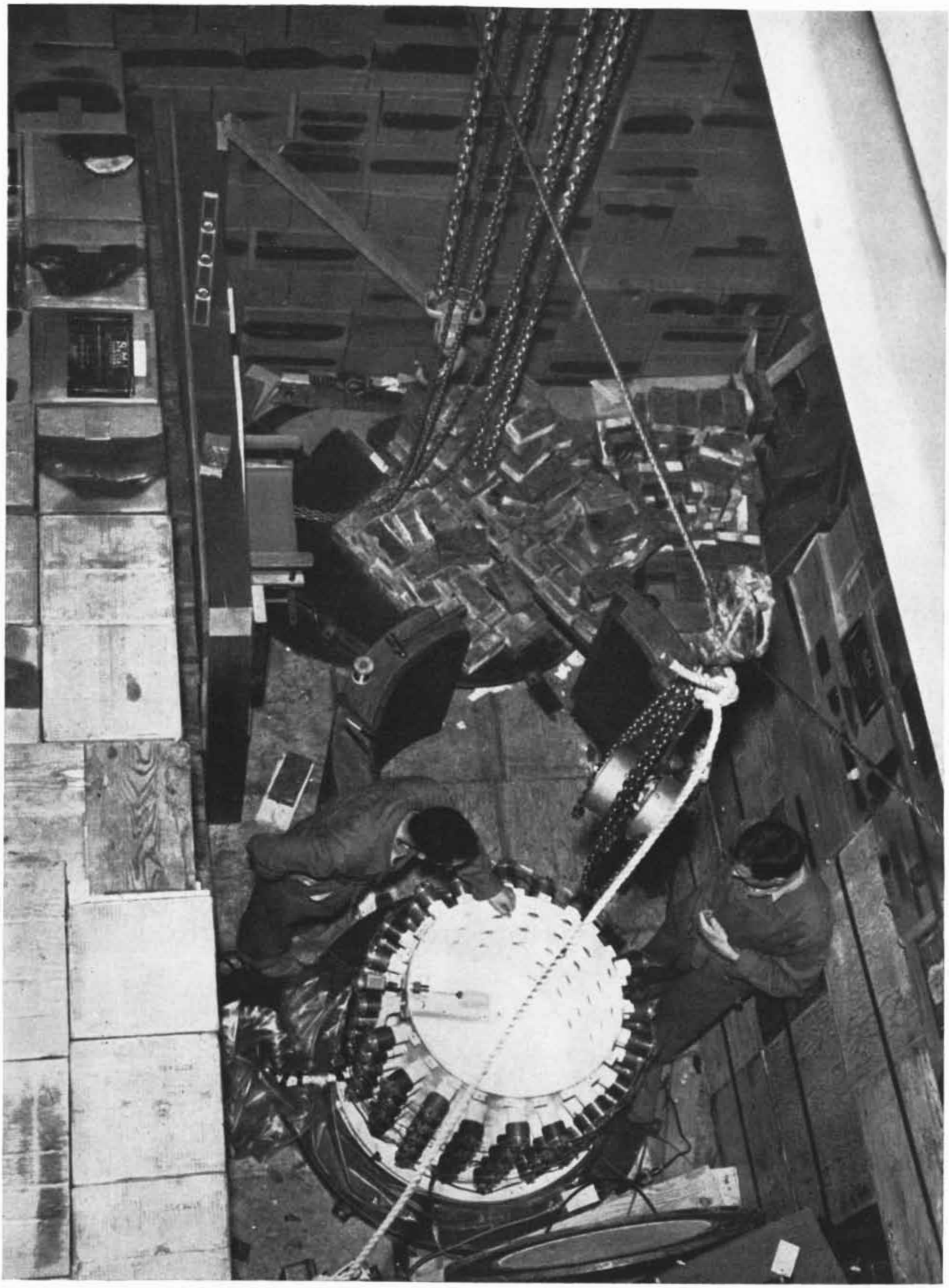


SCINTILLATION COUNTER was used by Frederick Reines, Clyde L. Cowan, Jr., and colleagues in an attempt to detect the neutrino. The counter is the cylindrical object at the bottom. It was set up near a reactor at the Hanford Works of the Atomic Energy Commission. Since this experiment was performed, Reines and Cowan have designed a new experiment using even larger equipment.

THE NEUTRINO

For 25 years the theoretical structure of physics has assumed a fundamental particle which has never actually been detected. Its existence may now be confirmed by a remarkable experiment

by Philip Morrison

The full triumph of classical mechanics came one clear night in the fall of 1846. On that night a German astronomer named Johann Galle pointed the telescope of the Berlin Observatory toward a spot in the heavens where he had been told to look, and there first saw the faint disk of the planet we now call Neptune. His discovery was the most dramatic possible confirmation of Newton's laws of gravitation, and of the calculations of the mathematician Urbain Leverrier, who had predicted from the perturbations in the movement of the planet Uranus that a new planet must lie where Galle found it.

Physics today is looking expectantly for another such discovery. There is a Neptune among its fundamental particles—a strange particle which is on every physicist's list, whose measurements and properties are well known, but which has not yet been "discovered." The particle is called the neutrino. Recognizing that all physical "facts" of nature are no more than inferences, physicists are almost as sure of the existence of the neutrino as they are of anything, but still we will not like to admit that it has really been discovered until it signals its presence by some track or click in our apparatus.

For Christmas not long ago one of the Los Alamos physicists who have been laying ingenious plans to trap the neutrino gave his colleagues a present. Under the gift wrapping they came to a neatly decorated matchbox, clearly labeled: "Guaranteed to contain at least 100 neutrinos." They looked into it warily, and saw a simple empty box. The conceit did not come home until the gift-giver explained it to his friends. The label was literally correct. Such a volume, any such volume on earth, whether a box or your hand or a cupful of water, contains neutrinos. They are moving through it, as they always move, in straight lines at the speed of light.

