Superconductivity Research in Japan

—Kakenhi Bear Fruit with Fundamental Research—

Hidetoshi Fukuyama, Director General, Research Institute for Science & Technology, Tokyo University of Science; Professor Emeritus, The University of Tokyo

Bio: A former Director of the Institute for Solid State Physics (The University of Tokyo), Professor Fukuyama has taken a leading role in advancing the theoretical and experimental underpinnings of high-temperature superconductivity. He received the Medal with Purple Ribbon in 2003.

1. Recent Japanese Discoveries of Superconducting Materials

Superconductivity is a crowning phenomenon in solids. Because of the dramatic feature of the complete elimination of electrical resistivity in metals, it has become a subject of broad interest and has been fueling a quiet but steady worldwide search for materials that promise even the slightest increase in the critical temperature at which superconductivity sets in. Jun Akimitsu and I were recently involved as editors of a book *Chodendo handobukku* (Superconductivity handbook). That venture reaffirmed that almost all of the most exciting superconducting materials discovered in the field of material science over the past 30 years had their origins in Japan. Following is a brief chronology. Starting with confirmation of superconductivity (Meissner effect) in copper oxides, and identification of their chemical composition and crystal structure in 1986 (Shoji Tanaka, Koichi Kitazawa, Shinichi Uchida, and Hidenori Takagi), the list includes "bismuth copper oxides" (Hiroshi Maeda) in 1988, "electron-doped copper oxides" (Yoshinori Tokura, Hidenori Takagi, Shinichi Uchida) in 1989, "Sr_2RuO_4" (Yoshiteru Maeno) in 1994, "copper oxide ladder compounds" (Jun Akimitsu, Nobuo Mori) in 1996, MgB_2 (Jun Akimitsu) in 2001, "Cobalt oxides" (Eiji Muromachi) in 2003, and "iron pnictides" (Hideo Hosono) in 2006 and 2008.

Unsurprisingly, the researchers behind these achievements have been honored with prestigious international awards (personally I find it regrettable that

Shoji Tanaka and his colleagues were not nominated for a Nobel Prize, though.).

Why were so many important accomplishments of this kind in the field of superconductivity research possible? One point worth bearing in mind in this context is the fact that details of electronic states in solids determine the appearance of superconductivity, making integrated research necessary, and fundamental research accordingly has a crucial role to play. Many novel and interesting superconducting materials have been discovered only through steady, persistent research with a low probability of luck, and their discoverers are sure to become stars within the scientific community.

2. Start of Research on High-Temperature Superconductivity

Systematic superconductivity research in Japan had its start with a project funded by a Grant-in-Aid for Co-operative Research (B) in FY1981 on "Atarashii taipu no chodendo" (new types of superconductivity). This project involved a group of 13 theoreticians led by Prof. Sadao Nakajima of the Institute for Solid State Physics at The University of Tokyo (Nakajima served as institute director from 1981 to 1984). Around 1980, a series of new findings of superfluidity and superconductivity were reported in the fields of heavy electrons, organic (molecular) crystals and helium-3, which had a major impact on solid-state physics research in the years that followed. The above-cited project in Co-operative Research (B) had the objective of developing a systematic understanding of these diverse phenomena of superconductivity. As one result, there was a growing interest toward research on superconductivity, leading to a new project in Co-operative Research (B) in FY1982 and, in FY1984, the start of a three-year undertaking in Specific Research on "Shin chodendo busshitsu" (new superconducting materials) led by Prof. Sadao Nakajima. When three of my senior colleagues—professors Nakajima, Shoji Tanaka, and Ko Yasukochi—gathered in my small office to exchange views and figure out details on the inauguration of this research group, the atmosphere of enthusiasm was intense. The new research group basically abandoned the traditional theoretician-led approach and was launched with 32 members, including many experimentalists. In particular, many of researchers of material synthesis, who in general had a relatively low-profile at the time, were included. From a global perspective, the birth of this research group had huge implications not only for research on superconductivity but also for research in the field of material science in a broader spectrum. Prof. Nakajima disclosed the group's objectives at the Sixth Taniguchi International Symposium in 1983 and also in letters addressed to 10 internationally acclaimed investigators, including three Nobel laureates. Although the group and its objectives received strong encouragement from many quarters, at another extreme it was criticized as a baseless proposal aiming at securing research funding. John Bardeen (who had won the Nobel Prize in Physics twice—first for the invention of the transistor, and later for the fundamental theory of superconductivity) offered warm and friendly words of encouragement. Bardeen and Nakajima resembled each other in their appearance, the way they spoke, and their strong enthusiasm for research (Fig. 1). Though now deceased, both had a dignified scholarly aura that is not that common in the university setting anymore. The stunning discovery of high-temperature copper oxide compounds occurred in the course of this project in Specific Research. At a November 1986 research seminar I organized in Ajiro on Japan's Izu Peninsula, a change in the program schedule allowed Prof. Shoji Tanaka's group to deliver a paper on the confirmation of high-temperature superconductivity in copper oxides, the possibility of which had been indicated by Bednorz and Muller in the spring of 1986. The report created a strong sense of excitement among all the participants there. I still have a lasting impression of the red glow from the eruption of Mt. Mihara that could be observed from the seminar site that evening.

