Recent New Developments in Superconductors

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Excitement ran high earlier this year among researchers on superconductivity, as also among the enthusiasts of a variety of applications of superconductors, due to two separate claims made on observations of superconductivity at room temperature. The first claim was by a research group from University of Rochester, USA in March 2023 on N-doped lutetium hydride (NLH), under application of mild pressures [1], and the second was by a S. Korean research group who reported superconductivity at ambient pressure and temperatures up to 127 °C (400 kelvin), on a compound of approximate composition $Pb_{10-x}Cu_x(PO_4)_6O$, dubbed LK-99 [2].

Even though the phenomenon of superconductivity is known now for over 112 years [3], any news of ambient temperature superconductivity creates a buzz because superconducting materials discovered thus far, which include metals, alloys, chalcogenides, oxides, and even organic compounds, exhibit superconductivity only when cooled to low temperatures. Cuprate ceramics, for instance, show superconductivity at ~35 K for the system Ba–La–Cu–O, 90 K for $YBa_2Cu_3O_{7-\delta}$, and 133K for $HgBa_2Ca_2Cu_3O_{>8}$, all at ambient pressure. Some hydrides do show superconductivity at warmer temperatures, or even at room temperature, but need to be compressed under high pressures before they do so [4, 5].

When Dr. Ranga Dias and his collaborators published that NLH showed superconductivity at room temperature (21 degrees Celsius, or 294 degrees Kelvin), under moderate applied pressure of just 10 kilobars (i.e., 145,000 pounds psi) [1], the lowest ever to drive superconductivity in hydrides, it was highlighted by the international press, the very next day. Why? For two reasons: first, a superconductor exhibits no resistance to the flow of electricity; and second, magnetic fields are expelled from the materials in a superconducting state, allowing magnets to levitate over them. This highlights the potential of superconducting materials for applications in at least three important sectors that impact our lives: (a) Energy, with applications in generators and motors, power transmission and distribution, energy storage systems, and magnets for fusion power and for magneto-hydrodynamic power; (b) Transportation, by using superconducting magnets for levitated trains, ship propulsion, and for automobiles; and (c) Healthcare, when employed in magnetic resonance imaging (MRI), and magnetoencephalography (MEG), etc. However, many scientists greeted the results by Dr. Dias with scepticism because an earlier paper by him and his colleagues describing near room-temperature superconductivity in a different material had been retracted by Nature [6].

In July 2023, arXiv preprints of two papers by a South Korean team led by Sukbae Lee and Ji-Hoon Kim at the start-up firm Quantum Energy Research Centre, proposed a lead-based compound, LK-99, having approximate composition $Pb_{10-x}Cu_x(PO_4)_6O$, to be a well-above-room-temperature, ambient-pressure superconductor, which shows the two key signs of superconductivity at normal air pressure and at temperatures up to 127 ℃ (400 Kelvin), viz. zero resistance and magnetic levitation resulting from the Meissner effect [2]. In another paper titled "Consideration for the development of room-temperature ambient-pressure superconductor (LK-99)" published in a Korean language Journal, 'Journal of the Korean Crystal Growth and Crystal Technology', the same S. Korean authors reported the discovery of the same superconducting material with the critical temperature of 97 °C, at atmospheric pressure. There is scepticism about LK-99 claim, too, because some other research groups have found the data published on LK-99 to be inconclusive and requiring further validation.

LK-99 may not end up being the room-temperature ambient-pressure superconductor as proposed, but the renewed excitement caused by it may well lead to other advances opening up the discovery of room-temperature superconductors in new, unexpected ways. In any case, both hydrides and organic superconductors have potential to offer superconductivity at room temperatures or even higher. W.A. Little [7] predicted in 1965 that using the excitonic mechanism of superconductivity one could produce organic superconductors with very high T_c values, even in excess of 1000 K.

