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Nobel Lecture: *CP* violation and flavor mixing[*]

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I. INTRODUCTION

We know that ordinary matter is made of atoms. An atom consists of the atomic nucleus and electrons. The atomic nucleus is made of a number of protons and neutrons. The proton and the neutron are further made of two kinds of quarks, u and d. Therefore, the fundamental building blocks of ordinary matter are the electron and two kinds of quarks, u and d (see Fig. 1).

The standard model, which gives a comprehensive description of the current understanding of the elementary particle phenomena, however, tells us that the number of species of quarks is six. The additional quarks are called s, c, b, and t. The reason why we do not find them in ordinary matter is that they are unstable in the usual environment. Similarly, the electron belongs to a family of six members called leptons. Three types of neutrinos are included among these six.

Another important ingredient of the standard model is the fundamental interactions. Three kinds of interactions act on the quarks and leptons. The strong interaction is described by quantum chromodynamics (QCD) and the electromagnetic and weak interactions by the Weinberg-Salam-Glashow theory in a unified manner. All of them belong to a special type of the field theory called gauge theory.

The standard model was established in the 1970s. It was triggered by the development of the studies of gauge theories. In particular, it was proved that the generalized gauge theory is renormalizable ('t Hooft, 1971; 't Hooft and Veltman, 1972). This opened the possibility that all the interactions of the elementary particle can be described by the quantum field theory without the difficulty of divergence. Before this time, such a description was possible only for the electromagnetic interaction.

The discovery of the new flavors made in the 1970s played an important role in the establishment of the standard model. In particular, the τ lepton and c and b quarks were found in the 1970s. When we proposed the six quark model to explain *CP* violation with Dr. Toshihide Maskawa in 1973 (Kobayashi and Maskawa, 1973), only three quarks were widely accepted, and a slight hint of the fourth quark was there, but no one thought of the six quarks.

In the following, I will describe the development of the studies on *CP* violation and the quark and lepton flavors, putting some emphasis on contributions from Japan. The next section will be devoted to the pioneering works of the Sakata School, from which I learned many things. The work on *CP* violation will be discussed in Sec. III. I will explain what we thought and what we found at that time. Section IV will describe subsequent development related to our work. Experimental verification of the proposed model has been done by using accelerators called B factories. A brief outline of those experiments will be given. Finally in Sec. V, I will glance over the flavor mixing in the lepton sector because this is a phenomenon parallel to the flavor mixing in the quark sector, and Japan has made unique and important contributions in this field.

II. SAKATA SCHOOL

Both Dr. Maskawa and I graduated from and obtained our Ph.D.'s from Nagoya University. When I entered the graduate program, the theoretical particle physics group of Nagoya University was known for its unique research activity, led by Professor Shoichi Sakata (see Fig. 2).

In the early 1950s, a number of strange particles were discovered, while its first evidence was found in the cosmic ray events in 1947. In the current terminology,

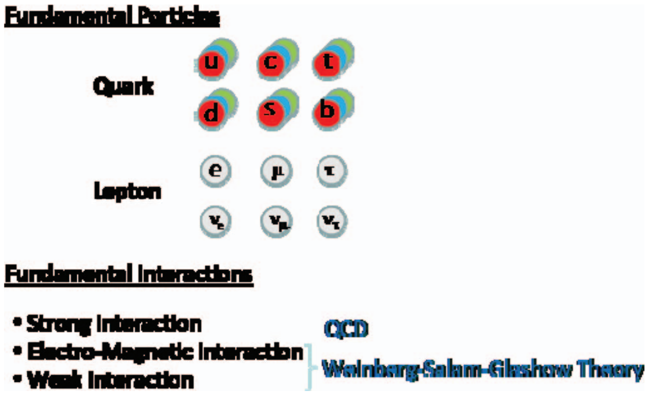

FIG. 1. (Color) The standard model.

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[*] The 2008 Nobel Prize for 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.

FIG. 2. (Color) Shoichi Sakata 1911–1970 (courtesy of Sakata Memorial Archival Library).

strange particles contain s quark or anti-s quark as a constituent, while nonstrange particles do not. But what we are about to consider is the era before the quark model appeared.

