Discovery of Parity Violation

Breakdown of a Symmetry Principle

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Symmetry principles are very dear to physicists in their quest for the understanding of nature. These reflect the regularities that are present in nature and help in understanding the laws governing them. A good definition of symmetry in a physical system was given by Herman Weyl as: "A thing is symmetrical if there is something we can do to it so that after we have done it, it looks the same as it did before." In other words the system is invariant under the operation we performed. A few examples of such operations for a physical system are: translation in space or time, rotation through a fixed angle, uniform velocity in a straight line, reversal of time, reflection in space, interchange of identical particles and change of matter to antimatter. They arise from our basic perceptions about the nature of space and time and usually lead to conservation laws. The invariance under translations in space and time lead to conservation of linear momentum and energy, respectively. Invariance under rotation leads to the law of conservation of angular momentum and invariance under mirror reflection, i.e. symmetry between left and right, leads to conservation of parity (see *Box* 1).

The question of symmetry between left and right belongs to a category, which is not apparent from our daily life. We appear to move and act differently than our images in a mirror. In biological phenomena, it was known from Louis Pasteur's work in 1848 that organic compounds appear often in the form of only one of two kinds. These molecules rotate polarised light to the left and are called laevo (left)-rotatory. However, both left and right rotating molecules occur in inorganic processes and are mirror images of each other. In fact, Pasteur had considered for a time the idea that the ability to produce only one of the two forms of molecules was the very prerogative of life. However, if

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Box 1. Symmetries, Parity, Interactions

Among the symmetry principles, some are continuous and others are discrete symmetries. Translations in space and time are examples of continuous symmetries, whereas mirror reflection is an example of discrete symmetry. The continuous symmetries always lead to conservation laws in classical physics; the discrete symmetry does not. However, in quantum mechanics the discrete symmetries also lead to conservation laws. The left-right mirror symmetry then leads to the conservation of parity. There are also a number of symmetries, which appear only in quantum mechanics without any classical analogue. The concept of parity can be understood considering the simple case of one-dimensional time-independent Schrödinger equation

$$- h^2/2md^2\,\Psi(x)/dx^2 + V(x)\;\Psi(x) = E\,\Psi(x). \qquad (1)$$

If we now change $x \rightarrow -x$, we get the equation for the mirror image position,

$$- h^2/2md^2\,\Psi(-x)/dx^2 + V(-x)\;\Psi(-x) = E\,\Psi(-x). \qquad (2)$$

If the potential energy is symmetric about $x = 0$, then $V(-x) = V(x)$ and the equation becomes,

$$- h^2/2md^2\,\Psi(-x)/dx^2 + V(x)\;\Psi(-x) = E\,\Psi(-x). \qquad (3)$$

Comparing (1) and (3), we find that for the same potential V, there are two solutions, $\Psi(x)$ and $\Psi(-x)$. These solutions can only differ by a multiplicative constant P, i.e., $\Psi(-x) = P\,\Psi(x)$.

Now, changing sign of x in the above we get, $\Psi(x) = P\,\Psi(-x)$

Therefore, $P^2 = 1$ or $P = \pm 1$.

So the solutions of the Schrödinger equation are either even or odd under a change of sign in the space co-ordinates if the potential function is unchanged by the parity transformation. The even solutions have even parity and the odd solutions have odd parity.

The symmetries and their consequent conservation laws can be classified in two categories, ‘absolute’ and ‘restricted’. Absolute conservation laws are those that are obeyed in all situations by all the known interactions, whereas the restricted symmetries are those which are violated by only some interactions. Parity is the symmetry of mirror reflection and is a restricted symmetry. The interactions are of four types, viz., strong, electromagnetic, weak and gravitation. The strengths of these interactions, defined by how they couple to matter are: 1 (normalised) for strong, 1/137 for electromagnetic, 10^{-14} for weak and 10^{-38} for gravitation. The strong and weak interactions have very short ranges and manifest themselves only in the sub-atomic world. The electromagnetic and gravitation are long-ranged and their manifestations are apparent in the macroscopic world. The idea that all these four interactions are essentially one at some level has driven the efforts for unifying all the interactions through the ages, leading to the current grand unified theory which unites electromagnetic, weak and strong interactions. Gravity still waits for the right theory of unification and some current researchers hope that string theory will be able to provide the unification of all four interactions.

Under space reflection, a wave function ψ can go either to ψ or to $-\psi$ if parity invariance holds.

we stop to think for a while, there is no reason that a mirror image world, in which the living organisms are made up of right handed molecules, would not function as effectively as our own.

