# Chien-Shiung Wu: The First Lady of Physics*

*D Indumathi*

**C S Wu was a Chinese-American experimentalist, best known for her path-breaking experiment that showed that parity is not conserved in beta decay. Her results gave a deeper insight into the nature of weak interactions and enabled the correct formulation of the theory behind such interactions. She was a passionate advocate of women entering into hitherto 'forbidden' fields of physics and mathematics and was as outspoken against gender discrimination as she was concerned about environmental conservation. It was generally felt that she was overlooked for the Nobel Prize, perhaps because she was a woman, and a Chinese one at that.**

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## 1. Introduction

Chien-Shiung Wu (*Figure* 1), was born in the Jiangsu province of the Republic of China on 31 May 1912, more than one hundred years ago. The legacy of this brilliant scientist lives on as a crucial piece of what is known as the Standard Model (SM) of Particle Physics, which describes the nature of elementary particles and their interactions, as we know it today.

### 1.1 *Early Life*

Wu first studied mathematics and later moved to physics. She was one of the top students of the class even while being active in student politics. After studies at Nanjing University, she moved to Zhejiang University as an assistant and began her PhD at the Institute of Physics under Prof. Gu Jing-Wei. Prof. Gu was a doctorate from the University of Michigan, USA, and she encouraged

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**Figure 1.** Photograph of C S Wu. (Photo courtesy: Smithsonian Institute via *Wikimedia Commons*)

Wu to also go there and study. Wu left for the USA in August 1936. It would be 37 years before she returned to China.

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When Wu reached San Francisco, California, she heard that at Michigan University, women were not even allowed to use the front entrance and had to enter through a side door! A fellow Chinese, Luke Yuan, showed her around the laboratories in the University of California, Berkeley. She decided to study at Berkeley. The Head of the Department offered her a place in the graduate school programme even though the term had already begun. She began to work with Ernest O. Lawrence, who would soon win the Nobel Prize for inventing the cyclotron accelerator. Although she was officially the student of Lawrence, she worked with Emilio Segrè, who later won the Nobel Prize for his discovery of the anti-proton.

## 1.2 *At the Manhattan Project*

Wu's early work on beta decay was a part of her thesis, although she did not at that time work on the parity-violating beta-decay experiment that would make her so famous (more on that later). She also worked on isotopes of xenon and became an expert in the area. Despite that, she did not get a job in any University, and finally joined a women's college—Smith College—where there was only teaching and no research programme. Frustrated with this, she quit and eventually joined the Manhattan Project at Columbia University. The Manhattan Project was an R&D project which led to the development of the world's first nuclear weapons. Although there is now a lot of criticism of the manufacture of such weapons in general, and the atomic bombings of Hiroshima and Nagasaki (in Japan) in particular, at that time, many of the best scientists in the US were a part of this effort. Wu was part of the group involved with the instrumentation for studying uranium enrichment. Also, her input was crucial in solving the problem of the 'stalled' chain reaction[1] at the Hanford reactor. The reactor went critical as expected but the power output soon dropped, and the reactor shut down. Enrico Fermi contacted Wu, who reasoned that this was because of neutron poisoning from $Xe^{135}$, which is produced in the process. The problem was solved and this helped them get the reactors going again.

[1] $Xe^{135}$ produced in the fission process is a powerful neutron absorber. Absorption reduces the neutron population and the chain reaction is prevented from building up and hence 'stalls'. Eventually, the reactor shuts down due to Xenon accumulation. Wu helped trouble-shoot problems with the smooth running of the first nuclear reactor.

## 1.3 *Awards and Honours*

When the war was over, Wu was offered a position as an associate research professor at Columbia University, where she remained for the rest of her career. Due to the Chinese civil war, she could not go back and meet her family, and she eventually became a US citizen. She was the first woman to hold a tenured faculty position at Columbia University (*Figure 2*), the first woman to receive a DSc from Princeton University, a member of the (American) National Academy of Sciences, and the first woman to lead the American Physical Society as its president. Her awards include the National Medal of Science, the Wolf Prize, the Research Cor-

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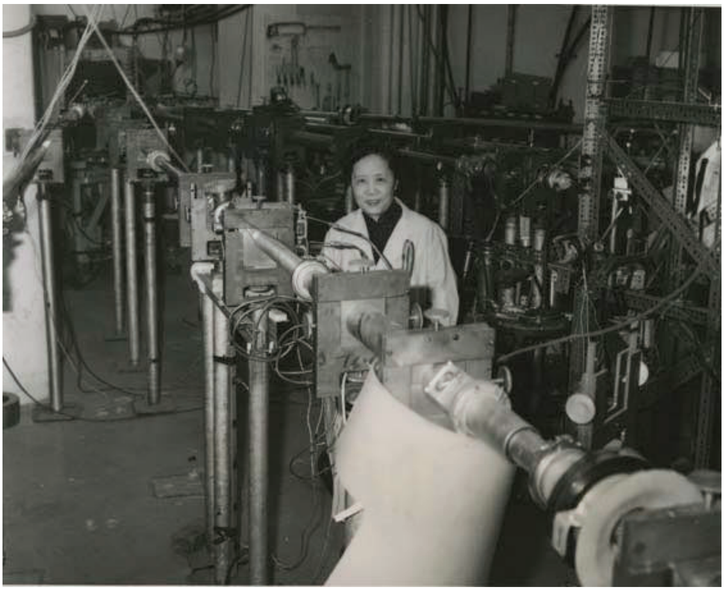