In 1956, Sakata (Sakata, 1956) proposed a model which is known as the Sakata model. In this model, all hadrons, strange and nonstrange, are supposed to be composite states of the triplet of baryons; the proton (p), the neutron (n), and the lambda (Λ). In other words, three baryons, p, n, and Λ, are the fundamental building blocks of the hadrons in the model. Eventually, the Sakata model was replaced by the quark model, where the triplet of quarks, u, d, and s, replace p, n, and Λ. But the root of the idea of fundamental triplet is in the Sakata model.

In the following, we focus on the weak interactions in the Sakata model. Usual beta decays of the atomic nucleus are caused by the transition of the neutron into the proton. Similarly we can consider the transition of the lambda into the proton. In the Sakata model, all the weak interaction of the hadrons can be explained by these two kinds of transitions among the fundamental triplet.

This pattern of the weak interaction is quite similar to the weak interaction of the leptons:

$$\begin{array}{ccccccccc} & & p & & & & & \nu & \\ & \swarrow\nearrow & & \nwarrow\searrow & \Leftrightarrow & \swarrow\nearrow & & \nwarrow\searrow & . \\ n & & & & \Lambda \quad e & & & & \mu \end{array}$$

It should be noted that at that time the neutrino was thought as a single species. This similarity of the weak interaction between the baryons and the leptons was pointed out by Gamba *et al.* (1959).

In 1960, Maki *et al.* (1960) developed the idea of baryon-lepton or B-L symmetry further and proposed the so-called Nagoya model. They considered that the triplet baryons, p, n, and Λ, are composite states of a hypothetical object called B matter and the neutrino, the electron, and the muon, respectively,

$$p = \langle B^+\nu\rangle, \quad n = \langle B^+ e\rangle, \quad \Lambda = \langle B^+\mu\rangle$$

where B matter is denoted as B^+.

Although the composite picture of the Nagoya model did not lead to a remarkable progress, some ideas of the Nagoya model developed in an interesting way. In 1962, it was discovered that there exist two kinds of neutrinos, corresponding to each of the electron and the muon. When the results of this discovery at BNL (Danby *et al.*, 1962) were to come out, two interesting papers were published: one written by Maki *et al.* (1962) and the other by Katayama *et al.* (1962). Both papers discussed the modification of the Nagoya model to accommodate two neutrinos in the model.

In the course of the argument to associate leptons and baryons, Maki *et al.* discussed the masses of the neutrinos and derived the relation describing the mixing of the neutrino states,

$$\nu_1 = \cos\theta\nu_e + \sin\theta\nu_\mu,$$

$$\nu_2 = -\sin\theta\nu_e + \cos\theta\nu_\mu,$$

where ν_1 and ν_2 are the mass eigenstates of neutrinos, and they assumed that the proton is the composite state of the B matter and ν_1. Although the last assumption is not compatible with the current experimental evidence, it is remarkable that they did present the correct formulation of lepton flavor mixing. To recognize their contribution, the lepton flavor mixing matrix is called the Maki-Nakagawa-Sakata matrix today.

Lepton flavor mixing gives rise to the phenomenon called neutrino oscillation. Many years later, neutrino oscillation was discovered in an unexpected manner. We will come back to this point later.

Another important outcome of this argument is the possible existence of the fourth fundamental particle associated to ν_2. This was discussed by Katayama *et al.* in some detail. At the moment, the fundamental particles were still considered baryons but the structure of the weak interaction discussed here is the same as that of the Glashow-Illiopoulos-Miani (Glashow *et al.*, 1970) scheme.

These works were revived in 1971, when Niu and collaborators found new kinds of events in the emulsion chambers exposed to cosmic rays (Niu *et al.*, 1971). One of the events they found is shown in Fig. 3. In this event, we see kinks on two tracks, which indicate the decay of new particles produced in pair. The estimated mass of the new particle was 2–3 GeV and the life was a few times that of 10^{-14} s under some reasonable assumptions.

