A case study of a world-class research project accomplished in China: discovery of the quantum anomalous Hall effect

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INTRODUCTION

China has achieved very impressive economic growth in the past three decades, but this success is unlikely to continue unless future economic growth is based on technological innovation, derived from strong and sustainable basic research. The Chinese leadership has clearly recognized the need for the development of world-class research universities and the need for a thorough reform of its science and technology (S&T) administrative and funding systems [1].

As part of a project to study the evolution of the leading Chinese universities, we here focused our attention on a specific case of a recent scientific discovery—the Quantum Anomalous Hall Effect (QAHE)—by a multi-institutions research effort led by Qikun Xue at Tsinghua University, who won the Future Science Prize for physical science (http://gbtimes.com/china/chinese-scientists-win-inaugural-future-science-prize) following his ground-breaking discoveries in QAHE. The discovery of the QAHE in thin films of chromium-doped (Bi,Sb)₂Te₃ provides another classic example demonstrating how a lab-created new material can make a significant contribution to condensed matter physics [5].

From this perspective, we analyse the QAHE discovery process, with the focus on the emerging research culture in post-Cultural-Revolution China, explore how an effective research leader can mobilize all relevant resources toward one common goal, and discuss how reform in China’s S&T administration and funding may facilitate similar scientific breakthrough and innovation.

BACKGROUND

Condensed matter and materials physics

In modern condensed matter and materials physics, scientists study the phenomena that arise from a large number of interacting atoms and electrons, reflecting the collective behavior of the assemblage. Novel phenomena are often observed through studies of new artificially structured materials and new experimental tools, which also push the boundaries of theoretical understanding, as shown in Fig. 1. Since the birth of the transistor in 1947 at Bell Labs, the field of condensed matter and materials physics has spawned many Nobel Prizes in the physical sciences and has created a technological revolution [2–4].

The discovery of the QAHE in thin films of chromium-doped (Bi,Sb)₂Te₃ provides another classic example demonstrating how a lab-created new material can make a significant contribution to condensed matter physics [5]. Theoretical studies contributed by other groups also provided the essential stimulus for fabricating the growth of perfectly layered materials that in turn requires the state-of-the-art diagnostic experimental instruments.

The Hall effect family

The ordinary Hall effect discovered by American physicist Edwin R. Hall in 1879 was a phenomenon in which the voltage drops across a conductor transverse to the applied electrical current in the conductor with a magnetic field perpendicular to the current. Hall tried similar experiments on ferromagnetic materials and observed that the Hall resistance shows an unusually large slope at a low field—a phenomenon known as the anomalous Hall effect. In 1980, German physicist Klaus von Klitzing observed the steps in the Hall voltage–current relationship in a 2D Si/SiO₂ field effect transistor in a strong magnetic field [6]. These steps, which showed quantization of the Hall conductance, were a major scientific discovery and led to the Nobel Prize in Physics 1985 (http://www.nobelprize.org/nobel-prizes/physics/laureates/1985/).

In high-mobility 2D electron layers confined at the interface of GaAs/AlGaAs, Horst L. Störmer, Daniel C. Tsui and Arthur C. Gossard observed that, in a very high magnetic field and low temperature, the quantization of the Hall plateaus occurred at fractional values of the electronic charge, whose theoretical origin was provided by Robert B. Laughlin [7,8]. For their work, Robert B. Laughlin, Horst L. Störmer and Daniel C. Tsui shared the Nobel Prize in Physics in 1998 (http://www.nobelprize.org/nobel-prizes/physics/laureates/1998/).
These milestone discoveries made the quantum Hall effect one of the most important fields in modern condensed matter physics. A quantized version of the anomalous Hall effect, namely the QAHE, represents the realization of the quantum Hall effect in the zero magnetic field, which has long been sought after.

The project leader

The chief leader of the QAHE project, Qikun Xue at Tsinghua University, received his B.S. education at Shandong University from 1980 to 1984, and M.A. and Ph.D. education at the Chinese Academy of Sciences (CAS) from 1987 to 1994. After serving as a research associate at Tohoku University, as well as a visiting assistant professor at North Carolina State University from 1994 to 1999, he joined CAS in 1999 and moved to Tsinghua University in 2005. The first college entrance examination, resumed in late 1977 after the end of the Cultural Revolution, was based on the historical speech by Deng Xiaoping (then Vice Prime Minister) at the opening ceremony of the National Conference on Science, emphasizing the importance of science, technology and education to China’s development. Thus, Xue is among the first generation of the Chinese scientists who received complete B.S.-to-Ph.D. education in China in this new era.

Personnel, equipment and funding

Before launching the QAHE project, Xue had already formed a team of people with the necessary technical expertise to operate the complicated facilities and obtained adequate research funding. The entire discovery process lasted over four years, involving more than 10 professors and 20 Ph.D. students from four academic institutions in China and the USA. Former Ph.D. students and research associates of Xue, including Ke He, Lili Wang, Shuaihua Ji and Xucun Ma, have all played important roles in this project.

