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**CUPRATE HIGH TEMPERATURE
SUPERCONDUCTORS: A brief review**
(methodological manual)

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A brief information about High-Temperature Superconductive Cuprates is collected in the manual. In particular, the main physical parameters and crystal structure of cuprates are given. Recommendations for the use of digital technologies in the teaching of superconductivity physics are given.

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Introduction

Getting the student interested in science is the most urgent pedagogical problem. For this reason, the goal of modern education is not only to give knowledge to the student, but also to awaken the student's interest in science, to form and develop his scientific worldview, and to educate him as a person who can find his place in a competitive society and fully realize his abilities. In this regard, systematic educational reforms are being carried out in our country. In particular, wide-scale issues such as teaching physics, attracting young people to the field of physics and further developing their interest in physics are reflected in the decision of the President of the country ¹.

Among the many sections of solid-state physics, the section of superconductor physics celebrated its centenary in 2011 and continues to develop rapidly. In this regard, there is an urgent educational and methodological need to introduce senior undergraduate and graduate students to the course of the section, familiarizing them in a brief form with the basics of superconductor physics, including high-temperature superconductivity of the cuprate. This methodological manual aims to briefly familiarize the reader with the basic physical properties of cuprate high-temperature superconductors². In doing so, basic parameters of La-, Y-, Bi-, Tl- and Hg-based cuprate high temperature superconductors, including their crystal structures, will be given within the methodological manual.

In addition, the manual discusses the use of digital technology in teaching a course in superconductivity. In particular, the usefulness of “Youtube.com” platform and “Comsol Multiphysics” simulation software in

¹ Decree of the President of the Republic of Uzbekistan, No. PQ-5032 dated 19.03.2021.

² Due to the limited volume of the methodological manual, we will limit ourselves to considering only hole-doped cuprates.

teaching superconductor physics course is emphasized. Some use of above platform and simulation software is pointed in teaching the course ¹.

§ 1. A Brief History of HTSC of Cuprates

In September of 1986, J.G. Bednorz and K.A. Müller, two physicists of the IBM Zürich Research Laboratory, discovered HTSC in La-Ba-Cu-O system at a relatively high temperature compared to existing ones ². SC CT of the discovered material was somewhere around 30 K. The phase responsible for SC was identified to have nominal composition of $\text{La}_{2-x}\text{Ba}_x\text{CuO}_4$ ($x=0.2$). The latter compound had a perovskite layered phase of the type K_2NiF_4 with lattice periods $a=3.79 \text{ \AA}$ and $c=13.2 \text{ \AA}$. Bednorz and Müller published their findings in April 1986 in the German scientific journal *Zeitschrift für Physik*³ and in the next 1987 year they were awarded the Nobel Prize in physics.

Cava et al., doped La_2CuO_4 Mott insulator by chemical element Sr, partially replacing La by Sr thereby reproducing chemical pressure, and obtained the compound of chemical composition $\text{La}_{1.8}\text{Sr}_{0.2}\text{CuO}_4$ which has SC CT $T_c=36 \text{ K}$ ⁴.

A year later, the groups of physicists from University of Alabama (group leader M.K. Wu) and University of Houston (group leader C.W. Chu) discovered SC in the Y-Ba-Cu-O system, in which $\text{YBa}_2\text{Cu}_3\text{O}_7$ (YBCO-123 or

¹ A. Abdimuratova, B.Ya. Yavidov. Teaching Superconductivity Physics with Aurora from Comsol Multiphysics Platform // "Fizika Fanini O'Qitishda Raqamli Texnologiyalardan Foydalanishning Dolzarb Muammolari" mavzusidagi Respublika ilmiy-amaliy konferensiyasining to'plami, Jizzax DPU 2024-yil 11-noyabr. 112-114 betlar.

² At the time of discovery, the maximal superconducting critical temperature $T_c=23.2 \text{ K}$ belong to intermetallic compound Nb_3Ge that was established in 1973.

³ J.G. Bednorz and K.A. Müller. Possible high T_c superconductivity in the Ba-La-Cu-O system. *Zeitschrift für Physik B Condens. Matter* **64**, 189–193 (1986).

<https://doi.org/10.1007/BF01303701>

⁴ R.J. Cava, R.B. Dover, B. Batlogg, E.A. Rietman. Bulk superconductivity at 36 K in $\text{La}_{1.8}\text{Sr}_{0.2}\text{CuO}_4$. *Phys. Rev. Lett.* **58**, 408–410 (1987).