**Figure 2.** C S Wu at Columbia University, 1963. (Photo courtesy: Smithsonian Institute via *Wikimedia Commons*)

poration Award, the John Price Wetherill Medal of the Franklin Institute, the Cyrus B Comstock Prize, the Tom Bonner Prize of the American Physical Society, and several more.

## 2. The Standard Model of Particle Physics

We will first introduce a few key concepts and ideas in order to understand and appreciate Wu's work on parity violation [1] in weak interaction processes such as beta decay.

Electrons are 'elementary', that is they cannot be broken up further. In contrast, the protons and neutrons in the nucleus are found to be made up of elementary particles called *quarks* and *gluons*.

### 2.1 *Elementary Particles*

Electrons are 'elementary', that is they cannot be broken up further. In contrast, the protons and neutrons in the nucleus are found to be made up of elementary particles called *quarks* and *gluons*; see the list of elementary particles in *Figure* 3. The standard model of particle physics describes both the nature and interactions of particles. For a non-technical review on elementary particles and their interactions, see [2].

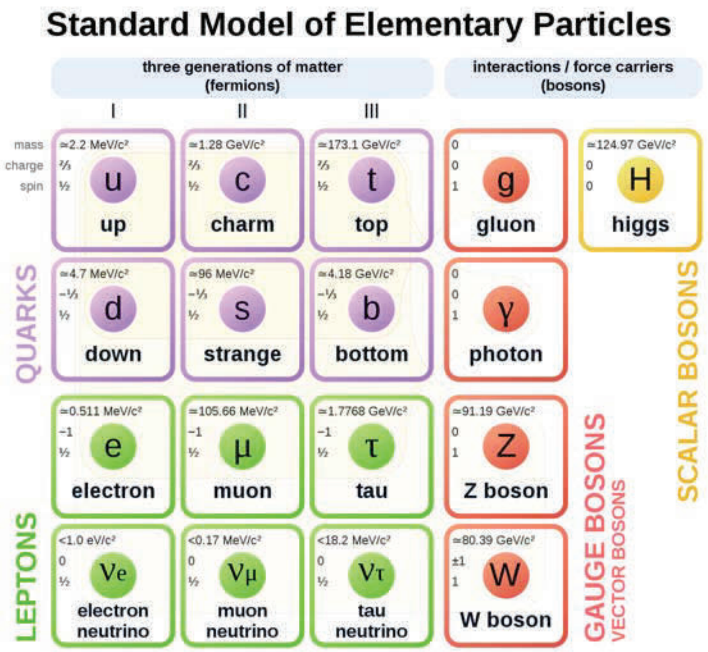


**Figure 3.** List of known elementary or fundamental particles. (Figure source: *Wikipedia*)

For instance, we know that the electron is negatively charged (charge = $-1$ in natural units called $e$). The proton is considered to be composed of two up-type ($u$) and one down-type ($d$) 'valence' quarks, with charges $+2/3e$ and $-1/3e$ respectively, so that the net charge of the proton is $+1e$. Each quark is a fermion with spin $(1/2)\hbar$ so the proton is also a fermion, as required by observation. Here $\hbar = h/(2\pi)$ where $h$ is the Planck's constant. Henceforth, we will simply denote the charge and spin in units of the proton charge and $\hbar$ respectively. Gluons carry no charge. They are spin 1 particles, just like the photon. The neutron is composed of valence quarks $ddu$ so that its net charge, $((-1/3) + (-1/3) + (+2/3))$, is zero.

The word 'valence' means that these are the minimum number of quarks required to account for the proton's or neutron's charge. There may be additional (in fact an infinite number of) quarks, provided, they come in quark–anti-quark pairs so that they do not alter the net charge[2].

[2] Of course, the net spin of the proton arises from all the quarks and gluons it is composed of. Understanding this is a very difficult problem and outside the scope of this article.

Apart from the up and down ($u$ and $d$) quarks that make up the protons and neutrons in the nucleus, there are several other types of quarks as well, (see *Figure* 3). The quark that is of interest here is the *strange* quark, having the same charge and spin as the down-type quark.