In the realm of modern physics, the rate of scientific progress is largely determined by the advance in experimental technologies. The tools to grow artificially structured materials that made the discovery of the QAHE possible are Molecular Beam Epitaxy (MBE), Angle Resolved Photoemission Spectroscopy (ARPES) and Scanning Tunneling Microscope (STM). MBE was invented in the late 1960s at Bell Laboratories. It relies on in situ characterization of surfaces and interfaces during the growth process. The STM, invented in the early 1980s at IBM Zürich Research Laboratories, allows imaging of surfaces at the atomic resolution (http://www.nobelprize.org/nobel_prizes/physics/laureates/1986/).

ARPES enables direct observation of the Fermi surface and underlying electronic structure of crystals. It is a tour de force to integrate these three milestone instruments of modern condensed matter and materials physics for controlled materials growth because they are available in only a few laboratories worldwide and extremely difficult to operate.

Xue’s team originally focused on STM-related studies, a field distant from the QAHE, but team members were encouraged to explore new research topics. In 2008, several studies on topological insulators (TI) and quantum spin hall phase caught the attention of a Ph.D. student, Yaoyi Li, who pointed out that ‘the materials described in the theory are similar to ours, it is so exciting that some big physics can be discovered in these materials’. A few months later, another theoretical study predicted that 3D TI could be found in Bi$_2$Se$_3$, Bi$_2$Te$_3$ and Sb$_2$Te$_3$ systems [9]. The corresponding author, Shoucheng Zhang at Stanford University, is internationally recognized for his theoretical contribution in TI. Being adventurous with scientific intuition, Xue’s team decided to step into this new field.

Existing expertise

In the study of the QAHE, as well as in the study of many other sub-fields of modern condensed matter physics, including superconductivity and magnetism, scientists always emphasize the importance of materials. The key challenge for the QAHE is to grow the required material with absolute purity—the exact 2:3 mixing ratio of Bi and Te for making Bi$_2$Te$_3$. For a cluster of 1 million molecules, there should be exactly 0.4 million Bi molecules and 0.6 million Te molecules. With 20 years of experience in synthesizing various materials, Xue’s team was able to successfully establish a strategy for cultivating Bi$_2$Te$_3$ that satisfies the requirement of the precise mixing ratio. Many teams worldwide were in the quest of growing the same material with various techniques. This time, Xue’s techniques, which were developed in a very different field, proved to be highly competitive in the TI studies.

Collaboration for theoretical guidance

In June 2009, Xue reported his initial result, ‘ARPES and STM Study of Bi$_2$Te$_3$ Topological Insulators on Si Prepared by MBE’, at a conference on ‘TI' and initiated collaboration with multiple
theorists, particularly Shoucheng Zhang, who had been seeking collaboration with experimentalists in order to realize the QAHE. With the theoretical support, a series of significant results on TI were obtained, prior to the experimental discovery of the QAHE.

Collaboration for transport measurement

Transport measurements essential for observing QAHE requires the capability of making measurements as a function of temperature. Yayu Wang, an expert on transport measurements, happened to join the Tsinghua faculty in 2007 and was invited to participate in the QAHE project. The two laboratories established close interaction by holding joint group meetings and regular communication among students, with the free flow of ideas becoming a distinct part of the research culture.

Collaboration for extreme temperature

The transport measurements showed a signature of the quantization of the anomalous Hall effect in October of 2012. The available measurement temperature could not be lowered enough to see the full quantization of the anomalous Hall effect. The third team, led by Li Lu from CAS, a long-term friend of Xue, was invited to contribute. The friendship was an important basis for their collaboration, providing mutual trust and expectation for a fair distribution of the credit. Within two months, the QAHE was successfully observed and soon reported in Science magazine in an article entitled ‘Experimental observation of the quantum anomalous Hall effect in a magnetic topological insulator’ [5].

The credit of this important discovery was eventually shared among more than 20 authors from three institutions: Tsinghua, CAS and Stanford. Three professors were listed as corresponding authors, and four students as co-first authors.

The collaboration network continues to expand after the discovery of the QAHE. Xue’s team has already entered the superconductivity field with experimental techniques, despite the fact that his team had little previous experience in this field. The challenge is still to artificially grow the perfectly structured new materials. Their recent achievement on interface-enhanced high-temperature superconductivity in the FeSe/SrTiO3 heterostructure in 2012 was regarded as the most exciting discovery in iron-based high-temperature superconductors in the last five years, acclaimed to have opened ‘A New Frontier for Superconductivity’ [10,11].