When this result came to his attention, Shuzo Ogawa, a member of the Sakata group, immediately pointed out that this new particle might be related to the fourth element expected in the extended version of the Nagoya model (Ogawa, 1971). At that moment, the Sakata

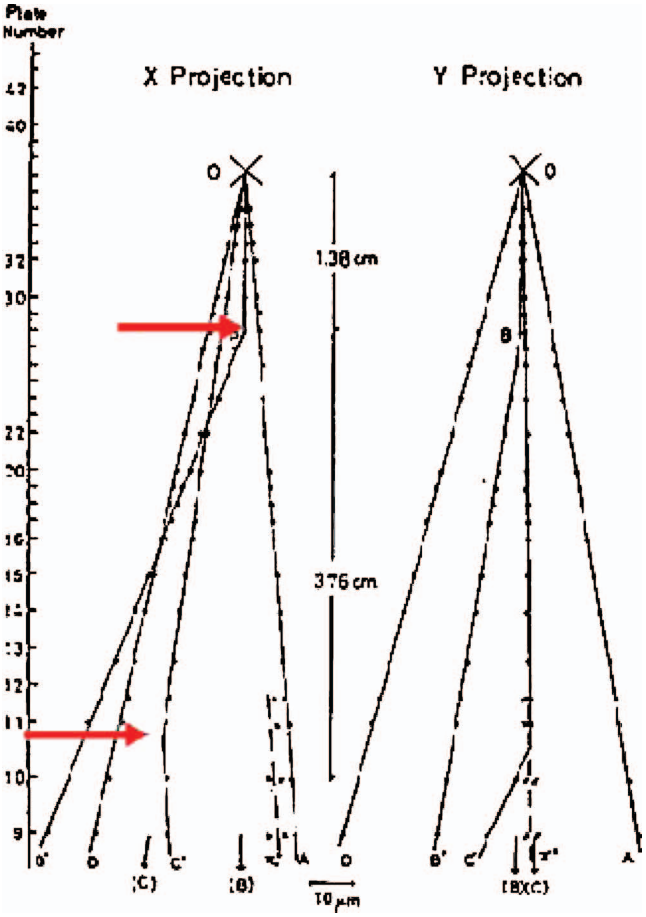

FIG. 3. (Color) A cosmic ray event (Niu *et al.*, 1971).

model was already replaced by the quark model, so that what he meant was that those new particles might be charmed particles in the current terminology. Following this suggestion, several Japanese groups, including myself, began to investigate the four quark model (Hayashi *et al.*, 1972; Kobayashi *et al.*, 1972; Kondo *et al.*, 1972; Maki *et al.*, 1972). At that time, I was a graduate student of Nagoya University.

So far I have explained about unique activities of the Sakata School. I mentioned about the four quark model in some detail. But, I do not mean to imply that the six quark model we proposed is a simple extension of the four quark model. What was most important for me was the atmosphere of the particle physics group of Nagoya University. Although most of the work we discussed in this section had been done by Sakata and his group before I entered the graduate course, the spirit grown through these works was still there. I learned the importance of capturing the entire picture, which is necessary for this kind of work.

III. SIX QUARK MODEL

In 1971, renormalizability of the non-Abelian gauge theory was proved ('t Hooft, 1971; 't Hooft and Veltman, 1972). This enabled a description of the weak interactions with the quantum field theory in a consistent manner, and the Weinberg-Salam-Glashow (Glashow, 1961; Weinberg, 1967; Salam, 1968) theory began to attract attention. In 1972, I obtained my Ph.D. from Nagoya University and moved to Kyoto University. Then the work on *CP* violation started.

CP violation was first found in 1964 by Christenson *et al.* (1964) in the decay of the neutral *K* meson. *CP* violation means violation of symmetry between particles and antiparticles. The discovery of *CP* violation implies that there is an essential difference between particles and antiparticles.

We thought that if the gauge theory can describe the interactions of particles consistently, *CP* violating interaction should also be included in it. It was rather straightforward to solve the problem. We simply investigated conditions for *CP* violation in the renormalizable gauge theory. What we found then is summarized as follows (Kobayashi and Maskawa, 1973).

At that time only three quarks were widely accepted, but the three quark model has some flaw in the gauge theory. Therefore, from the theoretical point of view, the four quark model of the Glashow-Iliopoulos-Maiani type was thought a preferable one. However, it is impossible to accommodate *CP* violation in the model of the Glashow-Iliopoulos-Maiani (GIM) type. We found that even if we relax the condition of the GIM type, we cannot make any realistic model of *CP* violation with four quarks. This implies that there must be some unknown particles besides the fourth quark. I thought that this was quite strong and an important conclusion of our argument.

