4

The Discovery of the Parity Violation in Weak Interactions and Its Recent Developments

Chien-Shiung Wu

Abstract This address was presented by Chien-Shiung Wu as the Nishina Memorial Lecture at the University of Tokyo, March 31, 1983

It is a great honor and privilege for me to deliver the Nishina Commemorative Lecture. Dr. Yoshio Nishina made not only fundamental and important contributions to various scientific fields; his great leadership, inspiration and dedication to scientific research and higher education in this country is a most moving and inspiring story to commemorate.

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The topic of my talk today on the Discovery of the Parity Violation in Weak Interactions and Its Recent Developments is already twenty-six years old. On January 16, 1957, the world of Physics was suddenly shocked by the news that parity is not conserved. The Jackson Professor Otto Frisch of Cambridge University described the announcement as "the obscure phrase 'parity is not conserved' circled the globe like a new gospel." Why has the news caused such excitement? What is the real meaning of the law of Conservation of Parity? What are the implications and consequences of the overthrow of the law of parity on Physics?

Put in the simplest language, it means that the results of this discovery unequivocally proved that many natural phenomena, and also the objects of the microscopic world, are not necessarily symmetrical with respect to left and right. Now, one must be even more puzzled and want to understand why people should be so shocked by the discovery in which things turned out not necessarily left-right symmetrical.

Chien-Shiung Wu (1912 – 1997).
Columbia University (USA) at the time of this address

Part I: Symmetry and Is Parity Conserved in Weak Interactions?

(1) Symmetry and Bilateral Symmetry:

The general concept of symmetry has a much broader meaning and it has occupied a very important position in the history of human civilization. The left–right symmetry is a bilateral symmetry and also a very prominent one. When the well known mathematician Professor Herman Weyl retired from Princeton University only a few years before the question of parity became the focal point in the theory of particle physics; he gave a series of four beautiful lectures to expound on the subject of symmetry and presented their forms, meanings and corresponding in variance elements ('Symmetry' [1], Princeton University Press, 1952). In the limited time permitted for this lecture, only a selected few illustrations will be shown which may give you some ideas that symmetry is indeed present everywhere in nature as well as in works of art or architecture. From such popular consensus and conviction, it is not difficult to imagine how one's ancestors came to appreciate the idea of symmetry, particularly, the simple *bilateral symmetry*.

(2) A Few Illustrations of Various Forms of Symmetry : (Fig. 4.1–Fig. 4.8)

It seems not an unreasonable conjecture that the concept of symmetry has something to do with these beautiful objects and phenomena existing in nature and also in the works of art and architecture developed with time.

(3) Symmetry in Sciences:

Since symmetry occupies such an important position in the history of human civilization, philosophers and scientists have naturally attempted to make use of this idea, but the attempts met with little success. For instance, in 1595, Kepler tried to use the symmetry of geometrical structure to explain the ratio of the diameters of planetary orbits (see Fig. 4.9).

The six spheres correspond to the six planets, Saturn, Jupiter, Mars, Earth, Venus, Mercury, separated in this order by cube, tetrahedron, dodecahedron, octahedron, icosahedron. This unsuccessful way of seeking harmony in static forms such as in regular solids by Kepler was long before his famous discovery of the three dynamic laws now bearing his name. Later, scientists no longer sought this harmony in static forms but in dynamic laws. By the 19th century, the idea of symmetry had become the central theme in a number of modern scientific disciplines; the obvious ones are
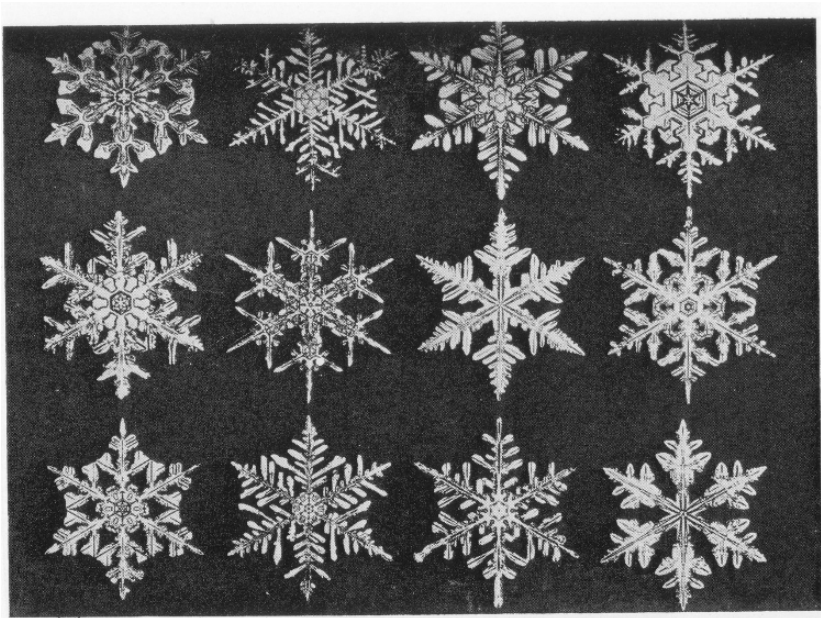
Fig. 4.1 Snowflakes or little marvels of frozen water are the best known specimens of *hexagonal symmetry*. They were the delight of old and young
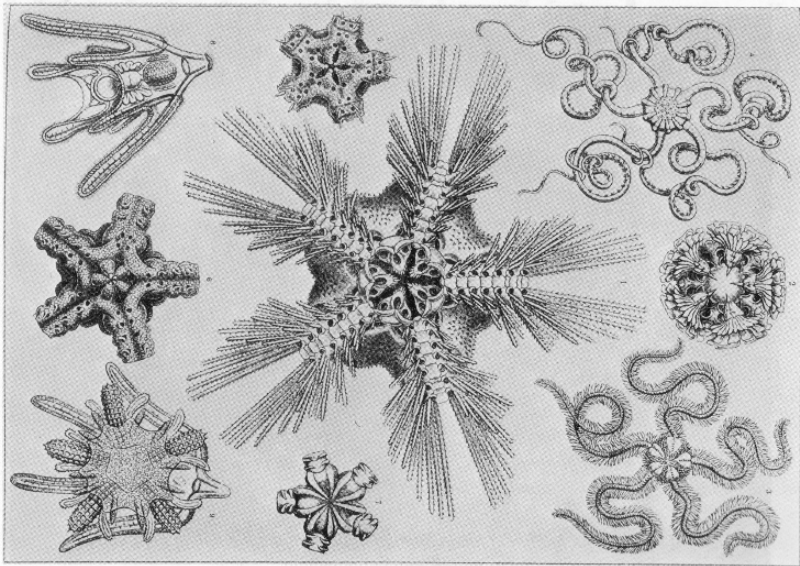

Fig. 4.2 This figure shows *cyclic symmetry of 5* of echinoderma from Ernest Haeckel's 'Kunstformen der Natur.' Their larvae are organized according to the principle of *bilateral symmetry*
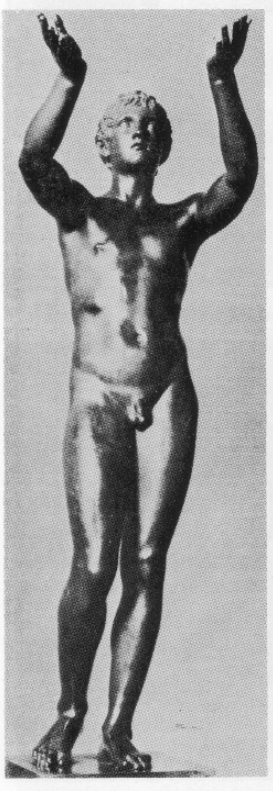
Fig. 4.3 This figure of a Greek sculpture of a noble praying boy can be used to illustrate *bilateral symmetry*

