Discovery of Parity Violation

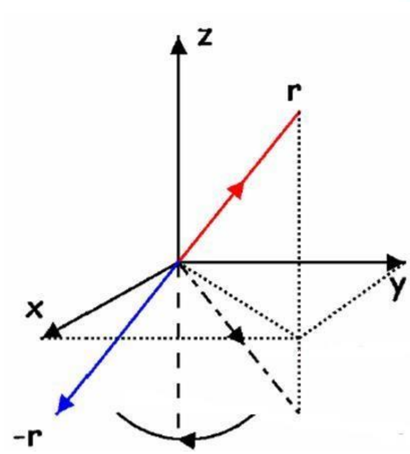
Simmetry

Symmetries have long played a crucial role in physics. The conservation laws of the past had more fundamental roots within the symmetry of the Universe. However, sometimes scienti c reasoning lead Tsung-Dao Lee and Chen Ning Yang to reconsider one of the most successful and long believed symmetries of nature, that of parity.

Parity

In this report we will talk about the simmetry of space inversion [1], which although applicable to classical systems, only gains its full signi cance in the study of systems described by quantum mechanics. Parity is a Quantum Mechanical concept and the term parity is used in two ways, rst, as the operation P of spatial inversion (it is also known as mirror symmetry, or left-right symmetry, hence invariance under space inversion is equivalent to the indistinguishability of left and right), second, as a numerical quantity associated with the system. Parity in the rst sense is an operator P for a wavefunction $\Psi(\vec{r})$ which reverses the coordinate $\vec{r}$ to $-\vec{r}$:

$$P\,\Psi(\vec{r}) \longrightarrow \Psi(-\vec{r})$$



Besides, Ψ is an Eigenfunction of P [1] and so

$$\Psi(-\vec{r}) = \lambda\Psi(\vec{r}),$$

[1]For a Hamiltonian of this kind [2]:

the energy eigenfunctions are of the form $\psi_{nlm}(r) =$

$$R_{nl}(r)Y_l^m(\vartheta,\phi).$$

Under the operation of mirror inversion in the origin, which in spherical polar coordinates is represented by:

$$r \longrightarrow r$$
$$\vartheta \longrightarrow \pi - \vartheta$$
$$\phi \longrightarrow \phi + \pi$$

we nd from the properties of the spherical harmonics

,

where

se $m \geq 0$ se

$m \leq 0$

and

with

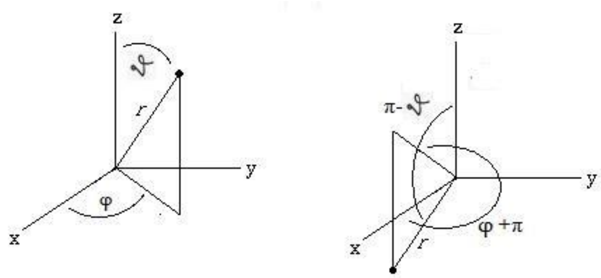
that $Y_l^m(\pi - \vartheta, \phi + \pi) = (-1)^l\, Y_l^m(\vartheta,\phi)$, so that $\psi_{nlm}(r) = (-1)^l$

$\psi_{nlm}(r)$.

$(-1)^l$ is called parity of the state and in this case is determined by the orbital angular momentum.

where λ is the Eigenvalue; consequently it is clear that if we do this twice we have to get back to our starting

$$H = -\frac{\hbar^2}{2m}\nabla^2 + V$$



$$Y_l^m(\vartheta,\varphi) = \epsilon\sqrt{\frac{(2l+1)(l-|m|)!}{4\pi(l+|m|)!}}e^{im\varphi}P_l^m(cos\vartheta)$$

$$\epsilon = \begin{cases} (-1)^m \\ 1 \end{cases}$$

$$P_l^m(x) = (1-x^2)^{|m|/2}\left(\frac{d}{dx}\right)^{|m|}P_l(x)$$

$$P_l(x) = \frac{1}{2^l l!}\left(\frac{d}{dx}\right)^l(x^2-1)^l,$$

point:

$$P^1\Psi(\vec{r}) \longrightarrow \Psi(\vec{r}) = \lambda^2\Psi(\vec{r}),$$

therefore $\lambda = \pm 1$. If the Eigenvalue of Ψ is $+1$ we say that Ψ is even or positive, otherwise odd or negative. Parity in the second sense is a multiplicative quantum number which could be $+1$ or -1. The total parity of a system of particles is the product of their intrinsic parities and the spatial parity given by $(-1)^l$, where l denotes angular momentum of the wave function.

