IJARSCT

ISSN (Online) 2581-9429

International Journal of Advanced Research in Science, Communication and Technology (IJARSCT)

International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal

Impact Factor: 7.301

Volume 4, Issue 3, January 2024

# Unraveling The Quantum Nature of Materials

**Rahane Ramnath Nivrutti[1] and Dr. Puranaik Shankar Naik[2]**

Research Scholar, Department of Physics[1]

Professor, Department of Physics[2]

Sunrise University, Alwar, Rajasthan, India

**Abstract:** *The fundamental interaction between electrons and atoms is described in quantum mechanics, which forms the basis of the physical description of all substances. While classical descriptions at the macroscopic level can often approximate these quantum effects, there has been an increasing focus in recent years on material systems where quantum effects persist across a broader spectrum of energy and length scales. Superconductors, graphene, topological insulators, Weyl semimetals, quantum spin liquids, and spin ices are examples of such materials. A considerable number of these entities obtain their characteristics through reduced dimensionality, specifically by confining electrons to two-dimensional surfaces. Furthermore, these materials often consist of electrons that cannot be regarded as independent particles due to their intense interactions; instead, they generate quasiparticles, which are collective excitations. However, it is worth noting that quantum-mechanical effects profoundly modify the properties of the material in every instance. This review provides an overview of the electronic characteristics of quantum materials as observed via the electron wavefunction. It investigates how the topology and entanglement of the material lead to an extensive range of quantum states and phases, which are more difficult to characterize classically than conventionally ordered states that are also influenced by quantum mechanics, including ferromagnetism.*

**Keywords:** Quantum Materials, Condensed Matter Physics, Electronic Structure.

## REFERENCES

**[1].** Parkin, S. S. P. et al. Giant tunnelling magnetoresistance at room temperature with MgO (100) tunnel barriers. Nat. Mater. 3, 862–867 (2004).

**[2].** Yuasa, S., Nagahama, T., Fukushima, A., Suzuki, Y. & Ando, K. Giant room-temperature magnetoresistance in single-crystal Fe/MgO/Fe magnetic tunnel junctions. Nat. Mater. 3, 868–871 (2004).

**[3].** Yin, J. et al. Satellite-based entanglement distribution over 1200 kilometers. Science 356, 1140–1144 (2017).

**[4].** Schrödinger, E. Discussion of probability relations between separated systems. Math. Proc. Cambr. 31, 555–563 (1935).

**[5].** Shoenberg, D. Magnetic Oscillations in Metals (Cambridge Univ. Press, 1984).

**[6].** Bardeen, J., Cooper, L. N. & Schrieffer, J. R. Theory of superconductivity. Phys. Rev. 108, 1175–1204 (1957).

**[7].** Bednorz, J. G. & Müller, K. A. Possible high Tc superconductivity in the Ba–La–Cu–O system. Z. Phys. B 64, 189–193 (1986).

**[8].** Drozdov, A. P., Eremets, M. I., Troyan, I. A., Ksenofontov, V. & Shylin, S. I. Conventional superconductivity at 203 kelvin at high pressures in the sulfur hydride system. Nature 525, 73–76 (2015).

**[9].** Balasubramanian, G. et al. Ultralong spin coherence time in isotopically engineered diamond. Nat. Mater. 8, 383–387 (2009).

**[10].** Maurer, P. C. et al. Room-temperature quantum bit memory exceeding one second. Science 336, 1283–1286 (2012).

**[11].** Savary, L. & Balents, L. Quantum spin liquids: a review. Rep. Prog. Phys. 80, 016502 (2017). This paper provides a timely and accessible review of theoretical work on quantum spin liquids and the challenges facing materials research in this field.

**[12].** A longer overview under the auspices of the US Department of Energy is ‘‘Basic Research Needs Workshop on Quantum Materials for Energy Relevant Technology’’, Broholm, C., Fisher, I., Moore, J. & Murnane, M. (Office of Science, US Department of Energy, 2016); http://science.energy.gov/bes/ efrc/research/bes-reports

**[13].** Basov, D. N., Averitt, R. D. & Hsieh, D. Controlling the properties of quantum materials. Nat. Mater. 16, 1077–1088 (2017).

**[14].** Tokura, Y., Kawasaki, M. & Nagaosa, N. Emergent functions of quantum materials. Nat. Phys. 13, 1056–1068 (2017).

**[15].** James, H. M. & Coolidge, A. S. The ground state of the hydrogen molecule.

**[16].** J. Chem. Phys. 1, 825–835 (1933).

**[17].** Blunt, N. S. et al. Semi-stochastic full configuration interaction quantum

**[18].** Monte Carlo: developments and application. J. Chem. Phys. 142, 184107 (2015).

**[19].** Goodenough, J. B. Theory of the role of covalence in the perovskite-type manganites [La, M(II)]MnO3. Phys. Rev. 100, 564–573 (1955).

**[20].** Kanamori, J. Superexchange interaction and symmetry properties of electron orbitals. J. Phys. Chem. Solids 10, 87–98 (1959).

**[21].** Franchini, C. et al. Maximally localized Wannier functions in LaMnO3 within PBE+U, hybrid functionals and partially self-consistent GW: an efficient route to construct ab initio tight-binding parameters for eg perovskites. J. Phys. Condens. Matter 24, 235602 (2012).