Fig. 4.4 A bronze statue from Northern Wei dynasty (385–534) in China also represents *bilateral symmetry*
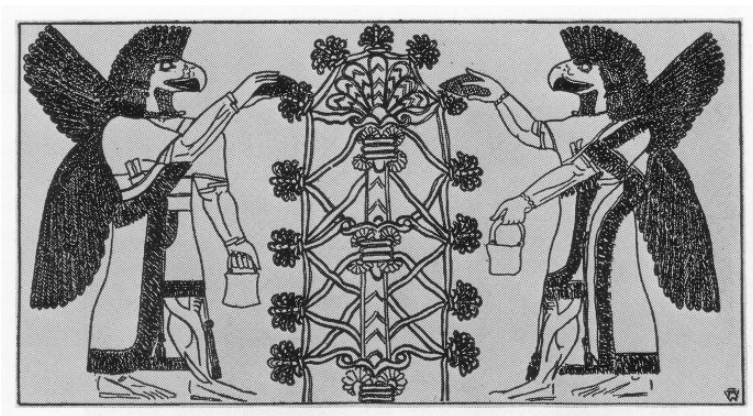

Fig. 4.5 The Sumerians seem to have been particularly fond of strict *bilateral symmetry*. Alas! in this picture the two eagle-headed men are nearly but not quite symmetry (look at their arms)

Fig. 4.6 (*left*) Bronze wall "Gui," Shang dynasty
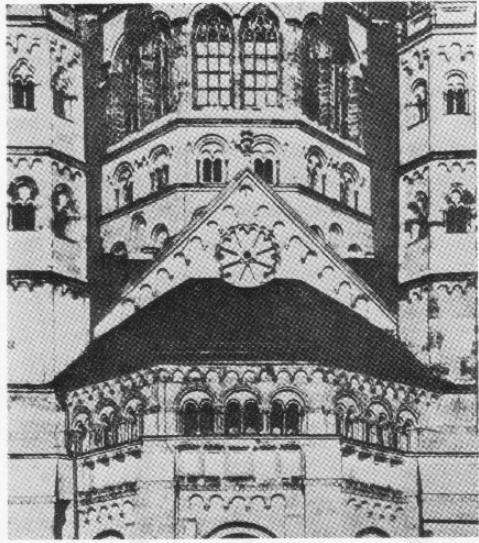
Fig. 4.7 (*right*) The rear view of the Romanesque cathedral in Mainz. Here shows repetition in the round arcs of the friezes, *octagonal central symmetry* in the small rosette and the three towers, while *bilateral symmetry* rules the structure as a whole as well as almost every detail
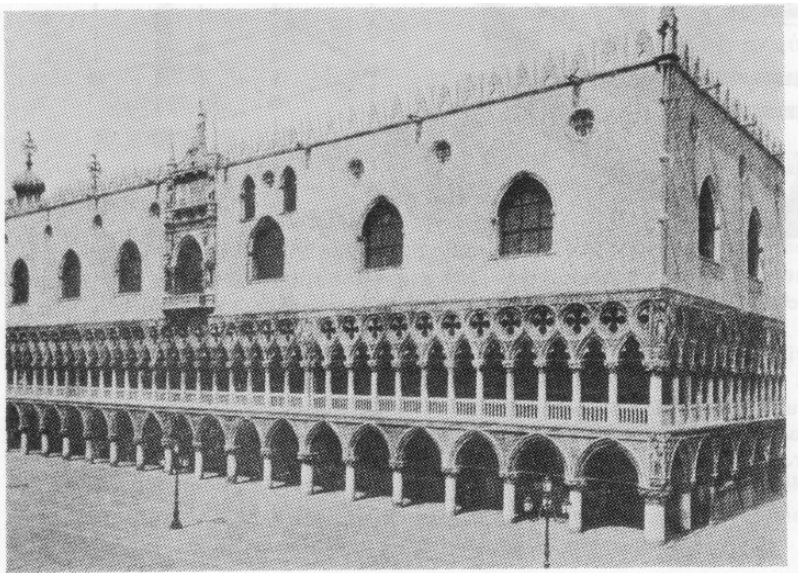

Fig. 4.8 The Palace of the Doges in Venice may stand for *translational symmetry* in architecture

crystallography (see Fig. 4.10), then molecular, atomic, nuclear, particle physics, chemistry and so forth. The importance of symmetry principles eventually dictated the types of fundamental interactions among various elementary particles.

(4) Conservation Laws and Symmetry:

The first and perhaps the most important concept of symmetry is that space and time are isotropic and homogeneous. All points and all directions in space are equivalent so that there is no real distinction of absolute location in time and space. These are known as symmetry principles or equivalently *invariance principles*. The basic laws of conservation of momentum and energy are the direct consequences of the invariance of physical laws under space and time displacements. In other words, "*Symmetry and Conservation Laws are really one and the same thing*." (See Fig. 4.11)

(5) The Conservation of Parity and Right-Left Symmetry:

The symmetry between the left and right was debated at length by philosophers in the past. The laws of physics have always shown complete symmetry between the left and the right, that is, in all physics, nothing has appeared which would indicate intrinsic differences between left and right.

Left and right being a discrete symmetry, therefore the law of right-left symmetry did not play any great important part in classical physics. It came to its eminence with the introduction of quantum mechanics. In fact, the conservation of parity is the direct consequence of the law of left-right symmetry.

The Law of Parity Invariance states that for any atomic or nuclear system, no new physical law should result from the construction of a new system differing from the original by being a mirror image. That is, there is no absolute distinction between a real object (or event) and its mirror image. In other words, two worlds, one based upon a right-handed system (say, real object) and one based upon a left-handed system (say, mirror image) obey the same laws of physics. This law has been built into all physical theories from the 1920's to 1957 and has severely restricted the predicted behavior of elementary particles.

(6) The "Tau" and "Theta" Puzzle:

Up to about 1956 all theoretical physicists accepted the validity of parity conservation, and no experimentalists ever thought of devising tests to challenge its validity. Then, the big puzzle in K-meson decay [2] came onto the scene to stun the experts. K-mesons are unstable particles which were discovered in 1952–1953. Some
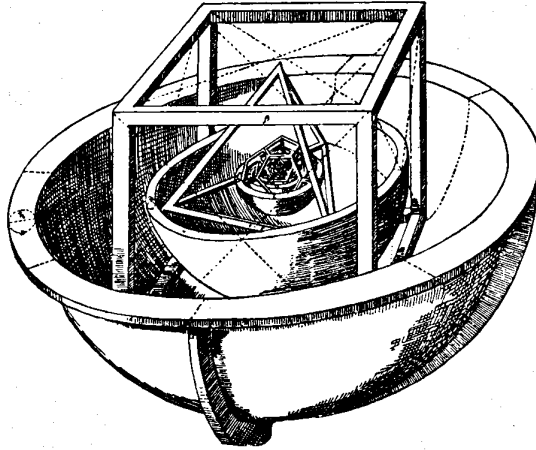
Fig. 4.9 Kepler made an attempt to deduce the distances in the planetary system to regular bodies which are alternatingly inscribed and circumscribed to spheres. This figure was published in 1595 in his 'Mysterium Cosmographicum,' by which he believed he had penetrated deeply into the secrets of the Creator

Fig. 4.10 Crystal structure is closely related to symmetry and invariance elements. A crystal lattice has a large number of invariance elements such as displacing to the right by one unit, or upwards by one unit, etc

對稱
Symmetry

不變元
Invariance element

守恆定律
Conservation law

（只適用於量子力學）
(only in quantum mechanics)

