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The B factories revolution

La révolution des usines à B

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ABSTRACT

In this article, I will sketch the progress of B physics leading to the discovery of large **CP** 23 violation in $B \to J/\psi K_S$, which in turn lead to the B factory revolution.

RÉSUMÉ

Dans cette contribution, je retrace les étapes qui ont conduit à la mise en évidence d'une violation de la symétrie CP importante au moyen de la physique du B, en particulier dans le canal $B \to J/\psi K_S$, ce qui constitue le début de l'apport révolutionnaire des « usines à B » dans le domaine.

1. A brief history of the revolution

The operator **CP** transforms a particle to its antiparticle and vice versa.[1] Thus **CP** symmetry implies that physics of particles is the same as that of antiparticles. Consider a term in the Hamiltonian h. Under **CP**, h transforms as $\mathbf{CP} h \mathbf{CP}^\dagger = h^\dagger$, where $h^\dagger$ is related to h by interchanging particles and antiparticles. Since the total Hamiltonian must be Hermitian, these interactions must be introduced as:

$$H = ch + c^* h^\dagger \tag{1}$$

where c is a constant.

Note that if c is real, H is invariant under **CP** transformation, *i.e.* $\mathbf{CP} H \mathbf{CP}^\dagger = H$. So, we see that **CP** symmetry breaking is caused by phases in the theory.[2]

2. Why *B*?

A meson is a bound state of a quark and an antiquark. A state like K^0, a bound state of $(d\bar{s})$, through an exchange of W boson, transforms to a *virtual* $(t\bar{t})$ state, and through another exchange of a W boson, it further transforms to $(s\bar{d})$. This is shown in Fig. 1(a). Note that through this chain reaction, K^0 transforms to its antiparticle $\overline{K}^0$.

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[1] Editor's note: In this contribution, "antiparticle" is defined as the CP-conjugate (rather than simply the C conjugate as often used in the framework of quantum electrodynamics or chromodynamics). This choice is quite natural, as it reflects the particle content of the chiral fields. The issue is discussed further in the article by J.-M. Frère, "CP, T and fundamental interactions", this issue.

[2] Note that the converse of above statement is not true. The complex phase will not always result in observable **CP** violation.

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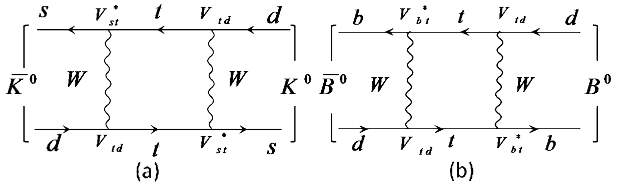

Fig. 1. Transition between particle and antiparticle can occur in the second order weak interaction. In B^0 meson, B^0–$\overline{B}^0$ transition can also happen through an intermediate state of t–$\bar{t}$.

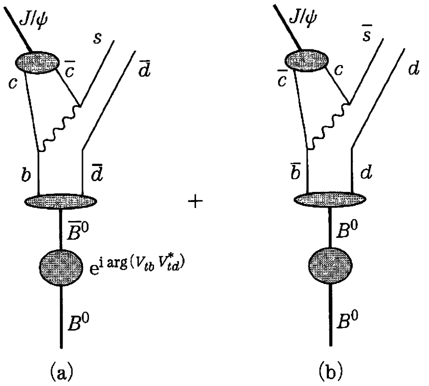

Fig. 2. Two amplitudes contributing to B^0 decay which look almost the same final states.

In the KM theory, all three families must participate in producing a **CP** violating observable. Through the diagram in which the intermediate virtual state is $t\bar{t}$, the third family gets into the act. This way, all three families contribute. Indeed $V_{st}^* V_{td}$ is complex and this phase is responsible for the observed **CP** violation. The smallness of K meson **CP** violation can be traced[3] to the smallness of

$$\frac{\mathrm{Im}\, M^K{}_{12}}{\mathrm{Re}\, M^K{}_{12}} \propto \frac{\mathrm{Im}(V_{st}^* V_{td})}{\mathrm{Re}(V_{su}^* V_{ud})}$$

Inter-generational mixing tends to be small [1].

Going from K physics to B physics involves exchanging s quark to b quark. Though this seems like a trivial exchange, physics changes drastically, as it leads to large **CP** violation. First, there should be B^0–$\overline{B}^0$ mixing, as seen in Fig. 1(b). **CP** violating effects come from phases in decay amplitudes. For B meson, $\frac{\mathrm{Im}\, M^B{}_{12}}{\mathrm{Re}\, M^B{}_{12}} \propto \frac{\mathrm{Im}(V_{bt}^* V_{td})}{\mathrm{Re}(V_{bt}^* V_{td})}$ can be $O(1)$. Since there is no reason for the phase factor in the KM matrix to be small, we may hope to observe large **CP** violation in B decays.

