Lecture about the Recent Nobel Prize
— From B Factory to the Large Hadron Collider —

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These are the transcriptions of "a talk describing the theoretical insights of those honored (and the one who wasn't) and how this has led to all the physics we have been doing over the last couple of decades." After prologue, we first deal with Nambu's insight on Spontaneous Symmetry Breaking, which is rooted in an analogy with the BCS theory of superconductivity. The insight resonates to this day, as we await the LHC era to dawn. The second half starts from Gell-Mann–Lévy–Cabibbo theory, through the GIM mechanism that completed the 2×2 rotations, to the insight of Kobayashi and Maskawa that CP violation could arise from the charged currents, if there exists a 3rd generation of quarks. The richness that followed defines this (FPCP) conference. We end with a perspective on a (possible) redux with a 4th generation of quarks.

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0. Prologue: Predicting the 2008 Prize

On September 30th, 2008, Ling-Fong Li gave a colloquium at NTU on the Higgs particle. At the end, I commented on the Higgs Mechanism ..., that Spontaneously Broken Gauge Theory (SBGT) of $SU(2) \times U(1)$ is already verified experimentally, and that it does not require a physical Higgs boson. Then I said, roughly "There should be enhanced chance for Japanese receiving the Prize this year, because former KEK Director General, Totsuka sensei, passed away in July. Second, BaBar shut down in April, marking a transition for the B Factory era. Therefore, as we await the LHC era to dawn, Cabibbo, Kobayashi and Maskawa have good chance this year."

Turning around to my colleague, Yeong-Chuan Kao, a Nambu fan, I said, "Could it be Nambu and Goldstone ?! Nambu certainly well deserves, and he's really old !" After all, his 65th birthday was over 20 years ago. Kao then stated adamantly that Nambu will get the prize.

On October 2nd, I gave a seminar at the IPMU of Tokyo University, and stated after showing the recent CKM fit, "Could this be the Year of CKM ?" Hitoshi Murayama responded that "the announcement should be tomorrow." He got the date wrong, but it did prompt me to check ...

In the evening of October 7th, a little tired and bored, I recalled the date and went on-line, and was exhilarated to witness the announcement ... and the genius of the Nobel Committee. Though "predicting" all three Japanese names, I was certainly astonished by the brutal cut-and-paste by the Committee.

So, 1/4 each of The Nobel Prize in Physics 2008 goes to Kobayashi sensei and Maskawa sensei, "*for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature.*" The B factory workers (this one included) feel as honored, by demonstrating the Standard Model mechanism of CP Violation (CPV) is indeed as pointed out by KM. Of course, by implication of the ordering, the more important 1/2 of The Nobel Prize in Physics 2008 goes to Nambu sensei, "*for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics.*" (SSB) It is clear that SSB, the "Higgs" particle, the Origin of Mass, is the main goal at the Large Hadron Collider.

I wonder whether the above can be called a "premonition," but I certainly did not expect to be here to deliver this "lecture." But here goes.

1. Introduction: the Trouble of Mass(es)

With Chadwick's discovery of the neutron, the near equality of $m_n \cong m_p$ prompted Heisenberg to propose isospin symmetry, that the two form an isodoublet, the nucleon N, and thus introducing "internal symmetries." From Yukawa's proposal to Powell's discovery, as the dust settled, the pion also came in as an isotriplet. But why, then, $m_\pi \ll m_N$?

It was Fermi and Yang who, in 1949, put forward the suggestion [1] that maybe there is some compositeness behind the scene. They pointed out that these particles were assumed "elementary," which essentially means "structureless." But then they state that "all such particles ... should be elementary becomes less and less as their number increases." With this, they suggest that the pion π is a bound state of $N\bar{N}$, but admitting immediately that $m_\pi \ll 2m_N$ is a real difficulty.

