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Chien-Shiung Wu's trailblazing experiments in particle physics

Chon-Fai Kam, Cheng-Ning Zhang, and Da Hsuan Feng

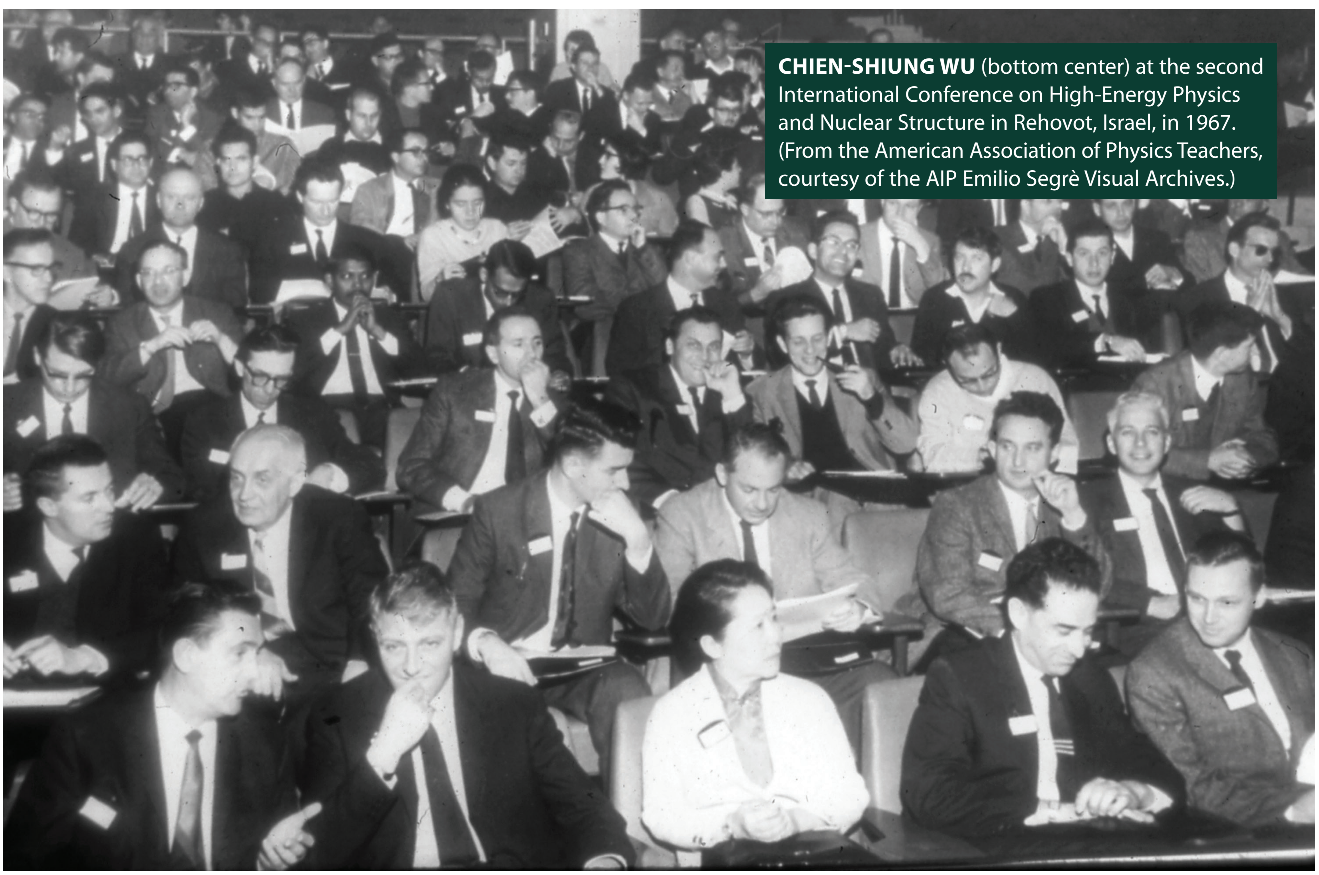
The Chinese American physicist led groundbreaking experiments that demonstrated parity violation and photon entanglement. Many in the physics community say Wu deserved more accolades in her lifetime.