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, two similar radioactive particles spinning in opposite directions about a vertical axis should emit their decay products with the same intensity upwards and downwards.

The τ-θ puzzle

Two particles have all the same properties except that they are of opposite intrinsic parity

Prior to 1956 it was assumed that the parity was conserved in all the fundamental interactions[2] and certainly in the case of electrodynamics, this fact had been tested, and found to hold. Without realizing it, most physicists simply carried the assumption that the same would be true in the weak interactions. It took an experimental anomaly to shake that assumption: the original motivation for the experimets which led to the discovery of parity violation came from the τ-θ puzzle. In the early 1950's there were two particles called the tau (this is not the same as the tau lepton, discovered in 1975) and theta particle that were both discovered in cosmic rays and that appeared to be identical in every aspect: careful studies had shown that the masses, charges, spin and lifetimes of the two mesons were equal within experimental errors. However, they had one striking di erence; they exhibited di erent decay modes, mediated by the weak interaction: tau decayed into three pions, while theta turned into two.

$$\tau^+ \longrightarrow \pi^+ + \pi^+ + \pi^-$$
$$\theta^+ \longrightarrow \pi^+ + \pi^0$$

The intrinsic parity of the pion was estabilished to be -1: thus the parity of a particle of spin l decaying into two pions is just $(-1)^l$ and that of a particle of spin l decaying into three pions equals $(-1)^{l+1}$. So, if the parity were conserved in weak interactions, the parity of τ^+ is $(-1)^{l+1} = -(-1)^l$, whereas the parity of θ^+ is $(-1)^l$. Therefore these two particles looked the same, except for parity. The nagging thing, of course, is that apart from this parity di erence, the tau and theta particles are identical and despite searching for tiny di erences, no experiment could detect any variation. The parity conservation law implied that such particles could decay into either an even or into an odd number of pions, but not into both. Consequently it was believed that tau and theta were di erent.

In 1954, R.H. Dalitz ([4], [5] and [6]) looked at the decays of the tau into three pions and in doing so introduced the Dalitz plot[2] into physics. The rst use of the Dalitz plot revealed that the theta particle appeared to be the same as the tau, which was paradoxical. The puzzle persisted for two years: Dalitz mused his colleagues that perhaps the law of odds and evens was not true, even though all the evidence said otherwise [7].

The solution to this puzzle emerged rapidly. Two theorists, Tsung-Dao Lee and Chen Ning Yang published a landmark paper [8] in which they showed that there was actually not a shred of evidence available that the weak interactions conserved parity. For over twenty years people had just assumed without checking it. Lee and Yang argued that the τ-θ puzzle was an evidence that, perhaps, the weak interactions didn't conserve parity after all. They found that while there was plenty of evidence for the validity of parity conservation in electromagnetic and strong interactions, there was no experimental evidence[3]

[1] Since invariance under space re ection is intuitively so appealing (why should a left and a right-handed system be different?), conservation of parity quickly became a sacred cow [3].

[2] The Dalitz plot is a scatterplot (a type of mathematical diagram using Cartesian coordinates to display values for two variables for a set of data) used to represent the relative frequency of various manners in which the products of certain three-body decays may move apart. The axes of the plot are the squares of the invariant masses of two pairs of the decay products. For example, τ^+ decays to particles π_1^+, π_2^+, and π_3^-, a Dalitz plot for this decay could plot m_{12}^2 on the x-axis and m_{23}^2 on the y-axis.

[3] A few weeks after the Sixth Rochester Conference, late April or early May (1956) Lee and Yang met in New York at the White Rose Cafe near 125th and Broadway and discussed the possibility that parity could be violated in weak processes. Afterwards Lee asked his colleague from Columbia, Chien Shiung Wu, an expert in β-decay, whether she knew of any experiments related to this question. Lee and Yang soon discovered that nobody has ever proved that parity conservation was valid for weak interactions. They decided to analyze the problem thoroughly. On June 22 1956, their paper entitled Is Parity Conserved in Weak Interactions? was submitted to the Physical Review. The editor of that journal, Samuel Goudsmit, protested against using the question mark in the title. The

whatsoever for parity conservation in β-decay or the weak decays of the mesons then known. They were proved to be right, and in 1957 won a well-deserved Nobel Prize. The tau and theta particle today are known as the K strange meson [9]:

	$K = (us)$ +
Mass	493.677±0.016 MeV
Charge	+1
Mean life	$(1.2380 \pm 0.0021) \times 10^{-8}$ s
	$\frac{1}{2}$
	-1

Lee and Yang, prior to the publication of their paper, had relayed their ideas [4] to an experimentalist Chien-Shiung Wu. Following on this analysis Wu with her coworkers Ambler, Hayward, Hoppes and Hudson showed conclusively that parity is violated in β-dacay [10].

