AUTHOR COMMENTARIES - 2010

Yoshinori Tokura, Pioneer of Correlated Electron Materials, Dreams of New Technologies for a Sustainable Society: The Magic of “4”

by David Pendlebury, Special correspondent for ScienceWatch.com

PDF

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Professor Yoshinori Tokura is one of Japan's most distinguished condensed-matter physicists and a global leader in the cutting-edge field of correlated electron materials.

Correlated electron systems (sometimes called strongly correlated electron systems) are those in which electron-electron interactions determine the properties of the material. These interactions—including charges, spins, and orbitals—can, under certain conditions, produce a wide and surprising array of electronic phases, which hold promise for a new type of electronics. Examples of correlated electron materials include high-temperature (high-Tc) superconductors, spintronics materials, Mott insulators, and many others.

"One of the triumphs of twentieth century physics was the development of quantum theories of the behavior of electrons in solids," notes Andrew P. Mackenzie, Professor of Physics at the University of St. Andrews. "These theories underpin our understanding of many simple materials, and are directly responsible for the way in which silicon technology has so profoundly changed the world in which we live and work. They are reliant, however, on the key assumption that electron-electron interactions can be treated in a mean-field approximation.

"The challenge of the twenty-first century will be to understand and exploit the huge class of materials in which this approximation breaks down. In these compounds, the position and motion of each electron are correlated with those of all the others. The correlated electron problem in solids is one of the most profound quantum mechanical problems faced by modern physics…The scientific and technological promise of correlated electron materials is enormous."

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Among Professor Tokura's major achievements in the field are the development of new types of high-Tc superconductors, the establishment of a general rule for high-Tc materials design and synthesis, detailed descriptions of colossal magnetoresistance in oxide materials, especially in manganites, systematic investigation of the Mott transition in perovskite materials, and the discovery of gigantic non-linear optical properties in one-dimensional Mott insulators.

Professor Yoshinori Tokura is one of Japan's most distinguished condensed-matter physicists and a global leader in the cutting-edge field of correlated electron materials.

Professor Tokura (see also) earned B.S. and Ph.D. degrees in applied physics, both from the University of Tokyo, where he currently holds the rank of Professor. He is also Research Director of the ERATO-JST's Tokura Multiferroics Project, Group Director of RIKEN's Cross-Correlated Materials Research Group, and an AIST Fellow of Japan's National Institute of Advanced Industrial Science and Technology.

In recognition of his outstanding research contributions, Professor Tokura has been awarded a number of prestigious prizes, including the IBM Japan Science Prize (1990), the Nissan Science Prize (1998), the Asahi Prize (2003), and the James C. McGroddy Prize for New Materials of the American Physical Society (2005).

Also, in 2000 Thomson Reuters named Professor Tokura one of Japan's 30 Citation Laureates of 1981-1998. These individuals were selected not merely for their high citation totals but also their authorship of multiple highly cited papers. In 2002, Thomson Reuters chose Professor Tokura as one of its Citation Laureates forecast to win the Nobel Prize.

Today, he ranks among the 10 most-cited physicists of the last three decades, having published nearly 1,000 research articles which have been cited close to 45,000 times. His h-index is fast approaching 100, signifying authorship of 100 papers each cited 100 or more times. Professor Tokura's 10 most-cited papers are listed in Table 1 on the next page.

ScienceWatch.com *special correspondent David Pendlebury had the honor of meeting with Professor Tokura at the University of Tokyo in late October 2009. The following is an edited version of their conversation.*

SW: In the 1980s, after your graduate work and some teaching at the University of Tokyo, you went to IBM in San Jose, California, for a one-year research position. Is that right?

Yes. During 1987 and beginning of 1988.

SW: That was a very important moment in the history of condensed matter physics.

Yes, this year almost coincided with the period of "high-Tc fever." Actually, Professor Tanaka, my neighbor here, had just confirmed the 1986 results (of J. Georg Bednorz and K. Alex Müller of IBM, who won the Nobel Prize in Physics in 1987 for their discovery of cuprate high T-c superconductors).

If I had stayed in Japan, I might have never attacked that problem. But in the United States, I was completely independent and I began my high-Tc work. That was very good for me.

SW: You have described the cuprate superconductor as a wonderful example of a correlated electronic system. What other materials are good examples of correlated electron materials?