The US Postal Service in 2021 released a commemorative stamp honoring a woman from China named Chien-Shiung Wu, a nuclear physicist who played a crucial role in the Manhattan Project. That brought her into the exclusive ranks of physicists, including Albert Einstein, Enrico Fermi, and Richard Feynman, who have been celebrated by the USPS. It also brought renewed attention to the ways that Wu's career and work have not always received the recognition and acclaim they deserve.

For the Manhattan Project, Wu worked on the process of separating isotopes of uranium-235 and uranium-238 by gaseous diffusion; the process was later scaled up at the K-25 plant in Oak Ridge, Tennessee. She also refined Geiger counters to better measure nuclear radiation levels. She is thought to be the sole Chinese individual involved in the Manhattan Project.[1,2]

Wu's expertise in neutron absorption cross sections made a lasting impression on J. Robert Oppenheimer, the head of the Manhattan Project; he had been a member of her doctoral committee in 1940 at the University of California, Berkeley. Oppenheimer affectionately referred to her as *Jiejie*, meaning elder sister in Chinese.[3]

In celebration of Wu's legacy, the USPS released her commemorative stamp on 11 February 2021, the International Day of Women and Girls in Science. Wu worked more than 40 years in the male-dominated physics field and became adept at testing fundamental physics theories through pre-



CHIEN-SHIUNG WU (bottom center) at the second International Conference on High-Energy Physics and Nuclear Structure in Rehovot, Israel, in 1967. (From the American Association of Physics Teachers, courtesy of the AIP Emilio Segrè Visual Archives.)

WU ASSEMBLING AN ELECTROSTATIC GENERATOR at the Smith College physics laboratory, circa 1942. (Courtesy of the AIP Emilio Segrè Visual Archives.)

cise experiments.[4] Her highly classified work significantly advanced the process of splitting and harnessing the power of uranium atoms and ultimately contributed to the creation of the world's first atomic bomb.[5]

But that is not the end of the story; it's not even the beginning.

Broken mirror

Wu gained international recognition for her experiment confirming the theory that earned the 1957 Nobel Prize in Physics for its authors, Tsung-Dao Lee of Columbia University and Chen Ning Yang of the Institute for Advanced Study in Princeton, New Jersey.[6] The year before, the two young Chinese theoretical physicists proposed the idea that parity symmetry in weak interactions might not be obeyed in the natural world. Wu, with her outstanding influence and extraordinary talent in the fields of experimental physics and beta decay, led a team of scientists from Columbia and the National Bureau of Standards in Washington, DC, to test the groundbreaking prediction by Lee and Yang.

The experiment, which Wu conducted in late 1956 and early 1957, measured whether an equal number of beta particles are emitted by radioactive cobalt-60 nuclei in the direction of their spin and in the opposite direction. She found that far more beta particles flew off in the direction opposite the spin of the nuclei, thus shaking the conventional understanding of symmetry in the physical world (see the illustration on page 34). The experiment revealed that a fundamental particle and its mirror image are not always identical.[7] The universe, at times, can distinguish between left and right.

The experimental verification by Wu and her collaborators of the theoretical proposal of parity violation by Lee and Yang resulted in the Nobel Prize being awarded to the two theorists. But the accolade eluded Wu. This was a case in which the typical pattern of favoring experimentalists for the prize was flipped.

Less well known until recently are Wu's groundbreaking contributions to the foundations of quantum mechanics.

