Lu Yu: the past and future of condensed matter physics

By Mu-ming Poo and Ling Wang

Lu Yu, a distinguished theoretical physicist at the Institute of Physics (IOP) of Chinese Academy of Sciences (CAS), has witnessed the development of Chinese physics over the past five decades, from the difficult period of 1960s when physicists worked in a ‘half-fed’ state to the present flowering springtime of Chinese physics in which many breakthroughs at the frontier of physics are attracting international recognition. He considers these achievements to be not merely ‘intermittent bubbles’, but the cumulative result of sustained governmental support of basic research over the past decades. In his area of condensed-matter physics, Yu sees ‘a big deep-rooted tree with many branches—some old branches have withered away, but new shoots continue to appear’. In a recent interview with NSR, Yu reflected upon the recent history of condensed-matter physics in China—what has been accomplished and what lies ahead—and his view on the development of physics in general.

NSR: Can you summarize your career at the Institute?

Yu: I joined the Institute of Physics of CAS in 1961, following undergraduate and graduate training in physics at National Kharkov University of the former Soviet Union. With the support of the director of theoretical physics at the Institute, Professor Yin-Yuan Li, a group of young physicists interested in quantum many-body physics and superconductivity began to work together. During the three years of the most difficult period, we hardly had enough to eat, but were still full of enthusiasm for our research. We were isolated from the rest of the world, but fortunately the library regularly acquired international journals that kept us updated to some extent on developments in our field. Our lack of supervision was compensated by intensive literature studies as well as mutual teaching and learning: out of our group, four people were later elected to the CAS membership. In that quite unique atmosphere I found, through calculation, the existence of bound states within the energy gap of superconductors doped with magnetic impurities. This work was published in the 1965 issue of Chinese Journal of Physics (Acta Physica Sinica). It predated by a few years similar findings of H. Shiba of Japan and A. I. Rusinov in Russia, and predicted results that were confirmed only after the invention of scanning tunneling microscope. Even during the ‘cultural revolution’, together with Bai-lin Hao we calculated the critical exponents for continuous phase transitions to higher orders, using diagrammatical techniques in parallel with the pioneering work of E. Brezin et al., which in turn was inspired by K. Wilson’s invention of renormalization group. In 1986, I took a position at the International Center for Theoretical Physics at Trieste in Italy, and returned to the Institute in 2002.

MERGING MICROSCOPIC AND COSMOSCOPIC VIEWS

NSR: What is the major trend in physics over the past several decades?

Yu: Viewing the physics as a whole, I think the most prominent trend is the merging of microscopic and cosmoscopic views of the world. For a long period, cosmology was a descriptive and speculative science, but now it is becoming more quantitative. On the basis of research on the cosmic microwave background radiation, together with inputs from particle physics, there emerged the current field of astro-particle physics, which promotes the experimental verification of theoretical predictions. The hottest topics in cosmology now are dark matter and dark energy, which together constitute 95% of the materials in the universe. Since they do not interact with light, they cannot be directly detected.

NSR: Might dark matter and dark energy be interconvertible in the same way as ordinary matter and energy?
In quantum mechanics, we have learned that observation inevitably disturbs the microscopic state of the particle, which appears to rule out precise quantum manipulation. Nevertheless, experimental results have now demonstrated that quantum manipulation can indeed be achieved.

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Yu: No, they cannot be interconverted. But they play the key role in determining the fate of the universe. Research on dark matter and dark energy is very active internationally. There are several approaches to the search for these strange entities. In China, there is a unique opportunity provided by the Jingping Hydro-Power Station, where there is an underground laboratory 2400 meters beneath the Earth’s surface, well shielded from interference by cosmic rays. This project began in 2009, and interesting findings have been obtained within the short six-year period of operation that are already recognized by international peers.

NSR: Can you briefly summarize the recent findings of Chinese scientists in this area?

