“Lost Origins of the Third Generation of Quarks:

Theory, Philosophy, and Experiment”*

(Running Head: “The Third Generation of Quarks”)

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Kent Staley’s research lies primarily in the history of recent particle physics, the philosophy of experimental inference, and related issues.

Abstract: Physicists generally attribute the introduction of a third generation of quarks (the “top” and “bottom” quarks) into the standard model of the elementary particles to a 1973 paper by Makoto Kobayashi and Toshihide Maskawa. I describe the historical background to that paper, emphasizing the largely forgotten role of theorists at Nagoya University and the “Nagoya model” they developed. Several of the authors of the Nagoya model embraced the philosophy of dialectical materialism, and I discuss the role that such metaphysical commitments play in physical theorizing. Both theoretical and experimental developments that generated great interest in Japan, and ultimately stimulated Kobayashi and Maskawa’s 1973 work, went almost entirely unnoticed in the U.S. The episode exemplifies both the importance of untestable “themata” in developing new theories, and the difficulties that may arise when two parts of a research community work in relative isolation from one another.

Keywords: elementary particles, standard model, Nagoya model, dialectical materialism, Shoichi Sakata, Makoto Kobayashi, Toshihide Maskawa

Introduction: The Standard History of the Standard Model

I will begin by briefly sketching the usual story of how the standard model of the elementary particles grew from three to six quarks, beginning in 1964. Later, I will discuss an entire dimension that is missing from this standard history of the standard model.

Among the many inhabitants of the particle "zoo" known to physicists in the 1960s were two classes of particles subject to the "strong force" (the force responsible for holding together the atomic nucleus), the baryons and the mesons. In addition, there were three known leptons, the electron, muon, and neutrino. The leptons do not respond to the strong force. In 1964, Murray Gell-Mann and George Zweig independently introduced what Gell-Mann called "quarks" as a way of bringing order to the many baryons and mesons.[1] According to the quark theory, the baryons and mesons could be represented as combinations of quarks or anti-quarks.

The 1964 quark model featured three quarks: up, down, and strange (u, d, and s). This basic triplet fit nicely with symmetries that had been found earlier by Gell-Mann and Yuval Ne'eman among the various baryons, a symmetry that Gell-Mann dubbed the "eightfold way," but which exemplified a more general type of symmetry known as SU(3).[2] In the quark model, baryons are composed of three quarks bound together (for example, a proton is composed of two up quarks and one down quark: <uud>), while mesons are composed of quark-antiquark pairs (the positive pion π^+, for example, is the pair <$u\bar{d}$>).*

Also in 1964, J. D. Bjorken and Sheldon Glashow proposed that there might be four fundamental strongly-interacting particles, giving the name “charm” to this new theoretical entity, although none of the known baryons or mesons seemed to represent charm. In terms of the quark theory, Bjorken and Glashow’s hypothesis involved a quartet rather than a triplet of quarks.[3]

Experimentalists James Cronin and Val Fitch made 1964 a landmark year while examining the weak decays of the strangeness-carrying K meson. They found that once in a while in such decays, a symmetry known as CP symmetry is violated. The operator C relates a particle to its antiparticle, while the operator P yields the mirror image of a particle. The idea behind CP symmetry is that the mirror image of a particle decay looks exactly like that decay in the world of antiparticles. Cronin and Fitch found that, while weak K-meson decays almost always respected CP symmetry, they violated it on rare occasions.[4]

In 1973, two Japanese physicists, Makoto Kobayashi and Toshihide Maskawa (see figures 1 and 2), were studying the problem of CP violation in theories that involved a quartet of fundamental strongly interacting particles — theories such as Bjorken and Glashow’s. Kobayashi and Maskawa showed that, to account for CP-violating decays while respecting certain plausible constraints, additional strongly-interacting fields were needed beyond the four that theorists were entertaining at the time. In particular, a six-field theory seemed to allow for CP violation in a fairly natural way. Thus the possibility of a theory with six quarks was introduced, and the new ones came to be called "top" and "bottom."[5]

Kobayashi and Maskawa were far ahead of their time, for as of 1973 no one had yet discovered any charmed particles experimentally. The charmed J/ψ particle was not discovered until November 1974, when two independent groups led by Samuel Ting and Burton Richter discovered the new particle more or less simultaneously.[6] Leon Lederman and a group at Fermilab found the bottom quark in 1977.[7] In 1995 two collaborations at Fermilab found the top quark,[8] thus completing in experiment the picture sketched in theory by Kobayashi and Maskawa more than twenty years earlier.

The importance of Kobayashi and Maskawa's paper is indisputable, and is widely recognized by physicists. According to the SLAC-SPIRES database of journal articles in high energy physics, it is the third most frequently cited article in the literature for the period from 1974 to the end of 1998, with over 3,000 citations in that literature to date.[9] But why did Kobayashi and Maskawa write that paper? How did they come to seem so far ahead of their time?

The standard history just related is incomplete in the sense that it does not adequately address these questions. Furthermore, the more detailed versions of this standard history in various scholarly publications are also incomplete. They omit the context out of which Kobayashi and Maskawa's work grew — specifically, the context of Japanese physics in the 1960s and early 1970s.

