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CHIEN-SHIUNG WU
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A Biographical Memoir by
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Biographical Memoir

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CHIEN-SHIUNG WU

May 31, 1912–February 16, 1997

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CHIEN-SHIUNG WU ranks as one of the foremost physicists of the 20th century. Her pioneering and definitive work on beta decay and parity nonconservation provided major, unambiguous experimental tests of new and fundamental paradigms and models of subatomic physics.

Chien-Shiung Wu was born on May 31, 1912, in Liu He, a small town near Shanghai, China. Her parents, Zhong-Yi Wu and Funhua Fan, provided a warm, happy, and nurturing home where education and learning were of utmost importance. She had an older and a younger brother to whom she was also quite close. Her grandfather Yi-Feng Wu had been a junior scholar in the National Civil Service Examinations System. He was at first more interested in his male heirs but he soon recognized Chien Shiung's vivid imagination and great intelligence and stimulated and supported her curiosity. Her father, an engineer by training, founded and served as headmaster of one of the first schools admitting girls in China, the Ming De School. He had been involved in political activities in 1909-1912 that led to the founding of the Republic of China. He stimulated his daughter's natural curiosity with the science and mathematics books and news from the outside world that he brought home. These were complemented by substantial discussions of ideas of freedom and justice. Zhong-Yi Wu encouraged his daughter to study on her own. His impact on Chien-Shiung's intellectual development was profound.

Miss Wu attended this school until 1923, at which time she left home to transfer to a boarding school, the Soochow School for Girls. She enrolled in the Normal School program, which led to a teaching career. The Normal School was a famous school where renowned scholars from China and abroad lectured. The curriculum emphasized classical humanities and writing. Chien-Shiung wrote well and was an excellent student, but she really was interested in mathematics, physics, and chemistry. She borrowed books from her friends who attended the regular high school program and worked through these subjects at night.

After her graduation from the Soochow School for Girls in 1929, she attended the Shanghai Gong Xue (Public School) for one year. The president of Shanghai Gong Xue was Professor Shi Hu. Professor Hu was a world-renowned Chinese scholar, with whom Chien-Shiung Wu was in constant touch and developed a long-standing student-teacher relationship until his passing away in 1962 in Taiwan. It is probably fair to say that her father, Zhong-Yi Wu, and Professor Shi Hu were the two most influential people in her life.

In 1930 Chien-Shiung Wu enrolled at the school later known as the National Central University in Nanjing. She originally majored in mathematics but switched to physics in the second year. Those were years of great physics developments in Europe and it is clear that news of the extraordinary discoveries had reached the campus. Wu was attracted to the challenge modern physics presented. Among others she was aware of the accomplishments of the woman, Marie Curie, who became the role model for generations of young women interested in physics.

A rarely mentioned aspect of her life between 1930 and 1934 concerns her activities as a student leader. China was undergoing considerable unrest due mainly to the humiliating Japanese invasion of Manchuria in 1931 followed by many more "incidents" aimed at destabilizing the government. Actually she was more interested in her academic work but she was chosen by her colleagues as their leader because they felt the authorities would have trouble dismissing her, one of the best students, from the university. She led several demonstrations, but on the whole she kept a low profile. Nevertheless, these events weighed heavily on her as she related them to me in the middle of the night during long experiments in the Columbia Pupin Physics Laboratory in the early 1950s, long before the student demonstrations against the Vietnam War in the late 1960s. She graduated in 1934 with top honors at the head of her class with a B.S. degree.

She taught for a year at the National Chekiang (Zhejiang) University in Hangzhou, but most importantly, she was asked to work as well in a physics laboratory at the Academia Sinica. She carried out her first experimental research in X-ray crystallography (1935-1936) under the mentorship of a female professor, Jing-Wei Gu, who had just returned from the United States.

Chien-Shiung Wu, encouraged by Prof. Gu and with financial help from her uncle, was able to come to the United States in 1936 to pursue graduate studies at the University of Michigan. However, upon her arrival she first visited the University of California at Berkeley, where she met another Chinese physics student, Luke Chia Yuan, who escorted her around campus. Luke introduced her to Professor Ernest Lawrence, who immediately, recognizing Miss Wu's intelligence and dedication, encouraged her to stay at Berkeley and pursue a Ph.D. In addition, she had also heard that the

University of Michigan at that time did not accept women in the student union; the decision to stay at Berkeley was made easily.

