THE DOWNFALL OF PARITY — THE REVOLUTION THAT HAPPENED FIFTY YEARS AGO*

Andrzej K. Wróblewski

Physics Department, Warsaw University
Hoża 69, 00-681 Warszawa, Poland
akw@fuw.edu.pl

(Received January 7, 2008)

Physics of elementary particles changed profoundly in January 1957 when it was experimentally demonstrated that parity is not conserved in the weak interactions. An account is given of events which led to the parity revolution.

PACS numbers: 01.65.+g

1. How it all began?

In 1924 Otto Laporte analyzed the structure of the spectrum of iron and found that there are two kinds of energy levels, which he called "stroked" ("*gestrichene*") and "unstroked" ("*ungestrichene*"). He discovered a selection rule (later called Laporte's rule) that the transitions occurred always from stroked to unstroked levels or *vice versa*, and never between stroked or between unstroked levels [1]. A few months later similar observation on the spectrum of titanium was made by Henry Norris Russell [2]. No convincing explanation of the existence of two types of levels was found within the framework of the old quantum theory. Then, in 1927, Eugene Wigner [3] analyzed Laporte's finding and showed that the two types of levels and the selection rule followed from the invariance of the Schrödinger equation under the operation of inversion of coordinates $x \longrightarrow -x$, $y \longrightarrow -y$, $z \longrightarrow -z$. This property was originally called "*Spiegelung*", at least until 1933, when the term was still used by Pauli [4]. The name "parity" appeared later. In 1935, Condon and Shortley used the term "parity operator" in their book [5] on atomic spectra.

* Presented at the XXX Mazurian Lakes Conference on Physics, Piaski, Poland, September 2–9, 2007.

In modern language the two types of energy levels found by Laporte are states of positive and negative parity. The electric dipole transitions between states of the same parity are forbidden by parity conservation. The intrinsic parity of the emitted photon is negative and in order for the total parity of the system to be conserved the parity of the atomic state must change.

The concept of parity conservation was quickly accepted by physicists. "Since invariance under space reflection is intuitively so appealing (why should a left- and a right-handed system be different?), conservation of parity quickly became a sacred cow" [6].

2. The tau–theta puzzle

Complications appeared in the early 1950s. Several new "mesons", *i.e.* particles with mass intermediate between the electron and the proton, were discovered. Initially there was no general rule of naming these particles. Thus, there was $\theta^0 \longrightarrow \pi^+ + \pi^-$, $\kappa^\pm \longrightarrow \mu^\pm +$ 2 neutrals, $\chi^\pm(\theta^\pm) \longrightarrow \pi^\pm$ + 1 neutral, $\tau^\pm \longrightarrow \pi^\pm + \pi^+ + \pi^-$, and so on[1]. At the Bagnéres-de-Bigorre conference in 1953 it was agreed to adopt the name "L-mesons" for π and μ and "K-mesons" for the new particles with mass intermediate between the pion and the proton. Consistent symbols were adopted for charged K-meson decay modes. The decay into two pions was denoted as $K_{\pi 2}$ or θ, the decay into three pions as $K_{\pi 3}$ or τ, the two body decay with a muon as $K_{\mu 2}$ *etc.* In 1955 a new quantum number, "strangeness" was officially introduced by Gell-Mann [7].

When more precise data on strange particles became available there was growing evidence of the approximate equality of masses and lifetimes of K mesons [8]. In particular, the two particles $K_{\pi 3} \equiv \tau^\pm \longrightarrow \pi^\pm + \pi^+ + \pi^-$ and $K_{\pi 2} \equiv \theta^\pm \longrightarrow \pi^\pm + \pi^0$ appeared to have almost identical masses and lifetimes, although their parities seemed to be different. This became known as the tau–theta puzzle.

The term "parity" is used in two ways, first, as the operation P of spatial inversion, and the second as a numerical quantity associated with the system. Parity in the second sense is a multiplicative quantum number which could be $+1$ or -1. The total parity of the system of particles is the product of their intrinsic parities and the spatial parity given by $(-1)^l$, where l denotes the angular momentum of the wave function. The intrinsic parity of the pion was established to be odd or negative. Thus the parity of a particle of spin l decaying into two pions is just $(-1)^l$ and that of a particle of spin l decaying into three pions equals $(-1)^{l+1}$.

[1] The symbol τ is no longer used for a meson but denotes the charged lepton of the third family (taon). One should also remember that in the 1950s the μ was still called a "meson".