Theory: The Sakata Model and the Nagoya Model

One of the most important physicists in Japan in the 1950s and 1960s was Shoichi Sakata of Nagoya University (see figure 3). Sakata was the author of a model of the fundamental particles, first suggested in a 1956 paper, called the "Sakata model."[10] Like the Gell-Mann–Ne'eman eightfold way, the Sakata model was based on an SU(3) symmetry. The idea behind SU(3) was that symmetry considerations would lead to predictions about how families of particles could be grouped together and assigned quantum numbers. However, one can express SU(3) symmetry with families of various sizes: 1, 3, 6, 8, and 10 are all possibilities. Gell-Mann and Ne'eman's approach was to include all eight of the baryons that have spin equal to one-half in a single family. Only later did Gell-Mann seek to find a smaller, more fundamental family (the up, down, and strange quarks) to serve as the basis for the eightfold way. Sakata, by contrast, singled out the proton, neutron, and lambda, and gave them a special status as the fundamental baryons. He represented all of other baryons as built up from these three particles and their anti-particles.

The Sakata model was the precursor to the still more ambitious Nagoya model, developed by Sakata along with other physicists at the University of Nagoya: Ziro Maki, Masami Nakagawa, and Yoshio Ohnuki. The Nagoya model, first proposed in 1960,[11] attempted to include not just the baryons, but the leptons as well, in a simple theory. In the Nagoya model the fundamental baryons were still the proton, neutron, and lambda, but each of these was regarded as a compound of one of the leptons — neutrino, electron, and muon, respectively — with something called "B-matter," which carried a positive charge. With B-matter, the Nagoya physicists were postulating a new kind of matter, the properties of which could serve to explain various known symmetries, including a symmetry between baryons and leptons themselves.*

In 1962, experiments at Brookhaven National Laboratory began to yield evidence of a second neutrino. That same year, two papers extending the Nagoya model to incorporate two neutrinos appeared, one by the Nagoya physicists Maki, Nakagawa, and Sakata,[12] and the other by physicists at the University of Kyoto: Yasuhisa Katayama, Ken-iti Matumoto, Sho Tanaka, and Eiji Yamada.[13]

The paper by the Nagoya group focused on an extension of the model in which they postulated that one of the neutrinos ($\underline{\nu}_2$) does not bind to $\underline{B}$-matter. According to that proposal there would be four fundamental leptons but only three fundamental baryons — hence the baryon-lepton symmetry that was central to the original Nagoya model was sacrificed, but the $\underline{SU}(3)$ structure of the baryon family was maintained . Maki, Nakagawa, and Sakata relegated to a footnote the comment that, "Alternatively, we can assume that $\langle \underline{B}^+ \underline{\nu}_2 \rangle$ corresponds to a new kind of baryon with a very large mass."

The Kyoto group gave greater consideration to the possibility of a fourth baryon. Their extension of the Nagoya model featured four fundamental baryons composed of the following lepton-B-matter composites: $\underline{p} = \langle \underline{B}^+ \underline{\nu}_1 \rangle$, $\underline{n} = \langle \underline{B}^+ \underline{e}^- \rangle$, $\underline{\Lambda} = \langle \underline{B}^+ \underline{\mu}^- \rangle$, $\underline{V} = \langle \underline{B}^+ \underline{\nu}_2 \rangle$. Here $\underline{V}$ is a new baryon with positive charge and a new quantum number. $\underline{\nu}_1$ and $\underline{\nu}_2$ are superpositions of the observed electron and muon neutrinos.

A further important development in the Nagoya model was proposed by Ziro Maki and Yoshio Ohnuki in 1964.[14] Rather than taking the proton, neutron, and lambda as the most fundamental baryonic states, Maki and Ohnuki hypothesized what they called "urbaryons." In their "revised Nagoya model," the urbaryons were represented as a triplet

$\underline{\chi} = (\underline{\chi}_1, \underline{\chi}_2, \underline{\chi}_3)$, and a fourth singlet urbaryon $\underline{\chi}_0$. Maki and Ohnuki retained the B-matter concept, and represented the $\underline{\chi}_1, \underline{\chi}_2, \underline{\chi}_3$ urbaryons, like the $\underline{p}$, $\underline{n}$, $\underline{\Lambda}$ baryons of the original Nagoya model, as lepton-B-matter composites: $\underline{\chi}_1=<\underline{B}^+\underline{\nu}_1>$, $\underline{\chi}_2=<\underline{B}^+\underline{e}^->$, $\underline{\chi}_3=<\underline{B}^+\underline{\mu}^->$.