Miss Wu's official adviser was Professor Lawrence, but she actually worked under the direct supervision of Professor Emilio Segré. Her success hinged on her considerable skill in developing the appropriate instrumentation to carry out accurate measurements.

Her Ph.D. thesis in 1940 involved studies of fission products of uranium, a topic of major interest at the time. In particular, her identification of two Xe isotopes and the determination of their lifetime and decay properties earned her wide recognition sometime later during the war years. The development of nuclear piles depended critically on the knowledge and avoidance of materials that would poison and shut off the reactors. Enrico Fermi had been asked to explain why the Hanford reactor was shutting down and starting again with some time delay. He thought that Miss Wu's work with the Xe isotopes might lead to an understanding of this effect. Indeed, when she was asked to comment, it became clear to her that ^{135}Xe had a huge affinity for neutron capture and a short lifetime. Shortly after its production, the ^{135}Xe produced in the fission of U absorbed the free neutrons that were required to maintain a chain reaction. After some time, most of ^{135}Xe would decay allowing the reactor to resume operation. Her very careful work on ^{135}Xe identified this isotope as the culprit in the reactor malfunction and made it possible to devise techniques to better control the operation of reactors.

She wanted to stay at Berkeley after completion of her Ph.D., but at that time major research-oriented U.S. universities were reluctant to hire women, Jews, Asians, or people of color in a tenure-track professorial position. But in 1942 the nation was at war, most physicists were engaged in the war effort, and young men were at the front. Chien-Shiung Wu accepted an offer of a teaching position at Smith College, a women's institution on the East Coast. Luke Yuan had received his Ph.D. from the California Institute of Technology in 1937 and an appointment at RCA in Princeton in 1942 to work on radar development. Luke and Chien-Shiung married and moved East together.

Although Smith College was very supportive, it did not have a research infrastructure, which Chien-Shiung missed thoroughly. In order to live closer to Luke she left Smith in 1943 and accepted an offer from Princeton University as the first female instructor ever hired on the faculty. But she really needed to work in a laboratory. She was invited to join the Manhattan District Project at Columbia University in March 1944 as a senior scientist. She moved to New York and returned to Princeton on weekends. By 1946 Luke was working as a research associate at Princeton University. Their son Vincent (Wei-Cheng Yuan) was born in Princeton in 1947.

The rest of her career was spent in the Department of Physics at Columbia, an institution to which she was deeply loyal, even though full recognition of her accomplishments came very late in her career. At Columbia she first worked on gaseous diffusion processes for mass separation of uranium, and later on measurements by time-of-flight techniques of the energy dependence of neutron reaction cross-sections.

The end of the war in 1945 allowed her to finally take the direction of her career in her own hands and to focus on a problem that was to make significant advances in our understanding of nature. Chen Ning Yang described well Wu's approach to science: "If you choose the right problem you get important results that transform our perception of the underlying structure of the Universe." The observation of electrons, or beta particles, emitted from radioactive nuclei with a continuous energy spectrum confounded the community, as it appeared that energy was not conserved in this decay. In order for Enrico Fermi to present a scenario that agreed with the observations, it took many years of experimental work by Charles D. Ellis and Lise Meitner, among others; the discovery of the neutron; and finally a bold proposal by Wolfgang Pauli. Pauli postulated in 1930 that not one but two particles were emitted in beta decay: the electron and another neutral particle. This particle was assumed to have remarkable properties, namely, it was massless, had spin just like protons and electrons, but barely interacted with matter. In fact, this particle was not actually detected until 1956. The idea was received with skepticism, but by 1932 when James Chadwick discovered the neutron, the existence of this elusive particle became more acceptable. Fermi, in 1933, outlined a theory to describe the beta decay process. This approach took account of the new particle, which Fermi named the "neutrino," and a new force called the "weak interaction" responsible for the decay. The understanding of the weak interaction and the nature of the neutrino became Chien-Shiung Wu's lifelong commitment.