The decay properties of the θ were simple. The decay $\theta^0 \longrightarrow \pi^0 + \pi^0$ has been observed. The Bose–Einstein statistics requires the system of two neutral pions to have even parity and therefore even orbital momentum l. The intrinsic parity of the θ must be even and its spin must be zero[2].

In order to determine the spin of the τ meson Richard Dalitz invented a convenient two-dimensional plot (later named the Dalitz plot) to represent the distribution of energies of the three pions from τ decay [10]. A similar analysis was independently proposed a little later by Ettore Fabri [11]. Already in May 1954 Dalitz concluded on the basis of 13 events that "the available data are insufficient for any strong conclusion to be drawn but rather suggest even spin and odd parity for the τ meson ..." [12]. By the time of the Rochester Conference in February, 1955, he had 53 events from which he concluded [13] that "if the spin of the τ meson is less than 5, it cannot decay into two pions". An independent analysis of 71 τ^+ decays found in emulsions exposed at the Bevatron led to the conclusion that "the τ and θ mesons have different spin-parity configurations and that the only reasonable possibilities for the τ are (0−) and (2−)" [14].

There were several attempts to solve the tau–theta puzzle. Of course it could have been just a coincidence: two different particles of almost identical mass and lifetime. But usually physicists are wary when they encounter coincidences.

In August, 1955, Tsung Dao Lee and Jay Orear [15] proposed to explain the tau–theta puzzle by assuming that there are two different particles; the heavier one decays rapidly into the lighter: $\tau \longrightarrow \theta + \gamma$ or $\theta \longrightarrow \tau + \gamma$. They proposed that the heavier of these two had a lifetime of 10^{-8} s with a significant branching ratio for gamma decay to the lighter one. If the lighter particle had a lifetime of order of 10^{-9} s then the two particles could have different lifetimes but in most experiments appeared to have exactly the same lifetime. This hypothesis had soon to be rejected because of negative results of the search for gammas reported by Luis Alvarez [16] at the Sixth Annual Rochester Conference in April, 1956.

In December, 1955, Lee and Yang submitted a paper with yet another possible explanation [17]. All particles with odd strangeness S were assumed to be "parity doublets", that is, two particles with opposite parity. The θ^+ and τ^+ were assumed to have the same spin but opposite parity (such as, *e.g.* 0^+ and 0^-): "For every strong reaction... there exists a parity-conjugated reaction of equal strength. In particular, for the reaction $\pi^+ + n \longrightarrow \Lambda_1^0 + \theta^+$, one obtains a reaction of equal amplitude by taking the parity conjugation of all the particles $\pi^+ + n \longrightarrow \Lambda_2^0 + \tau^+$. Here Λ_2^0 is the parity conjugated state of Λ_1^0. Corresponding particles in the two reactions have the same spin

[2] The values 2, 4... of the spin of the θ were excluded by absence of radiative decays $\theta \longrightarrow \pi + \gamma$, as shown by Dalitz [9].

and orbital states. Therefore Λ_2^0 must have opposite intrinsic parity to that of Λ_1^0, and consequently must be a different particle".

Tsung Dao Lee and Chen Ning Yang first met in 1944, in Kunming, Yunnan, where professors and students from all parts of China fled because of the Japanese invasion of their country. Lee was born in 1922 in Hofei, Anwhei. He received M.Sc. degree from Tsinghua University, which had moved to Kunming. Yang, born in 1926 in Shanghai, attended the National Southwest University in Kunming. At the end of the war Lee and Yang moved to the United States to continue their studies. They both obtained Ph.D. from the University of Chicago, Yang in 1948, Lee in 1950, and remained in USA. Since 1949 Yang had been working at the Institute for Advanced Study, Princeton. Lee had been at Columbia University since 1953. Lee and Yang's collaboration in research began in the early 1950s.

Nearly one hundred ninety physicists participated in the Sixth Annual Rochester Conference on April 3th–7th, 1956. One of its main topics was the rapidly growing field of the new elementary particles. The session on "Theoretical Interpretation of New Particles" was chaired by Oppenheimer who opened it with a comment [18]: "There are the five objects $K_{\pi 3}, K_{\pi 2}, K_{\mu 2}, K_{\mu 3}, K_{e3}$. They have equal, or nearly equal, masses, and identical, or apparently identical, lifetimes. One tries to discover whether in fact one is dealing with five, four, three, two, or one particle. Difficult problems arise no matter what assumption is made".

