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The law of parity conservation and other symmetry laws of physics

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It is a pleasure and a great privilege to have this opportunity to discuss with you the question of parity conservation and other symmetry laws. We shall be concerned first with the general aspects of the role of the symmetry laws in physics; second, with the development that led to the disproof of parity conservation; and last, with a discussion of some other symmetry laws which physicists have learned through experience, but which do not yet together form an integral and conceptually simple pattern. The interesting and very exciting developments since parity conservation was disproved, will be covered by Dr. Lee in his lecture[1].

I

The existence of symmetry laws is in full accordance with our daily experience. The simplest of these symmetries, the isotropy and homogeneity of space, are concepts that date back to the early history of human thought. The invariance of physical laws under a coordinate transformation of uniform velocity, also known as the invariance under Galilean transformations, is a more sophisticated symmetry that was early recognized, and formed one of the corner-stones of Newtonian mechanics. Consequences of these symmetry principles were greatly exploited by physicists of the past centuries and gave rise to many important results. A good example in this direction is the theorem that in an isotropic solid there are only two elastic constants.

Another type of consequences of the symmetry laws relates to the conservation laws. It is common knowledge today that in general a symmetry principle (or equivalently an invariance principle) generates a conservation law. For example, the invariance of physical laws under space displacement has as a consequence the conservation of momentum, the invariance under space rotation has as a consequence the conservation of angular momentum. While the importance of these conservation laws was fully understood, their close relationship with the symmetry laws seemed not to have been clearly recognized until the beginning of the twentieth century[2]. (Cf. Fig. 1.)

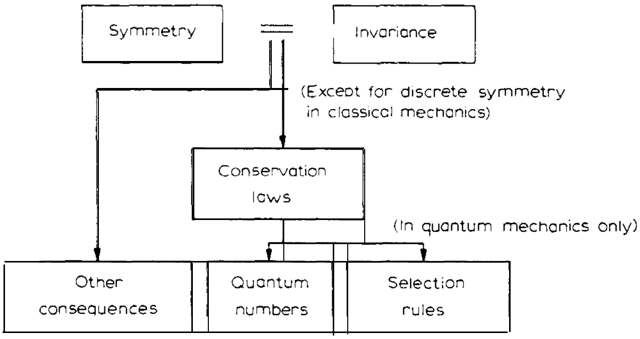

Fig. 1.

With the advent of special and general relativity, the symmetry laws gained new importance. Their connection with the dynamic laws of physics takes on a much more integrated and interdependent relationship than in classical mechanics, where logically the symmetry laws were only consequences of the dynamical laws that by chance possess the symmetries. Also in the relativity theories the realm of the symmetry laws was greatly enriched to include invariances that were by no means apparent from daily experience. Their validity rather was deduced from, or was later confirmed by complicated experimentation. Let me emphasize that the conceptual simplicity and intrinsic beauty of the symmetries that so evolve from complex experiments are for the physicists great sources of encouragement. One learns to hope that Nature possesses an order that one may aspire to comprehend.

It was, however, not until the development of quantum mechanics that the use of the symmetry principles began to permeate into the very language of physics. The quantum numbers that designate the states of a system are often identical with those that represent the symmetries of the system. It indeed is scarcely possible to overemphasize the role played by the symmetry principles in quantum mechanics. To quote two examples: The general structure of the Periodic Table is essentially a direct consequence of the isotropy of Coulomb's law. The existence of the antiparticles - namely the positron, the antiproton, and the antineutron - were theoretically anticipated as consequences of the symmetry of physical laws with respect to Lorentz transformations. In both cases Nature seems to take advantage of the simple mathematical representations of the symmetry laws. When one pauses to consider the elegance and the beautiful perfection of the mathematical reasoning involved and contrast it with the complex and far-reaching physical consequences, a deep sense of respect for the power of the symmetry laws never fails to develop.