1. Prof. Sadao Nakajima and Prof. John Bardeen (in May 1986 at the Institute for Solid State Physics, The University of Tokyo).

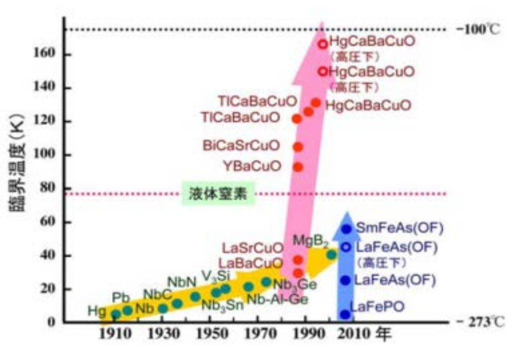
3. A Discovery of the Century

Afterward, four researchers of the Tanaka group, who were later called the "Gang of Four"—Shoji Tanaka, Koichi Kitazawa, Shinichi Uchida, and Hidenori Takagi (Fig. 2)—worked day and night on intensive research that resulted first of all in the confirmation of Meissner effect, and the identification of the chemical composition and crystal structures that set the stage for the phenomenon of superconductivity to appear. In early December that year, Kitazawa presented these findings at the MRS Meeting in Boston, effectively sparking a firestorm of interest worldwide. This was a "find of the century" that prompted the fast-track launch, in FY1987, of another project in Specific Research, on the "Sankabutsu koon chodendotai no kenkyu" (studies on high-temperature superconducting oxides), following in the footsteps of the earlier Specific Research project on "Shin chodendo busshitsu" (new superconducting materials).

2. The "Gang of Four" responsible for stoking the fever of interest in copper-oxide superconductivity. From left: Kitazawa, Tanaka, Uchida, and Takagi. (1986)

As illustrated in Fig. 3, with the discovery of novel copper-oxide compounds, the critical temperature at which superconductivity sets in rose initially from 23 Kelvin to 30 Kelvin, and then, in the spring of 1987, leaped all the way to 100 Kelvin. Because this was higher than the 77 Kelvin (-196 C) boiling point of liquid nitrogen, the prospects for commercial applications of superconductivity attracted broad public interest and spurred a widening global race to find materials with even higher critical temperatures. The high-temperature superconductivity "fever" had taken hold. (Fig. 3 includes data for some other high-temperature superconductive materials that were discovered later, including MgB_2 and iron compounds.) Some of the nation's leading newspapers ran a series of front-page columns documenting research activity in the field and several manga-style primers on the subject were also published. Fig. 4 is an example. To see some of my colleagues rendered as protagonists and supporting characters in comic-book style was a very unusual yet somewhat bizarre experience. This media attention not only provided coverage of research activities, it also introduced to the public some of the leading researchers' family lines. Around this time, phone calls were made around the globe by those wanting to know how high the critical temperature had been measured or the temperature that Prof. "So-and-So" had achieved. That was the scene in my home practically every evening as well. In fact, even my son, then in the early years of elementary school, was in the habit of asking me, "Dad, what temperature today?"

