The fall of parity

PAUL FORMAN

Twenty-five years ago, between Christmas and New Year's Day, the first exciting results emerged from a difficult but fundamental scientific experiment at the National Bureau of Standards in Washington. The experiment showed, strikingly and convincingly, that there is an intrinsic handedness to at least one fundamental physical process. Consequently, our world is distinguishable from its mirror image. Physicists had long assumed the opposite. They constructed their theories so as to ensure that the corresponding mathematical property, called parity, remains unaltered – is conserved – in all subatomic processes. Thus this experiment brought about the fall of parity from its exalted position alongside such well conserved physical quantities as energy, momentum, and electric charge.

Parity: What's not conserved?

The preference we give to right over left is a mere human convention. So physicists had assumed. Nature could not possibly have made such a distinction, whether in favor of right or of left. To be sure, her organic creations on this planet are not perfectly symmetric: our hearts *are* on the left sides of our bodies, our intestines *do* all wind in the same sense, and many chemicals synthesized by plants and animals have a definite handedness. But the advance of physical theory has been so closely connected, historically, with the endeavor to free our conceptions of the world about us from all parochialisms, that physicists have grown allergic to concepts which appear to have no better basis than their accordance with our accustomed ways of viewing our everyday experiences.

One test for anthropocentric assumptions is to ask whether it would be possible to convey an understanding of the concept in question to an intelligent being, in a distant galaxy, who could neither see us nor receive any object sent by us. In particular, how could such a being know which way to turn at the order, "Right face!"? Clearly, our brainy exobiotic would be at a loss, unless – and here we rely upon the universality of the laws of nature – unless it were possible to instruct it to perform some physical experiment whose outcome differentiated between right and left. In the entire development of physics, up through the early decades of this century, no such phenomenon, law, or experiment had come to light. Physicists therefore felt themselves more than justified in assuming that none such existed, that nature herself made no distinction between left and right. Great was their surprise when, 25 years ago, they discovered that nature is a semi-ambidextrous southpaw.

It is a familiar fact that right-handed things are converted into left-handed things by reflection in a mirror. But mirror reflection, while familiar, is awkward to express mathematically. More convenient is space inversion, in which the physical object or process is described by a new set of coordinates which are

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*This article reproduces in altered form the label texts and illustrations of an exhibit with the same title at the National Museum of American History (formerly Museum of History and Technology), Washington, D.C. The exhibit, whose centerpiece is the experimental apparatus here described, as restored under the eye of Raymond Hayward and Dale Hoppes at the National Bureau of Standards, will continue through the end of this year.

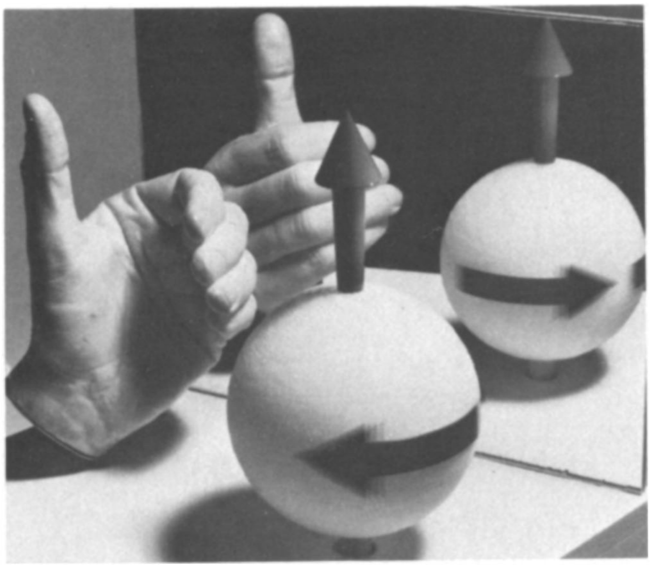


Fig. 1. If there were an object which, like the rotating sphere here, always spun in a left-handed sense relative to its direction of motion (indicated by the arrow mounted upon it), then parity would not be conserved in any process that object entered. The "neutrino," the lightest of the subatomic particles, appears to be just such an object, constantly spinning left-handedly.

If there were a radioactive nucleus which, like the rotating sphere here, spun in a left-handed sense relative to the direction in which it usually emitted radiation (indicated by the arrow mounted upon it), then parity would not be conserved in that process. The nucleus of the cobalt atom behaves in just this way when emitting beta rays.

just the negatives of the original set. This transformation of coordinates is called the parity transformation. It is equivalent to a mirror reflection followed by a 180° rotation parallel to the mirror. For example, a glove may be "inverted" by turning it inside out; right goes to left (reflection), up goes to down (rotation). As we feel perfectly sure that our world would appear no differently if turned upside down, any want of symmetry we may experience must be attributed not to the rotation but the reflection. Thus we infer that mirror invariance implies invariance also under a parity transformation.

With the notion of invariance under reflection in a mirror we approach the conservation of parity. Speaking a bit loosely, to say that something is invariant is to say that something is conserved. Indeed, all the conserved quantities in physics – energy, momentum, electric charge, etc. – are intimately connected with the invariance of physical processes under one or another transformation of the coordinate system. If the physical process proceeds in exactly the same way when referred to an inverted coordinate system, then parity is said to be conserved. If, on the contrary, the process has a definite handedness, then parity is not conserved in that physical process.

On the 22nd of June 1956 the editor of the *Physical Review* received for publication a short paper raising the question whether parity is conserved in weak interactions and suggesting several experiments to decide the issue. The authors, Chen Ning Yang and Tsung Dao Lee (Fig. 2), although aged only 33 and 29, respectively, already carried high reputations as theoretical physicists. They had met some twelve years before, in 1944, in Kunming, where professors and students from all parts of China had fled the Japanese invasion. At the end of the war both came to the United States to continue their studies, and here they remained to pursue theoretical research.