<https://doi.org/10.1103/PhysRevLett.58.408>

Y123) structure exhibits a sharp SC transition around 93 K¹. Almost all the rare earth (Re) elements can be substituted for Y with similar atomic structures and high SC CT values. These materials are often referred to as ReBCO. YBCO-ReBCO were the first SC materials whose CT lies well above the liquid nitrogen boiling point of 77 K, and they have continued to be leading SC materials for electric power applications.

Subsequent studies led to the discovery of HTSC in a number of cuprates. Thus, HTSC was discovered in Bi-, Tl- and Hg-based cuprates.

In 1988, discovery of a new high temperature oxide SC without the rare earth elements was reported by Maeda et al.². Namely, a multiphase sample of the Bi-Sr-Ca-Cu-O compound was synthesized with SC CT 105 K. The highest SC CT of 110 K was obtained in the Bi-Sr-Ca-Cu-O compound having a composition $\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_{10}$ ^{3,4}.

In November 1987 Sheng and Hermann detected superconductivity above 90 K in $\text{TlBa}_2\text{Cu}_3\text{O}_x$ compounds⁵, which was obtained by replacing Re with non-magnetic trivalent Tl in Re-123. By partially substituting Ca for Ba,

¹ M.K. Wu, J.R. Ashburn, C.J. Torng, P.H. Hor, R.L. Meng, L. Gao, Z.J. Huang, Y.Q. Wang and C.W. Chu. Superconductivity at 93 K in a New Mixed-Phase Y-Ba-Cu-O Compound System at Ambient Pressure. *Phys. Rev. Lett.* **58**, 908 (1987).
<https://doi.org/10.1103/PhysRevLett.58.908>

² Hiroshi Maeda and Yoshiaki Tanaka and Masao Fukutomi and Toshihisa Asano. A New High-Tc Oxide Superconductor without a Rare Earth Element. *Jpn. J. Appl. Phys.* **27** (2A), L209 (1988). <https://dx.doi.org/10.1143/JJAP.27.L209>

³ R.M. Hazen, C.T. Prewitt, R.J. Angel, N.L. Ross, L.W. Finger, C.G. Hadidiacos, D.R. Veblen, P.J. Henaey, P.H. Hor, R.L. Meng, L. Gao, J. Bechtold, C.W. Chu. Superconductivity in the high- T_c Bi-Ca-Sr-Cu-O system: Phase identification. *Phys. Rev. Lett.* **60**, 1174–1177, 1988.
<https://link.aps.org/doi/10.1103/PhysRevLett.60.1174>

⁴ J.M. Tarascon, W.R. McKinnon, P. Barboux, D.M. Hwang, B.G. Bagley, L.H. Greene, G.W. Hull, Y. LePage, N. Stoffel, M. Giroud. Preparation structure and properties of the superconducting compound series $\text{Bi}_2\text{Sr}_2\text{Ca}_{n-1}\text{Cu}_n\text{O}_y$ with $n=1, 2$ and 3 . *Phys. Rev. B* **38**, 8885, 1988.
<https://link.aps.org/doi/10.1103/PhysRevB.38.8885>

⁵ Z.Z. Sheng and A.M. Hermann. Superconductivity in the rare-earth free Tl-Ba-Cu-O system above liquid nitrogen temperature. *Nature* **332**, 55–58, 1988.
<https://doi.org/10.1038/332055a0>

they discovered a multiphase sample of Tl-Ba-Ca-Cu-O in February 1988. Tl-Ba-Ca-Cu-O system showed SC CT about 120 K ¹.

