Extended Essay:

ROOM-TEMPERATURE SUPERCONDUCTORS

Research Question:

Considering the established experimental facts and extent of current research regarding the critical temperature T_c of superconductors, to what extent is the creation of Room-Temperature Superconductors (RTS) that can be usefully applied in scientific research and technology feasible?

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Table of Contents

Introduction

Scientist Martin Fleischmann claimed: "It doesn't matter whether you can(…)achieve high temperature superconductivity(…), they will always be on the list because if you could achieve them they would be extremely valuable."[1] The discovery of superconductors was revolutionary: materials that conduct without resistance present a range of new possibilities in science and technology. The caveat however is that superconductivity necessitates extremely low temperatures, limiting its practical applicability. Therefore the creation of the first High-Temperature-Superconductors (HTS) in 1993 was a major milestone. These superconductors operate above 77K. Although Fleischmann would now rest assured superconductivity is indeed achievable at temperatures that are high relative to the temperatures necessary for the first superconductors, the "high temperatures" are still very low, with the highest achieved to date at around 250K Therefore the truly interesting question is whether superconductivity can exist at even higher temperatures, closer to "room-temperature". Room-Temperature Superconductors would allow a wide range of breakthrough technological applications, from frictionless quantum locked railways to new supercomputer applications. Thus arises the question of this investigation: Are "Room-Temperature Superconductors" (RTS) achievable?

Approach and guiding questions:

In order to discuss whether it is feasible for future scientists to create RTS, one must first understand the underlying concept of superconductivity and the requirements for RTS to potentially exist. The approach of this investigation is to consider a range of scientific papers, observations and experimental evidence to first present the physics of superconductivity, and

[1] Tinsley, C. (1996). An Interview with Professor Martin Fleischmann: Conducted by Christopher P. Tinsley. *Infinite Energy*. Issue 11. Available at: <https://www.infinite-energy.com/iemagazine/issue11/fleishmann.html>. (accessed 20.02.2021).

consequently describe the subatomic conditions that could potentially enable RTS. Potential types of materials for RTS and the implications for the use of superconductivity and established evidence for RTS will also be considered. Because the mechanisms of superconductivity are not yet fully understood, it is necessary to explore experimental data and established theories to evaluate whether the requirements for RTS could potentially be met.[2]

The limitations of this approach are that there is a lack of understanding of certain mechanisms of superconductivity and further research is essential for a definitive answer. A future discovery could refute existing evidence and researchers could find that useful RTS cannot be created. Nonetheless, the aim of this investigation is to evaluate to what extent the creation of RTS is feasible, based on established experimental facts and the extent of current research. If researchers reflect on the likely conditions necessary and the most promising approaches in the search for RTS, achieving RTS could be more probable.

The questions that will be considered are:

1. How is superconductivity achieved, classified and understood?
2. What are the necessary conditions for RTS?
3. Can the requirements for superconductivity be achieved at room temperature?
4. Which approaches have been used in the search for RTS?
5. What experimental evidence exists for the possibility of RTS?
6. What evidence suggests that the creation of RTS is not feasible?

[2] Mourachkine, A. (2004). Room-Temperature Superconductivity. Cambridge International Science Publishing

Main Body

Section 1: How is superconductivity achieved, classified and understood?

Superconductivity describes the properties of certain materials at certain temperatures to expel magnetic fields and attain a state of zero electrical resistance. [3] The basic properties universal to all superconductors are:[4] **perfect electrical conductivity** and **perfect diamagnetism**.[5] Perfect diamagnetism is known as the **Meissner Effect**: the expulsion of magnetic fields surrounding the superconductor. At a **critical temperature** T_c the material transitions into this superconductive state,[6] known as the **Meissner state**.[7]

Superconductivity can only be achieved below T_c.[8] Low-Temperature-Superconductors (LTS) have a T_c<30K and High-Temperature-Superconductors (HTS) have T_c>30K.[9] If an applied magnetic field doesn't exceed a value specific to the superconducting material, low applied currents flow in the superconductor with zero resistance and can be maintained with no voltage.[10] This has major implications in scientific research, technology and energy efficiency.