LESSONS FROM THE QAHE PROJECT

R&D expenditure

For experimental physical sciences, the resource requirements can be extensive, involving access to substantial expensive equipment. The cost of the QAHE project (four sets of equipment in Tsinghua and CAS, and the operation cost) is in the range of 35 million RMB. With very impressive economic growth in the past three decades, China’s gross domestic spending on R&D has increased dramatically since 2000 and had exceeded $344 billion by 2014 (https://data.oecd.org/rd/gross-domestic-spending-on-r-d.htm). It would have been inconceivable that China could support scientists to conduct these capital-intensive scientific explorations in the 1980s and 1990s. China’s strong economy provided a necessary external condition for Xue’s success. Assuming that China could maintain its high GDP growth rate and raise the gross R&D intensity to an even higher level, many more ground-breaking research achievements may appear, with the premise that the allocation mechanism is efficient: sufficient funding flows to the right people [12].

Flexibility

Given the nature of uncertainty in scientific exploration, scientists should be able to adjust their own research directions according to their interest and judgments on the ever-changing research frontier. Xue’s 973 Project was not funded to support the QAHE project. The provision of research funding should not prevent scientists from adjusting their research direction in the course of the project. In China, such an adjustment mechanism is becoming relatively common after the nearly 20-year practice of the 973 Program, particularly for experienced PIs like Xue. This was not the case for most other major national research programs, including those funded by the Natural Science Foundation of China, another major funding agency for fundamental research. In the last few years, there were many discussions about how to provide scientists with more flexibility in adjusting the use of funds while ensuring accountability of expenditure. In response to the widespread complaints, the government recently announced a major policy that gives PIs much more latitude in using research funds (http://news.xinhuanet.com/tech/2016-07/31/c_1119311230.htm).

Risk

The progress of S&T happens in many ways: step-by-step advances building on previous discoveries often lead to unexpected breakthroughs, great advances may also arise through innovation in the theoretical front, invention of new instruments may allow scientists to ‘see’ what could not be seen before and new design of engineered materials may reveal unexpected behaviors. However, there is always high uncertainty in the scientific frontier; taking the risk of failure is a prerequisite for making breakthrough discoveries [13,14]. In fact, throughout the process that led to the discovery of the QAHE, the thought of terminating the experiments had occurred multiple times, due to the fact that the team members felt that the experimental goal appeared to be impossible to reach. It was the audacity of the team leaders in taking the risk that finally led to the discovery.
Leadership

For a research team to excel, it must be led by a visionary leader with excellent managerial as well as scientific/technical abilities. The team leader must recognize the change in the status of research and restructure the team accordingly. The leader must have strong people-management skills and create an environment where people know the boundaries and are able to push the frontier. The leader must be able to diagnose the capability limit within his team and know how to build collaborations. Xue’s team made the initial thrust, but the experiment could not be completed within his laboratory. Collaboration with others was the key to his success. The long-term friendship among the PIs was the foundation for this multi-institution collaboration. Moreover, Xue served as the director for the State Key Laboratory for Surface Physics at CAS and was familiar with the administrators at both Tsinghua and CAS. This unique experience permitted him to coordinate the resources on both sides efficiently and settle the disputes when they occurred.

CONCLUSION

In a different context, one of the authors of this study has described the design of radically innovating institutions [18]. Above all, they require visionary leadership, a strategic plan with targeted investments in selected areas to build critical mass, stable funding, and a culture of transdisciplinary research that bridges disciplines and the basic–applied dichotomy, with a delicate balance between freedom and focus. As China embarks on creating world-class research institutions, the lessons learned from this initial foray in developing a world-class effort in condensed matter physics over the last decade at Tsinghua are instructive. Breakthrough research resulted from a collaboration that began with Xue’s targeted recruitment of key individuals from CAS in an effort to build a critical mass of researchers who spanned different but related areas of condensed matter and materials physics. Key ingredients included recruitment of a leader (e.g. Xue) with support from the highest level of the university (e.g. Tsinghua’s President), significant and stable multiyear funding, a world-class instrumentation infrastructure, ability to recruit other faculty members of the team, and allowance for the team to adjust its stated research direction and build a supportive culture as new opportunities arose. It took a leader who encouraged other members of the team, who was willing to share credit and who worked to facilitate a culture of support in a climate of excellence. In some ways, this example is reminiscent of how UCSB transformed itself via strategic recruitment from leading industrial research laboratories (e.g. Bell Laboratories) and in selected areas of physics, applied physics, materials science and engineering and the support of federal funding agencies that wanted to foster a research culture that crossed boundaries.

The case study reported here is a microcosm of what needs to be further developed. Similar endeavors need to be initiated in other areas of sciences and engineering, e.g. applied physics, electronic materials and electrical engineering, soft materials chemistry and chemical engineering, structural materials and mechanical engineering, and so on. In order to address societal grand challenges, this culture will need to flower more broadly. Wider engagement with social sciences and professional schools will need to be fostered to bridge theory and practice. This will also require changes in governance structures, recruiting and faculty reward structures, with proper application of the greatly enhanced faculty reward structures, with proper application of the greatly enhanced.

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