Yu: Using a germanium detector, the Tsinghua University team (CDEX) has shown that several recent claimed possible sightings of dark matter reported by other groups were false events, while the Shanghai Jiao Tong University team (PandaX) has substantially improved the sensitivity of xenon detectors, casting serious doubt on the ‘suspicious’ detections of dark matter claimed by other groups.

NSR: Is progress here dependent largely on the development of better detection technology?

Yu: Indeed, there is intense competition in this area. Detector of dark matter often requires the use of liquid xenon. In the beginning we used 100 kilograms of xenon, and now we are making a detector that uses half a ton of xenon. This is a huge engineering challenge.

RAPID PROGRESS IN QUANTUM MANIPULATION

NSR: How is the progress in your area of condensed-matter physics?

Yu: The most important development in condensed-matter physics is the rapid advance in handling the quantum world. We are experiencing a transition from the era of observing quantum phenomena to that of controlling them. During the 20th century, the development of the theory of relativity and quantum mechanics resulted in rapid progress of information technology—both the laser and computer technologies are based on quantum mechanics. However, before the invention of scanning tunneling microscopes, we could not observe the quantum world directly and had to rely upon indirect spectroscopic approaches. As the technology advances, now we are able not only to observe individual molecules and atoms but also to manipulate them with various tools. This is a revolutionary change in solid-state physics. In quantum mechanics, we have learned that observation inevitably disturbs the microscopic state of the particle, which appears to rule out precise quantum manipulation. Nevertheless, experimental results have now demonstrated that quantum manipulation can indeed be achieved.

When I returned full-time to China in 2002, the country was preparing its Mid- to Long-term Plan of Science and Technology Development (2006–2020). We proposed that quantum control (manipulation) be included as a major research program. It was indeed included in the Plan: together with protein science, nanoscience, and developmental/reproductive biology, it constitutes one of the four major programs announced at the beginning of 2006.

Right after that, the US Department of Energy issued a report in 2007 on ‘Directing Matter and Energy: Five Challenges for Science and Imagination’, which identified technologies for manipulating electrons, atoms, and molecules as the most exciting pioneering areas for the 21st century. The report posed five grand challenges: control of materials at the level of electrons, synthesis of materials with tailored properties, complex correlations and emergent properties, nanotechnologies with capabilities rivaling biology, and characterization and control of matter far from equilibrium. This report provided us with very useful guidance and suggestions. In parallel, the National Research Council of National Academies has issued the AMO (Atomic, Molecular and Optical Sciences) 2010 Committee report on ‘Controlling the Quantum World’, describing how quantum manipulation may affect the areas of atoms, molecules, and optics. I think these two reports are excellent and in retrospect very insightful.

NSR: What is the main focus in quantum manipulation?

Yu: There are two types of research in quantum manipulation: one focuses on small quantum systems, meaning individual particles like atoms and molecules, while the other looks at quantum materials, such as the topological insulators, unconventional superconductors, colossal magnetoresistance materials, etc. In non-interacting systems, the basic structural unit is identical to the moving unit, but this is not true in quantum materials, because of interactions among particles. Based on our experience in superconductivity research, we can anticipate that quantum materials are highly complex and can exhibit exciting and diverse emergent phenomena.

NSR: Are there any special characteristics of quantum manipulation research in China?

Yu: China is actively pursuing research for both small quantum systems and quantum materials. Jian-Wei Pan’s team at University of Science and Technology of China (USTC) is doing top-level research in quantum information based on small quantum systems. After receiving his Ph.D. training in Austria, Pan realized that cold atom techniques are very important to quantum manipulation. He decided to continue his research in Germany and nurtured a group of young physicists there, while building his laboratory during 2003–2008 in USTC. Later, these young
physicists joined him at USTC through CAS recruitment programs, now forming a very competitive team in the international scene.

