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Physicists in Wartime Japan

During the most trying years of Japan's history, two brilliant schools of theoretical physics flourished

by Laurie M. Brown and Yoichiro Nambu

"The last seminar, given at a gorgeous house left unburned near Riken, was dedicated to [electron] shower theories.... It was difficult to continue the seminars, because Minakawa's house was burnt in April and the laboratory was badly destroyed in May. The laboratory moved to a village near Komoro in July; four physics students including myself lived there. Tatuoki Miyazima also moved to the same village, and we continued our studies there towards the end of 1945."

—Satio Hayakawa, astrophysicist

Between 1935 and 1955 a handful of Japanese men turned their minds to the unsolved problems of theoretical physics. They taught themselves quantum mechanics, constructed the quantum theory of electromagnetism and postulated the existence of new particles. Much of the time their lives were in turmoil, their homes demolished and their bellies empty. But the worst of times for the scientists was the best of times for the science. After the war, as a numbed Japan surveyed the devastation, its physicists brought home two Nobel Prizes.

Their achievements were all the more remarkable in a society that had encountered the methods of science only decades earlier. In 1854 Commodore Matthew Perry's warships forced the country open to international trade, ending two centuries of isolation. Japan realized that without modern technology it was militarily weak. A group of educated samurai forced the ruling shogun to step down in 1868 and reinstated the emperor, who had until then been only a figurehead. The new regime sent young men to Germany, France, England and America to study languages, science, engineering and medicine and founded Western-style universities in Tokyo, Kyoto and elsewhere.

Hantaro Nagaoka was one of Japan's first physicists. His father, a former samurai, initially taught his son calligraphy and Chinese. But after a trip abroad, he returned with loads of English textbooks and apologized for having taught him all the wrong subjects. At university, Nagaoka hesitated to take up science; he was uncertain if Asians could master the craft. But after a year of perusing the history of Chinese science, he decided the Japanese, too, might have a chance.

In 1903 Nagaoka proposed a model of the atom that contained a small nucleus surrounded by a ring of electrons. This "Saturnian" model was the first to contain a nucleus, discovered in 1911 by Ernest Rutherford at the Cavendish Laboratory in Cambridge, England.

As measured by victories against China (1895), Russia (1905) and in World War I, Japan's pursuit of technology was a success. Its larger companies established research laboratories, and in 1917 a quasigovernmental institute called Riken (the Institute of Physical and Chemical Research) came into being in Tokyo. Though designed to provide technical support to industry, Riken also conducted basic research.

A young scientist at Riken, Yoshio Nishina, was sent abroad in 1919, traveling in England and Germany and spending six years at Niels Bohr's institute in Copenhagen. Together with Oskar Klein, Nishina calculated the probability of a photon, a quantum of light, bouncing off an electron. This interaction was fundamental to the emerging quantum theory of electromagnetism, now known as quantum electrodynamics.

When he returned to Japan in 1928, Nishina brought with him the "spirit of Copenhagen"—a democratic style of research in which anyone could speak his mind, contrasting with the authoritarian norm at Japanese universities—as well as knowledge of modern problems and methods. Luminaries from the West, such as Werner K. Heisenberg and Paul A. M. Dirac, came to visit, lecturing to awed ranks of students and faculty.

Hiding near the back of the hall, Shinichiro Tomonaga was one of the few to understand Heisenberg's lectures. He had just spent a year and a half as an undergraduate teaching himself quantum mechanics from all the original papers. On the last day of lectures, Nagaoka scolded that Heisenberg and Dirac had discovered a new theory in their 20s, whereas Japanese students were still pathetically copying lecture notes. "Nagaoka's pep talk really did not get me anywhere," Tomonaga later confessed.