The laws of physics had always shown complete symmetry between left and right. In 1924, O Laporte discovered that energy levels in complex atoms could be classified in two groups, even and odd. He established selection rules for transitions between the two classes but could not explain the basis of their existence. E P Wigner later showed that the two classes of levels follow from the invariance of a system under space reflection. The magnitude of the wave function does not change but the sign could be either the same or opposite. The levels for which the wave function change sign are assigned an odd parity and for those wave function which remained unchanged an even parity. This symmetry was so appealing that it was elevated to a dogma. The idea of parity conservation was taken over into nuclear and particle physics domains and proved to be immensely useful. The observed left-right asymmetries in nature were all blamed on initial conditions.

This was the situation till 1956, when two Chinese–American physicists C N Yang and T D Lee were trying to understand some puzzling observations in the decay of mesons named τ (tau) and θ (theta). Tau, in the course of time, disintegrated into three π (pi) mesons and theta into two π mesons. What baffled everyone was that in every property except the mode of decay, tau and theta were identical twins. Could they be one and the same particle? The principle of parity conservation certainly would not allow the same particle to decay into modes of opposite parity. The two-pion set had even parity, whereas the three-pion set had an odd parity.

Lee and Yang faced the challenge of reconciling the seemingly inconsistent evidences and it appeared to them that the only way out was to abandon the principle of conservation of parity in the decay of the tau-theta meson, which belongs to a special class of reactions known as ‘weak interactions’. They searched the then existing literature and did not come up with any information on the validity of the principle of left-right symmetry in the realm of weak interactions. They claimed that the tau and theta were the same particle (it is now known as the K meson) and that left-right symmetry was violated in weak interactions. It became then absolutely essential to gather independent experimental evidence for establishing the breakdown of parity symmetry. They proposed experimental tests for this principle in weak-interaction processes like beta-decay of nuclei, $\pi-\mu$ (mu) meson decays and decays of strange particles.

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The essence of the experiment involving beta-decay was to line up the spins of the beta emitting nuclei along a given axis and observe whether the beta particles (electrons or positrons) were emitted preferentially in one direction or the other along the axis. The two positions of the beta counter with respect to the axis are mirror images of each other as shown in *Figure* 1. A positive result would confirm the violation of parity. T D Lee approached his experimental colleague at the Columbia University, C S Wu, who had worked extensively on beta-decay of nuclei. She immediately realised the significance of the experi-

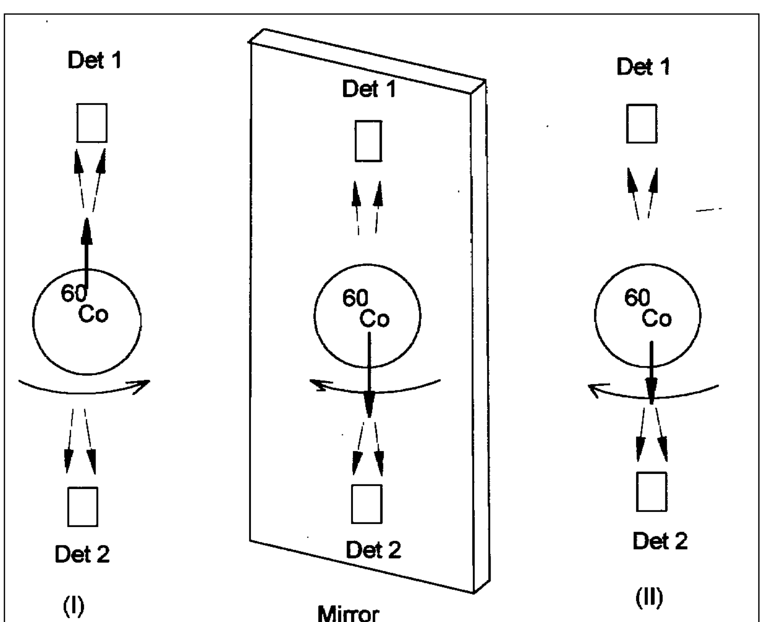

Figure 1. Sketches showing conceptually parity violation in beta decay. The vertical arrow depicts the direction of polarisation of the ^{60}Co nucleus. The situation depicted in (I) and (II) are mirror symmetric to each other. The difference in counting rates in detectors 1 and 2 in arrangements (I) and (II) would indicate parity violation.

