The laureate of the China State Preeminent Science and Technology Award: Qi-Kun Xue

Junqi Yang
Department of Physics, Huazhong University of Science and Technology
Wuhan 430074, China
December 30,2024

***Abstract*—This article focuses on Professor Qi-Kun Xue, a prominent Chinese physicist who was awarded the China State Preeminent Science and Technology Award for his significant contributions to topological materials and the Quantum anomalous Hall (QAH) effect. The article is written for a course on the history of physics, Huazhong University of Science and Technology.**

Keywords: Qi-Kun Xue, Quantum anomalous Hall effect, quantum Hall effect, Magnetic topological insulator.

I. Introduction

In 1988, F. D. M. Haldane team proposed the theoretical foundation for QAH [1]effect in his paper [2], introducing a new theoretical model for the quantum Hall effect (QHE) [3] that does not rely on traditional Landau levels (LL). This differs from the earliest explanation of the QHE, that electron transitions between these LL result in quantized Hall conductance [3].The model proposed by Haldane can simulate a similar quantization of conductance by introducing an effect known as the "parity anomaly". [2]

In 2009, Haijun Zhang team's paper [4], which discusses three types of topological insulator materials, whose surface states not only exhibit strong topological protection but also remain stable under low-temperature conditions. This research lay the foundation for the study of the QAH effect in magnetic topological insulators (MTI).

In Hasan, M. Z. and Kane, C. L. team's paper [5], they discuss the experimental observation of the QAH effect in MTI. The QAH effect is a form of QHE which occurring in the absence of an external magnetic field. The article introduces the uniqueness of the QAH effect in topological insulators, particularly how quantized Hall conductance can be achieved without the application of an external magnetic field. The study shows that MTI can spontaneously generate the QAH effect.

In 2010, Rui Yu team's paper [6] declared that the surface states of topological insulators exhibit unique properties due to spin-orbit coupling. In conventional topological insulators, the observation of the QHE relies on an external magnetic field. Researchers aimed to realize the QAH effect in MTI, which would occur without the need for an external magnetic field.

The research team employed techniques such as Scanning Tunneling Microscopy (STM) and Angle-Resolved Photoemission Spectroscopy (ARPES) to investigate the surface states and electronic structures of the materials. These methods verified whether the material could perform QAH effect in the absence of an external magnetic field. This experiment confirmed that in the MTI can realize the QAH effect in the absence of an external magnetic field. The results offer valuable guidance for the design and performance optimization of topological quantum materials.

And then it comes to Qi-Kun Xue team's work in 2013, we will only give a brief introduction to this article, as its content will be discussed in detail in the main body of this article. The paper [7] reviews the basic principles of the QHE. The key idea of the study is in how spin-orbit coupling and intrinsic magnetism inside of the MTI work together to realize the QAH effect.

The main body of the article will begin with a review of Qi-Kun Xue's life and academic career.

Secondly, we will introduce Qi-Kun Xue team's work, especially first-time experimental observation of the QAH effect. As the Nobel laureate Yang Chen-Ning said, "The results achieved by Qi-Kun Xue's team are Nobel-level experimental achievements, as recognized by other physicists. "Qi-Kun Xue's work has provided theoretical support for cutting-edge fields such as quantum computing and quantum communication.

Subsequently, the article will summarize Qi-Kun Xue's personal experiences, and will explore the reasons behind his outstanding contributions. The article will also highlight the lessons that can be learned from his career.

Finally, the article will discuss the current research teams in the field of quantum materials and related areas, and will forecast the potential applications of quantum physics in future technological advancements.

II. MAIN BODY

A. The life and career of Qi-Kun Xue

In 1963, Chinese physics seemed to be still stuck in the darkness before dawn. As we all know, at that time, New China, as a rising sun, had been established for less than fifteen years. That winter, Qi-Kun Xue was born in a small village in Linyi, Shandong Province.

