Nobel Lecture: What does *CP* violation tell us?*

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I would first like to thank the Royal Swedish Academy of Sciences and the Nobel Foundation for awarding me this honor, of which I had never even dreamt.

I was born in 1940, the son of a furniture craftsman in a local city, Nagoya, in Japan. My father wanted to change his job and was taking a correspondence course to become an electrical engineer, while he was a trainee furniture craftsman. However, he told me that he could not really understand sine and cosine, since he had not received a basic education. Eventually, though, he did manage a small furniture factory employing a few craftsmen and worked there himself. But this came to nothing because of the war—that reckless and miserable war which our country caused.

After the war, he displayed in front of his house the door hinges, wood screws, and other pieces of furniture which remained at hand. They sold quite well. Getting a taste for selling, he became a merchant dealing with sugar as an ingredient for cakes.

He still wanted to boast of his knowledge of electricity, but he could not find anyone suitable to explain it to. One day, though, he found a good target, his son.

In those poor days after the war, almost all the houses were without bathrooms and so people went to the public bath. On his way to and from the public bath, he boasted of his knowledge: Why do three-phase current motors rotate? Why don't the solar and lunar eclipses occur every month? He explained proudly that it was because of the revolution planes of the earth around the sun and the moon around the earth that are tilted at an angle of 5°.

This was the reason why I was a strange pupil at school. I had a poor record but could answer the teacher's questions when he digressed and spoke about subjects outside of the textbooks.

My parents neither observed their children carefully nor helped with their study. One day, my mother realized that she had never seen her son studying at home. So she told my teacher at a parent's association meeting, "Please give my son homework at least occasionally. Otherwise, he never studies at home." My teacher answered, "Your son has never done his homework despite the fact that I give him homework every day!"

Disastrous was that night. I got a two hour lecture from my parents.

An event that gave me a strong wish to become a physicist happened after I went on to high school. I went to high school with no strong motivation. But, one day when I was in the first or second year, I found a newspaper article explaining that Professor Shoichi Sakata at Nagoya University had published a revolutionary theory (Sakata, 1956) about the composite model for elementary particles in which he chose the proton, neutron, and lambda particles as the fundamental three constituents.

I was so childish at that time that I thought that all of science had already been completed in Europe during the 19th century. If Professor Sakata's theory had come from Tokyo, I would have thought it irrelevant to me. But scientific discoveries were being developed right in Nagoya, where I was living! I became eager to join in such research activity there. My father, however, wanted his son to succeed him in the family business. So I was given only one chance to take an entrance examination for the university and could not fail it. I worked very hard to prepare for the entrance examination to Nagoya University.

Fortunately, I was accepted. The lectures at university were very different and much more stimulating than those in high school. The first class was about mathematical analysis. I learned about an axiom from Archimedes explaining that, for any two positive numbers, ϵ and δ, there is an integer N such that $N \times \epsilon > \delta$. And then the teacher continued the lecture to explain Dedekind's cut. It was a culture shock. Everything that I experienced in the university, including those lectures, was fresh and stimulating. Each time I began to study a new field, I was totally absorbed in it and told the people around me that I would research that subject in future.

When I was a senior, a professor in the Mathematics Department told me, "You will, of course, take an entrance examination for a mathematics graduate course, won't you?" When I answered, "No, I already sent the application form to a physics graduate course," the professor looked upset hearing this totally unexpected answer. Probably, I had been saying that I was planning to go on to a mathematics graduate course until just before.

This capriciousness of mine did not change even when I went to the physics graduate course in 1962. I thought that research of the brain was important and began a voluntary circle to study a perceptron with a few friends. However, when I had to write my Master's thesis in the

*The 2008 Nobel Prize in physics was shared by Yoichiro Nambu, Makoto Kobayashi, and Toshihide Maskawa. This paper is the text of the address given in conjunction with the award.

second year, I was preparing a paper on particle physics in Professor Sakata's laboratory.