Aligning the magnetic moments of nuclei requires extraordinarily clever techniques.

ment and thought about using a ^{60}Co beta-source polarised by the demagnetisation method.

Now lining up nuclei is not an easy task, as the only way to manipulate nuclei is with their magnetic moment. The magnetic fields required for this purpose are too large ($\sim 10^6$ gauss) to be generated in a laboratory even today, and only within atoms themselves do such large fields exist. So special atoms are first lined up to produce a field (this requires only a few hundred gauss field), which in turn lines up the magnetic nuclei. The aligning force is, however, not strong enough to maintain the orderly alignment at room temperature. The thermal agitation of the atoms must be reduced to a minimum and this can obviously be done only at very low temperatures, near a few millikelvin above absolute zero. Such low temperatures can be produced by the principle of adiabatic demagnetisation(see *Box* 2) of a paramagnetic salt. But once the temperatures are produced, it needs to be maintained for a sufficient length of time for the experiments to be performed. Specially designed vacuum bottles known as cryostats are used where an object can be maintained at these low temperatures.

This made the experiment considerably complicated, as the electron detector had to function inside a liquid helium cryostat (the electrons would be stopped in the cryostat walls) and this had not been done before. The electron detector usually was a scintillator crystal, which produces light pulses when radiation impinges on it. These light pulses are then detected by photomultipliers, which convert the light falling upon them to an electrical pulse suitable for handling, by further electronic circuits. The then available photomultipliers would not work at the low temperatures and hence the light from the scintillators had to be brought out of the cryostat, so that the photomultiplier could be placed in room temperature environment. The beta-source had to be located in a thin surface layer (otherwise the electrons would get absorbed in the material) and polarised for a period long enough to obtain sufficient number of counts. Wu enlisted the help of the team of E Ambler, R W Hayward, D D

Box 2. Polarisation, Adiabatic Demagnetisation and Angular Distribution

For particles with a value of spin=$\hbar/2$, the direction of spin could be either parallel or anti-parallel with respect to the direction of motion (this direction can be considered as the quantisation direction). Polarisation of a beam of particles means that the spins of the particles are lined up either parallel to the direction of motion or anti-parallel to it. The polarisation P is defined as:

$$P = (N_+ - N_-)/(N_+ + N_-),$$

where N_+ is the number of particles with spins lined up along the direction of motion and N_-, the number of those with anti-parallel spins. In the case of nuclei, an external magnetic field can provide the reference direction along which the nuclear spins could be lined up. With sufficiently large magnetic fields H, and at low temperatures T, nuclei with magnetic moment m, may be lined up to produce polarisation given by,

$$P = \tanh(\mu H/kT),$$ where k is the Boltzmann's constant.

Nuclear moments are associated with the protons and neutrons, and these are smaller by a factor of about 2000 than the atomic moments associated with the electrons. Direct polarisation of the nuclear moments thus requires very larges fields compared to those for atoms.

In the adiabatic demagnetisation method, the external magnetic field orients the electron spins of the paramagnetic salt crystal in the direction of maximum susceptibility, while the crystal is in thermal contact with liquid helium through the helium gas in the cryostat. The heat of orientation is absorbed by liquid helium. The sample is thereafter thermally isolated from the helium bath by removing the helium gas, and the magnetic field is then removed. The resulting random orientations of the electrons absorb energy from the crystal lattice, which is thereby cooled.

The ^{60}Co nucleus has a spin of 5^+ in its ground state and decays by electron emission to an excited state with spin 4^+ in ^{60}Ni. The decay scheme is shown in *Figure* A. The number of electrons emitted in different directions with respect to the nuclear spin orientation is governed by the change in nuclear spin value in the decay and the precise nature of the interaction mediating the decay process. The angular distribution of beta particles emitted can be represented by the equation

$$I(\theta) \propto (1 + \alpha \cos\theta),$$

where θ is the angle between electron momentum and the nuclear spin direction, α is the asymmetry coefficient determined by the change of spin value in decay and the precise nature of the interaction responsible for the decay. For the case of ^{60}Co decay, the observed value of $\alpha = 0.25$ meant that parity was violated maximally.

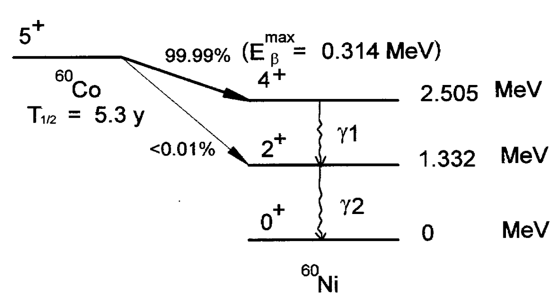

Figure A. Decay scheme of the nucleus ^{60}Co.