Lee and Yang's collaboration in research began in the early 1950s upon questions raised by the results then beginning to pour forth from the many high-energy accelerators ("atom smashers") constructed in the United States immediately after the Second World War. Numerous subatomic particles, either wholly new or not previously seen in sufficient numbers for their properties to be ascertained, challenged the theoretical physicist to find explanations for their existence and their behaviors.

At this time the principle of conservation of parity, as extended to individual subatomic particles and their interactions, seemed wholly warranted, not merely on the most general theoretical grounds, but also by its successes

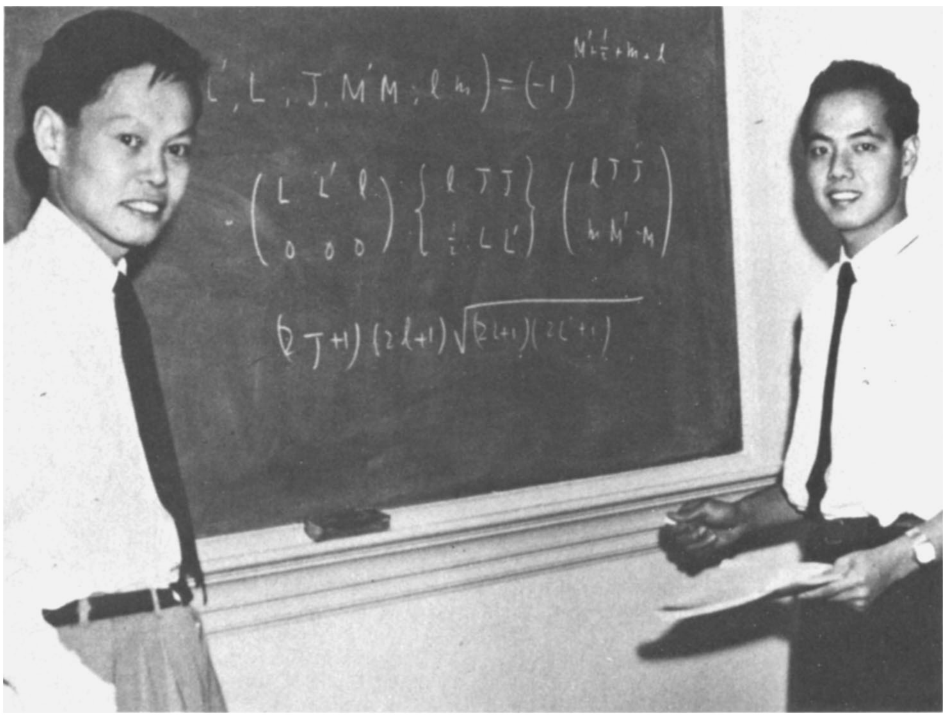


Fig. 2. C. N. Yang (left) and T. D. Lee at the Institute for Advanced Study, Princeton, N.J. Their elation is either at the experimental confirmation of their hypothesis that parity is not conserved, or at the Nobel Prize their work had won them. (Photo: Alan W. Richards.)

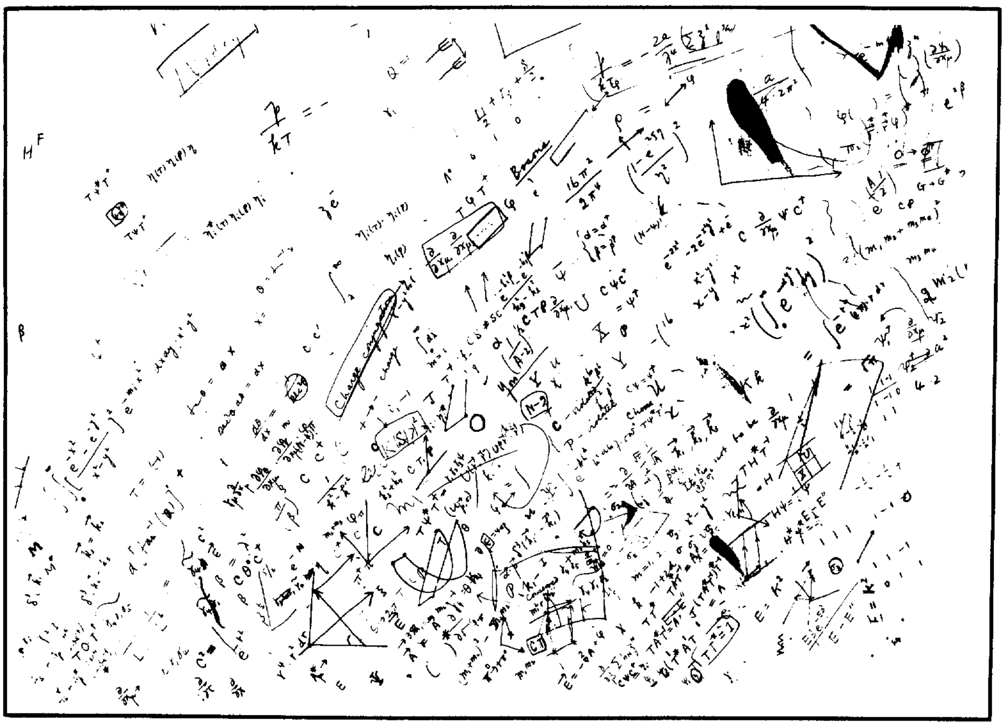


Fig. 3. Fragments of ideas and calculations jotted down by T. D. Lee in the summer of 1956 – the detritus of directed thinking upon parity violation and its consequences. (Photo: Brookhaven National Laboratory, Neg. 1-505-57.)

in accounting for what those particles did and didn't do. By the end of 1955, however, a puzzling contradiction had emerged between the parity principle and the other principles employed to order the subatomic zoo. Lee and Yang were among the first to fret about this situation, and the most constant in the pursuit of a solution (Fig. 3).