**[22].** Marques, M. A. L. et al. Ab initio theory of superconductivity. II. Application to elemental metals. Phys. Rev. B 72, 024546 (2005).

**[23].** Giustino, F. Electron–phonon interactions from first principles. Rev. Mod. Phys. 89, 015003 (2017).

**[24].** Jackeli, G. & Khaliullin, G. Mott insulators in the strong spin–orbit coupling limit: from Heisenberg to a quantum compass and Kitaev models. Phys. Rev. Lett. 102, 017205 (2009).

**[25].** This theoretical work showed how bond-directional exchange interactions and Kitaev models can be realized in magnetic insulators with strong spin–orbit coupling.

**[26].** Plumb, K. W. et al. α-RuCl3: a spin–orbit assisted Mott insulator on a honeycomb lattice. Phys. Rev. B 90, 041112(R) (2014).

**[27].** Takayama, T. et al. Hyperhoneycomb iridate β-Li2IrO3 as a platform for Kitaev magnetism. Phys. Rev. Lett. 114, 077202 (2015).

**[28].** Chun, S. H. et al. Direct evidence for dominant bond-directional interactions in a honeycomb lattice iridate Na2IrO3. Nat. Phys. 11, 462–466 (2015).

**[29].** Rüegg, Ch. et al. Pressure-induced quantum phase transition in the spin-liquid TlCuCl3. Phys. Rev. Lett. 93, 257201 (2004). These authors established a model system that allows detailed, quantitative neutron scattering experiments on the evolution of spin correlations across a quantum phase transition.

**[30].** Jain, A. et al. Higgs mode and its decay in a two-dimensional antiferromagnet. Nat. Phys. 13, 633–637 (2017).

**[31].** Hong, T. et al. Higgs amplitude mode in a two-dimensional quantum antiferromagnet near the quantum critical point. Nat. Phys. 13, 638–643 (2017).

**[32].** Pekker, D. & Varma, C. M. Amplitude/Higgs modes in condensed matter physics. Annu. Rev. Condens. Matter Phys. 6, 269–297 (2014).

**[33].** Cercellier, H. et al. Evidence for an excitonic insulator phase in 1T-TiSe2.

**[34].** Phys. Rev. Lett. 99, 146403 (2007). The photoemission data presented in this paper revived interest in excitonic insulators. The data were taken on a material system that is now being studied intensely in the form of exfoliated monolayers.

**[35].** Wakisaka, Y. et al. Excitonic insulator state in Ta2NiSe5 probed by photoemission spectroscopy. Phys. Rev. Lett. 103, 026402 (2009).

**[36].** Lu, Y. F. et al. Zero-gap semiconductor to excitonic insulator transition in Ta2NiSe5. Nat. Commun. 8, 14408 (2017).

**[37].** Jérome, D., Rice, T. M. & Kohn, W. Excitonic insulator. Phys. Rev. 158, 462–475 (1967).

**[38].** Morosan, E. et al. Superconductivity in Cux TiSe2. Nat. Phys. 2, 544–550 (2006).

**[39].** Kusmartseva, A. F., Sipos, B., Berger, H., Forró, L. & Tutiš, E. Pressure induced superconductivity in pristine 1T-TiSe2. Phys. Rev. Lett. 103, 236401 (2009).

**[40].** Joe, Y. I. et al. Emergence of charge density wave domain walls above the superconducting dome in 1T-TiSe2. Nat. Phys. 10, 421–425 (2014).

**[41].** Edge, J. M., Kedem, Y., Aschauer, U., Spaldin, N. A. & Balatsky, A. V. Quantum critical origin of the superconducting dome in SrTiO3. Phys. Rev. Lett. 115, 247002 (2016).

**[42].** Ruhman, J. & Lee, P. A. Superconductivity at very low density: the case of strontium titanate. Phys. Rev. B 94, 224515 (2016).

**[43].** Ohtomo, A. & Hwang, H. Y. A high-mobility electron gas at the LaAlO3/SrTiO3 heterointerface. Nature 427, 423–426 (2004). A variety of quantum states have now been observed to emerge at atomic-scale interfaces between correlated materials. The creation of such interfaces was enabled by progress in materials synthesis highlighted in this paper.

**[44].** Boschker, H. & Mannhart, J. Quantum-matter heterostructures. Annu. Rev. Condens. Matter Phys. 8, 145–164 (2017).

**[45].** Novoselov, K. S., Mishchenko, A., Carvalho, A. & Castro Neto, A. H. 2D materials and van der Waals heterostructures. Science 353, aac9439 (2016).

**[46].** Kamihara, Y. et al. Iron-based layered superconductor: LaOFeP. J. Am. Chem. Soc. 128, 10012–10013 (2006).

**[47].** Hsu, F. C. et al. Superconductivity in the PbO-type structure α-FeSe. Proc. Natl Acad. Sci. USA 105, 14262–14264 (2008).

**[48].** Si, Q., Yu, R. & Abrahams, E. High-temperature superconductivity in iron pnictides and chalcogenides. Nat. Rev. Mater. 1, 16017 (2016).

**[49].** Dai, P. C. Antiferromagnetic order and spin dynamics in iron-based superconductors. Rev. Mod. Phys. 87, 855–896 (2015).