β-decay

β-decay is mediated by the weak interaction and involves the transformation of a neutron into a proton, or vice versa, and the creation of an electron and neutrino. β-decay of a nucleus can be used as a test of parity conservation when the magnetic moment of the nucleus is polarized in the z-direction. To understand how this come about, we describe the physics of this system. The magnetic moment of the nucleus is polarized in the z-direction using a magnetic eld; when the nucleus undergoes β-decay, it will liberate an electron which will y out of the nucleus at a certain angle, and that is the end of the interaction.

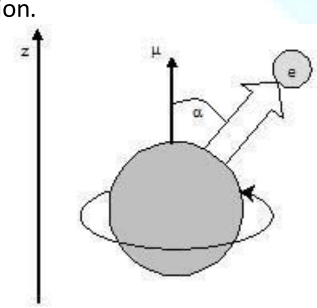


Figure 1: β-decay of a nucleus. The magnetic moment is drawn according to the right hand rule and the spin of the nucleus is suggested by the looping arrow. The electron has a velocity α-angle relativly the magnetic moment μ.

To see why this is relevant to parity, we look at the mirror image of the same system. In the mirror, the electron ies out of the nucleus at the same angle to the positive z-axis; however, in the mirror the nucleus is spinning the other way around, and so its magnetic moment is now in the negative z-direction. This means that the angle between the electron trajectory and the magnetic moment of the nucleus has changed.

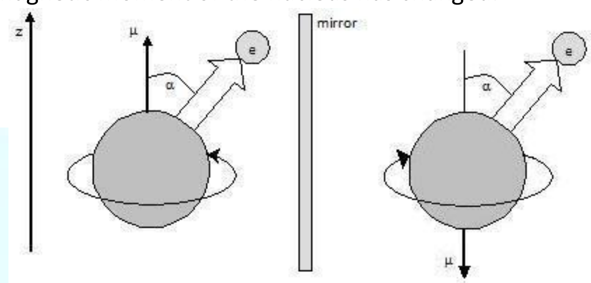


Figure 2: β-decay in the mirror. In the mirror the nucleus now spins in the opposite direction, as indicated by the looping arrow, and the direction of the magnetic moment μ ips to the negative z-direction. Thus the angle between the electron trajectory and the magnetic moment changes.

To be precise, if the magnetic moment is pointing in the z-direction and it is found that the angle between the electron trajectory and the positive z-axis is α, then in the mirror the angle between the two is $\pi - \alpha$. Therefore, if parity is a true symmetry of nature, the electrons should shoot o in equal numbers in both directions [5]. The experiment by Wu shows that this is not true and in fact one of these angles is favoured by nature. It turns out that electrons leave the nucleus preferentially away from the magnetic moment with an angle of $\frac{\pi}{2} < \alpha < \pi$. This asymmetrical e ect has been observed in the case of oriented Co^{60}.

The Wu experimet: β-decay of Co^{60}

Wu knew that the nuclear orientation work was then being carried out at the National Bureau of Standards in Washington by a group headed by Ernest Ambler. She also

paper was nally published as Question of Parity Conservation in Weak Interactions [8].

[4] The paper by Lee and Yang [8] was published only on October 1, 1956, but many physicists around the world knew about their ideas earlier because of a circulated preprint of their paper. There was strong opposition to the idea of parity nonconservation. Most physicists rejected it as too fantastic and adverse to universally accepted notions on symmetries in physics. Lee and Yang were still backing two horses and, in parallel to their parity nonconservation paper [8], submitted another paper on the parity doublets idea [11].

[5] The angular distribution of β-radiation is of the form:

$I(\alpha)d\alpha$ = (constant)$(1 + a\cos\alpha)\sin\alpha d\alpha$ if a 6= 0, one would have a positive proof of parity nonconservation in β-decay [8].

knew that Ambler's thesis had been done on Cobalt-60. Ambler's team consisted of Raymond Hayward, Dale Hopper, and Ralph Hudson. The experiment was to be performed at the NBS.