By 1956, Fermi had died, while Yang was busy with parity violation. It was Shoichi Sakata of Nagoya University who followed up on the point. More particles have appeared since. Undaunted

by the mass issue, Sakata proposed [2] that it is N and Λ (or p, n and Λ), an isodoublet and an isosinglet, respectively, that are "elementary," and all other particles, whether the heavier hyperons, or the "θ" or "τ" mesons of the day, were composites à la the Fermi–Yang suggestion.[1]

This was one step away from quarks. In the poster of "The Jubilee of the Sakata Model" held at Nagoya University in October 2006 [3], it was shown, ingeniously, how (Λ, p, n), turned upside down, became (u, d, s), the quarks of Gell-Mann. In the latter seminal paper [4], however, Gell-Mann refers to "the old Sakata model" but without giving a citation.

Still, where does the proton mass come from? [In fact, where does "Mass" come from? This is still the prevailing question of the day.] And, can one understand $m_\pi \ll 2m_N$ with compositeness? It was Nambu who guided the way, as documented [5] in "Broken Symmetry," which is also the namesake of the 2008 Nobel Prize in Physics.

2. Squalid State to the Rescue — Nambu's Insight

It was Gell-Mann who quipped the words "Squalid State Physics," but it was Squalid State Physics that came to the rescue. Nambu, who received a Sc.D. from Tokyo University in 1952, acknowledges that [6] "my early exposure to condensed matter physics has been quite beneficial to me." And Particle Physics (and physics as a whole) is forever grateful.

Scientific American reran their "Profile: Yoichiro Nambu" of 1995, immediately after the Nobel announcement, with the title [7] "Strings and gluons — The seer, this year's physics Nobel laureate, saw them all." Ed Witten is quoted as saying "*People don't understand him, because he is so farsighted.*" And Murray Gell-Mann says "*Over the years, you could rely on Yoichiro to provide deep and penetrating insights on very many questions.*" Sound like all praises. However, in Nambu's own words, that he wrote decades later to encourage a junior colleague: "*Everyone seemed smarter than I. I could not accomplish what I wanted to and had a nervous breakdown.*" He was referring to the Institute of Advanced Study, the place he went after his doctorate. Even when he was already an associate professor at Chicago, when he proposed a new particle in 1957, he was met with ridicule. Richard Feynman shouted "*In a pig's eye!*" at the conference, recalls Laurie Brown [8]. The omega was discovered the next year.

But this was a momentous time, both at Chicago, and at Illinois. "*Give it another month, or a month and a half. Wait 'til I get back and keep working. Maybe something'll happen.*" With these parting words to Bob Schrieffer, John Bardeen left for Sweden in late November of 1956 to accept the Nobel Prize in Physics, his first, for the discovery of the transistor [9]. The rest is history. The BCS theory of superconductivity was published in 1957 [10], a triumph of Squalid State Physics!

In his autobiography notes in Broken Symmetry [5], Nambu writes, "*One day before publication of the BCS paper, Bob Schrieffer, still a student, came to Chicago to give a seminar on the BCS theory in progress ... I was very much disturbed by the fact that their wave function did not conserve electron number. It did not make sense ... At the same time I was impressed by their boldness and tried to understand the problem.*" Schrieffer soon joined the Chicago faculty, and Nambu could discuss with him in depth. In July 1959, Nambu submitted the paper [11] "Quasiparticles and Gauge Invariance in the Theory of Superconductivity." He obtained Ward identities

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[1]Early indication of nucleon structure is the measurement of anomalous magnetic moment of proton by Otto Stern. At time of the Sakata paper, Hofstadter was uncovering nucleon structure at Stanford with e-beams.

— telltale signs of gauge invariance — that, despite the broken symmetry, rendered the Meissner effect calculation strictly gauge invariant. He further observes that "a pair of a particle and antiparticle interacting with each other to form a bound state with zero energy and momentum" was crucial for understanding the mechanism by which gauge invariance was restored. This is the "Nambu-Goldstone boson" of zero mass. Let us digress.

Nambu-Goldstone Boson and Higgs Mechanism

Nambu later reflects [6, 12] on the mechanism of BCS theory:

"The BCS theory assumed a condensate of charged pairs of electrons or holes, hence the medium was not gauge invariant. There were found intrinsically massless collective excitations of pairs (Nambu-Goldstone modes) that restored broken symmetries, and they turned into the plasmons by mixing with the Coulomb field."

