CP VIOLATION AND FLAVOUR MIXING

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by

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1. 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. A proton and a 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.

The standard model, which gives a comprehensive description of 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 fundamental interactions. Three kinds of interactions act on the quarks and leptons. The strong interaction is described by Quantum Chromodynamics (QCD) and the electro-magnetic and weak interactions by the Weinberg-Salam-Glashow theory in a unified manner. All of them belong to a special type of field theory called gauge theory.

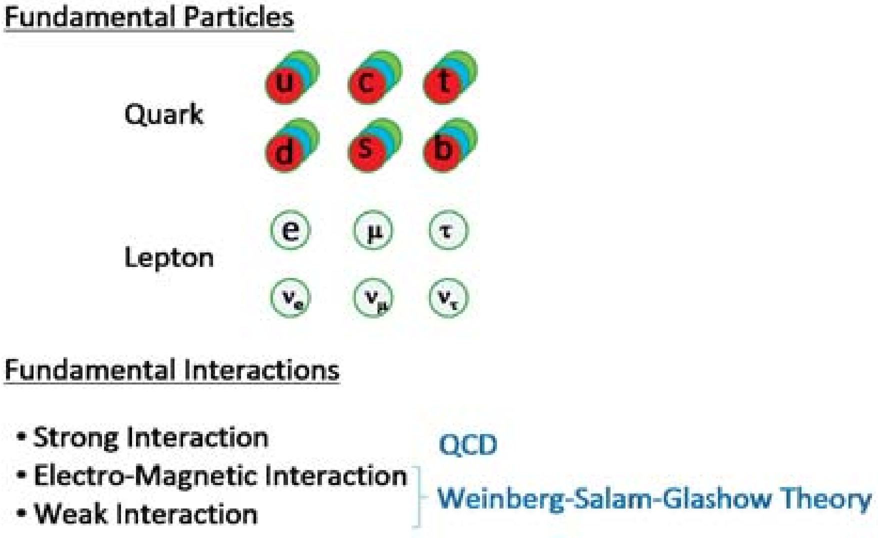

Figure 1. The Standard Model.

The standard model was established in the 1970s. It was triggered by the development of studies of gauge theories. In particular, it was proved that generalised gauge theory is renormalisable [1]. This opened the possibility that all the interactions of an elementary particle can be described by the quantum field theory without the difficulty of divergence. Before this time, such description was possible only for electro-magnetic interaction.

The discovery of the new flavours made in 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 [2], only three quarks were widely accepted, and a slight hint of the fourth quark was there, but no one thought there would be six quarks.

In the following, I will describe the development of the studies on CP violation and the quark and lepton flavours, 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 Section 3. I will explain what we thought and what we found at that time. Section 4 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 Section 5, I will look briefly at flavour mixing in the lepton sector, because this is a phenomenon parallel to the flavour mixing in the quark sector, and Japan has made unique and important contributions in this field.

2. SAKATA SCHOOL

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

Figure 2. Shoichi Sakata 1911–1970 (Courtesy of Sakata Memorial Archival Library).

In the early 1950s, a number of strange particles were discovered, with the first evidence having been found in the cosmic ray events of 1947. In the current terminology, strange particles contain an s-quark or anti-s-quark as a constituent, while non-strange particles do not. But what we are about to consider is the era before the quark model appeared.

In 1956, Sakata [3] proposed a model which is known as the Sakata model. In this model, all hadrons, strange and non-strange, 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 a neutron into a proton. Similarly we can consider the transition of a lambda into a 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;

$$\begin{tikzcd} & p \arrow[dl, shift left] \arrow[dr, shift left] & & & & \nu \arrow[dl, shift left] \arrow[dr, shift left] & \\ n \arrow[ur, shift left] & & \Lambda \arrow[ul, shift left] & \Leftrightarrow & e \arrow[ur, shift left] & & \mu \arrow[ul, shift left] \end{tikzcd}$$

It should be noted that at that time, the neutrino was thought of as a single species. This similarity of the weak interaction between the baryons and the leptons was pointed out by Gamba, Marshak and Okubo [4].

In 1960, Maki, Nakagawa, Ohnuki and Sakata [5] 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 remarkable progress, some ideas in the Nagoya model developed in an interesting way. In 1962, it was discovered that there exist two kinds of neutrinos, corresponding to the electron and the muon, respectively. When the results of this discovery at BNL [6] were to come out, two interesting papers were published, one written by Maki, Nakagawa and Sakata [7] and the other by Katayama, Matsumoto, Tanaka and Yamada [8]. 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 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 flavour mixing. To recognise their contribution, the lepton flavour mixing matrix is called the MNS matrix today.