Coming from a poor family, with hardworking parents who worked day in and day out, he was the son of ordinary farmers. However, for this generation of Chinese youth, the journey of "growing up with the motherland" seemed destined to be particularly "earth-shattering".

In his teenagers, Qi-Kun Xue was described as "playful, smart, and also passionate about learning." He performed extraordinarily in academic when he was young. During the Chinese College Entrance Examination, he scored 99 out of 100 in physics, and was successfully admitted to the Laser Technology program in the Department of Physics at Shandong University.

In 1984, Qi-Kun Xue graduated from university with great ambition and decided to pursue profound studies, but challenges came unexpectedly. He failed to pass the graduate entrance exam first time. He then began teaching at Qufu Normal University. While teaching in Qufu Normal University, he attempted the exam a second time, but again failed to pass the graduate entrance exam. Reflecting on his failure, he realized,"I was still unprepared, not steady enough, and relied on clever tricks."

Determined to try again, he made a third attempt at the graduate entrance exam. In 1987, he was finally admitted to the Condensed Matter Physics major at the Institute of Physics, Chinese Academy of Sciences. After completing his Master's degree, Qi-Kun Xue chose to continue his doctor's studies. In 1992, through the recommendation of his advisor, Professor Lu Hua, he went to the Institute for Materials Research at Tohoku University in Japan for further study and research work. It was there that he met another challenge in his scholar career. During his time in Japan, Qi-Kun Xue worked in the laboratory of his Professor Toshio Sakurai, which was known as the "7-11 Laboratory." The lab had a strict schedule: students work six days a week, and everyone had to arrive before 7 a.m. and could not leave before 11 p.m. "Every day we just do three things: eating, sleeping, and doing research." Because of his diligence and resilience, despite the challenges of "language barriers, unfamiliar techniques, and lack of sleep", Qi-Kun Xue managed to overcome these barriers. After overcoming the adaptation period, Qi-Kun Xue became the first to arrive at the laboratory each day and the last to leave. In just a year and a half, Qi-Kun Xue made a significant breakthrough in his research field, which was the most groundbreaking achievement in Professor Toshio Sakurai's lab in nearly 30 years. The "7-11" routine has continued to this day also.

From 1992 to 1999, Qi-Kun Xue spent eight years studying and serving as a visiting assistant professor at Tohoku University in Japan and the North Carolina State University.

However, being far away from home, Qi-Kun Xue still care about his hometown. " I am just a little boat sailing out from Yimeng Mountains," he said. He was deeply concerned about the significant gap between Chinese and foreign physics laboratories. He said: "I hope that through my efforts, our country's science and technology can become exceptionally strong, and that our people can live very happy lives."

In 1999, Qi-Kun Xue returned to China. He joined the Institute of Physics, Chinese Academy of Sciences.

In 2005, Qi-Kun Xue moved to the Department of Physics at THU, where he established a research team composed of members of various ages and backgrounds. In November of the same year, he became the youngest "new academician" of the Chinese Academy of Sciences in that batch.

The first machine built by Qi-Kun Xue's team in THU's laboratory combined three technologies: Molecular Beam Epitaxy (MBE), STM, and ARPES. They were the only team have the realization and capability to integrate these technologies.

Two or three years after the establishment of the laboratory at THU, research on topological insulators became a tendency. With the suitable experimental tools and the foundation of prior scientific research, Qi-Kun Xue's team, having "prepared well in every aspect," immediately seized the opportunity and delved deeply into this field. In 2008, Ethnic Chinese physicist Shoucheng Zhang proposed the possibility of realizing the QAH effect in MTI. However, finding suitable materials for this phenomenon was an immensely challenge.

Despite not knowing whether the experiment would succeed, Qi-Kun Xue decided to aim for this "one of the best and highest scientific goals"—the QAH effect.

Starting in 2009, Qi-Kun Xue, together with research teams from THU, the Institute of Physics at the Chinese Academy of Sciences, and Stanford University, try to overcome these challenges together. "If one path doesn't work, we will improve the method. If it still doesn't work, we will keep improving."