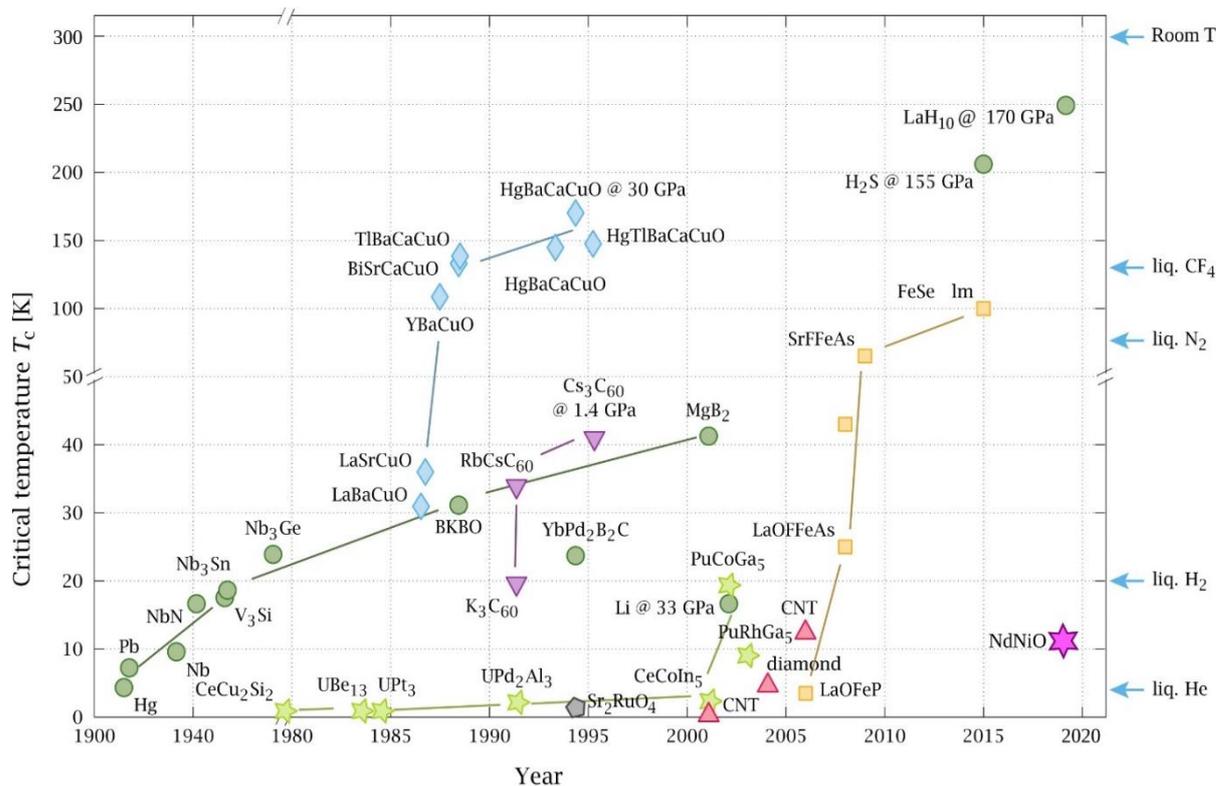


Figure 1. The chronology of the discoveries of superconducting compounds.

Detection of HTSC in Hg-based cuprates was done in September 1992 by Putillin et al., who found that the $\text{HgBa}_2\text{CuO}_x$ compound with only one CuO_2 layer shows SC CT of up to 94 K ². It was, therefore, rather natural to expect that SC CT can be increased by adding more CuO_2 layers in the per unit formula to the compound. In April 1993, Schilling et al. reported the detection of superconductivity at temperatures up to 133 K in $\text{HgBa}_2\text{Ca}_2\text{Cu}_3\text{O}_x$ ³. The SC CT of $\text{HgBa}_2\text{Ca}_2\text{Cu}_3\text{O}_x$ cuprate was found to

¹ Z.Z. Sheng, A.M. Hermann, A. El Ali, C. Almasan, J. Estrada, T. Datta, R.J. Matson. Superconductivity at 90 K in the Tl-Ba-Cu-O system. *Phys. Rev. Lett.* 60:937–940, 1988. <https://link.aps.org/doi/10.1103/PhysRevLett.60.937>

² S. Putilin, E. Antipov, O. Chmaissem, M. Marezio. Superconductivity at 94 K in $\text{HgBa}_2\text{CuO}_{4+\delta}$. *Nature* 362, 226–228 (1993). <https://doi.org/10.1038/362226a0>

³ A. Schilling, M. Cantoni, J.D. Guo, H.R. Ott. Superconductivity above 130 K in the Hg-Ba-Ca-Cu-O system. *Nature* 363, 56–58, 1993. <https://doi.org/10.1038/363056a0>

increase to 153 K with the application of 23 GPa pressure ¹. The chronology of the discovery of superconducting compounds can be found in Fig. 1 in which blue diamonds represent cuprate family of HTSC among other families of LTSC and HTSC. To date, a plenty of superconducting cuprates are identified. In Table 1 some of cuprate SC are listed alongside with chemical formula, notation, SC CT in Kelvins, number of CuO₂ planes in the unit cell, crystal structure and lattice constants in Angstrom (Å).

TABLE 1. SC transition temperature (T_c), Crystal structure and Lattice constants of some cuprate HTSC ².