Sons of Samurai

He was, however, destined to go places, along with his high school and college classmate Hideki Yukawa. Both men's fathers had traveled abroad and were academics: Tomonaga's a professor of Western philosophy, Yukawa's

IN JANUARY 1942 author Yoichiro Nambu reads in laboratory room 305 of the physics department at the University of Tokyo. Soon after, he was drafted. When the war ended, Nambu lived in this room for three years; neighboring laboratories were similarly occupied by homeless and hungry scientists.

COURTESY OF YOICHIRO NAMBU

a professor of geology. Both were of samurai lineage. Even before going to school, the younger Yukawa had learned the Confucian classics from his maternal grandfather, a former samurai. Later he encountered the works of Taoist sages, whose questioning attitude he would liken to the scientific pursuit. Tomonaga was inspired to study physics by hearing Albert Einstein lecture in Kyoto in 1922, as well as by reading popular science books written in Japanese.

The two men obtained their bachelor's degrees in 1929 from Kyoto University, at the start of the worldwide depression. Lacking jobs, they stayed on as unpaid assistants at the university. They taught each other the new physics and went on to tackle research projects independently. "The depression made scholars of us," Yukawa later joked.

In 1932 Tomonaga joined Nishina's lively group at Riken. Yukawa moved to Osaka University and, to Tomonaga's annoyance, confidently focused on the deepest questions of the day. (Yukawa's first-grade teacher had written of him: "Has a strong ego and is firm of mind.") One was a severe pathology of quantum electrodynamics, known as the problem of infinite self-energy. The results of many calculations were turning out to be infinity: the electron, for instance, would interact with the photons of its own electromagnetic field so that its mass—or energy—increased indefinitely. Yukawa made little progress on this question, which was to occupy some of the world's brilliant minds for two more decades. "Each day I would destroy the ideas that I had created that day. By the time I crossed the Kamo River on my way home in the evening, I was in a state of desperation," he later recalled.

Eventually, he resolved to tackle a seemingly easier problem: the nature of the force between a proton and a neutron. Heisenberg had proposed that this force was transmitted by the exchange of an electron. Because the electron has an intrinsic angular momentum, or spin, of one half, his idea violated the conservation of angular momentum, a basic principle of quantum mechanics. But having just replaced classical rules with quantum ones for the behavior of electrons and photons, Heisenberg, Bohr and others were all too willing to throw out quantum physics and assume that protons and neutrons obeyed radical new rules of their own. Unfortunately, Heisenberg's model also predicted the range of the nuclear force to be 200 times too long.

Yukawa discovered that the range of a force depends inversely on the mass of the particle that transmits it. The electromagnetic force, for instance, has infinite range because it is carried by the massless photon. The nuclear force, on the other hand, is confined within the nucleus and should be communicated by a particle of mass 200 times that of the electron. He also found that the nuclear particle required a spin of zero or one to conserve angular momentum.

Yukawa published these observations in his first original paper in 1935 in *Proceedings of the PMSJ* (Physico-Mathematical Society of Japan). Although it was written in English, the paper was ignored for two years. Yukawa had been bold in predicting a new particle—thereby defying Occam's razor, the principle that explanatory entities should not proliferate unnecessarily. In 1937 Carl D. Anderson and Seth H. Neddermeyer of the California Institute of Technology discovered, in traces left by cosmic rays, charged particles that had about the right mass to meet the requirements of Yukawa's theory. But the cosmic-ray particle appeared at sea level instead of being absorbed high up in the atmosphere, so it lived 100 times longer than Yukawa had predicted.

Tomonaga, meanwhile, was working with Nishina on quantum electrodynamics. In 1937 he visited Heisenberg at Leipzig University, collaborating with him for two years on theories of nuclear forces. Yukawa also arrived, en route to the prestigious Solvay Congress in Brussels. But the conference was canceled, and the two men had to leave Europe hurriedly.

War brought the golden age of quantum physics to an abrupt end. The founders of the new physics, until then concentrated in European centers such as Göttingen in Germany, scattered, ending up mainly in the U.S. Heisenberg, left virtually alone in Germany, continued at least initially to work on field theory—a generalization of quantum electrodynamics—and to correspond with Tomonaga.

