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A look into the realm of Room-Temperature Superconductors

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Abstract
Condensation of hydrogen atoms into solid-state (metallic) under high pressure (~ 500 GPa) was one key experimental fact in this millennium. Triggering a race to explore the conditions necessary to produce a metallic state in metal-hydride compounds under high-pressures by using a diamond anvil cell, although some laboratories did not only obtain others compounds in metallic-state, they also achieved the superconducting state. In October 2020, carbon, sulfur and hydrogen compound became room-temperature superconductor ($\sim 287,7$ K) under pressure close to ~ 267 GPa, sparking again the interest in superconducting materials, and coming back one more time the dream of the technological applications of room-temperature superconductors without cooling liquid.

Keywords: Superconductors, Room temperature, High-pressure, Diamond anvil cell.

Una mirada hacia el reino de los superconductores a temperatura ambiente

Resumen
La condensación de átomos de hidrógeno en estado sólido (metálico) a alta presión (~ 500 GPa) fue un hecho experimental clave en este milenio. Desencadenando una carrera para explorar las condiciones necesarias para producir un estado metálico en compuestos de hidruro metálico a altas presiones mediante el uso de una celda de yunque de diamante, aunque algunos laboratorios no solo obtuvieron otros compuestos en estado metálico, sino que también lograron el estado superconductor. En octubre de 2020, el compuesto de carbono, azufre e hidrógeno se convirtió en superconductor a temperatura ambiente ($\sim 287,7$ K) bajo una presión cercana a los ~ 267 GPa, despertando nuevamente el interés por los materiales superconductores, regresando una vez más al sueño de las aplicaciones tecnológicas de los superconductores a temperatura ambiente sin líquido refrigerante.

Palabras clave: Superconductores, Temperatura ambiente, Alta presión, Celda de yunque de diamante.

In a near future, manufacturing processes of room-temperature superconductors (RTS) will be available and its costs will be comparable to ordinary conductors. RTS will replace normal conductor in virtually all devices involving electricity and magnetism. A useful RTS for most applications must have two main items: a) critical temperature over room-temperature, and b) capability to sustain superconductivity in presence of magnetic fields whereas carrying a significant current load [1]. RTS is the culmination of a dream that began to take shape

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from the discovery of superconductivity in mercury in 1911 by using liquid helium as a cooling liquid, passing through superconducting copper oxides in 1987 cooled with liquid nitrogen cheaper than liquid helium. Now it will be possible to cool the new room-temperature superconductors recently discovered [2] with conventional cooling devices saving large amounts of money, and possibly this circumstance will open a new door of research in Peru.

Superconducting materials always has puzzled and intrigued physicists for more than three decades. In low-temperature superconductors (classical superconductors), the disappearance of resistivity below certain critical superconducting temperature (T_c), and the expulsion of magnetic flux due to the Meissner effect are generally understood in terms of interactions between electrons with the host lattice (phonons), which can be described by the Bardeen, Cooper and Schieffer (BCS) theory [3]. Superconductivity can occur if the usual repulsive interaction between electrons turns into an attractive one. In this situation, the response of surrounding atoms to the charge and spin of electrons indirectly leads to electron pairing, known as Cooper pairs. Electrons associate in pairs at low temperatures, overlap each other to occupy a single wave that covers all the material. This is the idea of why superconductivity is called the most spectacular macroscopic quantum phenomenon. This single wave is not sensitive to any defects in the material so this is the reason how electrical resistance disappears. Despite its successes to unravel low-temperature superconductivity, this theory has been unable to describe the type of superconductivity observed in copper oxide superconductors [4], and explaining high-temperature superconductivity remains one of the great unsolved challenges of fundamental science.