In just over four years, Qi-Kun Xue's team achieved "one of the best in the world" in areas such as material preparation, control, and using the scanning tunneling microscope to control material.

After studying more than 1000 atomic-level samples, Qi-Kun Xue's team finally discovered MTI film that met the requirements. In the evening of October 2012, they observed signs of the QAH effect in their experiments.

Upon receiving the exciting news, Qi-Kun Xue, who had just left the laboratory, rushed back to organize the team to design a plan. They needed to measure the perfect QAH effect and ensure it could be retested in different samples. After two months testing, the experimental data was perfect.

On the day the final data was obtained, Qi-Kun Xue's tram celebrate the "miracle moment" with his team and students. This marked the first-time experimental observation of the QAH effect in the world, making an important contribution to fundamental physics research.

B. Introduction to the main work of Qi-Kun Xue

At the end of 20th century and the beginning of the 21st century, there were several areas such as Quantum Computing and Quantum Information, Condensed Matter Physics, Nanotechnology and Material Physics. Under the background, Qi-Kun Xue has followed the trends of the times and keep mind of the development of fundamental physics in China. Qi-Kun Xue making outstanding contributions in the fields of topological insulator materials, condensed matter physics, and quantum physics.

In 1988, F. D. M. Haldane introduced the concept of "topological insulators" and defined the fundamental characteristics of topological phase transitions and topological states of matter [2]. This provided the theoretical foundation for the subsequent development of topological insulators.

In 2009, Hai-jun Zhang team's paper, discussed topologically protected surface states. The experiments, verified by ARPES, provide important support for the study of topological phases.

Then it comes to 2013, Qi-Kun Xue's team paper reported the experimental observation of the QAH effect. The paper firstly reviewed the fundamental principles of the QHE. Since the QHE typically requires an external magnetic field, while the QAH occurs in the absence of the external magnetic field. Researchers aim to achieve the QAH effect in topological insulators without external magnetic field by placing intrinsic magnetism into the material.

The team utilized MBE growth method and co-evaporation to realize the growth of Cr-doped $(BixSb_1-x)_2Te_3$ films on $SrTiO_3$ substrates. During the growth process, the fluxes of SbSb and Bi in the film needed monitored. The fluxes of Sb and Bi were calibrated by the growth rates of Sb_2Te_3 and Bi_2Te_3 thin films, through intensity oscillation of reflective high energy electron diffraction or quantum-well state peak positions in ARPES. [8], [9] By replacing components in the MBE chamber, modifying the surface treatment conditions of the $SrTiO_3$ substrates, and carefully adjusting the thickness and composition of the Cr-doped $(BixSb_1-x)_2Te_3$ films, the sample quality was significantly improved. These efforts led to larger terraces, reduced bulk carrier density, and higher mobility, which in turn resulted in larger anomalous Hall resistance and lower longitudinal resistance. These parameters explain how the sample quality was improved.

The second part of the paper briefly explains the relationship between the Hall resistance and carrier density in Cr-doped (BixSb1-x)2Te3. This relationship is discussed based on previous work [10]. By this relationship, through measurements of the Hall coefficient RH, carrier density, and Hall resistance in different directions we can interpret the material's charge transport properties, and further determine the occurrence of the QAH effect.

The research team conducted detailed electrical transport measurements on the magnetic topological insulator Cr-doped $(BixSb_1-x)_2Te_3$ films and found that when the temperature was lowered to very low levels (30 mK), the sample exhibited quantized Hall conductance in the absence of an external magnetic field. This phenomenon is a direct confirmation of the QAH effect. The quantized Hall conductance is reflected in the quantized Hall resistance, indicating that the material exhibits properties distinct from the conventional Hall effect. Furthermore, this phenomenon is not driven by external magnetic field but results from the interaction between the material's intrinsic magnetism and spin-orbit coupling.