The idea of an experiment with Co^{60} was simple only in theory. In order to make the measurement possible the radioactive nuclei should have been polarized so that their spins pointed in the same direction. It required very low temperatures, otherwise the thermal motion of the nuclei would have destroied the alignment[6]. At that time it was already known that Co^{60} nuclei could be aligned by the Gorter Rose method ([14], [15] and [16]) in cerium magnesium nitrate. The e ciency of the method was checked [17] by a team of physicists from Oxford which included Ambler.

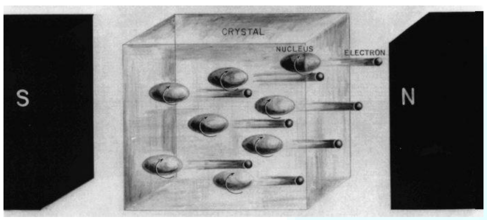


Figure 3: Idealized drawing shows polarization of Co^{60} nuclei in a magnetic eld at a temperature near absolute zero. The nuclei behave as small spinning magnets whose north poles are conventionally taken to be the direction of righthanded spin. Thus, at very low temperatures, where atoms lose most of their random thermal motion, the nuclei line up in a magnetic eld so that their spin axes are parallel. The experiments at NBS showed that emission of electrons in β-decay of Co^{60} nuclei is greater in the direction of the south pole of the nucleus (pointing toward the north pole of the magnet), as indicated in the drawing.

Polarization of the nuclei was achieved by cooling a paramagnetic crystal containing Co^{60} to within 0.003 degrees of absolute zero, and subjecting it to a magnetic eld. The magnetic polarity of the nucleus is determined by its direction of spin, and, under the inuence of a magnetic eld, most of the Co^{60} nuclei align themselves so that their spin axes are parallel to the eld.

As Co^{60} is radioactive, its nuclei continuously emitted both β and γ rays. Temperature has no e ect on radioactivity, so the chilled, lined-up cobalt atoms went right on disintegrating and emitting electrons. If parity is conserved in such interactions, then the intensity of the β-emission should be the same in either direction along the axis of spin. This, of course, was the critical question in the Co^{60} experiments. It was resolved by measuring the intensity of β-emission in both directions, along and against the eld direction.

The degree of polarization could be measured by the anisotropy of the γ-radiation, which was more released in the polar direction than in the equatorial plane[7].

The β particles from Co^{60} could not penetrate any substantial thickness of matter. For this reason Wu and her collaborators had to locate the radioactive nuclei in a very thin layer of only 0.05 mm on a surface of cerium magnesium nitrate. The β counter had to be placed inside the demagnetization cryostat. The β particles emitted by Co^{60} nuclei were detected by scintillations in a thin anthracene crystal located inside the vacuum chamber about 2 cm above the Co^{60} source. The scintillations were transmitted through a glass window and a Lucite light pipe 1.22 m long to a photomultiplier located at the top of the cryostat (not shown in Fig.4). The end of the lucite pipe at the crystal-pipe interface was machined into a logarithmic spiral shape for maximum light collection. In addition to the beta counter within the vacuum chamber, two sodium iodide γ scintillation counters (NaI) were used externally to measure the directional intensity of the more penetrating γ radiation. In this way the investigators were able to determine the degree of polarization of the Co^{60} nuclei. The two γ counters were biased to accept only the pulses from the photopeaks in order to discriminate against pulses from Compton scattering.

[6] The Bureau's low temperature laboratory was chosen for the experiments because of its previous experience in lowtemperature alignment of atomic nuclei ([12] and [13]) an essential feature of the β-decay study. Such temperatures could be reached through a process called adiabatic demagnetization.

[7] Cobalt-60 decays into Nickel-60 through negative β-decay, which converts a neutron into a proton, given by:

$$n^0 \longrightarrow p^+ + e^- + \nu_{-e}.$$

The Ni^{60} is produced in an excited state and quickly relaxes by emitting two γ-rays. When the Gorter-Rose method is applied,