After some attempts to isolate the problem as peculiar to the stranger of the subatomic particles, the question gradually came to the fore: could it be that parity is not conserved, not even in well trod fields of atomic physics? In the spring of 1956 Lee and Yang set themselves the task of critically examining all the evidence. They found that although there was much in support of the conservation of parity in many different physical processes, none of these processes were among the so-called "weak interactions." Lee and Yang proposed several tests to decide the question. The first of these, a "relatively simple possibility," the two theorists opined, was as follows:

> Select a nucleus which has an intrinsic spin and which decays radioactively by emitting high-speed electrons. Orient a bunch of such nuclei so that their spins are in the same direction – say clockwise when viewed from above. Count the numbers of electrons emitted upward and downward.

Only if these numbers are equal will the "mirror" experiment give the same result, for when viewed in a mirror the distribution of rays is unchanged, but the direction of spin is reversed (Fig. 4). Experiment showed that more electrons are emitted upward than downward. Therefore the decay process is not mirror invariant; parity is not conserved.

The experiment required

The idea behind the experiment is very simple; the experiment itself was very difficult. It required melding two sophisticated and demanding experimental techniques that had never before been combined: on the one hand, "beta spectroscopy," the accurate observation of the high-speed electrons emitted by radioactive nuclei; on the other hand, "cryogenics," the production of the very lowest attainable temperatures.

The axis of a spinning atomic nucleus will keep point-

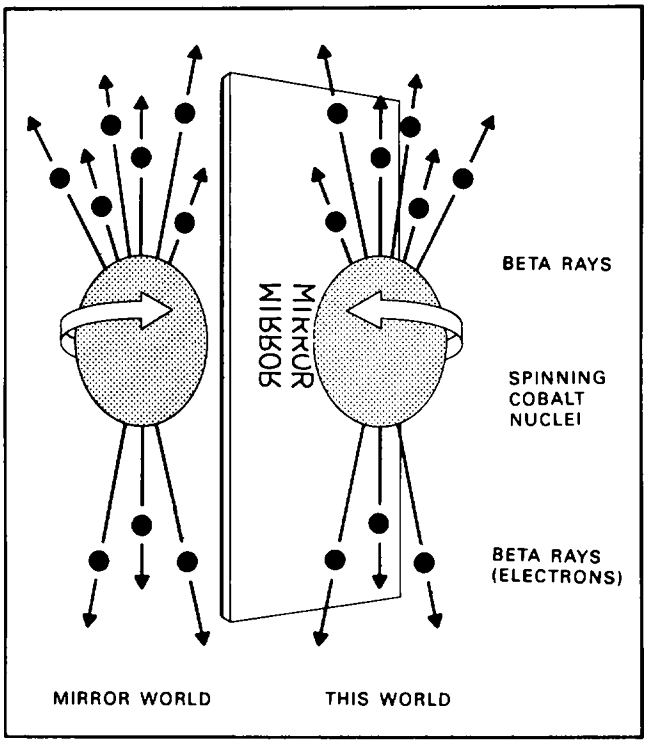
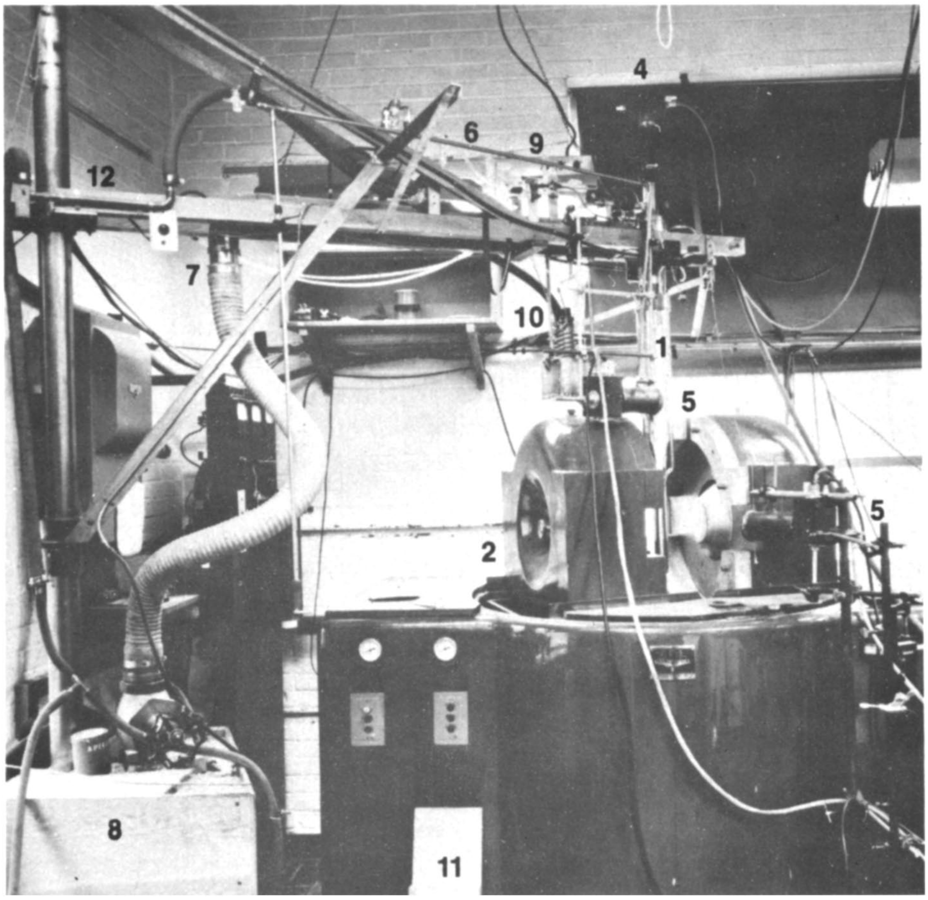
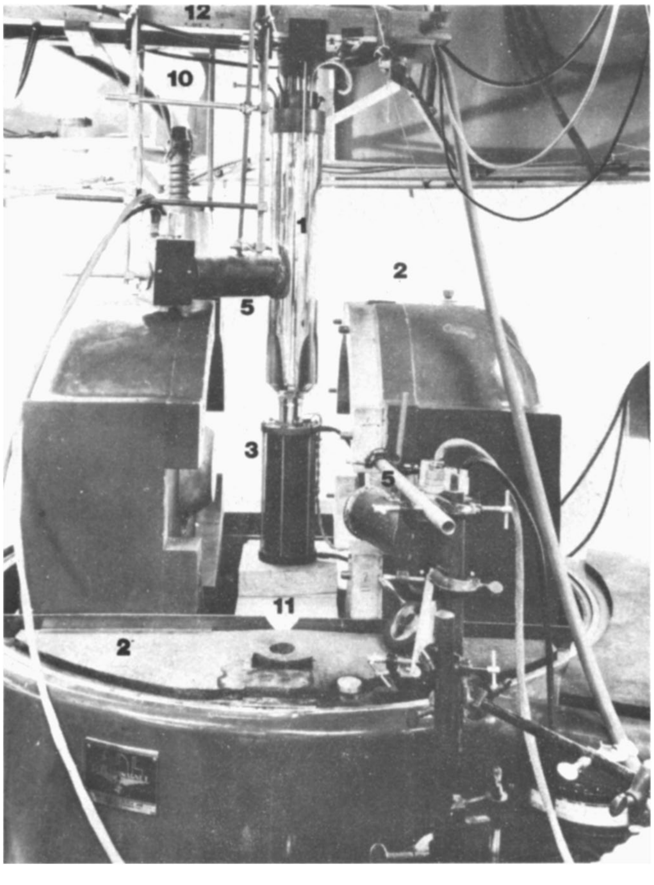