[3] Nave, R. Superconductivity. Available at: <http://hyperphysics.phy-astr.gsu.edu/hbase/Solids/scond.html>. (accessed 15.10.2020).
[4] Mnyukh, Y. & Vodyanoy, V. (2016). Superconducting State and Phase Transitions. *Research Gate.* Available at: <https://www.researchgate.net/publication/305491462_Superconducting_State_and_Phase_Transitions> (accessed 20.06.2020).
[5] Mourachkine, A. (2004). Room-Temperature Superconductivity. Cambridge International Science Publishing
[6] Tinkham, M. (1996). Introduction to Superconductivity. *Dover Publications, INC. p. 8. ISBN 0486435032.*
[7] Tinkham, M. (1996). Introduction to Superconductivity. *Dover Publications, INC. p. 8. ISBN 0486435032.*
[8] Webb, G. W. & Marsiglio, F. & Hirsch, J. E. (2015). Superconductivity in the Elements, Alloys and Simple Compounds. *Physica C: Superconductivity and its Applications.* Volume 514.
[9] Webb, G. W. & Marsiglio, F. & Hirsch, J. E. (2015). Superconductivity in the Elements, Alloys and Simple Compounds.
[10] Nave, R. Superconductivity. Available at: <http://hyperphysics.phy-astr.gsu.edu/hbase/Solids/scond.html>.

Fundamentally, there are two phenomena necessary for superconductivity to exist in materials:

1. **Electron/Quasiparticle pairing**
2. **The onset of long-range phase coherence**.[11]

T_c is the temperature at which the **onset of long-range phase coherence** occurs. This is the formation of a quantum condensate because electron pairs in the superconductor condensate[12]. They enter the same energy states and barely move relative to each other, behaving like a quantum mechanical identity, which can be described by a wave function[13] (a function describing the probability of the quantum state of a particle)[14].

Superconductors can be classified into three groups according to their response to magnetic fields and their mechanisms. Group 1 includes **type 1** superconductors, which includes most metal superconductors and some metallic alloys.[15] They lose all superconductivity if the magnetic field is greater than the critical field (B_c), and completely expel magnetic fields smaller than B_c.[16] Their mechanism is **conventional** because they expel magnetic fields completely ("pure" Meissner state) when superconducting. Conventional superconductors are not very suitable for applications since they require such a low T_c along with a low critical magnetic field B_c.[17] Their superconductivity can be explained by the Bardeen-Cooper-Schrieffer **(BCS) Theory**[18], as follows:

[11] Mourachkine, A. (2004). Room-Temperature Superconductivity. Cambridge International Science Publishing
[12] Mourachkine, A. (2004). Room-Temperature Superconductivity. Cambridge International Science Publishing
[13] Perkowitz, S. (2008) Bose-Einstein Condensate: State of Matter. *Encyclopedia Britannica.* Available at: <https://www.britannica.com/science/Bose-Einstein-condensate>. (accessed 25.10.2020).
[14] Helmenstine, A. M. (2019, October). What is a Wave Function?: Definitions in Physics. *ThoughtCo.* Available at: <https://www.thoughtco.com/definition-of-wavefunction-605790>. (accessed 04.11.2020).
[15] Mourachkine, A. (2004). Room-Temperature Superconductivity. Cambridge International Science Publishing
[16] Kleiner, R. & Buckel, W. (2015, September). Superconductivity: An Introduction
[17] Mourachkine, A. (2004). Room-Temperature Superconductivity. Cambridge International Science Publishing
[18] Webb, G. W. & Marsiglio, F. & Hirsch, J. E. (2015). Superconductivity in the Elements, Alloys and Simple Compounds.

In classical physics, **resistance** is the effect of colliding free electrons and phonons (crystal lattice vibrations) and the electron scattering due to impurities in conductors. This interrupts the electron flow in a conductor.[19] In superconductors, there is effectively zero resistance. BCS Theory explains this phenomenon in conventional superconductors by the interaction of electrons and phonons.

Electron-phonon-electron-interactions can be understood as the interactions that lead to electron pairing. In a conventional superconductor, the positive lattice ions and negative electrons in the material attract each other, distorting the lattice. The distortion creates a local positive charge density (although there are negative electrons, the net charge per unit length is positive).[20] These regions of positive charge attract more negative electrons with a certain momentum. One electron emits a **phonon**. This is a quantum of vibrational mechanical energy, like a photon is a quantum of light energy.[21] It is absorbed by the second electron, thus forming an indirect exchange of energy between the electrons.[22] This attractive electron-phonon-electron-interaction is greater than the usual repulsive Coulomb interaction. Momentum is transferred and pairs of electrons with equal and opposing spin and momentum form due to the conservation of momentum.[23] The electron pairs are called **Cooper Pairs** (CPs). A CP acts as a single new particle (boson) and can be described by a wavefunction like all particles.

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[19] Meaden, G. T. (2013) Electrical Resistance of Metals. Springer. Available at: <https://books.google.de/books?hl=en&lr=&id=UFv0BwAAQBAJ&oi=fnd&pg=PR9&dq=electrical+resistance&ots=2KkS2r0E54&sig=K-M1k5ZXgnEoSUWAeX5bZBLRzfQ&redir_esc=y#v=onepage&q=electrical%20resistance&f=false> (accessed 05.11.2020).