They argued, however, that the fourth urbaryon $\underline{\chi}_0$ had to be treated differently. In the 1962 two-neutrino versions of the Nagoya model, the combination of $\underline{B}^+$ with a second neutrino state $\underline{\nu}_2$ had been postulated either to correspond to no baryon (in the Nagoya group's version) or to a newly introduced baryon $\underline{V}$, which would have quite different properties from the other baryons (this was the Kyoto group's proposal, and was mentioned in passing in the Nagoya paper). But by 1964, Maki and Ohnuki were finding both of these proposals "hard to accept physically," since both required that "one and the same $\underline{B}^+$ should behave in a quite different way as soon as it couples to $\underline{\nu}_2$."[15] So Maki and Ohnuki introduced neutral B-matter, $\underline{B}^0$. They could then write the fourth baryon as: $\underline{\chi}_0=<\underline{B}^0\underline{\nu}_2>$.*

Of course these new urbaryons had to be related to observed particles in some way. To do this, Maki and Ohnuki used a two-stage construction. First they suggested two triplets of new mesons: $\underline{\theta}=(\underline{\theta}_1, \underline{\theta}_2, \underline{\theta}_3)$ and $\underline{\bar{\theta}}=(\underline{\bar{\theta}}_1, \underline{\bar{\theta}}_2, \underline{\bar{\theta}}_3)$, where $\underline{\theta}_i=\underline{\chi}_i\underline{\bar{\chi}}_0$ and $\underline{\bar{\theta}}_i=\underline{\chi}_0\underline{\bar{\chi}}_i$. Observed baryons were then bound states of these mesons with a third urbaryon, for example the proton, $\underline{p}=<\underline{\bar{\theta}}_3, \underline{\chi}_1>$, and the neutron, $\underline{n}=<\underline{\bar{\theta}}_3, \underline{\chi}_2>$.

Noteworthy are two aspects of the development of the Nagoya model that have a bearing on the standard history of the standard model. First, the Nagoya and Kyoto physicists postulated a fourth fundamental baryon (the Kyoto group in more detail than the Nagoya group, to be sure). These papers were published two years before the appearance of Bjorken and Glashow's famous "charm" paper. Second, in the "urbaryon" proposal of 1964, the Nagoya physicists had their own version of the idea that the known baryons were composite states of more fundamental particles, quite independently from the quark proposal of Gell-Mann and Zweig.* The two proposals even share certain features, such as the representation of mesons as particle-antiparticle pairs, and of baryons as composed of three of the more fundamental particles.

Philosophy: Dialectical Materialism

Sakata, like several of his Nagoya colleagues, was deeply committed to what he regarded as the metaphysical and methodological lessons of the philosophy of dialectical materialism, particularly as articulated by Lenin and Engels. He professed on numerous occasions that his theories were guided by insights drawn from their writings. In 1969, for example, Sakata wrote that Engels's <u>Dialektik der Natur</u> "has been continuously sending invaluable light into my studies of about forty years as a precious stone."[16] In <u>Dialektik der Natur</u>, Engels embraced the view, which he traced to the ancient Greeks, that "the whole of nature, from the smallest element to the greatest, from grains of sand to suns, from Protista to man, has its existence in eternal coming into being and passing away, in ceaseless flux, in unresting motion and change." Furthermore, Engels saw this metaphysical belief as having been given definite scientific underpinnings that it had lacked in the time of the ancient Greeks.[17]

Sakata placed special emphasis on a doctrine of Lenin's known as "inexhaustibility."** According to inexhaustibility, each "fundamental" particle would ultimately be shown to have a lower-level structure, and the elements of that structure would in turn be revealed to have their own structure, <u>ad infinitum</u>. Each level, or stratum, would be governed by a distinct set of laws, and each would be continually changing.

The doctrine of inexhaustibility entailed rejection of the idea that the "elementary particles" postulated at any given stage in the development of physical theory could be "point" particles without structure or extension. Sakata also drew the conclusion that quantum mechanics eventually would prove to be incomplete. In 1959 he wrote, "Elementary particles are not the ultimate of Matter. Quantum mechanics is, likewise, not the ultimate theory. . . . Elementary particles are not points. Now is the time to say goodbye to the point model and to, in some way, form a non-local theory."[18]

Another aspect of the dialectical materialist philosophy of the Nagoya group was a three-stage epistemology attributed to Mituo Taketani. Sakata and Taketani had both been students of Hideki Yukawa when he was a lecturer at Kyoto University, and when Yukawa took a position at Osaka Imperial University, both of his former students became collaborators with Yukawa there, contributing to his work on meson theory. Taketani also became involved in a leftist magazine, <u>World Culture</u>, both as an editor and as a writer.[19] According to Taketani's model, understanding of nature progresses through <u>phenomenological</u>, <u>substantial</u>, and <u>essentialist</u> stages: "The phenomenological stage is the one in which one observes and describes natural phenomena as they are. In the substantialistic stage, one investigates structure of the object. Finally, one finds physical rule governing the object in the essentialistic stage."[20] Sakata regarded his own model of the "fundamental" particles as an advance from the phenomenological to the substantial stage.[21]

Even for those who were not full-fledged dialectical materialists, the three-stage epistemology was influential, according to Ziro Maki, who studied and worked with Sakata beginning in 1955. Maki wrote, "There was a tendency for particle theorists, who grew up after the War in Japan, to accept the three-stage theory without question," and he noted that he himself used it "as a guide" in his own research. For Maki, the three-stage epistemology's usefulness lay in that it "encourages the elucidation of the role of 'substance' as a theoretical moment which mediates between a phenomena [sic] and its essence. As a result one begins to ask questions as to the nature of that 'essence', and by doing so, the substance, which is tied to the essence and phenomena, gradually becomes specified."[22] That is, the theorist thinking in terms of these three stages begins at the level of phenomena, but escapes the dilemma of either getting "stuck" at the level of mere correlations among phenomena or leaping from that level too quickly to some postulated "true nature" of those phenomena. Thinking in terms of a "substance" that underlies those phenomena, and then inquiring into the properties that such a substance must have for those phenomena to be the result (its essence), mediates the theoretical move from phenomena to underlying cause. Sakata used the slogan "from a logic of form to a logic of matter" to refer to this process.