He found that zero modes necessarily emerged because the broken symmetry is continuous, the essence of the Goldstone theorem. Let us not repeat the mathematics. It is well known that a "Mexican hat" illustrates the point, so let me quote directly from Steven Weinberg's talk "From BCS to the LHC," delivered at the BCS@50 celebration [9], and published in the CERN Courier [13]: "Though the hat is invariant under rotations about a vertical axis, a small ball will come to rest off the axis of symmetry, somewhere on the brim of the hat, but it can move freely with no restoring force around the brim." This is precisely the content of the Goldstone Theorem [14], made rigorous in a subsequent paper by Goldstone, Salam and Weinberg. Though getting ahead of ourselves, let me continue with Weinberg's words: "Broken approximate symmetry is illustrated by slightly tilting the hat; this produces a small restoring force, analogous to the small mass of the pion."

The broken symmetry in superconductivity is not just continuous, but it is the gauged symmetry of electromagnetism itself. Thus, as we quoted from Nambu above, the "Nambu-Goldstone modes ... turned into the plasmons by mixing with the Coulomb field." This explains the Meissner effect in a gauge invariant way (as insisted by Nambu), which is nothing but the Higgs Mechanism. The claim to the Higgs mechanism is of course a contentious one. There is the argument based on BCS theory itself by Philip Anderson [15], and three papers, by François Englert and Robert Brout, by Peter Higgs, and by Gerald Guralnik, Carl Hagen and Tom Kibble [16].[2]

In reference to the Higgs mechanism, Nambu himself uses [12] the term Ginzburg–Landau–Higgs "effective" field, citing the Ginzburg–Landau theory [17], the precursor to the BCS theory of superconductivity. He further comments [6]: "*In hindsight I regret that I should have explored in more detail the general mechanism of mass generation for the gauge field. But I thought the plasma and the Meissner effect had already established it. I also should have paid more attention to the Ginzburg-Landau theory which was a forerunner of the present Higgs description.*"[3] On other examples of BCS type of SSB, such as ^{3}He superfluidity and nucleon pairing in nuclei, he offers his opinion on fermion mass generation in the Standard Model [6]: "*my biased opinion, there being other interpretations as to the nature of the Higgs field.*" Let me now return to Nambu's prize.

The Penetrating Analogy: m_N as "BCS Energy Gap" and π as "collective excitation"

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[2]We note in passing that Englert, Brout and Higgs received the EPS Prize in 1997, and the Wolf Prize in 2004.
[3]The underlining is mine.

Nambu followed a keen interest in understanding gauge invariance in the presence of SSB. He was certainly more a particle and field theorist, than a condensed matter physicist. With the proposal of $V - A$ theory of weak interactions and CVC in 1958, many were interested in a possibly conserved axial vector current. In the paper [18] "Axial Vector Current Conservation in Weak Interactions," Nambu constructed the axial vector current, and having derived the Goldberger–Treiman relation in a satisfactory way, he made the penetrating analogy from his understanding of BCS theory: gauge invariance $\leftrightarrow \gamma_5$ invariance; energy gap $\leftrightarrow$ baryon mass; and collective excitations $\leftrightarrow$ mesons. He went on to conclude that "It is interesting that pseudoscalar mesons automatically emerge in this theory as bound states of baryon pairs. The nonzero meson masses and baryon mass splitting would imply that the γ_5 invariance of the bare baryon field is not rigorous, possibly because of a small bare mass of the order of the pion mass." Although the last statement was not entirely correct, the insight was clearly profound: what was behind the Fermi–Yang–Sakata model was becoming clearer! Yukawa's pion has become the Nambu–Goldstone boson of spontaneous Chiral Symmetry Breaking (χSB), and light had been shed on why $m_\pi \ll 2m_N$. The dominant part of our body mass, or that of the Earth or the Sun or the visible Universe, arose through χSB.

Table 1: Nambu's analogy between the BCS theory of superconductivity, and spontaneously broken chiral symmetry of the strong interactions (adapted from Ref. [19]).