Fermi's theory predicted a very specific shape for the energy spectrum of the electrons emitted in beta decay. By 1945 the existing experiments disagreed with Fermi's theory, again causing some turmoil in the physics community, leading to revised theories that were far less elegant than Fermi's. Chien-Shiung Wu, however, quickly understood the experimental problems. She realized that electrons emitted from thick targets scattered upon exiting the target and entered the spectrometer with lower energy. She also realized that previous experimentalists had used magnetic spectrometers with iron cores that produced hysteresis effects and hence recorded wrong values for the magnetic field. She found at Columbia an old iron-free solenoid spectrometer that had been built before the war. She developed techniques to prepare ever thinner targets so as to continuously reduce the expected scattering. She thus measured with exquisite precision, the shapes of the electron spectra down to very low energies, and found perfect agreement with Fermi's theory. These experiments settled all theoretical and experimental disagreements. She investigated different types of beta decay, the so-called "allowed" and "forbidden" transitions, and showed unambiguously that the Fermi theory of beta decay was correct in all its details.

These experiments brought her worldwide recognition. She was now poised to handle the next challenge. It came in the form of a puzzle in particle physics that was the dominant subject of discussion at the April 1956 Rochester conference on high-energy physics. Two of the newly discovered particles, the θ and τ, had the same mass, spin, and lifetime, and yet one decayed into two pions while the other decayed into three pions. These two decay modes were of opposite parity, meaning that parity was not conserved, further implying that reflection symmetry was not obeyed. This symmetry, a property of physical systems obeyed in all the observed interactions studied up to that time, requires that a mirror image of a process, obtained by reversing all directions and velocities, be identical to the original process. The τ-θ puzzle led Professor Tsung Dao Lee at Columbia to review the data presented by Professor Jack Steinberger's group at Columbia on the production and decay of strange particles. The idea that parity might not be a good quantum number was raised, and Professor Lee suggested that the data be plotted over the whole 360° space. Unfortunately, the statistics of these early data were not sufficient to establish an unambiguous conclusion concerning the validity of parity in these reactions.

Back at Columbia, Professor Lee and Professor Yang at the Institute for Advanced Study, with whom he collaborated, recognized a vital point. They noted that while the experimental evidence was consistent with the concept of parity symmetry in the production process of these particles, a strong interaction process, the validity of that symmetry had not been probed in the particles' decay via weak interactions. The best and well studied examples of weak interaction decays were to be found in beta decay processes. However, the most accurate studies of beta decay, carried out by Wu in the previous years, only considered the description of the exact shape of the electron spectrum as a function of energy. Such spectra would not display a term related to parity. What needed to be measured was a pseudoscalar quantity involving the product of a spin and momentum.

T. D. Lee immediately sought the advice of Chien-Shiung Wu, the undisputed leading experimentalist in beta decay and weak interaction physics. It became obvious from a thorough literature search that there was no evidence whatsoever for parity conservation or nonconservation in weak interactions. The question of what experiment to do to investigate this problem was very quickly answered by Wu. She realized that the beta decay of ^{60}Co, a nucleus whose spin could be polarized in a well determined direction with respect to the emission of its electrons, would be a perfect candidate for this study. She had confirmed Fermi's theory describing the decay, was aware of the different forms of the weak interaction possible in different nuclei, and knew to select a case where the spins of the parent and daughter nuclei corresponded to a single interaction in the decay, namely, the Gamow-Teller interaction. This situation would lead to a simple decay pattern dominated by only one matrix element, free of interference terms and would yield an unambiguous result. ^{60}Co was the choice nucleus.

Chien-Shiung Wu then designed the experiment that would test directly the parity symmetry principle in the weak interaction. The ^{60}Co nuclei had to be polarized, that is, they had to be assembled in such a form that the nuclear spins were predominantly directed along a direction provided by an external magnetic field. This situation prevailed at very low temperatures, a physics subfield in which Wu was not an expert. It had been known that ^{60}Co could be polarized by embedding the radioactive nuclei in a cerium magnesium (cobalt) nitrate crystal kept at 0.01K. In this crystal unpaired electrons, polarized by modest external magnetic fields, cause very large (100T) magnetic fields at the position of the paramagnetic Co ions, thus polarizing the ions.