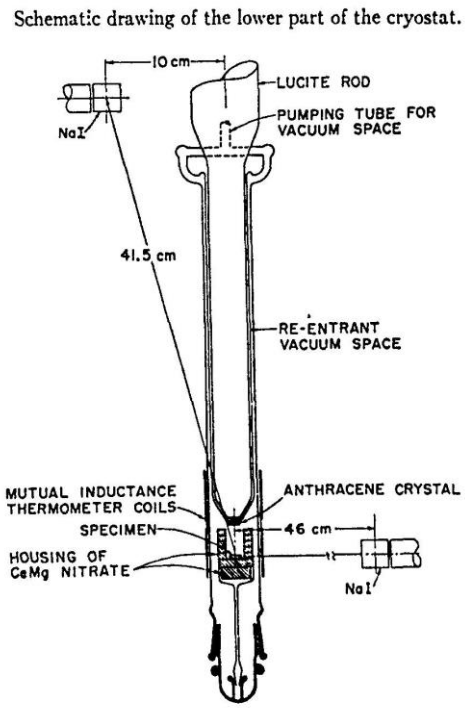


Figure 4: The apparatus used by Wu, taken from her original paper.

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the direction at which the γ-rays exit the Ni-nucleus is correlated to its magnetic moment, and so in the experiment done by Wu Co^{60} is magnetically polarized in the z-direction using magnetic elds and this polarization can be checked by detecting the exiting γ-rays. To implement this check, Wu used two NaI scintillators placed at the predicted angles for polarization along the z-axis, as seen in Figure 3.

By comparing the detection rate of β-particles when the Co^{60} nuclei were polarized in the positive $z$direction to when they were polarized in the negative z-direction an anisotropy was found indicating a violation of parity[8]. Although it was di cult by this experiment to quantify the amount of asymmetry, Wu estimated that it was nearly 70% of all the electronswas emitted from the direction of the magnetic moment.

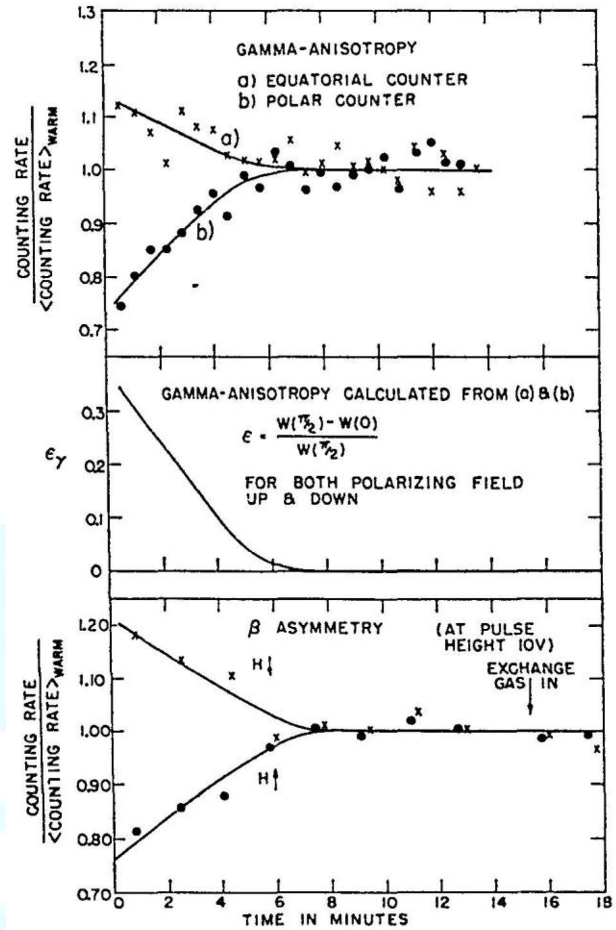

Figure 5: γ-anisotropy and β-asymmetry for polarizing eld pointing up and pointing down.

The Figure 5 shows Wu's results, taken from her original paper [10]. The top graph shows the output of the NaI detectors as the sample depolarizes. The splitting of the curves results by the anisotropy in the γ-ray emissions which disappears as the magnetization vanishes according to the Gorter-Rose method. The bottom graph shows the β-particle detections. Here the splitting occurs due to parity violation. Note that the γ and β anisotropy vanishes at the same time, which is the expected behaviour.

The observed β-asymmetry didn't change sign with the reversal of the direction of the demagnetization eld, indicating that it wasn't caused by the remanent magnetization in the sample. The asymmetry coe cient sign was negative, thus the emission of β-particles was more favoured in the direction opposite to that of the nuclear spin.

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[8] First readings con rming parity violation were obtained by Wu's team on December 27, but the results were not consistently reproducible in the following days. Finally, about two o'clock in the morning of January 9 (1957), after everything had been checked and rechecked, Chien Shiung Wu and her collaborators uncorked a bottle of Chateau La te-Rotschild and they drank to the overthrow of the law of parity.

