Reversal of the Parity Conservation Law in Nuclear Physics

In late 1956, experiments at the National Bureau of Standards demonstrated that the quantum mechanical law of conservation of parity does not hold in the beta decay of ^{60}Co nuclei. This result, reported in the paper *An experimental test of parity conservation in beta decay* [1], together with ensuing experiments on parity conservation in μ-meson decay at Columbia University, shattered a fundamental concept of nuclear physics that had been universally accepted for the previous 30 years. It thus cleared the way for a reconsideration of physical theories, especially those relating to symmetry, and led to new, far-reaching discoveries regarding the nature of matter and the universe. In particular, removal of the restrictions imposed by parity conservation first resolved a serious conflict in the theory of subatomic particles, known at the time as the tau-theta puzzle, and later led to a fuller understanding of the strong, electromagnetic, and weak interactions. The better understanding of their characteristics has led to a more unified theory of the fundamental forces.

The beta-decay experiments were carried out by C. S. Wu of Columbia University in collaboration with NBS staff members Ernest Ambler, Raymond W. Hayward, Dale D. Hoppes, and Ralph P. Hudson. The Bureau's low temperature laboratory was chosen for the experiments because of its millikelvin-region research capability [2] and the staff"s experience in the spatial orientation of atomic nuclei [3], an essential feature of the beta-decay study.

Basically, parity conservation in quantum mechanics means that two physical systems, one of which is a mirror image of the other, must behave in identical fashion. In other words, parity conservation implies that Nature is symmetrical and makes no distinction between right- and left-handed rotations, or between opposite sides of a subatomic particle. Thus, for example, in beta decay there should be no preferential direction of emission with respect to the direction of the spin of the emitting nucleus, i.e., no (nuclear) spin—(electron) momentum correlation.

Since 1925, physicists had accepted the principle that parity is conserved in all types of interactions. During the 1950s, however, phenomena were found in high-energy physics that could not be explained by existing theories. The available accelerators produced a variety of subatomic particles. One such particle is the short-lived K meson emitted in the collision of a high-energy proton with an atomic nucleus. The K meson seemed to arise in two distinct versions, one decaying into two π mesons, the other decaying into three pions, with the two versions being identical in all other characteristics. A mathematical analysis showed that the two-pion and the three-pion systems have opposite parity; hence, according to the prevalent theory, these two versions of the K meson had to be different particles.

Early in 1956, T. D. Lee of Columbia University and C. N. Yang of the Institute for Advanced Study, Princeton University, made a survey [4] of experimental information on the question of parity. They concluded that the evidence then existing neither supported nor refuted parity conservation in the "weak interactions" responsible for the emission of beta particles, K-meson decay, and such. They thus proposed that the K-meson itself may have definite parity, and the observed opposite parity of the two systems of decay products may be the manifestation of parity non-conservation in its decay. They suggested that parity may not be conserved in weak interactions, saw that there was no experimental evidence that proved that this was or was not true, and proposed a number of experiments that would provide the necessary evidence. One of the proposed experiments, which involved measuring the directional intensity of beta radiation from oriented ^{60}Co nuclei, seemed to them to be the best prospect for success in testing their hypothesis. Yang and Lee had turned to beta-spectroscopist and Columbia University friend and colleague Chien-Shiung Wu for advice on how to pursue their preferred suggestion. Wu, in turn, approached Henry Boorse of Columbia and his close associate Mark W. Zemansky of the City College of New York, who together ran a modest research program in cryophysics at Columbia. Although these scientists lacked the "parity-required" facilities, they were active members in the international low-temperature-physics community, well acquainted with the NBS program and the recent move thereto of Ernest Ambler, a graduate from the Oxford (UK) "cryonuclear physics" research program [5]. It was they who suggested that Wu make initial contact with Ambler and, in fairly short order, arrangements were made to carry out this experiment in the Bureau's low-temperature laboratory.

The envisaged experiment was far from routine and involved many unknowns at the outset. The source of the β-rays would have to be in intimate contact with the cooling medium (paramagnetic crystal) and also on the surface, so that the beta particles could get out of the crystal. Could the contact and refrigeration be made adequate? Would back-scattering be, in consequence, a major drawback? How to count the β-rays? In situ? Remotely? And either way—exactly how? What of the external magnetic field necessary for polarizing the cobalt nuclei without heating up the refrigerating salt? What was the optimum activity of the β-source—large being best for detection sensitivity, small for minimizing local heating?