The experimental confirm the existence of the QAH in MTI, showing that this effect can be achieved without an external magnetic field. This discovery not only provides significant experimental support for quantum physics but also lays the foundation for future applications in quantum computing, quantum communication, and other related technologies.

Qi-Kun Xue, as the first contributor, was awarded the 2018 National Natural Science Award. Qi-Kun Xue is also the first Chinese scientist to receive the highest international award in low temperature physics, the 2020 Fritz London Memorial Prize, and the 2024 Oliver E. Buckley Condensed Matter Physics Prize, which is the highest international award in the field of Condensed Matter Physics.

The experimental realization of the QAH effect for the first time in the world contributed an important scientific discovery to fundamental physics research. The ”world first” achieved by Qi-Kun Xue's team secured China a strategic vantage point in the new wave of the information technology revolution.

C. The worthy qualities of Qi-Kun Xue

”Looking back on my life, I feel that everyone must have a kind of belief,” said Qi-Kun Xue. ”When you have belief, no matter how great the difficulties or challenges you have to face, you will continue to move forward with determination and enthusiasm, because your belief keeps you going and raises you up.”

“Patience is key in life”. Here, writer would like to define patience to diligence, perseverance, and resilience. Reviewing the scientific journey of Qi-Kun Xue, writer believe that, diligence, perseverance, and resilience are the key factors to his success. These three qualities are also what I believe to be the most valuable qualities for our generation of young people to learn.

There was a little story [11] between Qi-Kun Xue and currently president of Westlake University Yigong Shi.In a recommended letter from Qi-Kun Xue's advisor Yang Weisheng, there were few words: ”Hard-working, enduring hardship, different from others”. Qi-Kun Xue said, ”When I first returned to China, I heard that Professor Yigong Shi was very hard-working. Since I considered myself 'hard-working, enduring hardship, and different from others,' I wanted to see how hard Yigong Shi worked.”

Qi-Kun Xue considered that if Yigong Shi worked hard, he might be wake up early, next day, he waked up early, however, Qi-Kun Xue failed to meet Yigong Shi at 7 a.m. for two days. Qi-Kun Xue thought: “Maybe Yigong Shi wake up early”. Qi-Kun Xue tried to meet Prof. Shi at 6 a.m. next two days but failed again. At last, Qi-Kun Xue met Yigong Shi at 5 a.m. when Prof. Shi went back home. This little story reveals how hard Chinese scientists like Qi-Kun Xue and Yigong Shi work. Such a level of hard-working is worth us, the younger generation learning. The resilience Qi-Kun Xue have while meeting challenges worth us learning else. Qi-Kun Xue took the graduate entrance exam three times. He failed the first two times due to bad preparation, but he didn't give up. Instead, with his passion for physics and strong determination, he took the exam for the third time and succeeded.

What we can learn most from Qi-Kun Xue is his deep love to China and his sense of dedication. In one of his lectures, he mentioned: ”The highest stage of a scientist's research is to have a native land emotion to devoted oneself to the happiness of the people, the prosperity of the nation, and the revitalization of the people, and to have a selfless spirit of dedication, striving for technological independence and strength without hesitation." When Qi-Kun Xue came to Shenzhen Middle school (which is writer's mother school) [12], through his own difficult experiences, Qi-Kun Xue encourages us to have a spirit of perseverance and boundless pursuit of excellence. He also emphasizes the importance of an optimistic attitude, fearlessness to challenges, a passion of scientific innovation and pragmatism.

Qi-Kun Xue pointed out that personal success related to the strength of the nation. He gave students the "Questions for Youth": What is ideal? What is historical responsibility? Do we have the determination and confidence to shoulder the mission and responsibility from your homeland?

Qi-Kun Xue said, "Science has no borders, but scientists have their own homeland". Qi-Kun Xue earnestly hopes that young people will carry a sense of historical responsibility, determined to fulfill their mission.