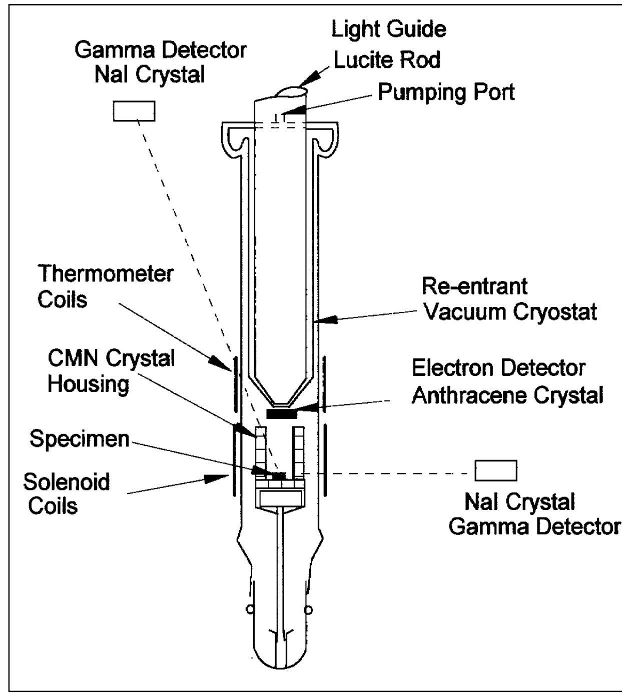

Figure 2. Schematic diagram of the apparatus used by C S Wu and others. (Reproduced from Physical Review Letters, Vol. 105, pp. 1413-1414, 1957 with permission from American Physical Society).

Hoppes and R P Hudson of the National Bureau of Standards at Washington DC, who were equipped to do nuclear orientation experiments. Their collaboration resulted in the measurement set-up sketched in *Figure* 2. The set-up took about six months to design, prepare, test and get ready for the experiment. Wu made the ^{60}Co specimen for the beta-ray measurement by taking a good single crystal of the paramagnetic salt cerium magnesium nitrate (CMN) and growing on the upper surface only an additional crystalline layer containing ^{60}Co. The thickness of the radioactive layer was about 0.05 mm and contained a few micro-curies ($=10^{-6}$ Curie, 1 Curie = 3.7×10^{10} decays/sec) of activity. She prepared another specimen with the ^{60}Co activity spread evenly throughout a CMN crystal for the study of anisotropy of gamma rays. The beta particles were detected in a thin anthracene crystal 3/8" diameter and 1/16" thick located inside the cryostat vacuum chamber about 2 cm above the ^{60}Co source. The scintillation light produced in the anthracene crystal were transmitted outside the cryostat through a glass window and carried to a photomultiplier at the top of the cryostat through a 1" diameter Lucite pipe 4 feet long. The Lucite head was machined to a logarithmic spiral shape for maximum light collection. The stability of the beta counter was carefully checked for any magnetic or temperature effects and none were found. The effect of backscattering of the beta particles from the CMN crystal was also thoroughly investigated as this could interfere with the asymmetry effect. Two additional sodium iodide scintillation detectors were installed, one in the equatorial plane and one near the top of the cryostat, to measure the gamma rays emitted in the decay of ^{60}Co. The observed gamma ray anisotropy was used as a measure of polarisation and effectively, temperature. The temperature reached in the experiment was $\sim$0.01 K.

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After demagnetisation, the magnet was opened and a vertical solenoid was raised around the lower part of the cryostat, the solenoid providing the polarising field. This polarising field was applied in the direction of minimum susceptibility of the CMN crystal to minimise the heating of the crystal. This process took about 20 sec, after which beta and gamma counting were started. The measurements were then taken by reversing the polarising field. This ensured that beta particles emitted in directions both parallel to the magnetic field and anti-parallel to the magnetic field were measured without disturbing the source and the counter.