The neutrinos in us and all around us come from the deep interior of the sun, where they are born in the same nuclear reactions that make the sun shine. Unlike other particles emerging from these reactions, the neutrinos go clean through the sun's great layers, more transparent to them than is the clearest air to the golden terrestrial sunlight, and move out into space. Perhaps 6 or 8 per cent of the total energy released by the sun is in this transcendent form, passing without change or effect through star and space and planet. Even at night neutrinos come streaming to us from the hidden sun, traveling right through the massy earth as though it were not there. The neutrino flux from the sun carries 40,000 times more energy than moonlight, and yet we have never seen, heard or felt its presence.

How such a paradox of a particle has been pressed for decades upon the physicists by hard experience, and how it is today proposed to catch it at last, are the main topics of this article.

The Law of Conservation

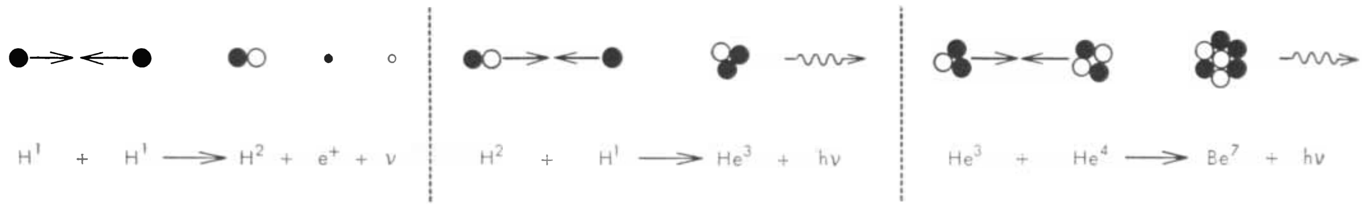
The keystone of physics is the law of conservation of energy. Yet for three decades there has lain within the well-accepted facts of nuclear physics a carefully studied phenomenon which a rigorous and candid observer would have to cite as a *prima facie* contradiction to the famous law. This scandal lies in a strange disappearance of energy when a neutron sheds an electron—the phenomenon known as beta-decay.

A wide variety of evidence indicates that the uncharged neutron, like its charged fellows the proton and the electron, has a perfectly definite mass. Now the neutron, building block though it is, is not fully stable. It spontaneously decays into a proton and an electron. The neutron's half-life is some 12 minutes, which is to say that if 1,000 neutrons are kept free from any interaction with the outside world, after 12 minutes only 500 will remain neutrons, and after about 24 minutes, only 250.

By the principle of the convertibility of mass into energy, the total energy content of a stationary neutron is just the energy equivalent of its mass. Now the products of its decay—proton and electron—do not add up in mass to the initial mass of the neutron. The missing mass has been converted into energy, and this appears as kinetic energy of the two product particles, which fly apart after the neutron's disintegration.

The law of the conservation of energy says that the kinetic energy shared by the neutron's decay products (the lion's share goes to the light electron) must be precisely equivalent to the lost mass. Their kinetic energy has been measured, and its maximum value has been determined to be about 780,000 electron-volts. But the numerous measurements have shown that comparatively seldom does the kinetic energy released by a neutron's decay reach this value. Sometimes the proton plus electron have a total kinetic energy of only a few thousand electron-volts. The decay energies observed range over the whole spectrum from zero to 780,000 electron-volts. On the average, only a fraction of the maximum expected energy release appears when a neutron (or any radioactive atomic nucleus) splits by beta-decay.

What happens to the missing energy? Decades ago nuclear physicists came to the plausible conclusion that it must go off with some undetected particle. They



PROTON-PROTON SEQUENCE is one of two nuclear processes in the sun which are assumed to shower the earth with neutrinos. In the first reaction of the sequence two protons (*nuclei of hydrogen 1, or* H^1) collide to yield a deuteron (*nucleus of hydrogen 2, or* H^2), a positive electron (e^+) and a neutrino (ν). In the second reaction the deuteron collides with a proton to yield a triton (*nucleus of hydrogen 3, or* H^3) and a gamma ray ($h\nu$). In the third reaction the triton collides with an alpha particle (*nucleus of helium*

tried hard to catch the invisible particle in their best counters, and in a foot or two of lead. But they failed. And in a dark year there came the thought that perhaps here in the fundamental processes of the nucleus the conservation of energy actually failed.

After the successes of the quantum theory, which no less than classical physics is based upon energy conservation, Wolfgang Pauli first sketched and Enrico Fermi later worked out in detail the properties of the presumed particle that must fly off in beta-decay if energy was to be conserved. It was easy to see what some of these properties must be.

First, the particle must have no charge, for balancing charges (the positive proton and negative electron) come out of the decaying neutron. Secondly, the particle must be practically weightless, according to careful measurements of the energy and mass relations of the various particles involved. For simplicity it is considered to have zero mass. Thirdly, the particle must have angular momentum, *i.e.*, spin. The neutron's angular momentum is one half a quantum unit; when it decays it produces two particles each with one-half unit spin; so to conserve angular momentum the invisible particle should have one-half unit spin.

Such a particle, with no charge, no mass, spin one half and birth only in beta-decay, was postulated by Pauli and by Fermi. It became known as the neutrino—"little neutral one"—in the beautiful language of Fermi.

But now we are on thin ice. Faced with a failure of energy conservation, physicists refuse to admit it but instead postulate an unseen and perhaps unseeable particle—a little neutral one so cunningly designed that it has no properties other than those which will preserve the laws of conservation. How does this differ from plain failure of the conservation laws?

The Challenge

The first attempt at an answer was to examine carefully the scene of the crime. The particles issuing from a decaying neutron or atomic nucleus carry momentum as well as energy; hence they should recoil from each other, just as the firing of a shell causes the cannon to recoil. If only a proton and an electron came off, conservation of momentum would require them to move in opposite directions along one straight line. But if a neutrino carrying momentum also comes out, the other pair must recoil from *it*, and their tracks should form a V. A number of elegant experiments recording the beta-decay of various nuclei and of the neutron itself have proved that this is indeed the form that the tracks actually take.

