THE SEARCH
FOR
GOLD IN BEAUTY DECAYS

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ABSTRACT

The prediction of large **CP** violation in B decays some 23 years ago has been verified by SLAC and KEK teams in 2001. The search has an interesting history. When it was predicted, B meson had not been discovered yet. The asymmetry could be detected at CLEO only if a $B-\overline{B}$ pair were in an even angular momentum state. Soon it was shown to be in a P-wave state. This forced us, eventually, to consider asymmetric colliders. Some 7 years later $B-\overline{B}$ mixing was discovered. The life time of the B meson was shown to be long - if you think 1.5 pico-second is long. While the large **CP** violation was predicted only in a particular region of the KM parameter space, as the time went on, we slowly zoomed into that special region. Machine physicists at both KEK and SLAC performed wonders - colliders worked much beyond our expectations. The intense competition to build the collider, detector, and analyze the data ended in both groups publishing at the same time in the same issue of PRL! There were only winners - healthy competition is great for advancement of science. The flavor physics will continue to guide our way to discovery of new physics for tens of years to come.

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Prelude

It was a hot summer Saturday afternoon. There was no air-conditioning in the class room, and the windows were all opened. We could hear a school of kids playing outside in the play ground. I was supervising a math test - a method which I used to make ends meet. It was not easy sending kids to private schools in Manhattan.

Sitting at the front of the class room, I was working on a problem which I had been struggling already for a week. It was to make two amplitudes

$$\begin{array}{rcl} \overline{B} \to & c & \overline{u}d\overline{d} \\ & \hookrightarrow & s\overline{d}u \\ B \to & \overline{c} & u\overline{d}d \\ & \hookrightarrow & \overline{s}d\overline{u} \end{array} \tag{1}$$

interfere.

Since I could compute $B - \overline{B}$ mixing amplitude, I knew that large phase in the KM matrix would show up - if I could make these two amplitudes interfere. But, they didn't. The final states were different. One was $s\overline{d}u\overline{u}d\overline{d}$ and the other was $\overline{s}d\overline{u}ud\overline{d}$. It was 10 minutes to go until the end of the test. Then 5 minutes. I suddenly realized that experimentalists didn't detect neither K^0 nor $\overline{K}^0$ - they detected K_L or K_S. So, I could make these two amplitudes interfere. Then stop - I had to collect the exam papers. It was just as well. I prefer to stop when I think I am ahead. From my past experiences, I knew that most of my ideas don't materialize. I might as well enjoy them while I think I got something.

To open this year's SLAC Summer School, I was asked to talk about the various encounters and personal recollections of the road toward the discovery of large **CP** violation in B decays. Above is an incident which I still remember some 23 years later, the moment I discovered that there exist, at least in principle, a large **CP** violation in B meson decays.

1 Bit of ancient history

Necessity for beauty originated during 60's and 70's at E-ken (which stands for elementary particle physics laboratory) - the laboratory to which I belong at Nagoya University. 40 years ago, research in this laboratory was very far from the main stream of theoretical physics. It is ironic that around this time, for example US researchers, were sure that nuclear democracy and bootstrap ideas were correct, and quarks are mere mathematical objects. This can be illustrated best from the following quotation by Gell-Mann[1]:

> "In other words, we construct a mathematical theory of the strongly interacting particles, which may or may not have anything to do with reality, find suitable algebraic relations that hold in a model, postulate their validity, and then throw away the model. We may compare this process to a method sometimes employed in French cuisine: a piece of pheasant meat is cooked between two slices of veal, which are then discarded. Their non-appearance could certainly be consistent with the bootstrap idea, and also possibly with a theory containing a fundamental triplet, which is hidden, *i.e.*, has effectively infinite mass."

This was not the attitude taken at Nagoya. Theorists here believed in the existence of a set of fundamental particles - today we call them quarks. At that time Sakata and his coworkers were working on the concept that all quarks are made up of still more fundamental particles.[2] They argued that quarks were bound states of (B^+, B^0) * and four leptons.

They not only took the fundamental nature of these particles seriously, but also they took lepton quark symmetry seriously.[3]

1.1 The origin of neutrino mixing and Cabibbo mixing

It is useful to go over their reasoning. They assumed that fundamental particles, what we call quarks today, are proton, neutron, lambda and they are bound states[4]:

$$p = \langle B^+\nu_1\rangle, \quad n = \langle B^+e^-\rangle, \quad \Lambda = \langle B^+\mu^-\rangle. \tag{2}$$

Now, knowing the work of Gell-Mann and Lévy,[5] they claim to explain the origin of "universality" of hadronic currents as the mixing of neutrinos.

$$\begin{aligned} \nu_1 &= \nu_e \cos\delta + \nu_\mu \sin\delta \\ \nu_2 &= -\nu_e \sin\delta + \nu_\mu \cos\delta. \end{aligned} \tag{3}$$

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*I follow the original notation. Here these are not B mesons.