On the other hand, quantum mechanics tells that every material can come into metallic state under high enough compression, in the order of GPa (million times atmospheric pressure at sea level). High-pressure studies of condensed matter at extreme densities have uncovered various new phenomena in simple molecular and elemental substances. One of the most significant pressure-induced changes in materials properties is the transformation of insulators into metals or maybe in superconductors. Previous studies of compressed sulphur indicated transitions to metallic phases at 90 GPa [5], and 162 GPa [6]. Struzhkin [7] has demonstrated that at 93 GPa, elemental sulphur transforms not only to metallic state, but also into superconducting state with a Tc $= 10,1$ K. Added to this fact, the extraordinary achievement of the transformation of hydrogen atoms into metallic state under high-pressure ($\sim$ 500 GPa) and very low-temperature ($5,5$K) [8] triggered the exploration of the superconducting state in hydride systems [9]. Experimental observation of metallic state of hydrogen atoms made possible to answer the theoretical prediction about superconducitivity in hydrogen formulated by N.W. Aschcroft in sixties decade. [10].

Diamons Anvil Cells

The need of very high-pressure experiments [11] brougth to the appareance in scene of advanced diamons anvil cells (DAC) with different configurations, and applications in several research fields such as materials science, physics, chemistry, geoscience, and bioscience. Briefly, DAC is considered one of the dominant devices to generate ultrahigh static pressure, and a formidable tool for detecting high-pressure phase transitions using a variety of methods. DAC squeezes samples in between two opposing diamonds to generate extremely high static pressure. The range of high static pressure attainable today extends to 640 GPa, much higher than the estimated pressures at the Earth's center ($\sim$ 360 GPa) [12]. Also, the phase transitions (in many cases) can be observed visually by changes in color, refractive index, texture, or shape of the sample. Next to visual observation, one can use other detection methods such as Raman, infrared, reflection, or transmission spectroscopy; synchrotron X-ray diffraction; nuclear magnetic resonance; magnetic or resistivity measurements; and Mössbauer spectroscopy.

Copper Oxide Superconductors

The highest Tc = 133 K at ambient pressure has been achieved to date in the copper oxide system [13], and Tc = 164 K under quasihydrostatic pressures up to 45GPa [14]. As described previously, the nature of superconductivity in these materials is still not fully understood because they are not conventional superconductors. The prospects for achieving still higher transition temperatures in copper oxide system under high-pressure are not clear. In contrast, the BCS theory of conventional superconductivity gives a guide for achieving high Tc with no theoretical upper bound—all that is needed is a favourable combination of high-frequency phonons, strong electron–phonon coupling, and a high density of states [10]. These conditions can in principle be fulfilled for metallic hydrogen and covalent compounds dominated by hydrogen [15] [16], as hydrogen atoms provide the necessary high frequency phonon modes as well as the strong electron–phonon coupling. Numerous calculations support this idea and have predicted transition temperatures in the range 50 – 235 K for many hydrides [9] [17]. The computational and experimental exploration of the phase diagrams of binary hydrides under high-pressure has uncovered phases with novel stoichiometries and structures, some which are superconducting at quite high temperatures (near to- or room-temperature).

Substitution Chemistry

Most superconducting materials have been created by using substitutional chemistry. This was possible by replacing iso- or alio-valent cations and/or anions in the unit cell structure [18] [19]. This replacing produces an internal chemical pressure capable of altering the occupation, and position of the neighbouring atoms in the unit cell. Therefore, this chemical pressure has a direct influence on Tc due to charge-transfer phenomenon, leading the resulting compound from semiconductor state to the superconducting state, or perhaps increasing its Tc.