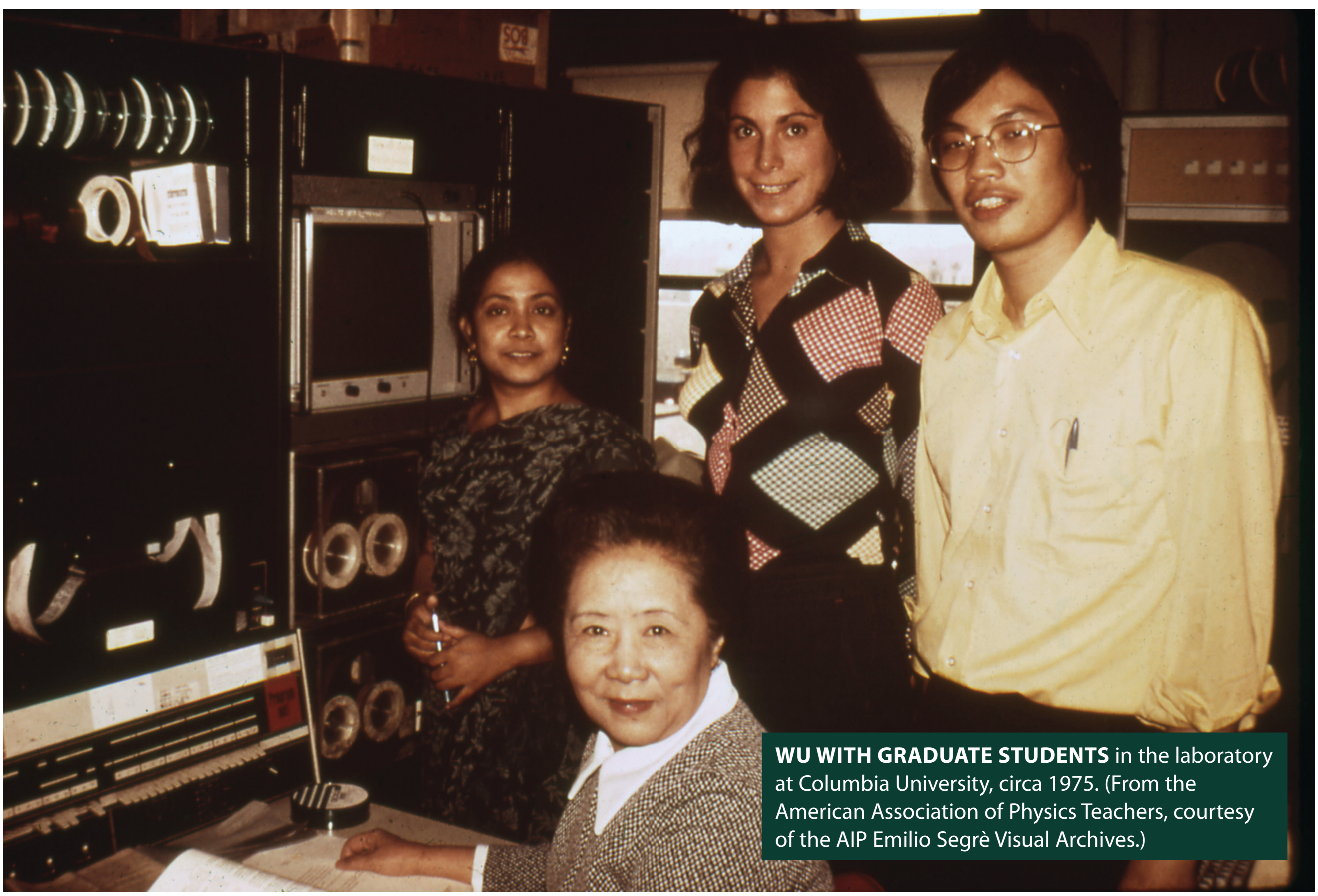
At a September 2022 gathering outside Washington, DC, to commemorate Wu and the 110th anniversary of her birth,[8] Lars Brink, who was a member of the Nobel Committee for Physics for several years between 2001 and 2013 and served as its chair in 2013, said he believed that Wu's parity violation experiment was "Nobel class." He reported that Yang had once told him at a dinner that Wu should have been a corecipient of the 1957 prize.

Going further, Brink said that the parity violation experiment was just one of what he called Wu's "two gems in a box of pearls." The second gem, though lesser known in the scientific community, revolves around an inaugural experimental validation of photon entanglement that Wu conducted in 1949.[9] Despite the introduction of the idea of quantum entanglement in the 1930s, the research community's focus on particle physics meant that only intermittent attention was paid to the topic until later in the 20th century. In recent decades, quantum entanglement has emerged as the cornerstone of the burgeoning fields of quantum information, quantum computation, and quantum technology.