Fig. 4. The ellipse on the right represents a large number of cobalt nuclei, all with their spins in the same direction, all emitting beta rays. (In reality, any one cobalt nucleus emits only one beta ray – transforming itself thereby into a nickel nucleus.) On the left this process is seen in a mirror. The direction of spin is reversed, while the direction in which most beta rays are emitted remains unchanged. The mirror world is thus distinguishable from the real world.

The mirror world becomes the inverted, or parity-transformed world by turning the mirror image upside down. The spins of the cobalt nuclei are thus returned to their original direction, but most beta rays are now emitted downward – contrary to experimental fact. The parity-transformed world is not identical with the real world; parity is not conserved.





Figs. 5 and 6. The apparatus in the Cryogenic Physics Laboratory at the National Bureau of Standards in Washington, D.C. (Now the campus of the University of the District of Columbia.) (Photo: *Life*.)

1 Dewar ("thermos") flasks hold liquid nitrogen and liquid helium to keep the temperature of the cobalt atoms within a degree of absolute zero, -273°C.

2 Powerful electromagnet further cools the cobalt atoms within a hundredth of a degree of absolute zero by "adiabatic demagnetization." (Magnet shown after cooling completed, switched off and opened.)

3 Solenoid produces vertical magnetic field which orients the cobalt atoms and their nuclei. (Not visible in Fig. 5.)

4 Photoelectric detector converts into electronic pulses the light flashes produced by the beta rays emitted by the cobalt nuclei in the cryostat at the bottom of the Dewar flask. The pulses, and thus the numbers of beta rays emitted upward, may then be counted electronically.

5 Gamma-ray detectors, one looking from the side, one from above, work much like the beta-ray detector, **4**. Together they tell what fraction of the cobalt nuclei have their spins oriented vertically.

6 Double-walled metal tube for filling inner Dewar with liquid helium.

7 Copper pipe and corrugated hose connect inner Dewar to powerful vacuum pump in basement below. The temperature of the liquid helium is reduced to one degree absolute (three degrees below its normal boiling point) by rapidly pumping off the helium vapor above the boiling liquid.

8 Wooden box filled with sand dampens vibrations of vacuum pump below. Near absolute zero mechanical vibrations cause rapid heating.

9 "Exchange gas" manifold. The rate of flow of heat between the cooling salt (with the cobalt nuclei bedded in it) and the liquid helium jacket depends upon the degree of vacuum in the space between them. Heat flow is facilitated by admitting small amounts of helium as "exchange gas"; conversely, by pumping out even this rarified gas the flow of heat is slowed.

10 Vacuum pump and "cold trap" for removing the exchange gas.

11 Board to support polarizing solenoid, **3**.

12 Oak boom with attached apparatus rotates about vertical steel pole so that Dewars may be swung clear of massive iron magnet for accurate measurements of the magnetic susceptibility of the cooling salt – the best index of its temperature.

ing in a given direction only if the atom and its surroundings are cooled to within a hundredth of a degree of absolute zero. (Only then is the energy in the random motion of the atoms insufficient to knock the nuclei out of alignment with the magnetic field which orients them.) In the midfifties there was just one way to get so close to absolute zero: adiabatic demagnetization or "magnetic cooling." Certain complex salts when subjected to a strong magnetic field become magnetically polarized and evolve heat; conversely, they absorb heat when the field is reduced or removed. If after the magnetic field has been applied the salt is thermally isolated, then when the magnetic field is subsequently removed – i.e., the salt crystals are adiabatically demagnetized – the temperature of the salt will fall. (Thermal isolation prevents the salt drawing in the heat which it requires simply to maintain its temperature.)