During these turbulent years, the format for the presentation of research findings had its share of problems. Because amateurish mistakes that were frequently committed during basic measurements of electrical resistivity (for example, observations of "negative" resistivity, which is impossible) and the media reporting of "astonishing findings" that were based on such mistakes could have the effect of undermining the credibility of the scientific community, Prof. Nakajima's message that "ethics are vital to researchers" and Prof. Tanaka's announcement of "three rules for the confirmation of superconductivity" were also published by the newspapers.



3. Changes with the times in the critical temperature for superconductivity.

4. The cover of Shoutaro Ishinomori's *Ishinomori Shoutaro no Chodendo koza* (Shoutaro Ishinomori's lectures on superconductivity) (Kodansha 1988) and manga images of Prof. Nakajima on the cover and page 1. The term "tokutei kenkyu" ("specific research") also appears.

In March 1987, the American Physical Society Meeting in New York held a special symposium. It was extremely crowded with so many participants (by some accounts, over 2,000 were in attendance). The reports at that gathering began around 7:30 p.m. and lasted until after 3:00 a.m. the following morning. Immediately after this symposium, the Japanese telecommunications firm Kokusai Denshin Denwa (KDD) sponsored a satellite-TV panel discussion with the participation of Prof. Tanaka, Stanford University Prof. Malcolm Beasley, and some others from a New York studio and Prof. Nakajima and others in Otemachi, Tokyo. This, too, was reported by the newspaper. Because it had so many participants, the symposium was later dubbed the "Woodstock" of physics. (Incidentally, on our way by taxi from JFK airport to get to the symposium site, near East River just before entering Manhattan, our taxi driver suddenly veered off into a side street, stopped the car in front of an abandoned building, and demanded a fare tantamount to extortion. Unwilling to give in, Prof. Kitazawa spiritedly exclaimed, "That's absurd! We'll go to the police!" Showing the wisdom of a man of his age, however, Prof. Tanaka anxiously informed Kitazawa that we had no choice but to pay, and we managed to reach the hotel safely.)

Not long afterward, the Physical Society of Japan held an annual meeting for 2,000 attendees in a hall meant to seat only 800 on the campus of the Nagoya Institute of Technology, and on that occasion, the fervent discussions and debates raged from 9:30 a.m. to after 11:00 p.m. At the following MRS Meeting in Anaheim, CA, that May, Prof. Tanaka had plans to erase the image of Japan as a free-rider in fundamental science —a theme that had gained some currency within Western circles. Prof. Kitazawa went to great lengths to put those plans into motion and had 1,000 copies of the JJAP letters —a hastily prepared collection of Japanese research papers—handed out at the MRS venue. As circumstances would have it, in August that year, the 18th International Conference on Low-Temperature Physics (held once every three years) convened in Kyoto. Here, too, pandemonium prevailed, as the organizers were flooded with advance applications and had to deal with a vastly higher-than-expected turnout on the opening day. (Fig. 5 is a scene from that event.) Securing enough funding to cover expenditures is always one of the biggest headaches in preparing for events of this scale. As such, organizers tend to depend on corporate donations. Although the business sector had initially been reluctant to make donations, by early 1987 it had warmed up to the "superconductivity" buzzword so much that event organizers were assured of exceeding their fundraising goals. In fact, fundraising officers were even faced with the unprecedented situation of having to ask some donors to reduce the size of their pledges.

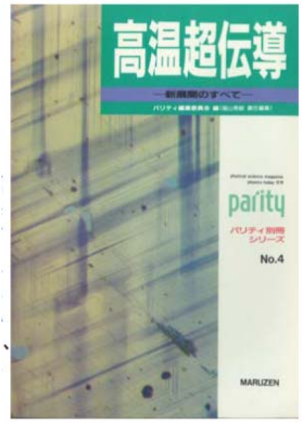
5. At the 18th International Conference on Low-Temperature Physics in Kyoto International Conference Center which was fully attended. Many members of the press are visible in front.