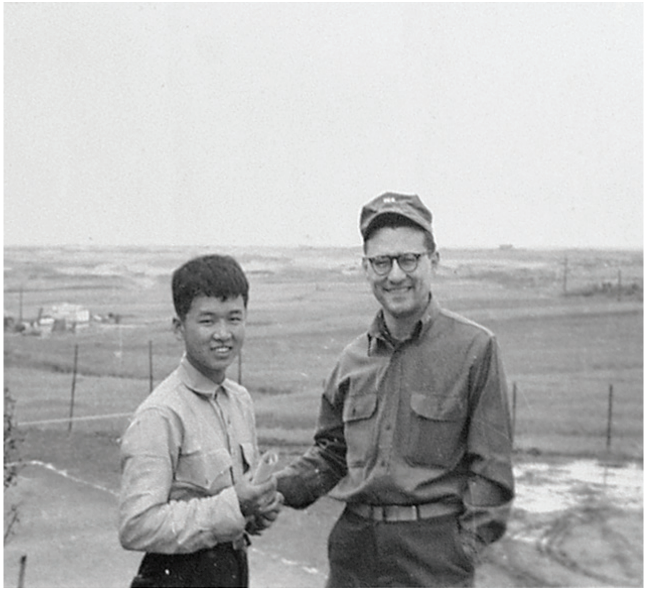
Early entanglement

The concept of quantum entanglement was brought to light in May 1935 by Einstein, Boris Podolsky, and Nathan Rosen, who were all at the Institute for Advanced Study at the time. Their groundbreaking paper, "Can quantum-mechanical description of physical reality be considered complete?," delved into the novel idea.[10] In that influential work, later dubbed the EPR paper, the trio investigated a pair of particles deliberately prepared with a separation far exceeding the range of their mutual interaction and with a total momentum of zero. Their exploration revealed a dilemma: There is an inherent inconsistency among locality, separability, and completeness when describing physical systems with wavefunctions.

The EPR paper asserts that by measuring the position of the first particle without disturbing the second, it should be possible to predict with certainty the value of the second particle's position because of the perfectly correlated positions of the particle pair. On the other hand, by performing a measurement of the first particle's momentum rather than position, it should be possible to predict with certainty the value of the second particle's momentum because of the perfectly anticorrelated momenta of the particle pair. The uncer-



WU WITH GRADUATE STUDENTS in the laboratory at Columbia University, circa 1975. (From the American Association of Physics Teachers, courtesy of the AIP Emilio Segrè Visual Archives.)



IRVING SHAKNOV (**left**, wearing cap), a graduate student of Chien-Shiung Wu, earned a Bronze Star for valor in World War II. After completing his PhD, he joined the Operations Evaluation Group, a military service agency to the US Navy. He was killed in the Korean War on the night of 14 May 1952, at the age of 30. (Center for Naval Analyses, "Irving Shaknov: A Singular Life," https://www.cna.org/about-us/research/history/irving-shaknov-a-singular-life.) **LARS BRINK (right)**, a theoretical physicist at Chalmers University of Technology in Sweden, served as a member of the Nobel Prize Committee for Physics and was its chair in 2013. He gave a lecture about Chien-Shiung Wu's Nobel-worthy experiments just one month before he died in October 2022. (Alex Ljungdahl © Nobel Outreach AB 2013.)

tainty principle in quantum mechanics, however, prevents the precise attribution of values to both the position and momentum of a single particle.

The EPR dilemma thus forces the conclusion that the quantum mechanical description of physical reality given by wavefunctions is not complete if one insists that the real states of spatially separated objects are independent of each other. The key in the EPR thought experiment is a nonfactorizable wavefunction describing two particles moving away from each other into spatially separated regions and yet always having perfectly correlated positions and anticorrelated momenta. Here, nonfactorizable means that a wavefunction cannot be expressed as a simple product of the wavefunctions of its local constituents. The peculiar property of composite quantum systems, characterized by a nonfactorizable wavefunction, is now recognized as quantum entanglement.