During this process, CAS provided Pan’s team with very strong support, much more than what is possible in Europe. Of course, he has met expectations, having made a series of important breakthroughs, including the experimental realization of a ‘Schrödinger’s cat’ state for eight photons and the use of eight-photon entanglement to realize topological quantum entanglement. Pan’s team is leading the CAS’s Pioneering Strategic Research Program in space science. They will launch the first ‘Quantum Science Experimental Satellite’ soon, which will realize high-speed satellite-land quantum communication. Pan’s research has promoted the development of other areas. For example, Jiang-feng Du, a young scientist at USTC, is now doing pioneering work on electron and nuclear spin imaging.

The progress in quantum materials research in China has also attracted lots of attention from the international community in recent years. Quantum materials are systems composed of large numbers of interacting atoms and molecules that exhibit macroscopic quantum effects. We call these effects emergent properties, since they are not present when we consider the constituents individually. This is similar to the emerging properties we observe in biology when moving from a lower to a higher level of organization. The understanding of emergent properties of quantum materials, such as superconductivity, has been one of the most important developments in quantum physics, making a strong impact on particle physics and cosmology.

SUPERCONDUCTIVITY: CHINESE EXPERIENCE

NSR: Research on high-temperature superconducting materials has long been an active area in China. Why is that?
Yu: Although superconductivity was discovered by the Dutch scientist Heike Kamerlingh Onnes in 1911, it was not until 46 years later, in 1957, that a microscopic theory of superconductivity—the BCS theory—was established. Following that, there was a boom in superconductivity research, which anticipated that there would be a substantial rise in the transition temperature (Tc) and consequent large-scale applications. But the pace of progress remained relatively slow for a long period, in both theory and experiment.

In the CAS Institute of Physics, the team of Zhong-xian Zhao independently discovered in 1987 materials that superconduct at liquid-nitrogen temperatures, which earned international attention. However, since the 1990s there has been no breakthrough in our understanding of the mechanism and structural principles of high-Tc superconducting materials, and the rise of transition temperature has remained slow. Many scientists in the US and other countries have given up research in this area or have shifted their main focus elsewhere. There was even a period in the US when most applications to NSF funding in superconductivity research were denied. Fortunately, research in this area continued in China and the government remained supportive. This is why in 2008 there was a sudden emergence of iron-based superconductivity research in China.

NSR: The research team responsible for iron-based superconductors received the First Prize in Natural Sciences in China, which has been vacant for many years and created quite a sensation. Can you recount how this discovery happened?
Yu: The Japanese scientist Hideo Hosono was the first to discover high-Tc superconductivity in iron-based materials. Hosono was a materials scientist studying organic electrodes, not superconducting materials, and thus he made a ‘cross-disciplinary’ discovery. This discovery was quite a surprise, because iron is magnetic, and past experience tells us that magnetism disrupts superconductivity. Hosono’s discovery of iron-based materials that superconduct at 26 K was announced by the Japanese media before his paper was published. A young researcher, Gen-fu Chen from IOP Nan-lin Wang’s group, happened to be in Japan some time ago, and he understands Japanese. Grasping this opportunity, Wang’s group quickly started researching these materials in China. Within one week, the material was synthesized in the Institute and a paper...
reporting the result was put on the Internet, triggering a new wave of interest in high-T_c superconductivity in which the transition temperature was raised repeatedly. Later, Zhong-xian Zhao’s team raised the temperature to 55 K by applying pressure to the material. This remains the record transition temperature for iron-based superconductors. All this happened within a period of a few weeks, during which people worked day and night. Science magazine once commented that iron-based superconductivity research has put Chinese research at the forefront of this area. Zhao and colleagues have also received high honors, quite deservedly.

I should note that without government’s continuous investment and the persistent effort of researchers in this area, it would not have been possible for the Chinese team to reach this pioneering position quickly in 2008. Over the past decades, the total support for superconductivity research in China was in fact higher than that in the US and UK. This steady support is critical for researchers to have peace in mind while focusing on their work.

NSR: Did the Chinese accomplishments in superconducting materials attract more international collaboration?