Then we considered a few possible mechanisms of *CP* violation by introducing new particles. We proposed the six quark model as one of such possible mechanisms.

Below we discuss the quark flavor mixing in some detail in order to understand why four quarks are not enough and six quarks are needed to accommodate *CP* violation.

In the framework of the gauge theory, flavor mixing arises from mismatch between gauge symmetry and particle states. Gauge symmetry lumps a certain number of particles into a group called a multiplet. However, each multiplet member is not necessarily identical to a single species of particles, but sometimes it is a superposition of particles. The flavor mixing is nothing but this superposition. In the present case, the relevant gauge group is SU(2) of the Weinberg-Salam-Glashow theory and the multiplet is a doublet.

Assuming that four quarks consist of two doublets of the SU(2) group, we can denote the most general form of them as

$$\begin{pmatrix} u \\ d' \end{pmatrix}, \quad \begin{pmatrix} c \\ s' \end{pmatrix},$$

where d' and s' are the superposition of real quark states d and s, described in a matrix form as

$$\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} \\ V_{cd} & V_{cs} \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix},$$

where the matrix describing the mixing should be what is called a unitary matrix in mathematics.

The next problem is what the condition for *CP* violation is. In the quantum field theory, *CP* violation is related to complex coupling constants. To be more concrete in the present formulation, *CP* violation will occur if irreducible complex numbers appear in the elements of the mixing matrix. The matrix elements of a unitary matrix are complex numbers in general, but some of them can be made real by adjusting the phase factor of the particle state without changing the physics results. In such a case, those complex numbers are called reducible, and otherwise, irreducible. Therefore, the condition of *CP* violation is that there remain complex numbers which cannot be removed by the phase adjustment of the particle states.

In the four quark model, adjustment factors are described by two diagonal matrices whose elements are mere phase factors. It is easy to see that if we choose them properly, we can make any 2×2 unitary matrices into a real matrix as

$$\begin{pmatrix} e^{i\phi_u} & 0 \\ 0 & e^{i\phi_c} \end{pmatrix} \begin{pmatrix} V_{ud} & V_{us} \\ V_{cd} & V_{cs} \end{pmatrix} \begin{pmatrix} e^{-i\phi_d} & 0 \\ 0 & e^{-i\phi_s} \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}.$$

Therefore, in this case, we cannot accommodate *CP* violation.

How does this argument change in the six quark model? In this case, we can express the flavor mixing as follows:

$$\begin{pmatrix} u \\ d' \end{pmatrix} \quad \begin{pmatrix} c \\ s' \end{pmatrix} \quad \begin{pmatrix} t \\ b' \end{pmatrix},$$

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}.$$

This time the mixing matrix is a 3×3 unitary matrix. In this case, however, we cannot remove all the phase factors of the matrix elements by adjusting the phases of quark states. The best we can do by adjusting the phases is to express them by a certain standard form with four parameters. A popular parametrization is

$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix},$$

where $c_{ij}=\cos\theta_{ij}$ and $s_{ij}=\sin\theta_{ij}$ with $i,j=1,2,3$. We note that, unless $\delta=0$, the imaginary part remains in the matrix elements and, therefore, *CP* symmetry is violated.

Taking into account the hierarchy of the actual values of the parameters, the following approximate parametrization is frequently used in the phenomenological analyses:

$$V \approx \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4).$$

In this parametrization, if η is not zero, the system is violating *CP* symmetry.

We thought that this mechanism of *CP* violation is very interesting and elegant, but we had no further reason to single out the six quark model from the other possibilities. The model was not so special because if the system has sufficiently many particles, it is not difficult to violate *CP* symmetry. However, the subsequent experimental development pushed up the six quark model to a special position.

In 1974, the J/Ψ particle was discovered (Aubert *et al.*, 1974; Augustin *et al.*, 1974), and soon it turned out that it is the bound state of the fourth quark c and its antiparticle. The discovery had a great impact on particle physics, but it had little effect on the six quark model.