To detect this phase, we have to find decays in which there are two amplitudes leading to the same final state. With the particle–antiparticle mixing, amplitudes that may interfere are shown in Fig. 2. Note that final states shown in Fig. 2 are not the same, as they involve $(s\bar{d})$ and $(d\bar{s})$, respectively, in their final states. These quark–antiquark states correspond to K^0 and $\overline{K}^0$ states, respectively. Indeed if K^0 and $\overline{K}^0$ states are detected, they do not interfere. But, since K^0–$\overline{K}^0$ mixing exists, K^0 and $\overline{K}^0$ are not mass eigenstates. The mass eigenstates K_S and K_L are linear combinations of K^0 and $\overline{K}^0$. Both $(s\bar{d})$ and $(d\bar{s})$ are detected as K_S or K_L. Since only K_S decays to $\pi^+\pi^-$, detecting K_0 and $\overline{K}^0 \to \pi^+\pi^-$ allows us to detect $B^0 \to J/\psi K_S$. Detecting this final state, there is no way for us to distinguish decay contribution from (a) or (b). This is like the Young's double slit experiment. The wave going through both slits will interfere. The phase difference of two waves added together coherently will produce the interference pattern. Similarly, two amplitudes with different relative phase will cause interference.

In 1980, B meson was yet to be discovered. Thus we had a problem. We did not know how W bosons couple to the third family quarks, *i.e.* V_{ij}'s involving b or t quarks were not known. In fact we did not know the top quark mass either. There was a rumor that $m_t < 50$ GeV. So, we took $m_t = (20\text{–}30)$ GeV in our computation of the B^0–$\overline{B}^0$ transition amplitude.

If B^0 mixes with $\overline{B}^0$, they are not mass eigenstates. A B^0 state can oscillate into $\overline{B}^0$ and oscillate back to B^0. It is a time dependent state. We denote the state which is $B^0[\overline{B}^0]$ at $t = 0$ to be $B^0(t)[\overline{B}^0(t)]$. With this notation, we find [2,3]

$$A_{\psi K_S} \equiv \frac{\Gamma(\overline{B}^0(t) \to \psi K_S) - \Gamma(B^0(t) \to J/\psi K_S)}{\Gamma(\overline{B}^0(t) \to J/\psi K_S) + \Gamma(B^0(t) \to J/\psi K_S)} = \sin\bigl(|\Delta M_{B^0}|t\bigr)\sin(2\phi_1) \tag{2}$$

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[3] The notations are introduced in the article by Ciuchini and Silvestrini (this issue).

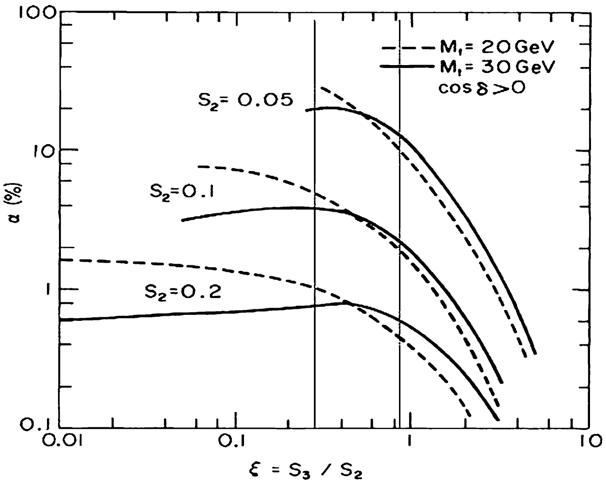

Fig. 3. The first prediction [2] of large **CP** violation in B decays. $s_2 \approx |V_{cb}|$ and $s_3 \approx |V_{ub}|$. We know today that $|\frac{s_3}{s_2}| = (0.25\text{–}0.83)$, and $s_2 = (0.024\text{–}0.043)$. The former constraint implies the allowed range is between the two vertical lines. The latter constraint implies that the value of the asymmetry is even bigger than our prediction at that time. So, although the Nature could have chosen anywhere for the KM parameters, she has chosen to exhibit largest **CP** violation possible. Note that the B^0–$\overline{B}^0$ amplitude is computed by using $m_t = (20\text{–}30)$ GeV. We know today that $m_t \approx 172$ GeV. Our estimate is considerably an underestimate since B^0–$\overline{B}^0$ mixing amplitude goes like $(m_t/m_W)^4$.

Here ΔM_{B^0} is the difference between two mass eigenvalues. The phase ϕ_1 is the **CP** violating phase coming from the phase of KM matrix elements V_{ij}.

The prediction of the **CP** violating effect, with known constraints on parameters as of 1980, is given in Fig. 3.

We see that **CP** violation could be rather small, as in K decay. Retrospect, our mother Nature has chosen the parameter region which leads to a maximal **CP** violation.