In a paper presented at a conference in Kyoto in 1965, Maki, Ohnuki, and Sakata claimed that a very strong methodological link existed between the Nagoya model and dialectical materialism. By 1965 the Nagoya model had been developed to its revised form, which included the quark-like "urbaryons." Maki, Ohnuki, and Sakata denounced any instrumentalist interpretation of particles — such as quarks or urbaryons — that had been theorized as constituents of baryons or mesons. Such an approach was positivism, and they predicted that if positivist thinking were allowed to flourish, dire consequences would follow. The positivists would get stuck at the level of phenomena in that they would be simply recording whatever symmetries could be found among the hadrons (baryons and mesons). Maki, Ohnuki, and Sakata declared, "For these positivists, symmetries are considered to be the first principle of physics given by the Providence of God, and hence, the scientific thinking which goes beyond the hadronic level will actually be forbidden."[23]

They saw their own efforts as the antidote to such positivistically-mandated theoretical stagnation. They had "proposed in 1959 the Nagoya Model which belongs to the next level hidden behind" the baryonic level.* Thus, Maki, Ohnuki, and Sakata saw the Nagoya model as an attempt to delve one level deeper into the strata of nature than others had gone, and in so doing to explain, in terms of "the logic of matter," the symmetries (such as baryon-lepton symmetry or the "eightfold way") that were apparent at the higher level, and described in terms of "the logic of form." Thus, they proclaimed, "the development of the composite model to the Nagoya model was performed by the faithful application of our methodology — to arrive at 'the logic of matter' by starting with 'the logic of form'."[24]

In reflections on the Sakata and Nagoya models published in 1989, Maki still described the importance of the Nagoya model largely in terms of the three-stage epistemology. But his claims were more modest than they had been in 1965. Maki noted that the properties of the B-matter of the Nagoya model were left mostly unspecified. They would be simply whatever they needed to be to make that model work. Maki suggested that the Nagoya model should perhaps be classified as "pre-physics" rather than “physics.”[25] Different proposals for how leptons and B-matter would bind to one another were offered, but the Nagoya group had described these, even in 1960, as merely “possible forms of construction” presented “in accordance with our intuitive pictures.”[26]* Maki consequently described the Nagoya model as an “imaginary construct” or “Vorstellung,” the significance of which was that it “provided us with moral support, convincing us of the importance of baryon-lepton symmetry.”[27]

According to Maki, the Nagoya model is an example of the usefulness of the three-stage epistemology. By postulating a potentially imaginary “substance” (B-matter), with yet-to-be-determined properties beyond those necessary for saving the known “phenomenological” symmetry relations at the level of baryons and leptons, the Nagoya model set the stage for proceeding to an investigation of the “essential” features of matter underlying those symmetries. Hence, even if this imaginary construct turned out to be completely fictitious, it encouraged theorizing regarding a deeper stratum of nature, and was consequently a valuable contribution to physical theory.

Experiment: The X-particle

Japanese physicists intensified their scrutiny of the Nagoya model in 1971 when a group led by Kiyoshi Niu of the University of Tokyo seemed to find evidence for a new, short-lived particle with a mass of approximately 2 GeV/c^2 (where GeV stands for Gigaelectron Volts and c is the velocity of light).[28] Recording cosmic-ray events with nuclear emulsions flown on a Jet Cargo Aeroplane of Japan Air Lines, Niu’s group found an extremely energetic event that could be reconstructed as a massive new particle decaying into a neutral pion and another charged hadron. They calculated the estimated mass of the unknown particle X according to two different plausible decay modes. Assuming the X had decayed to a neutral pion–charged pion pair, they estimated the mass of X to be 1.78 GeV/c^2. For decay into a neutral pion–proton final state, they estimated a mass of 2.95 GeV/c^2. This particle later came to be referred to as the "X-particle."

This single cosmic-ray event initiated a flurry of articles appearing in Progress of Theoretical Physics (PTP). As Shuzo Ogawa pointed out, PTP published fifteen articles in the years 1971–73 that were directly related to the X-particle event.[29] In the United States, by contrast, the X-particle seems to have received very little attention. During 1972, there were no citations of Niu et al.'s 1971 paper in either Physical Review Letters or Physical Review D, the two most prominent journals in the U.S. that publish papers on elementary particles and fields.

The fifteen articles in PTP can be divided into two general categories: (1) those that examined the X-particle to identify it from the standpoint of various theories, and (2) those that considered quartet models of fundamental particles more generally, citing the X-particle as a motivation for doing so. In both categories, the Nagoya model was of central importance.