The introductory talk was delivered by Yang who gave a summary of experiments and several propositions to explain the tau–theta puzzle. Dalitz presented [19] his newest analysis of 600 τ decays. All these events, when plotted on the "Dalitz diagram" gave a remarkably uniform distribution. This would point to a τ meson of spin-parity 0^-, Dalitz declared. Other possibilities, such as 2^-, were not excluded, but required unusually complicated conditions. During this marathon session several participants presented their ideas, some quite exotic. Oppenheimer mediated the discussion with cryptic remarks, such as [20]: "The τ meson will have either domestic or foreign complications. It will not be simple on both fronts ... The moment had come to close our minds ... Perhaps some oscillation between learning from the past and being surprised by the future of this θ–τ dilemma is the only way to mediate the battle".

It was during that discussion that the idea of parity nonconservation was first seriously discussed in large audience. Richard Feynman, who was a participant, gave a lively recollection of the event [21]: "I was sharing a room with a guy named Martin Block, an experimenter. And one evening he said to me, 'Why are you guys so insistent on this parity rule? Maybe the tau and theta are the same particle. What would be the consequences if the parity rule were wrong?'

I thought a minute and said, 'It would mean that nature's laws are different for the right hand and the left hand, that there's a way to define the right hand by physical phenomena. I don't know that that's so terrible, though there must be some bad consequences of that, but I don't know. Why don't you ask the experts tomorrow?'

He said, 'No, they won't listen to me. You ask'.

'So the next day at the meeting ... I got up and said, 'I'm asking this question for Martin Block: What would be the consequences if the parity rule was wrong?'

Lee, of Lee and Yang, answered something complicated, and as usual I didn't understand very well. At the end of the meeting Block asked me what he said, and I said I did not know, but as far as I could tell, it was still open — there was still a possibility. I didn't think it was likely, but I thought it was possible ...".

The Sixth Annual Rochester Conference ended with no solution of the tau–theta puzzle.

3. The idea and its testing

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

In their seminal paper Lee and Yang suggested several possible experimental tests of parity conservation in β decay. The first one concerned nuclear β decay.

"A relatively simple possibility is to measure the angular distribution of the electrons coming from β decays of oriented nuclei. If θ is the angle between the orientation of the parent nucleus and the momentum of the electron, an asymmetry of distribution between θ and $180° — \theta$ constitutes an unequivocal proof that parity is not conserved in β decay. To be more specific, let us consider the allowed β transition of any oriented nucleus, say Co^{60} ... The angular distribution of the β radiation is of the form:

$$I(\theta)d\theta = (\text{constant})(1 + a\cos\theta)\sin\theta d\theta \ldots$$

if $a \neq 0$, one would then have a positive proof of parity nonconservation in β decay… " [22].

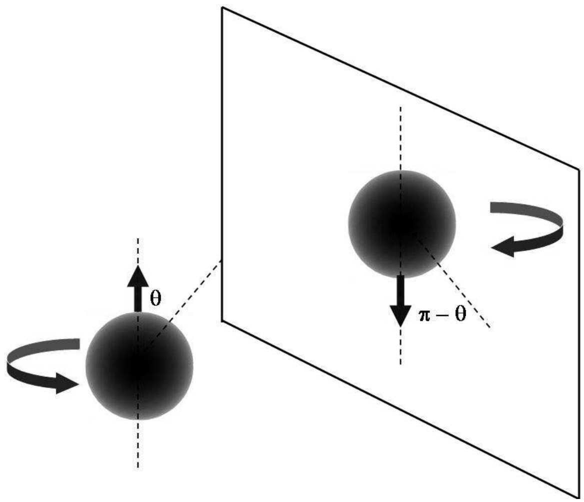

Fig. 1. The direction of rotation and the spin of rotating object are reversed by mirror reflection. Thus, if parity is conserved, the emission of electrons at angles θ and $180° - \theta$ must be the same.

Another experimental proposal by Lee and Yang concerned meson decay[3].

"In the decay processes $\pi \longrightarrow \mu + \nu$, $\mu \longrightarrow e + \nu + \nu$, starting from a π meson at rest, one could study the distribution of the angle θ between the μ-meson momentum and the electron momentum, the latter being in the center-of-mass system of the μ meson… If parity is not conserved… the distribution will not in general be identical for θ and π–θ" [22].