Lepton flavour 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 with ν_2. This was discussed by Katayama *et al.* in some detail. At the time, 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 [9] scheme.

These works were revived in 1971, when Niu and his collaborators found new kind of events in emulsion chambers exposed to cosmic rays [10]. One of the events they found is shown in Figure 3. In this event, we see kinks on two tracks, which indicate the decay of new particles produced in pairs. The estimated mass of the new particle was 2~3 GeV and the life was a few times 10^{-14} sec. 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 [11]. By that time, the Sakata model had already been 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 mine, began to investigate the four-quark model [12]. At that time, I was a graduate student at Nagoya University.

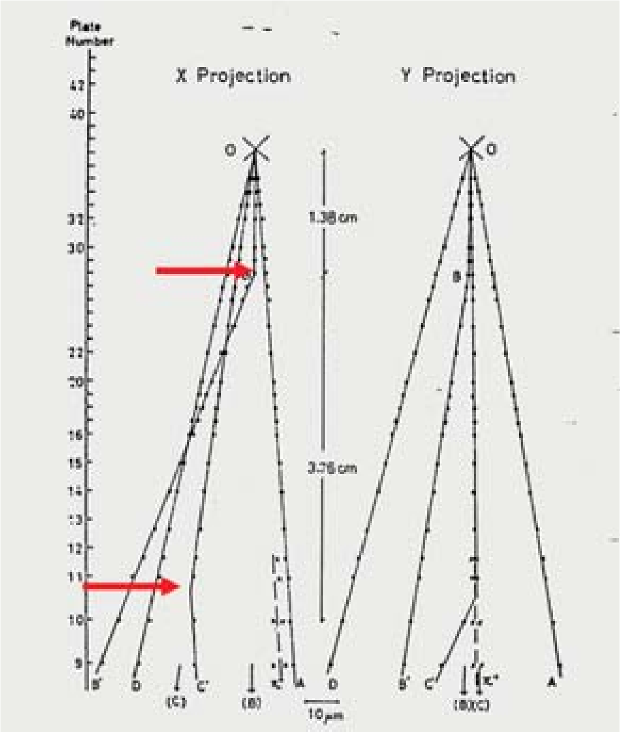

Figure 3. A cosmic ray event [10].

So far I have explained about the unique activities of the Sakata School. I mentioned 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 created by this work was still there. I learned the importance of capturing the entire picture, which is necessary for this kind of work.

3. SIX-QUARK MODEL

In 1971, the renormalisability of the non-Abelian gauge theory was proved [1]. This enabled a description of the weak interactions with the quantum field theory in a consistent manner, and the Weinberg-Salam-Glashow [13] theory began to attract attentions. In 1972, I obtained my PhD from Nagoya University and moved to Kyoto University. Then my work on CP violation started.

CP violation was first found in 1964 by Cronin, Fitch *et al.* [14] in the decay of the neutral K-meson. CP violation means violation of symmetry between particles and anti-particles. The discovery of CP violation implies that there is an essential difference between particles and anti-particles.

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 renormalisable gauge theory. What we found then is summarised as follows [2].

At that time only three quarks were widely accepted, but the three-quark model had some flaws in the gauge theory. Therefore, from a theoretical point of view, the four-quark model of the GIM type was considered preferable. However, it is impossible to accommodate CP violation in a model of the GIM type. We found that even if we relax the conditions for 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 such possible mechanism.

Below we will discuss the quark flavour 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 frame work of the gauge theory, flavour mixing arises from a 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 flavour 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

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

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 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 case, those complex numbers are called reducible, and otherwise, irreducible. Therefore, one 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 2x2 unitary matrices into a real matrix:

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

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 flavour mixing as follows:

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

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

This time the mixing matrix is a 3x3 unitary matrix. In this case, however, we cannot remove all the phase factors of the matrix elements by adjusting the phases of the 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 parameterisation 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 parameterisation is frequently used in 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 parameterisation, 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 [15], and soon it turned out that it is the bound state of the fourth quark c and its anti-particle. 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 [16]. This discovery had a significant effect on our model. The τ-lepton is the fifth member of leptons. Although it is a lepton, it suggested the existence of a third family in the quark sector, too. That was when people began to pay attention to our model. Early works which discussed the six quark model include Ref. [17] and Ref. [18].

In 1977, the Upsilon particle was discovered [19], 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, occurred as recently as in 1995 [20], but before that time the six-quark model became a standard one.