Among the papers that sought to interpret the X-particle as a new particle, nearly all identified it either as the fourth baryon V of the extended Nagoya model, or as a fourth baryon in light of some other theory directly descended from the Nagoya model. Physicists at Hiroshima University had proposed a Nagoya-type theory in which the baryons p, n, λ, and the hypothetical heavy V were formed from B^+ and lepton-antilepton pairs — conceived to be analogous to mesons — rather than single lepton states.[30]

Following a suggestion by Hiroshima physicist Shuzo Ogawa, physicists at Nagoya and Hiroshima published papers interpreting the X-particle as the fourth baryon of both the original and modified versions of the Nagoya model. Significantly, for our purposes, Makoto Kobayashi, then a Nagoya graduate student, was a co-author of the earliest of these papers,[31] along with Takemi Hayashi of Hiroshima University, Hidemitsu Nitto of Nagoya University, and Masami Nakagawa, who had been at Nagoya University when he co-authored the 1962 paper extending the Nagoya model to four leptons, and had since taken a position at Meijo University, also in Nagoya.

The second category of papers responding to the X-particle consists of papers that examined more closely theories featuring four fundamental, strongly-interacting particles, or "quartet" theories, citing the X-particle specifically as a motivation. Here again, the focus for papers appearing in PTP was on the Nagoya model or some descendant of it. Physicists at Hiroshima, Nagoya, Meijo, and Kyoto all contributed to an upsurge of interest in quartet theories. At Kyoto, Ziro Maki and Toshihide Maskawa worked together on three articles on quartet theories — specifically the revised Nagoya model proposed by Maki and Ohnuki in 1964. Maki, of course, had worked with Sakata at Nagoya earlier, and Maskawa recently had taken a position at Kyoto, but had received both his Ph.D. degree and a postdoctoral fellowship at Nagoya. Meanwhile, Makoto Kobayashi, still a Nagoya graduate student, along with Nagoya's Hidemitsu Nitto and Masami Nakagawa of Meijo University, published a paper on yet another descendant of the Nagoya model, this time with fractional charges (as in the quark model) assigned to the quartet of fundamental hadrons.[32]

Of the fifteen PTP articles identified by Ogawa that were prompted by the X-particle discovery, only one does not cite explicitly the paper by Niu et al.: the 1973 Kobayashi-Maskawa paper itself. However, there is ample evidence that Kobayashi and Maskawa were prompted to take up the problem of CP-violation in quartet theories as a response to the X-particle discovery in the context of a serious interest in the Nagoya model.

First, from several of the papers discussed above, we know that both Kobayashi and Maskawa were well-acquainted with the authors of the Nagoya model and with the theory itself. In fact, they were involved with attempts to analyze the X-particle in light of four-particle versions of the Nagoya model, sometimes appearing as co-authors on papers with some of the creators of that theory.

Kobayashi's own later testimony establishes conclusively the connection between the X-particle, the Nagoya model, and the 1973 Kobayashi-Maskawa paper. He noted that their work on CP violation was done in the midst of speculation that Niu's team in fact had already discovered a fourth fundamental particle subject to the strong force. Kobayashi recalled that it was Shuzo Ogawa who first suggested that the X-particle might be the fourth baryon of the extended Nagoya model, and that:

> "[f]ollowing Ogawa's suggestion, a few Japanese groups, including myself, started the investigation of the cosmic ray events based on the four-quark models, so that, more or less, we were familiar with the structure of the weak interactions in the four-quark scheme."[33]

As a result of these studies,

> [w]e accepted [the Glashow-Weinberg-Salam theory of the weak interaction's] extension to the hadron based on the GIM [Glashow-Iliopoulos-Maiani][34] scheme as a quite realistic possibility, because the fourth quark already existed for us in a sense. Sometimes it is said that our CP paper was written before the discovery of charm. In this sense, however, our paper came after the charm.[35]

All of this preceded the spectacular events that took place in 1974 in the United States. In November of that year, a group at SLAC led by Burton Richter and group at Brookhaven led by Samuel Ting discovered a new, quite narrow resonance at 3.1 GeV. This new particle came to be known as the J/ψ (Ting's group had dubbed it the J, while Richter's group called it the ψ). These discoveries, with a quick confirmation from a group at the ADONE ring at Frascati, Italy, were taken to establish the existence of charmed particles.[36]

Niu's lonely cosmic-ray event, which had garnered so much attention in Japan, and even had been called "charm" by a number of Japanese physicists, was quickly overshadowed. In the wave of papers on charm and the J/ψ that appeared after the "November revolution"—as it came to be called—the X-particle and the four-baryon Nagoya model were almost never mentioned. An exception is a review of the charm issue, published in 1975, by Mary Gaillard, Benjamin Lee, and Jonathan Rosner.[37] The main body of this article was written before the Ting and Richter groups had made their discoveries, and the authors added a "note in proof," nearly as long as the original article, discussing the new findings. In the portion of the paper written before the November revolution, they mentioned the X-particle event among the "few candidates" for already-observed charmed particles. They also mentioned Maki and Ohnuki's 1964 urbaryon paper among theories including a charmed quark (but not the earlier Nagoya model papers).

