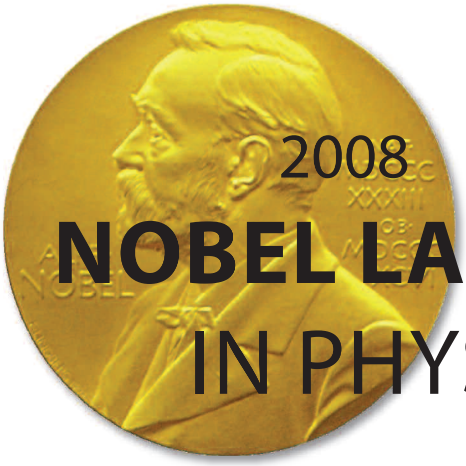


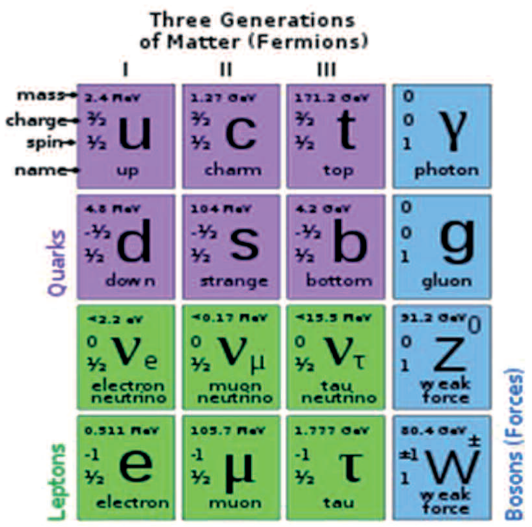
2008 NOBEL LAUREATES IN PHYSICS

I. Sanda,
Institute for Physics
Kanagawa University
DOI: 10.1051/epn/2009401

CONGRATULATIONS NAMBU SENSEI, MASKAWA SAN, KOBAYASHI SAN!

We have been waiting for a long time for this festive occasion. For Nambu Sensei, it should have happened many years ago, for many reasons. For Maskawa San and Kobayashi San, it could have happened anytime after the 2001 discovery of the large CP violation in B decays by Belle and Babar.

Finally it happened! First, I will discuss my personal contacts with the three Nobel Laureates. Next, I will discuss spontaneous symmetry breaking in connection with the standard model, on which the Kobayashi-Maskawa theory is based. Then I will discuss CP symmetry and what I know about how the theory was discovered. Finally, I will very briefly discuss how the prediction of the KM theory, the large **CP** violation in *B* decays, was verified. Of course Nambu Sensei's discoveries spans through the entirety of particle physics. Here, I have to restrict myself to those topics, which played crucial roles in the discovery of the KM theory. It took 35 years and funding of all together 700 million US$ to build asymmetric e^+e^- colliders at KEK and SLAC to discover the large **CP** violation. Thus the experimental aspect is a story in itself. Unfortunately, I will not be able to do justice in covering this fascinating tale.



▲ **FIG. 1:** In today's standard model (SM), there are 3 generations of quarks and leptons, and a set of gauge bosons *W*, *Z* and a photon. The figure is obtained from Wikipedia

Introduction

How could I address Professor Nambu as anything but "Sensei", which means teacher in Japanese. When I was in High School, I lived with my parents in the suburb of Chicago. A bit more than 47 years ago, I visited his office at University of Chicago to talk to him about the possibility of becoming a physicist. Sensei gently explained various aspects of doing research to this kid who just happened to drop in.

Later on, as a graduate student, I remember that I was deeply moved when I studied many of Sensei's works. Then I often met him at Fermilab, where I too have been working, and he was a frequent visitor. He explained his ideas to us young physicists in a fatherly manner. One night, I saw him in a parking lot at Fermilab. He showed me the stars through a telescope, which he placed on the roof of his car. Nambu Sensei's Nobel Prize citation reads: "for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics". He brought in the concept of spontaneous broken symmetry, which was used to explain many solid state phenomena, into fully relativistic field theory.