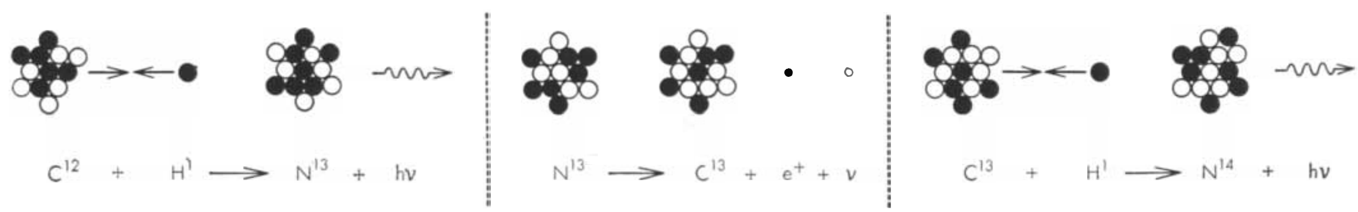
The critics can still say: Momentum and energy are intimately connected, so your recoil experiment proves nothing except that both energy and momentum are lost in a single parcel. Until you can somehow trace the missing energy, momentum and the rest, you are merely balancing the books with a fictitious entry.

There is only one sure answer to the criticism. The missing energy, the "little neutral one," must be caught. The energy it carries must be reconverted into some measurable form, or the neutrino, however universally accepted, remains but a sign of the physicist's ignorance.

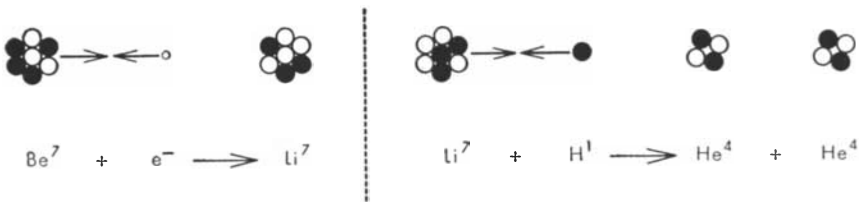
Of course the neutrino theory has by no means been unfruitful. It has provided a basis for interpreting various measurable features of beta-decay, for predicting the approximate lifetimes of all beta-decaying nuclei, and so on. We could not give up the real triumphs of the neutrino postulate without tearing the present closely webbed fabric of nuclear physics. But still the challenge to track down the neutrino itself remains.

The behavior of physicists in the face of this challenge may seem unworthy. For a generation we have been satisfied to use the neutrino theory and explore its manifold ramifications, but slow to respond to the challenge to deliver up the thing itself as a legitimate member of the particle family, not a mere bookkeeper's evasion. Why have we been so laggard in seeking out the neutrino directly?

The answer is simple, and yet in some ways wondrous. Compared to other nuclear events, beta-decay is fantastically slow, and therefore rare. It takes a neutron some 18 minutes on the average to emit an electron; with the same energy available, a gamma ray would come out in a millionth of a billionth of a second.



CARBON CYCLE is the second solar nuclear process which may produce neutrinos. In the first reaction of the cycle carbon 12 (C^{12}) collides with a proton to yield nitrogen 13 (N^{13}) and a gamma ray. In the second reaction nitrogen 13 decays spontaneously into carbon 13 (C^{13}), a positive electron and a neutrino. In the third reaction carbon 13 collides with a proton to yield nitrogen 14 (N^{14})



4, *or* He^4) to yield beryllium 7 (Be^7) and a gamma ray. In the fourth reaction the beryllium 7 collides with a negative electron (e^-) to yield lithium 7 (Li^7). In the fifth and final reaction of the sequence lithium 7 collides with a proton to yield two alpha particles. The protons are represented by the larger black balls; the neutrons, by white balls of the same size.

The prodigiously slow beta process has a far smaller probability than any other method of nuclear decay. Beta-decay is much rarer, on the nuclear time scale, than death by meteorite bombardment among men. It is only the chance that some nuclei are immortal except for beta-decay that allows us to observe this event at all.

Now this slowness of decay implies that the opposite process, the capture of a passing neutrino by a nucleus, also is slow and rare. Gamma rays, which are notoriously unlikely to interact with nuclei, will travel on the average through eight or 10 feet of lead before they do so. But a neutrino, to interact with a nucleus, must travel on the average through about 50 light-years of solid lead! A shielding wall capable of thinning out a beam of neutrinos would have to be as thick as a hundred million stars. To all intents and purposes neutrinos simply do not see solid matter at all. Here is the nub of the difficulty. The neutrino is almost uncapturable.

The Challenge Accepted

Deterred by the logic of the matter, physicists did not begin to think seriously about hunting neutrinos until great masses of radioactive material became available in the fission products of uranium reactors. With a truly prodigal effort, they now seek to catch the almost uncatchable neutrino. From the high-power reactors stream currents of neutrinos which rival the sun's beam. They pass through the shielding walls and fly in perfectly undeviating straight lines from the place of their birth to outer space. Patrolling these great beams near their source, physicists hope to capture an occasional unlucky neutrino. Last month a group of workers began the vigil by placing their neutrino detectors in the beam from the most powerful reactors in the world—those at the Savannah River plant of the Atomic Energy Commission.

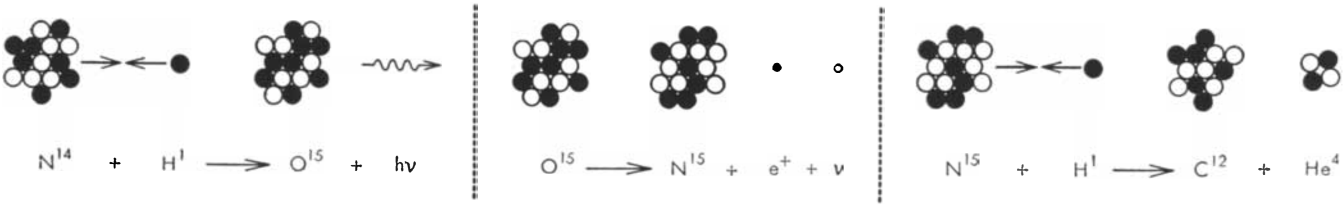
The more spectacular of two schemes for trapping the little neutral ones is based on the technique of scintillation counting. Tireless photocells will keep a continuous surveillance over a large tank full of a clear scintillating liquid, recording the flashes of light that signal ionizations among the nuclei in the liquid. A Geiger counter can record only the ionizing events occurring in a few milligrams of gas; the scintillation tank scheme makes it possible to patrol tons of nuclei at a time.