In 1975, the τ lepton was discovered (Perl *et al.*, 1975). This discovery had significant effect on our model. The τ lepton is the fifth member of leptons. Although it is a lepton, it was suggesting the existence of the third family in the quark sector too. It was when people began to pay attention to our model. Early works which discussed the six quark model include Pakvasa and Sugawara (1976) and Ellis *et al.* (1976).

In 1977, the upsilon particle was discovered (Herb *et al.*, 1977), and it turned out that it is a bound state of the fifth quark b and anti-b. The discovery of the last quark, t, was as late as in 1995 (Abachi *et al.*, 1975; Abe *et al.*, 1995), but before that time the six quark model became a standard one.

Meanwhile, it was pointed out that we can expect large *CP* asymmetry in the B-meson system (Bigi and Sanda, 1981; Carter and Sanda, 1981). This opened the possibility to test the model with B factories. B meson implies a meson containing b or anti-b as a constituent,

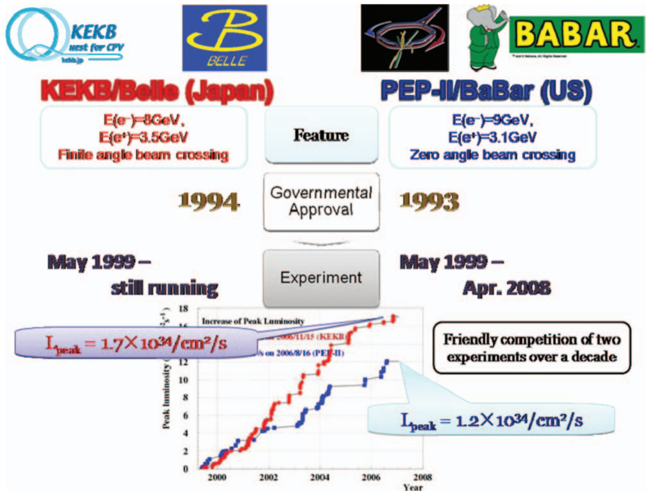

FIG. 4. (Color) KEKB/Belle and PEP-II/BaBar.

and B factory means an accelerator which produces a lot of B mesons like a factory.

IV. EXPERIMENTAL VERIFICATION AT *B* FACTORIES

In order to verify the six quark model experimentally, two B factories, KEKB at KEK in Japan and PEPII at SLAC in the USA, were built. Those accelerators are unusual ones. Colliding electrons and positrons have different energies, so that the produced B mesons are boosted. Both experimental groups, Belle (KEKB) and BaBar (PEPII), are large international teams organized with the participation from many countries (see Fig. 4).

They were approved and started experiments almost at the same time. PEPII/BaBar ceased operation this year, while KEKB/Belle is still running. They achieved the luminosities of more than $10^{34}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, which are record highs. The luminosity is a key parameter representing the performance of the colliding accelerator.

One of the typical methods of measuring CP violation in the B-factory experiment is shown in Fig. 5. The six quark model predicts fairly large asymmetry between B meson and anti-B meson in the decay time distribution of, for example, $B(\bar{B})\to J/\psi + K_S$. Thanks to the boost of the produced B mesons, we can find the decay time distribution of B or anti-B by measuring its decay position. This requires, however, measuring the decay position to the accuracy of 10 μm, so that a sophisticated device called a vertex detector is installed.

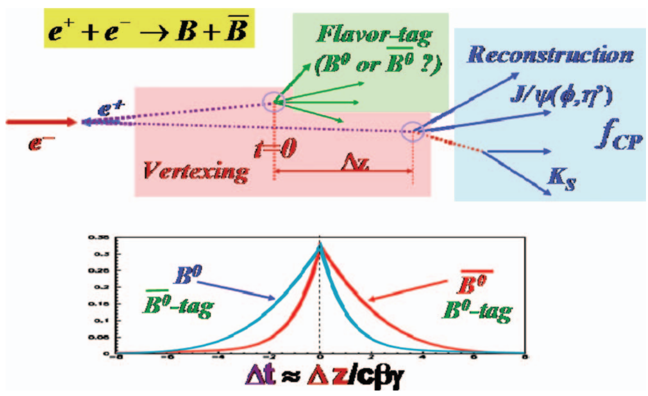

FIG. 5. (Color) A typical method of measuring CP violation in the B-meson decay.