But these are merely philosophical deliberations based on thought experiments. During World War II, physicists' interests were predominantly drawn to the mechanism of nuclear fission. It wasn't until October 1946, 11 years after the EPR paper, that John Wheeler, back at Princeton University after working on the Manhattan Project, outlined an experiment to test proposals about quantum electrodynamics that were made by Paul Dirac in the 1930s.

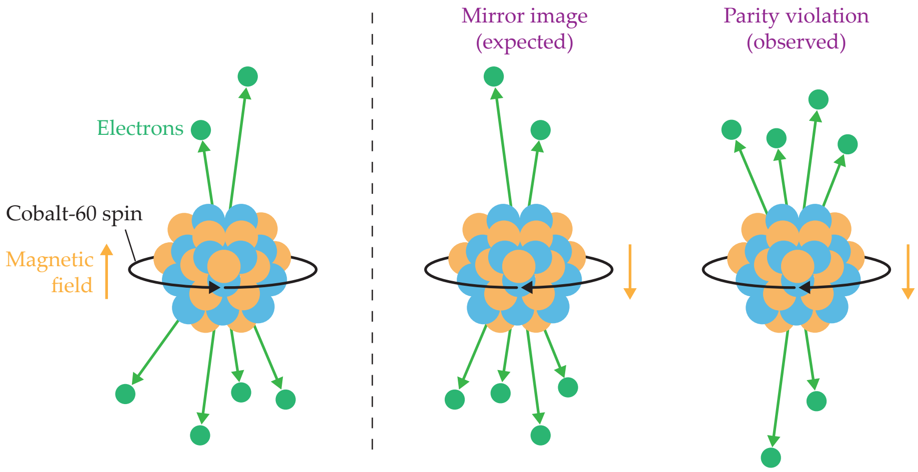
In a paper titled "Polyelectrons," Wheeler considered positronium, an unstable hydrogen-like system composed of an electron and a positron.[11] His proposal involved the detection of an entangled pair of gamma-ray photons produced by the annihilation of the electron and positron. Wheeler highlighted that the gamma-ray photons mainly come from the spin-singlet state—a quantum state characterized by antiparallel spins and a total angular momentum of zero. The conservation of total angular momentum requires that the gamma-ray photons head in opposite directions with orthogonal linear polarizations.

Intriguingly, spatially extended unbound singlet states are exactly what Einstein, Podolsky, and Rosen proposed in their thought experiment to illustrate the incompleteness of quantum theory. To measure the entangled gamma-ray photons experimentally, Wheeler proposed that the photons each undergo Compton scattering by collision with electrons and then be individually detected. Coincident detections would indicate that the two gamma-ray photons were generated from the same annihilation event.

Each scattering event can be described by a scattering angle relative to the photon's initial trajectory and by an azimuthal scattering direction. Although the scattering angles of a gamma-ray pair may be identical, the scattering directions can be parallel or perpendicular. Wheeler proposed studying the asymmetry between the probabilities of the two relative directions for a given scattering angle by calculating the ratio between the difference and the sum of the probabilities. That proposal quickly inspired two independent groups to conduct more detailed computations.

QED

British physicist Maurice Pryce, with Oxford University, and his PhD student John Clive Ward authored a June 1947 paper



PARITY VIOLATION was demonstrated in an experiment led by Chien-Shiung Wu.[7] She and her colleagues measured the emission of beta-decay electrons from cobalt-60 nuclei polarized in an applied magnetic field. If the weak interaction conserved parity, then the direction of electron emission should be independent of the direction of the nuclear spin. The observation of a dependence on the polarization direction of the nuclei confirmed the theory that weak interactions do not obey mirror symmetry.

exploring the angular correlation effects of annihilation radiation.[12] Five months later, three physicists from Brookhaven National Laboratory—Hartland Snyder, renowned for collaborating with Oppenheimer on the initial theoretical analysis of stellar collapse into black holes, Simon Pasternack, and John Hornbostel—published a paper that explored the same topic.[13] Both research groups found that the maximum asymmetry ratio is 2.85 and occurs when the scattering angle is 82°.