Cuprate HTSC		SC CT, T_c K	Number of CuO ₂ planes in the unit cell	Crystal structure	Lattice constants, Å
Formula	Notation				
La _{1.6} Ba _{0.4} CuO ₄	214	30	1	Tetragonal	$a=3.79, c=13.21$
La _{1.84} Sr _{0.16} CuO ₄	214	38	1	Tetragonal	$a=3.78, c=13.23$
YBa ₂ Cu ₃ O ₇	Y123	92	2	Orthorhombic	$a=3.82, b=3.89, c=11.68$
YBa ₂ Cu ₄ O ₈	Y124	80	2	Orthorhombic	$a=3.84, b=3.87, c=27.23$
Y ₂ Ba ₄ Cu ₇ O ₁₄	Y247	40	2	Orthorhombic	$a=3.85, b=3.87, c=50.2$
Bi ₂ Sr ₂ CuO ₆	Bi-2201	20	1	Tetragonal	$a=5.39, c=24.6$

¹ A. Yamamoto, N. Takeshita, Ch. Terakura and Y. Tokura. High pressure effects revisited for the cuprate superconductor family with highest critical temperature. *Nature Commun.* **6**, 8990 (2015). <https://doi.org/10.1038/ncomms9990>

² The table is adopted from the book "Handbook of High-Temperature Superconductor Electronics", edited by Neeraj Khare, Marcel Dekker, Inc. (2003).

$\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$	Bi-2212	85	2	Tetragonal	$a=5.39, c=30.6$
$\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_{10}$	Bi-2223	110	3	Tetragonal	$a=5.39, c=37.1$
$\text{TlBa}_2\text{CuO}_5$	Tl-1201	25	1	Tetragonal	$a=3.74, c=9.00$
$\text{TlBa}_2\text{CaCu}_2\text{O}_7$	Tl-1212	90	2	Tetragonal	$a=3.85, c=12.74$
$\text{TlBa}_2\text{Ca}_2\text{Cu}_3\text{O}_9$	Tl-1223	110	3	Tetragonal	$a=3.85, c=15.87$
$\text{TlBa}_2\text{Ca}_3\text{Cu}_4\text{O}_{11}$	Tl-1234	122	4	Tetragonal	$a=3.86, c=19.01$
$\text{Tl}_2\text{Ba}_2\text{CuO}_6$	Tl-2201	80	1	Tetragonal	$a=3.86, c=23.22$
$\text{Tl}_2\text{Ba}_2\text{CaCu}_2\text{O}_8$	Tl-2212	108	2	Tetragonal	$a=3.86, c=29.39$
$\text{Tl}_2\text{Ba}_2\text{Ca}_2\text{Cu}_3\text{O}_{10}$	Tl-2223	125	3	Tetragonal	$a=3.85, c=35.9$
$\text{HgBa}_2\text{CuO}_4$	Hg-1201	94	1	Tetragonal	$a=3.87, c=9.51$
$\text{HgBa}_2\text{CaCu}_2\text{O}_6$	Hg-1212	128	2	Tetragonal	$a=3.85, c=12.66$
$\text{HgBa}_2\text{Ca}_2\text{Cu}_3\text{O}_8$	Hg-1223	134	3	Tetragonal	$a=3.85, c=15.78$
$(\text{Nd}_{2-x}\text{Ce}_x)\text{CuO}_4$	T	30	1	Tetragonal	$a=3.94, c=12.07$
$(\text{Nd,CeSr})\text{CuO}_4$	T*	30	1	Tetragonal	$a=3.85, c=12.48$

In the following paragraphs the main physical properties of various cuprates will be given in brief form.

§ 2. La-based Cuprates

The simplest crystal structure among cuprates belongs to La-based cuprates. La-based cuprates laid the foundation for the physics of high-temperature superconductivity. Studying the crystal structure of cuprates is an important aspect of understanding their superconducting properties. It has been studied that the critical temperature- T_c of superconductivity in bulk cuprate samples can be increased using external influences. For example, the superconductivity T_c of cuprate films differs from the superconductivity T_c of bulk samples. If a bulk cuprate sample is grown on a substrate, it is

referred to as a cuprate thin film. Experiments have shown that by changing the La content in La_2CuO_4 and doping it with another element (such as La or Ba), the superconducting critical temperature can be modified. In this section of the methodological guide, we will focus on some information about La-based cuprates. As the first representative of La-based superconducting cuprates, the Ba-doped LBCO cuprate can be mentioned.