As mentioned earlier, Chien Shiung Wu had been the first to learn about Lee and Yang's ideas. She was born in 1912 in China. In 1936 she graduated from the National Central University in Nanking, China, and then traveled to the United States. After graduate studies in physics at the University of California at Berkeley under Ernest O. Lawrence she earned her Ph.D. in 1940. Since 1944 she worked at Columbia University.

[3] In 1956 it was believed that there is only one kind of neutrino (the muon neutrino was discovered in 1962). Also at that time there was no generally accepted rule of the usage of terms "neutrino" and "antineutrino" (see [23], especially Note 1).

In 1956 Chien Shiung Wu planned to travel to China with her husband Chia Liu Yuan. It was to be a sentimental journey on the twentieth anniversary of their emigration from China. They had already booked a cabin on the *Queen Elisabeth*. After talking to Lee and Yang, Wu decided to stay and persuaded her husband to make the journey alone. She resolved to try an experiment even before Lee and Yang submitted their paper to the *Physical Review*.

Wu knew that nuclear orientation work was then being carried out at the National Bureau of Standards in Washington by a group headed by Ernest Ambler. She also knew that Ambler's thesis work had been done on ^{60}Co. 'It was on June 4, 1956, that I called and put the proposition directly to him. He accepted enthusiastically' — she recollected. Ambler's team consisted of Raymond Hayward, Dale Hopper, and Ralph Hudson. The experiment was to be performed at the NBS.

The idea of an experiment with cobalt-60 was simple only in theory. In order to make the measurement possible the radioactive nuclei must be aligned (polarized) so that their spins pointed in the same direction. It required very low temperatures, otherwise the thermal motion of the nuclei would destroy the alignment. At that time it was already known that nuclei can be aligned by the Gorter–Rose method [24] in cerium magnesium (cobalt) nitrate (CMN). The efficiency of the method was checked [25] by a team of physicists from Oxford which included Ambler.

The cobalt-60 nucleus emits both β and γ rays. The degree of polarization can be measured by the anisotropy of the gamma radiation, which is emitted more in the polar direction than in the equatorial plane. The beta particles from ^{60}Co could not penetrate any substantial thickness of matter. For this reason Wu and her collaborators had to locate the radioactive nuclei in a very thin layer of only 0.002 inch on a surface of CMN. The beta counter had to be placed inside the demagnetization cryostat. The beta particles emitted by ^{60}Co nuclei were detected by scintillations in a thin anthracene crystal located inside the vacuum chamber about 2 cm above the ^{60}Co source. The scintillations were transmitted through a glass window and a Lucite light pipe 4 feet long to a photomultiplier located at the top of the cryostat.

The paper [22] by Lee and Yang was published only on October 1, 1956, but many physicists around the world knew about their ideas earlier because of a circulated preprint of their paper. There was strong opposition to the idea of parity nonconservation. Most physicists rejected it as too fantastic and adverse to universally accepted notions on symmetries in physics. Lee and Yang were still backing two horses and, in parallel to their parity nonconservation paper [22], submitted another paper on the parity doublets idea [26]. Yang defended their theories during the International Conference on Theoretical Physics, held in September 1956 in Seattle [27].

During the October 1956 meeting in Russia Lev Landau still maintained that parity nonconservation was an absolute nonsense. Richard Feynman bet Norman Ramsay 50$ to 1$ that experiments would prove Lee–Yang hypothesis wrong. He later paid [28]. As late as 17 January, 1957, Wolfgang Pauli wrote to Victor Weisskopf: "I do not believe that the Lord is a weak left-hander, and I am ready to bet a very large sum that the experiments will give symmetric results". Just after sending off the letter he learned about the outcome of the experiments at Columbia.

First readings confirming parity violation were obtained by Wu's team on December 27, but the results were not consistently reproducible in the following days. Finally, about two o'clock in the morning of January 9, 1957, after everything had been checked and rechecked, Chien Shiung Wu and her collaborators uncorked a bottle of Chateau Lafite-Rotschild, 1949, and they drank to the overthrow of the law of parity.