	Superconductivity	Strong Interactions	realization
elementary particle	electrons	hypothetical fermions	u, d quarks
interaction	phonon exchange	unknown	QCD
	energy gap	m_N	
	collective excitations	π (meson boundstate)	
	electric charge	chirality	
broken symmetry	gauge invariance	chiral (γ_5) invariance	

Table 1 illustrates the full power of Nambu's analogy. Considering that the "hypothetical fermions" were put forth 4 years before the quark model [4, 20], and the fact that it took another decade (after the emergence of QCD that took the place of the "unknown" interaction) for the latter to be accepted, Nambu's insight by analogy is truly penetrating. He saw through the veil of what baryons and mesons really are, even before the rather difficult dynamics was understood. We should remember that color SU(3) was also proposed by him [21], on the grounds of statistics. Here he followed Gell-Mann's quark model paper, but unfortunately did not follow the simplest possibility of fractionally charged quarks. With the latter, we have the familiar picture that the proton (neutron) has uud (udd) constituents, whereas π^+ is $u\bar{d}$.

Although the true dynamics was not yet known, Nambu went further to construct dynamical chiral symmetry breaking, eventually resulting in the Nambu–Jona-Lasinio (NJL) model [22], and the foundations of chiral perturbation theory (χPT). For clarity, perhaps we need to backtrack to what Nambu saw in the nucleon with χSB vs. BCS theory, and we would need a few formulas.

The quasi-particles near the Fermi surface of a superconductor is a coherent mixture of electron and hole states with momentum p and spin $+$,

$$E\,\psi_{p,+} = \quad \varepsilon_p\,\psi_{p,+} \quad + \phi\,\psi_{-p,-}^{\dagger},$$
$$E\,\psi_{-p,-}^{\dagger} = -\varepsilon_p\,\psi_{-p,-}^{\dagger} + \phi\,\psi_{p,+}, \qquad (2.1)$$
$$E = \pm\sqrt{\varepsilon_p^2 + \phi^2},$$

where ε_p is the kinetic energy from the Fermi surface, and ϕ is the gap parameter [6, 22]. Nambu saw an analogy with the (relativistic) Dirac equation, which reads, in the Weyl representation,

$$E\,\psi_1 = \quad \sigma \cdot p\,\psi_1 + m\,\psi_2,$$
$$E\,\psi_2 = -\sigma \cdot p\,\psi_2 + m\,\psi_1, \qquad (2.2)$$
$$E = \pm\sqrt{p^2 + m^2},$$

where $\psi_{1,2}$ are eigenstates of the chirality operator γ_5. The Dirac mass corresponds to the gap parameter ϕ, which touches base with our former discussion. But from here, NJL states [22] "As the energy gap ϕ in a superconductor is created by the interaction, let us assume that the mass of a Dirac particle is also due to some interaction between massless bare fermions."[4] Going further, "It is perhaps not a coincidence that there exists such an entity in the form of the pion. For this reason, we would like to regard our theory as dealing with nucleons and mesons. The implication would be that *the nucleon mass is a manifestation of some unknown primary interaction between originally massless fermions, the same interaction also being responsible for the binding of nucleon pairs into pions*." (italics are mine) This is the starting point not only in constructing the NJL model, but χPT, and effective field theories in general. Note that χPT works at long distance when QCD doesn't, and even lattice QCD calculations call on χSB to interface with data.

We see the power of one person's insight through analogy.

3. Spontaneous Symmetry Breaking and SU(3) × SU(2) × U(1)

SSB is clearly an integral part of the Standard Model, both in dynamical χSB, and the SSB of electroweak gauge interactions.

With the "unknown" interaction of spontaneous/dynamical χSB established as the non-Abelian gauged dynamics of color SU(3), we recall the breakthrough of asymptotic freedom that preceded it, and the correct selection of the gauge group by Gross and Wilczek (and Fritzsch and Gell-Mann), even though Han and Nambu had proposed it much earlier. So, the global $\text{SU}_L(3) \times \text{SU}_R(3)$ chiral symmetry is dynamically broken down by QCD, as well as explicit quark masses, to approximate $\text{SU}_V(3)$. But, just as in the NJL model, even when QCD is not applicable in the strong coupling regime (low energy), χPT is applicable. This is the precursor to effective field theories.