### 2.2 *Enter the Pions*

We see that protons and neutrons are not elementary but are composed of quarks and gluons, with three valence quarks. Such type of particles composed of three quarks are called *baryons*. It turns out that it is possible to make another type of particle called *meson* by combining[3] a quark (denoted by $q$) with an anti-quark (denoted by $\overline{q}$). The most common mesons you may have heard of are the pions; for instance, $\pi^{\pm}$ contain valence quarks ($u\overline{d}$) and ($d\overline{u}$) respectively, while the neutral pion $\pi^0$ is a combination of ($u\overline{u}$) and ($d\overline{d}$). The particle that set off immense interest in the study of the parity properties of weak interactions is the $K$-meson or kaon. We now know that $K^{\pm}$ is composed of the valence quarks ($u\overline{s}$) and ($s\overline{u}$) respectively. It was the observation of $K^+$ mesons in cosmic rays that focussed attention on the parity puzzle. But what is parity?

[3] Quarks carry a 'colour' quantum number which reflects a certain symmetry that accounts for strong interactions that help to keep the quarks and gluons bound into the baryons and mesons. The existence of both baryons and mesons is related to this symmetry.

### 2.3 *The Parity Operator*

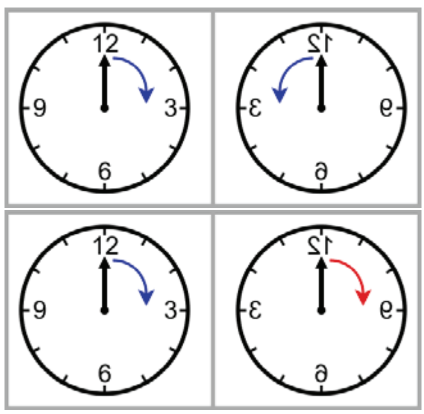


**Figure 4.** Learning about parity from clock faces. Top: Parity conserving set; Bottom: Parity violating set of clocks. See text for explanation. (Figure source: *Wikimedia commons*)

Consider a clock whose ticking you are observing in a mirror. As the clock goes from 12:00 to 03:00, its mirror image does the same; see the top panel of *Figure* 4. This symmetry under reflection is called parity symmetry[4]. If parity were violated, the mirror-reflected clock on the right will start at 12:00 and show 09:00 after three hours, as can be seen from the bottom panel of *Figure* 4. If we take coordinates $x$ and $y$ in the plane of the mirror and $z$ perpendicular to the mirror then the mirror reflection changes the vector ($x$, $y$, $z$) to ($x$, $y$, $-z$); Under parity conservation, the angular velocity vector pointing into the clock will point out after reflection. Now we can generalise the notion to include reflection about the origin, so that a vector $\vec{x} \equiv (x, y, z)$, under the parity operation reverses 'every' coordinate: $\mathcal{P}\vec{x} \rightarrow -\vec{x} = (-x, -y, -z)$. For instance, electromagnetic interactions are invariant under parity. This means that an even parity state for which the wave function $\psi(\vec{x})$ is such that $\mathcal{P}\psi(\vec{x}) = \psi(-\vec{x}) \equiv \psi(\vec{x})$, cannot transform to an odd-parity state where $\mathcal{P}\psi(\vec{x}) = \psi(-\vec{x}) \equiv -\psi(\vec{x})$, under the electromagnetic interaction.

[4]Technically this is true only in odd dimensions.

All particles have intrinsic parity as per quantum mechanics. The pion has negative parity. In 1953, Dalitz [3] showed that the state with three pions ($3\pi$ state) has a spin-parity of $0^-$ (that is, spin zero and negative parity) while the $2\pi$ state was already known to have a spin-parity of $0^+$, i.e., the state with two pions has even parity and the one with three pions has odd parity.

All particles have intrinsic parity as per quantum mechanics.

## 2.4 *The Charge Conjugation Operator*

We know that the electron and positron have equal and opposite charge while having the same mass. They are 'charge conjugates' of each other. So we can think of a charge conjugation operator that converts a particle into an anti-particle and vice-versa: $C\psi \rightarrow \overline{\psi}$, where $\overline{\psi}$ is the wave function corresponding to the anti-particle. Note that 'all' the quantum numbers related to charge are swapped in this operation. Again, electromagnetic interactions conserve charge conjugation parity (also called 'C parity').

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### 2.5 *The Tau–Theta Puzzle*

The 'puzzling' experiment was the observation of two 'apparently distinct' charged particles called tau ($\tau$) and theta ($\theta$), which were observed in the interactions happening when cosmic rays from outer space impinge on Earth. Now we know that these are mesons (specifically kaons) containing strange quarks and hence called strange mesons. They were given this name because of their strange behaviour. Observations showed that these two strange mesons otherwise appeared to be identical but one of them decayed[5] into three pions while the other decayed into two:

[5] The kaon mass is about 500 MeV compared to the pion mass of about 140 MeV; hence kaons eventually decay into pions.

$$\begin{aligned} \tau^+ &\rightarrow \pi^+ + \pi^+ + \pi^- \ , \\ \theta^+ &\rightarrow \pi^+ + \pi^0 \ . \end{aligned}$$

The masses and lifetimes (decay rates) of the two particles were so close that it was suspected they were the same particle. However, since $\tau$ and $\theta$ decayed into three and two pions respectively, they must have odd and even parity. Hence they cannot be the same particle, 'unless parity was violated in the decay'. Indeed, it eventually turned out that 'both' these particles are the $K^+$ meson[6], and parity in fact, is violated in these 'weak interactions'. Wu's experiment on beta decay established that parity is violated in weak interactions. Before we present the details of this experiment, we will discuss nuclear beta decay.