[20] Gross, R. (2001-2015). Chapter 4: Microscopic Theory. *Walther-Meißner-Institut.*

[21] Perkowitz, S. (2009). Phonon: Physics. *Encyclopedia Britannica*. Available at: <https://www.britannica.com/science/phonon> (accessed 18.10.2020).

[22] Hillary, H. J. L. (2018). BCS (Bardeen, Cooper, Schrieffer Theory). *YouTube.* Available at: <https://www.youtube.com/watch?v=bjMhAgHmodk>. (accessed 28.10.2020).

[23] Mourachkine, A. (2004). Room-Temperature Superconductivity. Cambridge International Science Publishing

In a superconductor, all CPs in the absence of a current can be described by a single wavefunction because they are "phase coherent" (all pairs have the same phase)[24]. This explains the first phenomenon necessary for superconductivity: **electron pairing**.

The second requirement (onset of long-range phase coherence) is mediated by **Josephson-Coupling** in conventional superconductors.[25] Unlike normal electrons, many CPs can simultaneously occupy the same energy state. Simply put, Josephson-Coupling can be imagined as the wavefunctions of many CPs "locking together" in phase, creating a network/fluid of linked CPs. To excite this fluid, a minimum amount of energy is required, called an **energy gap**.[26] Since excitation normally leads electrons to jump to higher energy levels, there is a gap between the base state and higher energy levels in superconductors. The CPs "condensate" to occupy the same energy level. Due to this energy gap, when CPs transmit current, the electron collisions due to this current do not suffice to shift their energy. The only available energy state thus is the base state. As a result, there is no energy dissipation and thus zero resistance in conventional superconductors, which are very stable because the CPs are at such low energy states.[27]

Whilst the BCS Theory provides an explanation for conventional superconductivity, it doesn't predicate a rule for predicting superconductivity in different compounds and limits superconductivity to low temperatures. Generally, T_c<10K, depending on the strength of the electron-phonon-electron-interactions within the superconducting material. Therefore, other

[24] Nave, R. Superconductivity. Available at: <http://hyperphysics.phy-astr.gsu.edu/hbase/Solids/scond.html>.
[25] Mourachkine, A. (2004). Room-Temperature Superconductivity. Cambridge International Science Publishing
[26] Lisenfeld, J. (2007). Experiments on Superconducting Josephson Phase Quantum Bits. *Friedrich-Alexander-Universität Erlangen-Nürnberg*.
[27] Mourachkine, A. (2004). Room-Temperature Superconductivity. Cambridge International Science Publishing

mechanisms for superconductivity were sought to describe High-Temperature-superconductors.[28]

Group 2 superconductors are called "multi-component"[29] and include low-dimensional, non-magnetic compounds such as binary compounds, semiconductors, and the A-15 superconductor.[30] They are better appliable than conventional superconductors due to a higher B_c and higher T_c and many applied superconductors are type 2 superconductors. T_c depends on the material and is generally $20K< T_c<40K$. Their mechanism is **half-conventional** because it consists of two interacting superconducting subsystems: BCS Theory and unconventional superconductivity.

Group 3 includes **Type 2** superconductors: mostly impure and compound in nature. The materials are low-dimensional magnetic compounds such as oxides, organic materials, cuprates, hybrids and deuterides. They are generally magnetic, have strong electron correlations, unstable lattices and complex structures.[31] Magnetic fields that are between two critical fields (B_{c1} and B_{c2}) partially penetrate these superconductors.[32] Thus they are **unconventional** (expel small magnetic fields completely and partially expel higher fields).

There is no established theory to explain unconventional superconductivity because of the lack of understanding of normal-state properties of their materials.[33] Unconventional superconductors cannot be explained by the BCS Theory. The Coulomb interactions are

[28] Flores-Livas, J. A., Boeri, L., Sanna, A., Profeta, G., Arita, R. & Eremets, M. (2020, February). A Perspective on Conventional High-Temperature Superconductors at High Pressure: Methods and Materials. *Physics Reports 856 (2020) 1-78.*
[29] Kleiner, R. & Buckel, W. (2015, September). Superconductivity: An Introduction (Chapter 1: Fundamental Properties of Superconductors). *Wiley-VCH Verlag.*
[30] Mourachkine, A. (2004). Room-Temperature Superconductivity. Cambridge International Science Publishing
[31] Mourachkine, A. (2004). Room-Temperature Superconductivity. Cambridge International Science Publishing
[32] Kleiner, R. & Buckel, W. (2015, September). Superconductivity: An Introduction
[33] Mourachkine, A. (2004). Room-Temperature Superconductivity. Cambridge International Science Publishing

stronger, so the attractive electron-phonon coupling described by the BCS theory, is not enough to overcome the Coulomb repulsion.[34] Although there is no clear mechanism for unconventional superconductivity, there exists some idea of the quasiparticle pairing and onset of long-range phase coherence.