Meanwhile, it was pointed out that we could expect large CP asymmetry in the B-meson system [21]. This opened the possibility to test the model with B-factories. B-meson implies a meson containing b- or anti-b as a constituent, and B-factory means an accelerator, which produces a lot of B-mesons like a factory.

4. 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 US, were built. Those accelerators are unusual ones. Colliding electrons and positrons have different energies, so that the B-mesons produced are boosted. Both experimental groups, Belle(KEKB) and BaBar(PEPII), are large international teams organised with participation from many countries.

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 luminosities more than 10^{34} cm^{-2}s^{-1}, which are record high. Luminosity is a key parameter representing the performance of the colliding accelerator.

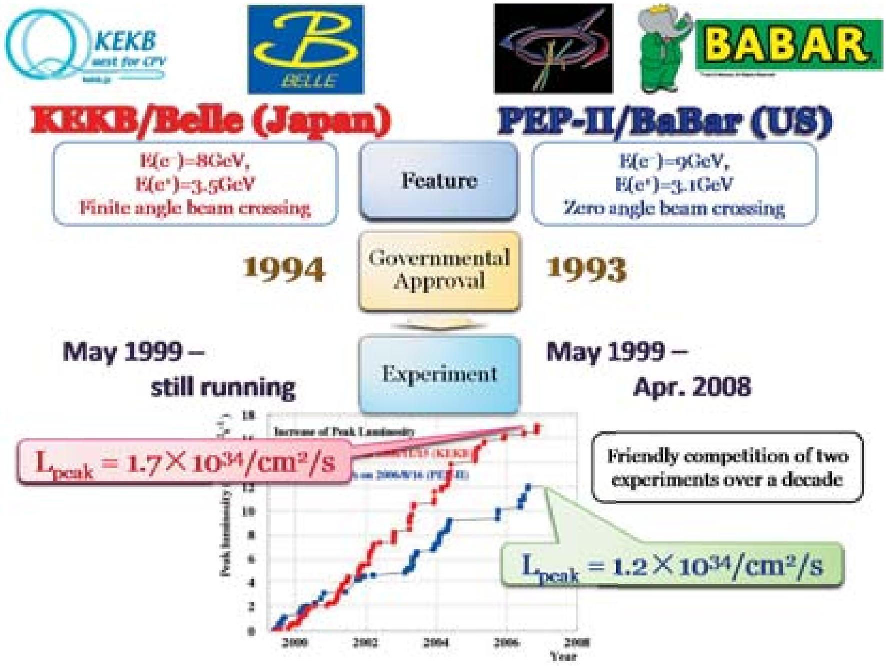

Figure 4. KEKB/Belle and PEP-II/BaBar.

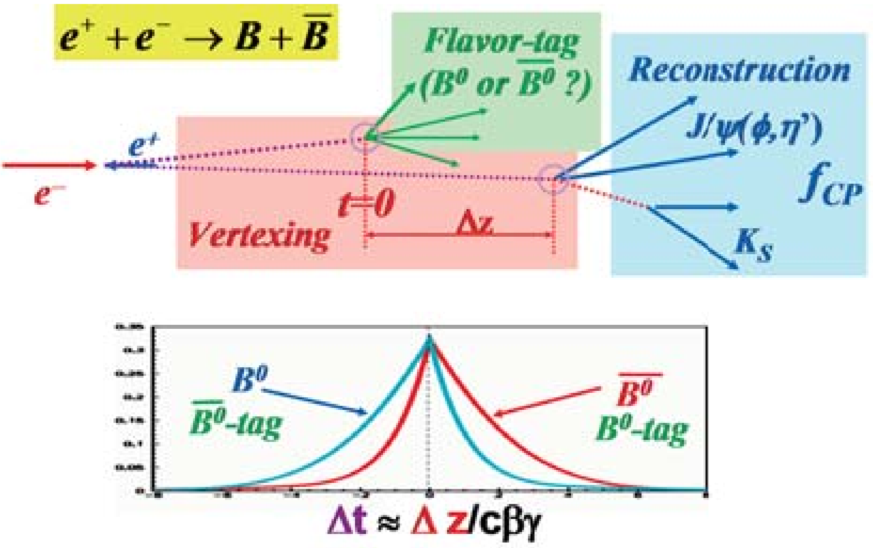

Figure 5. A typical method of measuring CP violation in the B-meson decay.

One of the typical methods of measuring CP violation in the B-factory experiment is shown in Figure 5. The six-quark model predicts fairly large asymmetry between B-meson and anti-B-meson in the decay time distribution of, for example, $B(\bar{B}) \rightarrow J/\psi + K_S$. 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 microns, so that a sophisticated device called a vertex detector is installed.