D. Relevant international teams and the HUST team

In 2016, Shifei Qi's team discusses [13] the realization of the high-temperature QAH in np co-doped topological insulators. By using an n-p co-doping method, it is possible to realize QAH effect at higher temperatures, to push the practical application of the quantum Hall effect. By doping the material with suitable n-type (electron-doped) and p-type (hole-doped) elements, magnetic doping enhances the spin-orbit coupling, enabling the material to perform QAH effect at high temperatures. The authors conducted a series of experiments to verify this phenomenon. The authors suggest that future work could focus on optimizing doping strategies, material structures, and surface treatments to improve the performance of these MTI and promoting their applications in quantum computing and other quantum technologies.

In 2020, Yang Li's team paper [14] focuses on controlling the topological properties of iron-based superconductors through Li-decoration to explore the possibility of achieving high-temperature QAH effect. The experimental results show that the adding of Lithium effectively controls the material's magnetism and electronic structure, promoting the formation of spin-polarized topological surface states, which are crucial for the realization of the QAH effect.

In Department of Physics, Huazhong University of Science and Technology, Professor Ying-Hai Wu is also conducting research on topological phase transitions and fractional quantum Hall effect.

III. CONCLUSION

Qi-Kun Xue, a prominent physicist, has made significant advancements in the study of topological states of matter, particularly the QAH effect and its applications in quantum computing. His work bridges the gap between Condensed Matter Physics and quantum information science. His achievements, including the receipt of the 2018 State Natural Science Award, the Fritz London Prize, and the Oliver Buckley Prize in Condensed Matter Physics, highlight the importance and far-reaching implications of his research.

Qi-Kun Xue's work has a profound impact on the field of quantum computing, particularly in the development of topologically protected quantum states. Unlike conventional quantum bits (qubits), the topologically protected states studied by Qi-Kun Xue are inherently resistant to errors, making them a promising candidate for the next generation of quantum computing systems. This research has significant implications for the reliability of quantum computers, which are critical for solving complex problems in fields such as materials physics and quantum computing.

In summary, Qi-Kun Xue's contributions to the study of topological materials, particularly in the realization and application of the QAH effect, have a transformative impact on both theoretical and applied physics. His work continues to shape the development of quantum technologies, positioning him as a central figure in the undergoing exploration of topological states and their potential in quantum computing. Future research, building on his insights, will undoubtedly further enhance Chinese and world's scientists understanding of quantum matter and its technological applications, driving progress in both basic science and practical innovations.

ACKNOWLEDGMENT

Thank myself for my courage to use English to accomplish my paper, what's more, using LaTeXto typesetting.

Thank to Miss Li, you give me the motivation and courage to keep moving.

REFERENCES

[1] E. H. Hall *et al.*, "On a new action of the magnet on electric currents," *American Journal of Mathematics*, vol. 2, no. 3, pp. 287–292, 1879.

[2] F. D. M. Haldane, "Model for a quantum hall effect without landau levels: Condensed-matter realization of the "parity anomaly"," *Phys. Rev. Lett.*, vol. 61, pp. 2015–2018, Oct 1988.

[3] K. v. Klitzing, G. Dorda, and M. Pepper, "New method for high-accuracy determination of the fine-structure constant based on quantized hall resistance," *Phys. Rev. Lett.*, vol. 45, pp. 494–497, Aug 1980.

[4] H. Zhang, C.-X. Liu, X.-L. Qi, X. Dai, Z. Fang, and S.-C. Zhang, "Topological insulators in bi2se3, bi2te3 and sb2te3 with a single dirac cone on the surface," *Nature physics*, vol. 5, no. 6, pp. 438–442, 2009.

[5] M. Z. Hasan and C. L. Kane, "Colloquium: Topological insulators," *Rev. Mod. Phys.*, vol. 82, pp. 3045–3067, Nov 2010. [Online]. Available: https://link.aps.org/doi/10.1103/RevModPhys.82.3045

[6] R. Yu, W. Zhang, H.-J. Zhang, S.-C. Zhang, X. Dai, and Z. Fang, "Quantized anomalous hall effect in magnetic topological insulators," *science*, vol. 329, no. 5987, pp. 61–64, 2010.