This way they concluded that the hadronic current can be written as

$$J_\lambda = (\overline{n}p)_\lambda \cos\delta + (\overline{\Lambda}p)_\lambda \sin\delta, \tag{4}$$

and the Hamiltonian for weak interaction is

$$H_W = \frac{G_F}{\sqrt{2}} J_\lambda J_\lambda^\dagger \tag{5}$$

So, they were talking about the dynamical origin of the Cabibbo angle. Note that this is before Cabibbo introduced it.[6]

They also stated that $\langle B^+\nu_2\rangle$ do not bind or that it binds, but it is heavy. We of course know that this state is charm. If they had taken their idea seriously, they could discover GIM mechanism also.

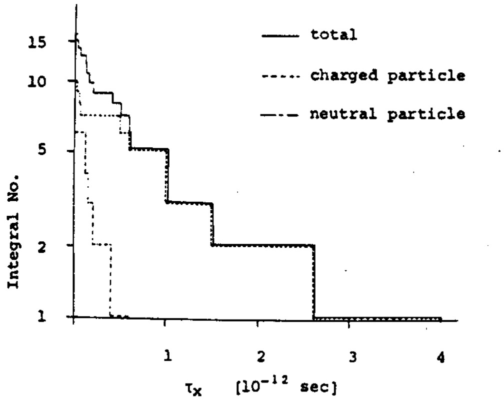

Figure 1: Niu and his group has measured the life time of neutral and charged D. They were determined to be $\tau_\pm = (1 \sim 2)\times 10^{-12}$ sec and $\tau_0 = (3 \sim 4)\times 10^{-13}$ sec. This was before the detection of charm particles at SLAC.

1.2 Necessity of Beauty

With this theoretical activity, there was also an important discovery from the experimental side. Niu and his collaborators discovered what is today know as charged and neutral D mesons.[7] The discovery of D meson at SLAC was announced a year later.[8] All this was preceded by the discovery of a beautiful single event,[9] which was believed, at Nagoya, to be the missing charm particle.

In this atmosphere, when Kobayashi and Maskawa took the six quark model seriously, it was not as crazy as physicists in the west thought. After all if you know that there are at least 4 quarks, why not 6 quarks. Nagoya was ideally suited for their discovery.

2 Search was on

Around 1978, Pais gave a seminar at Rockefeller University. The seminar was entitled "**CP** violation on charmed-particle decays".[10] My recollection of how Pais started out his seminar is as follows:

> "There is good news and bad news! The good news is that **CP** violation in a heavy meson system is quite similar to that of the K meson system. The bad news is that there is little distinction like K_L and K_S mass eigenstates. For heavy meson system, life times are both short."

The work of Pais and Treiman stimulated my search for large **CP** violation in B decays. I thought their work was interesting but it lacked imagination. How could anyone conclude that B physics is quite similar to K physics. I was determined to find the difference!

2.1 CP violation

There was some indication that **CP** violation in B decay is different from that of K decay. If we write

$$\begin{aligned} |B_1\rangle &= \frac{1}{\sqrt{|p|^2+|q|^2}}[p|B^0\rangle + q|\overline{B}^0\rangle] \\ |B_2\rangle &= \frac{1}{\sqrt{|p|^2+|q|^2}}[p|B^0\rangle - q|\overline{B}^0\rangle], \end{aligned} \tag{6}$$

I knew that

$$\frac{q}{p} = e^{2i\arg M_{12}}, \tag{7}$$

can deviate from unity in a major way, if parameters of the KM matrix fell in a certain region in the parameter space. Here $M_{12} = \langle B|H|\overline{B}\rangle$. But this is a phase convention dependent statement. The problem is to find an experimental observable which is proportional to $Im\frac{q}{p}$.

B mesons are produced in harsh environment - in colliders - unlike measurement of neutron electric dipole moment where neutron lives practically for ever compared to the lifetime of B mesons. To overcome this difficulty, we need effects at least at the 10% level.