Back in the day, the telephone and fax machine were still the two mainstream modes of communication, and the international lines were busy with all the traffic. The research papers that were faxed to my office in a short period at the Institute for Solid State Physics (ISSP) in Roppongi, Tokyo, filled some 200 filing folders, each 8-cm thick. I put them in the theory salon so that all researchers could review them and held weekly paper reporting sessions at the Institute of Solid State Physics. Each time, the room was filled to more than capacity. As a "national institute for joint research," I believe that this effort of

ISSP in "information disclosure" ultimately contributed in no small way to the global lead that Japan later gained in the field of materials science research. These efforts as well as a variety of other related research activities were made possible through the cooperation of many individuals, not all of whom were researchers. At the time, Ms. Shizue Maruyama, my office secretary, handled most of the work involved in contacting and coordinating with other researchers in Japan and around the globe. (I don't think there is anyone she has not helped in some way. In fact, a quarter-century later, I had her help in preparing this manuscript.) The monthly science magazine *Parity*, which has a tie-up with the US physics journal *Physics Today*, has a monthly feature section on "Topikkusu: koon chodendo no shintenkai" (Topics: new developments in high-temperature superconductivity) (Fig. 6). In a turbulent world rife with dubious information, this effort to select and provide feature coverage of the latest, reliable research findings had been instrumental in maintaining the health of the material science research community. This feature column starts with an article written by Prof. Kitazawa titled "U.S.O. revealed: high-temperature superconductors." (Of course, here U.S.O. is not a play on the Japanese word for a lie ["uso"], but an acronym for "Unidentified Superconducting Object. ")

4. Revolution and Serious Dissent

Research undertakings aiming at unraveling and exploring the mechanism of superconductivity in copper-oxide compounds eventually transitioned into several new projects: Priority Area research on "Chodendo hatsugen kiko no kaimei" (Elucidation of the mechanisms of high-temperature superconductivity) (1988–1990; Yoshio Muto, principal investigator); "Koon chodendo no kagaku" (the science of high-temperature superconductivity) (1992–1994; Masashi Tachiki, principal investigator); and "Motto teni kinbo no ijo kinzokuso" (Anomalous Metallic State near the Mott Transition) (1995–1997; Hidetoshi Fukuyama, principal investigator).



6. *Parity* editorial board, editors. *Koon chodendo-shintenkai no subete* (High-temperature superconductivity–all the latest developments) (*Parity* supplement series, No. 4) (Maruzen).

This was a general introduction to developments that had taken place in the field in the preceding year-and-a-half and combined into one volume articles from the *Parity* journal's feature column, "Topikkusu: koon chodendo no shintenkai" (Topics: New developments in high-temperature superconductivity) with translated articles from *Physics Today*.