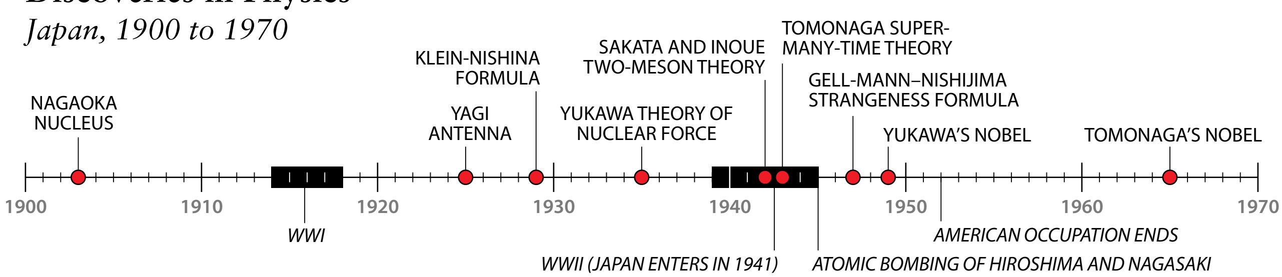
A War Like No Other

By 1941, when Japan entered the world war, Yukawa had become a professor at Kyoto. His students and collaborators included two radicals, Shoichi Sakata and Mitsuo Taketani. At the time, Marxist philosophy was influential among intellectuals, who saw it as an antidote to the militarism of the imperial government. Unfortunately, Taketani's writings for the Marxist journal *Sekai Bunka* (*World Culture*) had drawn the attention of the thought police. He had been jailed for six months in 1938, then released into Yukawa's custody thanks to the intervention of Nishina. Although Yukawa remained totally wrapped up in physics and expressed no political views at all, he continued to shelter the radicals in his lab.

Sakata and Taketani developed a Marxist philosophy of science called the three-stages theory. Suppose a researcher discovers a new, inexplicable phenomenon. First he or she learns the details and tries to discern regularities. Next the sci-

Discoveries in Physics

Japan, 1900 to 1970



BRYAN CHRISTIE

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entist comes up with a qualitative model to explain the patterns and finally develops a precise mathematical theory that subsumes the model. But another discovery soon forces the process to repeat. As a result, the history of science resembles a spiral, going around in circles yet always advancing. This philosophy came to influence many of the younger physicists, including one of us (Nambu).

Meanwhile, as war raged in the Pacific, the researchers continued to work on physics. In 1942 Sakata and Takeshi Inoue suggested that Anderson and Neddermeyer had not seen Yukawa's particle but instead had seen a lighter object, now called a muon, which came from the decay of the true Yukawa particle, the pion. They described their theory to the Meson Club, an informal group that met regularly to discuss physics, and published it in a Japanese journal.

Yukawa was doing war work one day a week; he never said what this entailed. (He did say that he would read the *Tale of Genji* while commuting to the military lab.) Tomonaga, who had become a professor at the Tokyo Bunrika University (now called the University of Tsukuba), was more involved in the war effort. Together with Masao Kotani of the University of Tokyo, he developed a theory of magnetrons—devices used in radar systems for generating electromagnetic waves—for the navy. Through the hands of a submarine captain he knew, Heisenberg sent Tomonaga a paper on a technique he had invented for describing the interactions of quantum particles. It was in essence a theory of waves, which Tomonaga soon applied to designing radar waveguides.

At the same time, Tomonaga was tackling the problem of infinite self-energy that Yukawa had given up. To this end, he developed a means of describing the behavior of several interacting quantum particles, such as electrons, moving at near the speed of light. Generalizing an idea due to Dirac, he assigned to each particle not just space coordinates but also its own time coordinate and called the formulation "super-many-time theory." This work, which became a powerful framework for quantum electrodynamics, was published in 1943 in Riken's science journal.