One of the symmetry principles, the symmetry between the left and the right, is as old as human civilization. The question whether Nature exhibits such symmetry was debated at length by philosophers of the pasts. Of course, in daily life, left and right are quite distinct from each other. Our hearts, for example, are on our left sides. The language that people use both in the orient and the occident, carries even a connotation that right is good and left is evil. However, the laws of physics have always showncomplete symmetry between the left and the right, the asymmetry in daily life being attributed to the accidental asymmetry of the environment, or initial conditions in organic life. To illustrate the point, we mention that if there existed a mirror-image man with his heart on his right side, his internal organs reversed compared to ours, and in fact his body molecules, for example sugar molecules, the mirror image of ours, and if he ate the mirror image of the food that we eat, then according to the laws of physics, he should function as well as we do.

The law of right-left symmetry was used in classical physics, but was not of any great practical importance there. One reason for this derives from the fact that right-left symmetry is a discrete symmetry, unlike rotational symmetry which is continuous. Whereas the continuous symmetries always lead to conservation laws in classical mechanics, a discrete symmetry does not. With the introduction of quantum mechanics, however, this difference between the discrete and continuous symmetries disappears. The law of right-left symmetry then leads also to a conservation law: the conservation of parity.

The discovery of this conservation law dates back to 1924 when Laporte[4] found that energy levels in complex atoms can be classified into « gestrichene » and « ungestrichene » types, or in more recent language, even and odd levels. In transitions between these levels during which one photon is emitted or absorbed, Laporte found that the level always changes from even to odd or *vice versa.* Anticipating later developments, we remark that the evenness or oddness of the levels was later referred to as the parity of the levels. Even levels are defined to have parity +1, odd levels parity -1. One also defines the photon emitted or absorbed in the usual atomic transitions to have odd parity. Laporte's rule can then be formulated as the statement that in an atomic transition with the emission of a photon, the parity of the initial state is equal to the total parity of the final state, i.e. the product of the parities of the final atomic state and the photon emitted. In other words, parity is conserved, or unchanged, in the transition.

In 1927 Wigners took the critical and profound step to prove that the empirical rule of Laporte is a consequence of the reflection invariance, or right-left symmetry, of the electromagnetic forces in the atom. This fundamental idea was rapidly absorbed into the language of physics. Since right-left symmetry was unquestioned also in other interactions, the idea was further taken over into new domains as the subject matter of physics extended into nuclear reactions, β-decay, mesoninteractions, and strange-particle physics. One became accustomed to the idea of nuclear parities as well as atomic parities, and one discusses and measures the intrinsic parities of the mesons. Throughout these developments the concept of parity and the law of parity conservation proved to be extremely fruitful, and the success had in turn been taken as a support for the validity of right-left symmetry.

II

Against such a background the so-called ϑ—τ puzzle developed in the last few years. Before explaining the meaning of this puzzle it is best to go a little bit into a classification of the forces that act between subatomic particles, a classification which the physicists have learned through experience to use in the last 50 years. We list the four classes of interactions below. The strength of these interactions is indicated in the column on the right.

1. Nuclear Forces	1
2. Electromagnetic Forces	10^{-2}
3. Weak Forces (Decay Interactions)	10^{-13}
4. Gravitational Forces	10^{-38}

The strongest interactions are the nuclear interactions which include the forces that bind nuclei together and the interaction between the nuclei and the π mesons. It also includes the interactions that give rise to the observed strange-particle production. The second class of interactions are the electromagnetic interactions of which physicists know a great deal. In fact, the crowning achievement of the physicists of the 19th century was a detailed understanding of the electromagnetic forces. With the advent of quantum mechanics, this understanding of electromagnetic forces gives in principle an accurate, integral and detailed description of practically all the physical and chemical phenomena of our daily experience. The third class of forces, the weak interactions, was first discovered around the beginning of this century in the β-radioactivity of nuclei, a phenomena which especially in the last 25 years has been extensively studied experimentally. With the discovery of π-μ, μ-e decays and μ capture it was noticed independently[6] by Klein, by Tiomno and Wheeler, and by Lee, Rosenbluth and me, that these interactions have roughly the same strengths as β-interactions. They are called weak interactions, and in the last few years their rank has been constantly added to through the discovery of many other weak interactions responsible for the decay of the strange particles. The consistent and striking pattern of their almost uniform strength remains today one of the most tantalizing phenomena - a topic which we shall come back to later. About the last class of forces, the gravitational forces, we need only mention that in atomic and nuclear interactions they are so weak as to be completely negligible in all the observations with existing techniques.