This, however, was an isolated instance. Although in the aftermath of the November revolution many articles appeared in PTP that discussed the X-particle and the revised Nagoya model, very little mention was made of either in the Physical Review, and the developments in Japan that led up to the introduction of a third generation of matter generally have been omitted from historical accounts.*

But the many papers on the X-particle that appeared at the time in PTP, along with Kobayashi's remarks, clearly indicate that the mostly forgotten — possibly charmed — cosmic-ray event found by Niu's group had helped to stimulate an idea that already was far ahead of the quartet model that had predicted the existence of charm, and that the great deal of attention received by that event in Japan was at least in part driven by interest in the extended Nagoya model and its various modifications.

The Kobayashi-Maskawa paper

Noteworthy is what Kobayashi and Maskawa did not discuss in their paper. Although they are generally held to have predicted the existence of the third generation of quarks, their paper did not explicitly employ the quark model. They considered different possibilities for the number of fundamental hadrons, but "hadron" is in this context a generic term for whatever particles are subject to the strong force. Kobayashi and Maskawa denoted the four fundamental fields in the quartet model as p, n, λ and ξ, to which they assigned the charges Q, $Q-1$, $Q-1$, and Q, respectively. This was compatible with both the Nagoya model's assignment of 1, 0, 0, 1 and the assignments given in the quark scheme. In their 1970 paper introducing a quartet model of quarks, Glashow, John Iliopoulos, and Luciano Maiani were still considering both a fractional charge assignment (2/3, –1/3, –1/3, 2/3) and an integral charge assignment (0, –1, –1, 0 — which would have required a different representation of the fundamental particles).[38]

Furthermore, the term "predict" suggests a stronger assertion than one actually finds in the Kobayashi-Maskawa paper regarding the "6-plet" model they discussed. The central claim made by Kobayashi and Maskawa was that no "realistic" quartet model allows for CP-violating weak interactions: "in the case of the . . . quartet model, we cannot make a CP-violating interaction without introducing any other new fields," or somehow violating at least one of two additional conditions: (1) that the mass of the fourth particle ξ be large (since if it were a light particle it would presumably have been detected previously); and (2) that "the model should be consistent with our well-established knowledge of the semi-leptonic processes."[39]

Kobayashi and Maskawa made their argument by considering the different possible ways of representing a quartet theory of the fundamental hadrons, and showed case-by-case that no CP-violating processes could occur in a quartet theory without violating the above constraints.

They then discussed three different possibilities in which new fields were introduced to allow for CP-violating weak decays. First, they postulated an entirely new scalar-doublet field ψ, with which the hadrons interact through an entirely new force.* This possibility would require new fields and a new force, but not a third generation of hadrons. The second CP-violating possibility involved the introduction of a new scalar field S mediating the strong interaction. Such a field then would interact both with the fundamental hadrons and with the scalar-doublet field $\underline{\phi}$ (this is the field, introduced by Steven Weinberg in 1967,[40] that gives rise to the "intermediate vector bosons" — the W and Z particles).

Only after these since-forgotten proposals were described did Kobayashi and Maskawa take up the "6-plet" model, which they called "another interesting model of CP violation." They showed how the matrix used to describe the weak interaction for a 6-plet model would have to be rewritten in such a way that CP-violating processes would be allowed.

Kobayashi and Maskawa suggested a third generation of fundamental hadrons as one possibility among others that could accommodate CP-violation. They admitted that other kinds of schemes less closely modeled on that proposed by Weinberg could also accommodate CP-violation. For their reserve in presenting a revolutionary idea, they were rewarded with several years of neglect by their fellow physicists. How their work eventually became famous is itself a good story, but one that deserves its own separate telling.

Discussion: Dogmatism, Themata, and Bias

There were two central elements in the dialectical materialism that drove much of the thinking behind the Nagoya model. The first was the doctrine of inexhaustibility: the claim that there is no truly fundamental level of analysis in nature, and that each level of the material constitution of the universe is governed by a distinct set of laws. The second was the methodology put forth in the three-stage epistemology. According to this methodology, the physical theorist can advance the understanding of nature most fruitfully by postulating a substance governed by laws at a lower level than those currently known, to advance one's investigation from the level of phenomena to the level of those essential lower-level material facts that provide the proper explanation for those phenomena.

In one of the few discussions of the Nagoya model published outside of Japan, the Israeli physicist Yuval Ne'eman described the adherence of the group surrounding Shoichi Sakata to Lenin and Engels's dialectical materialism as "an extreme orthodoxy which can only be compared with a fundamentalist's attachment to the biblical story of Genesis."[41] While Ne'eman acknowledged that "interest in a materialist lower stratum as predicted by Dialectical Materialism had indeed been useful in triggering the introduction of the U(3) group. . . . the motivation was so overwhelming that it overshadowed the experimental facts."[42] Ne'eman further charged the Nagoya group with having developed a dogmatic tactic of attacking other theorists whose approaches disagreed with their own, as when Yoichi Fujimoto criticized Gell-Mann for entertaining the possibility of treating elementary particles as points. Ne'eman remarked, "It is . . . a sad development when a scientist falls back into the medieval way of preferring dogmas to actual physical theory."[43]*