By this time most students had been mobilized for war. Nambu was among those assigned to radar research for the army. (Intense rivalry between the army and the navy led each to duplicate the other's efforts). Resources were short and the technology often very primitive: the army could not develop mobile radar systems to pinpoint enemy targets. Nambu was once handed a piece of Permalloy magnet, about three by three inches, and told to do what he could with it for aerial submarine detection. He was also told to steal from the navy Tomonaga's paper on waveguides, labeled "Secret," which he accomplished by visiting an unsuspecting professor [see "Strings and Gluons—The Seer Saw Them All," by Madhusree Mukerjee, News and Analysis; SCIENTIFIC AMERICAN, February 1995].

(Curiously, Japan's past technical contributions included excellent magnetrons designed by Kinjiro Okabe and an antenna; the latter, invented by Hidetsugu Yagi and Shintaro Uda in 1925, still projects from many rooftops. The Japanese armed forces learned about the importance of the "Yagi array" from a captured British manual.)

Younger physicists around the Tokyo area continued their studies when they could; professors from the University of Tokyo, as well as Tomonaga, held special courses for them on Sundays. In 1944 a few students (including Satio Hayakawa, whose quote begins this article) were freed from war research and returned to the university campus. Even so, times were difficult. One student's house was burned down, another was drafted, and a third had his house burned down just before he was drafted. The venue for the seminars shifted several times. Tomonaga, who had always been physically weak, would sometimes instruct his students while lying sick in bed.

Meanwhile Nishina had been instructed by the army to investigate the possibility of making an atomic bomb. In 1943 he concluded that it was feasible, given enough time and money. He assigned a young cosmic-ray physicist, Masa Takeuchi, to build a device for isolating the lighter form of uranium required for a bomb. Apparently Nishina thought the project would help keep physics research alive for when the war ended. Taketani, back in prison, was also forced to work on the problem. He did not mind, knowing it had no chance of success.

Across the Pacific, the Manhattan Project was employing some 150,000 men and women, not to mention a constellation of geniuses and $2 billion. In contrast, when the Japanese students realized they would need sugar to make uranium hexafluoride (from which they could extract the uranium) they had to bring in their own meager rations. A separate effort, started by the navy in 1943, was also far too little, too late. By the end of the war, all that the projects had produced was a piece of uranium metal the size of a postage stamp, still unenriched with its light form.

And two atom bombs had exploded in Japan. Luis W. Alvarez of the University of California at Berkeley was in the aircraft that dropped the second bomb over Nagasaki, deploying three microphones to measure the intensity of the blast. Around these instruments he wrapped a letter (with two photocopies) drafted by himself and two Berkeley colleagues, Philip Morrison and Robert Serber. They were addressed to Riokichi Sagane, Nagaoka's son and a physicist in Tomonaga's group. An experimenter, Sagane had spent two years at Berkeley learning about cyclotrons, enormous machines for conducting studies in particle physics. He had become acquainted with the three Americans who now sought to inform him of the nature of the bomb. Although the letter was recovered by the military police, Sagane learned of it only after the war. After the Japanese surrender in August 1945, the country was effectively under American occupation for seven years. General Douglas MacArthur's administration reformed, liberalized and expanded the university system. But experimental research in nuclear and related fields was essentially prohibited. All cyclotrons in Japan were dismantled and thrown into the sea, for fear that they might be used to research an atomic bomb.

In any case, the miserable economy did not allow the luxury of experimental research. Tomonaga was living with his family in a laboratory, half of which had been bombed to bits. Nambu arrived at the University of Tokyo as a research assistant and lived for three years in a laboratory, sleeping on a straw mattress spread over his desk (and always dressed in military uniform for lack of other clothes). Neighboring offices were similarly occupied, one by a professor and his family.