In this period, research based on dispersion relations resulting from causality was popular in the world and a "bootstrap model" advocated by G. F. Chew was in fashion. In Sakata's laboratory, the composite model (Sakata, 1956) for "elementary" particles was popular, which was originally proposed by Professor Sakata in 1955.

At that time the symmetry between leptons and baryons concerning weak interactions which Gamba *et al.* (1959) had pointed out at the Kiev Conference in 1951 occupied the interest of the laboratory (Maki *et al.*, 1960); that is,

$$(\nu,e,\mu) \leftrightarrow (p,n,\Lambda).$$

Following this line, when the muon neutrino ν_μ was found, the majority of the Sakata laboratory naturally began to research the quartet constituent models. Indeed, in 1964, a quartet constituent model was proposed by Maki (1964), the associate professor at the laboratory.

Although I did not write papers during this period, I was very fascinated by the spontaneously broken chiral symmetry after reading Professor Nambu's papers (Nambu, 1960; Nambu and Jona-Lasinio, 1961a, 1961b). I was also interested in developments in current algebra and partially conserved axial-vector current (PCAC). Extending my interest in this direction, I encountered important papers such as "The Axial Vector Current in Beta Decay" by M. Gell-Mann and M. Levy (1960) and "Question of Parity Conservation in Weak Interactions" by T. D. Lee and C. N. Yang (1956). As the keystones of my research in particle physics, those papers strengthened my interest in observing how particles emerge through their weak interactions.

Although I did not publish it, I calculated several physical quantities in the framework of the Nambu–Jona-Lasinio (NJL) model (Nambu and Jona-Lasinio, 1961a, 1961b). For instance, I computed the pion decay constant f_π, but felt it rather small given the fact that it has a typical quantity characterizing the strong interaction. I persistently examined how the decay constant could be decreased by adjusting the free parameters in the NJL model: the coupling constant and the uv cutoff. I could get no definite answer since the contribution from the momentum region near the uv cutoff was most dominant. But I recognized the importance of renormalizability from this experience.

Although this research wasn't being paid much attention in Japan, there were physicists around the world who were examining higher order effects of weak interactions. If weak interaction is described by the current-current type four-fermion interaction, then the higher order effects diverge. So, these authors replaced the four-fermion interaction by a box diagram, as shown in Fig. 1 in which heavy scalar bosons and heavy fermions propagate in the intermediate state. This reduces to the usual four-fermion interaction in the heavy limit of scalar and fermion masses. It did not yet give a satisfactory model, but did allow the possibility of making the weak interaction renormalizable by scalar boson mediation. I was also paying attention to papers which persistently examined the higher order effects of the current-current interaction.

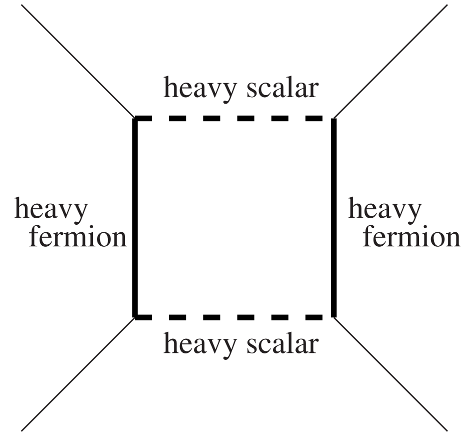

FIG. 1. Box diagram.

The laboratory subscribed to only one physics journal and so many people wanted to read the latest issue. Partly to resolve this problem, Sakata's laboratory also had a journal club in which members took turns to read and report on the new issue. When my turn came for the first time, the journal contained the paper by Christenson *et al.* (1964) reporting the observation of *CP* violation. This made a strong impression on me and raised the question: What is this? However, I had no clue at all how to attack the problem and thus laid it aside for eight years.