The LBCO cuprate has a tetragonal crystal structure. The crystal structure LBCO showed in Fig. 2.1. Its lattice constants are as follows: $a=3,788 \text{ \AA}$ and $c=13,23 \text{ \AA}$ and its space group $I4/mmm$. Experiments have shown that

doping with Sr instead of Ba leads to a significant increase in the critical temperature of superconductivity. This Sr-doped cuprate is represented by the chemical formula $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$ (LSCO). The cuprate $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$ is sometimes referred to as La214 in certain literature. This designation arises from its crystal structure, which contains two La (Sr) atoms, one copper (Cu) atom, and four oxygen (O) atoms. Figure 2.2 presents the crystal structure of the cuprate $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$. As seen in Figure 2.2, an oxygen atom is positioned above the Cu atoms located in the CuO_2 plane. This oxygen is called the apical oxygen. The distance between the Cu atom and the apical oxygen atom is called the apical distance. This distance has a certain effect on the change in the value of the superconductivity critical temperature. In cuprates, charge carriers move along the copper-oxygen planes. This is precisely why, due to the stretching along the c -axis, the superconductivity critical temperature increases in experiments. The reason is that stretching along the c -axis

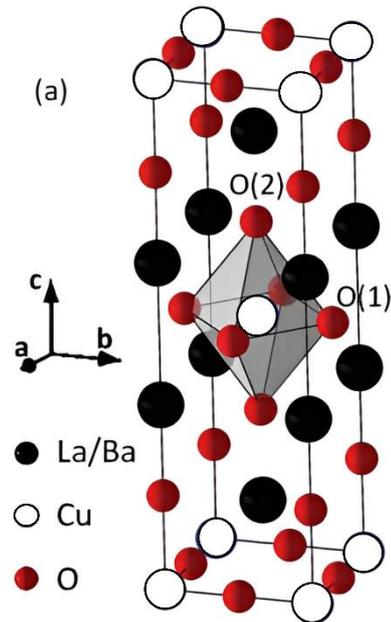


Figure 2.1. The crystal structure of LBCO.

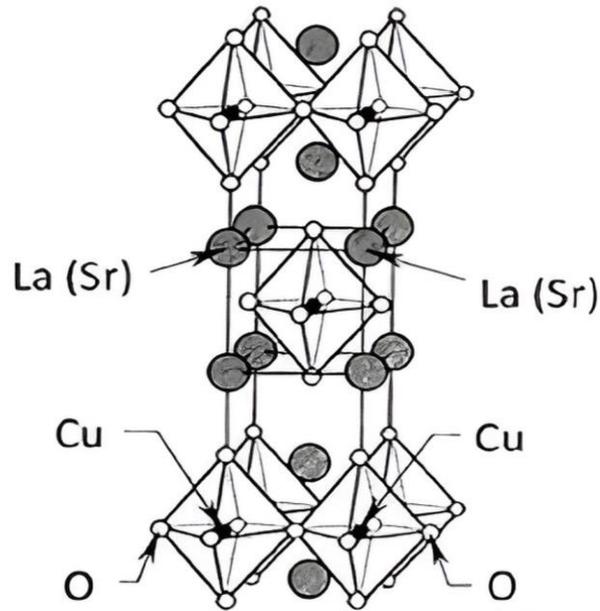


Figure 2.2. Crystal structure of $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$ cuprate

expands the movement zone of the charge carriers, which increases the apical distance. The cuprate $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$ achieves the maximum value of its superconductivity critical temperature at a doping level of $x = 0,15^1$. This doping level is called the optimal doping level.

§ 3. Y-Based Cuprates

The discovery of superconductivity in La-based cuprates inspired scientists to conduct further experiments on cuprates. As a result, it soon led to the synthesis of Y-based cuprates. We provide brief information about the $\text{YBa}_2\text{Cu}_3\text{O}_7$ cuprate, a representative of Y-based cuprates. This represents the case of the $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ cuprate when $\delta=0$. The superconducting critical temperature of $\text{YBa}_2\text{Cu}_3\text{O}_7$ cuprate is above 90 K, and it has two types of crystal structures. The first is an orthorhombic crystal structure, and the second is a tetragonal crystal structure. In its crystal structure, there are also

¹ Michio Naito*, Hisashi Sato, Akio Tsukada, Hideki Yamamoto. Epitaxial effects in thin films of high- T_c cuprates with the $K_2\text{NiF}_4$ structure. *Physica C: Superconductivity and its applications* 546 (2018) 84–114. <https://doi.org/10.1016/j.physc.2017.11.010>

Cu-O chains along with CuO_2 planes (Figure 3.1). These Cu-O chains are oriented along the b-axis. As shown in Figure 3.1, each copper atom in the