Wu formed collaborations with the experts in low-temperature spin polarization at the National Bureau of Standards in Washington: Ernest Ambler, Raymond W. Hayward, Dale D. Hoppes, and Ralph P. Hudson. Together they assembled an apparatus in a cryostat in which the source was kept at a low temperature, and the temperature was measured by gamma-ray detectors placed outside the cryostat at around 90° and close to 0°. The electrons were detected in an anthracene crystal attached to a 4-foot-long light pipe that guided the signal to a photomultiplier tube located outside the cryostat and the polarizing magnetic field. The gamma-ray anisotropy provided a measure of the sample polarization. Thus, they could measure the forward/backward asymmetry of electron emission by reversing the polarizing field.

Again, in this instance as in many cases in her work, Wu contributed a crucial element to the experiment, namely, the overall vision of what experiment needed to be carried out, as well as the essential details, such as the large crystals of paramagnetic salts necessary for the polarization of the ^{60}Co nuclei. She spent the summer of 1956 testing various aspects of the measurement, which involved a complex array of low-temperature techniques and detectors that would operate at low temperature and in magnetic fields.

Finally, by the end of December 1956, a large effect was observed, was found to be reproducible, and rang the death knell for the concept of parity conservation in weak interactions. The historic paper (1957) describing this work, "Experimental Test of Parity Conservation in Beta Decay," has become a classic.

At the same time but after the magnitude of the effect had been ascertained, Leon Lederman, Richard Garwin, and Marcel Weinrich at the Columbia Nevis cyclotron laboratory were able to detect the asymmetry in muon decay, confirming the universality of the concept of parity nonconservation in weak decays other than beta decay. A similar experiment was carried out by Valentine Telegdi and Jerome Friedman in Chicago in an experiment involving photographic emulsions.

The implications of the National Bureau of Standards experiment went much beyond the notion of parity conservation. The asymmetry effect implies that not only the conservation of parity is violated but also that the invariance under charge conjugation is violated as well. The magnitude of the effect also required that violation of time reversal symmetry, if any, must be relatively small.

These investigations, together with the theoretical underpinning provided by Lee, Yang, and colleagues, opened up a whole new world of physics centered on the two-component nature of the neutrino, which is still at the core of research efforts today. These events, coupled with corrections of mistakes in older experiments, firmly confirmed the final formulation of the Fermi theory of beta decay based on the vector-axial vector (V-A) form of the weak interactions.

Wolfgang Pauli, who originally postulated the existence of the neutrino, was skeptical of the whole idea of breaking down the notion of parity conservation in weak interactions and thought these ideas were only "mathematical play." Nevertheless, he yielded to the experimental evidence and wrote in a letter dated January 19, 1957, to Wu: "I congratulate you (to the contrary of myself)." For Wu, experiment was quintessential to describe nature: "It is the courage to doubt what has long been believed and the incessant search for verification and proof that pushes the wheels of science forward."

Wu's beautiful and definitive work on beta decay established the Fermi theory of weak interactions. The elegant and momentous experiment that established the nonconservation of parity and the violation of particle-antiparticle charge conjugation symmetry in physics altered forever our view of the Universe. As T. D. Lee described her and her work, "C. S. Wu was one of the giants of physics. In the field of beta-decay, she had no equal."

Contrary to other scientists who somehow slow down after such a major accomplishment, Wu's drive did not abate. She continued her studies of fundamental processes. In 1958 Feynman and Gell-Mann published a paper entitled "Theory of Fermi Interaction" that noted the similarity between beta-decay and muon decay. Their hypothesis, called the "Conserved Vector Current" (CVC), was based on a universal form of the Fermi interaction. Furthermore, there was an analogy between the weak vector interaction form factor and the electromagnetic form factors. These theorists urged Wu to explore its validity with a beta decay experiment that compared the beta decays of ^{12}B and of ^{12}N to the electromagnetic transition in ^{12}C corresponding to states within the same isotopic triplet.