Yu: Indeed. I mentioned the period when superconductivity research in the US was stagnant. Realizing the progress in China, the US began actively pursuing collaboration with China. In 2010, Harold Weinstock of US Airforce Office of Scientific Research (AFOSR) proposed and co-sponsored with Zhong-xian Zhao the first ‘China-US Bilateral Meeting on Exploration of Superconductivity Materials’ in Beijing. Two more meetings were held in Santa Barbara and Hong Kong in subsequent years.

In addition to the AFOSR, the US Department of Energy (DOE) also proposed collaboration with China. This is quite unusual, since over the preceding decades US has always been exporting knowhow to Chinese high-energy physics. But in the case of superconductivity, China is on equal footing in the collaboration. Harriet Kung of the DOE once said that she hopes the collaboration might lead to a shared Nobel Prize for Chinese and US scientists.

Since 2002, the CAS Institute of Physics, the CAS Institute of Theoretical Physics and Tsinghua University have sponsored the ‘Beijing Forum on High-Temperature Superconductivity’ each year (with only one year of interruption due to the SARS outbreak), attracting a large number of international scientists in this area. These meetings have established an effective format of communication that consists of mainly discussions, and served a useful function in elevating the research. Editors of Nature Materials often attended these meetings, and their influence is increasing.

NEW WORLD OF TOPOLOGICAL MATERIALS

NSR: Besides new superconducting materials, topological insulators appear to be a major research focus in recent years.

Yu: Indeed. I noticed that NSR already had a special topic on this subject. The study of topological properties began with the discovery of the quantum Hall effect in the 1980s. Topological insulators opened a new area in condensed-matter physics, in which the concepts of Landau-Fermi liquids no longer apply. Scientists began to search for new theory to explain this regime.

Many Chinese scientists have made seminal contributions in this area. For example, Shou-cheng Zhang of Stanford University successfully predicted the existence of two-dimensional materials for topological insulators, which were soon confirmed by experimentalists in Germany. Zhang has been quite active in collaborating with Chinese scientists. Calculations made by the CAS Institute of Physics’s Zhong Fang and Xi Dai, in collaboration with Zhang, predicted the most important three-dimensional topological insulators in the family of Bi_xSe_y compounds. Soon afterwards they realized that these three-dimensional topological insulators, when doped with magnetic materials to break time-reversal symmetry, would be an ideal material for observing the quantum anomalous Hall effect (QAHE). After this work was published, many scientists around the world began to compete to be the first to observe this phenomenon. In 2013, after growing and measuring over 1000 samples, the team led by Qikun Xue at Tsinghua University succeeded in producing rather complicated (quaternary) topological insulators with 3D magnetically ordered chromium (CrBiSbTe), and observed a clear quantum anomalous Hall effect.

Looking back, the path to this discovery was not straightforward. In the beginning, Duncan Haldane of Princeton University predicted that one may find an anomalous Hall effect in a honeycomb lattice like graphene that breaks the time-reversal symmetry. But that could not be realized at the time. Later, several different proposals were made to observe the QAHE, including various combinations involving topological insulators. Although Zhong Fang and colleagues predicted the 3D material for potential discovery, it was very difficult to prepare and study ideal materials. There were many failures, but experimentalists trusted that the theoretical calculations were correct. The success of this project is a good demonstration of a new paradigm in condensed matter physics: theorists work in very close collaboration with sample growers, making precise predictions of what is the most promising material in which to look for new phenomena, and with experimentalists advising them on what kind of results they should anticipate.

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The measurement of the quantum anomalous Hall effect requires extremely high precision at low temperatures, and it happens that only Li Lv’s group at the Institute of Physics could cool the electron temperature to 4 mK. This is clearly top technology in the world. Although the QAHE does not require such ultra-low temperature, the ultra-low noise level was the key element for high-quality data. There was an interesting episode in the story. When the paper by Xue’s team was submitted to Science, the reviewers originally did not believe it, but finally became convinced when the original raw data were shown to them.