晶體結構
及其他應用
**Crystal structure
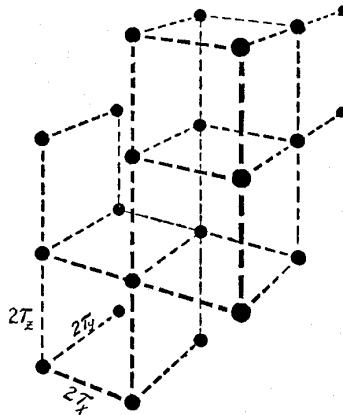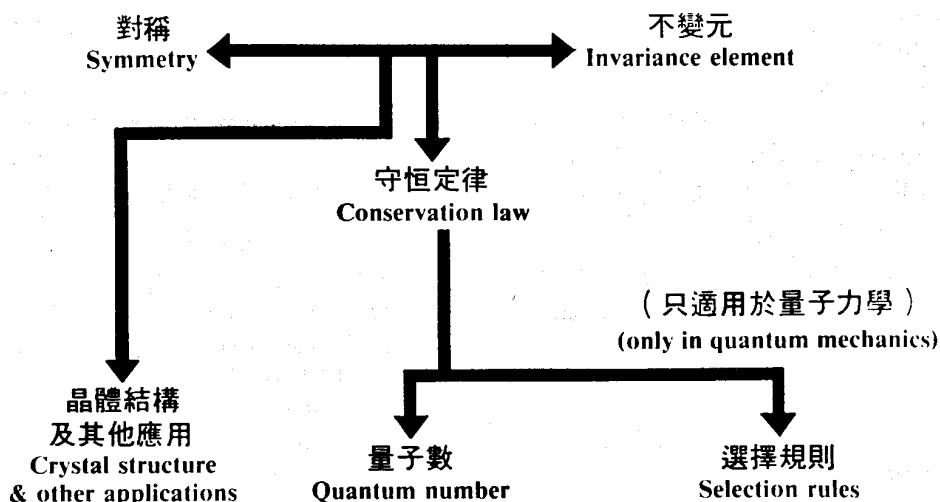& other applications**

量子數
Quantum number

選擇規則
Selection rules

Fig. 4.11 Symmetry and conservation laws are really one and the same thing. After the introduction of quantum mechanics in discussing the structure of atoms or molecules, we must refer to their quantum numbers, the idea of which has its roots in symmetry principles

K-mesons decay into two π-mesons, others into three π-mesons. The K-mesons yielding two π-mesons are called "Theta"; those yielding three π-mesons are called "Tau." "Tau" and "Theta" are identical twins of same mass and same lifetime.

$$\theta \longrightarrow 2\pi$$
$$\tau \longrightarrow 3\pi$$

The decays into two or three π-mesons are permitted by theory and therefore, it is nothing startling. But the two decay modes cannot be reconciled with the law of conservation of parity. "Tau" decays to an odd number of π-mesons of odd parity; "Theta" to an even number of π-mesons of odd parity. If one of them observes the conservation of parity, the other must violate it. So deeply rooted was this conception of parity that the physicists involved in the K-meson problem were greatly puzzled by this riddle. To recapture the atmosphere of that frustrating period, I might quote Dr. C. N. Yang [3] who said that 'the physicist at that time was like a man in a dark room groping for a way out. He is aware of the fact that in some direction there must be a door which will lead him out of his predicament. But in which direction?' After the parity experiment in polarized ^{60}Co nuclei showed definitely that both parity and charge conjugation in beta decay were violated, Yang telegraphed the news to J. R. Oppenheimer, who was vacationing in the Virgin Islands. He cabled back "Walked through door..." referring to Yang's above comment.

(7) The Question of Parity Conservation in Weak Interactions:

By April of 1956, various participants in the sixth Rochester Conference began to express their doubt of the *Universal Validity* of parity. Lee and Yang immediately plunged into a systematic investigation of the status of experimental knowledge concerning the parity conservation and were surprised that although parity was conserved in strong interactions, no experiments had ever been designed specifically to test such an invariance in weak interactions. The weak interactions include β-decay, π-meson and μ-meson decay and strange particle interaction.

So, the anxiety that began with a single isolated puzzle in "Tau" and "Theta" cases is now applied to a broad and pressing question: *"Is Parity Conserved in All Weak Interactions?"* [4]

Part II: Conservation of Parity Operation in Radioactive Decays

To use "Tau" and "Theta" particles themselves in these tests is impractical. However, the beta decays of radioisotopes are perfectly suited for this experimentation. To understand the meaning of the experiment on polarized nuclei, one must first examine the meaning of conservation of parity in radioactive decays.
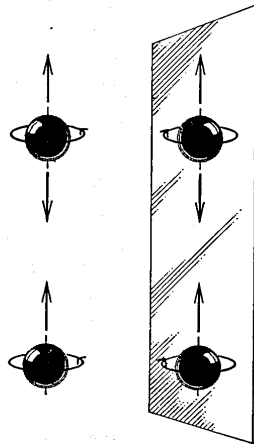
Fig. 4.12 The mirror reflection of a spinning ball. The image and the real object could not be distinguished because the top right one looks just like the real ball turned upside down. Reflection can be detected if there is a preferred direction

The law of parity dictates that the physics phenomena of atomic or nuclear systems in the original and its mirror twin should be indistinguishable. Fig. 4.12 shows the mirror reflection of a spinning ball. If the ball ejected particles equally in both

directions along its axis, the image and the real object could not be distinguished because the top right one looks just like the real ball turned upside down. However, if there is a preferred direction for the ejection of particles, then the reflection can be detected. The image at bottom cannot be mistaken for the real thing, as they have reversed handedness.

Mathematically, it states that a pseudoscalar term $\langle \boldsymbol{\sigma} \cdot \boldsymbol{p} \rangle$ changes sign under space inversion where $\boldsymbol{p}$ is the electron momentum and $\boldsymbol{\sigma}$ the spin of the nucleus. If the distribution of emitted electrons from polarized nuclei is asymmetrical (see Fig. 4.13) the pseudoscalar term $\langle \boldsymbol{\sigma} \cdot \boldsymbol{p} \rangle$ of the radioactive decay is not identically equal to zero. The pseudoscalar term $\langle \boldsymbol{\sigma} \cdot \boldsymbol{p} \rangle \neq 0$ will change sign under space inversion therefore the parity is not conserved.
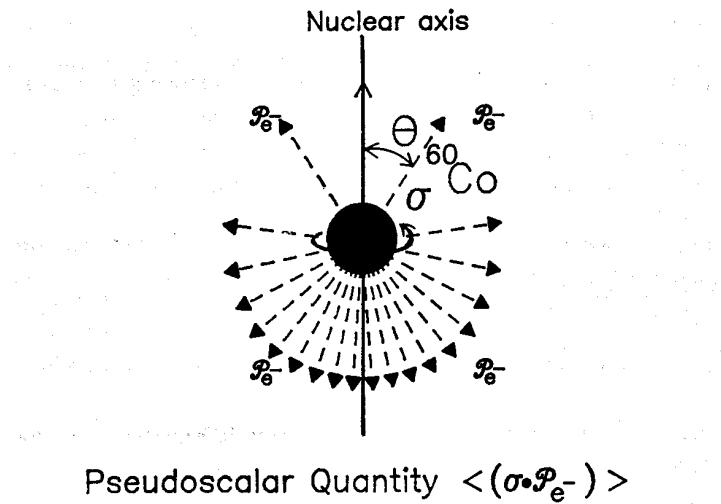