During this period, an atmosphere of increasingly serious antagonism began to develop gradually in research community and it still casts a shadow over the field to some extent even today. Copper-oxide compounds had disclosed a problem of importance to the very foundation of solid-state physics, a field of fundamental science that strives to shed light on the properties of materials. As one of the most fundamental of all material properties, electrical conductance, that is, whether electricity flows through a material or not, is a property defining the differences between metals and insulators. Materials are collections of an unfathomably large number of atoms and molecules. (If, for example, we substituted tennis balls for the atoms in a cubic centimeter of a typical material, the resulting box would measure 3000 km along one side.) This is the reason why materials are referred to as condensed matter systems. Properties of a collection of atoms this large are vastly different from those of each individual atom in that collection. Metals and insulators exemplify this difference. The basis for this difference depends on whether quantum mechanical particles that are bound by an atom—the electron—will become free to move around within the material or not. In general, the basis for being an insulator may be divided into two scenarios: one that derives from the Pauli exclusion principle—a fundamental concept of quantum mechanics—and another that derives from strong repulsive coulomb interactions ("strong correlation effects") between negatively charged electrons. The former are referred to as "band insulators" while the latter are called "Mott insulators." Adding very small quantities of electrons to band insulators can create a condition marked by a slight level of electrical conductance. This is the phenomenon behind the semiconductor leading to transistors which form one of the foundations of modern science and technology. Copper-oxide superconductivity, however, is realized when very small quantities of electrons are added to or extracted from Mott insulators. Because Mott insulators have magnetic properties, copper-oxide superconductivity occurs together with to magnetism. This property was not a part of our understanding before copper-oxides and was very unexpected. Revolutionary discoveries of this nature that have the power to upturn our conventional understanding of the material world can also breed severe divisions within society. Under these conditions of upheaval, researchers long considered to be experts in the field began to voice objections to ideas otherwise considered self-explanatory or tendered incomprehensible proposals, fueling confusion in the field. This happened on a global scale. Unfortunately, Japan was no exception, and to a serious degree. The quest for factual truth is a foundation of science. However, for a time, this principle was displaced by a "majority rule" fad, with many decisions based on nothing more than the influence of "many people say so." (As something that occurred in the natural sciences, which are engaged in a quest for truth, this uncommon situation may well qualify for social-scientific analysis. Now that a certain measure of calm has been restored, I wonder if anyone might be interested in pursuing a study along this line.)

5. Kakenhi Bear Fruit with Fundamental Research

In the years since, solid-state physics research in Japan has continued to attract worldwide attention thanks to the research activities I described earlier as well as new undertakings in Priority Areas. These include a project themed on "Seni kinzoku sankabutsu ni okeru atarashii ryoshigensho: supin, denka, kidou ketsugokei" (novel quantum phenomena in transition metal oxides: spin, charge, and orbital coupled systems) (1999–2003; Sadamichi Maekawa, principal investigator) and another on "Ijo ryoshi busshitsu no sosei—atarashii butsuri o umu shin-busshitsu" (the creation of anomalous quantum materials—new materials for new physics" (2004–2008; Jun Akimitsu, principal investigator). In particular, Japanese researchers have continued to enlighten the world to the breadth and depth of strongly correlated electron systems. A very visible example would be Prof. Yoshinori Tokura's work with a focus on multiferroics. In the spring of 2013, he launched the first-ever strategic center for research in the solid-state sciences at RIKEN. Another example is, Prof. Hideo Hosono, originally a chemist known for his achievements in the development of oxide semiconductor materials, has discovered superconductivity in iron-based systems. This is very unexpected, since iron is a typical element of magnetism, and is now stimulating diverse research activities. He has also discovered superconductivity in electrolytes (crystals that share the same atomic configurations as ionic crystals but the negative ions are replaced by electrons). Prof. Hosono, demonstrating the potential of electrolytes as a catalyst in the synthesis of ammonia as well, is establishing a bridge between material science and materials engineering. The stage has been set for these international stars as well as future generations of young researchers to continue blazing new trails in this field. Fig. 7 is a photo of a public lecture for high-school students.

Japan's current global lead in solid-state physics and the broader field of material science is entirely a product of the extensive financial support its government has extended to undertakings in basic research over many years. I cannot adequately underscore in words the importance of Kakenhi in aiding research undertakings from the bottom up.

7. Public lecture on superconductivity for high-school students (March 2013 at the National Museum of Emerging Science and Innovation.) From left: Kurokawa (Nihon Keizai Shimbun), Kitazawa, the author, Hosono, and Akimitsu. (Submitted by Masashi Furukawa of the JST.)

6. Acknowledgements

I wish to express my sincere gratitude for the extensive help I received in the preparation of this manuscript from Koichi Kitazawa, President of Tokyo City University, advisor of the Japan Science and Technology Agency, Professor Emeritus of The University of Tokyo, and Shizue Maruyama, former Technical Associate of the Division of Condensed Matter Theory, Institute for Solid State Physics, The University of Tokyo.