3. Challenge in detecting CP violation in *B* decay

The first shock was the time dependence of the asymmetry as shown in Eq. (2). Note that the asymmetry depends on $\sin(|\Delta M_B|t)$. It means that if we do not observe the time dependence, it corresponds to integrating over all t, and the asymmetry vanishes.

Then there is a major problem. A K meson beam can travel as far as 100 m, which allowed accidental discovery of **CP** violation. The life time of B^0 meson is about 1.5 ps, and even light travels only 0.45 mm during that time. So, there was no beam. We had to figure out how to make the beam of B mesons. B meson is produced in a reaction

$$e^+ + e^- \to \Upsilon(4S) \to B^0(t_1)\overline{B}^0(t_2) \tag{3}$$

The final state B pair is time dependent due to mixing. Despite of the mixing, we have to know the identity of meson which decays to $J/\psi K_S$. One way to differentiate B^0 from $\overline{B}^0$ is by their leptonic decay. Leptonic decay is flavor specific. $\mu^+[\mu^-]$ must come from the leptonic decay of $\bar{b}[b]$ which is contained in $B^0[\overline{B}^0]$.

$$B^0 \to \mu^+ + \nu + anything \quad \text{and} \quad \overline{B}^0 \to \mu^- + \overline{\nu} + anything \tag{4}$$

Once the identity of B meson is fixed, because the quantum mechanics of B^0–$\overline{B}^0$ oscillation is known, we get the identity of both B mesons at all times. The decay

$$\begin{aligned} e^+ + e^- \to \Upsilon(4S) \to B^0(t_1)&\overline{B}^0(t_2) \to J/\psi K_S \\ &\searrow \mu^+ + anything \end{aligned} \tag{5}$$

is depicted in Fig. 4. Let us assume that μ^+ was detected at time t_1. It implies that the decayed B meson was B^0 at t_1. This means that its partner was a $\overline{B}^0$, at that time, because if it were B^0, then two identical particles must be in a symmetric state. This is impossible as they are in angular momentum $J = 1$ state. So, at $t = t_1$, we have a $\overline{B}^0$ beam.

Now, in principle, we can detect this asymmetry if we had an ideal detector. But, a typical decay length is 20 μm – it is just too short to detect the time dependent **CP** violation.

4. Facing the challenge

By 1987, B^0–$\overline{B}^0$ mixing was discovered [4]. Experimentalists suddenly got interested in discovering the **CP** asymmetry. Around this time, Bigi and I had a discussion with P. Oddone. He brought up a crazy idea. He said it is possible to build

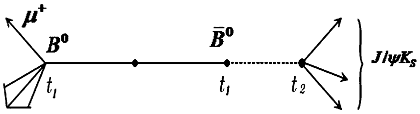

Fig. 4. Configuration for a $B^0\overline{B}^0$ event in which B^0 is identified at t_1 through its semileptonic decay with μ^+, and its partner, a $\overline{B}^0$ at t_1, decays to a **CP** eigenstate f at $t_2 > t_1$.

an asymmetric e^+e^- collider, *i.e.* with different energies for e^+ and e^- beams. His idea was to look at $e^+e^- \to B^0\overline{B}^0$ in a "moving lab frame". Then the decay length gets elongated. If we make the asymmetry too large, it would elongate B meson tracks, then most of the decay products would be lost in the beam pipe. Later it turned out that a 9 GeV electron and 3 GeV positron collision will produce a $B^0\overline{B}^0$ pair with a decay length of 200 μm, with tolerable loss in the detection efficiency.

What is the minimum luminosity needed to detect **CP** violation in B decay for sure? We cannot spend hundreds of millions of tax payer's money and say that the luminosity was too small to detect the **CP** violation. So, we designed a machine which is capable of measuring even the smallest possible value. (We got 15% by tuning all unknown parameters so that **CP** violation is minimal.) Considering the branching ratios for $B^0 \to J/\psi K_S$ and the leptonic decay, $B^0 \to \mu^+\nu +$ *anything*, we estimated that we needed $10^{34}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ to get enough events to discover 15% **CP** violation in one year. At that time the most intense e^+e^- collider was CESR at Cornell and it had a luminosity of $10^{-31}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. The new machine needed 1000 times more luminosity than the one which existed – not only that, it must be asymmetric.

After learning about the asymmetric collider from Oddone, I knocked at the door of KEK. Machine experts laughed at me saying that the beams will blow up. In spite of this discouraging experience, the B factory was built at both SLAC and at KEK.

The SLAC machine, PEP-II, started construction in January 1994. The construction of KEKB started in April of the same year. The race was on. And you know what happened! Experimentalists had a field day. **CP** asymmetry was much larger than the minimal value which we used to fix the luminosity. Lots of new results on flavor physics came out because we had more luminosity!

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