Tsung-Dao Lee has died, long live parity symmetry breaking!

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On August 4, 2024, Tsung-Dao Lee, a renowned theoretical physicist of Chinese origin, passed away at the age of 97. His most famous discovery dates back to 1956, when – together with Chen-Ning Yang – he postulated that parity symmetry might be broken by the weak interaction. They suggested experimental tests of this revolutionary idea, which were conducted within one year. The results confirmed the conjecture by Lee and Yang, thus changing a core paradigm of physics.

1. Is there a difference between left and right?

Imagine that you could talk on the phone to an extraterrestrial. The translation machine works well, each one narrates about his civilization, until a tricky question arises: you want to explain what we call "left" and "right", but how do you do it? It is not a video call, and he doesn't know our anatomy, so saying "the left is where we have the heart" or "the right-handed sugar molecules are the ones that our body digests" or something similar doesn't work. Is it even possible to explain this? Can you propose an experiment whose outcome could answer this question?

Until 1956, it was a core paradigm in physics that the laws of Nature are *parity invariant*; in the framework of Quantum Mechanics, this was pointed out by Eugene Wigner [1]. A parity transformation (P-transformation) means that the three spatial coordinates change sign, $P : \vec{r} \rightarrow -\vec{r}$, but we can instead simply imagine that we are observing the world in a mirror. Then, left and right are exchanged, but apparently the physical processes persist. For example, if we watch a billiard game in a mirror, it seems that nothing deviates from the natural laws. In fact, gravitational and electromagnetic forces, and even the strong interaction of Quantum Chromodynamics, remain invariant. If P-invariance were universally valid, there would be no way to explain to the extraterrestrial what we mean by "left" and "right".

In 1956, however, this paradigm was challenged by Tsung-Dao Lee and Chen-Ning Yang, two young Chinese in New York, aged 29 and 33, who wondered: Does parity symmetry also hold for the *weak interaction*, which, for example, causes the radioactive decay? It was standard to assume that this was obvious and that it had already been tested, but a critical review of the known experiments with the weak interaction showed that none of them had actually verified parity symmetry [2]. On the contrary, Lee and Yang (see Fig. 1) found an indication that it was broken.

At that time, there was extensive discussion about the so-called "θ^+–τ^+ puzzle": these two unstable particles had been observed in cosmic ray experiments since 1947. They are
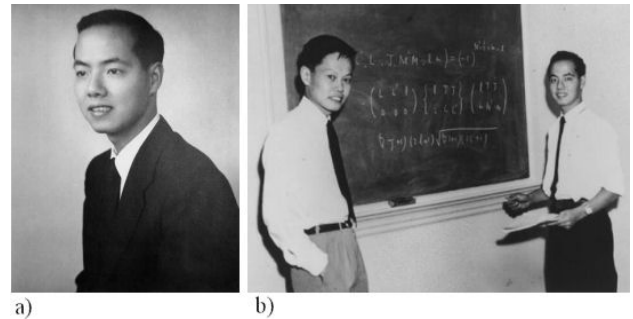

FIGURE 1. a) Tsung-Dao Lee, physics Nobel Prize laureate at the age of 30. b) Chen-Ning Yang (left) and Tsung-Dao Lee (right) in Princeton (credit to Alan Richards).

mesons with positive electric charge, one was assumed to decay into two pions and the other into three pions (pions, π, are the lightest mesons),

$$\theta^+ \rightarrow \pi^+ + \pi^0,$$
$$\tau^+ \rightarrow \pi^+ + \pi^+ + \pi^- \quad \text{or} \quad \pi^+ + \pi^0 + \pi^0 \,.$$

Pions have an intrinsic parity of -1, meaning that under a parity transformation, their fields change sign. This implies that the state of two pions has positive parity, $(-1)^2 = 1$, whereas the state of three pions has negative parity, $(-1)^3 = -1$ (at zero orbital angular momentum). Therefore, it was assumed that θ^+ had the intrinsic parity $+1$, and that it was -1 for τ^+.

But the puzzle was that the measurements indicated (within their precision) the same mass (494 MeV) and mean lifetime ($1.2 \cdot 10^{-8}$ s) for θ^+ and τ^+, which seemed like a strange coincidence. Lee and Yang correctly hypothesized that it was the *same* meson [2], which we now call a *kaon*, K^+. It has parity -1, but it can decay into two *or* three pions (among other decay channels) because its decay involves the weak interaction (therefore the lifetime is relatively long), which does *not* conserve parity. To be explicit: its purely hadronic decay modes have the branching ratios $\pi^+ + \pi^0$: 20.7%; $\pi^+ + \pi^+ + \pi^-$: 5.6% and $\pi^+ + \pi^0 + \pi^0$: 1.8%.