Wu seized the historical opportunity. In November 1949, Wu and her graduate student Irving Shaknov conducted photon measurement experiments in the basement of Columbia's Pupin Hall to verify the theoretically predicted angular correlations of entangled gamma-ray photons.

In the underground laboratory, Wu and Shaknov used accelerated deuterium nuclei to bombard copper foil and produced unstable copper-64 nuclei. The isotope undergoes beta decay, generating positrons that annihilate with nearby electrons and produce pairs of gamma photons moving in opposite directions. In the experiment, Wu and Shaknov loaded ^{64}Cu nuclei into an 8-millimeter-long microcavity and used two sets of gamma-ray detector systems composed of photomultiplier tubes and anthracene crystal scintillators (see the illustration on page 35).

Intriguingly, Wu was not the first to try to verify Wheeler's prediction on angular correlation. Ernst Bleuler and Helmut Bradt at Purdue University had already observed the angular correlation between a pair of gamma-ray photons.[14] As they reported in an April 1948 letter to *Physical Review*, they found an asymmetry ratio of 2.1 ± 0.64 at a scattering angle of 90°, but the large margin of error meant that the experiment provided insufficient evidence to validate or refute the theory. In August 1948, R. C. Hanna, at the Cavendish Laboratory in the UK, concluded from similar experiments that the asymmetry ratios observed are systematically smaller than what theory predicts.[15]

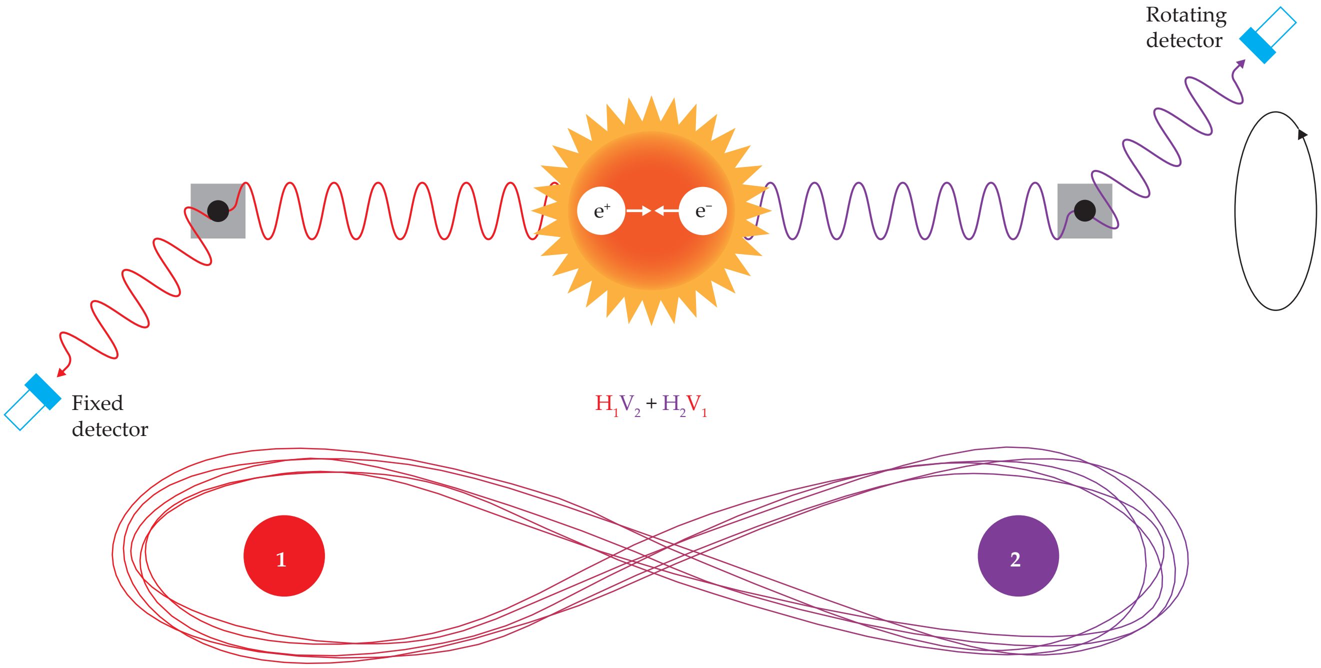
But Wu stood among the foremost experimentalists of her time, known for her ingenious and precise designs. Aiming to eliminate potential experimental errors in her angular correlation measurements, she maintained one detector in a fixed position and oriented the second at four different positions, with relative azimuthal angles of 0°, 90°, 180°, and 270°. Subsequently, the second detector was fixed, and the first one was rotated. The entire measurement process spanned a continuous period of 30 hours.