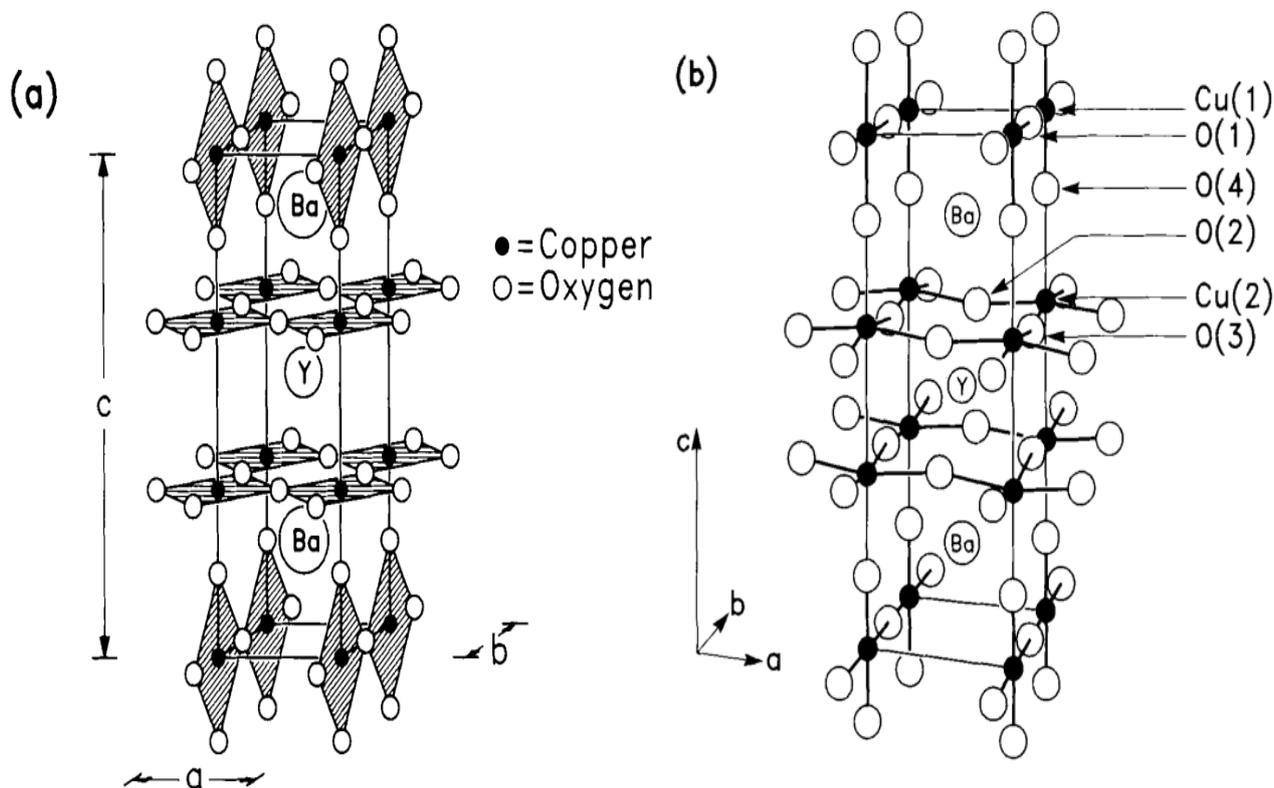


Figure 3.1. Crystal structure of $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ cuprate

Cu-O chain is surrounded by four oxygen atoms. This makes its crystal structure more complex compared to La-based cuprates. Moreover, the fact that there are two CuO_2 planes in its crystal structure ensures that its superconducting T_c is higher compared to La-based cuprates. The lattice constants are $a = 3,828$, $b = 3,888$ and $c = 11,65 \text{ \AA}$. The lengths of the bonds are $\text{Cu}(1)\text{-O}(1)=1,947$, $\text{Cu}(1)\text{-O}(4)=1,834$, $\text{Cu}(2)\text{-O}(2)=1,929$, $\text{Cu}(2)\text{-O}(3)=1,961$ and $\text{Cu}(2)\text{-O}(4)=2,341 \text{ \AA}^1$. One of the factors contributing to the high superconducting T_c of cuprates is the number of CuO_2 planes in their crystal structure. An increase in the number of Cu-O planes is observed to lead to an

¹ Calestani Rizzoli C. Crystal structure of the $\text{YBa}_2\text{Cu}_3\text{O}_7$ superconductor by single-crystal X-ray diffraction // *Nature*. -1987. -Vol. 328. -P. 606-607. <https://doi.org/10.1038/328606a0>

increase in the superconducting T_c value¹. Typically, the maximum superconducting T_c is achieved when the number of CuO_2 planes is three. It has been studied that the superconducting T_c of cuprates with fewer planes can also be altered by applying external influences. In the $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ cuprate, the critical temperature of superconductivity and the lattice constants vary depending on the numerical value of δ . As mentioned, the crystal structure of the YBCO cuprate is somewhat complex. This can also be observed from the table above, where changes are expressed depending on the value of δ . The superconducting properties of the YBCO cuprate continue to be studied by scientists.