[6] The $\tau$ and $\theta$ are the same particle, and it is parity that is violated.

### 2.6 *Nuclear Beta Decay*

Nuclear beta decay is a typical weak interaction, ${}_ZA \rightarrow {}_{Z+1}A + e + \overline{\nu}_e$ where $Z$ and $A$ represent the atomic number and mass number of the nucleus respectively. Consider the simplest case of neutron beta decay,

$$n^0 \rightarrow p^+ + e^- + \overline{\nu}_e \ .$$

In beta decay, the beta (electron) is emitted along with an (anti)-neutrino. Almost massless, and without any charge, the neutrino is almost impossible to detect in the beta decay, but its presence is required to conserve both energy-momentum and spin-statistics in the process. It was Wolfgang Pauli who postulated the existence of the neutrino although the name itself was given by Edoardo Amaldi, and was made famous by Enrico Fermi[7]. Electrons and neutrinos are together called as 'leptons'.

[7] I thank the referee for pointing out this nice historical fact.

Since charge is already conserved in beta decay, the neutrino is neutral, but since the initial state is a fermion with spin half ($\hbar/2$), the neutrino is required to be a fermion as well. Since there are three particles in the final state, they can 'share' the energy of the initial neutron in many ways and hence the observed electron or beta particle can have a 'continuous spectrum' of energies[8], as observed in beta decay. This is not the case if the additional nearly invisible neutrino is not also emitted in the reaction. (Anti)-neutrinos from a reactor were finally detected in 1956 by Cowan and Reines (the latter got a Nobel Prize for this work), the same year that Wu established parity violation in beta decay.

[8] Two particles in the final state share energy equally (note that there is a small correction due to their masses; however, the energy of the electron is still a fixed quantity) so either of them will have a single energy which exhibits as a line spectrum; three particles can share energy in any number of ways so each one of them will have a continuous spectrum.

## 3. Parity Violation in Beta Decay

Enrico Fermi had published his theory of beta decay [4] as early as 1934, based on which many nuclear beta decay rates were calculated.

T D Lee and C N Yang were two theoretical physicists of Chinese origin. They realised that parity conservation had been tested in both electromagnetic and strong interactions but not in weak interactions. They suggested a suitable experiment [5] that could study this[9] and approached Wu to get their idea tested. Their calculations predicted that the beta particles in the beta decay of cobalt ($Co^{60}$) nuclei would be 'asymmetrically emitted' if parity is violated in this weak interaction process.

[9] Lee and Yang suggested the experiment that Wu carried out, to prove parity is violated in weak interactions.

It is simplest to understand the process in terms of the spins or helicities of the particles involved: a particle with spin ($S_z$) aligned (anti-aligned) with the momentum direction has 'positive (negative) helicity'. In *Figure* 5, the thick (blue) arrows indicate the spins of the particles while the thin (black) arrows indicate their momenta. Here the anti-neutrino has positive helicity in the first case (indicated by the upward-pointing right thumb in the schematic)

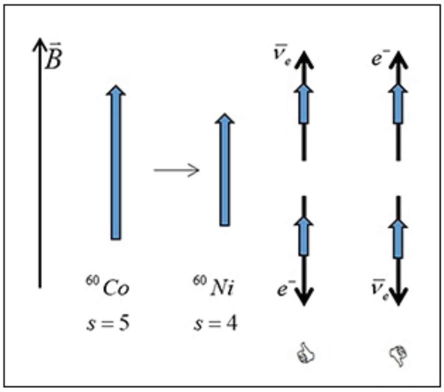



**Figure 5.** Schematic showing the two (symmetric) possible orientations of the electron spin/helicity in cobalt decay. (From [6])

and negative helicity in the second case (indicated by the downward-pointing right thumb in the schematic). In both the cases, the electron's helicity is opposite to that of the anti-neutrino's. Of the two particles, only the electron is observed in the experiment.

The decay of $Co^{60}$ can be expressed as:

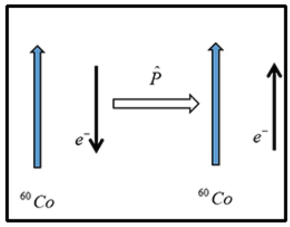
$$\mathrm{Co}^{60} \rightarrow \mathrm{Ni}^{60} + e^- + \overline{\nu}_e \ ,$$

analogous to neutron beta decay. To test parity non-conservation, a 'preferred direction in space' was needed, with respect to which the asymmetry could be measured. The obvious choice was the application of an external magnetic field $\vec{B}$ that would align the spins; see *Figure* 5. In a frame where the cobalt is at rest (so that the heavy nickel nucleus is also practically at rest), the electron and the anti-neutrino will have equal and opposite momenta, as shown.