In their paper, Lee and Yang suggested a multitude of experiments to directly test parity violation in the weak interaction [2]. Their first and simplest proposal refers to the β-decay of a neutron into a proton, an electron, and an anti-neutrino,

$$n \to p^+ + e^- + \bar{\nu}_e \ .$$

The neutron can be part of an unstable nucleus; Lee and Yang proposed $^{60}_{27}\text{Co}$. The spin of the nucleus has the direction of its magnetic moment, which can be aligned by applying a magnetic field. Spin is another intrinsic degree of freedom of particles, which behaves like angular momentum, $\vec{L} = \vec{r} \times \vec{p}$. Under parity transformation, the position vector $\vec{r}$ and the momentum $\vec{p}$ change sign, so $\vec{L}$ is invariant, as is spin. However, the momenta of the electron and the anti-neutrino do change sign.

This means that, if the β-decay is parity invariant, the electron flux – which is measurable – in the direction of the spin and in the opposite direction should be equally intense. Already in 1956, this experiment was carried out under the direction of Chinese-American physicist Chien-Shiung Wu (she cancelled a planned journey to Europe and Asia in order to work on it as soon as possible). There were practical challenges: to achieve significant polarization of the nuclei, a strong magnetic field was required, along with a very low temperature of 0.003 K (see Fig. 2).

The result for a sample of cobalt nuclei, with about 60% polarization, was clear and submitted for publication in January 1957: the electron flux in the direction opposite to the nuclear spin is stronger, demonstrating that the weak interaction breaks parity symmetry [3] (see Fig. 3). Somewhat more detailed descriptions are given in the Appendix and in Ref. [4].

If the extraterrestrial also performs this experiment, he will be able to distinguish between clockwise and counter-clockwise rotation, and finally understand what we mean by "left" and "right". This came as a great surprise in 1957;
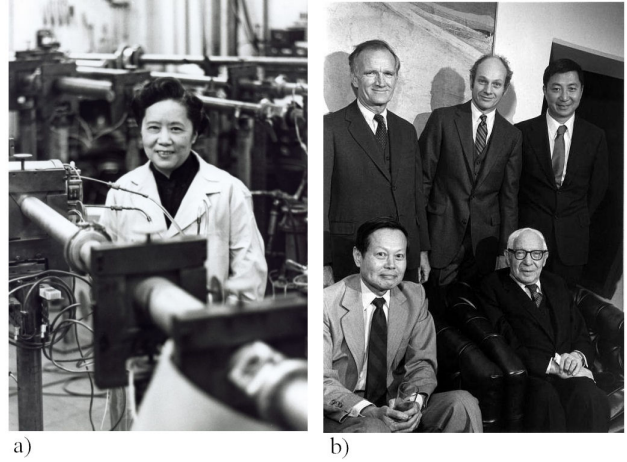
FIGURE 3. a) Chien-Shiung Wu in her laboratory. b) (from left to right, standing): Val Fitch, James Cronin (they discovered the CP-violation [8]), and Samuel Ting; (seated): Chen-Ning Yang and Isidor Rabi. They are all Nobel Prize winners.

at first, prominent physicists like Wolfgang Pauli did not believe it, but it was substantiated by further experiments [5]. Still in 1957, Lee and Yang received the Nobel Prize for this discovery, the same year when Albert Camus won the Nobel Prize in literature. Lee, at the age of 30, was the youngest Nobel Prize winner in physics since World War II. Lee and Yang were the first Nobel laureates from China. Unfortunately, Madame Wu (see Fig. 3) was not included, which many people consider unjust. In 1978, she was finally awarded the (inaugural) Wolf Prize in physics for this achievement.

We usually assume matter to dominate all regions of the Universe. However, if our extraterrestrial friend were made of anti-matter, he might misinterpret this experiment. Wu's experiment demonstrated not only the violation of P-invariance, but also of C-invariance [6], which exchanges matter and anti-matter. In fact, a decaying anti-cobalt nucleus emits a positron *in* the direction of its nuclear spin. The experiment is indistinguishable, however, under the combination CP, so CP-invariance became the new paradigm [7]. However, just a few years later, in 1964, it was refuted as well, this time with the decay of neutral kaons [8].

