SUPERCONDUCTORS
PAST, PRESENT AND FUTURE

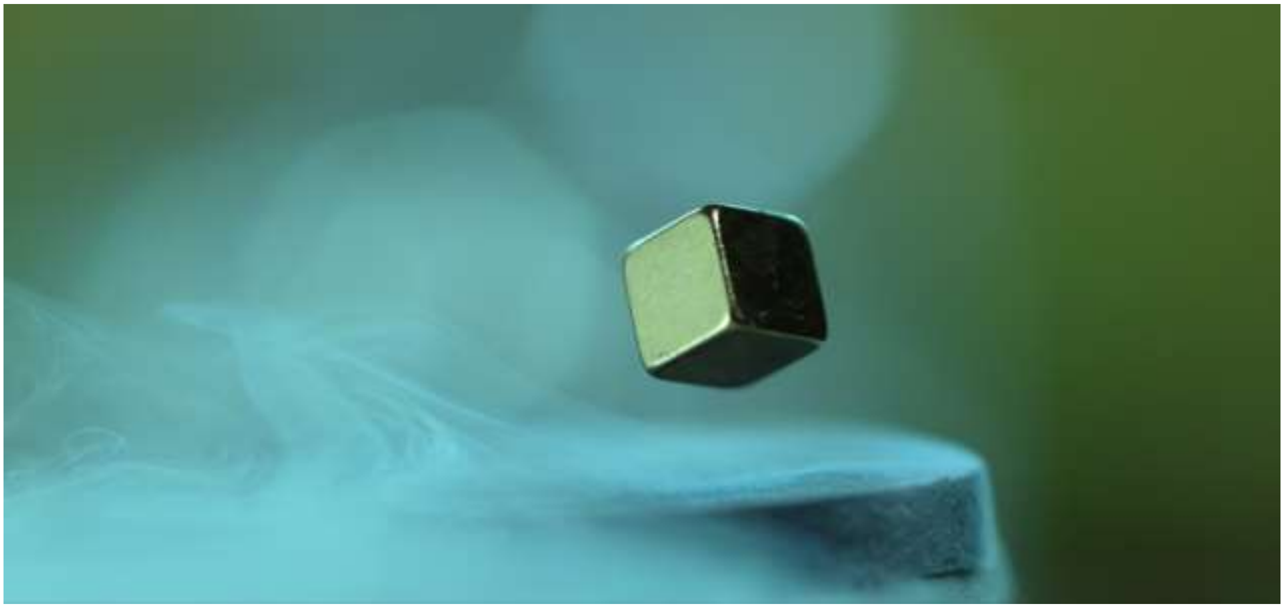

Figure 1: Superconductor levitation. (Source: Department of Theoretical Physics at Ural University)

Let's face it. Superconductors are *cool*. After all, they may one day allow us to manufacture levitating cars, hover boards, computers and circuits that never overheat and need no cooling, super-efficient motors, generators and smart electric grids that suffer from no power loss and of course sustain our very own giant artificial rotating world, as depicted in Larry Niven's Ringworld. Or will they?

THE DISCOVERY

In normal conductors the flow of electrons is continually hindered by impurities, grain boundaries, dislocations and lattice vibrations. Currents in superconductors, once cooled below a certain temperature, experience no resistance at all. This seems peculiar, to say the least. However, as Heike Kamerlingh Onnes discovered at on April 8, 1911, that is precisely what happened to his sample of solid mercury immersed in a cryostat cooled by liquid Helium, at a bone-chilling temperature of 4.2K[1].

He referred to this phenomenon as "supraconductivity" [1], which of course later turned into superconductivity. An interesting implication of this effect is that currents can flow *indefinitely* in a superconductor as long as it is kept