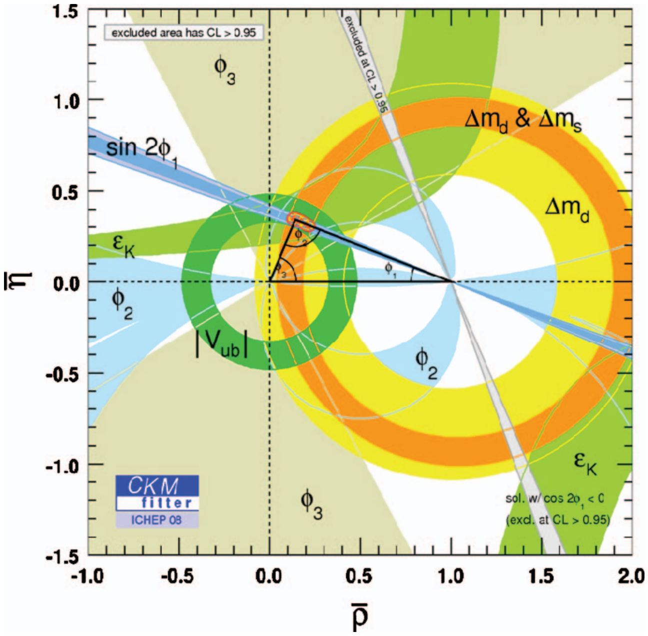

FIG. 6. (Color) The results of the B-factory experiments (Charles, 2005).

The most important results of the experiments are well described by Fig. 6 (Abe *et al.*, 2002; Aubert *et al.*, 2002). The colored circles and cones show the experimental constraints on the mixing parameters ρ and η. All the constraints overlap on a narrow region colored by red. This means the six quark model can explain all those results by choosing the parameters in this region.

In the light of the B-factory results, the present status of CP violation may be summarized as follows:

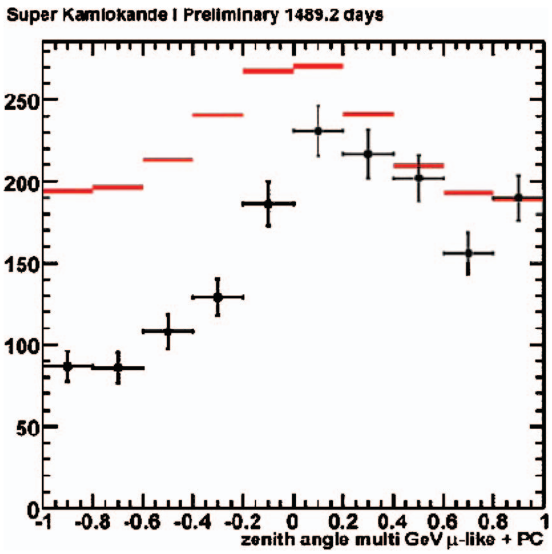

FIG. 7. (Color) The results of the observation of atmospheric neutrinos (Raaf, 2008).

FIG. 8. (Color) Yoji Totsuka 1911–2008 (courtesy of KEK).

- *B*-factory results show that quark mixing of the six quark model is the dominant source of the observed *CP* violation.
- *B*-factory results, however, allow small room for additional source from new physics beyond the standard model.
- Matter dominance of the Universe seems to require a new source of *CP* violation because it appears that *CP* violation of the six quark model is too small to explain the matter dominance.

It has been proposed that the last point may be related to the lepton flavor mixing, which is the counter part of the quark mixing. In regard to the lepton flavor mixing, very important contributions have been made in Japan, which will be discussed in the next section.

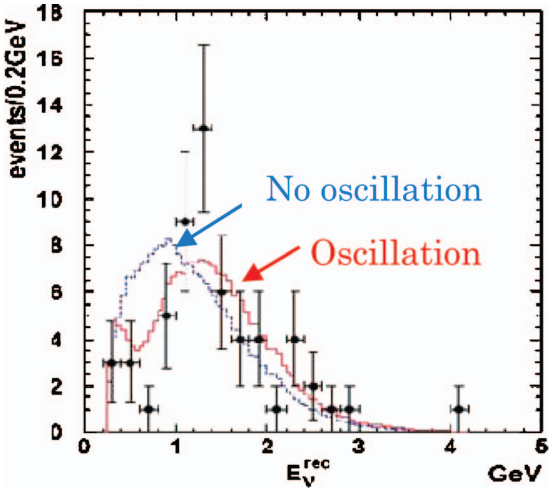

FIG. 9. (Color) The result of the K2K experiment (Ahn *et al.*, 2003, 2005).