What is still considered valid today is CPT-invariance, which additionally reverses the direction of time (like a movie played backwards). There are good reasons for this property to hold: in a quantum field theory – the successful formalism of particle physics – that is local and Lorentz invariant, CPT-invariance must hold [9]. The clearest proof was provided by Res Jost by means of analytic continuation, in a groundbreaking paper, which he wrote in German and published in a journal that no longer exists [10].
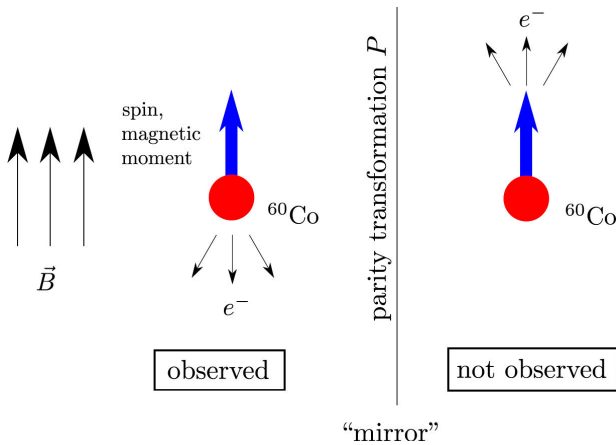

FIGURE 2. The concept of the Wu experiment: under parity transformation, the electron flux flips to the other side of the polarized $^{60}_{27}\text{Co}$ nuclei. So if P-invariance holds, this flux must be equally intense in both directions. The experiment demonstrated that this is *not* the case [3].

2. Who was Tsung-Dao Lee?

Lee – known as T.-D. Lee – was born in 1926 in Shanghai, where he grew up and first studied chemical engineering and

then physics. Due to the Japanese invasion, he left Shanghai and continued his studies in Kunming. After the war, he received a fellowship from the Chinese government under Chiang Kai-shek, which was granted to very few exceptionally gifted students to study in the United States. The goal was to promote the development of nuclear weapons in China upon their return [11]. Thus, Lee arrived 1946 in Chicago, where he completed his Ph.D. thesis about White Dwarfs under the supervision of Enrico Fermi in 1950, one year after the Chinese Revolution.

Yang, who was born in Hefei in 1922, also arrived in Chicago in 1946, where he obtained his Ph.D. in 1948 under the direction of Edward Teller, then he worked as an assistant of Fermi. In 1952, Lee and Yang published together two papers that still play an important role in Statistical Mechanics [12]. They deal with the density of zeros of a partition function, depending on an external source, as the volume increases, which serves as an indicator of phase transitions.

In 1956, the year when they conjectured the breaking of parity invariance, Lee already became a full professor at Colombia University. In the same year, Lee and Yang also introduced a more abstract, discrete symmetry, the G-parity [13]. Formally, a G-transformation is obtained by combining a C-transformation with an "isospin rotation" (from a modern point of view, this is a "rotation" between the lightest quark flavors u and d). It amounts to a sign flip of the pion fields, without performing a spatial inversion (the latter differs from a P-transformation). The strong interaction, limited to these two quark flavors, is G-invariant, therefore it cannot change the number of pions from even to odd, or vice versa.

Until 1962, Lee and Yang published together more than 30 papers that received great recognition. Apparently, the collaboration was lively: Colleagues of the time heard the two often shouting at each other, alternating between Chinese and English [14]. Later, there were disagreements related to the merits of these successful works, and ever since they have gone separate ways.

Both continued to feel connected to their home country. After U.S. President Nixon visited China in 1972, bilateral relations improved, and it also became possible for other US citizens to visit China. Lee and Yang immediately took this opportunity to undertake lecture tours (Yang already in 1971), where they were celebrated as heroes. Lee was received by Premier Zhou Enlai in 1972, and in 1974 also by Chairman Mao Zedong, who wanted to discuss with him the question of what symmetries mean from a philosophical perspective [15]. Mao regretted not having studied more science. With Zhou's support, Lee advocated for the resumption of natural science education during the Cultural Revolution.