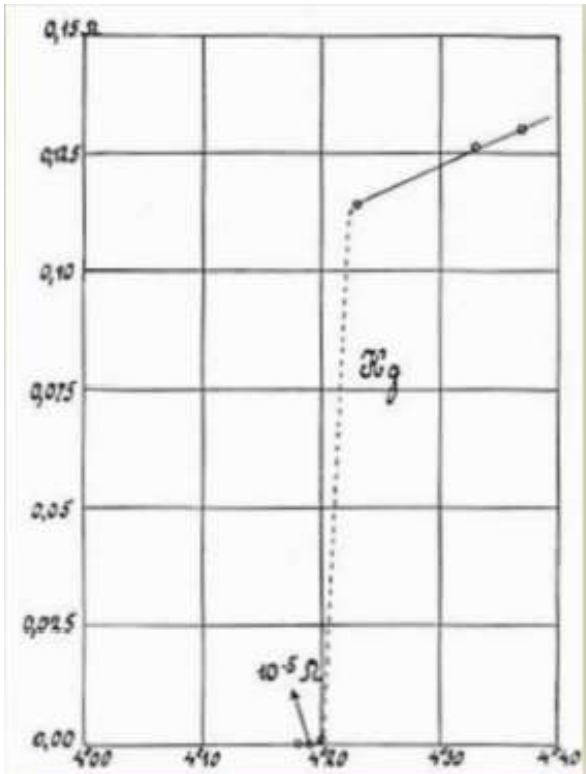

Figure 2: A historic graph of resistance against temperature showing the temperature at which mercury went superconducting, from Onne's notebook. (Source: H. Kamerlingh Onnes, Commun. Phys. Lab. Univ. Leiden. Suppl. 29)

below its critical temperature T_c where superconductive properties appear, and no other resistors are introduced. *Onne* soon discovered the effects of strong magnetic fields on such materials and found that a superconducting material would revert to its non-superconducting state either by passing a very large current through it or introducing a strong enough temperature dependent magnetic field, H_c.[1], even when it was kept below its T_c.

Shortly thereafter, it was discovered that mercury wasn't the odd one out; Lead also went superconducting at 7.2K. [2] A few years later Niobium was found to be superconducting at a slightly higher temperature of 9.2K [3]. What was common with all these materials however was their loss of superconductivity when exposed to high enough electric currents or magnetic fields, as well as requiring painfully low temperatures; difficulties that still limit the use of superconductors in everyday life.

THE FORCE IS STRONG WITH THIS ONE

Having infinitely low resistance is cool and all, but it wasn't until 1933 that two fine gentlemen by the names of W. Meissner and R. Ochsenfeld discovered a property of superconductors that the average layman is perhaps most familiar with: levitation [4]. This uncanny ability is a result of what has now become known as the Meissner Effect [5]. Such behaviour could not be predicted by simply applying Maxwell's infamous equations to a material that has zero electrical resistance, otherwise known as a perfect conductor. This was a clue that superconductors had entirely new properties.

The flux enclosed by a perfect conductor must remain constant in an applied magnetic field [6]. A direct consequence of this is that if a perfect conductor is cooled below its T_c in zero field and then introduced to an applied magnetic field,

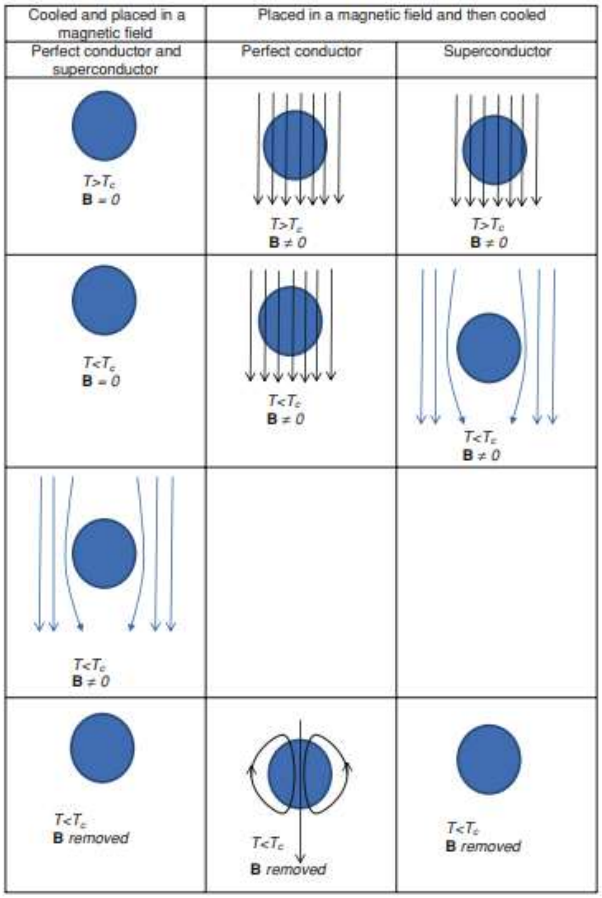

Figure 3: How both superconductors and perfect conductors react to cooling and magnetic fields (Source: https://onlinelibrary.wiley.com/doi/pdf/10.1002/9781118343180.ch4 , accessed: 14:35 GMT 04/01/2019)

since the magnetic flux before the introduction was zero and the flux enclosed must remain constant, the magnetic field is excluded from the interior of the perfect conductor.