We are familiar with Weinberg's usage of the Higgs mechanism to break SU(2) × U(1), and his conjecture that non-Abelian gauge theory is renormalizable, and that reordering of perturbation after SSB would not change the renormalizability [23]. These were of course later proven by 't Hooft and Veltman. What we wish to stress is that, while a single complex Higgs doublet field

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[4]The relativistic cutoff would take the place of the (nonrelativistic) Fermi surface.

developing a vacuum expectation value (v.e.v.) is the simplest realization of SU(2) × U(1) breaking, the Higgs field does not have to be elementary. One needs only an effective Ginzburg–Landau–Higgs field [6]; SSB is already an experimental fact, and regardless of the true origin of the SSB, the longitudinal W and Z are the would-be Nambu–Goldstone bosons!

4. Gell-Mann–Lévy–Cabibbo and GIM: from 3 to 4 Quarks

The proliferation of strange hadrons caused Sakata to propose his substructure model, their weak decay also pointed to some universal behavior.

In his seminal paper "Unitary Symmetry and Leptonic Decays" of 1963, Nikola Cabibbo made a comprehensive study of strangeness conserving ($\Delta S = 0$) and changing ($\Delta S = 1$) decays [24]. Writing before quarks, he used SU(3) currents and $V - A$ theory to compare e.g. π^+ vs. K^+ decay to $\mu^+ \nu_\mu$. He proposed a "unit length" of weak interaction strength, i.e. a $\cos\theta$, $\sin\theta$ factor for the $\Delta S = 0, 1$ currents, and found that a near universal value of $\theta \simeq 0.26$ could account for available data. He noted that, though overshooting a bit, the $\cos\theta$ factor to ^{14}O beta decay was in the right direction. Paraphrasing the Nobel Committee [19], "the Cabibbo Theory, with the Cabibbo angle," $\theta_C \cong 13°$, "quickly became a standard framework for the weak interactions. It turned out to be universal and an ever-increasing multitude of data could be fitted into it. It has been a cornerstone of weak interactions." In quark language, the d quark in weak interactions is a mixture,

$$d' = d \cos\theta_C + s \sin\theta_C, \tag{4.1}$$

of the d and s mass eigenstates.

Unfortunate perhaps for Cabibbo, the unitary transform of $\Delta S = 0$ and 1 currents had been consider 3 years earlier by Gell-Mann and Maurice Lévy [25] in their work "The Axial Vector Current in Beta Decay," as Cabibbo acknowledges in his footnote 4. Gell-Mann and Lévy noted that ^{14}O data implied $G/G_\mu \sim 0.97$. In a "*Note added in proof,*" they suggested to

"... consider the vector current for $\Delta S = 0$ and $\Delta S = 1$ together to be something like:

$$GV_\alpha + GV_\alpha^{(\Delta S=1)} = G_\mu \, \bar{p} \gamma_\alpha (n + \varepsilon \Lambda)(1 + \varepsilon^2)^{-\frac{1}{2}} + \cdots,$$

and likewise for the axial vector current. If $(1 + \varepsilon^2)^{-\frac{1}{2}} = 0.97$, then $\varepsilon^2 = .06$, which is of the right order of magnitude for explaining the low rate of β decay of the Λ particle."

to maintain universality. Although they did not press further, this is the same program as that pursued by Cabibbo (who had more data available), and may be why the Nobel Committee uses the wording "Gell-Mann–Lévy–Cabibbo" theory [19], something that is not in common use.

In 1964 Gell-Mann put forth the quark model [4], where, dispensing with the need of a "basic neutral baryon singlet," he discusses the simpler (and calling it more elegant) non-integer charged "quarks" (here, Gell-Mann is moving beyond the Sakata model). With the u, d and s quarks, Gell-Mann puts the electromagnetic current in the modern form, and uses the *quark mixture* of Eq. (4.1) for the first time. In so doing, Gell-Mann refers both to his previous work with Lévy, as well as stating "We thus obtain all the features of Cabibbo's picture."