§ 4. Bi-Based Cuprates

The discovery of superconductivity at temperatures above the boiling point of nitrogen led to an increase in research focused on discovering new types of materials with such superconducting properties. As a result, a critical superconducting temperature of 105 K was achieved in the Bi-Sr-Ca-Cu-O compound by Maeda et al. in 1988². The crystal structure of Bi-, Tl-, and Hg-based high- T_c superconductors are very similar to each other. The Bi-Sr-Ca-Cu-O system has three superconductivity phases forming a homologous series as $\text{Bi}_2\text{Sr}_2\text{Ca}_{n-1}\text{Cu}_n\text{O}_{4+2n+y}$ ($n=1,2,3$). Those Bi-2201, Bi-2212 and Bi-2223. Their crystal structure is shown in Figure 4.1.

The Bi-2201, Bi-2212, and Bi-2223 cuprates differ from each other in the number of CuO_2 planes. The CuO_2 planes in them are equal to one, two, and three, respectively. Crystal structure of Bi-based cuprates belongs to space

¹ N. Plakida. High-Temperature Cuprate Superconductors. –Berlin : Springer, 2010. –P. 581. <https://doi.org/10.1007/978-3-642-12633-8>

² Hiroshi Maeda and Yoshiaki Tanaka and Masao Fukutomi and Toshihisa Asano. A New High-Tc Oxide Superconductor without a Rare Earth Element. Jpn. J. Appl. Phys. **27** (2A), L209 (1988). <https://dx.doi.org/10.1143/JJAP.27.L209>

group $P4/mmm$. $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{10}$ cuprate lattice parameters are (all in nm) $a = 0,539$, $b = 0,539$, and $c = 3,71$.