As illustrated in the first column of Figure 3. This is achieved by induced surface currents known as *screening currents* [6], as dictated by Lenz's Law. In contrast, if a perfect conductor is first placed in an applied magnetic field, where the field simply goes through the material, and then cooled below its T_c, since there was some magnetic field going through the material beforehand and the flux must remain constant, the perfect conductor does not exclude the magnetic field from its interior. If the applied field is then removed, the perfect conductor will now generate its own magnetic field such that the flux remains constant. As illustrated in the second column of Figure 3.

A superconducting material doesn't bother with all this. The magnetic field inside a superconductor is always zero due to the screening currents, whether or not it was cooled in the presence of a magnetic field or the absence of one. As illustrated in the third column of Figure 3. This leads to superconductors being perfect *diamagnets* [7]. Their magnetic susceptibility is -1 which means the magnetization of a superconductor is always exactly equal and opposite to the applied field, only of course up to some critical magnetic field H_c. As if often the case with new science, this is later found to be more subtle by Alexi Alexeyevich Abrikosov [8] in his two works in 1952 and 1957.

At least that's one thing that's common between superconductors and frogs, they can both levitate. [9]

THE RISE OF SUPERCONDCUTORS

After the discovery of the Meissner effect, numerous other superconducting materials were discovered. In 1941, niobium-nitride was found to be superconducting at 16K [10].

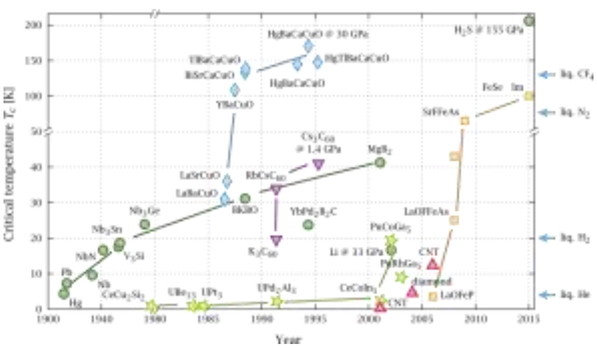

Figure 4: A history of superconducting materials (Source: Pia Jensen Ray. Figure 2.4 in Master's thesis, "Structural investigation of La(2-x)Sr(x)CuO(4+y) - Following staging as a function of temperature". Niels Bohr Institute, Faculty of Science, University of Copenhagen. Copenhagen, Denmark, November 2015

The first commercial superconducting wire was developed by scientists at Westinghouse in 1962[11] using an alloy of niobium and titanium. In the same decade, high-energy electromagnets made of copper-clad niobium-titanium were developed in the UK [12]. These were employed in the world's then most powerful superconducting particle accelerator at the Fermilab Tevatron[13] in 1987; bringing death by Black Hole that much closer to reality.

THE ROARING 50'S

Up until the 1950s, no one really knew how superconduction actually came about. The first inkling of hope was published by brothers Fritz and Heinz London in 1935 when they showed that the Meissner effect [4] was a result of the minimization of free energy in a superconducting current, now known as London Theory [14].

In the 1950s the field that was first conceived in Onnes lab almost 40 years earlier could finally breathe a sigh of relief. Physicists Vitaly Lazarevich Ginzburd and Lev Landau [15] published a mathematical theory describing superconductivity that expanded on the London Theory that explained the Meissner Effect. Following which the Russian physicist Alexi Alexeyevich Abrikosov showed in his works that superconductors could be divided into two classes [8]: Type 1 and Type 2.

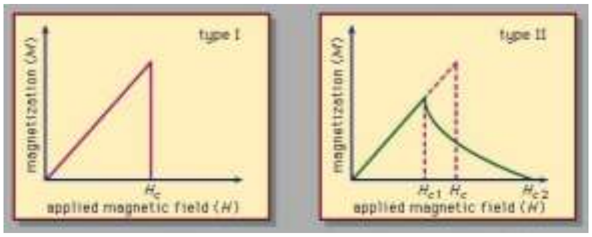

Figure 5: Magnetisation of Type 1 and Type 2 Superconductors (Source: Encyclopedia Britannica 1998)

Type 1 superconductors are normally pure metals like lead or mercury, although some alloys and doped materials like SiC:B are also Type 1. Superconductivity in such materials is attained instantly [16] as soon as the temperature drops below the critical T_c. These materials also show an immediate breakdown of superconductivity when the strength of an applied magnetic field **H** increases above a critical value $\mathbf{H_c}$.