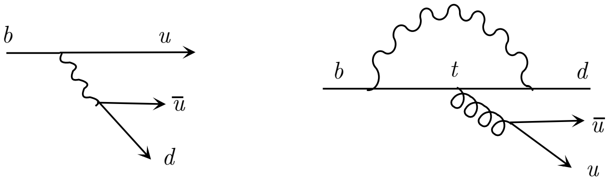

Figure 2: Two interfering diagrams considered by Bander, Silverman and Soni

Soon afterwards, came the paper by Bander, Silverman, and Soni.[11] They have discussed **CP** violation in b quark decay generated by penguin amplitudes shown in Fig. 2. They computed the asymmetry in quark decay rates:

$$a = \frac{\Gamma(b \to f q\bar{q}) - \Gamma(\bar{b} \to \bar{f}\bar{q}q)}{\Gamma(b \to f q\bar{q}) + \Gamma(\bar{b} \to \bar{f}\bar{q}q)}. \tag{8}$$

I concluded from their result that a is too small to be measured. How can we get a big effect? This was the issue!

If $\frac{q}{p} \neq 1$, at least in some phase convention, we should look for effects which involve mixing - the fact that the mixing has not been discovered made little difference as I could compute the mixing effect. I considered two diagrams shown in Fig. 3, which would exist if there is mixing: The problem was to have these two diagrams interfere. As these two diagrams have different final states $(s\bar{d})u\overline{u}d\overline{d}$ in (a) and $(\bar{s}d)u\overline{u}d\overline{d}$ in (b). One is $s\overline{d}$ and the other is $\overline{s}d$ and they can not interfere. This was the struggle which resulted in the scene discussed in the Prelude. These two diagrams can be made to interfere by detecting K_S states.

After noticing the fact that these two diagram interfere, and computed the asymmetry, I went to a freshly arrived research associate Ashton Carter [†] and we

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[†] Ash Carter is now a Ford Foundation Professor of Science and International Affairs at Harvard

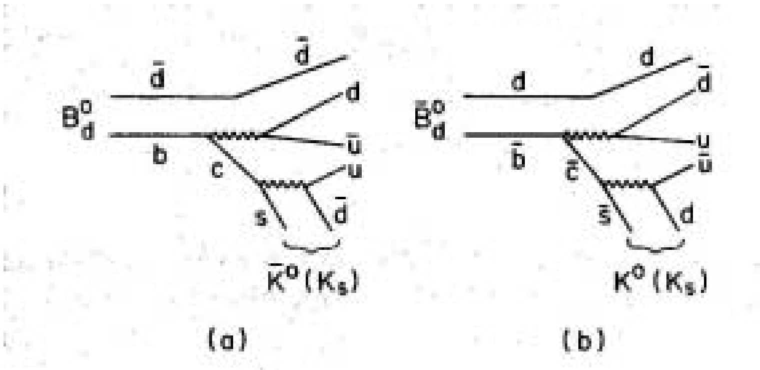


Figure 3: Two diagrams which may interfere if there is substantial $B - \overline{B}$ mixing.

made a suggestion[12] that asymmetries between two inclusive reactions given in Eq. (1) can be large. Note that these are major decay mode of the B meson. In Fig. 4, we show the numerical value of this asymmetry for various KM parameters and the top quark mass.

2.2 Bunch of problems

The collaboration between Ikaros Bigi and myself started right after my seminar at CERN in 1980. We realized that there were many problems. In inclusive reactions, the final state is a mixture of both **CP** even and odd states. If there is equal branching ratios for **CP**=+1 states and for **CP**=−1 states, the asymmetry for the inclusive reaction washes out to zero. For example, we have

$$\mathbf{CP}|\psi K_S \; n\pi^0\rangle = -(-1)^n|\psi K_S \; n\pi^0\rangle. \tag{9}$$

where n is the number of π^0's. This was not the only problem. Unlike in the K system we don't have B or $\overline{B}$ beam. We first have to produce $B - \overline{B}$'s in pairs then tag one of them. For example:

$$\begin{aligned} e^+e^- \to \Upsilon(4S) \to \quad & B \quad \overline{B} \to c\bar{c} + K_S + X \\ & \hookrightarrow \quad \mu^\pm + anything. \end{aligned} \tag{10}$$

University's John F. Kennedy School of Government and Co-Director of the Harvard-Stanford Preventive Defense Project.

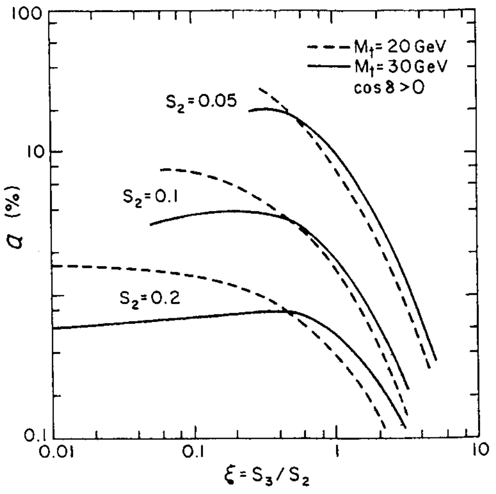


Figure 4: An estimate of the asymmetry as a function of $\xi = \sqrt{\rho^2+\eta^2}$ for each $s_2 \sim V_{cb}$. A set of favoured values today is $\xi \sim .5$, $s_2 \sim .05$, and, of course, $m_t \simeq 170 GeV$.