But the capture of the neutrino is a rare event indeed, and when one looks for the highly improbable, he must be prepared to see many other events, probable and improbable, which are irrelevant to what he is looking for. The tons of scintillator liquid will flash many times—from traces of radioactive dirt within the liquid, from cosmic rays, from escaping particles other than neutrinos which may come from the reactor. It is not enough simply to look for flashes; it is necessary to discriminate between those which arise from neutrino capture and those which arise from various other rare but much less interesting causes.

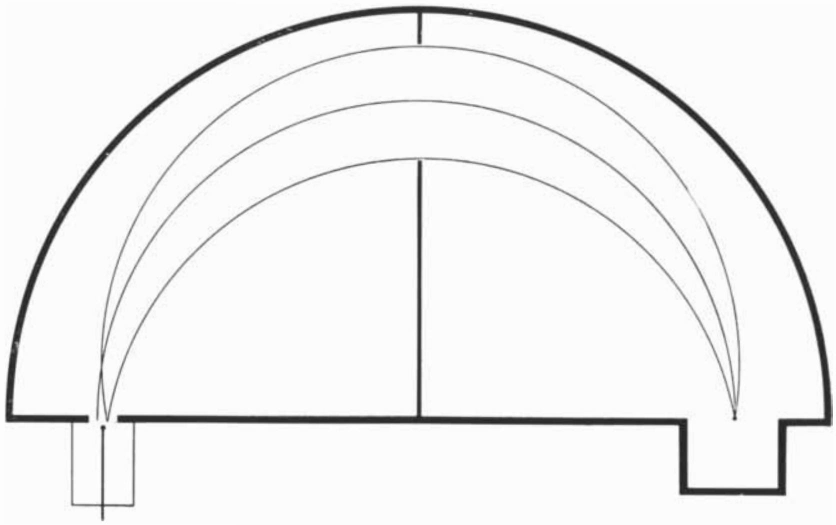
A group of Los Alamos investigators led by Clyde L. Cowan, Jr., Francis B. Harrison and Frederick Reines invented, and is pursuing with true virtuosity, an ingenious scheme to perform this feat. The reasoning is as follows. Capture of a neutrino being the reverse of its emission, the precise opposite of beta-decay must occur: that is to say, a proton plus an electron plus a neutrino plus energy combine to form a neutron. Now there is another type of "beta-decay" reaction in which, instead of a negative electron being absorbed, a positive electron, or positron, is emitted. Electric charge is conserved equally well in either case: in the second case the positive proton becomes a neutral particle not by absorbing a balancing negative charge but simply by releasing its own positive charge in the form of a positron. That such reactions actually occur has been verified by experiments. And so we can rewrite the equation for neutrino capture to say that a proton plus a neutrino plus energy may combine to yield a neutron and a positron. The ingenious Los Alamos group proposes to detect this event by observing its products—the neutron and the positron.

A Subtle Detection

The energy necessary to convert a proton into neutron and positron is supplied by the incoming neutrino. Neutrinos emerging from the fission products in a reactor are estimated to have, as a rule, something of the order of one million electron-volts more energy than is required for this conversion. The excess energy goes off as kinetic energy of the product neutron and positron—most of it in the positron, since it is much lighter. The charged positron ionizes atoms in its path as it goes, and thereby produces a good-sized flash in a scintillating liquid. After it has traveled a centimeter or two, which takes no more than a hundredth of a billionth of a second or so, the posi-



and a gamma ray. In the fourth reaction nitrogen 14 collides with a proton to yield oxygen 15 (O^{15}) and a gamma ray. In the fifth reaction oxygen 15 decays into nitrogen 15 (N^{15}), a positive electron and a neutrino. In the sixth reaction nitrogen 15 collides with a proton to yield carbon 12 and an alpha particle. The cycle makes an alpha particle, two electrons, three gamma rays and two neutrinos.



SPECTROMETER is used to measure the energies of beta particles. The apparatus in this diagram is placed in a magnetic field, in which the lines of force are perpendicular to the page. The particles emitted by the small sample at right describe curved paths and are counted at left. Particles of the same energy come to a focus at the same point. Thus the counter may be used to scan the various particle energies by changing the strength of the magnetic field.

tron comes to rest, having spent all its kinetic energy.

The flash from ionization by the moving positron is the first visible sign of the neutrino's capture, but it is by no means the last: there is more to come. The moment it comes to rest, the positron combines with an electron (there are plenty handy). When it does, the mass of the pair is instantly annihilated and turned into energy. The energy flies off as two gamma rays, traveling in opposite directions from the source and each amounting to about one half million electron-volts. After moving a foot or two, each gamma ray gives rise to an ionizing electron which produces a flash in the counter. So every neutrino capture that gives birth to an energetic positron should be signaled by three virtually simultaneous flashes in the scintillating liquid—a flash from ionization by the moving positron and a pair of flashes in different spots from the gamma rays.

Meanwhile the newborn neutron itself has moved off slowly, with very little kinetic energy. There is no flash to mark its passage, for the neutral particle cannot ionize. It wanders about the liquid in its usual random walk, slowing down to thermal motion as it goes. Eventually it is captured by some nucleus. Now the canny experimenter may add to his liquid scintillator some cadmium, which has a pronounced affinity for slowed neutrons. The cadmium nucleus seizes a neutron so vigorously that a few gamma rays are emitted in the process. In this moment of capture, therefore, the neutron signals its presence by a flash, as the positron did earlier. The neutron signal comes after a considerable delay, because the particle has traveled a yard or two, at a relatively slow speed, before its capture. This delay is some 10 or more microseconds, and it can be measured accurately by electronic techniques.