The $Co^{60}$ nucleus has unpaired protons and neutrons so that it has a net spin +5 in the ground state. When placed in an external magnetic field, therefore, the spins will line up along the direction of the magnetic field. The daughter nucleus, $Ni^{60}$, has a net spin of +4 — one less than that of cobalt. Hence for spin conservation, the final state electron and the anti-neutrino must have spin $+1/2$ each, so that the spins of the electron and anti-neutrino adds up to $+1$. So in both the possibilities shown on the right of *Figure* 5, the spins of both the emitted leptons are pointed upwards.

Parity operator flips the direction of the momentum[10] of the electron while leaving the spins unchanged. (Note that neither the neutrino nor the nickel are observed in the interaction).

[10]Only the direction of the electron's momentum is flipped under parity:




Now there are two possibilities — the momentum of the electron 'aligned opposite' to its spin (negative helicity), or the momentum 'aligned along' its spin direction (positive helicity). If parity was conserved, both should have equal probability. Hence, Lee and Yang suggested that observation of the direction of beta electrons in this process would yield a good test of parity conservation in weak interactions.

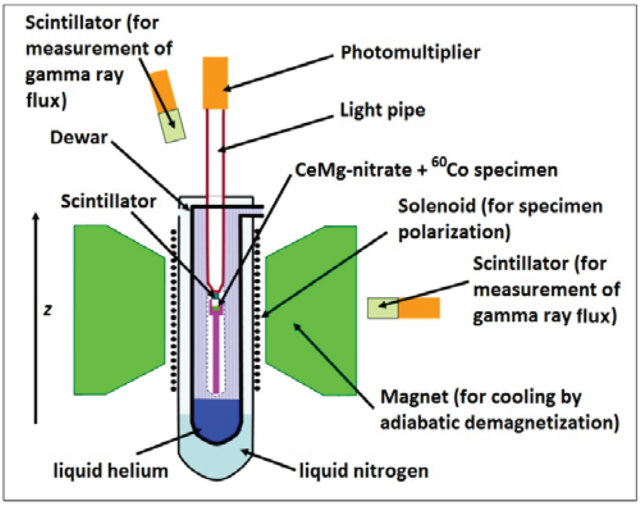
### 3.1 *Wu's Experiment on Parity Violation*

Wu needed to measure the asymmetry of emission of beta particles in the decay of $Co^{60}$ with respect to the external magnetic field. Cooling the system to low temperatures is critical for this result. That is because high/room temperatures spoil the alignment of the spin. So one of the crucial requirements for the experiment was to have good cooling systems that could cool the cobalt down to low temperatures, and for this, she took the help of experts at the National Bureau of Standards in Washington. A schematic of the experimental set-up is shown in *Figure* 6.

The sample was surrounded by a solenoid, which would create a magnetic field in either upward or downward direction. The scintillator kept closely above the sample was used to count the number of beta rays (electrons) emitted along, or opposite to the direction of the magnetic field. The asymmetry in these two measurements is called the 'beta asymmetry', as shown in the lowest panel of *Figure* 7.

When the system warmed up, the polarization of the Co nuclei would decrease and so would the asymmetry, if any. To keep track of the Co polarization, two scintillators were used to measure the gamma ray flux in the equatorial plane and in the polar direction, respectively (see *Figure* 6). The asymmetry between the fluxes in these two detectors (shown in the top two panels of *Figure* 7) would be a measure of the polarization at that instant.

**Figure 6.** Schematic of Wu's experiment. (Figure courtesy: *Wikimedia commons*)




[11]The paper that established parity violation was just two pages long.

[12]This experiment also led to the understanding that the anti-neutrino is 'right-handed', that is, its spin always points along the 'same direction' as its momentum; it has positive 'helicity' or positive 'chirality'. Analogously, the neutrino is 'left-handed' or left chiral. The helicity of the neutrino was established in a famous experiment by Goldhaber and his collaborators [7]; however, now that we know neutrinos have non-zero masses, the correspondence between helicity and chirality is no longer exact.

It took just a few weeks in December 1956 for them to get the data; see *Figure* 7. You can see from the graphs, reproduced from the original paper, that the system warms up in about six minutes, after which the asymmetry vanishes.

During these six minutes, Wu and her collaborators found that the electron was preferentially emitted in a direction opposite to that of the magnetic field. The results were published in a seminal paper[11] as *Letters to the Editor* in *Physical Review* journal [1]. Wu's experiment unequivocally showed that the electron is preferentially emitted in a direction whence it has negative helicity and hence parity is violated in this weak interaction process. Also, as can be seen from the lower panel of *Figure* 7, when the polarisation of cobalt disappeared due to the warming up of the sample (as evidenced by the loss of gamma-ray anisotropy), the asymmetry in the direction of emission of the beta particles also disappeared. This clearly showed that the origin of asymmetry was indeed parity violation.