A few days earlier, during a discussion among Columbia physicists over a meal in a cafe on Friday, January 4, Leon Lederman learned about Wu *et al.* results. He quickly realized that it was possible to check Lee and Yang's ideas about decay processes $\pi \longrightarrow \mu + \nu$, $\mu \longrightarrow e + \nu + \nu$, by using the muon beam from the cyclotron at the Nevis Laboratory of Columbia University. He explained the idea over the phone to his colleague, Richard Garwin. Garwin was an experimental wizard, in the words of Valentine Telegdi, "a phenomenon — completely comparable to Murray Gell-Mann... except he's an experimental physicist and not a theoretician" [29]. It took Garwin, Lederman, and Lederman's graduate student Marcel Weinrich, just little over 48 hours to prepare and carry out the experiment with a muon beam from the university cyclotron. Firstly they were considering the problem of rotating the electron telescope in order to determine the distribution of emitted electrons around the assumed spin axis. Then Garwin had an ingenious idea. "Look, he said, instead of moving this heavy platform of counters around, let's leave it in place and turn the muons in a magnet... The idea was so simple it was profound" [30]. At about 6 a.m. on January 8 Lederman called Lee and told him, "Parity is dead".

Columbia University called a press conference for the afternoon on January 15th, the day the two papers [31, 32] were submitted to the *Physical Review*. The next day news about nonconservation of parity made front page in newspapers all over the world.

The same chain of decays $\pi \longrightarrow \mu+\nu$, $\mu \longrightarrow e+\nu+\nu$ was studied at the University of Chicago. Valentine Telegdi read a preprint of Lee and Yang paper in August and, not knowing about Wu *et al.* effort, began an experiment similar in many respects to that of Lederman. With his postdoctoral researcher, Jerome Friedman, he exposed nuclear emulsion to a π^+ beam of the University of Chicago synchrocyclotron. They scanned the emulsions for characteristic $\pi \longrightarrow \mu + \nu$ events. In each case the scanner followed the muon to the end of its range and measured the angle of the positron emission. Telegdi and Friedman might have finished their experiment before Wu and Lederman, but a serious illness and death of Telegdi's father, who lived in Italy, delayed the work. Their paper [33] was submitted to the *Physical Review* on January 17, two days after the two papers from Columbia. With 2000 $\pi \longrightarrow \mu \longrightarrow e$ events they were able to determine that the electron emission indeed followed the linear law of the form $1 + a\cos\theta$, postulated by Lee and Yang, and determined $a = 0.174 \pm 0.038$.

It is now completely forgotten that the first ever experiment to check Lee and Yang idea about parity nonconservation was carried out in the summer of 1956 by a group from Rome, C. Castagnoli, C. Franzinetti, and A. Manfredini. Their results were announced in September during the XLII Congresso Nazionale di Fisica in Torino.

"We have examined all the $\pi \longrightarrow \mu$ events (from π's at rest) which had been observed in 600 μm emulsion exposed to cosmic rays. We have selected 410 events ... we get $a = -0.13 \pm\ 0.10$ ... This result does not exclude an asymmetric distribution but does not suggest a strong asymmetry... " [34].

The result was not convincing and did not arouse interest among physicists. A few months later, on March 1, 1957, the Rome group published their final results [35]. On the basis of 1028 π–μ–e events they determined $a = -0.222\pm\ 0.067$, in agreement with the result of Friedman and Telegdi. In the following months many experimental groups published results on emulsion studies of π–μ–e events. At that time it was the easiest and simplest experiment because emulsions and good microscopes were common in many laboratories.

At the beginning of 1957 an experiment similar to that of Wu *et al.* has also been done in Leyden with cobalt-58, which is a positron emitter [36]. It decays into iron-58 and emits a positron and a neutrino $^{58}\mathrm{Co} \longrightarrow {}^{58}\mathrm{Fe} + e^{+} + \nu$. In this case the positron was found to be preferentially emitted along the direction of the nuclear spin (magnetic field) (Fig. 2).

There were numerous experiments checking parity nonconservation in various circumstances. Good review of these works can be found in [37]. Parity nonconservation effects have been well explained by the two-component theory of the neutrino proposed independently by Landau [38], Salam [39], and Lee and Yang [40]. Massless neutrinos were assumed to possess a "handedness" to their spin. All neutrinos in nature were found to spin in a left-handed sense relative to their direction of flight, whereas antineutrinos were right-handed.

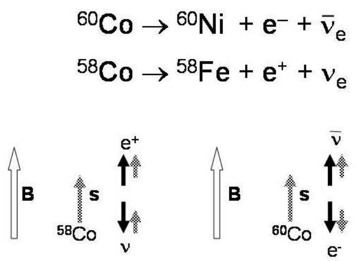

Fig. 2. Comparison of beta decays of ^{60}Co and ^{58}Co. The electrons from the ^{60}Co decay are emitted preferentially into the hemisphere opposite to the nuclear spin $\boldsymbol{s}$, whereas the positrons from the ^{58}Co are emitted preferentially along the spin of the nucleus.