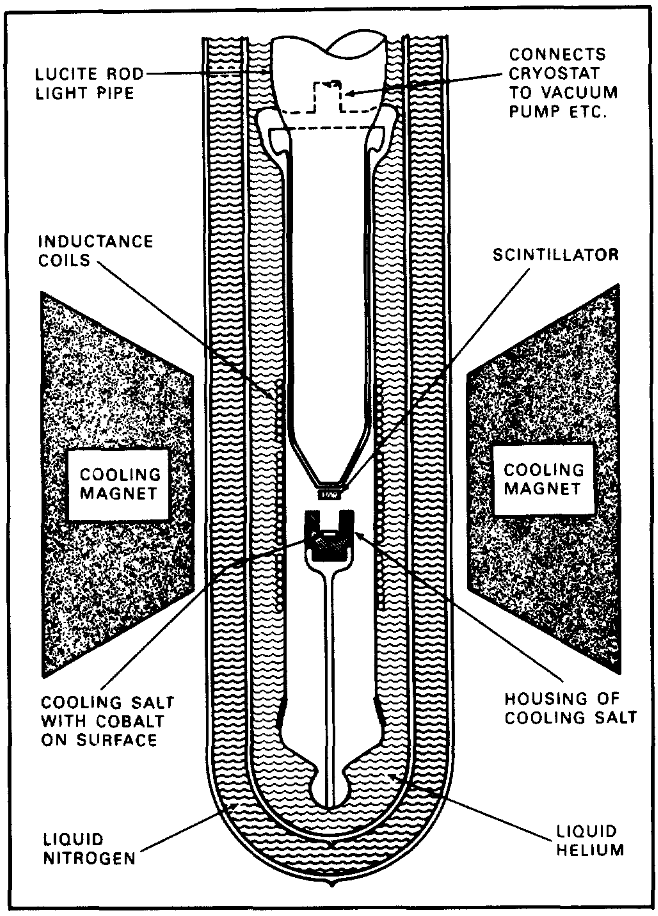


Fig. 7. Cross section of cryostat and surroundings.

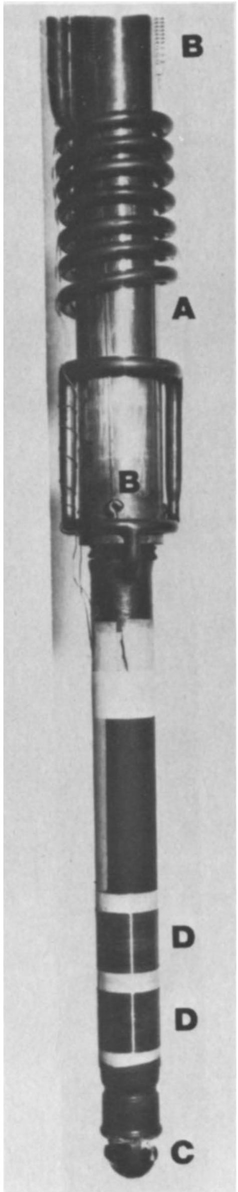


Fig. 8. Cryostat (final design, as preserved).
A Helical tube connects cryostat to exchange gas manifold, **9**, and vacuum pump, **10**. Tube and cryostat made of glass, covered with graphite ("Aquadag") to prevent exterior light from reaching light pipe. Helix allows cryostat to move up and down to follow the thermal contraction and expansion of the Lucite rod.
B Cryostat held snug to Lucite light pipe by springs and wires attached to glass hooks.
C Ground glass stopper (sealed with a mixture of glycerin and Palmolive soap) used to introduce and support cooling salt in cryostat.
D Inductance coils give measure of temperature of cooling of salt.

The starting point for this delicate process was already difficult enough to attain, namely the lowest temperature that could be produced by vigorously pumping off the vapor from a boiling bath of liquid helium. At this starting temperature, about one degree absolute, liquid helium is "superfluid," a unique condition which makes it extremely difficult to confine (Figs. 5 and 6).

All this elaborate technique for attaining ultralow temperatures had then to be married with a technique for detecting the beta rays emitted by cobalt nuclei. The technique employed, after a separate experiment established that it would still work at such low temperatures, was "scintillation counting."

The radioactive cobalt atoms were incorporated in a thin surface layer of a crystal of the cooling salt. About an inch above this surface, and parallel to it, a thin transparent crystal of the organic chemical anthracene was attached to the inside wall of the glass vacuum chamber. Electrons ejected upward from the cobalt nuclei strike the anthracene crystal. Each gives up its energy into a tiny flash of light, a "scintillation." Some of that light passes upward through the glass wall, is picked up by a specially shaped Lucite "light pipe," and transmitted up to the photoelectric detector atop the low-temperature apparatus (Figs. 7 and 8).

The experiment proper begins with the orienting of the cobalt nuclei. Upon completion of the magnetic cooling, a solenoid — a helix of wire — is slipped over the tip of the "thermos" flask. An electric current of a few amperes in the solenoid produces a vertical magnetic field. This field orients the cold cobalt atoms vertically, and the nucleus of each atom follows along because of the cobalt atom's extremely strong internal magnetic field. (The vertical magnetic field does not reheat the magnetically cooled salt because it is some fifty times weaker than the horizontal field of the massive cooling magnet, and because the salt used, cerium magnesium nitrate, has an extremely low magnetic susceptibility along one direction in the crystal, and that direction is set vertical.)