The results transformed the theoretical understanding of weak interactions. Eventually, the Fermi theory of beta decay was replaced by the more complete standard model of electromagnetic, weak and strong interactions, while incorporating this new under-

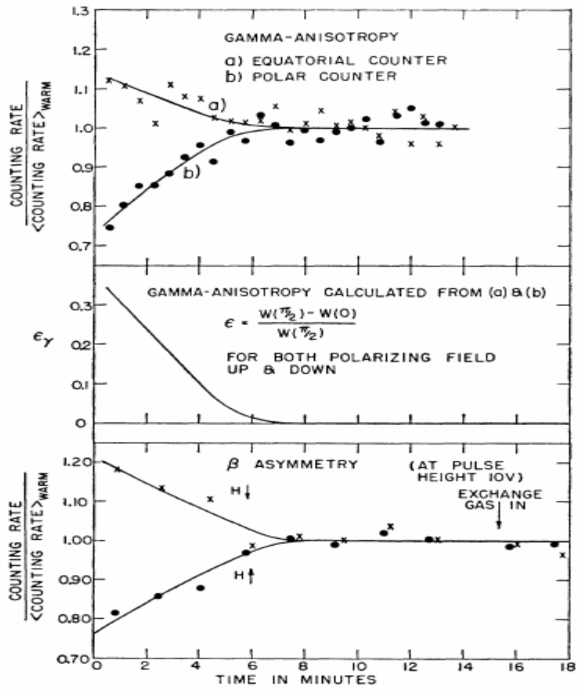



FIG. 2. Gamma anisotropy and beta asymmetry for polarizing field pointing up and pointing down.

**Figure 7.** Gamma and beta anisotropy as a function of time in minutes, showing the asymmetry in beta (electron) emission with respect to the magnetic field direction. (From the original paper [1])

standing[12] that parity is violated in weak interactions.

Interestingly, in the 1956 paper itself, Wu mentions[13] that, "According to Lee and Yang, the present experiment indicates not only that conservation of parity is violated but also that invariance under charge conjugation is violated." Also, Wu wrote in this paper, "Furthermore, the invariance under time reversal can also be decided from the momentum dependence of the asymmetry parameter $\beta$. This effect will be studied later." Here was an experimentalist who was aware of the various ramifications of the underlying theories of weak interactions.

[13]Lee and Yang were awarded the Nobel Prize the very next year for their theory of beta decay, but Wu, who helped them establish the correctness of the theory was never mentioned.

## 4. Wu and the CVC Hypothesis

It is not so easy to describe the details of the 'Conserved Vector Current' (CVC) hypothesis since it needs some technical information, and so we will provide only a brief outline. The starting point was Wu's experiment showing that parity was violated which led to a new (although still incomplete) formulation of the theory of weak interactions called the $V - A$ theory (to be read as $V$ minus $A$). This replaced Fermi's theory which did not include any parity violation.

### 4.1 *The $V - A$ Theory and CVC*

A very nice and readable review on the CVC hypothesis written by Wu herself can be found in [8] where she discusses the three independent theoretical approaches that led to the $V - A$ form of the weak interaction[14]. Here $V - A$ means that the weak interaction is due to a vector ($V$) and an axial-vector ($A$) interaction of equal and opposite strength (indicated by the negative sign between the two). In contrast, the electromagnetic and strong interactions are purely vector in type. It is the axial-vector part of the weak interaction that allows for parity violation. In her review paper, Wu contrasts the chirality invariance approach of Sudarshan and Marshak [9], the two-component formulation of Dirac spinors by Feynman and Gell-Mann [10], and the mass-reversal invariance hypothesis of Sakurai [11], all of which led to the $V-A$ theory.

[14]The $V - A$ theory led to the understanding of the nature of weak interactions which in turn paved the way for the modern standard model of particle physics.

Gerstein and Zeldovich, and later, Feynman and Gell-Mann, extended Fermi's theory into a more universal theory of weak interactions, and had hypothesised a conserved vector current (CVC) [12]. One of its predictions is that the 'vector' part of the $V - A$ weak interaction behaves 'similarly' to the electromagnetic interaction (which is a pure vector).

### 4.2 *CVC and Beta Decay*

A typical weak interaction process is nuclear beta decay, ${}_{Z}A \rightarrow {}_{Z+1}A + e + \overline{\nu}_e$ where $Z$ and $A$ represents the atomic number and mass number of the nucleus respectively. Normally, the interaction can proceed either through the vector ($V$) part of the weak interaction, or the axial-vector ($A$) part, or both.