Actually, all compounds of transition metal oxides—copper, but also iron or manganese oxide materials. Manganese oxide is the material in which we showed gigantic magnetoresistance. In correlated electron materials, the electrons are in a strictly localized state, catched…

Photo gallery of the interview with Professor Yoshinori Tokura and David Pendlebury

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SW: I think you have also used the term "pinned…"

Yes, pinned. Actually an electron can behave like a sort of wave in the solid, but only an electron can stop an electron by their mutual interaction—their motion is almost freezed out. That is the essence of correlated electrons.

In the case of the copper oxide high-Tc superconductors, the frozen electrons that make an insulator are turned into a metal, and then immediately its state is a high-Tc superconductor. But in another compound, it's sort of a ferromagnetic metal. Of course, the result is quite different, but still the common background is the melting of the electrons within the solid.

So the formula is that the methodologies are quite similar and also the basic concept is quite common in correlated electron materials.

SW: What is so fascinating about these materials is the possibility of changing, say, their optical properties just by exposing them to a magnetic field or other force. It does seem like magic.

Yes. For example, in gigantic magnetoresistance, or what we called colossal magnetoresistance, when we add a tiny or small magnetic field, then a completely insulating ceramic suddenly turns into metal. So, it's a sort of alchemy.

And high-Tc materials are the same. These are originally completely insulating, but when chemically modified, with only a small change in composition, they immediately turn into a metal.

So with this kind of the material—I mean the correlated-electron materials—my favorite word is "emergence." Emergence means many independent components come together to generate many very surprising outcomes.

SW: You're referring to quantum effects.

Yes.

SW: The collapse of the wave function, where the whole system takes on a particular property?

Indeed. This is best represented by Nobel laureate Philip W. Anderson's 1972 article "More is Different," (*Science*, 177 [4047]: 393–396). I mean the same thing. The entirety of the material's property cannot be described by the sum of the individual components.

SW: And so that leads to all kinds of possibilities, such as new kinds for computing and switching devices with these materials. Is that correct?

That's right.

SW: I read that you said within a 40-nanometer area you can have…I forgot the number...

Actually, almost a million electrons.

SW: So, within a 40-nanometer-sized box you can have one million electrons acting as a single mechanism.

Yes.

SW: You've been methodical about exploring all the transition metals in sequence.

Yes. I always say that perhaps the correlated electron materials represent an important area of science we need to realize our dreams. Of course, our dreams are not to know the ultimate nature of the universe or such a big thing as that, but we are trying to obtain very surprising or unconventional functions or electronic functions in solids. In other words, the goal is to develop new electronics—not in the narrow sense like semiconductor electronics.

I just read *Physics of the Impossible* (New York: Doubleday, 2008), by the US physicist Michio Kaku. I was very impressed by his book, and actually my goal is to realize the physics of semi-impossible in condensed matter science, which may lead to innovative and even revolutionary technologies. So, we aim at very, very fundamental issues. Only a new concept can lead to a revolution.

With this in mind, I have drawn up a list I call "Innovation 4." If these kinds of numbers could be realized (see Table 2), it would create a revolution in our daily lives through basic discoveries in physics.

In energy transfer, we need 400 Kelvin in order to realize a real room temperature superconductor. At the moment we have 130 or 140 Kelvin superconductors. So we need not only three times the effort to achieve this, but also three times the innovation.

Of course, if you can use liquid nitrogen and then maybe you can make any power transmission line, but it's still very difficult. High-Tc is a main target of our research. We are still struggling and often it's not so successful, but maybe we will one day reach the 400 Kelvin superconductor.

Another case is thermoelectric materials. Our goal is to produce materials for ultra-low energy consuming electronics. The thermoelectric effect tells us we can generate electricity from temperature differences. An example is the air conditioner, which uses a compressor for refrigeration—that's 19th century thermodynamics.

But if we could directly convert electricity to heat conduction, that would be better. We usually measure this by the so-called thermal figure of merit (ZT). At the moment, ZT is typically 1 or a little more. But if this value exceeds 3 or 4, then every compressor can go away and we can immediately replace it with a direct heat-electricity transformation.