The quasiparticles in unconventional superconductors are called solitons. Solitons are non-linear wave excitations localized in space; one soliton can be considered a solitary wave that behaves like a particle[35] in that its wave function is not altered in case of collision. A bisoliton[36] is formed by two consecutive dissipative solitons that preserve a fixed separation between them, and bisolitons are the quasiparticle pairs in unconventional superconductors. Moderately strong and nonlinear electron-phonon interaction is responsible for coupling of soliton-like excitations.[37]

Spin fluctuations are fluctuations in the magnetic (electron spin) moment. The relevant understanding for this investigation is that they result in an energy gap in unconventional superconductors. Therefore, spin fluctuations mediate the second requirement for superconductivity in unconventional superconductors: the onset of long-range phase coherence.

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[34] Sigrist, M. (2005, September). Introduction to Unconventional Superconductivity. *AIP Conference Proceedings789, 165.* Available at: <https://boulderschool.yale.edu/sites/default/files/files/Introduction-to-Unconventional-Superconductivity.pdf>. (accessed 20.07.2020).
[35] Zabusky, N. J. & Porter, M. A. (2010). Soliton. *Scholarpedia, 5(8):2068.* Available at: <http://www.scholarpedia.org/article/Soliton>. (accessed 19.10.2020).
[36] Liu, X. M., Han, X. X. & Yao, X. K. (2016, October). Discrete Bisoliton Fiber Laser. *Scientific Reports 6 Article Number: 34414.* Available at: <https://www.nature.com/articles/srep34414>. (accessed 26.10.2020).
[37] Mourachkine, A. (2004). Room-Temperature Superconductivity. Cambridge International Science Publishing

I have thus established that there are three groups of superconductors with different theories describing their mechanisms of superconductivity. Additionally, I have described the two fundamental phenomena necessary in superconductors:

1. **Electron/quasiparticle pairing**
2. **The onset of long-range phase coherence**.[38]

The **quasiparticle pairing** in conventional superconductors is the pairing of electrons. However, it is better to refer to **quasiparticles** when discussing the principle of particle pairing in superconductivity. They can be thought of as elementary excitations treated as particles. An example are spin waves.[39] The **Quantum Statistical Postulate** states that every particle is either a boson or fermion. Fermions are particles that have ½ integer spin, such as electrons. Bosons are particles with integer spin. Whether a composite object (e.g. atoms) is a fermion or boson depends on its number of elementary fermions.[40] The **Pauli Exclusion Principle** states that no two fermions can occupy the same energy state.[41] Therefore bosons are necessary in superconductors to enable the onset of **long-range phase coherence** because this involves the condensation of particles into the same energy state. Thus, quasiparticle pairing is necessary for pairs that represent bosons to exist. Quasiparticles need net forces of attraction to overcome the Coulomb repulsion, so they can pair and the onset of long-range phase coherence is possible. Thus the reason quasiparticle pairing is necessary is that it enables the second requirement for superconductivity.

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[38] Mourachkine, A. (2004). Room-Temperature Superconductivity. Cambridge International Science Publishing
[39] Höpfel, R. A. (1992). Holes (Electron Deficiencies): Electron-Hole Scattering In Quantum Wells. *ScienceDirect.* Available at: <https://www.sciencedirect.com/topics/physics-and-astronomy/holes-electron-deficiencies>. (accessed 12.11.2020).
[40] Mourachkine, A. (2004). Room-Temperature Superconductivity. Cambridge International Science Publishing
[41] Perkowitz, S. (2008) Bose-Einstein Condensate: State of Matter. *Encyclopedia Britannica*. Available at: <https://www.britannica.com/science/Bose-Einstein-condensate>. (accessed 25.10.2020).

The onset of long-range phase coherence creates the energy gap that prevents collisions from exciting the condensated quasiparticle pairs when a current is transmitted. Therefore there is no energy dissipation and zero resistance and superconductivity can be achieved.

This explains the mechanism behind superconductivity and the fundamental requirements for superconductivity to exist. The main obstacle in the application of superconductors is the low T_c they require, due to the cooling costs and impracticalities sustaining such low T_c entails.