The plan of the experiment at the Savannah River plant is this. A layer of liquid containing protons and doped with cadmium is placed like a sandwich filling between two thick scintillating layers sensitive to gamma rays. Photomultipliers watch all carefully. When a neutrino is captured by a proton, the resulting birth of a positron is instantly signaled by a flash in the sandwich layer. Practically simultaneously, after a time too short to measure, there comes a flash in each of the two "bread" layers, produced by the two gamma rays from the annihilation of the positron. A few millionths of a second later the capture of the wandering neutron by cadmium releases gamma rays whose flashes are seen in all three layers. In short, every neutrino capture is marked by two sets of flashes in all three layers, one following the other after a precisely stipulated interval. Moreover, the energy of the positron-annihilation flash helps to identify the event: it should total about one million electron-volts.

Combinations of events which simulate this pattern may occur by accident in the counter, but they are too infrequent to cause real trouble. Their spuriousness can, and will, be established by control experiments. Cosmic ray particles can cause spurious events (and did so seriously in the earliest versions of this experiment). These fast charged particles may trigger all three layers, and in addition liberate a neutron which will give a delayed pulse. But the energy they give to each layer is large, and the first flash will be too bright, and give away the spurious character of the event.

The whole apparatus is of prodigious size. Where most experiments of the kind use half a dozen photomultiplier tubes and their associated amplifiers, the neutrino searchers use 500. Where scintillation counters are normally counted big if they use a few gallons of liquid, this experiment uses 10 or 12 tons. The needs of the project have led to a whole complex of ingenious and painstaking developments. The chemical firm producing the scintillating liquid, which used to make it in quart amounts, has been persuaded to manufacture and purify it by the ton. A special tank truck has been built to transport the precious fluid in an inert atmosphere from the factory to the scene of the experiment; it must be kept minutely clean and oxygen-free throughout the long journey. The tank where the experiments are performed must be lined with a special glossy-white coating, to lose next to no light at all. A chemical must be added to the scintillating liquid to give the flashes a color which will be reflected most efficiently by the gleaming tank walls. The flashes that carry all the information for which the neutrino hunters are searching are too faint to be seen by the naked eye, and no effort must be spared to make sure that all of them are detected by the sensitive photomultipliers. Hundreds of the latter are required, and whole banks of other electronic gear. The detector tank itself is encased in lead and buried deep in the building housing the great Savannah River reactor.

After building and testing all this equipment, the experimenters began to install it at Savannah River last month. There they will count patiently, hour after hour, waiting for the evidence which they hope will restore the conservation of energy to honesty and will help them play the Galle to Fermi's Leverrier in the physics of the 20th century.

The Search by Chemists

Meanwhile another group pursues the search by a very different method. Just as the scintillation-counter plan is a *tour de force* of modern physical technique,

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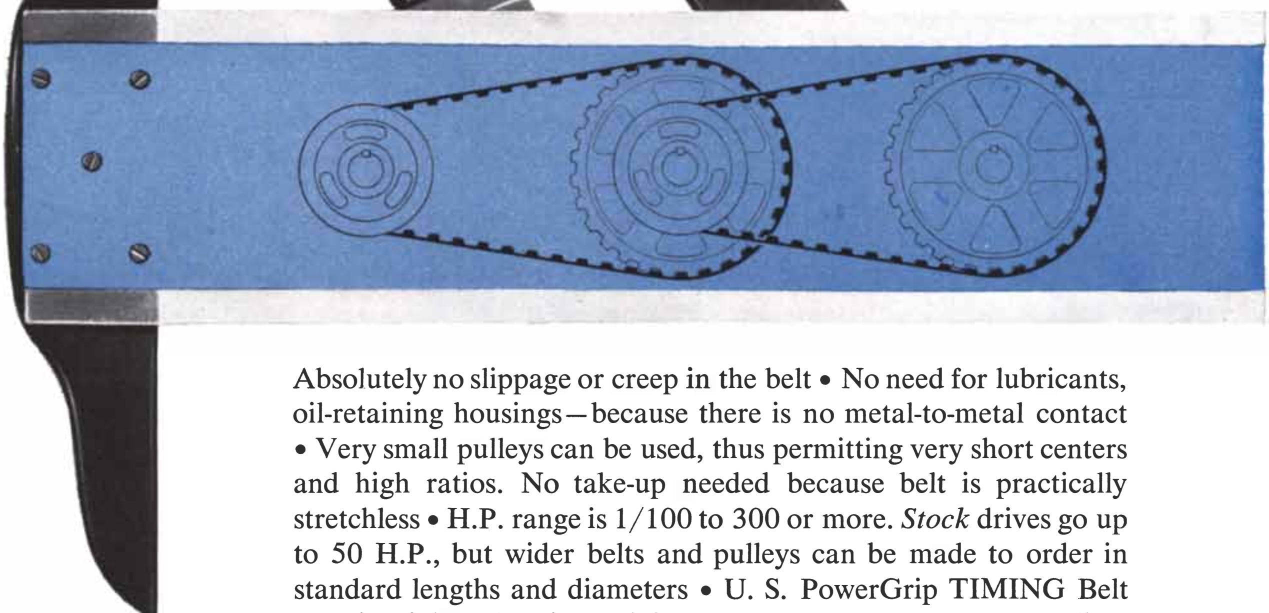