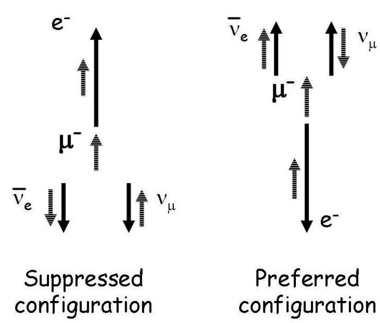

Fig. 3. Favoured and suppressed configuration of particles in the muon decay.

4. The aftermath

Barely a year after the parity revolution, the 1957 Nobel Prize in Physics was awarded to Tsung Dao Lee and Chen Ning Yang "for their penetrating investigation of the so-called parity laws, which has led to important discoveries regarding the elementary particles".

It is worth noticing that already in 1929 Hermann Weyl [41] considered a two component theory of spin particles. The hypothesis was rejected in 1933 by Pauli [42] because it would violate parity conservation!

In spite of almost universal belief in parity conservation among the physicists, G.C. Wick, A.S. Wightman, and E.P. Wigner wrote in October 1952[4], "That C is an exact symmetry property is moreover still far from proved. The disturbing possibility remains that C and I are both only approximate and CI is the only exact symmetry law. This would force us to regard the electric field as an axial vector. This possibility, however, seems rather remote at the moment" [43].

[4] The authors used the symbol I (inversion) instead of P (parity).

The discovery that parity is not conserved in weak interactions increased interest in the discrete symmetry operations, the charge conjugation C and time reversal T. It was shown that relativistic locality required invariance of the Lagrangian of any system under the combined operation CPT (irrespective of order of the three operations). The two-component theory of the neutrino allowed a natural formulation of a CP-conserving, but P- and C-violating, weak interaction.

The number of papers with the word "parity" in the title increased dramatically but soon decreased considerably. Then, in 1964, the unexpected discovery of CP nonconservation in kaon decay [44] took the physics community by surprise. It caused another boost in the number of such papers (Fig. 4).

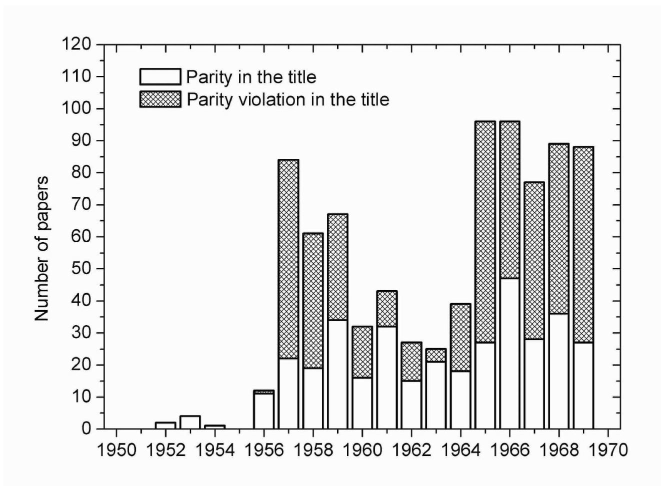

Fig. 4. The number of papers with the word "parity" or symbols P, C, CP or CPT in the title, as listed in the *Physics Abstracts*.

T.D. Lee wrote in March 1966: "The more we learn about symmetry operations — space inversion, time reversal and particle–anti-particle conjugation — the less we seem to understand them. At present, although still very little is known about the true nature of these discrete symmetries, we have, unfortunately, already reached the unhappy state of having lost most of our previous understanding" [45]. Fifty years that have passed since the parity revolution brought some progress in answering such questions, but our understanding of the problem is still incomplete. It is, however, another story.

REFERENCES

[1] O. Laporte, Die Struktur des Eisenspektrums, *Zeit. Phys.* **23**, 135 (1924).

[2] H.N. Russell, A New Form of Exclusion Principle in Optical Spectra, *Science* **49**, 512 (1924).

[3] E. Wigner, Einige Folgerungen aus der Schrödingerschen Theorie für die Termstrukturen, *Zeit. Phys.* **43**, 624 (1927).

[4] W. Pauli, *Handbuch der Physik* vol. **24**, 185, Springer, Berlin, 1933.