Type 2 superconductors, on the other hand, tend to be metal alloys or complex oxide ceramics like the cuprate-perovskite YBCO [17]. These materials become superconducting slowly[16] as the temperature is decreased, around some critical T_c. Type 2 superconductors also do not completely exclude a magnetic field, some field lines do penetrate into the interior leading to a phenomenon known as Flux Pinning.

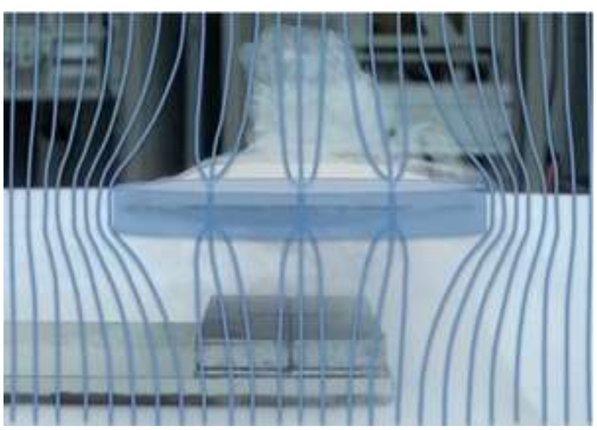

Figure 6: A Type 2 superconductor showing Flux Pinning (Source: http://scimad.com , accessed: 15.01 GMT 04/01/2019)

This occurs above a certain critical magnetic field that is different from the field strength required to destroy superconductivity.

In 1950 Maxwell and Reynolds published their results on how the critical temperature T_c of a superconductor depends on the isotopic mass [18]. All this was taken further by John Bardeen, Leon Cooper and John Schriffer in 1957 when they published their *Theories of Superconductivity* explaining the phenomenon on the microscopic scale [19], eventually leading to a macroscopic description. The theory won them a Nobel Prize in 1972 and is now known as BCS theory.

WE DEMAND AN EXPLANATION

BCS theory convincingly explained why exactly the resistance of certain materials would drop to zero below certain temperatures.

An electron flowing through a metal lattice will attract the positive lattice ions as it moves past them. This causes a small deformation in the neighbouring positive ions as they attempt to congregate towards the moving electron. This increased positive charge density then attracts other electrons. [20]

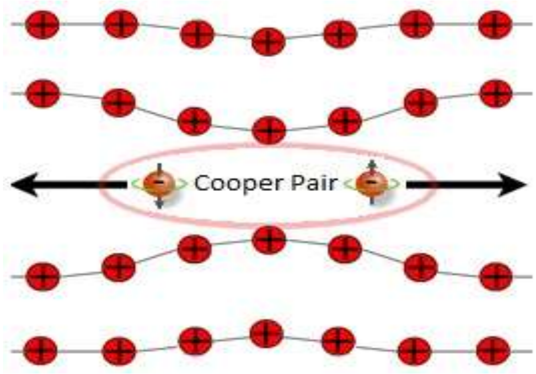

Figure 7: Illustration of a Cooper Pair (Source: https://web.pa.msu.edu/people/tessmer/s-S_TI.html , accessed 15:04 GMT 04/01/2019)

Two electrons with opposite spins attracted in this way can then become correlated and start to move as a Cooper Pair. A huge number of Cooper Pairs[21] moving in this way can then occupy the same energy state and move as a collective condensed state moving as one super-fluid. This of course is very much prohibited by the Pauli-exclusion principle whereby two fermions e.g. electrons cannot occupy the same energy state. The Cooper pairs however can be treated as bosons and so this principal does not apply to them. The entire fluid experiences no resistance because all of the Cooper Pairs share the same energy levels. A "collision" of a single moving electron with the positive ions in a lattice would usually break any such attractive bond with between two electrons. However when the Cooper Pairs move as a superfluid, sharing the same energy state, breaking a single Cooper Pair bond requires breaking all the Cooper Pair bonds throughout the material. Since this takes much more energy, Cooper Pairs can take on such collisions and experience absolutely no resistance at all.

IT'S A BIRD…IT'S A PLANE…IT'S SUPERCURRENT!