Potential of Room-Temperature Superconductors (RT-SCs) in Key Applications

Apart from the constraint imposed by T_c, the potential of any superconductor is also limited by two other parameters, viz. the critical current density, Jc, up to which it can carry currents before superconductivity is destroyed; and the upper critical field, Bc2, which determines the limit to which it can produce magnetic fields under the flow of current. Above Bc2 the superconductivity disappears. Temperature, magnetic field and current density thus determine together whether a material would remain superconducting or not, and its potential for applications requires that it keeps the values of Jc and Bc2 parameters reasonably high at room temperature. In contrast to T_c and Bc2, the Jc of a superconductor can be controlled by metallurgical processing, such as by introducing defects in it. A popular account of the phenomenon of superconductivity and characteristics of different superconducting materials and their potential for applications is provided in a book published by the author recently [8].

It can be said that the best superconducting material would be the one that exhibits superconductivity at about a hundred degrees C above room temperature, without application of pressure. Only then its full potential for applications would be available for exploitation with the room temperature falling deep inside the superconducting state.

Conventional iron-core electromagnets with Cu windings are bulky and can provide a maximum field of only 2 Tesla since their iron-core gets saturated. Besides, the enormous joule-heating caused by the passage of large currents through the windings requires effective heat removal by water-cooling.

The absence of joule-heating in superconducting magnets offers a compact size and no power losses unlike the conventional iron-core electromagnets with Cu windings which can provide a maximum field of only 2 Tesla, above which their iron-core gets saturated. 1960s saw the availability of 10 Tesla superconducting magnets made from coils of Nb-47% Ti alloy which superconducts at 10 degrees Kelvin. Nb_3Sn discovered later shows a superconducting transition temperature of 18 degrees Kelvin, using which 24 T magnets can be made, but largely for research purposes such as in particle accelerators, due to the requirement of liquid Helium (He).

Public perception of application of superconductivity came with MRI (magnetic resonance imaging) machines for medical diagnostics, which use powerful high-field superconducting magnets and a liquid He refrigeration system to produce large and uniform magnetic fields inside the patient’s body, to produce an image, called MRI scan, of small regions of organs in the human body, and their health in detail. Excellent soft-tissue contrast and the non-use of any ionizing radiation during the recording of an MRI scan has made it an indispensable tool, leading to over half a million MRI scans performed in the world, daily. Each MRI machine requires a large amount of liquid He daily, and cryogenic facilities to handle it. Obviously, the use of RT-SCs in MRI magnets that does not need the expensive liquid He would be a boon.

SQUIDs (Superconducting QUantum Interference Devices) offer unrivalled sensitivity in sensing very weak magnetic signals. SQUID magnetometers and gradiometers find applications in biomagnetism—to study the magnetic fields produced by the electrical currents flowing in body tissues like skeletal muscles, heart, and brain. A uniquely successful application of SQUIDs is for measurements of the tiny magnetic fields produced by the firing neurons in a human brain, using a technique known as magnetoencephalography (MEG). SQUIDs are useful to conduct magnetocardiography (MCG), too, under which one records the magnetic fields produced by the human heart, without using any electrodes, as done for ECG.

Room-temperature superconductors (RT-SCs) would have the greatest impact on energy generation, transmission and distribution. Currently, about 10 percent of all energy produced for electrical grids is lost as waste heat, and could be saved by use of RT-SCs. Using RT-SCs in electrical transformers, which lower high voltages in transmission lines to levels suitable for home use, and generators, which convert rotational energy into electrical power, could save another 30 percent to 40 percent of wasted power.

SMES rings buried underground can hold a massive amount of electricity (~5000 MW h) with 90%–95% efficiency, unlike some conventional alternatives such as compressed air, batteries or reverse-hydro, etc, which have only 65%–70% efficiency. Industrial-scale batteries could be replaced entirely by RT-SC based energy storage systems, removing the main challenges in developing renewable energy at scale, because RT-SC based storage systems would work by letting electrical current travel in an endless loop, with virtually no losses, allowing the energy to be tapped from the loop only when required. The total energy lost when charging and discharging a conventional battery is around 20 percent, while in the case of a superconducting storage system, it would be 5 percent, or even less. Superconducting magnetic energy storage of capacity 2 GJ, 100 MW can be useful for load compensation, apart from providing high power density and low discharge time energy storage for smart grids.