The asymmetry for $[B\overline{B}]$ pair with angular momentum L is given by

$$\begin{aligned} &\frac{\Gamma([B\overline{B}]_L \to l^- c\bar{c} + K_S + X) - \Gamma([B\overline{B}]_L \to l^+ c\bar{c} + K_S + X)}{\Gamma([B\overline{B}]_L \to l^- c\bar{c} + K_S + X) + \Gamma([B\overline{B}]_L \to l^+ c\bar{c} + K_S + X)} \\ = \quad & Im\left(\frac{qA(\overline{B} \to l^- c\bar{c} + K_S + X)}{pA(B \to l^- c\bar{c} + K_S + X)}\right) \sin[\Delta M_B(t_1 + (-1)^L t_2)], \end{aligned} \tag{11}$$

where t_1, and t_2 are times at which the leptonic decay, and $c\bar{c} + K_S + X$ decays are detected, respectively. To our agony, we found that the asymmetry for $L = 1$ vanished if we don't observe the decay times t_1 and t_2 - *i.e.* if we integrate over time. The time measurement is impossible at CSER since B's travelled no more than $20\mu\ m$ before it decayed. So, we had to rely on the decay

$$e^+e^- \to \Upsilon(4S) \to B\overline{B}^* \to B\overline{B}\gamma. \tag{12}$$

The initial state couples to an electromagnetic current which transforms like a $\mathbf{C} = -1$ state, the presence of a photon in the final state will guarantee that the $B\overline{B}$ pair is a $\mathbf{C} = +1$ state or L even state. So, we hoped that B^* was light enough to be produced in $\Upsilon(4S)$ decays. I was in close contact with CLEO and CUSP collaborators who were on the lookout for almost mono-energetic 50MeV photons. We now know that the reaction$\Upsilon(4S) \not\to B\overline{B}^*$ does not happen.[13,14]

Initially, this fact disappointed us, because it required us to go to the asymmetric collider. Retrospect, however, this was a blessing in disguise. It means that we have pure $B\overline{B}$ beam. If we had an admixture of $B\overline{B}$ and $B\overline{B}^*$ states, there will be additional hadronic uncertainty.

Note that asymmetry could be $\mathcal{O}(1)$ at the certain region of the parameter space. Today, we know that nature chose exactly the point where the asymmetry is maximal. Otherwise I would not be talking about the historical account!

2.3 Gold mine

In 1987, $B-\overline{B}$ mixing was discovered by the ARGUS collaboration in same sign di-lepton events.[15] Theorists knew that the mixing exists at some level. After all, if a person knew how to compute $K-\overline{K}$ mixing, then computing $B-\overline{B}$ mixing is a cinch. The problem is that the mixing went like[16] [‡]

$$x_B \equiv \frac{\Delta M_B}{\Gamma} \sim \frac{m_t^2}{700\,\mathrm{GeV}^2}. \tag{13}$$

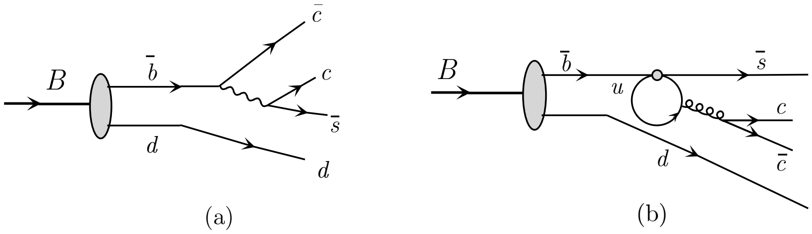
Because same sign di-lepton rates went like x_B^2, probability of observing the effect of mixing was proportional to m_t^4. At some point, there was an experimental result that the top quark mass is bounded by 50GeV, and theorists were lead astray - we could not stick out our heads and announce that experimentalists should see the effect of mixing.

3 Gold-plated decay mode

We realized that, statistically, it is better to look for large asymmetry at the expense of smaller branching ratio than to consider a mode with large branching ratio but small asymmetry. That is, it's better to consider a mode with pure **CP** quantum number, *i.e.***CP** eigenstate. Considering inclusive reaction to enhance the branching ratio does not help at all. So, we came up with the golden decay mode[17]:

$$B \to \psi K_S. \tag{14}$$

[‡] This result is based on out of date numbers for the bag parameter and f_B. But this is not important for our purpose here.