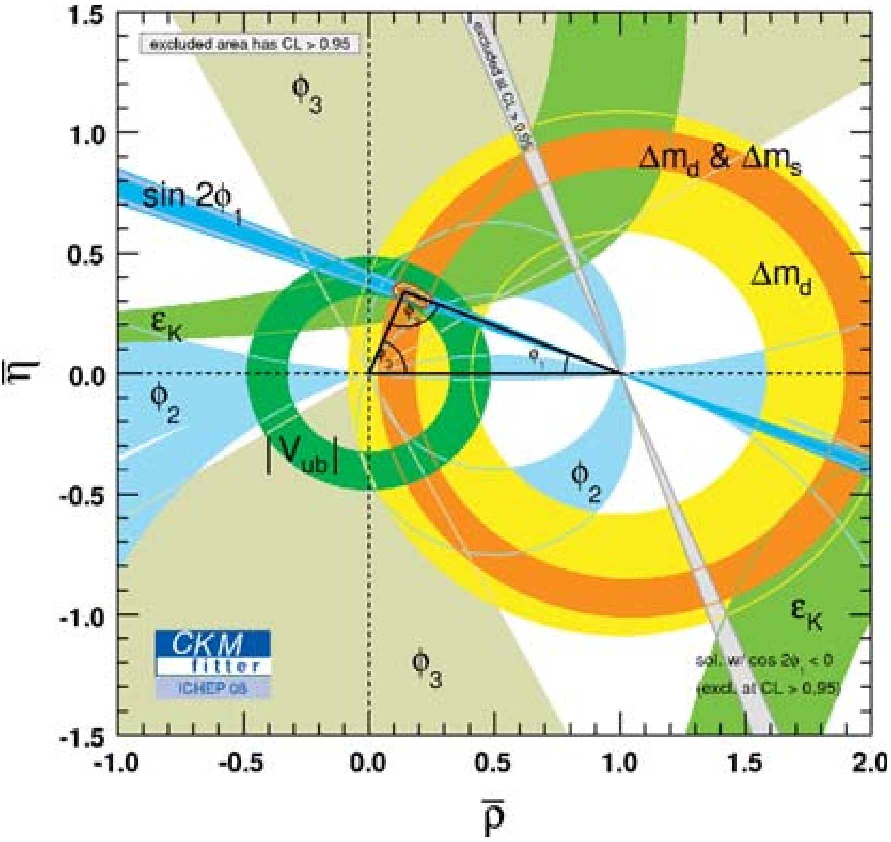

Figure 6. The results of the B-factory experiments [23].

The most important results of the experiments are well described by Figure 6 [22]. The coloured circles and cones show the experimental constraints on the mixing parameters ρ and η. All the constraints overlap on a narrow region coloured 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 summarised as follows.

- 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.
- And matter dominance of the Universe seems to require new sources of CP violation, because it appears that CP violation of the six-quark model is too small to explain matter dominance.

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

5. LEPTON FLAVOUR MIXING

The most important achievement is the discovery of neutrino oscillation at Super Kamiokande, which is a huge water tank detector built in the Kamioka mine in central Japan [24].

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 below. The neutrino oscillation implies the species of neutrino changes during its flight. So if the neutrino oscillation takes place while neutrinos are travelling the distance from the other side of the earth, the observed number of the particular kind of neutrino will be reduced.

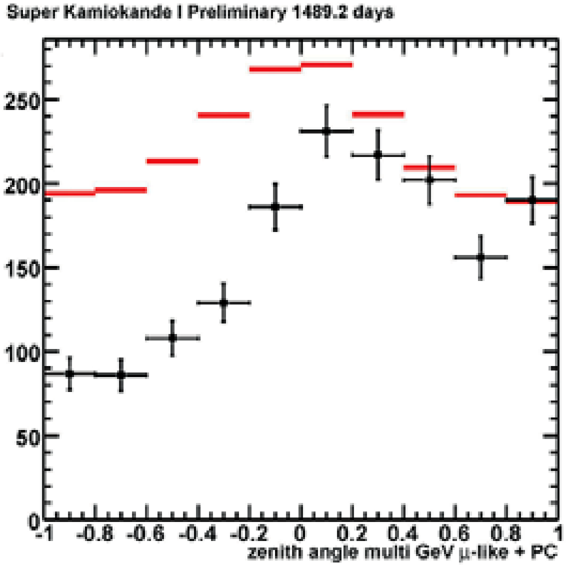

Figure 7. The results of the observation of atmospheric neutrinos [J. Raaf, Neutrino 2008].