I wish to explore another way of understanding the role that dialectical materialism played in the development of the Nagoya model. In their embrace of the doctrine of inexhaustibility, the Nagoya physicists were adopting, not a dogma, but what Gerald Holton calls a "thematic hypothesis," while the three-stage methodology constitutes what he terms a "methodological thema." Holton maintains that understanding how scientists make discoveries and accept or reject ideas requires analysis of the role of themata, which he describes as “those fundamental preconceptions of a stable and widely diffused kind that are not resolvable into or derivable from observation and analytic ratiocination.”[44] Examples of thematic hypotheses that have been prominent in science include the claims that certain properties are strictly conserved, that certain processes are symmetric in various ways (an important thema for the developments surveyed here), that processes are directed toward some purpose, and so on. Some of these themata survive, while others have been rejected.**

According to Maki, Ohnuki, and Sakata, as noted above, the search for some level of structure underlying the known baryons led to the proposal that there were more fundamental “urbaryons” of which those particles were composed. Ne’eman rightly pointed out in other comments on the Nagoya philosophy that the “bootstrap” model, which completely abandoned the search for underlying structures beneath the hadrons, and declared a “nuclear particle democracy” was no less useful for promoting phenomenological studies of hadrons. Two opposing themata can contribute to the advance of a scientific discipline, even simultaneously. However, when the adherents to a thema allow their commitments to “overshadow experimental facts,” or oppose other theories because they run afoul of the thema, according to Ne’eman they are being dogmatic.

Perhaps, but it is difficult to see how commitment to a thematic hypothesis could serve its positive function of guiding theorizing without at the same time causing a theorist to judge negatively theories that are inconsistent with that thema. One can find thematic underpinnings in various episodes in physics in which one theorist has found another’s ideas to be unsatisfactory in some way not directly linked to empirical inadequacy (arguably, for example, Einstein's opposition to Bohr's complementarity principle, or Galileo's failure to recognize the importance of Kepler's elliptical planetary orbits). While the Nagoya physicists may have been more explicit, and more strident, in their declarations of allegiance to their thema of dialectical materialism than other particle physicists typically have been in the deployment of such commitments, their reliance on a thematic commitment was not a violation of proper scientific method, but an unavoidable part of it.

Of course, not all themata are equally fruitful, and it still could be objected that the thema employed by the Nagoya school yielded only limited benefits for its adherents in terms of good theoretical ideas. This certainly was the position taken by Ne'eman in his paper, presented in 1971. Yet it could be countered that Ne'eman judged the Nagoya school prematurely, since this was two years prior to the Kobayashi-Maskawa paper, arguably a product of the Nagoya line of thought.

Here we run up against a difficulty in assessing the "fruitfulness" of a thematic hypothesis. It is true that the Nagoya school was influenced by dialectical materialism. It is also true that Kobayashi and Maskawa were part of a movement to update the Nagoya model, and to interpret the X-particle within that framework. Finally, it is true that in pursuing this task, they arrived at the idea of a third generation of fundamental, strongly interacting particles. All of this indicates a historical link between the commitments of Sakata and his colleagues and the events that led to the publication of the Kobayashi-Maskawa paper. This does not mean, of course, that Kobayashi and Maskawa themselves had any allegiance at all to dialectical materialism. Nothing in their writings indicates that they did. It would therefore be dangerous to conclude that the third generation of quarks is the direct fruit of the thema of dialectical materialism, or that the Kobayashi-Maskawa paper stands as a vindication of the dialectical materialism of the central figures of the Nagoya school.

In any case, such metaphysical commitments, while they appear to be an indispensable part of the scientific enterprise as a creative endeavor, arguably never become fully part of science as a body of well-tested knowledge, and this point is nicely illustrated by the case of Sakata's dialectical materialism. In Holton's account, such thematic commitments are part of "private science," while "public science" is "science-as-an-institution, textbook science, our inherited world of clear concepts and disciplined formulations."[45] The theoretical suggestions made by Kobayashi and Maskawa belong to Holton's "public science."

I would characterize the distinction differently, however. Sakata felt strongly enough about his metaphysics to discuss it frequently in the "public" vehicles of scientific communication, especially in talks given at conferences, and, as Shuzo Ogawa recalled, "in journals of popular science."[46] Nevertheless, however important Sakata's thematic commitments may have been to him personally as a motivating factor, other physicists could not have conceived any means of subjecting such claims to experimental testing. Consequently, these thematic hypotheses could not become part of that small, but growing, neighborhood of science where one finds well-tested, established scientific knowledge. (This may be an important reason why, even for theorists receptive to Sakata's theories, there was much greater interest in developing the Nagoya model itself than in responding to Sakata's philosophical pronouncements.) However, the proposals of Kobayashi and Maskawa, although they arose from a context in which Nagoya dialectical materialism was very influential, could be subjected to an experimental test. When they eventually were subjected to such a test, and passed it, they became part , not only of "public" science, but of well-tested scientific knowledge.

While it may be difficult to assess the precise extent of dialectical materialism's influence on the development of Japanese physics in the period from the mid-1950s to the mid-1970s, the impact of the Nagoya model and of the X-particle is undeniable. The many articles appearing in Progress of Theoretical Physics that were concerned with these two subjects attests to the influence that the Nagoya model and the X-particle had on the work of quite a few Japanese physicists, including Kobayashi and Maskawa. And yet these events received very little attention in the United States.