A Hungry Peace

Getting food was everyone's preoccupation. Nambu would sometimes find sardines at Tokyo's fish market, which rapidly produced a stench because he had no refrigerator. On weekends he would venture to the countryside, asking farmers for whatever they could offer.

Several other physicists also used the room. One, Ziro Koba, was working with Tomonaga's group at Bunrika on the self-energy problem. Some of the officemates specialized in the study of solids and liquids (now called condensed-matter physics) under the guidance of Kotani and his assistant Ryogo Kubo, who was later to attain fame for his theorems in statistical mechanics. The young men taught each other what they knew of physics and regularly visited a library set up by MacArthur, perusing whatever journals had arrived.

At a meeting in 1946 Sakata, then at Nagoya University—whose physics department had moved to a suburban primary school—proposed a means of dealing with the infinite self-energy of the electron by balancing the electromagnetic force against an unknown force. At the end of the calculation, the latter could be induced to vanish. (At about the same time, Abraham Pais of the Institute for Advanced Study in Princeton, N.J., proposed a similar solution.) Although the method had its flaws, it eventually led Tomonaga's group to figure out how to dispose of the infinities, by a method now known as renormalization.

This time the results were published in *Progress of Theoretical Physics,* an English-language journal founded by Yukawa in 1946. In September 1947 Tomonaga read in *Newsweek* about a striking experimental result obtained by Willis E. Lamb and Robert C. Retherford of Columbia University. The electron in a hydrogen atom can occupy one of several quantum states; two of these states, previously thought to have identical energies, actually turned out to have slightly different energies.

Right after the finding was reported, Hans Bethe of Cornell University had offered a quick, nonrelativistic calculation of the "Lamb shift," as the energy difference came to be known. The effect is a finite change in the infinite self-energy of the electron as it moves inside an atom. With his students, Tomonaga soon obtained a relativistic result by correctly accounting for the infinities.

Their work strongly resembled that being done, almost at the same time, by Julian S. Schwinger of Harvard University. Years later Tomonaga and Schwinger were to note astonishing parallels in their careers: both had worked on radar, wave propagation and magnetrons as part of their respective war efforts, and both used Heisenberg's theory to solve the same problem. The two shared a Nobel Prize with Richard Feynman in 1965 for the development of quantum electrodynamics. (Feynman had his own idiosyncratic take—involving electrons that moved backward in time—which Freeman Dyson of the Institute for Advanced Study later showed was equivalent to the approach of Tomonaga and Schwinger.) And both Tomonaga's and Schwinger's names mean "oscillator," a system fundamental to much of physics.

At about the time the Lamb shift was reported, a group in England discovered the decay of the pion to the muon in photographic plates exposed to cosmic rays at high altitude. The finding proved Inoue, Sakata and Yukawa to have been spectacularly correct. After the dust settled, it became clear that Yukawa had discovered a deep rule about forces: they are transmitted by particles whose spin is always an integer and whose mass determines their range. Moreover, his tactic of postulating a new particle turned out to be astoundingly successful. The 20th century saw the discovery of an abundance of subatomic particles, many of which were predicted years before.

In 1947 new particles began to show up that were so puzzling that they were dubbed "strange." Although they appeared rarely, they often did so in pairs and, moreover, lived anomalously long. Eventually Murray Gell-Mann of the California Institute of Technology and, independently, Kazuhiko Nishijima of Osaka City University and other Japanese researchers discovered a regularity behind their properties, described by a quantum characteristic called "strangeness." (Discerning this pattern was the first step in the three-stages theory.)

In subsequent years Sakata and his associates became active in sorting through the abundance of particles that were turning up and postulated a mathematical framework, or triad, that became the forerunner of the quark model. (This framework formed the second stage. At present, high-energy physics, with its precise theory of particles and forces known as the Standard Model, is in the third and final stage.)