The creation of the first High-Temperature-Superconductor (HTS) in 1993 with a T_c of 135K was therefore a milestone in superconductor research, after Bednorz and Müller discovered cuprate superconductors in 1986. Cryogenic liquid nitrogen can be used for cooling of HTS instead of liquid Helium because the T_c is higher than 77K (boiling point of nitrogen). Nonetheless, the necessity of cooling HTS is still a disadvantage as the highest T_c achieved to date lies at 250K (for LaH10; discovered in 2018).[42] HTS discovered to date are also predominantly brittle ceramics with limited application.[43] The creation of stable RTS could open the doors to new technical possibilities and scientific innovation.

Advantages could range from minor improvements in existing technology, improving energy efficiency and reducing dependence on conventional power plants, to compact

[42] Flores-Livas, J. A., Boeri, L., Sanna, A., Profeta, G., Arita, R. & Eremets, M. (2020, February). A Perspective on Conventional High-Temperature Superconductors at High Pressure: Methods and Materials.
[43] Hornigold, T. (2018, May). Why the Discovery of Room-Temperature Superconductors Would Unleash Amazing Technologies. *Singularity Hub*. Available at: <https://singularityhub.com/2018/05/13/the-search-for-high-temperature-superconductors/>. (accessed 17.11.2020).

superconducting cables, motors, to superconducting magnetic energy storage and advanced transport systems such as a superconducting Maglev trains.

The question thus is whether the requirements for superconductivity can be achieved at room-temperature.

Section 2: Can the requirements for superconductivity be achieved at room-temperature?

To explore this question, this essay must first establish the conditions necessary for a superconducting material, then explore the possibility of achieving these in certain materials. Finally, I review current approaches and achievements in the quest for RTS and the challenges these face in order to evaluate the feasibility of the creation of RTS.

One must first qualify the term ‘Room-Temperature Superconductor’. Practically, superconductivity is only useful when it is stable, and thus well below $T_{c.}$ Therefore RTS would need a T_c threshold of at least 350K to be applicable in small-scale technical applications. Large-scale, industrial operations on the other hand would require a T_c of 450K.[44] The highest T_c achieved to date is at 200K and 250K in hybrid materials. A research team at Harvard claims to have made metallic hydrogen and possibly observed the Meissner effect at 250K[45]

Experimental evidence shows that the first requirement of superconductivity - quasiparticle pairing - can be observed at and above room-temperature. Bisolitons have been found to exist in living matter, suggesting that quasiparticle pairs can be found at 37°C at least, which is around 310K. For instance, bisolitons have been found in organic polymers like polyparaphenylene, polypyrrole and polythiophene.[46] Living organisms can also exist at extreme conditions so quasiparticle pairs can, for instance, be found in certain organic

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[44] Mourachkine, A. (2004). Room-Temperature Superconductivity. Cambridge International Science Publishing
[45] The Rise of High Temperatures Superconductors. *Quantum Levitation.* Available at: <https://quantumlevitation.com/archives/5562>. (accessed 20.06.2020).
[46] Heeger, A. J., Kivelson, S., Schrieffer, J. R. & Su, W.-P. (1988, July). Solitons in Conducting Polymers. *APS Physics, Rev. Mod. Phys.* **60**, 781. Available at: <https://journals.aps.org/rmp/abstract/10.1103/RevModPhys.60.781>. (accessed 22.10.2020).

materials at about 550K.[47] This is relevant since there is a class of organic compound superconductors.

Two different approaches to finding RTS provide evidence for quasiparticle pairing at/above room-temperature in superconductors containing the organic compound carbon.[48] The first research approach performed resistivity and dc magnetic susceptibility measurements on a thin surface layer of the complex material $Ag_xPb_6CO_9$.[49] The second experiment research approach with single-walled carbon nanotubes (as an organic superconductor) proposes evidence of superconductivity above 600K.[50] Additionally, results published in 2019 in *Nature* [51] provide evidence using the LSCO[52] superconductor.

One must recall that the fundamental requirements for superconductivity are quasiparticle pairing and the onset of long-range phase coherence. Since there is evidence of quasiparticle pairing at room-temperature, the more important question is whether the onset of long-range phase coherence can occur at that temperature range. Experiments have not yet shown that the onset of long-range phase coherence can occur at RT, however, the nature of HTS and further research suggests under which conditions it would be possible.[53]