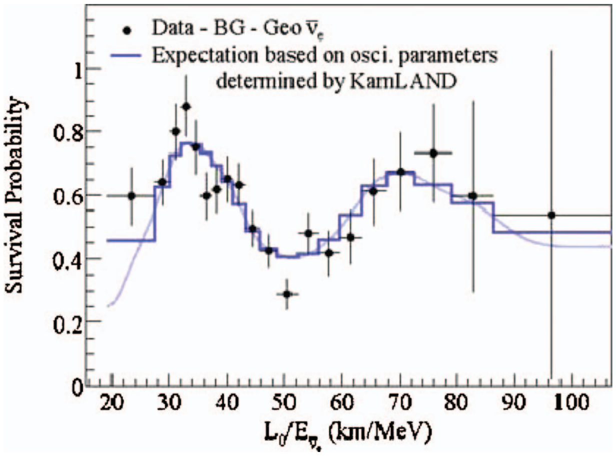

FIG. 10. (Color) The result of the KamLAND experiment (Eguchi *et al.*, 2003; Araki *et al.*, 2006).

V. LEPTON FLAVOR MIXING

The most important achievement is the discovery of the neutrino oscillation at Super Kamiokande, which is a huge water tank detector built in the Kamioka mine in central Japan (Fukuda *et al.*, 1998).

They were observing neutrinos produced by cosmic rays in the atmosphere surrounding the Earth. Since neutrinos penetrate the Earth, those neutrinos come to the detector also from the bottom. The neutrino oscillation implies the species of neutrino changes during its flight. So, if the neutrino oscillation takes place while neutrinos are traveling the distance from the other side of the Earth, the observed number of the particular kind of neutrino will be reduced.

Figure 7 shows the result of their observation. The red bars indicate the expectations for the nonoscillation case and the crosses are real data. The results show a clear deficit of the observed neutrinos and are completely consistent with the neutrino oscillation.

This great discovery was led by Yoji Totsuka (Fig. 8). To our deep regret, he passed away this last July.

The neutrino oscillation was further confirmed by two experiments using man-made neutrinos. One is the K2K experiment (Ahn *et al.*, 2003, 2006). In this experiment, neutrinos were produced by the proton synchrotron in the KEK laboratory and those neutrinos were observed by the Super Kamiokande. Figure 9 shows the observed neutrino spectrum. Data show a clear oscillation pattern.

The other experiment is the KamLAND experiment (Eguchi *et al.*, 2003; Araki *et al.*, 2005). The KamLAND detector uses a liquid scintillator instead of water and it is also located in the Kamioka mine. They observed neutrinos produced in the nuclear reactors in the surrounding area. Data show a clean agreement with the oscillation (Fig. 10).

While we have seen the past and present experiments, the T2K experiment is an upcoming future experiment. Neutrinos will be produced by the newly built accelerator J-PARC located in Tokai, 60 km north east of KEK, and sent to Super Kamiokande. The distance to the detector is more or less the same as the K2K, but the intensity will be much higher. The T2K experiment aims for the ν_e appearance measurement, which means the observation of ν_μ to ν_e oscillation. This measurement has a crucial importance for estimating the possible size of *CP* violation in the lepton sector, which may have some implication for the matter dominance of the Universe.

In summary, I think that Japan made important contributions to flavor physics. It includes early activities of the Sakata group on both hadron and lepton flavors, and the experimental studies of *B* meson system at KEK *B* factory and the observations of neutrino oscillation at Super Kamiokande and KamLAND. I am very glad that I was able to be an eyewitness of the many of these developments. In particular, it is unforgettable that I could work together with the colleagues of the *B*-factory experiments. Also above all things, I am very happy that I could make contributions through the work with Dr. Maskawa to these developments.

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