(a) (b)

Figure 5: $B \to \psi K_S$ decay gets contribution from tree and penguin graphs.

The asymmetry is given by

$$\frac{\Gamma(B^0(t) \to \psi K_S) - \Gamma(\overline{B}^0(t) \to \psi K_S)}{\Gamma(B^0(t) \to \psi K_S) + \Gamma(\overline{B}^0(t) \to \psi K_S)} = \mathrm{Im}\left(\frac{q}{p}\frac{\overline{A}(B \to \psi K_S)}{A(B \to \psi K_S)}\right)\sin\Delta M_B t, \quad (15)$$

where

$$\frac{q}{p} = \sqrt{\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}}. \quad (16)$$

It is well known that for the B system, $|\frac{i}{2}\Gamma_{12}| \ll |M_{12}|$. So, $\frac{q}{p} = e^{-i2\phi_M}$, where ϕ_M is the phase of M_{12}. Lets say that ψK_S mode has two contributions shown in Fig. 5.

Under **CP** transformation, weak phases reverse their signs, while strong interaction phases do not. So, if ξ_i and δ_i are weak and strong phases of amplitude i, respectively, we have:

$$\begin{aligned} A(B \to \psi K_S) &= e^{i\xi_1}e^{i\delta_1}|\mathcal{A}_1| + e^{i\xi_2}e^{i\delta_2}|\mathcal{A}_2|, \\ A(\overline{B} \to \psi K_S) &= e^{-i\xi_1}e^{i\delta_1}|\mathcal{A}_1| + e^{-i\xi_2}e^{i\delta_2}|\mathcal{A}_2|. \end{aligned}$$

(17)

We see that if there is only one weak amplitude, or if $\xi_1 = \xi_2$, we have

$$\frac{A(\overline{B} \to \psi K_S)}{A(B \to \psi K_S)} = e^{-2i\xi_1} \quad (18)$$

The reasons ψK_S mode is called a "Gold Plated" mode are two fold:

- The penguin amplitude has exactly the same weak phase so that the asymmetry is given by

  $$\mathrm{Im}\left(\frac{q}{p}\frac{\overline{A}(B \to \psi K_S)}{A(B \to \psi K_S)}\right) = -\mathrm{Im}\left(\frac{\mathbf{V}_{tb}^*\mathbf{V}_{td}}{\mathbf{V}_{tb}\mathbf{V}_{td}^*} \cdot \frac{\mathbf{V}_{cb}\mathbf{V}_{cs}^*}{\mathbf{V}_{cb}^*\mathbf{V}_{cs}}\right) = \sin(2\phi_1). \quad (19)$$

  where ϕ_1 is the angle of the unitarity triangle shown in Fig.6.

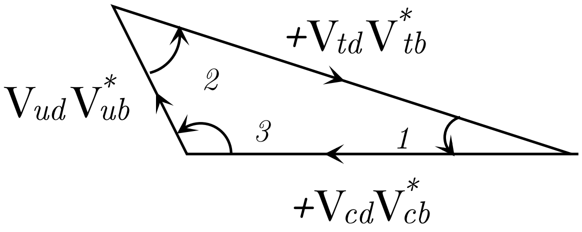


Figure 6: Unitarity of the KM matrix leads to a triangular relationship between elements of the KM matrix. The **CP** asymmetry can be related to angles of the triangle.[18]

- ψK_S mode has a very clear signature. $\psi \rightarrow \mu^+\mu^-$ decay can be identified in almost any environment. Identifying $K_S \rightarrow \pi^+\pi^-$ decay after an event is triggered by the presence of $\psi \rightarrow \mu^+\mu^-$ is relatively easy. So, hadronic colliders like CDF, D0, LHC can also study this decay.

4 Technical Difficulties-Numerous

There are plenty of reasons why it took more than 20 years to measure ψK_S asymmetry.

We need to “make” the B beam by tagging. If we tag B, say at time t, we know that the other one, at that instant, is a $\overline{B}$ as the pair is in a P-wave state. Tagging cost us in events as we have to overcome leptonic branching ratio and efficiency.