Polarization of the nuclei was achieved by cooling a paramagnetic crystal containing ^{60}Co to within 0.003 K and subjecting it to a magnetic field. At this temperature the effects of thermal agitation are so small that atomic nuclei can line up in a given direction within the crystal lattice when a magnetic field is applied. The magnetic polarity of the nucleus is determined by its direction of spin and, under the influence of a magnetic field, most of the ^{60}Co nuclei align themselves so that their spin axes are parallel to the field. If parity is conserved in beta decay, then the intensity of the beta emission should be the same in either direction along the axis of spin. This, of course, was the critical question in the ^{60}Co experiments. It was resolved by measuring the intensity of beta emission in both directions, i.e., along and against the field direction.

The ^{60}Co was located in a thin (50 μm) surface layer of a single crystal of cerous magnesium nitrate (CMN). The crystal was placed in an evacuated flask which, in turn, was immersed in liquid helium within a Dewar flask surrounded by liquid nitrogen. An inductance coil on the surface of the inner flask was used to measure the temperature of the crystal in terms of its magnetic susceptibility. CMN is extremely anisotropic: the trivalent sites in its plate-like natural form are almost non-magnetic along the (out-of-plane) c-axis, but are uniformly magnetic in the plane. Co ions, however, would go into divalent sites which are contrary magnetically, i.e., most easily magnetized *along* the crystallographic c-axis. Thus in magnetic anisotropy, CMN should be ideal for the experiment: major (magnetic cooling) field in the plane, small polarizing (solenoid) field perpendicular to the plane, with negligible temperature-raising effect. But might not that polarizing field exert a torque on the crystal of sufficient strength to break a typically fragile thermally-isolating mounting?

A major experimental problem was the location of a radiation counter within the evacuated flask for detection of beta particles. This problem was solved by placing a thin anthracene crystal inside the chamber to serve as a scintillation counter. The anthracene crystal was located about 2 cm above the ^{60}Co source. Scintillations caused by beta particles striking the crystal were transmitted through a glass window and a 120 cm lucite rod acting as a light pipe to a photomultiplier at the top of the flask. The resulting pulses were counted on a 10-channel pulse-height analyzer. It proved possible to design the light pipe so as to hold the resultant contribution to the liquid-helium loss rate to a tolerable level.

In addition to the beta counter within the vacuum chamber, two sodium iodide gamma scintillation counters were used externally to measure the directional intensity of the more penetrating gamma radiation. In this way the investigators were able to determine the degree of polarization of the ^{60}Co nuclei. The two gamma counters were biased to accept only the pulses from the photopeaks in order to discriminate against pulses from Compton scattering.

Close to midway through the six-month work-up period, the team reached the conclusion that problems arising from outgassing within the crucial chambers of the apparatus would never be surmounted, and the entire assembly was re-designed from stainless steel to glass and a new version quickly constructed and assembled.

Cooling to the low temperature necessary for nuclear alignment was accomplished by the process of adiabatic demagnetization using a magnetic field of about 2.3 T (23 kilogauss). This process involved isothermal magnetization and subsequent isentropic demagnetization of the paramagnetic salt, CMN, which supported the ^{60}Co specimen. The heat produced by magnetization was removed by transfer through helium "exchange gas" and the boiling off of liquid helium in the surrounding dewar. The specimen was then thermally isolated by pumping out the exchange gas and upon demagnetization the temperature fell to about 0.003 K.

Next, a vertical solenoid was raised around the lower end of the outer dewar to provide a magnetic field for polarization of the ^{60}Co nuclei. After the beta emission had been measured for this condition, the direction of the magnetic field was reversed and the beta emission again measured for the nuclei now polarized in the opposite direction. It was found that the emission of beta particles is greater in the direction opposite to that of the nuclear spin. Thus, a spinning ^{60}Co nucleus has a beta emission distribution that is not the same as that of its mirror image. This result unequivocally demonstrated that parity is not conserved in the emission of beta particles by ^{60}Co.