[5] E.U. Condon, G.H. Shortley, *The Theory of Atomic Spectra*, Cambridge University Press, Cambridge 1935.

[6] H. Frauenfelder, E.M. Henley, *Nuclear and Particle Physics*, p. 359, Benjamin, Reading, Mass. 1975.

[7] M. Gell-Mann, The Interpretation of the New Particles as Displaced Charge Multiplets, Proceedings of the 1955 Pisa Conference on Elementary Particles, *Suppl. Nuovo Cimento* **4**, 848 (1956).

[8] R.W. Birge, J. Peterson, D.H. Stork, M.N. Whitehead, Mass Values of the K mesons, *Phys. Rev.* **100**, 430 (1955); V. Fitch, R. Motley, Life of K^+Mesons, *Phys. Rev.* **101**, 496 (1955); L.W. Alvarez, F.S. Crawford, M.L. Good, M.L. Stevenson, Lifetime of K Mesons, *Phys. Rev.* **101**, 503 (1955).

[9] R.H. Dalitz, Isotopic Spin Changes in τ and θ Decays, *Proc. Phys. Soc.* **A69**, 527 (1956).

[10] R.H. Dalitz, On the Analysis of τ-Meson Data and the Nature of the τ-Meson, *Phil. Mag.* **44**, 1068 (1953).

[11] E. Fabri, A Study of τ-Meson Decay, *Nuovo Cimento* **11**, 479 (1954).

[12] R.H. Dalitz, Decay of τ Mesons of Known Charge, *Phys. Rev.* **94**, 1046 (1954).

[13] R.H. Dalitz, *High Energy Physics*, Proceedings of the Fifth Annual Rochester Conference, edited by H. P. Noyes, E.M. Hafner, G. Yekutieli, B.J. Raz, p. 140, Interscience Publishers Inc., New York 1955.

[14] J. Orear, G. Harris, S. Taylor, Spin and Parity Analysis of Bevatron τ Mesons, *Phys. Rev.* **102**, 1676 (1956).

[15] T.D. Lee, J. Orear, Speculations on Heavy Mesons, *Phys. Rev.* **100**, 932 (1955).

[16] L. Alvarez, Search for the Lee-Orear γ-Ray, *High Energy Physics*, Proceedings of the Sixth Annual Rochester Conference, April 3–7, 1956, edited by J. Ballam, V.L. Fitch, T. Fulton, K. Huang, R.R. Rau, S.B. Treiman, p. V-28, Interscience Publishers Inc., New York 1956.

[17] T.D. Lee, C.N. Yang, Mass Degeneracy of the Heavy Mesons, *Phys. Rev.* **102**, 290 (1956).

[18] J.R. Oppenheimer, *High Energy Physics*, Proceedings of the Sixth Annual Rochester Conference, April 3–7, 1956, edited by J. Ballam, V.L. Fitch, T. Fulton, K. Huang, R.R. Rau, S.B. Treiman, p. VIII-1, Interscience Publishers Inc., New York 1956.

[19] R.H. Dalitz, Present Status of τ Spin-Parity, *High Energy Physics*, Proceedings of the Sixth Annual Rochester Conference, April 3–7, 1956, edited by J. Ballam, V.L. Fitch, T. Fulton, K. Huang, R.R. Rau, S.B. Treiman, p. VIII-19, Interscience Publishers Inc., New York 1956.

[20] J.R. Oppenheimer, *High Energy Physics*, Proceedings of the Sixth Annual Rochester Conference, April 3–7, 1956, edited by J. Ballam, V.L. Fitch, T. Fulton, K. Huang, R.R. Rau, S.B. Treiman, p. VIII-22, VIII-28, VIII-29, Interscience Publishers Inc., New York 1956.

[21] R.P. Feynman, *Surely You're Joking, Mr. Feynman! The Adventures of a Curious Character as told to Ralph Leighton*, p. 247–248, W.W. Norton & Company, New York–London 1985.

[22] T.D. Lee, C.N. Yang, Question of Parity Conservation in Weak Interactions, *Phys. Rev.* **104**, 254 (1956).

[23] L.S. Rodberg, V.F. Weisskopf, Fall of Parity, *Science* **125**, 627 (5 April 1957).

[24] C.J. Gorter, A New Suggestion for Aligning Certain Atomic Nuclei, *Physica* **14**, 504 (1948); M.E. Rose, On the Production of Nuclear Polarization, *Phys. Rev.* **75**, 213 (1949).