Nuclear fusion produced by deuterium–tritium (DT) reaction is thought to be the ultimate solution to the energy problems of the world. Only about 15 g of DT fuel would be sufficient to produce all the electrical energy needed by a citizen of a large metropolis, for 80 years. The only waste from the DT reaction is atomic helium. The largest-ever tokamak fusion reactor ITER [International Thermonuclear Experimental Reactor] being built in France is aimed to demonstrate the initiation and sustaining of a controlled thermonuclear fusion aimed at getting more energy out than we put in, specifically to generate 500 MW output power on an input of just 50 MW. It is an international project, partnered by EC, India, Japan, S. Korea, Russia, USA, and China. Ten thousand tonnes of superconducting magnets are to be used by ITER to produce the magnetic fields that will initiate, confine, shape and control the ITER plasma.

A maglev train can travel on the principle of magnetic levitation, exploiting the diamagnetic property of a superconductor, in such a way that this train floats 10–20 mm above a track, under the influence of a magnetic field. Maglev technology has been under development in Japan for long. Powerful superconducting magnets levitate the train and also guide it along so that it can cruise at high speeds (500 km per hr) in a frictionless mode.

World’s first commercial maglev train, called Shanghai Transrapid, has been playing since 2004 at Shanghai in China. Maglev trains have been projected to open for public use in 2027 in Japan, running at speeds up to 375 miles per hour between Tokyo and Nagoya.

Computer chips made from superconducting materials would have potential to be around 300 times as energy efficient and 10 times as fast as our current silicon-based microelectronics (chips). Superconductor-based computing systems, where electrical resistance is zero, might solve the cooling challenge that increasingly bedevils the world’s data centres. Next-generation 6G chips would benefit from both the extreme speed and significantly lower power requirement of superconducting processors. The specialized computers inside cell phone towers that process wireless signals, are likely to benefit from superconducting computing tech.

Renewed hopes to use Y-Ba-Cu-O high-T_c superconductor for applications

Long-term economic and environmental benefits to be derived from superconductors are long overdue. Should they wait for new materials which superconduct above room-temperature? Can’t we try new innovative ideas which employ superconducting materials to upgrade at least the transportation and energy transport sectors, but in a cost-cutting manner?

A revolutionary idea has indeed been published in April 2023 by German scientists from ATZ and Leibnitz, in collaboration with Texas Centre for superconductivity at University of Houston by presenting a design that combines superconductor levitation, lossless electrical power transmission, and liquid H_2 (Hydrogen energy) transportation into one single system. The prototype of a combined system has been designed and demonstrated [9]. It is essentially a ‘super’ system that combines multiple functions: lossless electrical power transmission and storage; transport and storage of LH_2 energy and liquefied nitrogen (LN_2); and high-speed levitated transport of people and goods over long distances. In this system, vehicles with permanent magnets (or electromagnets) will be levitated above a superconductor guideway (“SClev”) which would also transmit and store electrical power.

They plan to build the SClev guideway on an existing highway infrastructure, allowing for simultaneous levitation of vehicles with magnetized undercarriages for rapid transport, and lossless transmission and storage of electricity. Vehicles with magnetized undercarriages can enter from or exit to residential, business, industrial, and recreational areas. LH2 and LN2 transported and stored in the system would cool the superconducting cables, and the LN_2 and vacuum layers thermally insulate the LH_2. A primary requisite for this project - the levitation of a magnet over a superconductor (YBCO) highway has been demonstrated in a model system. Construction of the ‘super’ system requires no land acquisition since it can be built on existing highway infrastructure to provide easy access to vehicles adapted for use on both standard and ‘super’ system roads.

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