Beyond the primary question resolved by this experiment, another matter of great interest was "how large was the effect" since, in principle, the asymmetry—if observed at all—could have turned out to be anywhere from zero to maximum (asymmetry parameter from 0 to 1); it was, in fact, *maximum.* Thus the general opinion (largely derisory!) about the likelihood of the

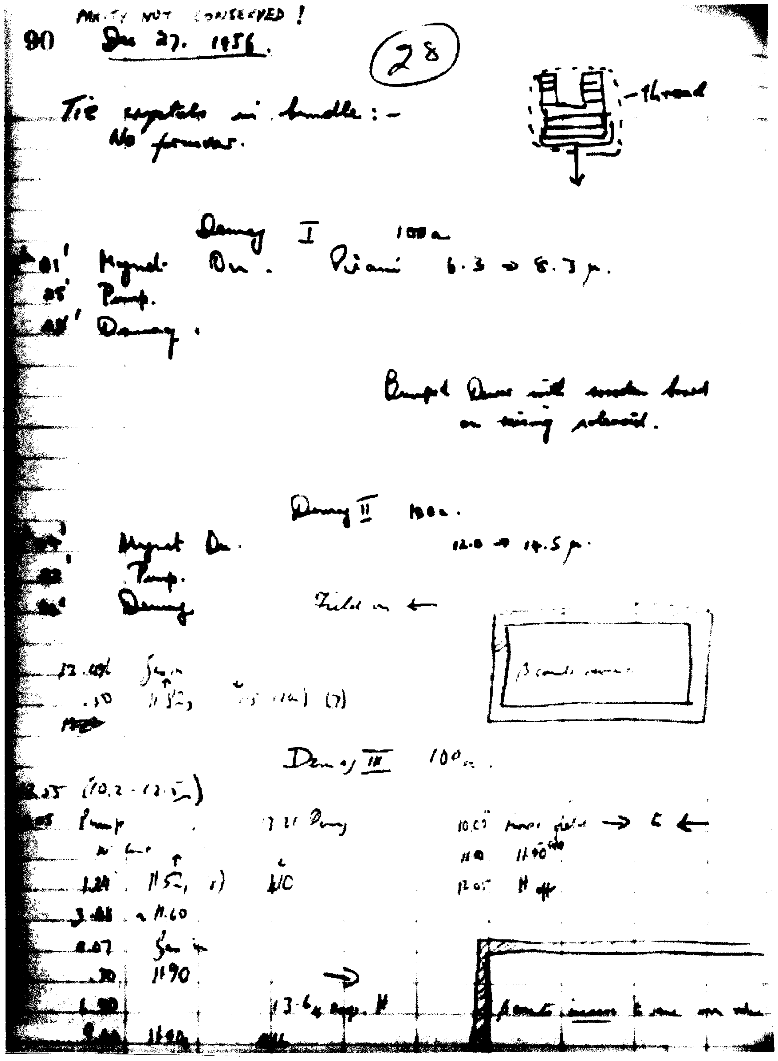

Fig. 1. The page of Ernest Ambler's notebook recording the first definitive evidence that parity is not conserved. The comment to that effect at the top left of the page was added by Ralph Hudson.

proposal of Lee and Yang bearing fruit changed overnight, and the nuclear physics community scrambled to try out other tests that would now be quite feasible. In fact, colleagues of C. S. Wu were able to design an experiment at the Columbia University cyclotron and demonstrate within a day or two the "parity effect" in a π-μ-e decay experiment [6], long before the NBS-Wu team could carry out all the "check experiments" they anticipated would now be demanded by the skeptics!

After those checks had been completed, a second experiment was performed [7] using ^{58}Co, which is a positron emitter. In this case the positrons were emitted preferentially in the opposite direction to that of the electrons, that is, β^+ particles are preferentially emitted along the direction of the nuclear spins. This provided additional confirmation of the conjecture of Lee and Yang and supported the new theory that was being developed at the time to explain parity non-conservation.

While the general U.S. physics community reacted rapidly with great interest and excitement to these momentous events, culminating in extraordinary jam-packed sessions at the New York meeting of the American Physical Society in January 1957, other sentiments intruded upon the otherwise euphoric scene: Skepticism leveled at the original Lee-Yang proposal was replaced, in some minds, by disbelief in the results of these validating experiments, for parity conservation was an article of faith not to be discarded lightly. The NBS team's colleague from Washington's Carnegie Institution Department of Terrestrial Magnetism, Georges M. Temmer, was on a laboratory odyssey in Western Europe at the time of the first news outbreak. At one point, Temmer found himself in the presence of *eminence grise* Wolfgang Pauli, who asked for the latest news from the United States. Temmer told him that parity was no longer to be assumed "conserved." "That's total nonsense" averred the great man. Temmer: "I assure you the experiment says it is not." Pauli (curtly): "Then it must be repeated!" [8].