Besides the experimental discovery [26] of CPV in $K_L^0 \to \pi\pi$, on the path to Kobayashi and Maskawa, there is one more important step, which is the mechanism proposed by Sheldon Glashow,

Jean Iliopoulos and Luciano Maiani (GIM) [27] in 1970, in the paper titled "Weak Interactions with Lepton–Hadron Symmetry." If the d' of Eq. (4.1) enters the charged current with the u quark, then in the Glashow–Weinberg–Salam theory, the Z^0 boson would couple to a $\bar{d}'d'$ pair, and K^0 (composed of $\bar{s}d$) should decay to $\mu^+\mu^-$, which was not observed. GIM pointed out that, if one adds the orthogonal combination[5] of $s' = -d\sin\theta_C + s\cos\theta_C$, then the $K^0(\bar{s}d) \to \mu^+\mu^-$ amplitude cancels away. This works also at the loop level (violated only by difference in masses), guaranteeing that flavor changing neutral currents (FCNC) are suppressed, which is consistent with experiment! This usage of unitarity of quark mixing matrix is the foundation of flavor loop calculations.

The Z^0 coupling to $\bar{s}'s'$ pair implies the existence of a new charge $+2/3$ quark. This "charm" quark, c in modern notation ($\mathscr{P}'$ as used by GIM), renders the "Cabibbo rotation" complete.

5. Insight of Kobayashi–Maskawa: 6 Quarks for CPV

The experimental discovery [26] of CP violation in neutral kaon system in 1964 came as a surprise. Before long, however, Andrei Sakharov pointed out [28] that CPV is needed to explain the absence of antimatter in our Universe, so understanding CPV gained *universal* importance.

The GIM paper did mention [27] "... suitable redefinitions of the relative phases of the quarks may be performed in order to make U real and orthogonal ...," and in this way they arrived at the 2×2 rotation matrix. But they were not concerned with CP violation.

The pursuit of CP violation was taken up by Makoto Kobayashi and Toshihide Maskawa (KM). Both received their Ph.D. from Nagoya University (hence immersed in the Sakata school), and both went to Kyoto University after graduation. Barely 5 months after Kobayashi had arrived, the two submitted the paper "CP Violation in the Renormalizable Theory of Weak Interaction" [29] on September 1st, 1972 to Progress of Theoretical Physics, the Japanese journal. Kobayashi was just 28 years old, and Maskawa 32. Although the title states "renormalizable," they refer only to Weinberg's paper [23]. Nor do they refer to GIM,[6] but they also use Sakata's notation of p, n, λ, plus ζ for the 4th, charge $+2/3$ quark (the charge was actually kept free in the work). At Nagoya, the school of Sakata, people were independently thinking of the existence of a 4th quark after ν_μ was demonstrated to be different from ν_e. So it came natural to the two Nagoya graduates.

KM quickly dispensed with the "quartet" model, that "With an appropriate phase convention of the quartet field we can take U as ..." the familiar 2×2 form. Targeting CPV, they conclude that "no realistic models of *CP*-violation exist in the quartet scheme without introducing any other new fields." So they consider adding new fields, such as extra scalar doublets.[7] As for "a 6-plet model, another interesting model of *CP*-violation," they note that "in this case we cannot absorb all phases of matrix elements into the phase convention...,"[8] and they give their parametrization of the 3×3 unitary matrix. The 3 "generation" Standard Model was born — *motivated by CPV*.

I bless the young postdoc(s) reading this to make similar impact at a tender age.

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[5]GIM uses the Sakata model notation of $\mathscr{P}$, $\mathscr{N}$, λ for the SU(3) triplet of quarks.

[6]Knowledge of GIM was acknowledged in the Nobel Lecture of Maskawa [30].

[7]The case of extra right-handed quark doublets were already considered by Rabindra Mohapatra [31].

[8]I learned from the Nobel Committee [19], that our usual exercise (in our Particle Physics course) of phase freedom of quark fields, the $n^2 - (2n-1) = (n-1)^2$ degrees of freedom in the $n \times n$ V_{CKM} matrix, is something called the Iwasawa decomposition [32] of the unitary matrix U that connects two n-component vector fields.