Now, with nature securely bound and tied, the

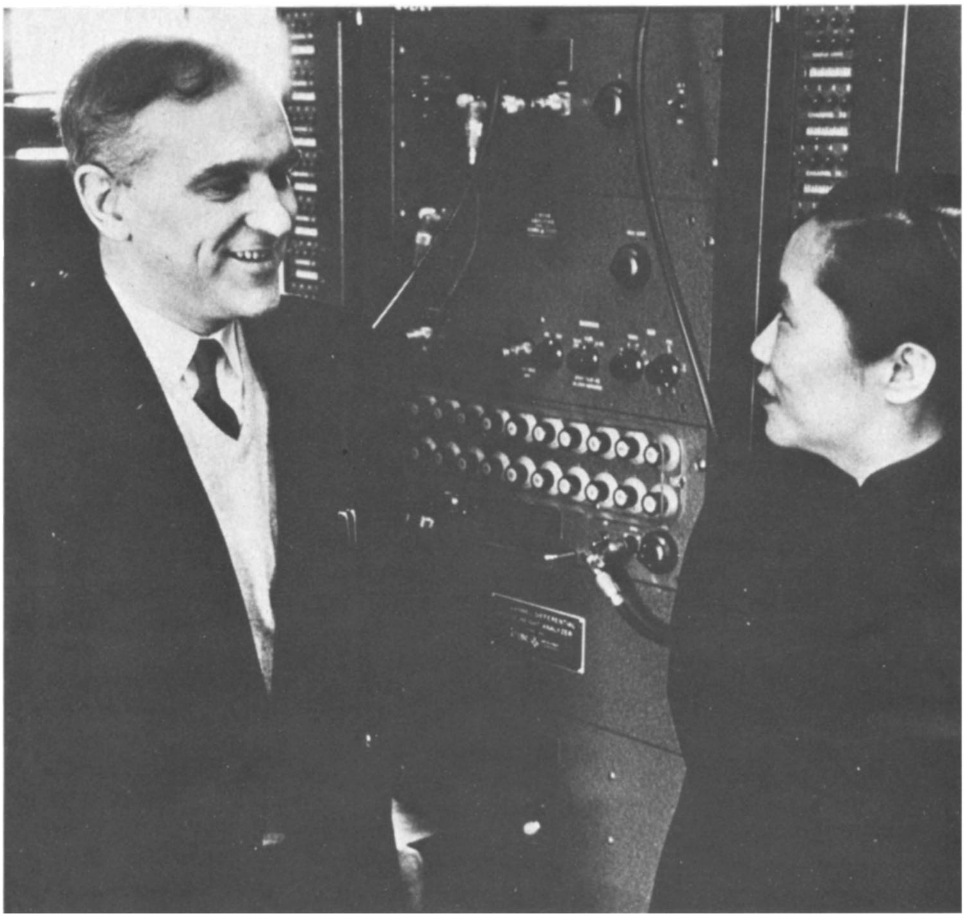


Fig. 9. Ernest Ambler with Chien-Shiung Wu, January 1957. (Photo: NBS, Neg. 26225.)

question is put to her thus: count the number of scintillations each second when the direction of the magnetic field in the solenoid is upward; this is the relative likelihood of an electron being emitted by a cobalt nucleus in the direction of its spin axis. Now count the number of flashes when the current in the solenoid is reversed; this is the relative likelihood of an electron being emitted in the opposite direction, for now the "tails" of cobalt nuclei face the detector. If these two numbers are not equal, mirror symmetry fails, parity falls.

The experiment performed

In the spring of 1956 T. D. Lee discussed with Chien-Shiung Wu, his colleague at Columbia University, the evidence for the conservation of parity in the weak interactions of subatomic particles. Wu was already a leading figure in the experimental study of the emission of high-speed electrons (beta rays) by atomic nuclei – the form of radioactivity arising from the weak interaction. She seized upon Lee and Yang's proposal to test the conservation of parity by observing the beta decay of oriented nuclei. Although she and her husband were booked on the *Queen Elizabeth* to visit Europe and the Far East, Wu opted to remain behind in order to carry out the proposed test, "... immediately, before the rest of the Physics Community recognized the importance of the experiment and did it first."

Professor Wu needed collaborators. A small violation of parity conservation translates into a small asymmetry in the distribution of beta rays. (That the violation would be as large as it could possibly be – as it proved in fact to be – seemed at the outset unlikely.) Observation of a small asymmetry requires a correspondingly high degree of orientation of the spinning nuclei. This could be attained only by cooling the nuclei to within a hundredth of a degree of absolute zero. And, as we have seen, so low a temperature could be reached only by adiabatic demagnetization. This sophisticated and demanding technique was then practiced at less than a score of laboratories in the world, and among these only a few were experienced in nuclear orientation. One of those few was the Cryogenic Physics Laboratory at the National Bureau of Standards in Washington.

Three years earlier, Ernest Ambler (Fig. 9) had come to the Bureau from Oxford University's Clarendon Laboratory, where his doctoral research involved the first demonstration of nearly complete orientation of a radioactive nucleus – ^{60}Co. In Washington he continued this work in collaboration with his former classmate, Ralph Hudson, an authority in cryogenics. Inevitably, Wu approached Ambler to propose collaboration. "It was on June 4, 1956 that I called and put the proposition directly to him. He accepted enthusiastically." Hudson soon added his collaboration, and in September two more physicists of the Bureau's staff, Raymond Hayward and Dale Hoppes, experienced in the detection of nuclear radiations, joined the team (Fig. 10).

Meanwhile, some crucial questions had been answered. At Columbia, Wu and her graduate student, Marion Biavati, showed that beta rays still produce light flashes even when the scintillator is cooled with liquid helium, and that these