Let us look at the branching ratio for detecting $B \rightarrow \psi K_S$ decay while tagging the other B or $\overline{B}$ with a leptonic decay.

$$\begin{aligned} Br(B \rightarrow \psi K_S) &\sim 10^{-4}, \\ Br(B \rightarrow l\nu X) &\sim 10^{-1}, \\ Br(\psi \rightarrow l^+l^-) &\sim 10^{-1}. \end{aligned} \tag{20}$$

From the allowed region in the KM parameters obtained from the leptonic decay $B \rightarrow u + l\nu + anything$, B meson life time, K meson **CP** violation, we determined that there is at least 15% **CP** violation in B decays, if the standard model with

KM ansatz is correct. Since we are proposing an expensive machine, the machine should be capable of detecting asymmetry at any size predicted by the standard model. This means we have to assume that the asymmetry is at its minimum - 15%. With 100% efficiency, we need to accumulate at least 10^8 $B-\overline{B}$ pairs per year to have 100 tagged ψK_S events. Knowing that the cross section for $\Upsilon(4S)$ production is about a nano-barn, we must have a collider with a luminosity of $10^{34} cm^{-2} sec^{-1}$, if we want the result after two or three years of running.

5 Designing experiments

To my knowledge, Bjorken was the first, in 1985,[19] to discuss how we might actually do this experiment. At the end of his discussion, he wrote:

> Should one think about following such a path? I don't know. A decision to do so requires a better understanding $\cdots$. All of this should be know better in a few years.
>
> But the real decision to follow such a path must come from those who would do the work. The task is a very long and arduous one and, even for those who would have doubts, the homework should be done. That alone leaves a lot to do for everyone.

He was right! But, this was about to change dramatically in a couple of years.

Discoveries which lead to construction of B factories:

- On the top of the list, certainly, is the discovery of $B\overline{B}$ mixing by the ARGUS collaboration.[15] As mentioned above, it was not much of a surprise for theorists, but this got experimentalists excited. In particular, at the workshop on Experiments, Detectors, and Experimental Areas held at Berkeley , there were a whole group of experimentalists who took Bjorken's advice and started to do their homework. Serious attempts to design detectors for this type of physics has been made.[20]
- To me the most important discovery is the longevity of B mesons.[21,22] An elementary particle must live long enough to show something fundamental about nature. In fact the lifetime kept on increasing every time a new experimental result came out. This was good for the asymmetry. The long lifetime means small $\mathbf{V}_{cb}$, *i.e.* small s_2. As you can see in Fig. 4, its prediction kept on increasing.

- Advances in vertex detectors. As you will see below, measurements of particle track with a resolution of about $20\mu m$ is required. This was not possible when we started thinking about this experiment. Around that time, Mike Witherell and his collaborators incorporated a vertex detector in a photo-production experiment.[23] They were able to obtain beautiful results on charm particle decays. This experiment showed the capabilities of vertex detectors.

- On January 27, 1987, Pier Oddone, Ikaros Bigi, Amajit Soni, Worner Hoffman and I were sitting in a restraunt in Westwood, California having dinner. We have attended a workshop at UCLA organized by David Cline. After a glass of wine, Oddone, Hoffman and I made couple of physics bets [§]. Afterwards, our discussion turned to the fact that it is impossible to determine the decay time in an e^+e^- collider as $\Upsilon(4S)$ is at rest in the laboratory frame and $B's$ travel only about $20\mu m$. Then Pier said, "Why not build an asymmetric collider. This will boost $\Upsilon(4S)$!" I went on to visit KEK and people at KEK assured me that if we collide electrons and positrons at the luminosity of $10^{34} cm^{-2} sec^{-1}$, with different energies, the beam will blow up! Ikaros Bigi recalls the following conversation with a knowledgeable machine physicist back in Europe.
  "How about this idea of Oddone?" Ikaros asked.
  "It will never work! Its a theorist's crazy idea!" said the expert.
  "But Odonne is an experimentalist!" said Ikaros.
  "Oddone is obviously more unrealistic than even a theorist!"

  But then came a bootstrap effect where KEK and SLAC machine physicists competed in improving the maximum luminosity in an asymmetric collider - on paper at least.

- In 1988, David Hitlin, Tatsuya Nakada and I were in Snowmass, Colorado for a workshop on "Summer Study on High Energy Physics in the 1990's". We asked a question[24]: "How asymmetric should an asymmetric collider be?"

  If it is too asymmetric, we would loose all the events in the beam pipe. It turned out that existing TRISTAN ring at KEK and PEP ring at SLAC would do the job!

[§] I have documents which states the terms for both of these bets - I obtained the dates mentioned above from this document. Incidentally, I won both of these bets!

Since 1980, I went all over the world to convince physicists that B physics was interesting. They all agreed. But, proposals were not forthcoming. Both KEK and SLAC were busy with other projects. KEK was the first, however, to announce its serious intention to build the B factory. Then there was decision to discontinue SSC, followed by the B factory proposal at SLAC.