Now to return to the ϑ—τ puzzle. In 1953, Dalitz and Fabri[7] pointed out that in the decay of the ϑ and τ mesons

$$\vartheta \rightarrow \pi + \pi$$
$$\tau \rightarrow \pi + \pi + \pi$$

some information about the spins and parities of the τ and ϑ mesons can be obtained. The argument is very roughly as follows. It has previously been determined that the parity of a π meson is odd (i.e. = -1). Let us first neglect the effects due to the relative motion of the π mesons. To conserve parity in the decays, the ϑ meson must have the total parity, or in other words, the product parity, of two π mesons, which is even (i.e. = +1). Similarly, the τ meson must have the total parity of three π mesons, which is odd. Actually because of the relative motion of the π mesons the argument was not as simple and unambiguous as we just discussed. To render the argument conclusive and definitive it was necessary to study experimentally the momentum and angular distribution of the π mesons. Such studies were made in many laboratories, and by the spring of 1956 the accumulated experimental data seemed to unambiguously indicate, along the lines of reasoning discussed above, that ϑ and τ do not have the same parity, and consequently are not the same particle. This conclusion, however, was in marked contradiction with other experimental results which also became definite at about the same time. The contradiction was known as the ϑ-τ puzzle and was widely discussed. To recapture the atmosphere of that time allow me to quote a paragraph concerning the conclusion that ϑ and τ are not the same particle from a report entitled « Present Knowledge about the New Particles » which I gave at the International Conference on Theoretical Physics[8] in Seattle, in September 1956.

« However it will not do to jump to hasty conclusions. This is because experimentally the K mesons (i.e. τ and ϑ) seem all to have the same masses and the same lifetimes. The masses are known to an accuracy of, say, from 2 to 10 electron masses, or a fraction of a percent, and the lifetimes are known to an accuracy of, say, 20 percent. Since particles which have different spin and parity values, and which have strong interactions with the nucleons and pions, are not expected to have identical masses and lifetimes, one is forced to keep the question open whether the inference mentioned above that the τ^+ and ϑ^+ are not the same particle is conclusive. *Parenthetically, I might add that the inference would certainly have been regarded as conclusive, and in fact more well-founded than many inferences in physics, had it not been for the anomaly of mass and lifetime degeneracies.* »

The situation that the physicist found himself in at that time has been likened to a man in a dark room groping for an outlet. He is aware of the fact that in some direction there must be a door which would lead him out of his predicament. But in which direction?

That direction turned out to lie in the faultiness of the law of parity conservation for the weak interactions. But to uproot an accepted concept one must first demonstrate why the previous evidence in its favor were insufficient. Dr. Lee and I[9] examined this question in detail, and in May 1956 we came to the following conclusions: (A) Past experiments on the weak interactions had actually no bearing on the question of parity conservation. (B) In the strong interactions, i.e. interactions of classes 1 and 2 discussed above, there were indeed many experiments that established parity conservation to a high degree of accuracy, but not to a sufficiently high degree to be able to reveal the effects of a lack of parity conservation in the weak interactions.

The fact that parity conservation in the weak interactions was believed for so long without experimental support was very startling. But what was more startling was the prospect that a space-time symmetry law which the physicists have learned so well may be violated. This prospect did not appeal to us. Rather we were, so to speak, driven to it through frustration with the various other efforts at understanding the ϑ—τ puzzle that had been made[10].

As we shall mention later there is known in physics a conservation law - the conservation of isotopic spin - that holds for interactions of class I but breaks down when weaker interactions are introduced. Such a possibility of an approximate symmetry law was, however, not expected of the symmetries related to space and time. In fact one is tempted to speculate, now that parity conservation is found to be violated in the weak interactions, whether in the description of such phenomena the usual concept of space and time is adequate. At the end of our discussion we shall have the occasion to come back to a closely related topic.

Why was it so that among the multitude of experiments on β-decay, the most exhaustively studied of all the weak interactions, there was no information on the conservation of parity in the weak interactions? The answer derives from a combination of two reasons. First, the fact that the neutrino does not have a measurable mass introduces an ambiguity that rules out[11] indirect information on parity conservation from such simple experiments as the spectrum of, β-decay. Second, to study directly parity conservation in β-decay it is not enough to discuss nuclear parities, as one had always done. One must study parity conservation of the *whole* decay process. In other words, one must design an experiment that tests right-left symmetry in the decay. Such experiments were not done before.