Fig. 4.13 $\boldsymbol{\sigma}$ the spin of the nucleus; $\boldsymbol{p}_e$ the electron momentum.
If parity conservation is valid; the expectation value of $\langle \boldsymbol{\sigma} \cdot \boldsymbol{p}_e \rangle \equiv 0$.
$$\langle (\boldsymbol{\sigma} \cdot \boldsymbol{p}_e) \rangle \equiv \int dr \psi^*(r) [\boldsymbol{\sigma}(r) \cdot \boldsymbol{p}_e(r)] \psi(r)$$
If parity invariance is valid; then P-operation gives
$$\mathbf{P}\psi(r) = \psi(-r) = \pm \psi(r)$$
then $\mathbf{P}\langle (\boldsymbol{\sigma} \cdot \boldsymbol{p}_e) \rangle = \int dr \psi^*(r)) [\boldsymbol{\sigma}(-r) \cdot \boldsymbol{p}_e(-r)] \psi(r)$
$$= - \int dr \psi^*(r) [\boldsymbol{\sigma}(r) \cdot \boldsymbol{p}_e(r)] \psi(r)$$
$$= -\langle (\boldsymbol{\sigma} \cdot \boldsymbol{p}_e) \rangle$$
If parity invariance is valid, $\langle (\boldsymbol{\sigma} \cdot \boldsymbol{p}_e) \rangle \equiv 0$, the expectation value $\langle ( ) \rangle$ of pseudoscalar quantity must be identically zero

Part III: Experimental Discovery of Parity Non-Conservation in Weak Interactions

During the years 1945 to 1952, I was completely submerged in the experimental studies of beta decay [5]. It was an exciting period, indeed for all who worked in this field. Although from 1952 on my interest was gradually turning away from beta decay, to me, β-decay was still like a dear old friend; there would always be a place in my heart especially reserved for it.

This feeling was rekindled when, one day in the early spring of 1956, my colleague T. D. Lee came up to my office on the thirteenth floor of Pupin Physics Lab. He asked me a series of questions concerning the status of the experimental knowledge of beta decay.

Unfortunately, I could not supply him with any information on the pseudoscalar quantity $\langle \boldsymbol{\sigma} \cdot \boldsymbol{p} \rangle$ from experimental results of β-decay. All the previous β-decay experiments investigated were essentially "only" scalar quantities, for example, the shape of the β-spectrum and the intensities or half lives, etc. Before T. D. Lee left my office, I asked him whether anyone had any ideas about doing this test. He said some people had suggested using polarized nuclei produced in nuclear reactions or using a polarized slow neutron beam from a reactor. Somehow I had great misgivings about using either of these two approaches. I suggested that *the best bet would be to use a ^{60}Co β-source polarized by the adiabatic demagnetization method*, by which one could attain a polarization as high as 65%. Dr. Lee was very much interested in the possibility of such a strongly polarized ^{60}Co β-source and asked me to lend him a reference book on the method.

(1) Polarized ^{60}Co Experiment—Adiabatic Demagnetization:

In this Demagnetization Method the principle of polarization is based upon the fact that in certain paramagnetic salts there are large magnetic fields ($\sim 10^5$–10^6 gauss) at the nuclei of the paramagnetic ions due to unpaired electrons and, at temperatures of the order of $0.01°K$, the nuclear magnetic moments become oriented with respect to these electron magnetic fields. Since the electron magnetism is easily saturated at low temperature, a field of a few hundred gauss suffices. Nuclear orientation will automatically follow. Because of my familiarity with the capability and limitations of this technique, it was only natural that the first thought which came to my mind was to use the polarized ^{60}Co source.

(2) My Decision to Go Ahead:

Following Dr. Lee's visit, I began to think things through. This was a golden opportunity for a beta ray physicist to perform a crucial test, and how could I let it pass? Even if it turned out that the conservation of parity in beta decay was actually valid, the experimental result would, at least, set a reasonably upper limit on its violation and thus stop further speculation that parity in β-decay is substantially violated.

(3) Two Major Difficulties:

As an experimentalist, I was also challenged by two techniques which had never been tried before and were difficult. One was to put an electron detector inside a cryostat at a liquid helium temperature and to make it function as a β-spectrometer; the other was to fabricate a β-source located in a very thin surface layer and have it stay polarized for a time period long enough to obtain sufficient statistics.

That spring, my husband and I had planned to make a lecture tour to Europe and the Far East. Our passages were booked. I suddenly realized that I had to do the experiment immediately, so I asked Chia-Liu to let me stay and told him to go without me. Fortunately, he fully appreciated the importance of the time element and finally agreed to go alone.

In order to do the demagnetization method, one needs very complicated ultra-low temperature equipment. There were only two or three low temperature labs in the United States which were equipped to do nuclear orientation experiments. Dr. Ernest Ambler, a pioneer in the nuclear orientation field, had moved from Oxford University to the Low Temperature Lab. at The National Bureau of Standards years earlier. I decided to contact him by phone to determine whether he would be interested in a collaboration. Although we had never met before, it was on June 4, 1956 that I called and put the proposition directly to him. He accepted immediately and enthusiastically.

(4) On the Long Road to Planning:

As soon as the spring semester ended in the last part of May, 1956, I started to work in earnest in preparation for the experiment. From the beginning of June until the end of July, two solid months were spent on testing our beta particle detectors. What type of scintillator would be best for this purpose? What shape should the head of the light-guide be? How could we bring the long lucite pipe (4ft) with a small diameter (1in) out of the cryostat? Could one leave the scintillator or the photomultiplier inside the helium cryostat? Would the polarizing magnetic field affect the counting rates? The thorough preparation was worth all the effort. The 4ft long, 1 inch diameter lucite light pipe gave the ^{137}Cs conversion line (624keV) a fine resolution of

17%, this excellent resolution was due mostly to the careful selection of a clear lucite rod, the machining of the lucite head to a logarithmic spiral for maximum light collection, above all, Mrs. Marion Biavati's personal attention to its surface polish played a major role.

In the middle of September, I finally went to Washington D. C. for my first meeting with Dr. Ambler. He was exactly as I had imagined from our numerous telephone conversations; soft-spoken, capable, and efficient. He has been the Director of the National Bureau of Standards since the late seventies. He took me to his lab and introduced me to Dr. R. P. Hudson, who was his immediate supervisor at that time. The two of them had been working closely together. Hudson's subsequent decision to join our exciting experiment was indeed welcome.

In the beta particle counting and the gamma ray anisotropy measurements, we required a great deal of electronics. Dr. R. W. Hayward of the National Bureau of Standards had offered us the use of his 10-channel pulse height analyser and other equipment. The eventual joining of Dr. Hayward and his research assistant D. D. Hoppes, greatly strengthened our group, particularly during the exasperating days and nights when we had hardly any sleep. We wished we could have more such able collaborators.

By the time of my third trip to Washington, D. C., I had grown two ^{60}Co specimens. One was made by taking a good single crystal of CMN (cerium magnesium nitrate) and growing on the upper surface only an additional crystalline layer containg ^{60}Co. The thickness of the radioactive layer used was about 0.002 inches and contained a few micro curies of activity. The others had the ^{60}Co evenly distributed throughout the CMN crystal for the study of the anisotropy of the ^{60}Co gamma rays.

(5) *Our Fear Confirmed:*

The polarization of the thick ^{60}Co γ-ray source was obtained with no difficulty. But we had no such luck for the thin surface ^{60}Co source. The polarization lasted no more than a few seconds, then completely disappeared. What we had feared all along finally happened: the polarization of a thin layer on the surface did not last long enough for actual observation. The reason for this disappearance of nuclear polarization on the surface was probably due to its sudden rise in temperature caused by heat that reached the surface of the specimen by means of radiation conduction or condensation of the He-exchange gas. The only remedy was to shield the thin CMN crystal in a cooled CMN housing. But where could one obtain many large single CMN crystals in a hurry? I decided to return to Pupin Laboratory at Columbia University and try to find ways to grow some CMN crystals.