In fact, there was a strong sense among some Japanese physicists that western physicists systematically ignored their work. This belief is reflected in some remarks made by Taketani at a conference held in Kyoto in 1965:

> Some English speaking people talk ten words when we talk one word, and do hardly take care of one word which we talk. This point is one of our complains [sic] in any international conference. We should like to ask English speaking people to hear about our talks with the special care. Otherwise our attendance to the international conferences would lose its true meaning, and we are led to consider that we are not welcomed as a matter of fact.[47]

In the same comments, Taketani charged that the proposal by Sakata and Takesi Inoue to distinguish the muon and pion as distinct particles (the "two meson theory"[48]) had been "intentionally neglected by some of the foreign physicists." Western physicists had instead given credit to Robert E. Marshak and Hans A. Bethe, who published a similar proposal somewhat later.[49] Taketani lamented:

> It is regrettable for us to find some workers in the major country insisting that the article which they did not read could have no contribution to the progress of science. We know that the works done by Sakata and his co-workers made the important contribution at least to the progress of physics in Japan. No one will deny that the achievements made by Japanese workers played an important role in the international developments of the meson theory.[50]

In reply, Marshak acknowledged that "without question" Sakata and Inoue had priority on the two-meson theory, but noted that "due to the war their paper did not reach to U.S. [sic] until 1948, which was at least 6 months after I presented my theory."[51] In fact, Sakata had proposed the theory several years earlier, in 1942, but during World War II Japanese physicists were not in communication with the West, and Progress of Theoretical Physics only came into existence in 1946, with Sakata and Inoue's paper in the first issue.[52] Marshak added that both the Sakata-Inoue and Marshak-Bethe proposals were only partly correct. Sakata and Inoue underestimated the π lifetime, and Marshak and Bethe assigned incorrect spins to the two particles. (This does not necessarily mean that the two papers were in fact on a par, however, since it is arguable that the quantum numbers correctly predicted by Sakata and Inoue are of more fundamental importance than the lifetime.)

In light of this contentious background, Ne'eman's indictment of the Nagoya school's dialectical materialism raises a troubling question. When the fruitfulness of an idea is assessed, to whose fruits should one look? In the above comments, Taketani insisted on the importance of Sakata and Inoue's two-meson paper because of its importance to the "progress of physics in Japan." At the time that Ne'eman pronounced the Nagoya philosophy to have been a stone around the neck of Japanese physics, Japanese physicists had established a kind of cottage industry based on investigations of the Nagoya model, the results of which were published prominently in PTP, and their interest in the theory continued unabated through the rest of the 1970s. The seminal papers that formed the core of the Nagoya model continued to be cited with great regularity in each issue of PTP that came out. While it seems apparent at the present time that this approach became a dead end, it is difficult to see how one could declare it to have been barren as of 1971, unless one were unaware of the proliferation of papers on the subject appearing in Japan. Even knowing that the Nagoya model ultimately did not pan out, we do know at least that it provoked a considerable amount of speculation in Japan, leading not least to the Kobayashi-Maskawa paper itself.* Most of this work remains little known, or at least little appreciated, in the West.

It is certainly not surprising that in physics, as in other realms, there are segments of the community whose work fails to become well-known, not because it is not worthwhile, but because it is not highly visible. More work is needed to know the exact reasons why ideas that took on such great importance in Japan remained obscure to physicists in the West. Was it a matter of anti-Japanese bias, or was it simply that one is much less likely to notice work that is done by people one does not know, especially when it appears in a journal that one does not consult regularly?

More general questions also remain: how strong is the obligation of a working scientist in any field to survey the literature, even into distant corners, looking for ideas that relate to one's own work? One certainly could argue that this obligation ought not to be made so strong as to make the pace of everyone's work sluggish. The present episode, however, points to a cost of allowing for what we might call "citation provincialism," a practice of citing only work that one comes across in one's interactions with like-minded, or at least nearby, colleagues. Whether a corner really is "distant" or not depends on where one starts; hence citation provincialism is likely to result in a fragmented scientific community. Under such circumstances, group A might remain oblivious to developments that group B perceives to have great significance, and even could prove helpful to group A. Add the circumstance that group A is larger and has greater resources, and it is hard to see how charges of anti-B bias and feelings of A-superiority could fail to develop.

However such issues are resolved, one thing is clear. As long as scientists fail to notice significant developments that have occurred in their own disciplines, historians of science will have worthwhile research projects trying to restore those parts of the story that have been lost.

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[Legends for figures]

Figure 1. Toshihide Maskawa. Courtesy of Makoto Kobayashi, National Laboratory for High Energy Physics, Japan.

Figure 2. Makoto Kobayashi. Courtesy of Robert Palmer, Brookhaven National Laboratory.

Figure 3. Shoichi Sakata (on the right). Also pictured are Sin-itiro Tomonaga (left) and Hideki Yukawa (center). University of Tsukuba, Tomonaga Memorial Room, courtesy AIP Emilio Segrè Visual Archives.

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