Once these points were understood it was easy to point out what were the experiments that would unambiguously test the previously untested assumption of parity conservation in the weak interactions. Dr. Lee and I proposed[9] in the summer of 1956 a number of these tests concerning β-decay, π-μ, μ-e and strange-particle decays. The basic principles involved in these experiments are all the same: *One constructs two sets of experimental arrangements which are mirror images of each other, and which contain weak interactions. One then examines whether the two arrangements always give the same results in terms of the readings of their meters* (or counters). If the results are not the same, one would have an unequivocal proof that right-left symmetry, as we usually understand it, breaks down. The idea is illustrated in Fig. 2 which shows the experiment proposed to test parity conservation in β-decay.

This experiment was first performed in the latter half of 1956 and finished early this year by Wu, Ambler, Hayward, Hoppes, and Hudson[12]. The actual experimental setup was very involved, because to eliminate disturbing outside influences the experiment had to be done at very low temperatures. The technique of combining β-decay measurement with low temperature apparatus was unknown before and constituted a major difficulty which was successfully solved by these authors. To their courage and their skill, physicists owe the exciting and clarifying developments concerning parity conservation in the past year.

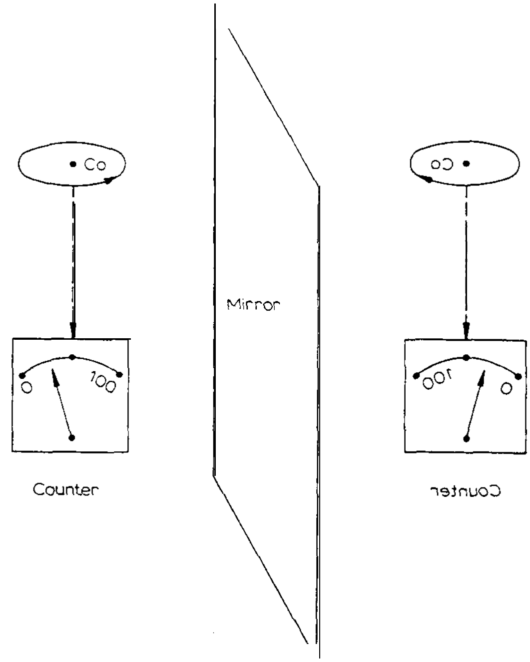

Fig. 2.

The results of Drs. Wu, Ambler, and their collaborators was that there is a very large difference in the readings of the two meters of Fig. 2. Since the behavior of the other parts of their apparatus observes right-left symmetry, the asymmetry that was found must be attributed to the β-decay of cobalt. Very rapidly after these results were made known, many experiments were performed which further demonstrated the violation of parity conservation in various weak interactions. In his lecturer Dr. Lee will discuss these interesting and important developments.

III

The breakdown of parity conservation brings into focus a number of questions concerning symmetry laws in physics which we shall now briefly discuss in general terms:

(A) As Dr. Lee[1] will discuss, the experiment of Wu, Ambler, and their collaborators also proves[13,14] that charge conjugation invariance[15] is violated for β-decay. Another symmetry called time reversal invariance[16] is at the present moment still being experimentally studied for the weak interactions.

The three discrete invariances - reflection invariance, charge conjugation invariance, and time reversal invariance - are connected by an important theorem[17] called the CPT theorem. Through the use of this theorem one can prove[13] a number of general results concerning the experimental manifestations of the possible violations of the three symmetries in the weak interactions.

Of particular interest is the *possibility* that time reversal invariance in the weak interactions may turn out to be intact. If this is the case, it follows from the CPT theorem that although parity conservation breaks down, right-left symmetry will still hold if[18] one switches all particles into antiparticles in taking a mirror image. In terms of Fig. 2 this means that if one changes *all* the matter that composes the apparatus at the right into anti-matter, the meter reading would become the same for the two sides if time reversal invariance holds. It is important to notice that in the usual definition of reflection, the electric field is a vector and the magnetic field a pseudovector while in this changed definition their transformation properties are switched. The transformation properties of the electric charge and the magnetic charge are also interchanged. It would be interesting to speculate on the possible relationship between the nonconservation of parity and the symmetrical or unsymmetrical role played by the electric and magnetic fields.

