors." But Reines points out the errors are large and not inconsistent with oscillations.

Sobel believes the reactor data are consistent if one discards some of the old data at 6 meters obtained by Frank Nezrick and Reines in 1965. For high energies, Reines feels that their detector efficiency was too low to trust the absolute normalization of these results.

For the past few years, the Irvine group has been building a movable detector that should be running this fall at Savannah River. They will be studying $\bar{\nu}_e + p \rightarrow n + e^+$, measuring the positron (that is, the $\bar{\nu}_e$) spectrum and moving the detector over the range 12–35 meters from the reactor core.

The Laue–Langevin experiment started running last November and will end this summer. The group, consisting of Felix Boehm, J. F. Cavaignac, D. H. Koang and B. Vignon (Institut des Sciences Nucleaires, Grenoble) and Franz von Feilitzsch and Rudolf Mossbauer (Technical University, Munich), also measured the neutrino-induced reaction on the proton. Their detector, placed 8.7 meters from the core, was a proton-rich scintillator (375 liters) that acted simultaneously as target, positron detector and neutron moderator. He^3 wire chambers detect neutrons in coincidence with positrons. Their signal-to-noise ratio was 1.5 and the event rate 1.5/hour.

Boehm told us they compared their positron spectrum with the theoretical spectra based on calculations of Davis and his collaborators and of Avignone and his collaborators. The Laue–Langevin experiment does not show evidence for neutrino oscillations if compared with the Davis spectrum, but at this time Boehm was not willing to quantify his statement. If there were full mixing, he said, their experiment sets a limit on $\Delta = m_i^2 - m_j^2$ of about 0.2 $(eV)^2$. However, if partial mixing is assumed, the limit on Δ is larger. In addition, in a few weeks the Laue–Langevin experimenters hope to have an on-line measurement of the actual electron spectrum from the reactor, which should resolve the discrepancy between the calculated spectra.[6,7]

This fall, Boehm told us, the Caltech and Munich experimenters will collaborate with a team from the Swiss Institute of Nuclear Research. The equipment will be moved to a 2700-MW power reactor at Gosgen, Switzerland and will make measurements at 38 and 65 meters, where the experiment will be sensitive to values of Δ as small as 0.03 $(eV)^2$.

The Soviet experiment at ITEP on the end point of the tritium beta-decay spectrum was first reported on at the Neutrino 76 conference in Aachen. At that time the group said they had an upper limit of 33 eV on the $\bar{\nu}_e$ mass. Tritium is useful for a neutrino-mass search because of all suitable beta decays, it has the smallest-energy electrons coming out. The mass difference between H^3 and He^3 is very small (18 keV), but one is interested in neutrino masses (about 30 eV) that are comparable to ionization energies.

Recently the ITEP group, consisting of V. A. Lyubimov, E. G. Novikov, V. Z. Nozik, E. F. Tretyakov and V. S. Kosik, submitted a paper to *Yadernaya Fizika* in which they reported results from five years of experiments. The source was valine ($C_5H_{11}NO_2$) containing 18% tritium; its thickness was about two micrograms/cm^2. The group used a beta spectrometer with a rotation angle of 720°. They estimate they had a rather high resolution (about 45 eV at the end of the tritium beta spectrum) and low background (0.03–0.1 counts per second).

After doing a χ^2 minimization for each of 16 samples, the group found a mean value for the mass of ν_e of (34.3 ± 4) eV. To check this value, they did a Monte Carlo simulation, and then discarded unlikely values. They also considered other sources of imitation of nonzero mass and took into account effects from the valine molecules and the atomic level structures of H^3 and He^{3+}. Their final value for the electron neutrino mass (which they still consider to be preliminary) is that it is in the range 14–46 eV with 99% confidence level.

At the University of Guelph in Ontario, Canada, John J. Simpson has recently measured the tritium endpoint spectrum using tritium implanted in silicon crystals. He obtained a ν_e mass limit of 70 eV, comparable to that obtained by K.-E. Bergkvist a decade ago. However, Simpson believes that in a future experiment he could set a 20-eV limit and measure a mass of 35 eV with a 95% confidence level.

Another experiment at the Savannah River reactor is being prepared by a Georgia Tech–University of South Carolina group led by Tino Ahrens and T. P. Lang (Georgia Tech). They will use coaxial scintillators whose outer detector contains lithium to detect the neutron produced. The inner detector can be either a deuterated or undeuterated scintillator, and the proton or positron produced can be detected. Thus they can observe for the deuteron both the neutral- and charged-current reactions and for the proton the charged-current reaction. At present, their equipment is at 15.4 meters but it can be moved as close as 13. The group plans to start taking data this fall.

At Brookhaven Larry Sulak and his collaborators at Harvard and the University of Michigan have been looking for oscillations at the AGS, where the 30-GeV accelerator was operated at 1.5 GeV to produce a pure ν_μ beam at 150–250 MeV. Unlike the other experiments discussed, they look for loss of ν_μ and the appearance of ν_e. Sulak told us that the Brookhaven experiment is sensitive to smaller masses than indicated by the reactor experiments. At this writing, the group is still analyzing 400 tapes of data from their run, which ended last November.

Impact of oscillations. Neutrino oscillations are of course an intriguing idea. After summarizing the present evidence at the APS meeting, Sheldon Glashow (Harvard University) remarked "Neutrino masses and mixing are suggested but not demanded by grand unification theories." Neutrinos changing their type on the way from the Sun to Earth would be one way out of the solar-neutrino puzzle. Massive neutrinos would also be of great importance cosmologically. Because there are roughly a billion relic neutrinos for each nucleon in the Universe, neutrinos with masses in excess of a few eV would dominate the total mass in the Universe. —GBL

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CERN hopes to finish LEP by 1986

If you thought a herd of bison grazing in the middle of the Fermilab accelerator was impressive, consider a colliding-beam accelerator whose electrons and positrons will circle more than a dozen villages in two countries. That is in fact the scale on which the Europeans hope to be doing high-energy physics by 1986.

At the June meeting of the CERN Council, the CERN management submitted its formal proposal for the construction of the LEP (Large Electron–Positron) colliding-beam accelerator. The acronym is understated. The LEP design calls for an underground ring 30.6 kilometers in circumference, straddling the French–Swiss border near Geneva. Where the accelerator passes under the Jura mountains west of CERN, three of the collision points and their experimental halls will be as much as a half mile below ground level.

These gargantuan dimensions are nec-