Meanwhile physicists in Japan were renewing ties with those in the U.S. who had made the atomic bomb. Their feelings toward the Americans were ambiguous. The carpet bombings of Tokyo and the holocausts in Hiroshima and Nagasaki had been shocking even for those Japanese who had opposed the war. On the other hand, the occupation, with its program of liberalization, was relatively benevolent. Perhaps the deciding factor was their shared fascination for science.

Reconciliation

Dyson has described how, in 1948, Bethe received the first two issues of *Progress of Theoretical Physics*, printed on rough, brownish paper. An article in the second issue by Tomonaga contained the central idea of Schwinger's theory. "Somehow or other, amid the ruin and turmoil of the war, Tomonaga had maintained in Japan a school of research in theoretical physics that was in some respects ahead of anything existing elsewhere at that time," Dyson wrote. "He had pushed on alone and laid the foundations of the new quantum electrodynamics, five years before Schwinger and without any help from the Columbia experiments. It came to us as a voice out of the deep." J. Robert Oppenheimer, then director of the Insti-

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GROUP SNAPSHOT taken in Rochester, N.Y., around 1953 features Japanese researchers with physicist Richard Feynman. Masatoshi Koshiba (*back row, left*) went on to design the Kamiokande facility; the others became prominent theorists. The picture was taken by Nambu (*front row, center*), whose skills lay in areas other than photography.

tute for Advanced Study, invited Yukawa to visit. He spent a year there, another at Columbia, and received the Nobel Prize in 1949. Tomonaga also visited the institute and found it extremely stimulating. But he was homesick. "I feel as if I am exiled in paradise," he wrote to his former students. He returned after a year to Japan, having worked on a theory of particles moving in one dimension that is currently proving useful to string theorists.

From the early 1950s, younger physicists also began to visit the U.S. Some, such as Nambu, stayed on. To an extent mitigating this brain drain, the expatriates retained ties with their colleagues in Japan. One means was to send letters to an informal newsletter, *Soryushiron Kenkyu*, which was often read aloud during meetings of a research group that succeeded the Meson Club. In 1953 Yukawa became the director of a new research institute at Kyoto, now known as the Yukawa Institute for Theoretical Physics.

In the same year he and Tomonaga hosted an international conference on theoretical physics in Tokyo and Kyoto. Fifty-five foreign physicists attended, including Oppenheimer. It is said that Oppenheimer wished to visit the beautiful Inland Sea but that Yukawa discouraged him, feeling that Oppenheimer would find it too upsetting to see Hiroshima, which was nearby. Despite their lifelong immersion in abstractions, Yukawa and Tomonaga became active in the antinuclear movement and signed several petitions calling for the destruction of nuclear weapons. In 1959 Leo Esaki, a doctoral student at the University of Tokyo, submitted a thesis on the quantum behavior of semiconductors, work that eventually led to the development of transistors. He would bring home a third Japanese Nobel in physics, shared with Ivar Giaever and Brian D. Josephson, in 1973.

One wonders why the worst decades of the century for Japan were the most creative ones for its theoretical physicists. Perhaps the troubled mind sought escape from the horrors of war in the pure contemplation of theory. Perhaps the war enhanced an isolation that served to prod originality. Certainly the traditional style of feudal allegiance to professors and administrators broke down for a while. Perhaps for once the physicists were free to follow their ideas.

Or perhaps the period is just too extraordinary to allow explanation.

The Authors

LAURIE M. BROWN and YOICHIRO NAMBU often collaborate on projects involving the history of Japanese physics. Brown is professor emeritus of physics at Northwestern University and has turned his interests in the past two decades to the history of physics. He is the author or co-author of eight books on the subject. Nambu is professor emeritus at the University of Chicago. He is responsible for several key ideas in particle theory and has received the Wolf Prize, the Dirac Medal, the National Medal of Science, the Order of Culture (from the Japanese government) and numerous other awards. Nambu last wrote for *Scientific American* in November 1976, on the confinement of quarks.

Further Reading

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