(6) Beautiful Sight of Those Large Single CMN Crystals:

I consulted some professional crystallographic experts and, unfortunately, they confirmed my fear that professional care would be needed to grow large-size CMN crystals (1 inch diameter). Both elaborate equipment and plenty of patience were required and we had neither the funds nor the time. Purely relying on ingenuity determination and luck. three of us: an enthusiastic chemist (Herman Fleishman), a dedicated student (Marion Biavati), and I worked together uninterruptedly to grow about ten large, perfect, translucent CMN single crystals at the end of three weeks. The day I carried these precious crystals with me back to Washington, I was the happiest and proudest person in the world.

To fabricate a housing out of these CMN crystals, one has to carve a large hole in each of these thin, brittle crystals without causing it to crack. We were so happy when a crystallographer suggested to us that we borrow a dentist's drill (which is designed in such a way so that it exerts pressure inwardly only).

The CMN crystal is known to have a highly anisotropic g-values : $g_{\perp} > g_{//}$. In making the housing, one must line up the crystal axis perpendicular to the demagnetization field and glue the CMN pieces together (see Fig. 4.14).

Dr. Ambler applied the DuPont cement as it was frequently used in room temperature. This time, we indeed saw an unmistakably asymmetrical effect on the counting rates when the polarization field was turned on. However, the effect was not only eminently clear but also *irreversible*! The counting rates never returned to their

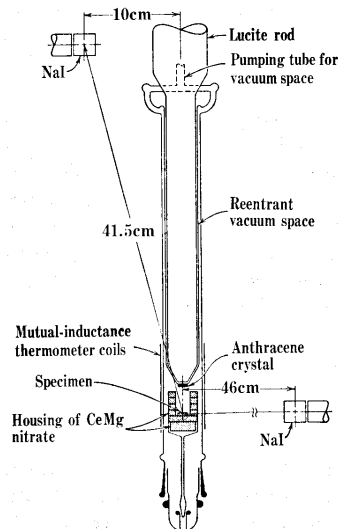**Fig. 4.14** A schematic diagram showing the demagnetization cryostat used in the measurement of the angular distribution of the electrons from the β-decay of oriented ^{60}Co nuclei. The ^{60}Co nuclei were polarized parallel to the axis of the cylindrical cryostat. The electrons were detected by an anthracene scintillation counter. Two NaI γ-ray scintillation counters are also shown

original values even when the source was warmed up. The shielding CMN house had caved in.

Then the cryostat was warmed up and opened, we saw that was exactly what had happened. As already mentioned, the CMN crystal has a highly anisotropic g-value. The axis of the crystal had not been set exactly parallel to the magnetic field, a strong torque developed, the ultra-low temperature caused the DuPont cement to completely lose its adhesive property; and the CMN housing under the torque came tumbling down!

(7) Genuine Asymmetry Effect Observed:

The second time the housing was put together, fine nylon threads were used to tie the pieces together and, for the first time, we finally saw a genuine asymmetry effect which coincided exactly with the γ-ray anisotropy effect (see Fig. 4.15).

That was already in the middle of December, 1956. One half year after the beginning of our planning. I remember the mood then was more cautious and subdued. The discovery would be big if our observation was real, but we cautioned ourselves that more rigorous experimental checks must be carried out before announcing our results to outsiders.

Between experimental runs in Washington, I had to dash back to Columbia for teaching and other research activities. One Thursday morning, as I was hurrying to the seminar room (Room 831) at Pupin, I passed Dr. Lee's office; the door was open and both Lee and Yang were there. As I stuck my head in to say hello, they inquired about the ^{60}Co experiment. I casually mentioned that it seemed there was a huge asymmetry effect. Upon hearing this they were excited and pleased. As I passed their room again, after the seminar, they wanted to know more. I told them the effect was large and reproducible, but it must be regarded as preliminary because some systematic checks were not yet completed. I remember on that occasion, Yang also wanted to know whether anyone had calculated the interference term between the G-T and Fermi interaction. I told him that Dr. Masato Morita had carried out these calculations in detail and the interference term might be destructive, depending on the signs between C_A and C_V. I said I was pleased that the beta transition in ^{60}Co was a pure G-T transition. We know now that the observed asymmetry parameter A in ^{60}Co $(5 \longrightarrow 4)$ is nearly -1, but it is much reduced in mixed transitions such as in Table 4.1.

Table 4.1

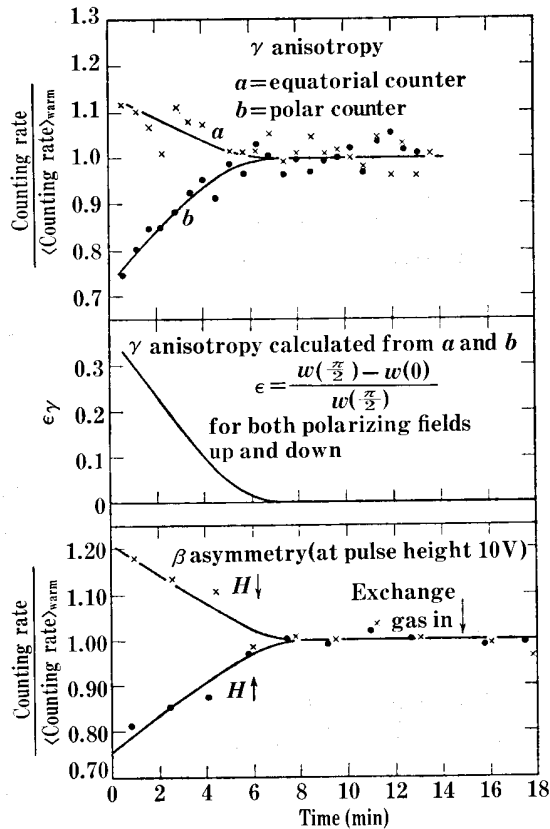|	$I_{\text{i}} \overset{\beta}{\longrightarrow} I_{\text{f}}$	Asymmetry Parameter A
^{60}Co	$5 \longrightarrow 4$	-1
^{1}n	$1/2 \longrightarrow 1/2$	-0.11
^{19}Ne	$1/2 \longrightarrow 1/2$	-0.057

Fig. 4.15 Results of β asymmetry and γ anisotropy from polarized ^{60}Co experiment. The disappearance of the γ asymmetry coincides exactly with the time of disappearance of γ anisotropy. The measured asymmetry indicates that the emission of electrons is preferred in the direction opposite to that of the nuclear spin

I was thoroughly pleased that I had selected the pure (G-T) transition β-decay in ^{60}Co for the crucial test of parity.

(8) Rigorous Experimental Checks:

One week later, after some modifications on the glass dewar were completed, we began to follow through intense experimental checks on the asymmetry effects observed. First, we had to prove that this asymmetry effect was not due to the strong magnetic field of the CMN crystals produced at extremely low temperatures. We also needed to show that this effect was not due to the remnant magnetization in the sample induced by the strong demagnetization field. The most clear-cut control ex-

periment would be one in which a beta activity would be introduced into the CMN crystal, but in which the radioactive nucleus would be known not to be polarized; thus no asymmetry effect should be detected. To carry out all these experiments would take several weeks.