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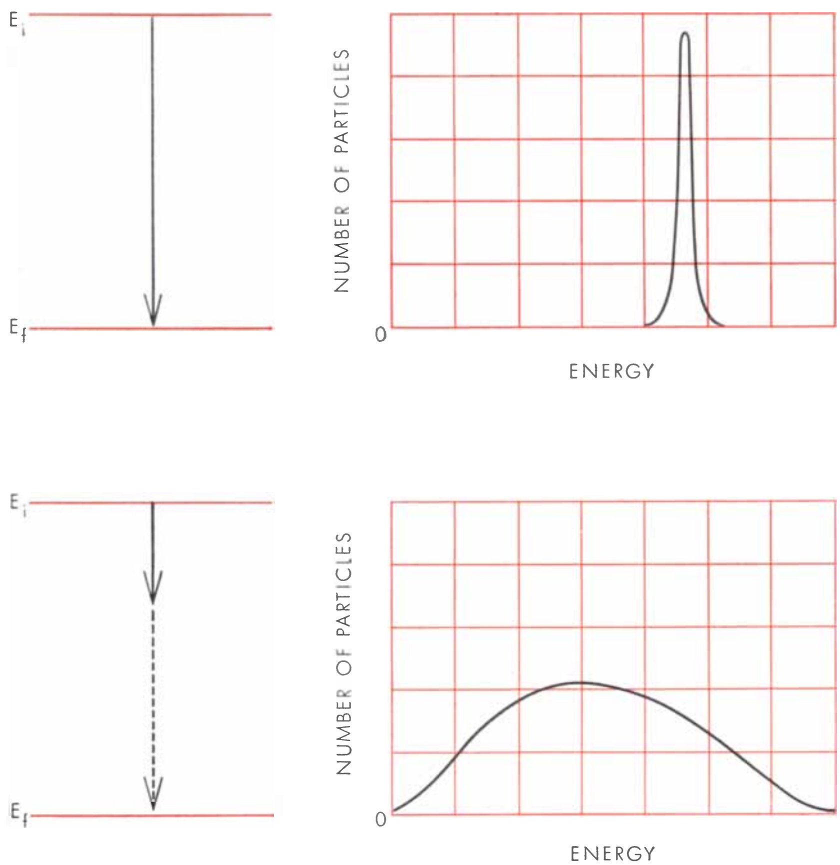
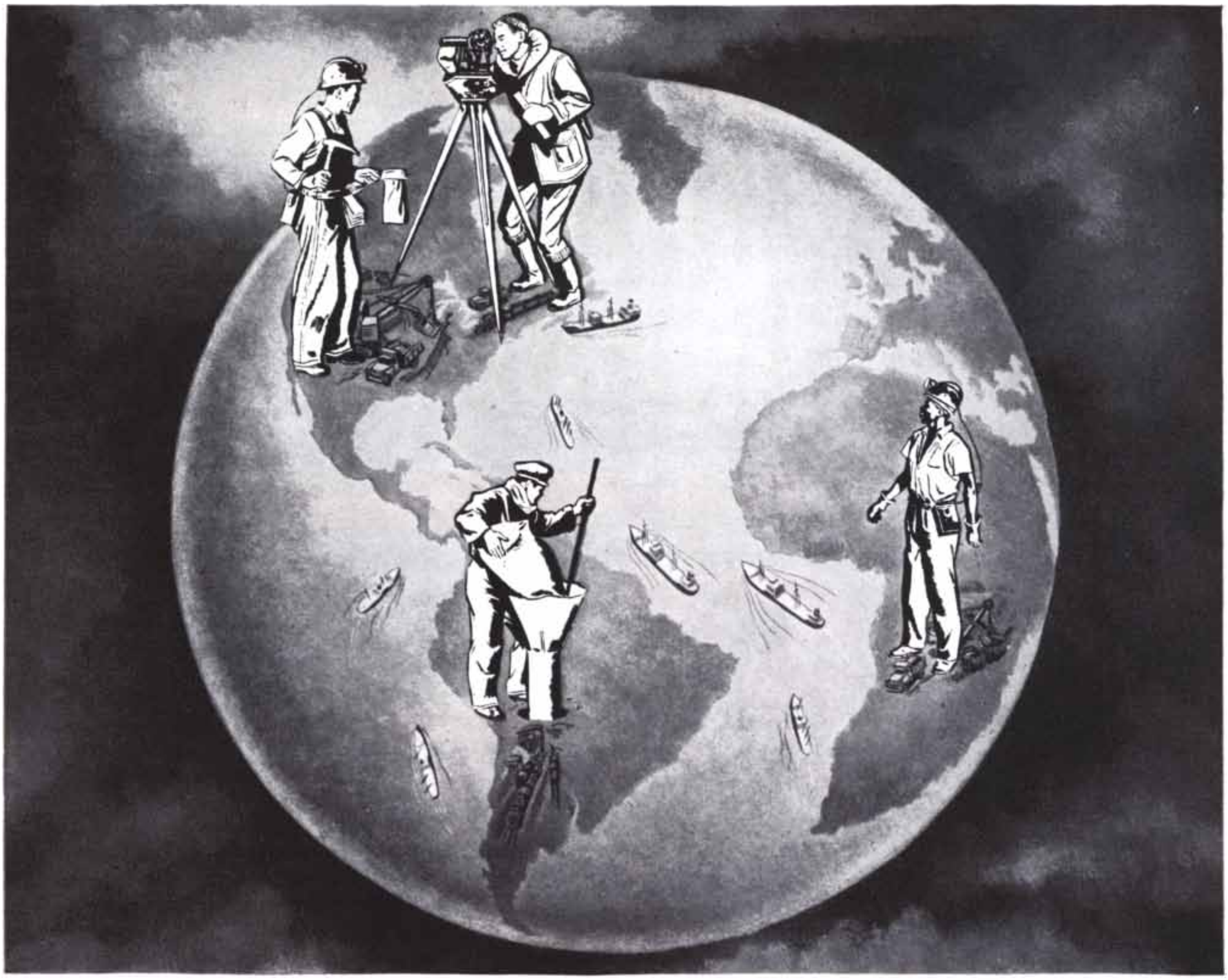
so there is a related piece of consummate skill which belongs to the chemist. The trick of identifying the capture of neutrinos by detecting products of the reaction may, it is hoped, be performed by chemical means. In this case the targets are not protons but nuclei of chlorine atoms. The isotope chlorine 37 may capture a neutrino and turn into an atom of the rare gas argon, emitting a negative electron in the process. The atom so produced, argon 37, is itself radioactive.