Room-Temperature Superconductor

High-temperature conventional superconductivity in hydrogen-rich materials has been reported in several systems under high-pressure [9]; this extreme condition produces the creation of guest–host structures in the compound that become into the appeareance of the building blocks of superconducting compounds. Bi [17] claimed that in their study on metal hydrides the propensity for superconductivity is dependent upon the species used to "dope" hydrogen, with some of the highest values obtained for elements that belong to alkaline and rare earth, or the pnictogen and chalcogen families. A landmark discovery leading to RTS was done by Snider [2] in october 2020. They claimed RTS in a photochemically transformed carbonaceous sulfur hydride system with a maximum $T_c = 287,7 \pm 1,2$K achieved at 267 ± 10 GPa (2.6 million times atmospheric pressure at sea level), and the compound does not have to be cooled for its electrical resistance to vanish. Also, they observed the superconducting state over a broad pressure range in the DAC, from 140 to 275 GPa, with a sharp up turn in transition temperature above 220 GPa. Moreover, they have established superconducting state by the observation of zero resistance, a magnetic susceptibility of up to 190 GPa, and they monitored the reduction of the Tc under an external magnetic field of up to 9,0 T, with an upper critical magnetic field of about 62,0 T according to the Ginzburg–Landau model [20] at zero temperature. Furthermore, they reported that the introduction of chemical tuning within their ternary system could enable the preservation of the properties of RTS at lower pressures so there are a lot of experiments to perform. However, much about the material remains unknown, as well as the crystal's exact structure and chemical formula are not yet understood because when one perform high-pressure experiments sample size gets smaller (diamond tip area $\sim 20\mu$m) so this kind of measurements are really challenging. Figure 2 shows timeline of metal-hydride-system versus temperature including copper oxide superconductors and sulphur for comparison purposes.

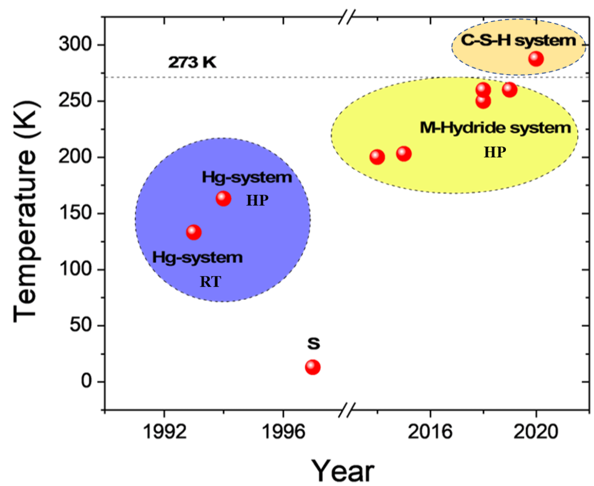

Figure 1: Timeline of M-Hydride-system at high-pressure.

Finally, what remains to be done for the scientific community?. Understanding the mechanism of non-BCS superconductivity must be more than just an issue of intellectual curiosity. Moreover, the use of powerful computers to search for new and better superconducting compounds will be limited by a poor comprehension of the superconductivity mechanism(s). It could change with a deep knowledge of RTS. The game in on.

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References

[1] A. Bussmann-Holder and H. Keller. High-temperature superconductors: underlying physics and applications. *Zeitschrift für Naturforschung B* ***75***, 3. https://doi.org/10.1515/znb-2019-0103 (2019).

[2] E. Snider, N. Dasenbrock-Gammon, R. McBride. Room-temperature superconductivity in a carbonaceous sulfur hydride. *Nature* ***586***, 373. https://doi.org/10.1038/s41586-020-2801-z (2020).

[3] J. Bardeen, L. Cooper and J. Schieffer. Theory of Superconductivity. *Phys. Rev.* ***108***, 1175. https://doi.org/10.1103/PhysRev.108.1175 (1957).

[4] M. Wu, J. Ashburn, C. Torng, P. Hor, R. Meng, R. Gao, Z. Huang, Y. Wang and C. Chu. Superconductivity at 93 K in a New Mixed-Phase Y-Ba-Cu-0 Compound System at Ambient Pressure *Phys. Rev. Lett.* ***58***, 908 https://doi.org/10.1103/PhysRevLett.58.908 (1987).

[5] H. Luo, S. Desgreniers, Y. Vohra and A. Ruoff. High pressure optical studies of sulfur to 121 GPa: optical evidence for metallization. *Phys. Rev. Lett.* ***67***, 2998. https://doi.org/10.1103/PhysRevLett.67.2998 (1991).

