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5th Anniversary of npj Quantum Materials

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npj Quantum Materials, a joint venture between Nanjing University and Springer Nature, was first published on July 27th, 2016—exactly 5 years ago from today. Establishing a new journal amongst a plethora of existing journals on materials science and condensed matter physics, was quite challenging. However, what *npj Quantum Materials* has achieved in the last 5 years, especially the excellence of its published papers, has been nothing short of extraordinary. I extend my congratulations and heartfelt appreciation to all editors and relevant editorial staff at Springer Nature. Of course, the best accolades should go to the authors themselves. In this difficult era defined by a global pandemic and emergent geopolitical conflicts, exchanging scientific results and ideas freely through an open access publication is more important than ever. In general, open access journals are immediately accessible, and highly discoverable. Apparently, open access articles are cited or downloaded significantly more than non-open access articles on average. In all respects, *npj Quantum Materials* has been highly successful and I have no doubt this will be the case moving forwards. I would like to take this humble opportunity to provide historical context on the rich terminology and key milestones regarding the field of quantum materials. The story here reflects a rather personal view, so I welcome any comments and criticism.

In the September issue of Physics Today in 2012[1], Joseph Orenstein at University of California, Berkeley wrote an article on "Ultrafast spectroscopy of quantum materials". Joe defined: "Quantum materials is a label that has come to signify the area of condensed matter physics formerly known as strongly correlated electronic systems." A number of researchers, including Je-Geun Park, Seoul National University, arranged Quantum Materials Symposium 2013, which was held from 27th January to 2nd February 2013 in Muju, S. Korea. Its scope statement includes: "This meeting is organized by the SCES (strongly correlated electron systems) community in Korea […], cover some of the exciting frontiers of condensed matter physics today, such as the physics of 4d/5d strongly spin-orbit coupled materials, multiferroics, strongly correlated electron systems, and superconductivity."

Therefore, "quantum material" basically started as a new terminology for strongly correlated electron systems. In fact, the rather long phrase "strongly correlated electron systems" reflects a rather specific view of condensed matter theorists of a certain class of materials, but had, by 2012–2013, been heavily used for about a quarter century by a wide community of condensed matter physics and materials science. The concept of strong correlation probably goes back to Mott physics[2]. However, it appears that the term "strongly correlated electron systems" started to be spread widely after three independent workshops in 1989. Soon after the discovery of high Tc superconductivity, H. Fukuyama, S. Maekawa, and A. P. Malozemoff organized the International Symposium on Strong Correlation and Superconductivity, Mt. Fuji, Japan from May 21-25 May 1989. The purpose of the symposium was to provide an opportunity for discussions on the problem of strong correlation of electrons in the context of high Tc superconductivity. Furthermore, Ganaputhy Baskaran, Andrei Ruckenstein, Yu Lu and Erio Tosatti organized "The Anniversary Adriatico Research Conference and Workshop on Strongly Correlated Electron Systems" in Trieste, Italy from 19th June to 21st July 1989. In addition, the heavy-fermion group at Los Alamos National Laboratory coordinated the "International Conference on the Physics of Highly Correlated Electron Systems" on 11-15 September 1989 in Sante Fe, NM. The main focus of these three presumably-independent workshops was heavy fermions and high Tc superconductors. It appears that the discovery of high Tc superconductors had a significant influence on the invention of this terminology, which was used in such a way to combine the new field of high Tc superconductors and the somewhat established field of heavy fermions. Actually, this aspect is well reflected in the 1993 article by Z. Fisk and J. R. Schrieffer: Highly Correlated Electron Systems, MRS Bulletin 18, 23–27[3].

There was an interesting twist after the initial use of "quantum materials" as a new term for strongly correlated electron systems. The concept of two-dimensional (2D) and 3D topological insulators was proposed between 2005–2007 and experimentally verified in 2007–2011[4,5]. These materials are insulators in their interiors but their surfaces contain topologically-protected metallic states. These surface states, in both of topological insulators and topological materials in general, are found to exhibit a plethora of new quantum phenomena such as quantum anomalous Hall effect and quantized Faraday effect. It turns out that electron–electron correlations in these topological materials are mostly weak or negligible, so most topological materials are not strongly correlated electron systems, but fit perfectly to the classification of quantum materials in the sense that the topologically-protected metallic surface states stem from true quantum physics. After the initial discovery on graphene in 2004[6], van der Waals materials such as MoS_2 have become highly topical. Now called 2D materials, they exhibit various new quantum phenomena, so certainly fit the label "quantum materials". Therefore, quantum materials encompass all the most exciting materials exhibiting emergent phenomena that cannot be understood in (quasi-)classical pictures, but result from true quantum waves or entanglement.

CIFAR (Canadian Institute For Advanced Research, pronounces "see-far") started a program in 1987 called Quantum Materials, which was meant to be mostly about superconductors. The first published paper bearing the word of "Quantum Materials" seems to be "Excitons in novel quantum materials: A Monte Carlo study" by E. G. Wang in the proceedings of "Electro-optic and second harmonic generation materials, devices, and applications" in 1996[7]. An Oxford Symposium on Quantum Materials 2011 bore the name of Quantum Materials, and was a meeting for scientists around Oxford, and dealt with frustrated magnetism, multiferroics, and superconductivity.

An important milestone for the development of the quantum materials field and community was the launch of Emerging Phenomena in Quantum Systems (EPiQS) Initiative by The Gordon and Betty Moore Foundation in 2013[8]. Even though "Quantum Systems" was used in the title of the initiative, it basically focused on quantum materials, which they define as substances in which collective behavior of electrons leads to many complex and unexpected phenomena, such as superconductivity, charge ordering, strange forms of magnetism, and emergent particles with properties unlike those of fundamental particles. In conjunction with the EPiQS Initiative, the 1st Quantum Materials Synthesis Symposium was held in 2016 at the World Trade Center, NY.

Early 2016, there was a Workshop on Quantum Materials chaired by Collin Broholm and sponsored by the Department of Energy, to discuss basic research needs of quantum materials for energy relevant technology[9]. This workshop was an important seed to start federal government support on quantum materials research in the US.

Three exemplary successful papers in *npj Quantum Materials* reflects the topics of papers published in it, including superconductivity, novel magnetism and topological materials. The examples include "Excitations in the field-induced quantum spin liquid state of alpha-$RuCl_3$" by A. Banerjee, et al. (3, 8 (2018)), which deals with novel magnetic excitations possibly due to Kitayev-type interaction[10]. The 2nd example is "Superconductivity from valley fluctuations and approximate SO(4) symmetry in a weak coupling theory of twisted bilayer graphene" by You, Y. and A. Vishwanath (4, 16 (2019)), which unveil a new approximate symmetry in superconducting twisted bilayer graphene[11]. The review paper of "$MnBi_2Te_4$-family intrinsic magnetic topological materials" by Ke He (5, 90 (2020)) summarizes what is happening the exotic $MnBi_2Te_4$-related topological materials[12].

It is quite intriguing to think about the history and the development of the quantum materials field. Another emerging area in science and technology is the field of quantum sensing, quantum computing, and quantum information. It is evident that the cross-fertilization of these two fields will be most challenging in science and technology in the coming years. Indeed, all of these are forming a broader field of quantum science that connects the traditional fields of condensed matter physics, materials science, computer science, and even particle physics.

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