In 1962 Welsh theoretical physicist Brian David Josephson made an important theoretical prediction. Josephson predicted that a current could flow [21] between two superconducting materials, separated by a thin film barrier, indefinitely without any applied voltage, through a device now known as the Josephson junction. [22]

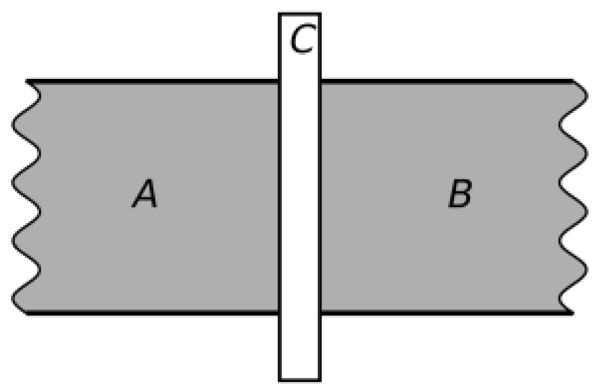

Figure 8: A Josephson junction with materials A and B being superconductors and C being the barrier (Source: https://en.wikipedia.org/wiki/Josephson_effect#/media/File:Single_josephson_junction.svg , Created by User Miraceti , accessed: 15:08 GMT 04/01/2019)

This was already known to happen with non-superconducting materials when a

DC current can quantum tunnel [23] through a barrier higher in potential energy than the incoming current. The thin film barrier could be an insulator, non-superconducting metal or a physical constriction that decreases the superconductivity e.g. a high enough magnetic field. The current is now known as a supercurrent and the phenomenon as the Josephson Effect.

The Josephson Effect occurs both with DC and AC currents. It is currently put to use in sensitive magnetometers called superconducting quantum interference devices, or SQUIDS. [24]

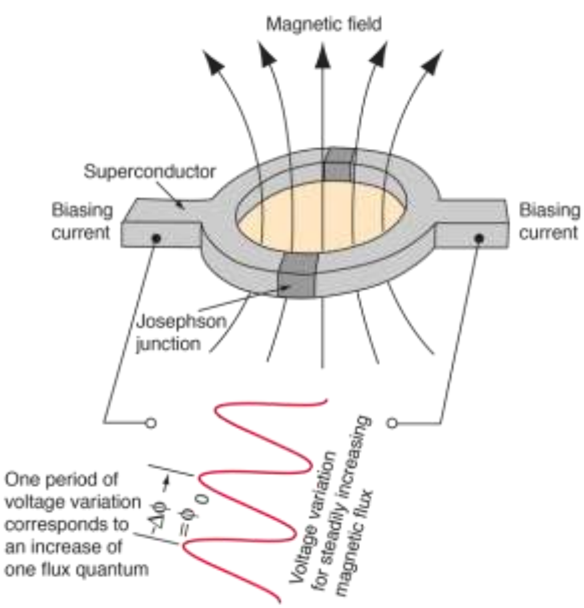

Figure 9: A diagram of a SQUID (Source: http://hyperphysics.phy-astr.gsu.edu/hbase/Solids/Squid.html , accessed 15:14 GMT , 04/01/2019)

Other applications exploit the precise voltage-to-frequency conversion of a Josephson junction in metrology [25]. These junctions are also incredibly useful in qubits in supercomputers [26]. Such junctions may also replace current CCDs [27] (charge coupled devices) used in astronomy right now.

A BREAKTHROUGH

BCS theory had predicted that superconductors with a critical temperature any higher than 30K [28] could not exist. This was proven to be incorrect by Johannes Georg Bednorz and Karl Alexander Muller in 1986 when they created a ceramic material that superconducted at 30k. The ceramic was LaBaCuO[29]. It was soon discovered that by replacing the Lanthanum by Yttrium raised the critical temperature to 92K. An absolutely astounding increase! This discovery ushered in a tremendous amount of research. Transition temperatures had moved high enough to use liquid Nitrogen, instead of the previously used liquid helium, as a refrigerant.

The discovery won the pair a Nobel Prize the very next year.

A new sub-field had been born: High temperature superconductivity. Several superconducting cuprates, materials that contain anionic copper, have since been discovered, continually pushing the transition temperature higher. In 2008, an iron-based high-temperature superconductor was discovered by Hideo Hosono and his colleagues [33]. It was found that replacing the Lanthanum in $LaO_{1-x}F_xFeAs$ with samarium lead to a superconducting material at 55k.