On Christmas Eve I returned to New York on the last train as the airport was closed because of heavy snow. I told Dr. Lee that the observed asymmetry was reproducible and huge, but we had not exhausted all experimental checks yet. When I started to make a quick rough estimate of the asymmetry parameter A, I found it was nearly −1. The asymmetry parameter A was estimated as follows:

The electron angular distribution is

$$W(\theta) = 1 + A \frac{\langle I_z \rangle}{I} \frac{v}{c} \cos\theta$$

"θ" is the angle between the nuclear spin and electron momentum direction. The actually observed asymmetry is $\sim 25\%$

$$\frac{W(0) - W(\pi)}{W(0) + W(\pi)} = -0.25 = A \frac{\langle I_z \rangle}{I} \frac{v}{c}$$

where $\frac{\langle I_z \rangle}{I} = 0.65$ calculated from observed γ anisotropy, $\frac{v}{c} \cong 0.6$ from the calibrated pulse height analysis. The back scattering of the electrons from the CMN crystal was found in a magnetic spectrometer to be 30–35. Therefore $A \cong -0.25 \times (0.65 \times 0.60)^{-1} \times \frac{3}{2} \cong -1$.

The result of $A = -1$ was the first indication that the interference between parity conserving and parity non-conserving terms in the G-T interaction Hamiltonian was close to maximum or, $C_A = C_{A'}$ This result is just what one should expect for a two component theory of the neutrino in a pure Gamow-Teller transition. It also implies that, in this case, *the charge conjugation is also non invariant*. Dr. Lee realized it then and said that this was very good. He told me that during the summer of 1956, when he and Yang worked together, they had not only entertained the idea of the two-component theory of the neutrino, but had also worked out some details of the theory [9]. However, they felt it was too rash to publish it before the violation of the law of parity was experimentally observed. Confronted by the clear evidence of the two-component theory of the neutrino, we discussed possible experiments one could do. One of them was the measurement of electron polarization; the other was the π-μ-e parity experiments. All these possible experiments were soon carried out in various laboratories the world over. The(9 correct interpretation of our very first pioneer experiment on parity non-conservation and charge-conjugation non-invariance played a decisive effect. It also suggested the combined "CP" invariance. This combined operation CP was examined by Landau [9], Wick [10], and Yang [11] even before the parity was overthrown.

(9) Law of Parity Overthrown:

On January 2nd, I went back to the Bureau to continue with our experimental checks. The atmosphere in the period between January 2nd and 8th was probably the most tense in our whole experimental venture. Our cryostat at the NBS was made of glass and the glass joints were put together with low temperature vacuum grease which was concocted by melting together glycerine and Palmolive soap (later on we changed to Ivory soap). The trouble which plagued us repeatedly was the super-fluid leak below the lambda point ($T = 2.3$K). Each time this happened, it took at least 6 – 8 hours to warm up, regrease and then cool the cryostat down again. To save time, Hopper slept on the ground near the cryostat in a sleeping bag. Whenever the cryostat reached liquid helium temperature he would telephone each of us to go to the lab, no matter what time of the night it was.

During the week of January 7th, rumors started to come in fast about the Nevis π-μ-e parity experiments. Very much alarmed and excited, the director and the high administration officials of the NBS came to call on us and wanted to know more about our experiment which was rumored to be as important as the Michelson-Morley one.

We were as vigilant as ever. Even after the muon decay had shown the violation of the law of parity, we still did not relax. We, ourselves, had to be totally convinced!

After we had finished all the experimental checks which we had set out to do, we finally gathered together around 2 o'clock in the morning of January 9th to celebrate the great event. Dr. Hudson smilingly opened his drawer and pulled out a bottle of wine which turned out to be actually a *Chateau Lafite-Rothschild, Vintage 1949*. He put it on the table with a few small paper cups. We finally drank to the overthrow of the Law of Parity.

I remember vividly several research workers in other sections of the low temperature laboratories stopping by our lab the next morning and being surprised by the silent and relaxed atmosphere. They suddenly turned around to take a look at our waste paper basket and nodded to themselves "All right, the law of parity in beta decay is dead."

I hurried back to the Pupin Laboratories on the night of January 10th and on the morning of the 11th, a Saturday, there was a meeting in Room 831. Lee, Yang, the Nevis group and I were all there. The discussion led by the two theorists was enthralling. Before that meeting our results had already been written up to be submitted to Physical Review [6]. What a great shock to the world of physics!

On the afternoon of January 15th, the Department of Physics at Columbia University called a press conference to announce the dramatic overthrow of a basic law of physics, known as the conservation of parity, to the public. The next day, the New York Times carried a front page headline "Basic Concept in Physics Reported Upset in Tests." The news burst into public view and quickly spread around the world. As Professor O. R. Frisch of Cambridge University described it in a talk at that time, "The obscure phrase 'parity is not conserved' circled the globe like a new gospel."

As usual, following an important discovery, we were asked to give symposia, colloquia, and lectures on our experiments. Finally, the American Physical Society held its annual meeting in New York around the end of January. A post-deadline

paper session was assigned to the topic of the non conservation of parity. Later, Dr. K. K. Darrow recorded the event with his lively and witty pen in the Bulletin of the American Physical Society 2 (1956–57):

> "*On Saturday afternoon to boot—the largest hall normally at our disposal was occupied by so immense a crowd that some of its members did everything but hang from the chandeliers.*"

The sudden liberation of our thinking on the basic laws of the physical world was overwhelming. Activities along these lines advanced at an unprecedented pace. First, the non-conservation of parity was also observed in the $\pi^{\pm} \rightarrow \mu^{\pm} \rightarrow e^{\pm}$ decays [7] and other weak interactions [8] not restricted to nuclear beta-decays. Thus the parity non-conservation is a *fundamental characteristic of the weak interactions* and the weak interaction has since manifested into *one of the four fundamental interactions in Nature*. The (v/c) dependence of the asymmetry parameter A of the beta particles from the polarized ^{60}Co was also used to examine the validity of the Time Reversal "T" and it was found, in general, sound. If the Time Reversal was still intact; it suggested the *Combined CP Invariance based on the CPT Invariance*.

Part IV: Recent Improvements on Parity Experiments on Polarized Nucle

Refinement in Experimentation:

Ever since the pioneer Fparity experiment on polarized ^{60}Co reported in 1957; practically all the beta-distribution measurements on polarized nuclei were limited to only two directions. One is in parallel and the other, anti-parallel to the nuclear spin axis (i.e. $\theta = 0°$ and $180°$). It was the goal of our research group in Nuclear Physics at Columbia to improve the cryogenic condition and magnetic field shielding of the parity experiments so that more reliable and precision results could be derived from asymmetry measurements.

a) Utilization of ^{3}He/^{4}He Dilution Refrigeration

In 1960, London [12] suggested the ^{3}He/^{4}He Dilution Refrigeration method to cool the ^{3}He/^{4}He mixing. Within a decade, the development of this method already showed remarkable success. We initiated the build-up of the ultra-low temperature Nuclear Physics Lab in Pupin Basement around 1972. The major cryogenic equipment was procured from SHE Co. It could deliver and maintain an ultra-low temperature as low as 11mK at the mixing chamber indefinitely and kept within 1% of fluctuation.

b) Minimization of the stray magnetic fields surrounding the β source.