Not long after this, the world settled down to the realization that Lee and Yang had been right. Interestingly, though, a reluctance to believe that NBS staff had played a significant role (indeed, any role for some minds) in the crucial experiment began to spread in the less-informed parts of the U.S. scientific community, and elsewhere. Even as early as that European tour of Temmer's, he encountered this. At a colloquium, also in Switzerland, and present when the proceedings were interrupted for an announcement of the "triumph at Columbia U.," Temmer spoke from the floor to make the correction that the work had been carried out at the National Bureau of Standards; he was—more or less politely—"hooted down." And despite his international standing—even especially in that particular community—he was pitied as being extraordinarily "mistaken." Later on, and forever afterward, hardly a speaker or writer referred to the event in any other term than "the Wu experiment" and only C. N. Yang himself and Chief Cryogenic Notable Nicholas Kurti went out of their way to try to set the record straight.

The further developments of the theory, together with a large number of follow-up experiments, have led to the unification of the weak and electromagnetic interactions. A description of both the history and the physics is available in the Nobel lectures by Weinberg, Salam, and Glashow [9].

In 1957, NBS moved rapidly to include those of its staff in the "parity experiment team" in its Honors & Awards for that year, presenting them with the Commerce Department"s Award for Exceptional Service (the Gold Medal). In 1964 it added its own highest recognition, the Samuel Wesley Stratton Award. In 1962, the Franklin Institute of Philadelphia awarded its John Price Wetherill Medal to the full team.

C. S. Wu resumed her full-time preoccupation with β-decay research at Columbia University and the concomitant training of graduate students there. Over the years she received many honors, including the National Medal of Science (1975), the Wolf Prize in Physics (1978), and election to the Presidency of the American Physical Society (1975), the first woman to achieve that distinction. Wu died in New York in February 1997 at the age of 84 [10].

Ralph Hudson was appointed Chief of the Heat Division at NBS in 1961, and Ernest Ambler moved up to take his place as Chief of the Cryogenic Physics Section. For several years Ambler continued to carry out research, in collaborative efforts on oriented nuclei and superconductivity. He then went on to occupy a series of positions of increasing responsibility at NBS, culminating in Director of the agency—after several years as Acting Director—a post he held from 1978 to 1988 [11]. During this period, he received the President's Award for Distinguished Federal Civilian Service. Prior to his retirement from NIST in 1989, at the age of 65, he was Acting Undersecretary for Technology in the Department of Commerce.

Hudson continued to do research, as administrative preoccupations would permit, on cryothermometry and low-temperature magnetism. A review article co-authored by him received NBS's Condon Award in 1976 for distinguished authorship [12]. In the NBS reorganization of 1978, the Heat Division was abolished and Hudson became Deputy Director, under Karl G. Kessler, of the Center for Absolute Physical Quantities, with additional responsibility for managing the standards activity in Mass and Length. He resigned in 1980 and went to work at the International Bureau of Weights & Measures in Sèvres, France, as Director of Publications and editor of the international journal *Metrologia.* Upon retirement therefrom in 1989, at the age of 65, he returned to the Washington area and took a three-year temporary post at the National Science Foundation as Program Director for Low-Temperature Physics.

Raymond Hayward, after involvement with his colleagues in several follow-up experiments in the Low-Temperature Laboratory, returned to duty in the Radioactivity Section (Wilfrid B. Mann, Chief). When a separate Nuclear Spectrometry Section was created he was appointed Chief. He wrote a monumental treatise on the dynamics of particles of higher spin (>1/2) [13], after which he devoted himself to the study of gravitation. He retired in 1980 at the age of 59.

Dale Hoppes continued experimental studies of beta-particle distributions from oriented nuclei [14] in the Nuclear Spectrometry Section, earning a Ph.D. from The Catholic University of America in 1961. He later returned to the Radioactivity Section, where he was involved in activity and gamma-ray-probability measurements. When Mann retired in 1981, Hoppes took over as Radioactivity Group Leader until his retirement from NIST in 1992 at the age of 64.