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[47] Mourachkine, A. (2004). Room-Temperature Superconductivity. Cambridge International Science Publishing
[48] Mourachkine, A. (2004). Room-Temperature Superconductivity. Cambridge International Science Publishing
[49] Djurek, D., Medunic, Z., Tonejc, A. & Paljevic, M. (2001). (PACO) Systems: Route For Novel Superconductors. *Physica C* **351**, 78. Available at: <https://www.sciencedirect.com/science/article/abs/pii/S0921453400016968>. (accessed 25.10.2020).
[50] Zhao, G.-m. (2002). Carbon Nanotubes: Ballistic Transport or Room-temperature Superconductivity?. *preprint* cond-mat/0208200.
[51] Zhou, P., Chen, L., Liu, Y., Sochnikov, I., Bollinger, A. T., Han, M.-G., Zhu, Y., He, X., Bozovic, I. & Natelson, D. (2019, August). Electron Pairing in the Pseudogap State Revealed by Shot Noise in Copper Oxide Junctions. *Nature 572, 493-496.* Available at: <https://www.nature.com/articles/s41586-019-1486-7>. (accessed 10.11.2020).
[52] Lanthanum Strontium Copper Oxide
[53] Mourachkine, A. (2004). Room-Temperature Superconductivity. Cambridge International Science Publishing

Experimental data has shown that in order for T_c to be at room-temperature, the mechanism for phase coherence must most likely be magnetic.[54] Because conventional superconductors have the lowest T_c, RTS will most likely to be unconventional superconductors, with quasiparticle pairs represented by bisolitons. Therefore the onset of long-range phase coherence likely must be due to spin fluctuations. The superconductors with the highest T_c to date rely on with this mechanism of phase coherence.[55] RTS will most likely be antiferromagnetic (ferromagnetic options should not be completely discarded though), since experimental data suggests that T_c is on average higher for antiferromagnetic materials.[56]

In his book *Room-Temperature Superconductivity*, Senior Research Associate at the Nanoscience Centre of the University of Cambridge Andrei Mourachkine[57] outlines likely necessary properties of materials for RTS more specifically. Based on a systematic review of the electromagnetic properties of the different types of superconductors, he concludes that materials susceptible to lend themselves to RT superconductivity must fulfil the following requirements:

[54] Steele, B. (2014, July). Proof: Magnetism Makes ‘Cooper Pairs’. *Cornell Chronicle.* Available at: <https://news.cornell.edu/stories/2014/07/proof-magnetism-makes-cooper-pairs>. (accessed 20.02.2021).
[55] Mourachkine, A. (2004). Room-Temperature Superconductivity. Cambridge International Science Publishing
[56] Mourachkine, A. (2004). Room-Temperature Superconductivity. Cambridge International Science Publishing
[57] Foley, C. (2004, November). A Challenging Read. *Materialstoday, Volume 7, Issue 11.* Available at: <https://www.sciencedirect.com/science/article/pii/S1369702104005140>. (accessed 22.02.2021).

Structural Requirements	Composite effects
- Be low-dimensional - Have a complex structure - Have an unstable lattice - Have electron-acceptor sites	- Have at least two interacting subsystems that enable quasiparticle pairing and the onset of long-range phase coherence respectively - Have subsystem with bisolitons; charge reservoirs; magnetic molecules

Based on these requirements, he concludes that the likely properties of materials suitable for RTS will be found among the following:

- Multicomponent, i.e. a hybrid compound of different materials
- Organic, i.e. a compound including carbon
- Oxidic, i.e. including oxygen

Mourachke hence suggests that the creation of RTS is feasible with such materials and compounds with these likely necessary properties. Research in these areas has intensified in recent years.[58]

[58] Service, R. F. (2020, October). After decades, room temperature superconductivity achieved. *Science*. Available at: <https://www.sciencemag.org/news/2020/10/after-decades-room-temperature-superconductivity-achieved>. (accessed 25.02.2021).

Section 3: Which approaches have been used in the search for RTS?

Unconventional superconductors, including cuprates, chalcogenides and pnictides currently have the highest T_c.[59] Therefore, the most promising approaches focus on unconventional superconductors. There are nonetheless several other approaches by which researchers have increased the T_c:

1. Improving the performance of known superconducting materials
2. Inducing conventional superconductivity at high pressures
3. Synthesis of materials containing quasiparticle pairs above RTP with intercalant molecules (molecules that are inserted into layers of a material)
4. Creating a train of quasiparticle pairs in a specially prepared Polymer

The potential of each of these approaches can be described as follows:

1. **Improving the performance of known superconductors** is already being attempted with Cuprates, since these currently exhibit the highest T_c and allow quasiparticle pairs to form at room-temperature.