Furthermore, we developed two intersecting closed magnetic loops which carried the magnetic flux to the permendur source foil (see Fig. 4.16). This design and arrangement greatly minimized the magnetic fields in the region between the source and the $\beta^{\pm}$ detector and permitted using a wide range of polarization angle θ.
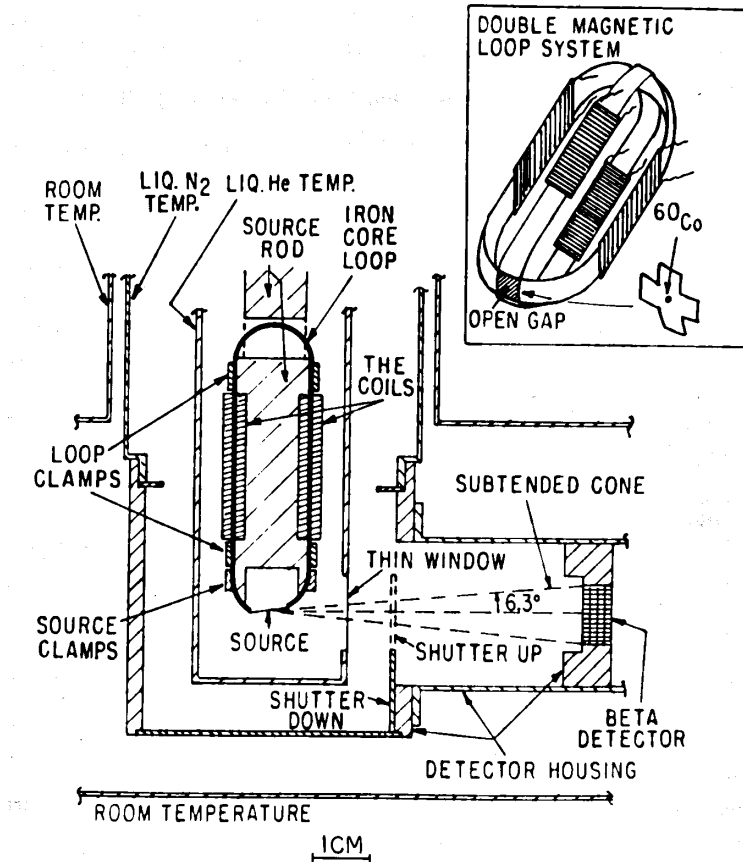
Fig. 4.16 Detailed drawing of the magnetic loop system and the beta source tail assembly. The detailed double magnetic loop system is shown in the insert to illustrate the three-dimensional arrangement of the two magnetic loops used to rotate the polarization of the ^{60}Co nuclei. The permendur cross containing the radioactive ^{60}Co source is clamped to the double magnetic loops in the region when the "open gap" is shown in the insert drawing

c) Determination of the hyperfine field

The magnetic hyperfine field at the Co nucleus in the permendur foil was measured using the NMR/ON technique and found to be 285kG.

d) The β-detector

The β-particles were detected using a Si(Li) crystal (10mm diameter, 5mm thick) mounted inside the dewar vacuum of the dilution refrigerator.

(2) Experimental Requirements:

This experimental arrangement satisfied the following requirements:

a) The β-detector was held in a fixed position but the polarization angle θ can be varied continuously over as much of a 0° to 360° range as possible.

b) The β-detector was placed inside the cryostat and operated at 100K and had a good energy resolution and

c) The ferromagnetic host of the β-source could be magnetized to near saturation. However, the magnetic field outside the source foil diminishes rapidly away from the surface to reduce any magnetic effects on the β-trajectories.

(3) ^{60}Co Sources:

Two different ^{60}Co sources were prepared. Both source hosts were 25 micron thick permendur foils.

a) In one of them, 15μCi of ^{60}Co were thermally diffused into the foil so that 2/3 of the activity lying within 10 microns of the front surface of the foil.

b) In the second source, 15μCi of ^{60}Co were thermally diffused so that 2/3 of the activity lying within one micron of the front surface of the foil.

Since the angular distribution of β-particles e$^-$ from ^{60}Co $\rightarrow$ ^{60}Ni $+$ e$^-$ $+\overline{\nu}_e$ based on the two component theory of the neutrino:

$W_{\text{th}}(\theta) = 1 + AP\frac{v}{c}\cos\theta$;

where, "P" is the polarizations$\equiv \frac{\langle I_z \rangle}{I}$, "A" the asymmetry coefficient.

$$\frac{v}{c} = \frac{\text{velocity of } \beta\text{-particle}}{\text{speed of light}}$$

(4) Excellent Agreements Between Experiments and Theory

The β-spectrum of ^{60}Co has an endpoint energy of 315keV and consequently, the region between 100keV and 200keV was chosen for analysis of the data. In the 100 to 200keV region, the data had the predicted energy dependence.

$$W(\theta) - 1 \sim \left(\frac{v}{c}\right)\left\langle\frac{W(\theta)-1}{v/c}\right\rangle \longrightarrow A_{\exp}\, P\cos\theta$$
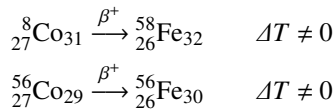
The numerical values of $A_{\exp}$ for the two different ^{60}Co sources were obtained by least-square fitting the quantity $1 + PA\cos\theta$ to the data shown in Fig. 4.17. For the "thin" source, where internal scattering is small, the experimental results are not only in excellent agreement with the form of the directional distribution, but the experimental asymmetry parameter $A_{\exp} = -1.01 \pm 0.02$ also in splendid agreement with the theoretical value $A_{\text{theory}} = -1$.

(5) The Allowed but Isospin-Hindered β-Transitions:($I^{\pi} \xrightarrow{\beta^{\pm}} I^{\pi}$; $T \longrightarrow T \pm 1$, $\Delta T \neq 0$)

The β transitions in these nuclei are of particular interest for studies of isospin conservation of nuclear forces and the Time-Reversal Invariance (TRI) tests of the weak interactions.

(1) Allowed Fermi transitions require $\Delta T = O$, and consequently, a non-zero value of the Fermi to Gamow-Teller mixing ratio $y \equiv C_V M_{\text{F}}/C_A M_{\text{GT}}$, in $\Delta T \neq 0$ nuclei violates isospin conservation.

(2) In TRI tests in nuclear β-decay, the magnitude of T-odd correlations are proportional to y. Consequently, precise measurements of y for these β transitions are of fundamental importance. The mixing ratio, y, can be determined by two rather different methods. One is by measuring the asymmetry of the angular distribution of β particles from *oriented nuclei* (NO), and the other is the asymmetry of the *β-γ circular polarization correlation methods* (CP). Both experimental methods are difficult and require extreme care to possible systematic errors. The reported results in the past have been in very poor agreements. Recently, we used our ^{3}He/^{4}He ultra-low temperature ($T \leqq 0.012$K) nuclear orientation equipment Fig. 4.16 in determining the value y in isospin-hindered allowed beta transaction.

$$_{27}^{8}\text{Co}_{31} \xrightarrow{\beta^+} {}_{26}^{58}\text{Fe}_{32} \qquad \Delta T \neq 0$$

$$_{27}^{56}\text{Co}_{29} \xrightarrow{\beta^+} {}_{26}^{56}\text{Fe}_{30} \qquad \Delta T \neq 0$$

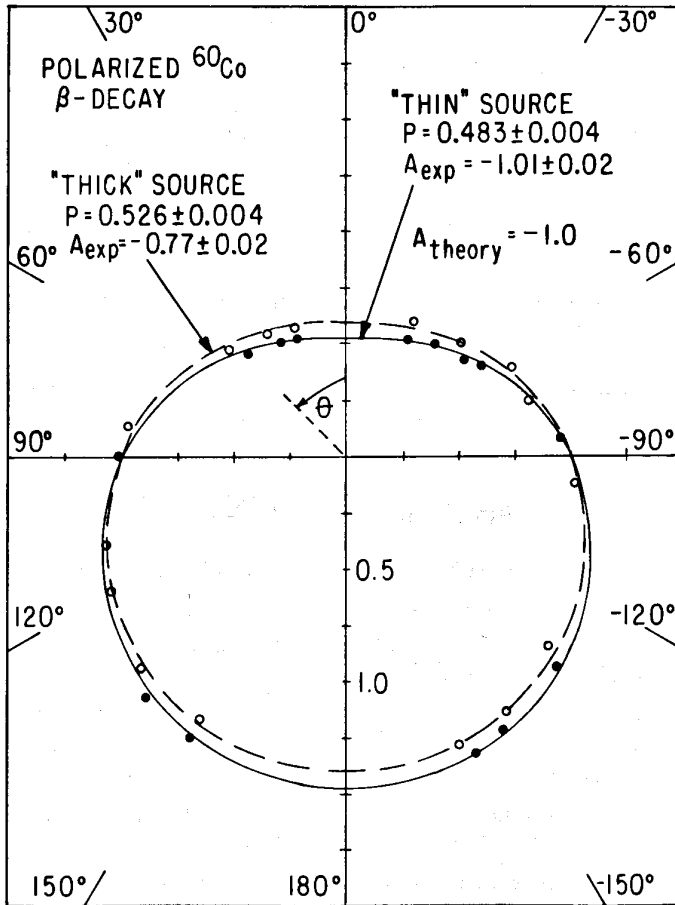The directional distribution of beta particles can be written as