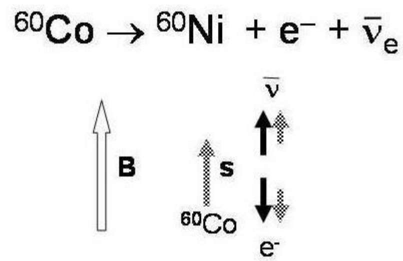


Figure 6: The electrons from the Co^{60} decay are emitted preferentially into the hemisphere opposite to the nuclear spin s.

Another exsperimental proposal by Lee and Yang

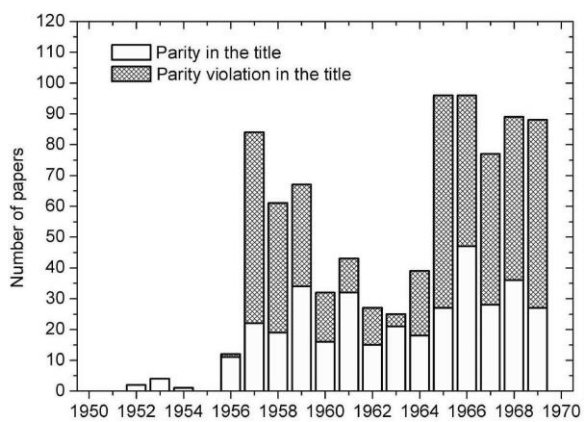
Meanwhile, Leon Lederman, at Nevis Laboratory of Columbia University, had learned from Lee and Yang [8] of an alternative experimental test that involved the pattern measuring of electrons produced by the decay of muons that themselves resultewd from the decay of cyclotron-generated pions. He chose to investigate the succesive reactions[9]:

$$\pi^+ \longrightarrow \mu^+ + \nu$$
$$\mu_+ \longrightarrow e_+ + 2\nu\,. \qquad (1)$$

The system (1) could proove parity violation because Lee and Yang had shown that if parity is violated, then there would be an asymmetry in the polarization of the μ along the direction of motion. Furthermore, one can use the angular distribution of electrons emitted from the second reaction to determine experimentally what the μ polarization is. Lederman teamed up with his colleague Richard Garwin and graduate student Marcel Weinrich and, over the course of a week in January 1957, they ran an experiment that produced clear evidence of parity violation [18].

The next studies

The number of papers with the word parity in the title increased dramatically.



The discovery that parity is not conserved in weak interaction increased interest in the discrete symmetry operations, the charge conjugation C and time reversal T. It was shown that relativistic locality required invariance of the Lagrangian of any under the combinate operation CPT (taken in any order).

In 2002 Oscar Greenberg proved that CPT violation implies the breaking of Lorentz symmetry [19], and that any study of CPT violation includes also Lorentz violation.

massive for us to produce, assuming they exist at all. For this reason mirror particles are one candidate for the dark matter of the Universe. If mirror particles exist in su cient abundance, we might detect them through their gravitational e ects.

It is de nitely true that parity is not conserved in the weak interactions of ordinary matter, and this will always be true, no matter how much we want to believe that the Universe should be more symmetric.

[9] In 1956 it was believed that there is only one kind of neutrino and there was no generally accepted rule of the usage of terms neutrino and antineutrino .

Several experimental searches of such violations have been performed during the last few years.

Future Outlook

The fall of parity cleared up the way for a reconsideration of physical theories and led to new, far-reaching discoveries regarding the nature of matter and the universe

The work of Lee and Yang, Wu, and Garwin has provided de nitive proof that mirror symmetry is broken in the weak interaction, and so we can say that mirror symmetry is not a true symmetry of the Universe as a whole. This is an unsettling conclusion, because the historical trend of physics up to this point was that of simpli cation and uni cation. In the case of parity violation, however, we learned that nature exhibits a very striking asymmetry for no apparent reason, and goes against our expectation of a symmetrical universe.

Beyond the weak interaction, there is a symmetry that might be tempt us to consider that parity breaking in the weak interaction is somehow balanced by an opposite breaking of parity somewhere else unknown. Theorists have considered what kind of physics would be required to restore the mirror symmetry to the Universe. In particular, mirror symmetry could be restored if the so called mirror particles would exist. It has been shown that mirror particles would interact very weakly with ordinary matter, except through the gravitational force. The fact that we have not observed the mirror force mediators means that they are too