And another case, in terms of energy conversion, is solar cells. As you know, the efficiency is now at 10%, but for industrial use 40% would be very important. So I think correlated electron materials may help. I am not sure, but we are working towards that purpose, and maybe with these correlated electron materials we can generate a surprising result. We will need a very new physics. Yes, it's a dream.

In silicon, light pumps out an electron leaving a hole, positively charged which generates an electric current. But with the use of these new materials, a photon of light comes in, then we have sort of metallic state, and the semiconductor or insulator suddenly turns into a metal. Of course, we have to consider the energy conservation rule, but still a lot of the electrons can be generated and extracted, so we may realize a very highly efficient solar cell. This may be 10 years away.

And batteries, too. This is the problem of energy storage. It's another dream of mine. The best performance of the present state-of-the-art batteries is 100 watt-hours per kilogram. If you could increase this performance three or four times, it would make a great difference in our mobile computing society.

Our battery technology is classical electrochemistry. So we are thinking there is a chance to move from the classical concept to more advanced quantum technologies.

So, in summary, the items in the Innovation 4 program show we are only one-third of the way to our ultimate goal in these areas.

SW: The Innovation 4 program is certainly visionary. What about the recent discovery of iron-based superconductors? How might this new class of high-Tc materials fit into your goals?

I think the Tc there is almost saturated. Obviously, the iron-based superconductors revealed a new physics concept, and that's very important, but I think in terms of the high-Tc, at 50 Kelvin it is already saturated.

Of course, people say that it has only been one year since this discovery, so it may increase. In reality, the science community is already mature, so almost immediately we can make a new series of materials. Maybe one month nowadays corresponds to the one year of 20 years ago.

SW: Chinese scientists have been very active in exploring iron-based superconductors and, more generally, in physics and materials science. Chinese science is growing rapidly, and the nation is now second in output of papers worldwide according to our data. What is your impression of research in China today?

Today, although the level of research tends to vary, I think China's possibilities are vast. I think there are some top-notch scientists working at a very high level. Tsinghua University has such scientists. I notice that our group will publish a paper describing a new experimental method or a new concept, and immediately many Chinese scientists work on the same subject, verifying our work.

China has a very good machine. They have perhaps helped my citation count! Many young people in China still want to study in the US, but some are now studying in Japan or Germany. China is not always on the top, but it has some very good fundamental research groups, so that will help the country develop much faster. I think, yes, this country, with its huge population and some very smart scientists, will rapidly develop.

View Tables

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Yoshinori Tokura's current most-cited paper in *Essential Science Indicators*, with 855 cites:

Kimura T., *et al*., "Magnetic control of ferroelectric polarization," *Nature* 426(6962): 55-8, 6 November 2003. Source: *Essential Science Indicators* from Thomson Reuters.

Additional information:

- Yoshinori Tokura's Researcher ID Profile
- Yoshinori Tokura is featured in ISIHighlyCited.com
- The *ScienceWatch.com* Special Topic of High-Temperature Superconductors

KEYWORDS: CORRELATED ELECTRON MATERIALS, HIGH-TEMPERATURE SUPERCONDUCTORS, HIGH-TC MATERIALS, MAGNETORESISTANCE, OXIDE MATERIALS, MANGANITES, MOTT TRANSITION, PEROVSKITE MATERIALS, NON-LINEAR OPTICAL PROPERTIES, CONDENSED MATTER PHYSICS, CUPRATE SUPERCONDUCTOR, EMERGENCE, QUANTUM EFFECTS, INNOVATION 4, ENERGY TRANSFER, THERMOELECTRIC MATERIALS, ENERGY CONVERSION, SOLAR CELLS, BATTERIES, ENERGY STORAGE, IRON-BASED SUPERCONDUCTORS.

PDF

back to top

ScienceWatch Home
Inside This Month...
Interviews

Featured Interviews
Author Commentaries
Institutional Interviews
Journal Interviews
Podcasts

Analyses

Featured Analyses
What's Hot In...
Special Topics

Data & Rankings

Sci-Bytes
Fast Breaking Papers
New Hot Papers
Emerging Research Fronts
Fast Moving Fronts
Corporate Research Fronts
Research Front Maps
Current Classics
Top Topics
Rising Stars
New Entrants
Country Profiles

About Science Watch

Methodology
Archives
Contact Us
RSS Feeds

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PDF

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Back to interview

Table 1

Professor Yoshinori Tokura's 10 most-cited papers:

Rank	Paper	Citations
1	**Title: Metal-insulator transitions** Author(s): IMADA, M.; FUJIMORI, A.; TOKURA, Y. Source: *Reviews of Modern Physics* Volume: 70 Issue: 4 Pages: 1039-1263 Published: Oct 1998	1840
2	**Title: INSULATOR-METAL TRANSITION AND GIANT MAGNETORESISTANCE IN LA1-XSRXMNO3** Author(s): URUSHIBARA, A.; MORITOMO, Y.; ARIMA, T.; *et al*. Source: *Physical Review B* Volume: 51 Issue: 20 Pages: 14103-14109 Published: May 1995	1525
3	**Title: A SUPERCONDUCTING COPPER-OXIDE COMPOUND WITH ELECTRONS AS THE CHARGE-CARRIERS** Author(s): TOKURA, Y.; TAKAGI, H.; UCHIDA, S. Source: *Nature* Volume: 337 Issue: 6205 Pages: 345-347 Published: Jan 1989	1323
4	**Title: Magnetic control of ferroelectric polarization** Author(s): KIMURA, T.; GOTO, T.; SHINTANI, H.; *et al.* Source: *Nature* Volume: 426 Issue: 6962 Pages: 55-58 Published: Nov 2003	929
5	**Title: Room-temperature magnetoresistance in an oxide material with an ordered double-perovskite structure** Author(s): KOBAYASHI, K. L.; KIMURA, T.; SAWADA, H.; *et al*. Source: *Nature* Volume: 395 Issue: 6703 Pages: 677-680 Published: Oct 1998	881
6	**Title: Giant magnetoresistance of manganese oxides with a layered perovskite structure** Author(s): MORITOMO, Y.; ASAMITSU, A.; KUWAHARA, H.; *et al*. Source: *Nature* Volume: 380 Issue: 6570 Pages: 141-144 Published: Mar 1996	788

7	**Title: Orbital physics in transition-metal oxides** Author(s): TOKURA, Y.; NAGAOSA, N. Source: *Science* Volume: 288 Issue: 5465 Pages: 462-468 Published: Apr 2000	783
8	**TITLE: ANOMALOUS DISAPPEARANCE OF HIGH-TC SUPERCONDUCTIVITY AT HIGH HOLE CONCENTRATION IN METALLIC LA2-XSRXCUO4** Author(s): TORRANCE, J. B.; TOKURA, Y.; NAZZAL, A. I.; *et al*. Source: *Physical Review Letters* Volume: 61 Issue: 9 Pages: 1127-1130 Published: Aug 1988	751
9	**TITLE: SUPERCONDUCTIVITY PRODUCED BY ELECTRON DOPING IN CUO2-LAYERED COMPOUNDS** Author(s): TAKAGI, H.; UCHIDA, S.; TOKURA, Y. Source: *Physical Review Letters* Volume: 62 Issue: 10 Pages: 1197-1200 Published: Mar 1989	657
10	**TITLE: OPTICAL-SPECTRA OF LA2-XSRXCUO4 - EFFECT OF CARRIER DOPING ON THE ELECTRONIC-STRUCTURE OF THE CUO2 PLANE** Author(s): UCHIDA, S.; IDO, T.; TAKAGI, H.; *et al*. Source: *Physical Review B* Volume: 43 Issue: 10 Pages: 7942-7954 Published: Apr 1991	652

SOURCE: Thomson Reuters *Web of Science*®, ResearcherID database.

Table 2

Professor Yoshinori Tokura’s vision of Innovation "4"

1 Ultra-low energy consuming electronics
(nearly dissipation-less, non-volatility, ultra-high density)

From heat to electricity ZT > 4

2 Energy conversion

From light to electicity F > 0.4

3 Energy transfer

Above room temperature superconductivity > 400 Kelvin

4 Energy storage

Quantum battery > 400 WH/Kg

SOURCE: Thomson Reuters *Web of Science*®, ResearcherID database.

Back to interview

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EFFECTS, INNOVATION 4, ENERGY TRANSFER, THERMOELECTRIC MATERIALS, ENERGY CONVERSION, SOLAR CELLS, BATTERIES, ENERGY STORAGE, IRON-BASED SUPERCONDUCTORS.

PDF

back to top