Fig. 4.17 Directional distribution of β-particles from polarized ^{60}Co. The open circles are data taken with the thick source foil and the solid circles are data taken with the "thin" source foil. **P** is the nuclear polarization obtained from the analysis of the gamma spectra taken with the Ge(Li) detectors. The curves shown for the "thin" source and for the "thick" source are plots of $(1 + A_{\exp} P \frac{v}{c} \cos \theta_\beta)$ versus θ_β

$$W_\beta(\theta, v) = 1 + A_\beta P \frac{v}{c} \cos \theta$$

(vel. of β^-/the speed of light)

asymmetry parameter

the nuclear polarization

the angle between β-particle and nuclear polarization axis.

The relations between A_β and y are

$$^{56}\text{Co}: \quad A_\beta = \frac{0.3333 - 1.6333y}{1 + y^2}$$
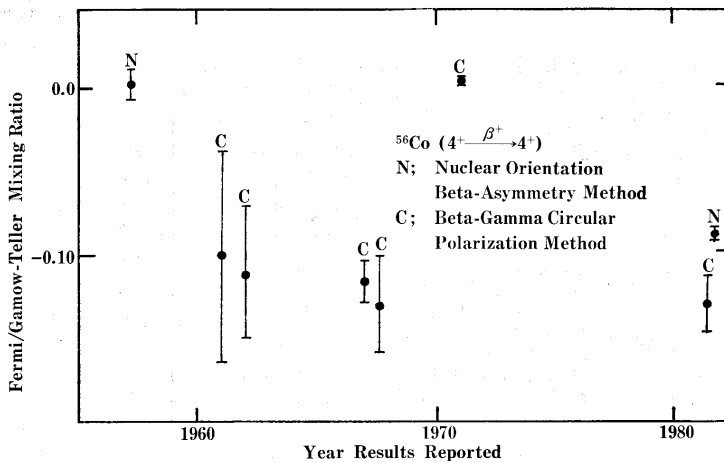
$$^{58}\text{Co}: \quad A_\beta = \frac{0.2000 - 1.789y}{1 + y^2}$$

From our $A_\beta(^{56}\text{Co}) = +0.359 \pm 0.009$ and $A_\beta(^{58}\text{Co}) = +0.341 \pm 0.013$ we find

$$^{56}\text{Co}: \quad y = -0.091 \pm 0.005$$

$$^{58}\text{Co}: \quad y = -0.005 \pm 0.008$$

It is interesting to note that ^{58}Co has a rather significant mixing $y = 0.091 \pm 0.005$. In a previous TRI test, using ^{56}Co (β-γ correlation on polarized ^{56}Co), Calaprice *et al.* [17] found $2|y|\sin\phi/(1 + |y|^2) = -0.011 \pm 0.022$ where $y = |y|e^{C\phi}$. Using our results
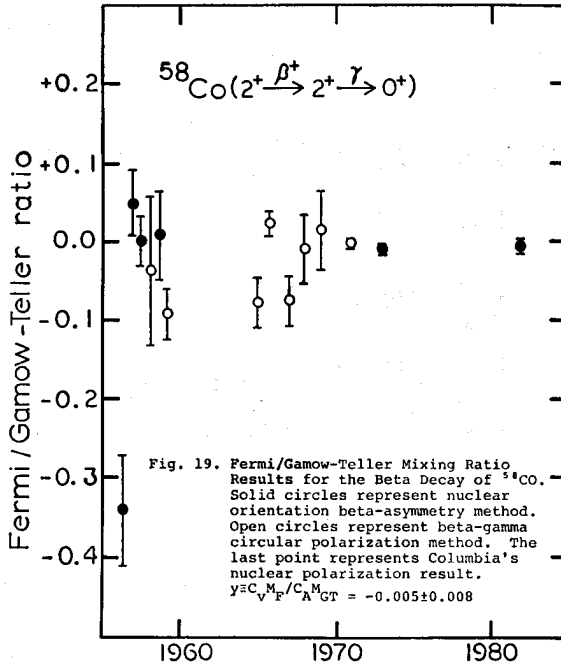

Fig. 4.18

Fermi/Gamow-Teller Mixing Ratio Results for the Beta Decay of ^{56}Co

Reading from left to right, the references for experimental points are: (Am 57b), (Da 61), (Ma 62), (Be 67), (Bh 67), (Pi 71), (Ma 82), (Gr 82).

Am 57b E. Ambler *et al.*,: *P. R.*, **108**, 503 (1957)
Da 61   H. Daniel *et al.*,: *Z. Naturforsch*, **160**, 118 (1961)
Ma 62   L.G. Mann *et al.*,: *P. R.*, **128**, 2134 (1962)
Be 67   H. Behrens: *Z. Phys.*, **201**, 153 (1967)
Bh 67   S. K. Bhattacherjes *et al.*,: *N. P.*, A**96**, 81 (1967)
Pi 71   O. Pingot: *N. P.*, A**174**, 627 (1971)
Ma 82   J. Markey: Private Comm.
Gr 82   J. Groves: *P. R. L.*, **49**, 109 (1983)
$y \equiv C_V M_F / C_A M_{GT} = 0.09l \pm 0.005$

Fig. 4.19

Fermi/Gamow-Teller Mixing Ratio Results for the Beta Decay of ^{58}Co

Our results on "y" of ^{56}Co and ^{58}Co are compared with previous workers in Fig. 4.18 and Fig. 4.19. For ^{56}Co, except for those of Ambler *et al*. (NO) and Pingot (CP), satisfactory agreements were obtained as compared to all other 5 results by CP methods. For ^{58}Co, the vanishing small value of y is strongly suppressed in the positron decay of ^{58}Co consistent with isospin selection rules. Solid circles represent nuclear orientation beta-asymmetry method. Open circles represent beta-gamma circular polarization method. The last point represents Columbia's nuclear polarization result.
$$y \equiv C_V M_F / C_A M_{GT} = -0.005 \pm 0.008$$

for y, we obtain $\phi = 183 \pm 7°$ consistent with non-evidence on T non-conservation. This is indeed a very sensitive method for "TRI" test in weak interaction. So the polarized nuclear experiments gave strong evidences to all *Non Parity-Conservation, Non Charge-Conjugation Invariance but still nearly intact Time Reversl Tests.*

The overthrow of the Parity Law drives home once again the idea that science is not static but ever growing and dynamic. It involves not just the addition of new information but the continuous revision of old knowledge. It is the courage to doubt what has long been established and the incessant search for its verification and proof that pushes the wheel of sciences forward.

It is my great pleasure and privilege to be able to share some of my exciting memories with you. These were moments of exaltation and ecstasy. A glimpse of

this wonder can be the reward of a lifetime. I often wonder, could it be that excitement and ennobling feeling in scientific research has unfailingly kept us scientists dedicating our lives to it contentedly.

Fig. 4.20 Scene of the lecture room of Professor Wu, at University of Tokyo, 1983

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