6. Richness of KM: from tau to top; FPCP

People often think Nambu as a cut above the other two recipients, and I concur. Nambu is a cut above most of us, maybe even a good fraction of the Nobel recipients. But the measure of success of a model is its predictive impact! And here, the KM model — the flavor (and CPV) part of the Standard Model — is indeed very successful. If Cabibbo captured half of the 2×2 quark mixing matrix, and he could account for practically all (tree level) strangeness decay and production with one parameter, then KM predicted the existence of two additional mixing angles, plus the crucial CPV phase to account for that enigmatic phenomena. There is the underlying prediction of the existence of the third generation τ (and ν_τ) lepton and b and t quarks. Though the values are not predicted, masses and mixings account for the major number of — dynamical — parameters in the Standard Model, which calls out for an explanation. This conference — Flavor Physics and CP Violation — is just shaping the foundation for the next step, i.e. understanding it all. The discovery of the third generation fermions, measuring their properties, confirming that it is indeed the source of CPV, is the enterprise that honors the insight of two young men. It is mostly the outcome of the B factories, as epitomized in the "CKM unitarity fit" (salutations to Cabibbo again), that lead to KM's Prize. This is our payback to these two gentlemen. The fact they did it from a "remote" part of the academic world just adds to the allure. The observation *did not* come from the big wigs of the West (or Russia?). This brings me, an East Asian, satisfaction.

There is unfinished business, however.

Towards the end of Kobayashi's Nobel Lecture [33], he comments on the state of affairs of CP violation studies. Though "B-factory results show that quark mixing is the dominant source of CP violation," they "allow room for additional source from new physics." This calls for further studies. What is even more enticing is that "Matter dominance of the Universe seems requiring new source of CP violation." Let us elucidate this a little.

What the B factories have checked in detail is that

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \tag{6.1}$$

forms a *nontrivial* triangle, and a nontrivial CPV phase in particular. However, at the more refined level, the Iwasawa decomposition for the 3×3 case demands nondegeneracy of the bi-vector space; in physical terms this means all like-charge quark pairs ought to be nondegenerate. Otherwise, one is effectively back to the 2 generation case, and the CPV phase can be removed. Cecilia Jarlskog captured the essence of this through her proposed invariant measure of CPV [34],

$$J = (m_t^2 - m_u^2)(m_t^2 - m_c^2)(m_c^2 - m_u^2)(m_b^2 - m_d^2)(m_b^2 - m_s^2)(m_s^2 - m_d^2)A, \tag{6.2}$$

which can be deduced from $\mathrm{Im}\,\det\left[m_u m_u^\dagger,\, m_d m_d^\dagger\right]$, where A is twice the area of the triangle of Eq. (6.1). Indeed, one sees that J vanishes with A, or when any pair of like-charge quarks are degenerate. Kobayashi's words that "Matter dominance of the Universe seems requiring new source of CP violation" refers to the despairing situation that J, normalized to the weak scale, seems to fall short of what is needed for the Sakharov conditions by at least a factor of 10^{-10}.

7. Epilogue: KM–N Redux? A Perspective

Nambu had a critical opinion on the nature of the Higgs field and fermion mass generation, while Kobayashi noted that his CPV phase with Maskawa, the one confirmed by the B factories, falls short of what is needed for matter dominance of the Universe. I then ask: Can there be a redux of Kobayashi–Maskawa–Nambu? In the following, I turn to offer a (personal) perspective, with the caution that — *I'm a born-again 4th generationist!* Stop here if you wish.

At this conference, considerable effort is spent on the theoretical understanding of charmless hadronic *B* decays. The prevailing wind since a few years is to brush aside the staggering, *unpredicted* direct CPV difference of $\Delta A_{K\pi} \equiv \mathscr{A}_{B^+ \to K^+\pi^0} - \mathscr{A}_{B^0 \to K^+\pi^-} > -\mathscr{A}_{B^0 \to K^+\pi^-} \sim 10\%$, as due to a large, hadronically enhanced color-suppressed amplitude C.[9] But, shocked by the emergence of $\Delta A_{K\pi}$ in 2004, I demonstrated [35], together with Makiko Nagashima and Andrea Soddu, that it could be due to the 4th generation: the nondecoupled $m_{t'}^2$ dependence of the *bsZ* penguin loop is tailor-made, while $V_{t's}^* V_{t'b}$ brings in a new CPV phase. Stressing that the *bsZ* penguin and the $b\bar{s} \leftrightarrow s\bar{b}$ box diagrams are closely linked, we made a prediction of $\sin 2\Phi_{B_s}$ (defined analogously to $\sin 2\beta/\phi_1$, but for $B_s \to J/\psi\phi$) on the basis of a finite t' effect in $\Delta A_{K\pi}$. The prediction was improved [36] to $\sin 2\Phi_{B_s} \simeq -0.5$ to -0.7 with a somewhat different argument, after Δm_{B_s} was measured by the CDF experiment in 2006.