The experiment was difficult and, before she started, Wu wanted to make sure that all theoretical corrections were well understood. She carried out this experiment in 1963 at Columbia together with Luke Mo and other students. She measured with great accuracy the shape difference in the two decays and showed that the measured shape factors agreed extremely well with that predicted by theory. This experiment displayed the phenomenon known as “weak magnetism,” confirmed the symmetry between the weak and the electromagnetic currents, and laid the cornerstone for the unification of these two basic forces into the electroweak force.

But her interest in the nature of the neutrino was as keen as ever and led her to yet more difficult experiments. Double beta decay is a process where either two neutrinos or none are emitted, depending on their characteristics. These are very low-yield experiments, but she was able to carry out new measurements on ^{48}Ca and ^{82}Se that lowered the upper limit for the occurrence of this process below anything achieved until that time.

She began to work in larger collaborations to examine the radiations of “exotic” atoms with muons or pions replacing electrons in order to determine nuclear charge radii with higher accuracy than previously measured. However, she definitely liked working in her laboratory with a small group of students better than in the burgeoning teams that are the standard today for work at large accelerators. She used new techniques, such as the Mössbauer effect, to further study time reversal invariance. With that apparatus operated at very low temperatures she conducted research in condensed-matter physics through the examination of magnetic transitions and relaxation effects in materials, and finally explored a current problem in biology, the structure of hemoglobin in sickle cell anemia.

In later years, especially after her retirement in 1981, she devoted much effort to educational programs in both the People's Republic of China and Taiwan as well as to the development of new facilities, such as synchrotron radiation light sources.

Chien-Shiung Wu was frequently honored and received many awards. She was promoted to an associate professorship at Columbia in 1952, the first woman to hold a tenured faculty position in the physics department, and a full professorship in 1958. She was appointed the first Michael I. Pupin Professor of Physics in 1973.

She was elected to the National Academy of Sciences (1958). She was honored with the National Medal of Science (1975) and was the first recipient of the prestigious Wolf Prize awarded by the State of Israel (1978). She received the Research Corporation Award (1958) and the John Price Wetherill Medal of the Franklin Institute (1962). Many distinguished honors followed, most notably the Cyrus B. Comstock Award (1964) and the Tom Bonner Prize of the American Physical Society (1975). She was inducted in 1998 into the American National Women's Hall of Fame. She was awarded many honorary degrees, but the first one that she truly appreciated was a Sc.D. from Princeton University (1958), awarded for the first time to a woman. Among other distinguished honorary degrees she received an honorary Sc.D. in the famous Galileo Galilei Aula Magna at the University of Padua in 1984. She was the first woman to serve as president of the American Physical Society (1975).

Chien-Shiung Wu was totally focused on her work. Wolfgang Pauli, in a letter to his sister after traveling with Chien-Shiung to Israel by plane in 1957, described her quite accurately: "Frau Wu is as obsessed with physics as I was in my young years." Wu became a trailblazer for women and joined Marie Curie and Lise Meitner as the role model for future generations of aspiring female physicists.

Beauty and aesthetics defined her work, her demeanor, her relationship with family, friends, and students. Together with her total devotion to physics, she was aware of her image and respectful of her Chinese origins. She dressed very elegantly, wearing *qipao* dresses most of her life, making her dresses herself when the supply from China withered during the years when China was closed to the outside world. She was proud of the intellectual development of her son, Vincent, who as a physicist also worked in parity nonconservation in compound nuclei and of the academic achievements of her granddaughter, Jada. She taught and nurtured about 33 graduate students whom she considered her extended family and many visiting scientists and postdoctoral fellows.

Chien-Shiung Wu died in New York following a stroke on February 16, 1997. Her ashes were taken to China to rest at the Ming De School in a characteristically elegant memorial site designed by Professor T. D. Lee. Her remarkable life can be portrayed by an ancient Chinese poem by Qu Yuan (ca. 340-278 BCE): "Although the road is long and arduous, I am determined to explore its entire length."

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