An interesting effect occurs in the decay of $B^{12}$ and $N^{12}$. Both of them decay to $C^{12}$ via beta decay: $B^{12}$ decays to $C^{12}$ via $\beta^-$ (electron) while $N^{12}$ decays via $\beta^+$ (positron). The leading contribution in both cases comes from the axial vector ($A$) contribution, but the 'sub-leading term' has a contribution from the vector ($V$) part.

Gell-Mann pointed out [13] that the sub-leading correction factors are such that the shapes of the energy spectrum of the particles in the two decays are proportional to $1 \pm (8/3)\, aE$, where the plus sign is expected for $\beta^-$ and the minus sign for $\beta^+$ decay. Here $E$ is the energy of the beta particle, and $a$ is the constant to be measured in the experiment.

Now CVC relates the vector ($V$) part of the weak decay to the pure vector electromagnetic current. It uses this correspondence to predict that the correction term, $a$, arising purely from the vector ($V$) part can be estimated to be

$$a(B^{12}) - a(N^{12}) = (1.10 \pm 0.17)\% \text{ per MeV} . \qquad (1)$$

Remember that when CVC was hypothesised, the weak interaction was not well-understood, and the weak bosons ($W^{\pm}, Z^0$) had not been postulated, let alone discovered. The CVC hypothesis was an outcome of 'observations' regarding the strength of the weak interaction where only the vector part contributed. This observation was a key ingredient in going from the approximate $V - A$ theory to the correct theory of electroweak interactions[15]. Hence it was very important to establish the correctness of this hypothesis.

[15]Feynman has mentioned in his autobiography [14] that CVC was one of the greatest achievements he has been involved in.

Wu and her collaborators (Photograph in *Figure* 8), studied beta decay in $B^{12}$ and $N^{12}$ to establish the correctness of CVC.

In the experiments, which took several months to complete, proton beams from Columbia's Van de Graaff accelerator were transmitted through pipes to strike a 2 mm boron target at the entrance to a spectrometer chamber. They confirmed the CVC hypothesis by obtaining [15] a value of,

$$a(B^{12}) - a(N^{12}) = (1.19 \pm 0.24)\% \text{ per MeV} , \qquad (2)$$

**Figure 8.** The experiments of Columbia University physicists (left to right) Chien-Shiung Wu, Y K Lee, and L W Mo confirmed the theory of conservation of vector current. (Photo courtesy: Smithsonian Institute via *Wikimedia Commons*)

close to the prediction of CVC; see (1). In contrast, the old Fermi theory predicted a result of 0.10% per MeV, which is very far from the observed value. Although Wu and her collaborators were not the first to test CVC, their experiment was completed shortly after the other experiments, taking into account many experimental considerations.

We know that CVC is only approximate. However, in the standard model of particle physics, we will see that this close connection between electromagnetic and weak interactions remains and in fact, becomes a part of some exact symmetries.

We know that CVC is only approximate. However, in the standard model of particle physics, we will see that this close connection between electromagnetic and weak interactions remains and in fact, becomes a part of some exact symmetries. Without attempting to explain the details (the interested reader may read the contents of *Box* 1), we simply note that the 'full' theory of weak interactions is actually a proper unification of electromagnetic and weak interactions and is called the 'electroweak theory'. The seeds of this unification can be seen from the days of the CVC.

**Box 1. Some technical details about the CVC hypothesis**

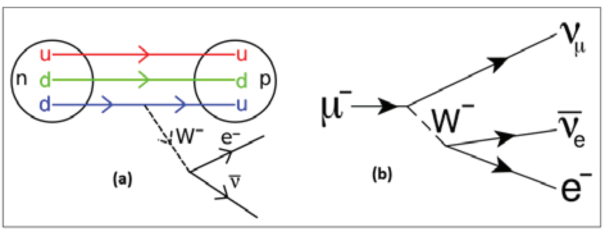
Let us assume that the electron (or quark) that interacts weakly (via $W^{\pm}$) can be represented by the weak $V - A$ current, $J^{\pm}_{\mu} = V^{\pm}_{\mu} - A^{\pm}_{\mu}$. Technically, CVC implies that $V^{\pm}_{\mu}$ and $j_{\mu}$ the electromagnetic current, are the three components of a vector $J^{i}_{\mu}$, $i = 1, 2, 3$, in a special internal space called isospin space.

In addition, all the components of this current are conserved, $\partial^{\mu} J^{i}_{\mu} = 0$, so that there are conserved 'isospin charges' associated with these currents. One of the consequences (see *Figure* a) of this hypothesis is the 'universality of coupling constants'. That is, consider the simplest case of neutron beta decay, $n \rightarrow p + e + \overline{\nu}_e$, where the $d$ quark in the neutron converts to a $u$ quark resulting in a proton. The interaction is mediated by a $W^-$ boson, as can be seen from the figure. Similarly the muon can decay to an electron via $\mu \rightarrow \nu_{\mu} + e + \overline{\nu}_e$, where $(\mu, \nu_{\mu})$ take on the roles (see *Figure* b) of $(d, u)$ in nuclear beta decay.