Introduction of spontaneous symmetry breaking into a gauge theory was a crucial step towards formulating the theory of electroweak interaction - which is the foundation of Kobayashi-Maskawa (KM) theory. The KM theory has its root in E-ken[1] of Nagoya University, where I worked from 1992 to 2006. The laboratory was set up by late Sakata Sensei. At E-ken all researchers were treated equal. This even included graduate students. So, everybody was addressed "San" which is equivalent to "Mr" or "Ms". As students, Kobayashi San and Maskawa San were nurtured by the E-ken atmosphere, which led to their discovery:

1. They truly believed in the existence of quarks- as did everybody at E-ken where the Sakata Model was born. This ▮▮▮

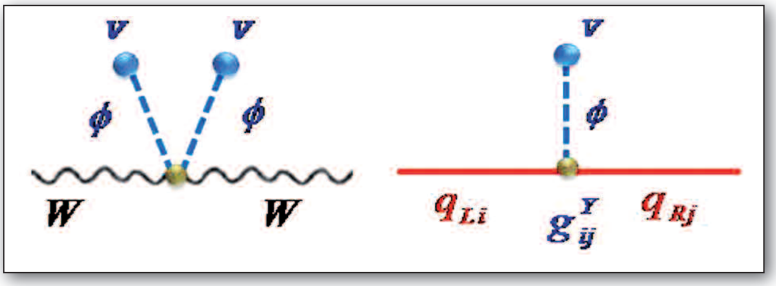
is not so for the inventor of the quark model, Gell-Mann. He stated, in his book Eightfold Way[1], that quarks are mathematical objects to be thrown out after calculation.

2. There were many field theory experts at E-ken. Ohnuki San was stressing the importance of freedom in rotating phases of fields. Remember that, in principle, the electric charge can be complex. For example, in classical electromagnetism, the forces on a particle with charge e is given by $\vec{F} = e\vec{E}$ and $\vec{F} = e(\vec{v} \times \vec{B})$. So the phases of $\vec{E}$ and $\vec{B}$ can be adjusted to define e to be real. Also, in quantum mechanics, the probability of observing a collision, $A+B \rightarrow C+D$, is given by $|\langle C+D|H|A+B\rangle|^2$. So, phases of $A\ldots D$ can be changed without affecting observables.
3. Their experimental colleague, Niu San had emulsion pictures of particle tracks corresponding to a particle with the mass of about 2GeV, and the lifetime consistent with a weakly decaying object.

While there were only 3 known quarks at that time, Kobayashi San and Maskawa San were convinced that 4 quarks existed: u, d, s and c shown in Fig. 1. They also knew that phases of quarks can be rotated so that certain coupling constants can be defined real.

Spontaneously broken symmetry

To break a symmetry of a theory we are used to adding a symmetry breaking term to a Lagrangian. There is another way. A Lagrangian respects the symmetry. But it may have large number of degenerate ground states consistent with the symmetry. The system chooses one of them. Thus the symmetry is broken. A simple example is the motion of a ball in a roulette wheel. It has rotation symmetry. When the ball settles into a particular number, the rotation symmetry is lost. We start out with a theory with $SU(2)\times U(1)$ symmetry. In this theory, weak bosons and quarks are massless. For this reason, the theory is renormalizable. But, for the same reason, it has nothing to do with the real world, where quarks, leptons and gauge bosons have masses. Weak bosons can be made massive by adding mass terms to the Lagrangian. But then, $SU(2)\times U(1)$ symmetry is broken and quantum corrections involving weak bosons become divergent - the theory becomes unrenormalizable. Weinberg suggested that $SU(2)\times U(1)$ symmetry is broken spontaneously. In this case the ground state is such that the Higgs boson acquires a vacuum expectation value v. That is, the ground state is filled with something analogous to "ether". Particles get masses through the interaction with ether. This is depicted in Fig.2. Then, weak bosons become massive and yet, like magic, there is enough symmetry left in the theory so that most of the infinities cancel - theory becomes renormalizable.



▲ **FIG. 2:** Through the interaction of Higgs particle, W bosons and quarks become massive. Here q_i stands for any one of (u, c, t) or (d, s, b) quarks. Of course, since ϕ is neutral, they must have same charge. The subscript L and R stand for left and right helicities, respectively. If $i \neq j$, the Higgs interaction changes a quark of one generation to another. The interaction is caused by a Yukawa coupling with coupling constant g^Y_{ij}.