Finally, on 1 January 1950, Wu and Shaknov published their experimental results as a letter of less than 1000 words.[16] The asymmetry ratio reported by Wu and Shaknov is 2.04 ± 0.08; the theoretical prediction is 2.00. With the satisfactory agreement of their result and the theoretical predictions, the experiment marked the first conclusive verification of photon entanglement, nearly 15 years after the publication of the EPR paper.

Bell inequalities

Building on the EPR paradox, John Bell published a landmark 1964 paper in which he introduced the famous eponymous Bell's theorem. That work demonstrated that for certain measurements, no local hidden-variable theories could explain the predictions of quantum mechanics; it thus provides a foundation for experimental tests of quantum entanglement. Inspired by Bell's work, John Clausen, while working as a postdoc at the University of California, Berkeley, designed and carried out experimental tests of Bell's theorem. A visit by Clauser to Columbia in 1975 reignited Wu's interest in the angular correlation of high-energy gamma-ray photons, which could be used to test the inequality at the heart of Bell's theorem.

Together with her graduate students Leonard Kasday and John Ullman, Wu conducted a new experiment on the angular distribution of Compton-scattered photons. One detector in the experiment could be set to arbitrary azimuth angles with respect to a second, fixed detector. The researchers concluded that if the polarization of the high-energy photons could be perfectly detected, their results would violate Bell's inequality and thus provide direct evidence against the exis-



IN THEIR 1949 EXPERIMENT, Chien-Shiung Wu and Irving Shaknov used copper-64 as a source for positrons, which collide with electrons to generate two gamma-ray photons polarized at right angles to each other, one horizontal (H) and one vertical (V). Those photons undergo Compton scattering in aluminum and are then measured by the flash generated as they collide with an anthracene crystal. The scattered photons were measured by a fixed detector on one side and a rotating detector on the other side.[17] The coincidence rates of the scattered annihilation photons demonstrated their entangled state.

tence of local hidden variables.[17] That finding not only reinforced the predictions of quantum mechanics but also contributed to the ongoing debate about locality, determinism, and the fundamental nature of reality.

On 4 October 2022, just over a week after Brink's remarks about the significance of Wu's experiments, the Royal Swedish Academy of Sciences announced that it had selected Alain Aspect, Clauser, and Anton Zeilinger as the recipients of that year's Nobel Prize in Physics "for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science." Because Wu died in 1997 and Nobel Prizes are not awarded posthumously, she could not have been considered for her early photon entanglement experiment. Despite at least 12 Nobel nominations and two leading-edge experimental contributions in topics that ultimately received the accolade, Wu never received the honor (see "Physics Nobel nominees, 1901–70," Physics Today online, 29 September 2022). That oversight, though, does not diminish her accomplishments.

Wu's scientific achievements transcend the development of the atomic bomb. She contributed to a profound and meticulous understanding of the physical universe. "As a woman in a field almost entirely dominated by men, when most doors were closed to women, she was a trailblazer with an indomitable spirit and determination and a focus on scientific inquiry," said Columbia's Elena Aprile at the 2022 anniversary celebration of Wu's life and work.[8] Aprile joined the physics department faculty at Columbia in 1986; she was the second woman to join the department, more than four decades after Wu.

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