[25] E. Ambler, M.A. Grace, H. Halban, N. Kurti, H. Durand C.E. Johnson, Nuclear Polarization of Cobalt 60, *Phil. Mag.* **44**, 216 (1953).

[26] T.D. Lee, C.N. Yang, Possible Interference Phenomena between Parity Doublets, *Phys. Rev.* **104**, 822 (1956); the paper was submitted on July 9, and published on November 1, 1956.

[27] C.N. Yang, Present Knowledge About the New Particles, *Rev. Mod. Phys.* **29**, 231 (1957).

[28] H. Frauenfelder, E.M. Henley, Ref. [6], p. 389.

[29] S. Lippincott, A Conversation with Valentine L. Telegdi — Part I, *Physics in Perspective* **9**, 445 (2007).

[30] L. Lederman, *The God Particle*, p. 268, Houghton Mifflin Company, Boston–New York 1993.

[31] C.S. Wu, E. Ambler, R.W. Hayward, D.D. Hoppes, R.P. Hudson, Experimental Test of Parity Conservation in Beta Decay, *Phys. Rev.* **105**, 1413 (1957).

[32] R.L. Garwin, L.M. Lederman, M. Weinrich, Observations of the Failure of Conservation of Parity and Charge Conjugation in Meson Decays: the Magnetic Moment of a Free Muon, *Phys. Rev.* **105**, 1415 (1957).

[33] J.I. Friedman, V.L. Telegdi, Nuclear Emulsion Evidence for Parity Nonconservation in the Decay Chain $\pi^+ \longrightarrow \mu^+ \longrightarrow e^+$, *Phys. Rev.* **105**, 1681 (1957).

[34] C. Castagnoli, C. Franzinetti, A. Manfredini, On Parity Conservation in Weak Interactions and Angular Distribution in $\pi \longrightarrow \mu \longrightarrow e$ Decays, XLII Congresso Nazionale di Fisica, Torino, 6–11 September 1956, *Supplemento al Nuovo Cimento* **6**, 441 (1957).

[35] C. Castagnoli, C. Franzinetti, A. Manfredini, Further Results on Parity Conservation in π–μ–e Decays, *Nuovo Cimento* **5**, 684 (1957).

[36] H. Postma, W.J. Huiskamp, A.R. Miedema, M.J. Steenland, H.A. Tolhoek, C.J. Gorter, Asymmetry of the Positron Emission by Polarized ^{58}Co Nuclei, *Physica* **23**, 259 (1957); H. Postma, W.J. Huiskamp, A.R. Miedema, M.J. Steenland, H.A. Tolhoek, C.J. Gorter, Asymmetry of the Positron Emission by Polarized ^{58}Co and ^{58}Mn Nuclei, *Physica* **24**, 157 (1958).

[37] C.S. Wu, Parity Experiments in Beta Decay, *Rev. Mod. Phys.* **31**, 783 (1959); V.L. Telegdi, The Early Experiments Leading to the $V-A$ Interaction, in: *Pions to Quarks. Particle Physics in the 1950s*, edited by L.M. Brown, M. Dresden, L. Hoddeson, Cambridge University Press, Cambridge 1989.

[38] L. Landau, On the Conservation Laws for Weak Interactions, *Nucl. Phys.* **3**, 127 (1957).

[39] A. Salam, On Parity Conservation and Neutrino Mass, *Nuovo Cimento*, **5**, 299 (1957).

[40] T.D. Lee, C.N. Yang, Parity Nonconservation and the Two-Component Theory of the Neutrino, *Phys. Rev.* **105**, 1671 (1957).

[41] H. Weyl, Elektron und Gravitation. I, *Zeit. Phys.* **56**, 330 (1929).

[42] W. Pauli, Die allgemeinen Prinzipien der Wellenmechank, *Handbuch der Physik* vol. **24**, 83–272, Springer, Berlin 1933.

[43] G.C. Wick, A.S. Wightman, E.P. Wigner, The Intrinsic Parity of Elementary Particles, *Phys. Rev.* **88**, 101 (1952).

[44] J. Christenson, J.W. Cronin, V.L. Fitch, R. Turlay, Evidence for the 2π Decay of the K_2^0 Meson, *Phys. Rev. Lett.* **13**, 138 (1964).

[45] T.D. Lee, Space Inversion, Time Reversal and Particle–Antiparticle Conjugation, *Physics Today*, **19**. No. 3, 23 (March 1966).