The question of the validity of the continuous space time symmetry laws has been discussed to some extent in the past year. There is good evidence that these symmetry laws do not break down in the weak interactions.

(B) Another symmetry law that has been widely discussed is that giving rise to the conservation of isotopic spin[19]. In recent years the use of this symmetry law has produced a remarkable empirical order among the phenomena concerning the strange particles[20]. It is however certainly the least understood of all the symmetry laws. Unlike Lorentz invariance or reflection invariance, it is not a « geometrical » symmetry law relating to space time invariance properties. Unlike charge conjugation invariance[21] it does not seem to originate from the algebraic property of the complex numbers that occurs in quantum mechanics. In these respects it resembles the conservation laws of charge and heavy particles. These latter laws, however, are exact while the conservation of isotopic spin is violated upon the introduction of electromagnetic interactions and weak interactions. An understanding of the origin of the conservation of isotopic spin and how to integrate it with the other symmetry laws is undoubtedly one of the outstanding problems in high-energy physics today.

(*C*) We have mentioned before that all the different varieties of weak interactions share the property of having very closely identical strengths. The experimental work on parity nonconservation in the past year reveals that they very likely also share the property of not respecting parity conservation and charge conjugation invariance. They therefore serve to differentiate between right and left once one fixes one's definition of matter vs. anti-matter. One could also use the weak interactions to differentiate between matter and anti-matter once one chooses a definition of right *vs.* left. If time reversal invariance is violated, the weak interactions may even serve to differentiate simultaneously right from left, and matter from anti-matter. One senses herein that maybe the origin of the weak interactions is intimately tied in with the question of the differentiability of left from right, and of matter from anti-matter.

1. T. D. Lee, *Nobel Lecture,* this volume, p. 406.
2. For references to these developments see E. P. Wigner, *Proc. Am. Phil. Soc.*, 93 (1949) 521.
3. Cf. the interesting discussion on bilateral symmetry by H. Weyl, Symmetry, Princeton University Press, 1952.
4. O. Laporte, *Z. Physik,* 23 (1924) 135.
5. E. P. Wigner, *Z. Physik,* 43 (1927) 624.
6. O. Klein, *Nature,* 161 (1948) 897; J. Tiomno and J. A. Wheeler, *Rev. Mod. Phys.,* 21 (1949) 144; T. D. Lee, M. Rosenbluth, and C. N. Yang, *Phys. Rev., 75 (1949) 905.*
7. R. Dalitz, *Phil. Mag.,* 44 (1953) 1068; E. Fabri, *Nuovo Cimento,* II (1954) 479.
8. *C. N. Yang, Rev. Mod. Phys.,* 29 (1957) 231.
9. T. D. Lee and *C. N. Yang, Phys. Rev.,* 104 (1956) 254.
10. T. D. Lee and J. Orear, *Phys. Rev.,* 100 (1955) 932; T. D. Lee and C. N. Yang, *Phys. Rev.,* 102 (1956) 290; M. Gell-Mann, (unpublished); R. Weinstein, (private communication) ; a general discussion of these ideas can be found in the *Proceedings of the Rochester Conference*, April 1956, Session VIII, Interscience, New York, 1957.
11. C. N. Yang and J. Tiomno, *Phys. Rev.,* 79 (1950) 495.
12. C. S. Wu, E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson, *Phys. Rev.,* 105 (1957) 1413.
13. T. D. Lee, R. Oehme, and C. N. Yang, *Phys. Rev.,* 106 (1957) 340.
14. B. L. Ioffe, L. B. Okun, and A. P. Rudik, *J.E.T.P. (U.S.S.R.),* 32 (1957) 396. English translation in *Soviet Phys.]ETP,* 5 (1957) 328.
15. Charge conjugation invariance is very intimately tied with the hole theory interpretation of Dirac's equation. The development of the latter originated with P. A. M. Dirac, *Proc. Roy. Soc. London,* A126 (1930) 360; J. R. Oppenheimer, *Phys. Rev.,*