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

Figure 8. Yoji Totsuka 1942-2008 (Courtesy of KEK).

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

The neutrino oscillation was further confirmed by two experiments using man-made neutrinos. One is the K2K experiment [25]. 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.

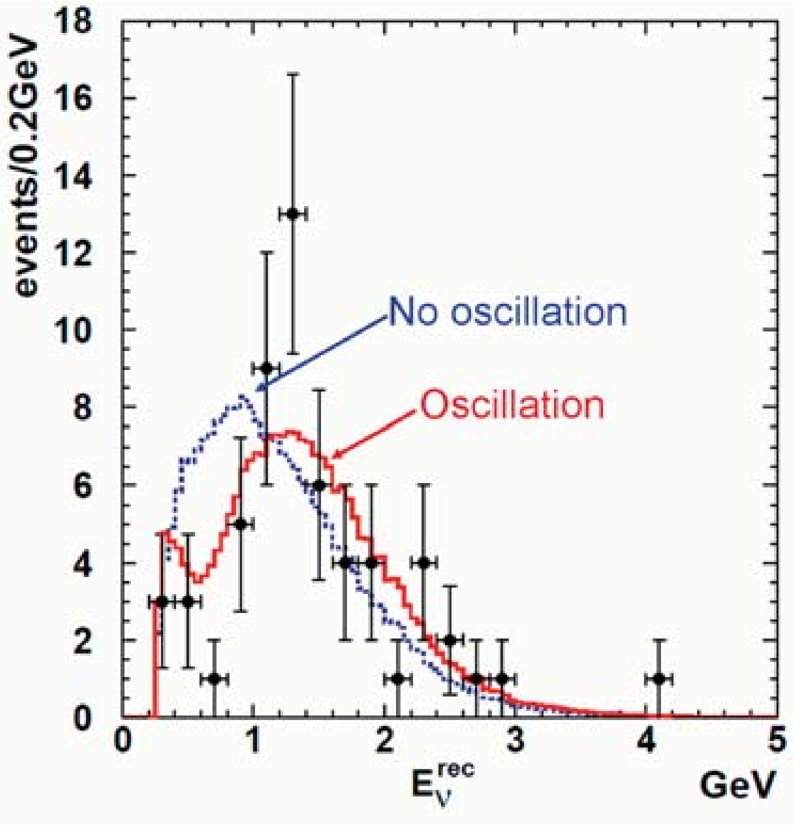

Figure 9. The result of the K2K experiment [25].

The other experiment is the KamLAND experiment [26]. The KamLAND detector uses 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. (Figure 10).

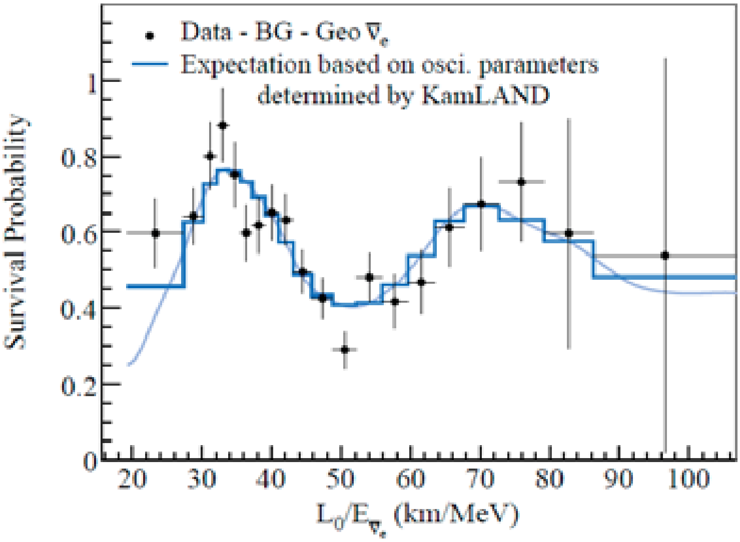

Figure 10. The result of the KamLAND experiment [26].

While we have seen 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 the ν_e appearance measurement, which means the observation of ν_μ to ν_e oscillation. This measurement has 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 has made important contributions to flavour physics. This includes the early activities of the Sakata group on both hadron and lepton flavours, 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 to many of these developments. In particular, it was unforgettable that I could work together with my colleagues on the B-factory experiments. And above all, I am very happy that I could contribute to these developments through my work with Dr. Maskawa.

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Portrait photo of Makoto Kobayashi by photographer Ulla Montan.