Research into **Conventional superconductivity at high pressures** builds on stablished theoretical and computational methods for experimental research into conventional superconductivity, which presents an advantage compared to unconventional superconductivity. Examples of such research include, firstly, the synthesis of the compound superhydride, which is superconducting at a pressure of 200GPa, and close to room-temperature, in a collaboration of Washington University and Argon National Lab.[60]

[59] Flores-Livas, J. A., Boeri, L., Sanna, A., Profeta, G., Arita, R. & Eremets, M. (2020, February). A Perspective on Conventional High-Temperature Superconductors at High Pressure: Methods and Materials.
[60] The Rise of High Temperatures Superconductors. *Quantum Levitation.*

Secondly, hydrides[61] appear to be a promising prospect in this field. The discovery of the hydrides H_3S (2015) and LaH_{10} (2018) set the record for the highest critical temperatures of 200K and 250K respectively.[62] The issues with this approach to finding RTS is that to exist and superconduct, hydrides need pressures more than one million times larger than ambient pressure.[63]

2. **The "Synthesis" approach** seeks to combine materials that have the optimal qualities for the two fundamental requirements for superconductivity at room-temperature: quasiparticle pairing and phase coherence. This research is focused on finding the right materials, specifically in organic molecules and oxides. Magnetism is required for this approach.[64]

3. The last approach seeks to achieve the onset of long range phase coherence by **overlapping wavefunctions of a train of bisolitons without the requirement of magnetism**, by arranging a specially prepared polymer in a stable crystal structure.[65]

[61] Flores-Livas, J. A., Boeri, L., Sanna, A., Profeta, G., Arita, R. & Eremets, M. (2020, February). A Perspective on Conventional High-Temperature Superconductors at High Pressure: Methods and Materials.
[62] Flores-Livas, J. A., Boeri, L., Sanna, A., Profeta, G., Arita, R. & Eremets, M. (2020, February). A Perspective on Conventional High-Temperature Superconductors at High Pressure: Methods and Materials.
[63] Mittiga, T. (2021, February). Physicists Take Another Step Towards Room Temperature Superconductivity: The New Superconducting Material Contains Carbon, Hydrogen, and Sulfur. *Massive Science.* Available at: <https://massivesci.com/notes/room-temperature-superconductivity-carbon/> (accessed 23.02.2021).
[64] Mourachkine, A. (2004). Room-Temperature Superconductivity. Cambridge International Science Publishing
[65] Mourachkine, A. (2004). Room-Temperature Superconductivity. Cambridge International Science Publishing

Section 4: What experimental evidence exists for the possibility of RTS?

To support the claim that the creation of RTS is feasible, further evidence of its plausibility can be found in the scaling progress of T_c in superconductors already researched. The first superconductor was the element of lead, with a T_c of 4.2K. The first HTS in 1993 had a T_c of 135K, which is a ratio of roughly $\frac{135K}{4.2K} = 32$. As temperature increase thus already achieved, this represents more than one order of magnitude higher than the more incremental ratio of temperature increase between HTS T_c and a targeted RTS T_c ($\frac{350K}{135K} = 2.6$). This scaling plausibility suggests a basic notion that the creation RTS is indeed feasible, because the increase in T_c already achieved is so much greater than the increase in T_c still necessary for RTS.

Furthermore, YBCO superconductors are predicted to be able to superconduct with T_c=300K if infrared laser pulses are used to bombard the superconductor.[66] Additionally, Scientists at NIST (National Institute of Standards and Technology) and the University of Colorado created a **fermionic condensate**. This can be seen as a new form of matter that could help improve understanding of superconductivity and superfluidity. Researchers claim that the pairing strength in the fermionic condensate would correspond to a room-temperature superconductor when adjusted for mass and density. This discovery makes the creation of RTS seem more plausible because the insight it provides could improve understanding of high-temperature superconductivity.[67]

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[66] Hornigold, T. (2018, May). Why the Discovery of Room-Temperature Superconductors Would Unleash Amazing Technologies. *Singularity Hub*.

[67] (2004, January). NIST/University of Colorado Scientists Create New Form of Matter: A Fermionic Condensate. *NIST.* Available at: <https://www.nist.gov/news-events/news/2004/01/nistuniversity-colorado-scientists-create-new-form-matter-fermionic>. (accessed 20.02.2021).

Moreover, in 2020, researchers at Rochester University used the "synthesis" approach and combined hydrogen with carbon and sulfur to photochemically synthesize simple organic-derived carbonaceous sulfur hydride.[68] The T_c of the material was found to be 15°C[69] (288K). However, high pressures of approximately 267 GPa[70] were necessary

Apart from the challenge of increasing T_c for the creation of RTS, the necessary pressure conditions shouldn't be too high, as high pressure requirements trade the impracticability of low temperatures for the other of stable high pressure. Therefore, research by the Indian-Institute-of-Science (IISC) could be relevant. Professor Anshu Pandey claims to have synthesized a material of gold and silver superconducting at 236K. Although this is not higher than the highest T_c of 250K in hydrides, it is significant because the latter's extremely high-pressure conditions were not needed for this approach. It suggests that RTS could be created without the impracticalities of high-pressure.