In their first 'run', Wu and her collaborators found that the thick ^{60}Co source was easily polarised, whereas for the thin surface source, the polarisation effect lasted only for a few seconds and then completely disappeared. They identified the cause of this correctly as due to the warming up of the surface layer caused by radiation, conduction or condensation of the He-exchange gas. They grew ten large size ($>$ 1" diameter) CMN crystals and these formed a housing surrounding the CMN crystal with the thin Co source, providing better thermal isolation. With this set-up, they observed for the first time a genuine asymmetry effect in the emission of beta particles. More beta particles were observed when the magnetic field was pointing in the direction of the

That the observed beta asymmetry did not change sign with reversal of the direction of the demagnetisation, ruled out the effect of remnant magnetisation.

beta-counter than in the opposite direction. The asymmetry observed for the beta particles matched exactly with that expected from the observed gamma-ray anisotropy effect. This effect was quite large and repeatable. But they still had to prove that this asymmetry effect was not due to the strong magnetic fields of the CMN crystals produced at these low temperatures. They also had to show that this effect was not due to the remnant magnetisation in the sample induced by the demagnetising field. That the observed beta asymmetry did not change sign with reversal of the direction of the demagnetisation, ruled out the effect of remnant magnetisation. Wu and her collaborators then dried a drop of Co solution on a thin plastic disk and cemented it to the bottom of the same housing of CMN crystals. In this way, they prevented the Co nuclei from reaching sufficiently low temperature to produce nuclear polarisation, whereas the CMN crystals would produce the large magnetic fields as before. No asymmetry was observed in this case. Thus they could attribute the asymmetry observed in their experiment to the effect of parity violation. The observed value of the asymmetry in the beta emission showed that in this decay parity violation was maximal. This result also indicated that charge conjugation symmetry was also violated in beta decay and paved the way for establishing the two-component theory of the neutrino.

While Wu and her collaborators were busy checking their first measured beta anisotropy and making sure of their result, another group of colleagues at the Columbia University learned about their result and embarked on the measurement of the π-μ-e decay at the Nevis cyclotron of Columbia University. This group consisted of R L Garwin, L M Lederman and M Weinrich. In the course of a week they not only confirmed the violation of parity but also opened the door to a whole new series of experiments. Both these papers were published in the same issue of *Physical Review Letters* next to each other (Vol. 105, No. 4, pp. 1413-1414 and 1415-1417, 1957).

Lee and Yang had suggested in their paper that parity violation would manifest itself as an asymmetry effect in the π-μ-e decay, if the emission of electron was measured with respect to the direction of polarisation of the mu meson. The $\pi^{\pm}$ meson is produced by bombarding high energy protons on a target. The $\pi^{\pm}$ decays in a few nanosecs into a $\mu^{\pm}$ meson and a neutrino. The $\mu^{\pm}$, in turn decays in about 2 microseconds into an $e^{\pm}$ and two neutrinos (or anti-neutrinos). Lederman and Garwin realised that on the basis of Lee and Yang's suggestion, muons moving in the forward direction in the decay of pions would already be polarised if parity violation occurred. So, all they had to do was to measure the asymmetry of the emitted electrons (or positrons) reliably. For measuring the electron asymmetry they had to stop the muons. They were worried that the muon spin might not retain its initial direction during the stopping process, or that the muons might be depolarised in the two microseconds before decay.

The experimental arrangement is shown in *Figure* 3. The T-shaped carbon block of length 8" was used to separate the μ^+ from the π^+ beam as the mean range of 85 MeV pions from the cyclotron is ~5". This arrangement allowed a maximum number of muons to come to rest in the one-inch carbon block

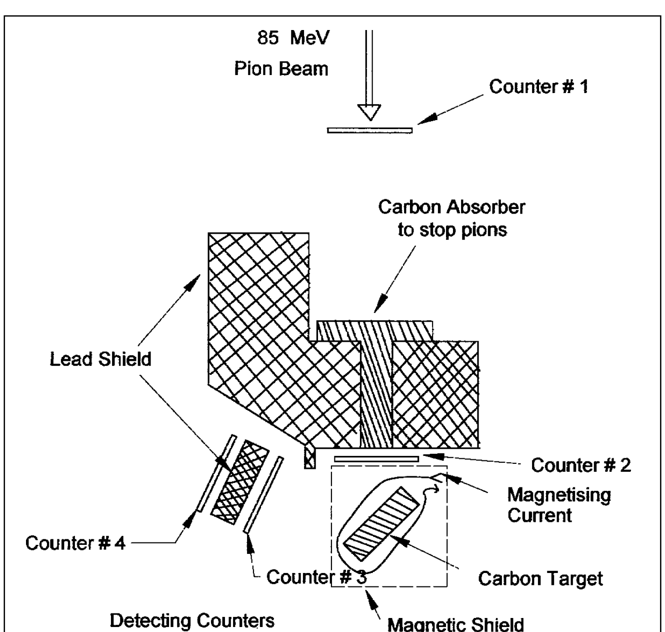

Figure 3. Sketch of the experimental arrangement of Garwin, Lederman and Weinrich. (Reproduced from Physical Review Letters, Vol. 105, pp.1415-1417, 1957 with permission from American Physical Society).