Now CVC implies that the coupling strength of the two interactions, one involving quarks, and the other involving leptons, is the same.

**Caveat**: It was found that not only does the $d$ quark 'decay' to the $u$ quark, i.e., $d \rightarrow u$, but we also have the strange quark contribution $s \rightarrow u$. Hence it can be regarded that there is a 'mixing' between the $d$ and $s$ quarks indicated by the Cabibbo mixing angle $\theta_c$. The correct statement is then that the coupling strength of the vector part of the interaction $n \rightarrow p$ (or equivalently $d \rightarrow u$), 'divided by $\cos\theta_c$', i.e., $V^{\pm}_{\mu} / \cos\theta_c$, must be the same as the electromagnetic case. This is expressed as the coupling strength $g_V$ (modulo $1/\cos\theta_c$ as mentioned above) in nuclear beta decay being equal to the coupling strength $g_{\mu}$ in muon decay.

The strengths of the interactions referred to above are called 'form factors'. Hence the CVC suggests that the weak vector form factors (divided by $\cos\theta_c$) are the same as the electromagnetic form factor.




## 5. Other Discoveries of C S Wu

In 1935, another famous physicist, Maria Goeppert-Mayer—the second woman to have been awarded the Nobel Prize after Marie Curie[16]—calculated the (very small) probability of simultaneous

[16]Marie Curie won Nobel Prizes in both Physics and Chemistry, the first person and only woman to do so.

emission of two electrons and two anti-neutrinos [16], the double beta decay ($2\beta$-decay). Wu and her collaborators conducted a series of experiments [17] on double beta decay in a salt mine under Lake Erie using Calcium ($Ca^{40}$) to study this very rare decay mode[17]. Unfortunately, they did not succeed, and it was only many years later, in 1987, that Michael Moe first discovered double beta decay using $Se^{82}$. However, Wu became an expert on beta decay. Her book with S Moszkowski called *Beta Decay* (published 1966) [18] was a standard reference on the subject for a very long time.

[17] Wu searched, unsuccessfully, for evidence for double beta decay.

Wu was also the first to confirm quantum results relevant to a pair of entangled photons as applicable to the Einstein-Podolsky-Rosen (EPR) paradox[18]. Her results confirmed Maurice Pryce and John Clive Ward's calculations on the correlation of the quantum polarizations of two photons propagating in opposite directions. She also studied magnetism and the Mössbauer effect during the 1960s. Later on, Wu also investigated the structure of haemoglobin to understand the causes of sickle-cell anaemia using advanced techniques in biophysics.

[18] Wu worked on entanglement and the EPR paradox.

## 6. Wu's Advocacy for Women in STEM

Wu retired from the University of Columbia in 1981, and devoted her time to educational programs in the People's Republic of China, Taiwan, and the United States. Due to various political constraints, she returned to China only in 1973, 37 years after leaving it in 1936.

Wu believed that scientific research and science education should complement each other: her practice in respect of various award monies that she won was to donate it for educational causes.

Wu believed that scientific research and science education should complement each other: her practice in respect of various award monies that she won was to donate it for educational causes.

She was a strong advocate for promoting girls in STEM (Science, Technology, Engineering, and Mathematics) and lectured widely to support this cause, becoming a role model for young women scientists everywhere. Wu tirelessly encouraged more women to pursue science. She said that it would be a "terrible waste of intrinsic talents" otherwise.

She said, "Men have always dominated the fields of science and technology. Look what an environmental mess we are in. They have pushed us to the brink of environmental disaster[19]. Air, lakes, rivers, and oceans have all been polluted." In a panel discussion on 'Women in Physics' in 1971, she quoted Rachel Carson, who warned about excessive use of DDT in her book, *The Silent Spring*. She mentioned Alice Hamilton, who raised the problem of occupational health, and Dr Frances Kelsey, who warned of the damage from thalidomide. She argued that the unique instinct of women, and their genuine concern, were exactly what society needed. She said , "The world would be a happier and safer place to live in if we had more women in science".

[19]Wu was concerned about environmental pollution and its effects on human health.

> The world would be a happier and safer place to live in if we had more women in science.
>
> – Chien-Shiung Wu

Chien-Shiung, whose name means "strong hero" in Chinese, was thus indeed a hero: passionate about her work with a strong love of science, and a role model to young men and women across the world, especially encouraging those interested in pursuing a career in science.

## Acknowledgements

I acknowledge material from various biographies on Chien-Shiung Wu that I have referenced below [19, 20, 21, 22]. The biography by Chiang Tsai-chien [19] is especially detailed. I also thank *Wikimedia Commons* as the source of several photographs. I thank K Indulekha, and the editors of this issue, Varsha Singh and Arti Kashyap, for giving me the opportunity to write this article, and M V N Murthy for comments and corrections. I also thank the referees for many crucial and relevant suggestions.

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