[7] C.-Z. Chang, J. Zhang, X. Feng, J. Shen, Z. Zhang, M. Guo, K. Li, Y. Ou, P. Wei, L.-L. Wang *et al.*, "Experimental observation of the quantum anomalous hall effect in a magnetic topological insulator," *Science*, vol. 340, no. 6129, pp. 167–170, 2013.

[8] Y. Zhang, K. He, C.-Z. Chang, C.-L. Song, L.-L. Wang, X. Chen, J.-F. Jia, Z. Fang, X. Dai, W.-Y. Shan *et al.*, "Crossover of the three-dimensional topological insulator bi2se3 to the two-dimensional limit," *Nature Physics*, vol. 6, no. 8, pp. 584–588, 2010.

[9] Y.-Y. Li, G. Wang, X.-G. Zhu, M.-H. Liu, C. Ye, X. Chen, Y.-Y. Wang, K. He, L.-L. Wang, X.-C. Ma *et al.*, "Intrinsic topological insulator bi2te3 thin films on si and their thickness limit," *Adv. Mater*, vol. 22, no. 36, pp. 4002–4007, 2010.

[10] C.-Z. Chang, J. Zhang, M. Liu, Z. Zhang, X. Feng, K. Li, L.-L. Wang, X. Chen, X. Dai, Z. Fang *et al.*, "Thin films of magnetically doped topological insulator with carrier-independent long-range ferromagnetic order," *Advanced materials*, vol. 25, no. 7, pp. 1065–1070, 2013.

[11] [Online]. Available: https://huxin.westlake.edu.cn/content.jsp?urltype=news.NewsConter

[12] [Online]. Available: https://mp.weixin.qq.com/s/1i9mVPVQi5Da9xZ0wU1UZA

[13] S. Qi, Z. Qiao, X. Deng, E. D. Cubuk, H. Chen, W. Zhu, E. Kaxiras, S. Zhang, X. Xu, and Z. Zhang, "High-temperature quantum anomalous hall effect in n-p codoped topological insulators," *Physical review letters*, vol. 117, no. 5, p. 056804, 2016.

[14] Y. Li, J. Li, Y. Li, M. Ye, F. Zheng, Z. Zhang, J. Fu, W. Duan, and Y. Xu, "High-temperature quantum anomalous hall insulators in lithium-decorated iron-based superconductor materials," *Physical Review Letters*, vol. 125, no. 8, p. 086401, 2020.

[15] D. C. Tsui, H. L. Stormer, and A. C. Gossard, "Two-dimensional magnetotransport in the extreme quantum limit," *Physical Review Letters*, vol. 48, no. 22, p. 1559, 1982.

[16] X.-L. Qi, T. L. Hughes, and S.-C. Zhang, "Topological field theory of time-reversal invariant insulators," *Physical Review B—Condensed Matter and Materials Physics*, vol. 78, no. 19, p. 195424, 2008.

[17] X.-L. Qi and S.-C. Zhang, "Topological insulators and superconductors," *Reviews of modern physics*, vol. 83, no. 4, pp. 1057–1110, 2011.

[18] R. B. Laughlin, "Quantized hall conductivity in two dimensions," *Physical Review B*, vol. 23, no. 10, p. 5632, 1981.

[19] D. J. Thouless, M. Kohmoto, M. P. Nightingale, and M. den Nijs, "Quantized hall conductance in a two-dimensional periodic potential," *Physical review letters*, vol. 49, no. 6, p. 405, 1982.

[20] N. Nagaosa, J. Sinova, S. Onoda, A. H. MacDonald, and N. P. Ong, "Anomalous hall effect," *Reviews of modern physics*, vol. 82, no. 2, pp. 1539–1592, 2010.