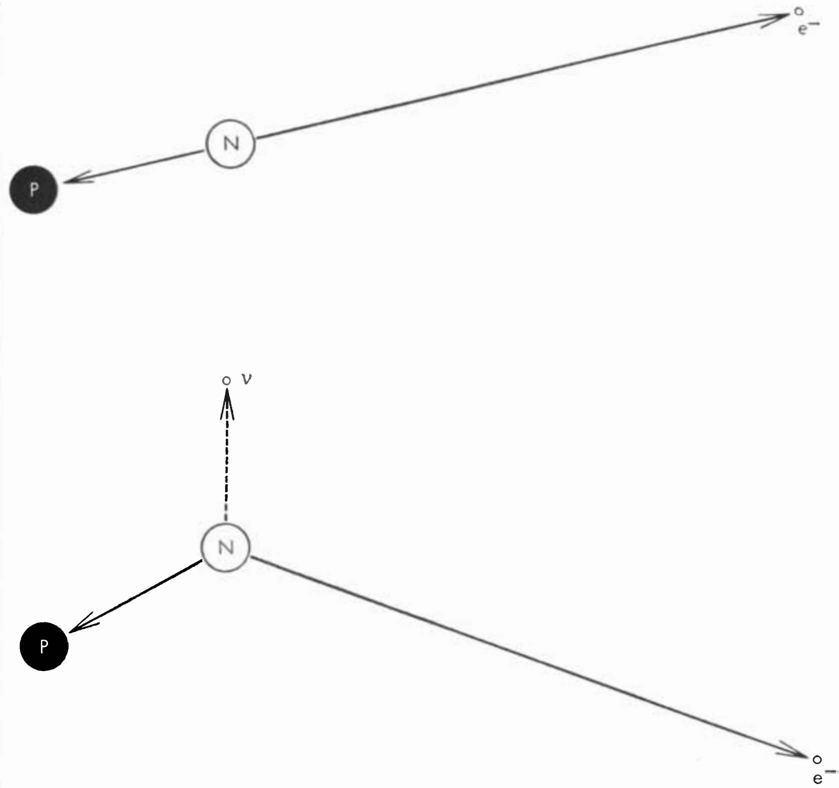
Its creation may be detected by a simple plan. A large tankful of a liquid containing chlorine is swept clean of argon (certainly of any radioactive argon) by a stream of helium bubbled through it, and then the liquid is exposed to neutrinos from a reactor. After some days' exposure, the tank again is swept with helium gas to bring out any argon that may have been formed. The argon (of which there must always be at least a slight trace) is separated from the helium by well-known techniques of physical chemistry, and a Geiger counter is used to see if there is any radioactive argon in the sample.

This method is based on such a refined chemical search for a few atoms in a great vat of solvent that it is surely the archetype of all needle-in-the-haystack endeavors. There are against it two objections. The first, of course, is that it leaves open the question of just what did make the active argon. Careful controls might dispose of this question. But then there is left a more fundamental, if not more serious, objection flowing from the theory of fundamental particles. If we reverse the neutrino-capture reaction, the theory says that the decay products must be chlorine 37, a neutrino and a positron rather than an electron. This



ALPHA- AND BETA-DECAY are accompanied by changes in the energy level of the nucleus. The diagram at upper left depicts the energy levels of a typical alpha-emitting isotope before and after decay. The curve at upper right shows how the energies of particles from this isotope are distributed. The fact that the particles occupy a narrow range of energies indicates that the difference between the initial energy of a single nucleus (E_i) and the final energy (E_f) is always accounted for by the energy of an alpha particle (*arrow*). The diagram at lower left depicts the energy levels of a typical beta-emitting isotope before and after decay. The curve at lower right shows how the energies of particles from this isotope are distributed. The fact that the particles occupy a broad range of energies indicates that the difference between the initial energy and the final energy is seldom accounted for by a beta particle (*solid arrow*). The missing energy is presumably carried off by a neutrino.





RADIOACTIVE DECAY OF THE NEUTRON also requires the neutrino. If the neutron (N) simply decayed into a proton (P) and a negative electron (e^-), the conservation of linear momentum would require that the decay particles go off in exactly opposite directions (*top drawing*). Actually they go off at an angle to each other (*bottom drawing*). This indicates that the missing linear momentum is carried off by a neutrino (*broken arrow*).

means that the neutrino is not precisely the same as in a normal beta-decay. Consequently the beta-decay neutrinos sent out by a reactor may not transmute chlorine into argon. However, it is possible that the two kinds of neutrino are actually equivalent in every respect, so that the experiment will really work.

Raymond Davis, Jr., of the Brookhaven National Laboratory will measure the argon activity induced in some four tons of carbon tetrachloride in a tank at the Savannah pile. It is a happy circumstance that both the scintillation counter and the chlorine experiments are being carried on at the same time and the same place, for the two should complement each other.

It would be ungracious not to mention that these are not the first experiments to seek out the neutrino directly. Quite a few brave experimenters have tried before, but on too small a scale. The chlorine experiment was first planned at Chalk River in Canada by Bruno Pontecorvo, who may for all we know now be completing it near some big reactor in the U.S.S.R. The proton-capture experiment in a smaller version was tried by the Los Alamos group at Hanford last year, and a doubtful positive result obtained. Most physicists will be willing to base conclusions only upon the really powerful effort now under way.

A New Astronomy

The neutrino provides in principle a new kind of astronomy. Until now the only radiations from outer space that we have studied are visible light and microwave radio. The neutrino beam from the sun and stars also comes to us bearing information about the universe, and we shall surely some day read a part of that text. The chlorine-capture experiment, with an increase of a factor of a hundred or so in bulk, and a well-shielded mine or the deep sea to work in, might measure the sun's neutrino flux. Modifications in the scintillation scheme also are under consideration. It is not too much to hope that some day we may directly verify the nuclear reactions in the sun's center by a study of their neutrino emission.