6 The race to get at the gold

Machine physicists at KEK and SLAC took quite different approaches to the prize. The SLAC group's upmost concern was to get there first. This meant that they did not want to deviate from the proven technology. They went for head on collision, conventional feed back system, conventional cavities, etc. The KEK group took a craftsman's approach. Their design called for 11 milli-radian crossing angle, superconducting cavities, ARES cavities, just to mention a few. This special renovations in the KEK design worried me to no end. We were racing. While trying out unproven technologies is interesting and important, we are in a race, and we must get there first. We cannot afford to stumble on any of these unproven technologies. For example, we knew that DORIS design for the finite angle crossing failed. Are we heading for the same disaster?

I was sitting in the Program Advisory Committee meeting, where the finite angle crossing was being discussed.
"How do you know that the finite crossing angle will work?" I asked.
"Our simulation said it will work!" speaker replied.
"Can you simulate the disaster at DORIS?" I asked.
"No, because we don't know the parameters!" he replied.
"Why don't you hop on a plane, go to DESY and find out the parameters!" I asked.
It tuned out that, the following summer, they invited an expert from DESY to simulate the disaster. It so happened that if DESY had the same computing power that existed at the time of KEK simulation, they could find the lattice so that their beam will collide.

We all know what happened to this race. After competing intensively for nearly 6 years, the result was a tie - there were no loser, just winners. KEK and

SLAC announced the result in a same PRL issue[25]:

$$\begin{aligned} \sin(2\phi_1) &= 0.82 \pm 0.20(stat) \pm 0.05(syst) \quad (Belle) \\ \sin(2\phi_1) &= 0.756 \pm 0.09(stat) \pm 0.040(syst) \quad (Babar) \end{aligned} \tag{21}$$

7 Its not so easy - Surprising penguins

There are other **CP** eigenstates besides ψK_S. The asymmetry in $B \to \pi^+\pi^-$ allows us to determine ϕ_2 shown in Fig.6, if the penguin amplitudes give negligible contribution compared to the tree graph.

If we just compute the penguin graph, without any QCD corrections, we find a suppression factor like

$$\frac{\alpha_s}{12\pi^3} \log \frac{m_t}{m_c} \sim \lambda^2, \tag{22}$$

Here $\lambda \sim \sin\theta_c \sim .23$. So, we felt that penguins will not play a crucial role. Then came the discovery of $b \to s\gamma$ decay.[26] Then CLEO Collaboration showed that[27]:

$$Br(B \to \pi\pi) < Br(B \to K\pi). \tag{23}$$

This is a very curious result.

These decays are generated by Feynman graphs shown in Fig. **??**. The $K\pi$ decay amplitudes for tree ($T(K\pi)$) and penguin($P(K\pi)$) contributions are:

$$\begin{aligned} T(K\pi) &= \frac{G_F}{\sqrt{2}} \mathbf{V}_{ub}^* \mathbf{V}_{us} [C_1(\mu) Q_{s1}^u(K\pi) + C_2(\mu) Q_{s2}^u(K\pi)], \\ P(K\pi)_c &= \frac{G_F}{\sqrt{2}} \mathbf{V}_{cb}^* \mathbf{V}_{cs} [C_1(\mu) Q_{s1}^c(K\pi) + C_2(\mu) Q_{s2}^c(K\pi)], \\ P(K\pi)_t &= \frac{G_F}{\sqrt{2}} (-\mathbf{V}_{tb}^* \mathbf{V}_{ts}) \sum_{i=3}^{10} C_i(\mu) Q_{si}(K\pi). \end{aligned} \tag{24}$$

For $B \to K\pi$, $P(K\pi)$ is $\mathcal{O}(\lambda^2)$ and $T(K\pi)$ is $\mathcal{O}(\lambda^4)$. For $B \to \pi\pi$, these diagrams give $T(\pi\pi) = \lambda^3 T$, $P(\pi\pi)_t = \lambda^3 P_t$, and $P(\pi\pi)_c = \lambda^3 P_c$.