CP symmetry

Quantum mechanics must be formulated in terms of complex numbers, as seen by its most important relation: $[x,p] = i\hbar$. Now, in quantum field theory, if there is an operator Ψ, because it is a complex operator, there is another operator $\Psi^\dagger$. It can be shown that, if Ψ creates a particle with charge e, $\Psi^\dagger$ creates a particle with charge $-e$ but exactly of the same mass. So, quantum field theory requires that, for each particle, there exist an antiparticle. The operator **C** changes particles to their corresponding antiparticles.

The parity operator **P** transforms position $\vec{r}$ to $-\vec{r}$. The discovery of parity violation gave a big shock to many physicists at that time. But they were relieved that combined symmetry CP remained conserved.

Their relief was short lived, however. In 1964 Cronin and Fitch discovered **CP** violation in K decays[2]. It was a tiny breaking, 0.2% - nevertheless, it gave another big shock.

It is easy to see that **CP** violation is caused by phases in the theory. Consider a term in the Hamiltonian h, which causes an interaction of particles. Then it can be seen that $h^\dagger$ causes an interaction of corresponding antiparticle, and $\mathbf{CP}h\mathbf{CP}^\dagger = h^\dagger$. Since the total Hamiltonian must be hermitian, these interactions must be introduced as:

$$H_{int} = ch + c^* h^\dagger, \quad (1)$$

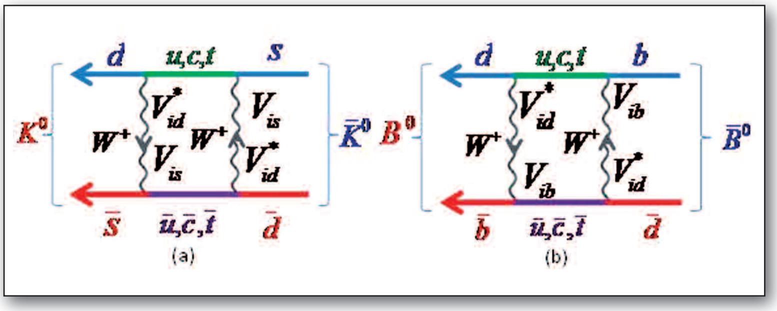
where c is a constant. Note that if c is real, H_{int} is invariant under CP transformation, *i.e.* $\mathbf{CP}H_{int}\mathbf{CP}^\dagger = H_{int}$. So, physics of **CP** violation is physics of phases.

The road to KM theory

As Kobayashi San was leaving for Kyoto University, he gave an introductory seminar on Glashow-Salam-Weinberg theory of electroweak interaction. At the end of the seminar, I hear that Ohnuki San asked the question *"How does one understand* **CP** *violation in this formalism?"* I think this was the question that triggered the investigation by Kobayashi San and Maskawa San.

Let us assume that there are 3 generations of massless quarks and denote them by a superscript "0". Weak interactions are given by:

$$L_{int} = ig(\bar{u}^0\ \bar{c}^0\ \bar{t}^0)\ L\gamma\mu \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} d^0 \\ s^0 \\ b^0 \end{pmatrix} W^\mu, \quad (2)$$



▲ **FIG. 3:** A diagram responsible for **CP** violation in K and *B* decays.

where g is the gauge coupling. Note that it does not change quark generations. We must however, derive the W boson interaction with real particles with masses. As described in Fig.2, quarks with same charge get totally mixed through interactions with the "ether". When L_{int} is written in terms of the mass eigenstates, it becomes:

$$L_{int} = ig(\bar{u}\ \bar{c}\ \bar{t})\ L\gamma\mu \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} W^{\mu}, \quad (3)$$

where **V** is a unitary flavour mixing matrix. The mixing matrix **V** contains phases coming from complex Yukawa couplings g_{ij}^{Y} shown in Fig.2. Note that when L_{int} is written in terms of mass eigenstates, it causes transition of a quark of one "flavour" to another. Let us assume that there are only two generations (u, d) and (c, s). Then unitary 2×2 matrix **V** has 4 parameters. Using the phase freedom of 4 quarks, discussed in Sec. 1, all elements of V can be made real. Thus **V** becomes an orthogonal matrix with one parameter: the Cabibbo angle.