Prepared by Ralph P. Hudson.

Bibliography

[1] C. S. Wu, E. Ambler, R.W. Hayward, D. D. Hoppes, and R. P. Hudson, Experimental test of parity conservation in beta decay, *Phys. Rev.* **105**, 1413-1415 (1957).

[2] See, for example, D. de Klerk and R. P. Hudson, Installation for Adiabatic Demagnetization Experiments at the National Bureau of Standards, *J. Res. Natl. Bur. Stand.* **53**, 173-184 (1954); E. Maxwell, Isotope effect in the superconductivity of mercury, *Phys. Rev.* **78**, 477 (1950) ; D. de Klerk, R. P. Hudson, and J. R. Pellam, Second sound propagation below 1 °K, *Phys. Rev.* **93**, 28-37 (1954).

[3] Low-Temperature Alinement of Radioactive Nuclei, *NBS Tech. News Bull.* **40**, 49-51 (1956); see also E. Ambler, R. P. Hudson, and G. M. Temmer, Alignment of Cerium-141 and Neodymium-147 Nuclei, *Phys. Rev.* **97**, 1212-1221 (1955); E. Ambler, R. P. Hudson, and G. M. Temmer, Alignment of Three Odd-*A* Rare-Earth Nuclei, *Phys. Rev.* **101**, 196-200 (1956).

[4] T. D. Lee and C. N. Yang, Question of parity conservation in weak interactions, *Phys. Rev.* **104**, 254-258 (1956).

[5] J. M. Daniels, M. A. Grace, and F. N. H. Robinson, An Experiment on Nuclear Alignment: the Anisotropy of γ-Radiation from Oriented Cobalt-60 Nuclei, *Nature* **168**, 780-781 (1951); E. Ambler, M. A. Grace, H. Halban, N. Kurti, H. Durand, C. E. Johnson, and H. R. Lemmer, Nuclear Polarization of Cobalt 60, *Philos. Mag.* **44**, 216-218 (1953).

[6] R. L. Garwin, L. M. Lederman, and M. Weinrich, Observations of the failure of conservation of parity and charge conjugation in meson decays: the magnetic moment of the free muon, *Phys. Rev.* **105**, 1415-1417 (1957).

[7] E. Ambler, R. W. Hayward, D. D. Hoppes, R. P. Hudson, and C. S. Wu, Further Experiments on β Decay of Polarized Nuclei, *Phys. Rev.* **106**, 1361-1363 (1957).

[8] G. M. Temmer—private communication. Temmer, a gifted scientist of infectious enthusiasm, had played an important part in establishing the solid reputation of the NBS Cryogenic Physics Section's nuclear orientation program, first while employed in the NBS Radioactivity Section, later after moving to the Department of Terrestrial Magnetism.

[9] Steven Weinberg, Conceptual foundations of the unified theory of weak and electromagnetic interactions, *Rev. Mod. Phys.* **52**, 515-523 (1980); Abdus Salam, Gauge unification of fundamental forces, ibid., pp. 525-538; Sheldon Lee Glashow, Towards a unified theory: Threads in a tapestry, ibid., pp. 539-543..

[10] R. L. Garwin and T. D. Lee, Obituaries: Chien-Shiung Wu, *Phys. Today* **50** (10), 120,122 (1997).

[11] E. Ambler, Historical Perspective: 1973-1989, in *NBS/NIST: A Historical Perspective, A Symposium in Celebration of NIST"s Ninetieth Anniversary, March 4, 1991,* NIST Special Publication 825, National Institute of Standards and Technology, Gaithersburg, MD (1992) pp. 31-40.

[12] R. P. Hudson, H. Marshak, R. J. Soulen, Jr., and D. B. Utton, Recent Advances in Thermometry below 300 mK, *J. Low Temp. Phys.* **20**, 1-102 (1975).

[13] Raymond W. Hayward, *The Dynamics of Fields of Higher Spin,* NBS Monograph 154, National Bureau of Standards, Washington, DC (1976).

[14] A. T. Hirshfeld and D. D. Hoppes, Transition Mixing Ratios Determined from a Study of the Electron and Gamma-Ray Distributions from Oriented Iridium-192, *Phys. Rev. C* **2**, 2341-2349 (1970).