In the latter half of the 1960s, my interest was mainly focused on chiral symmetry and chiral dynamics. In this period I found, for instance, in the Nambu–Jona-Lasinio model that the pion decay constant is rather small for a typical constant characterizing the strong interaction and that the pion squared mass is the quantity of the first order in the chiral symmetry breaking. I still didn't write any papers about this. I regard them as études for a physicist just as painters draw variations of changing poses or compositions.

The idea of spontaneous symmetry breaking in Nambu and Jona-Lasinio's paper was very attractive, but there are no massless particles interacting strongly in reality. So, many physicists began to focus their efforts on evading the Nambu-Goldstone (NG) theorem (Goldstone, 1961; Goldstone *et al.*, 1962). Higgs was among them. The reason why the NG massless boson appears is that there are only two form factors proportional to $\gamma_5 p_\mu$ and $\gamma_\mu\gamma_5$ in the axial current and the current conservation condition leads to the existence of a massless pole in one of the two form factors. This was what the NG theorem describes. Then Higgs (1964, 1966) appeared and developed his arguments in the Coulomb gauge where the manifest Lorentz invariance is lost so that one more form factor can appear and one can evade the NG theorem.

It was the paper of the Higgs mechanism with which not only the massless NG boson disappears but also the gauge boson becomes massive. I could not follow his logic. Soon, fortunately, Kibble (1967) appeared and made clear the mechanism in a Lorentz covariant manner, which I could understand. Then, the electroweak unified theory by Weinberg (1967) and Salam (1968), as well as the Faddeev-Popov paper (Faddeev and Popov, 1967) clarifying the Feynman rule for Yang-Mills theory, appeared.

In connection with the four quark model and from my interest in the higher order effects of weak interaction, I noticed a paper by Glashow, Iliopoulos, and Maiani (GIM) (1969) and called the attention of some of my colleagues to it. This reminded me of the four quark model once again, although all the graduates of Sakata laboratory already knew about it.

There is a paper from this period which was cited as "Z. Maki and T. Maskawa, RITP-146" (Maki and Maskawa, 1973) in my paper on *CP* violation with M. Kobayashi (Kobayashi and Maskawa, 1973). It was written just before the *CP* violation paper and the title was "Hadron Symmetries and Gauge Theory of Weak and Electromagnetic Interactions." This paper is little known since I never announced that it was published in *Progress of Theoretical Physics*. If the strong interaction chooses a specific direction in the four quark model, then its interference with the weak interaction would have easily caused *CP* violation. People came to know after 1974 that the strong interaction is described by quantum chromodynamics (QCD) and that it has no specific direction other than the quark mass terms specified by the Higgs field. This was, however, unknown at that time in 1972, so we needed the analysis of the strong interaction given in the paper above.

When the electroweak unified gauge theory appeared, I felt intuitively that the time had come to take up the *CP* violation problem. After finishing the graduate course, I became an assistant professor for three years in Nagoya University and then moved to Kyoto University in 1970. Kobayashi also came to Kyoto as an assistant professor two years later, in April 1972.

We have a series of holidays called Golden Week in the beginning of May in Japan. After the Golden Week, Kobayashi and I started a new collaboration. It was a good opportunity for us to work again in the same laboratory. I felt that the time was ripe for attacking the *CP* violation problem as stated above and proposed it as the theme of our collaboration. Kobayashi had also been approaching this problem in Nagoya.

We started to study the *CP* violation based on the quartet quark model in the electroweak unified gauge theory. First, we had to determine how the left- and right-handed components of the four quarks transform under the electroweak symmetry $SU(2)\times U(1)$:

(A) $4=2+2$,

(B) $4=2+1+1$,

(C) $4=1+1+1+1$.

There are these three cases for each of the left- and right-handed components, so that we have to consider nine cases in all. In all the cases except for case (A), (B) where the left-handed component is (A) and the right-handed component is (B), we see that the *CP* violation cannot occur if we take into account the freedom to arbitrarily choose the phases of the quark fields. The last case (A), (B) was an exception.