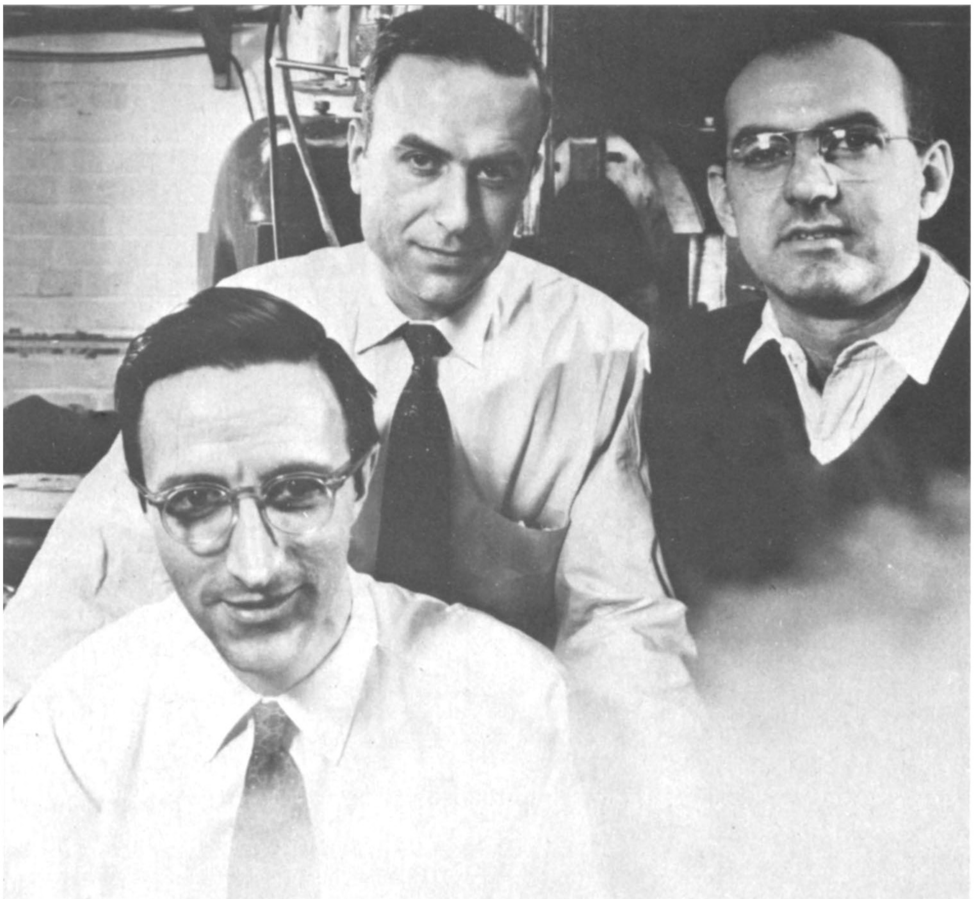


Fig. 10. Left to right: Hayward, Hudson, and Hoppes, January 1957. (Photo: *Life*.)

scintillations could still be seen by a photoelectric tube looking down a long light-pipe. Such a thick Plexiglas rod threatened to be an enormous "heat pipe." But at NBS ways were found to cool it and keep it cold with a tolerable consumption of liquid helium. Also, radioactive sources were prepared in which the cobalt atoms were incorporated in a thin surface layer of the cooling salt; for it was necessary that the energetic electrons emerge without change in their speed or direction.

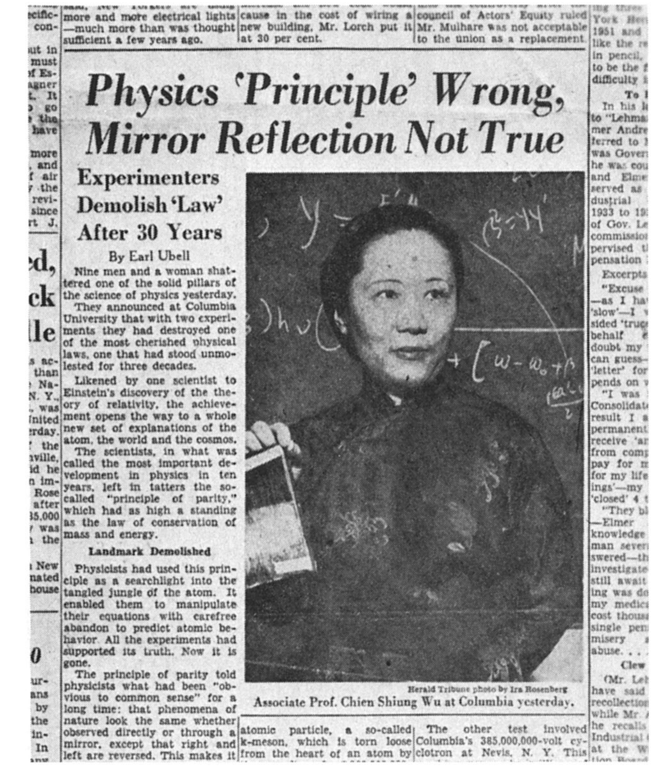
Early in October the team began to assemble and test the complete apparatus. Gamma rays, penetrating x rays emitted by the cobalt nuclei, told them that orientation was taking place but lasting only seconds. While the bulk of the cooling salt remained cold, its surface was rapidly warmed by gas evolved from the walls of the cryostat, the evacuable chamber containing the cooling salt and cobalt. This central portion of the apparatus had been constructed of metal so that it could be soldered shut, and so be proof against the dreaded superfluidity of the liquid helium in which it bathed. In November, after the failure of various expedients – notably enclosure of the radioactive specimen in a little "house" of cooling salt crystals – the cryostat and its vacuum connections were reconstructed completely of glass.

Glass eliminated the "outgassing," but brought the risk of "super-leaks" around the stopper which introduced and supported the cooling salt and radioactive specimen at the bottom of the apparatus. Leaks indeed occurred in the first trials. Then the "house" collapsed because of the forces exerted upon it by the cooling magnet. Finally, on December 27th, with the "house" lashed together with cotton thread, the experiment worked; the asymmetry in the emission of beta rays was impressively, excitingly large.

As exciting and encouraging were the results of December 27, so depressing and discouraging were those of the following week. The large asymmetry found in the emission of beta rays, implying a substantial violation of the conservation of parity, was not consistently reproducible in the following days' experiments.

This was the most trying moment in those many months of concentrated effort. Lee and Yang's paper had been published in October, and in November they presented their ideas to an exceptionally well attended congress of theoretical physicists in Seattle. It seemed certain that others would now be attempting the experiments they proposed. The results of December 27 convinced the group that Lee and Yang were right, that parity was not conserved. But the experiment would not work consistently enough to prove it.

A week of intense effort shook the bugs out of the experiment. Now large asymmetries were obtained consistently. A no less hectic week followed in which all conceivable checks were made to assure that the source of the asymmetry was nature's own left-handedness, not that of some human artifact. The group worked around the clock, assembling the apparatus many times, and took their breaks for a few hours sleep when the superfluid helium spoiled their vacuum by finding its way around the stopper at the


more and more electrical lights —much more than was thought sufficient a few years ago.

cause in the cost of wiring a new building, Mr. Lorch put it at 30 per cent.

council of Actors' Equity ruled Mr. Mulhare was not acceptable to the union as a replacement

Physics 'Principle' Wrong, Mirror Reflection Not True

Experimenters Demolish 'Law' After 30 Years

By Earl Ubell

Nine men and a woman shattered one of the solid pillars of the science of physics yesterday.

They announced at Columbia University that with two experiments they had destroyed one of the most cherished physical laws, one that had stood unmolested for three decades.

Likened by one scientist to Einstein's discovery of the theory of relativity, the achievement opens the way to a whole new set of explanations of the atom, the world and the cosmos.