But suppose the experiments do not work? Suppose no neutrino counts are seen? The logical chain is pretty tight;

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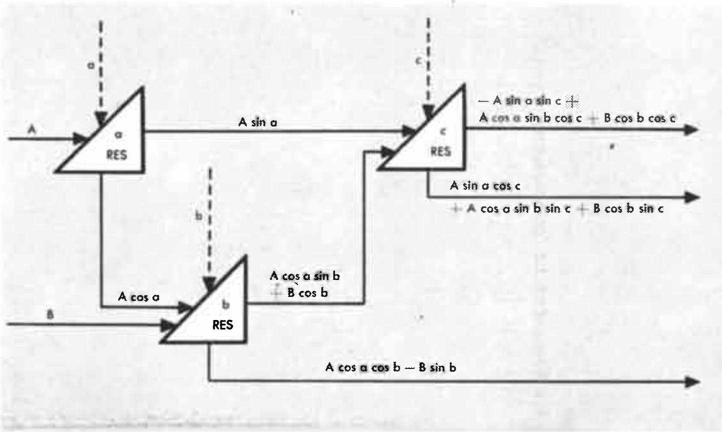

In view of the widespread use of resolvers to generate sine and cosine functions in modern electro-mechanical analogue computers, it is of great practical significance. Resolvers produced by the Ford Instrument Company have now reached such a high degree of precision, that it is possible to obtain, from an unloaded resolver (which accommodates a single angular quantity only), an accuracy to within less than one tenth of one percent. But most computing circuits call for the use of several resolvers, and once an ordinary resolver is loaded by another resolver, no matter how high its precision, the overall accuracy of the resolver cascade is seriously affected.

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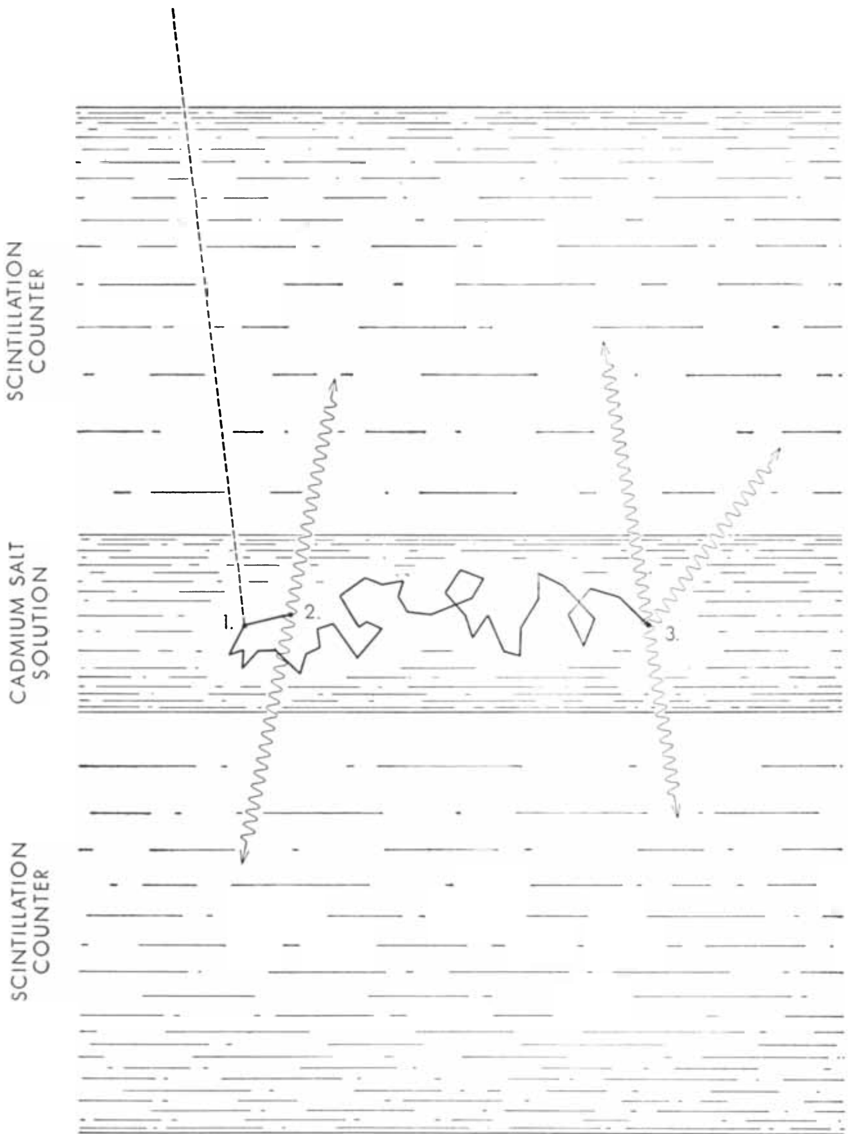
For accuracy and reliability—both vitally necessary in military instruments—experienced machinists must work to fine precision—in the order of .0005 of an inch. Here in one section of the shops of Ford Instrument Company, men are milling parts for an airborne computer.

During the past year Ford Instrument Company has been busy working on many contracts for the U. S. Air Force and the U. S. Navy Bureau of Aeronautics, designing and manufacturing complex computers, controls and their components. For over forty years, Ford Instrument Company has devoted most of its efforts in working for the government to the many problems of weapon controls.

the defeat would mean to many that energy conservation had at last really failed us, or, almost as bad for our theories, that a reaction was not accompanied by its inverse among the fundamental particles. We should be loath to accept either of these conclusions. So far I have thought of only one way out—a desperate evasion. The neutrino might leave the scene of its birth all right, starting life as a perfectly proper Fermi neutrino. But it might be unstable and decay into three other neutrinos (two is forbidden for dynamical reasons), which could of course not all be simultaneously caught at the other end to invert the reaction, because their directions would slightly diverge. This possible behavior would leave the beta-decay theory intact. But it would make the neutrino even more evanescent a notion than it now is, and would only pass the trouble on to later generations of physicists. It will be far better if the patient experimenters are successful, and if their scintillator clearly displays those few oscilloscope traces each hour which will mean that the fugitive neutrino has been caught at last.



DETECTION OF THE NEUTRINO is planned by Cowan and Reines on the basis of the events outlined in this diagram. A neutrino (*dotted line*) encounters a proton (1), causing it to change into a neutron (*zigzag path*) and a positive electron. In passing through the cadmium salt solution the positive electron causes a pulse of ionization. Then it is annihilated in an encounter with a negative electron (2). This gives rise to two gamma rays (*wavy lines*), one of which causes a pulse in the top scintillation counter and the other a pulse in the bottom scintillation counter. The neutron wanders for several microseconds until it is absorbed by a cadmium nucleus (3). This gives rise to three gamma rays. Thus when two consecutive pulses, separated by an interval of several microseconds, occur in both the cadmium solution and the scintillation counters, a neutrino is assumed to have been detected.