If the tree graph matrix elements dominate, $\frac{T(K\pi)}{T(\pi\pi)} \sim \lambda$, and we expect $\frac{Br(B\to K\pi)}{Br(B\to\pi\pi)} \sim \mathcal{O}(\lambda^2)$. Experimentally this is no so. This indicates that the penguin amplitude $P(K\pi)$ is at least as large as the tree amplitude, $T(\pi\pi)$. If $P(K\pi) \simeq T(K\pi)$, this suggests

$$\frac{[C_1(\mu) Q_{s1}^c(K\pi) + C_2(\mu) Q_{s2}^c(K\pi)]}{[C_1(\mu) Q_{s1}^u(\pi\pi) + C_2(\mu) Q_{s2}^u(\pi\pi)]} = \mathcal{O}(\lambda) \tag{25}$$

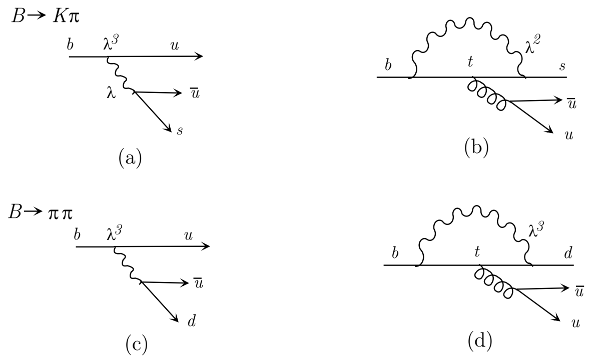


Figure 7: The tree and penguin graphs which contribute to $B \to \pi\pi$ and $B \to K\pi$ decays.

i.e., the penguin contribution is considerably larger^{28} than what a naive estimate of the loop graph suggested by Eq. (22).

Since we now have an evidence that loop graphs compete with tree graphs, we have to be prepared for a substantially more complex situation.

8 Penguin Pollution

I don't like the word "penguin pollution". Penguins are harmless and cute. In physics, it presents richness to the field. There are many interesting decays of B mesons, which we will not observe if penguin diagrams are absent. There will be many interesting **CP** asymmetries which will be generated by penguins. But, for **CP** asymmetry with $B-\overline{B}$ mixing, in particular for $B \to \pi\pi$ mode, it is an obstacle toward getting at one of the angles of the unitarity triangle.

Consider two operators differing in their KM parameters driving $B \to f$:

$$A(B \to f) = e^{i\xi_1}e^{i\delta_1}|\mathcal{A}_1| + e^{i\xi_2}e^{i\delta_2}|\mathcal{A}_2| \tag{26}$$

where δ_i and ξ_i are the strong interaction and weak phases, respectively; the moduli of the KM parameters have been incorporated into $|\mathcal{A}_i|$. We then find

$$\begin{aligned} \mathrm{Im}\frac{q}{p}\overline{\rho}(f) &\sim \sin 2(\Phi_m - \xi_1) + \Delta \\ \Delta &= -2\left|\frac{\mathcal{A}_2}{\mathcal{A}_1}\right| \sin\Delta\xi \cos(2\Phi_m - 2\xi_1 + \Delta\delta) \end{aligned} \tag{27}$$

where $2\Phi_m = \arg\left(\frac{q}{p}\right)$; $\Delta\xi = \xi_2 - \xi_1$, $\Delta\delta = \delta_2 - \delta_1$. In deriving Eq. (27), we have made an approximation, $|\mathcal{A}_2/\mathcal{A}_1| \ll 1$. The presence of a second weak operator poses a challenge in our ability to extract KM parameters from the data. How this difficulty be best overcome depends on the specifics of the channel under study.

For $B \to \pi^+\pi^-$ decay mode, Δ can easily be as big as the $\sin 2(\Phi_m - \xi_1) = \sin(2\phi_2)$ term. So, we must rely on the isospin analysis.[29] But the problem is that this method requires measurement of $Br(B \to \pi^0\pi^0)$ which is often swamped by backgrounds.

Much theoretical work is necessary along this direction. PQCD is one such attempt. It gives a useful guide as to where we should look for interesting effects. For example, PQCD predicts large **CP** asymmetries for some of $B \to K\pi$ and $B \to \pi\pi$ decay channels.[28,30] But, certainly we need to find a model independent search for new physics beyond the standard model.

9 Summary

What is happening now? As of today (Oct. 28, 2002), PEPII is shut down for maintenance - they will start soon. KEKB started to run after its maintenance. KEKB has just achieved a milestone of accumulating $100fb^{-1}$. Many interesting rare decays are being detected. The present B factories will be a gold mine for new discoveries. When LHCB and BteV get in to the game, there will be much competition. B factories must be upgraded by then. There is already plans to upgrade KEKB and PEPII. They are ambitious projects. But it must be done.

Was flavor physics in K decay over when **CP** violation was discovered? Of course not! K physics has generated mach excitement over the past 37 years. We are still designing experiments to study its properties. And these experiments probe fundamental nature of the world we live in. I am absolutely sure that the same statement can be made about B physics. I am sure we will be talking about B physics in year 2050. Its not too late to join the quest for new knowledge through the B system.

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