Lee continued to promote China's investment in basic research. Later, he was in contact with Deng Xiaoping and acted as an (unofficial) scientific advisor. He created the China-U.S. Physics Examination and Application (CUSPEA) system to select brilliant Chinese students for Ph.D. studies in the USA or Canada. In the period from 1979 to 1989,

915 students benefited from this opportunity, which advanced their careers, in a time when the physics departments in China were still developing. On the other hand, many of them did not return to their homeland, so this system could also be viewed as a mechanism of "brain drain".

That was not the case anymore with the Chun-Tsung Endowment program, which Lee established in 1998, in memory of his wife, Jeannette Hui-Chun Chin, who had died in 1996. That program awarded over 4000 scholarships to undergraduate Chinese students, giving them opportunities to receive scientific research training at one of six leading universities in China. Regarding research in particle physics inside China, Lee promoted, in particular, the construction of the *Beijing Electron Positron Collider* (BEPC), which went into operation in 1989.

In contrast, Yang recommended that China focus on applied research, as well as social and environmental issues. In 2016, this led him to reject the planned *Circular Electron Positron Collider* (CEPC, a "Higgs factory" of 100 km circumference and center-of-mass energies up to 240 GeV). Not surprisingly, this provoked objections from the active generation of Chinese physicists, who expect a beneficial boost in science and technology, if the construction of the CEPC will be approved [16].

Yang taught at Stony Brook University in New York from 1965 to 1999. He is also famous for non-Abelian gauge theory (Yang-Mills theory) and the Yang-Baxter equation, a consistency condition for scattering processes. Yang is 102 years old and he now lives in Beijing.

I myself have encountered Lee (Fig. 4) on two occasions. First, when I was a *summer student* at CERN and Lee gave a colloquium on parity violation, which I heard again years later as a postdoc at MIT. He also published this well-designed and pedagogical lecture as a booklet [15], in which a variant of intergalactic communication about *left* and *right* is discussed already. The lecture starts with the picture of two cars that are mirror images of each other, so one would be allowed in most countries, while the other in countries like the UK or Japan. If parity invariance were universally valid, both cars would be equally fast, but if the weak interaction plays a
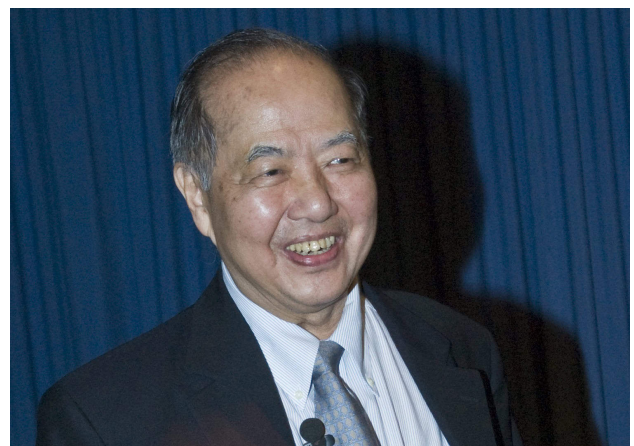

FIGURE 4. Tsung-Dao Lee visiting CERN.

role in the engine, this does not need to be true anymore. Additionally, Lee wrote an extensive textbook on particle physics [17].

At MIT, Lee also gave a seminar for the lattice group, proposing a new lattice field theory formulation, which, however, barely attracted interest. On the other hand, there was no doubt about his personal authority. When we met and shook hands, he simply said, with a friendly smile, "How do you do?", well aware that he did not need to introduce himself. When a colleague in the seminar commented: "I guess there is a non-locality in this formulation", he responded: "Don't try to guess, just follow the talk".

In the colloquium, someone raised an objection and added: "There are many people who think that Lorentz invariance could be broken". Lee again gave a decisive response: "Well, if you want to decide a scientific question through a popular referendum ...". Indeed, speculations about a possible breaking of Lorentz invariance became popular in the following years, but to this day, there is no evidence of it.

Despite the humorous formulation of his response, it is an interesting question how paradigm shifts actually occur in science. There are no votes or committees for this. A standard reference for the dynamics of such processes, from a sociological perspective, is a book by Thomas Kuhn [18]. These are rare events and therefore particularly important, like in 1956/7 when the seemingly sacred law of parity invariance in Nature was overturned.

Another major achievement, where Lee was involved, is known as the *Kinoshita-Lee-Nauenberg Theorem* [19]. It ensures that the infrared divergences cancel in the perturbative expansion of a class of quantum theories, which includes Quantum Electrodynamics and (as we know today) even the Standard Model. In fact, we are usually concerned only with ultraviolet divergences.