The scientists, in what was called the most important development in physics in ten years, left in tatters the so-called "principle of parity," which had as high a standing as the law of conservation of mass and energy.

Landmark Demolished

Physicists had used this principle as a searchlight into the tangled jungle of the atom. It enabled them to manipulate their equations with carefree abandon to predict atomic behavior. All the experiments had supported its truth. Now it is gone.

The principle of parity told physicists what had been "obvious to common sense" for a long time: that phenomena of nature look the same whether observed directly or through a mirror, except that right and left are reversed. This makes it

Herald Tribune photo by Ira Rosenberg

Associate Prof. Chien Shiung Wu at Columbia yesterday.

atomic particle, a so-called k-meson, which is torn loose from the heart of an atom by

The other test involved Columbia's 385,000,000-volt cyclotron at Nevis, N. Y. This

Fig. 11. *New York Herald Tribune*, January 16, 1957.

bottom of the cryostat. Hoppes then slept beside the apparatus, telephoning to the others as soon as its temperature was low enough to begin their experiments again. Finally, on January 9th, at 2 o'clock in the morning, Hudson brought out a bottle of Chateau Lafite-Rothschild, 1949, and they drank to the overthrow of the law of parity.

Meanwhile, back in New York, word of the startling results with polarized ^{60}Co led a few of Wu's colleagues to try an exceedingly simple and ingenious experiment using Columbia's cyclotron. In just a few days they obtained striking evidence that parity is not conserved when pi mesons decay into muons, and muons into electrons. Columbia called a press conference for the afternoon of January 15th, the day the two papers were submitted to the *Physical Review* for publication. The next day "Basic Concept in Physics Reported Upset" was front page news (Fig. 11).

The physicists' world – and thus our world – had been changed, changed in a fundamental way. It is now necessary to accept as fact what no one imbued with the spirit of physics would readily or willingly believe: for God-knows-what reason, the world happens to be slightly left-handed.

Exciting evidence – the original record

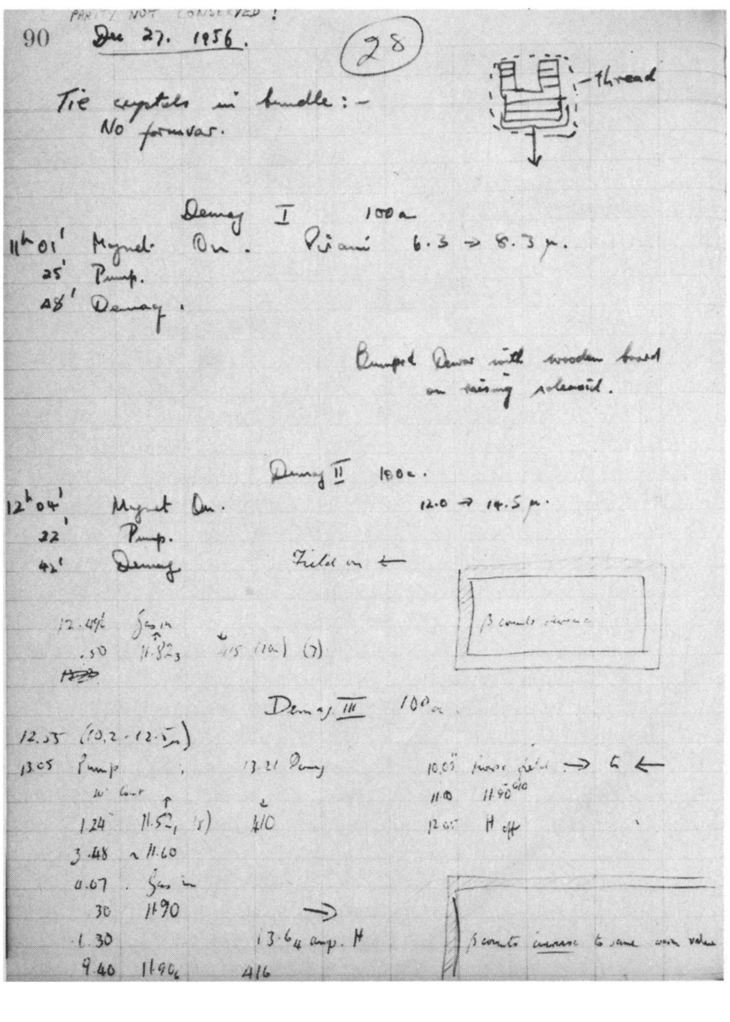


Fig. 12. Page 90 of Ernest Ambler's notebook for the experiment to test the conservation of parity. The entries begin in Ambler's hand. Following the date, we see the notation that the "house," the stack of crystals of the cooling salt (CMN) surrounding the radioactive source, is tied up with thread – in order that it not be demolished by the magnetic forces. "Demag I" is the first adiabatic demagnetization attempted on that day.

The electromagnet was energized with 100 A at 11:01 AM. This generated heat in the CMN which drove off absorbed gas, thus causing the pressure of the exchange gas in the cryostat to increase from 6.3 to 8.3 x 10^{-3} mm of mercury (as measured by a Pirani-type vacuum gauge). At 11:25, after this heat had been conducted away, the valves on the exchange-gas manifold were turned to connect the vacuum pump to the cryostat, and thus isolate thermally the CMN.

At 11:48 came the demagnetization proper. The electromagnet was turned off, causing the temperature of the CMN to fall below a hundredth of a degree. The solenoid which would generate the magnetic field to orient the nuclei was quickly raised around the tip of the outermost Dewar flask. But, as Ambler notes, they accidently bumped the Dewar with the wooden board which was to support the solenoid. The slight mechanical vibration thus produced immediately heated up the CMN; the run was ruined.

At 12:04 they began again. This and the following run were successful. Hudson's notation "Field on" (directly under "Demag II") refers to the magnetic field produced by the solenoid. A leftward throw of the switch produced a downward magnetic field, with the result that the "beta counts decrease" from an initially high value as the cobalt warms up. This result boxed for emphasis, was just what they had been looking for. "PARITY NOT CONSERVED!" Hayward lettered at the top of the page.