[6] H. Luo, R. Greene and A. Ruoff. β -Po phase of sulfur at 162GPa: X-ray diffraction study to 212GPa. *Phys. Rev. Lett.* ***71***, 2943. https://doi.org/10.1103/PhysRevLett.71.2943 (1993).

[7] V. Struzhkin, R. Hemley, H. Mao and Y. Timofeev. Superconductivity at 10–17K in compressed sulphur. *Nature* ***390***, 382. https://doi.org/10.1038/37074 (1997).

[8] R. Dias and I. Silvera. Observation of the Wigner-Huntington transition to metallic hydrogen. *Science* ***355***, 715. https://doi.org/10.1126/science.aal1579 (2017).

[9] D. Kim, R. Scheicher, H. Mao, T. Kang and R. Ahuja. General trend for pressurized superconducting hydrogen-dense materials *PNAS* ***107***, 2793. www.pnas.org/cgi/doi/10.1073/pnas.0914462107 (2010).

[10] N. Ashcroft. Metallic hydrogen: A high-temperature superconductor? *Phys. Rev. Lett.* ***21***, 1748. https://doi.org/10.1103/PhysRevLett.21.1748 (1968).

[11] A. Dewaele, P. Loubeyre, F. Occelli, O. Marie and M. Mezouar. Toroidal diamond anvil cell for detailed measurements under extreme static pressures. *Nature Comm.* ***9***, 2913. https://doi.org/10.1038/s41467-018-05294-2 (2018).

[12] R. Boehler. Diamond cells and new materials. *Materials Today* ***8***, 32. 10.1016/S1369-7021(05)71158-5 (2005).

[13] A. Schilling, M. Cantoni, J. Guo and R.O. Superconductivity above 130-K in the Hg-BaA-Ca-Cu-O system. *Nature* ***363***, 56. https://doi.org/10.1038/363056a0 (1993).

[14] L. Gao, Y. Xue, F. Chen, Q. Xiong, R. Meng, D. Ramirez, C. Chu, J. Eggert and H. Mao. Superconductivity up to 164 K in HgBa2Cam-lCum02m+2+6 (m=l, 2, and 3) under quasihydrostatic pressures. *Phys. Rev. B* ***50***, 4260. https://doi.org/10.1103/PhysRevB.50.4260 (1994).

[15] K. Johnson and N. Ashcroft. Structure and bandgap closure in dense hydrogen, *Nature* ***403***, 632. https://doi.org/10.1038/35001024 (2000).

[16] C. Pickard and R. Needs. Structure of phase III of solid hydrogen. *Nat. Phys.* ***3***, 473. https://doi.org/10.1038/nphys625 (2007).

[17] T. Bi, N. Zarifi, T. Terpstra and E. Zurek. The Search for Superconductivity in High Pressure Hydrides in Reference Module in Chemistry, Molecular Sciences and Chemical Engineering, Elsevier https://doi.org/10.1016/B978-0-12-409547-2.11435-0 (2019).

[18] JC. González, L. De Los Santos, A. Osorio, J. Flores and A. Bustamante. A retrospective vision of the first 14 years on superconducting ceramic oxidematerials research in the UNMSM. *Rev. Inv. Fis.* ***14***, 111401911 https://fisica.unmsm.edu.pe/rif/previo_files/2011-1/a10.pdf (2011).

[19] JC. González and A. Bustamante. Superconductors containing phosphates groups derivatives from YBa2Cu3O7. *Rev. Inv. Fis.* ***16***, 131602103. https://fisica.unmsm.edu.pe/rif/previo_files/2013-2/04gonzalez.pdf (2013).

[20] V. Ginzburg and L. Landau. On the Theory of Superconductivity. In: On Superconductivity and Superfluidity. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-540-68008-6_4 (2009).