I thought that it seemed to work since all the other cases failed and I asked Kobayashi whether he agreed. Kobayashi put his head a little to one side and answered "I will examine this in detail overnight." He probably knew the result already, but answered like that for safety. The next day he told me, "That case does not work since it predicts wrong sign for g_V/g_A contradicting the experiment."

During this time, I was a chief secretary of the labor union in Kyoto University. There was a growing problem related to the dismissal of secretaries in our Faculty of Science. I could not concentrate on my research pretending not to see these dismissals since the secretaries really supported our young researchers. I discussed physics with Kobayashi in the morning and worked at the union in the afternoon. Coming back home in the evening, I enjoyed dinner with my family and talked with them about the events of the day. After taking a bath I had time to think about my research. This was how I was living back in those days.

After Kobayashi eliminated the possibility of the case (A), (B), a search for the way out began, attempting to explain how the *CP* violation could be understood as a four quark model. We fought a tough struggle for a month or so. And one day, while taking a bath, I thought: No good model exists which can explain the *CP* violation in the four quark model if we stick to the renormalizable theory of weak interaction. So I made up my mind to write a negative paper which proved that *CP* violation cannot be explained in the four quark model in a framework of renormalizable electroweak theory.

Deciding to finish this work by writing a poor paper and thinking up an excuse, I got out of the bathtub. Probably this may have freed me from sticking to the four quark model. Suddenly, I recognized that it must work well in the six quark model. It was already clear from our many trials and calculations up until then that a complex phase could remain there.

In the framework of unified electroweak gauge theory, there is a scalar field called the Higgs field. When it develops a nonvanishing vacuum expectation value, the quark fields acquire their masses. If we rewrite the quark fields into those which have definite masses, then the charged current operators in the weak interaction develop a unitary matrix U. If a complex phase appears in the matrix elements of U, *CP* violation occurs.

This explanation may give the wrong impression that the complex phase always leads to *CP* violation. Actually, since the quark fields q_i are complex, we have the freedom to change their phases arbitrarily as $q_i \to e^{i\alpha_i} q_i$. Clearly this leaves physics intact, but the phases of the matrix elements of U are changed. Recall that the charged weak current has the structure, complex conjugate of up-type quark fields $\bar{u}_i$ times down-type quark fields d_j times the $i-j$ matrix elements U_{ij} of U: $\bar{u}_i U_{ij} d_j$. Here i,j run from 1 to N if there exist N generations of quarks.

Therefore, the phase change of the $2N$ quark fields,

$$u_i \to e^{ia_i} u_i, \quad d_j \to e^{ib_j} d_j, \tag{1}$$

induces the phase change of the matrix element

$$U_{ij} \to e^{-i(a_i - b_j)} U_{ij}. \tag{2}$$

Therefore, among the $2N$ phase changes for $2N$ quark fields, $2N-1$ degrees of freedom can be used to change the phase of U, since a common phase transformation for all quark fields does not change U.

The $N \times N$ unitary matrix U, which appears in the charged weak current when the $\mathrm{SU}(2) \otimes \mathrm{U}(1)$ doublet quark fields are rewritten in terms of the mass eigenstate quark fields, generally has $N(N+1)/2$ degrees of freedom for the complex phase. If we subtract the above freedom of quark field phase change, then we are left with

$$N(N+1)/2 - (2N-1) = (N-2)(N-1)/2$$

as the net number of physical complex phases in the matrix U.

This number vanishes for $N=1$ and $N=2$, which correspond to the two and four quark cases, respectively, explaining that we have no complex phases in the matrix U and thus no *CP* violation for the two and four quark cases. However, when we go to the $N=3$ generation case, i.e., the six quark model, then this number is 1 and the CP violation can occur for the first time!

We have thus completed our work. The origin of the *CP* violation was revealed partially at least.

It, however, took a long time: more than 30 years and vast efforts of many experimenters to really verify this theory. I would like to thank here all the people in the world who supported this grand project of humanity.

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