However, an explanation of how these materials can superconduct at such high temperatures remains unknown to this day, and is a major challenge faced by the field of condensed matter physics.

HOW DOES IT WORK?

There are two hypothesis on how high-temperature superconductivity might work. The resonating-valence-bond theory [30] and spin fluctuation theory [31]. The former was first proposed by physicist Philip Warren Anderson and theoretical physicist Ganapathy Baskaran in 1987. The theory proposes that in cuprate lattices, electrons from neighbouring ions can interact to form a valence bond, locking them in place. However, with appropriate doping these electrons can be made to act as Cooper Pairs and thus superconduct.

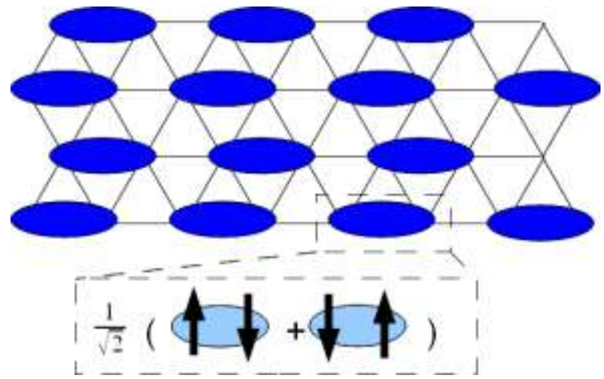

Figure 10: An illustration of resonance valnce bond theory (Source: https://commons.wikimedia.org/wiki/File:Valence_bond_solid.png , accessed 15:17 GMT 04/01/2019)

Spin fluctuation hypothesis proposes that electrons can form Cooper Pairs in high temperature superconductors via short-range spin waves called paramagnons. A magnon[32] is a quasiparticle, i.e. a collective excitation that is an emergent phenomenon that occurs when a solid behaves as if it were made up of weakly interacting smaller particles in free space. A paramagnon is a magnon in a magnetic material that is at a high temperature, disordered, state.

In 1988, BiSrCaCuO was discovered to superconduct at 110K [34], followed by a TI [35] at 120k. The next step up in critical temperature was discovered by Sergey Putilin in Moscow, in 1993, when Hg was found to superconduct at 134K[35].

WHATS THAT SMELL?

In 2014, a team of researchers in China predicted that H_2S, the compound responsible for the very much disliked rotten egg smell, could become a high-temperature superconducting material at the ridiculous pressure of 160 gigapascals. That is 1.6 million times atmospheric pressure! This was indeed observed in 2015[36] where superconductivity was observed at 203K by a team of researchers in Germany.

THIS JUST IN!

The most recent discovery in the field of superconductors occurred back in 2018 when a team of researchers at the University of Maryland observed superconduction in YPtBi[37]. That in itself was not too much of a surprise as the material was discovered to be superconducting in 2016[38]. What was surprising was that YPtBi should not have been superconducting at temperatures below 0.8 Kelvin, the researchers however found otherwise. It was then concluded that the electrons in the material must have spin states of 3/2 instead of the conventional 1/2. This had never been observed before and could be the birth of an entirely new type of superconductor.

WHAT NOW

Infinitely low power loss could hail a new era of electrical devices. Phones will last for weeks instead of hours, batteries will never heat up and your electrical bill will most certainly plummet as not a single device in your house wastes electricity as heat.

Room temperature superconductivity will allow for incredibly powerful magnets, just like the one in your local MRI machine, and who knows where that might lead? Science at energy scales never witnessed before? Levitation devices for everyone? Nuclear fusion? An evil supervillain terrorising the city with his Room Temperature Superconducting Magnetic Pulveriser 2000™?

Even though research at the University of Maryland in 2011 provided evidence that spin fluctuation theory is indeed the mechanism of high-T_c superconductivity[39], why exactly some materials can have unconventionally high critical temperatures is still under research.

Scientists in the US, at the Ames laboratory in 2014, used ultra-fast laser spectroscopy to essentially capture snapshots of $Ba(Fe_{1-x}Co_x)_2As_2$, a high-T_c superconductor, as it transitions into its superconducting state[40]. Studies like this hope to shed light into what exactly makes high-T_c superconductors tick.

One could say that room temperature superconduction is the holy grail of superconductivity science. The ridiculous temperatures and pressures required to sustain superconductivity in current materials is a major barrier, and the average layman is most certainly not going to adjust to life at a frosty 200K any time soon.

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