Topological materials is now a hot area around the Globe. Besides quantum anomalous Hall effect, the latest advance in China is in the area of topological semi-metals. In these 3D Dirac systems the Fermi level is located right at the Dirac cone top, but usually electrons of opposite chiralities are degenerate. By breaking the translational or other symmetries, this degeneracy is removed, and the Weyl fermions with right and left chiralities become independent of each other, leading to a number of exotic phenomena like giant magnetoresistance (a counterpart of the chiral anomaly in particle physics). In designing, making and precisely characterizing the Weyl semi-metals, the Chinese team again took the lead, through fruitful collaborations between theoreticians, materials scientists and experimentalists. Due to topological protection, the scattering between two opposite Weyl electron states is weak, so electron transfer can be realized at extremely low energy cost. This is a curious new phenomenon in condensed-matter physics, with potential applicability in the design of future room-temperature electronics with low energy cost.

CULTIVATION OF RESEARCH TALENT

NSR: It seems that progress in condensed-matter physics in China, either in the hard time of the 1960s or in the present relatively affluent climate, depends on a group of scientists who are fully devoted to basic research.

Yu: This is true. Over the past decades, our Institute had established a tradition of paying attention to the cultivation of young physicists, with a mentoring system in which elder physicists actively help the younger researchers to develop. As pointed out recently by Premier Li Keqiang when he visited our institute, basic research requires the investigators to have persistence, devotion, and an ability to dive deeply into fundamental problems without distraction. Providing an environment that allows the investigator to pursue their science without worrying about nonscientific matters is a prerequisite for making innovation and breakthrough in basic science.

Since returning to China full-time, I have established close interactions with physicists of all ages. I do not manage a research team myself, so there is no issue of competition for resources with others. My role has been to help younger scientists to pursue their interest and to realize their potential. As I have often said, I am the head of the cheerleaders.

BIG SCIENCE FACILITIES AND INTERNATIONALIZATION

NSR: What are the forthcoming big science projects in physics?

Yu: Modern astronomy and physics have become increasingly dependent on big facilities, requiring large investment by the government, and China is moving steadily towards building up big facilities. In the 12th five-year plan (2011–2015), sixteen large science facilities were planned. These include specialized facilities such as high-energy particle accelerators and telescopes, as well as general-purpose facilities—the most useful one is the Shanghai Light (Synchrotron Radiation) Source. A neutron spallation source is also under construction. Beijing is prepared to establish a comprehensive research center around a new Synchrotron Radiation source with higher energy than that in Shanghai. Our Institute plans to install in this Center general-purpose facilities for research in extreme conditions, including strong magnetic fields, ultra-low temperatures and high-power lasers. The Institute of Biophysics of the CAS will also incorporate bioscience equipment.

NSR: Large investments on general purpose facilities could be justified, but how about further internationalization?
The success of this project is a good demonstration of a new paradigm in condensed matter physics: theorists work in very close collaboration with sample growers, making precise predictions of what is the most promising material in which to look for new phenomena, and with experimentalists advising them on what kind of results they should anticipate.

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Yu: I think we need to make much bigger steps in international collaboration. Instead of building very large facilities by ourselves alone, we need to devote more resources directly to international big science facilities, in particular accelerators and telescopes. Furthermore, our institutes are not sufficiently internationalized in either their hardware or software. Take our institute, for example: we have many top visiting scientists, but few are willing to stay here for long-term collaboration. We need to build an environment that facilitates sustained international collaboration.

NSR: You have worked in the International Center of Theoretical Physics (ICTP) at Trieste for many years. Do you think the presence of ICTP has had a major influence on scientific development in Italy?

Yu: Yes, definitely. Condensed-matter physics in Italy used to lag far behind, but now it is first-rate. Through the influence of Abdus Salam, ICTP attracted a large number of scientists to study, work, or visit Trieste, greatly facilitated the development of Italian physics. I think China now has the economic capability to establish such an international center. This will greatly promote scientific development in the Asia-Pacific region.

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