[68] Marcotte, B. (2021, February). University Mechanical Engineering Professor Ranga Dias Named To the 2021 Time100 Next List of Innovators for his Work Synthesizing a New Room Temperature Superconductor. *Newscenter*. Available at: <https://www.rochester.edu/newscenter/rochester-sets-new-record-for-room-temperature-superconductor-455722/>. (accessed 22.02.2021).
[69] Conover, E. (2020, October). The First Room-Temperature Superconductor Has Finally Been Found. *ScienceNews*. Available at: <https://www.sciencenews.org/article/physics-first-room-temperature-superconductor-discovery>. (accessed 22.02.2021).
[70] Kresin, V. (2021, January). Room Temperature Superconductivity. *Journal of Superconductivity and Novel Magnetism 34, 315*. Available at: <https://link.springer.com/article/10.1007/s10948-020-05767-w> (accessed 22.02.2021).

Section 5: What evidence suggests that the creation of RTS is not feasible?

There are many doubts[71] in regards to the validity of current claims and evidence of RT superconductivity. Their validity is questioned because they often cannot be reproduced by others. These supposed superconductors are sometimes called ”unidentified-superconducting-objects“ (USOs) and the main issue is that the superconducting state is observed in very small fractions of samples containing many conducting compounds. Superconductivity may truly exist in these cases, but the phase responsible cannot be identified. In other cases, superconductivity has only been observed on the surface although the phase was known. This is an issue because the surface conditions are different from the bulk conditions in many materials.[72]

The two main issues in the creation of RTS are the low T_c and/or high pressures necessary for the onset of long-range phase coherence in superconductors so they enter the superconducting state. On the most basic level, resistance is proportional to temperature. Thus, a decrease in temperature leads to a decrease in resistivity. [73] Since a key characteristic of superconductors is zero resistance, it easily follows that superconductivity occurs at low temperatures. If they aren't cooled to the correct temperature, the necessary phase transitions in the materials do not occur.[74]

It might seem unlikely for RTS to be a near-future possibility when HTS have only recently been discovered, the BCS theory theoretically limits T_c of conventional

[71] Hornigold, T. (2018, May). Why the Discovery of Room-Temperature Superconductors Would Unleash Amazing Technologies. *Singularity Hub*.
[72] Mourachkine, A. (2004). Room-Temperature Superconductivity. Cambridge International Science Publishing
[73] Nave, R. Superconductivity. Available at: <http://hyperphysics.phy-astr.gsu.edu/hbase/Solids/scond.html>.
[74] Mourachkine, A. (2004). Room-Temperature Superconductivity. Cambridge International Science Publishing

superconductors to low temperatures, and there is little understanding of the mechanism of unconventional superconductors.

Conclusion

The search for RTS has eluded both material science and theoretical physics for the past decades. Superconductivity could revolutionize scientific research and technologies if it can be applied in less extreme conditions.

The limitations of this investigation's approach are that because of the lack of understanding of superconductivity, further research is essential for a definitive answer to the question of whether RTS can be created and applied. Nonetheless, the most effective way of addressing the question of this essay is to base the inquiry on existing evidence.

On the one hand, RTS seems implausible because BCS theory limits T_c of conventional superconductors, and there is very little understanding of unconventional superconductors. A RTS that can be practically applied on a large scale has not yet been created, and the validity of evidence for RTS has been questioned. Even in cases in which T_c has been successfully increased beyond HTS levels, very high pressures are needed, which limits the applicability of these superconductors.

On the other hand, it seems likely that novel approaches to superconductivity with unconventional materials will yield results that allow to create stable superconducting states at temperatures between 300-450K. There is a range of evidence that the two requirements for superconductivity can be met at room-temperature and some research suggests that the issue of high pressure can be reduced and RTS at ambient pressure could be created in the future.

One can use experimental results to predict the likely conditions necessary for quasiparticle pairing and long-range phase coherence, which are the two phenomena essential for superconductivity. Theoretical knowledge of different groups of superconductors and superconductor mechanisms can be used to deduce likely materials of RTS. Reflecting on this could help researchers evaluating which approaches to finding RTS are more likely to yield results and apply these to make the creation of RTS in the future more probable.

RTS could hence be harnessed to revolutionize energy efficiency and electromagnetic technologies such as to create magnetic levitation trains based on the phenomenon of quantum levitation.

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[75] Headings not included

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