Together with Gian Carlo Wick – a famous theoretical physicist from Italy, who had been Fermi's assistant in Rome in the 1930s – Lee proposed an effective model for unusual states of heavy nuclei [20]. They coupled the nucleons to a scalar field, which could take, in a limited region, a metastable state, associated with a non-global potential minimum. At strong coupling, the energy minimum of the system may temporarily favor a kind of exotic state of the nucleus, with a reduced "effective" nucleon mass. This work had some impact in the conceptual development of the quark-gluon plasma theory.

As the first director of the RIKEN-Brookhaven National Laboratory, from 1997 to 2003, Lee supported the funding of a teraflop supercomputer and, later, a 10-teraflop supercomputer for the lattice group. He taught at Columbia University from 1953 to 2012, that is, until the age of 85.

Lee was one of the most distinguished theoretical physicists of the 20th century. In addition to the Nobel Prize, he received 14 other major awards, and there is a *Tsung-Dao Lee Institute* at Jiao Tong University in Shanghai. On top of that, he was active in the artistic field: he conceptualized two

FIGURE 5. A 5-meter-tall sculpture representing Yin and Yang, related to a cyclotron-type accelerator. It is situated in front of the Institute of High Energy Physics in Beijing since 2001, and it was conceptualized by Tsung-Dao Lee. The left-hand side displays the following poem: "The Tao of All Matter: Tao creates matter, matter generates Tao. Tao shapes the action of matter, matter forms the completion of Tao. The Art of the universe is the Tao of all matter" (credit to the Institute of High Energy Physics).

sculptures representing "The Tao of All Matter" (Fig. 5) and Galileo Galilei, which are located in Beijing and Rome, respectively [14]. As a theoretical physicist, Lee always sought the connection with experiments, following Fermi's instruction. He expressed this principle in his colloquium with two rules: *"Without experimentalists, theorists tend to drift. Without theorists, experimentalists tend to falter"* [15]. We should remember his advice.

On August 4, 2024, Tsung-Dao Lee passed away in San Francisco at the age of 97; may he rest in peace.

Appendix

A. The Wu experiment from a modern perspective

Now that we are familiar with the Standard Model of particle physics, it is rather easy to understand the outcome of the Wu experiment. First, we should mention that the decay transforms the cobalt nucleus into an excited nickel nucleus,

$$ {}^{60}_{27}\text{Co} \quad \rightarrow \quad {}^{60}_{28}\text{Ni}^* + e^- + \bar{\nu}_e \,, $$
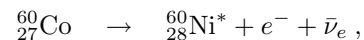
thus reducing the nuclear spin from $J = 5$ to 4 (in natural units, with $\hbar = 1$). The missing nuclear spin is carried away by the leptons e^- and $\bar{\nu}_e$ (without orbital angular

momentum), which both have spin $1/2$. Since the electron-anti-neutrino $\bar{\nu}_e$ is almost massless, we can safely assume its chirality to coincide with its polarization (in the nuclear rest system), such that right-handedness (left-handedness) means that its spin is oriented in (against) its direction of motion.

Thus, two scenarios are conceivable:

- A right-handed anti-neutrino $\bar{\nu}_{e,R}$ moves in the nuclear spin direction, and a left-handed electron e_L in the opposite direction.

- A right-handed electron e_R moves in the nuclear spin direction, and a left-handed electron anti-neutrino $\bar{\nu}_{e,L}$ in the opposite direction.

However, the Standard Model only contains left-handed neutrinos and right-handed anti-neutrinos, ν_L and $\bar{\nu}_R$, in any fermion generation. This fact alone shows already that the Standard Model cannot be P-invariant, nor C-invariant. Indeed, we have never detected any ν_R or $\bar{\nu}_L$. Even if they exist, they are sterile Majorana neutrinos, which are not involved in the weak interaction; therefore, they cannot emerge in the β-decay. This singles out the first of the two options mentioned above as the only valid one, which explains the observation in the Wu experiment [3].

(For completeness, we add that the excited nickel nucleus also emits two photons, $^{60}_{28}\text{Ni}^* \rightarrow {}^{60}_{28}\text{Ni} + 2\gamma$. That decay is electromagnetic, and therefore P-invariant. The angular γ-distribution showed to which extent the nuclei were polarized, and that the P-breaking in the electron-distribution was significant).

Acknowledgements

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