Encouraging results followed at the Tevatron. I am grateful to CDF for the wording [37] "... some source of new physics contributing to the electroweak penguin which governs the $b \to s$ transition. ... George Hou predicted the presence of a t' quark ... to explain the Belle result and predicted *a priori* the observation of a large *CP*-violating phase in $B_s^0 \to J/\psi\phi$ decays [7, 8]." This refers to our prediction of $\sin 2\Phi_{B_s}$. Although the (combination of) errors are still under discussion, it is astounding that the world central value of 2008 is about -0.6, with significance above 2σ, and deviating that much from the Standard Model (predicted from replacing *d* by *s* in the 3 generation relation of Eq. (6.1)). This is astounding, as theorists only look at central values.

A little more than a year ago, I made an unsettling observation. I learned about Jarlskog's invariant as a young postdoc, but only through the writing of the Belle *Nature* paper [38] on $\Delta A_{K\pi}$ did I learn more clearly the simple dimensional analysis argument that, when scaled by the electroweak phase transition temperature of $T \sim 100$ GeV (worse if v.e.v. is used), then J falls short of $n_{\mathscr{B}}/n_\gamma \sim 0.5 \times 10^{-9}$ by a factor of 10^{-10}. It occurred to me in late summer 2007, which I put forth in arXiv:0803.1234, that if there is a 4th generation, and if one shifts[10] from 123 to 234 in Eq. (6.2), then "J_{234}" gains a factor of $\sim 10^{15}$ [39]. The gain is mostly in large Yukawa couplings. *It seems that one would have enough CPV for matter dominance of the Universe*, and Nature would likely use this. Who can argue with the ".1234" number returned by arXiv on March 8, 2008?

Another thing I enjoyed learning in the same time frame, prior to Nambu getting his prize, is that heavy $\bar{Q}Q$ can condense through (the origins of) large Yukawa coupling. Concurrent with Nambu's "biased opinion," the Higgs boson would then become composite. Could SSB of electroweak gauge symmetry be due to condensation of b'/t' quarks near or above the unitarity bound of 500–600 GeV? Bob Holdom has explored [40] this theme in the past few years ($\sim$ the Bardeen–Hill–Lindner work 20 years ago), which is in fact nothing but the NJL model!! Interestingly, there

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[9]To me, this mouthful, as well as the oxymoronic "enhanced color-suppressed ...," are clear symptoms.

[10]This is valid in the *d-s* degeneracy limit, which is justified in our world.

is an AdS/CFT correspondence to this strong coupling regime, called [41] the "holographic 4th generation." I was therefore more than pleased with Nambu receiving the 2008 Nobel Prize.

So, are we in for a KM–N redux? The 10^{15} gain in CPV may be enough as the source of CPV for the matter dominance of the Universe (remember, the fermion masses are really Yukawa couplings, hence the dynamical effect may work even above the electroweak phase transition scale). This alone to me is reason enough that "*Maybe there is a 4th Generation!*" It is tantalizing that the Tevatron could bring indirect evidence for this through $\sin 2\Phi_{B_s}$ by 2010-2011; it could be easily pursued at LHCb, once data arrives. More important, direct search at the LHC by the CMS and ATLAS experiments could discover, or rule out, the existence of a 4th generation in 3-5 years time [42]. If found, we would have brought heaven on earth, and with luck, the riddle of electroweak symmetry breaking could be unveiled by the heaviness of the new chiral quarks.

And that would be the ultimate tribute to the insights of Kobayashi, Maskawa, and Nambu.

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