Box 3. Coincidence Counting

Using coincidence counting techniques, it is possible to establish experimentally if two events occurred within a finite interval of one another. Suppose the first event is identified in detector 1 producing an electronic pulse and the second event is identified by another pulse in detector 2. Both these pulses are fed as inputs to the coincidence circuit and an output is produced only if these two pulses appear within a short time interval, termed the resolving time of the circuit. Traditionally, for fast coincidence circuits the resolving time is a few nanoseconds, whereas for slow-coincidence circuits it is about a few microseconds. In a delayed coincidence, one of the pulses is intentionally delayed by a known time interval before it is fed to the coincidence circuit. In modern parlance, the coincidence circuit is an AND gate. Such coincidence circuits were developed for studying nuclear decays and are now ubiquitous.

chosen as the stopping material. The stopping of a muon was signalled by a fast coincidence (see *Box* 3) between counters 1 and 2. The subsequent beta decay of the muon was detected by the electron telescope 3-4, which normally required electron energies above 25 MeV to register. A delayed coincidence between counters 1-2 and 3-4 ensured that the electrons were emitted by the stopped muons. At first they wound a uniform solenoid on a hollow cylindrical lucite shell to serve as the magnet for producing a uniform magnetic field over the carbon block. During the initial run the lucite shell overheated and melted down. Then they wound the wire in the form of a rectangular solenoid directly over the carbon block. Although neither the muon spin nor its magnetic moment was known at that time, they assumed a value of one-half for the muon spin and that the gyromagnetic ratio had the value $g = 2$. The magnitude of the solenoid current was calculated on this basis. The electronic coincidence circuit used for this experiment was developed by Garwin earlier. They set about to measure the count rate in their electron counter as a function of the magnetic field in the solenoid and observed a sinusoidal variation, which gave the value of the angular distribution parameter, $a = -0.33 \pm 0.03$ for the decay of μ^+. They checked the experimental system by allowing the end of range pions from the beam to come to rest in the carbon target, thereby allowing electrons emitted by muons travelling in all directions to reach the counter. The total electron counting rate in this case did not vary with the magnetising current. This result confirmed that the asymmetry observed was due to the precession of the muon spin and confirmed the violation of parity in π-μ-e decay. From the observed variation of the asymmetry they could also deduce a value for the gyromagnetic ratio of the muon, $g_\mu = 2$, and hence its spin value of one-half. The asymmetry in μ^- decay was also observed and it gave the same value of magnetic moment as that for μ^+. These results were also verified by Telegdi and Friedman using the technique of nuclear emulsion to record the π-μ-e decay. Many precision measurements of the magnetic moment of the muon followed. The experiment also demonstrated that the muons do not lose their polarisation in being stopped in a target material. This fact was exploited in many experiments to probe solid state effects. Studies on mu-mesic atoms also proliferated afterwards.

This result confirmed that the asymmetry observed was due to the precession of the muon spin and confirmed the violation of parity in π–μ–ε decay.

When Lee and Yang first thought of the idea of parity violation, they searched the literature for experiments which might have tested the left-right symmetry. One publication which eluded their scrutiny was by R T Cox, C G McIlwraith and B Kurrelmeyer in *Proceedings of the National Science Academy* (Vol. 14, pp. 544-547, 1928), where the authors reported a study on the double scattering of beta particles and observed an asymmetry in the scattering which they attributed to the apparent polarisation of the beta particles. Other experiments on double scattering of electrons employing electron gun sources did not show the asymmetry. Since they had no idea that parity may be violated and no one was even willing to consider this option, their result remained unexplained for about 28 years. After the experiments of Wu and others were published, L Grodgins from MIT reanalysed the data of Cox and others and also repeated the double scattering experiment and found that though the magnitude of the asymmetry observed by Cox and others was right, their sign for the asymmetry was wrong. Despite this discrepancy, we find once again that an important experimental result was ignored as it did not fit into the prevailing notions of the time.

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