Thus they came to the conclusion that, with 2 generations, **CP** cannot be violated. Then according to Maskawa San, he suddenly had a thought while he was taking a bath. Rather than writing a paper with the negative conclusion, let's assume 3 generations of quarks. Then there are 9 parameters in **V**, and 6 quark phases that can be adjusted. They have shown that there remains 1 phase which can not be removed by any phase redefinition. This theory contains **CP** violation.

Confronting experiments

Now the big question is, "Does the KM theory have anything to do with the real world?" Indeed, over many years, members of the 3rd generation have been discovered. But, the crucial test is to find **CP** violation in *B* decays.

Fig.3 shows one of the most exciting quantum mechanical phenomenon. By exchanging 2 W bosons, a K^0 meson can transform itself into its antiparticle $\bar{K}^0$ and vice versa. The amplitude for this transition is written as $M_{K\bar{K}}$. The state K^0 will oscillate between K^0 and $\bar{K}^0$ before it decays. It goes through intermediate states which may be any combination of (u, c, t), and $(\bar{u}\ \bar{c}\ \bar{t})$. In particular, an amplitude which contains t or $\bar{t}$ quark intermediate state is proportional to $\mathbf{V}_{ts}\mathbf{V}_{td}^{*}$ which is complex, *i.e.* it will cause **CP** violation. Theoretical analyses show K^0 meson **CP** violation is observed in decays, which depend on this oscillation.

Now, if we replace the s quark with b quark, we have Fig.3(b). It predicts B^0 - $\bar{B}^0$ oscillation[4]. There will be **CP** violation in B^0 decay if $\mathbf{V}_{tb}\mathbf{V}^{*}_{td}$ has a phase. But, the lifetime of the B meson is only about 1.5ps - even light travels only about 0.45mm during this time. So, unless there is large **CP** violation, and lots of luck, it is impossible to see the effect. Now the crucial question is: "Could the values of the mixing matrix be such that $M_{K\bar{K}}$ is almost real, so that K meson **CP** violation is only 0.2%, and yet $M_{B\bar{B}}$ has a large phase?" I. Bigi, A. Carter and I investigated this possibility. In 1980, we have made a prediction of possible large **CP** violation in B decay, and it was verified in 2001 by Belle and BaBar. It should be mentioned that an asymmetric e^+e^- collider, with the luminosity 1000 times higher than the maximum available at that time, had to be built. Also a detector having the height of a three story building, and the spatial resolution of microns with excellent particle identification had to accompany the collider. Since B's are pair produced in $e^+e^- \rightarrow B^0\bar{B}^0$, one of them had to be tagged for particle identification. Then the search for the other to decay to $J/\psi K_S$ begins. It takes full use of EPR correlation. Looking back after 28 years, we now know that, out of all possible values for V_{ij}, Nature chose exactly that small region where there is almost 100% **CP** violation in B decays, and only 0.2% for K decays. The way Nature has chosen exactly this value that we needed, I am convinced, is not by accident. It seems like there is a law that states symmetries are broken in the largest possible way.

Remarks

KM theory states that CP violation is a natural consequence of the SM - which in general has complex Yukawa couplings. It is very elegant. On the second thought, how could the theory this elegant be so ugly? It has 18 complex Yukawa couplings which must be introduced by hand. Surely this is not the end of the story. These Yukawa couplings must be a natural consequence of a more fundamental theory. Solving this mystery will probably lead to the understanding of **CP** violation which causes the baryon asymmetry of the Universe. The real treasure is not yet discovered! ■

notes

[1] "E" stands for Elementary Particle, and "ken" stands for laboratory.

[2] K^0 is made out of $\bar{s}d$, where $\bar{s}$ stands for anti-*s* quark.

[3] Note that the converse of above statement is not true. The complex phase will not always result in observable **CP** violation, as it is shown below.

[4] B^0 meson is made out of $d\bar{b}$ quarks.

References

[1] M. Gell-Mann and Y. Ne'eman, *The Eightfold Way*, W.A. Benjamin Inc., New York, 1964.

[2] I.I. Bigi and A.I. Sanda: ***CP** Violation*, Cambridge Univ. Press,2000.