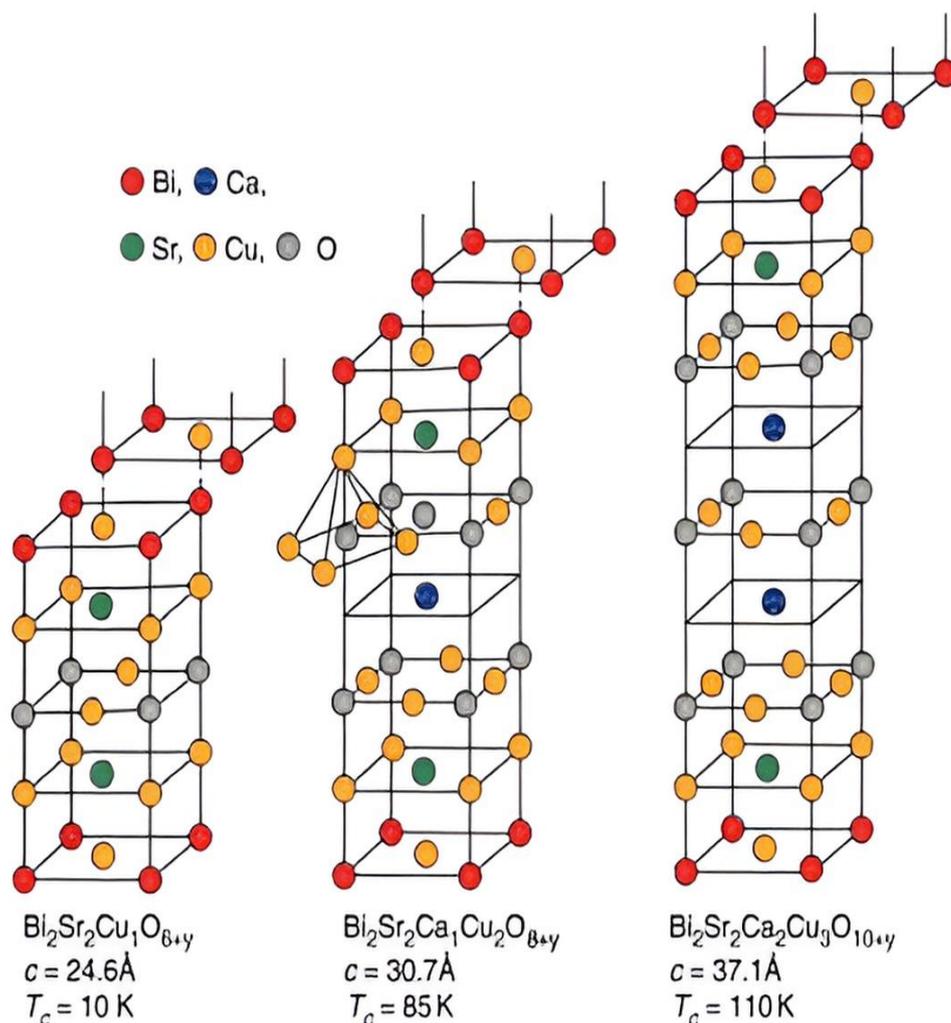


Figure 4.1. Crystallographic structures of $\text{Bi}_2\text{Sr}_2\text{Ca}_{n-1}\text{Cu}_n\text{O}_{4+2n+y}$ (BSCCO) family, with $n=1, 2, 3$.

As seen in Figure 4.1, the critical temperature of superconductivity differs for each representative of the Bi-based cuprate family. Similarly, their physical parameters also vary.

Tables 4.1 present numerical values taken from various literature sources for several representatives of the Bi-based cuprate family¹.

¹ Shamray, V. F., Mikhailova, A. B., & Mitin, A. V. (2009). *Crystal structure and superconductivity of Bi-2223*. *Crystallography Reports*, 54(4), 584–590.
<https://doi.org/10.1134/S1063774509040075>

Table 4.1. Superconductivity T_c , lattice parameters, and number of CuO_2 planes for the Bi-based high-temperature superconductors.

Compound	Desination	Number of CuO_2 planes	T_c , K	Lattice parameters, Å		
				a	b	c
$\text{Bi}_2\text{Sr}_2\text{CuO}_6$	Bi-2201	1	~12	5,3907	5,3907	24,534
$\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$	Bi-2212	2	95	5,399	5,398	30,78
$\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_{10}$	Bi-2223	3	110	5,411	5,409	37,082

§ 5. Tl-Based Cuprates

Table 5.1 presents numerical data on the critical temperature of superconductivity, lattice constants, and CuO_2 planes for several representatives of the Tl-based cuprate family.

Table 5.1. Superconductivity T_c , lattice parameters, and number of CuO_2 planes for the Tl-based high-temperature superconductor¹

Compound	Desination	Number of CuO_2 planes	T_c , K	Lattice parameters, Å		
				a	b	c
$\text{Tl}_2\text{Ba}_2\text{CuO}_6$	Tl-2201	1	95	3,8637		23,1392
$\text{Tl}_2\text{Ba}_2\text{CaCu}_2\text{O}_8$	Tl-2212	2	105	3,85432		29,3408
$\text{Tl}_2\text{Ba}_2\text{Ca}_2\text{Cu}_3\text{O}_{10}$	Tl-2223	3	125	3,84992		35,6967

There are two types of representatives in the Tl-based cuprate family: $\text{TlBa}_2\text{Ca}_{n-1}\text{Cu}_n\text{O}_{2n+3}$ and $\text{TlBa}_2\text{Ca}_{n-1}\text{Cu}_n\text{O}_{2n+4}$. This section presents some

¹ Shamray, V. F., Mikhailova, A. B., & Mitin, A. V. (2009). *Crystal structure and superconductivity of Bi-2223. Crystallography Reports*, 54(4), 584–590.
<https://doi.org/10.1134/S1063774509040075>

information about Tl-based cuprates given by the $\text{TlBa}_2\text{Ca}_{n-1}\text{Cu}_n\text{O}_{2n+4}$ ($\text{Tl-}22(n-1)n$) formula. Figure 5.1 illustrates the crystal structures of the $\text{TlBa}_2\text{CaCu}_2\text{O}_7$, $\text{TlBa}_2\text{Ca}_2\text{Cu}_3\text{O}_8$, and $\text{TlBa}_2\text{Ca}_3\text{Ca}_4\text{O}_{10}$ cuprates.

As shown in Figure 5.1, the $\text{TlBa}_2\text{CaCu}_2\text{O}_7$ compound contains two CuO_2 layers with Ca positioned between them. In $\text{TlBa}_2\text{Ca}_2\text{Cu}_3\text{O}_8$ and $\text{TlBa}_2\text{Ca}_3\text{Cu}_4\text{O}_{10}$, there are 3 and 4 CuO_2 planes, respectively.

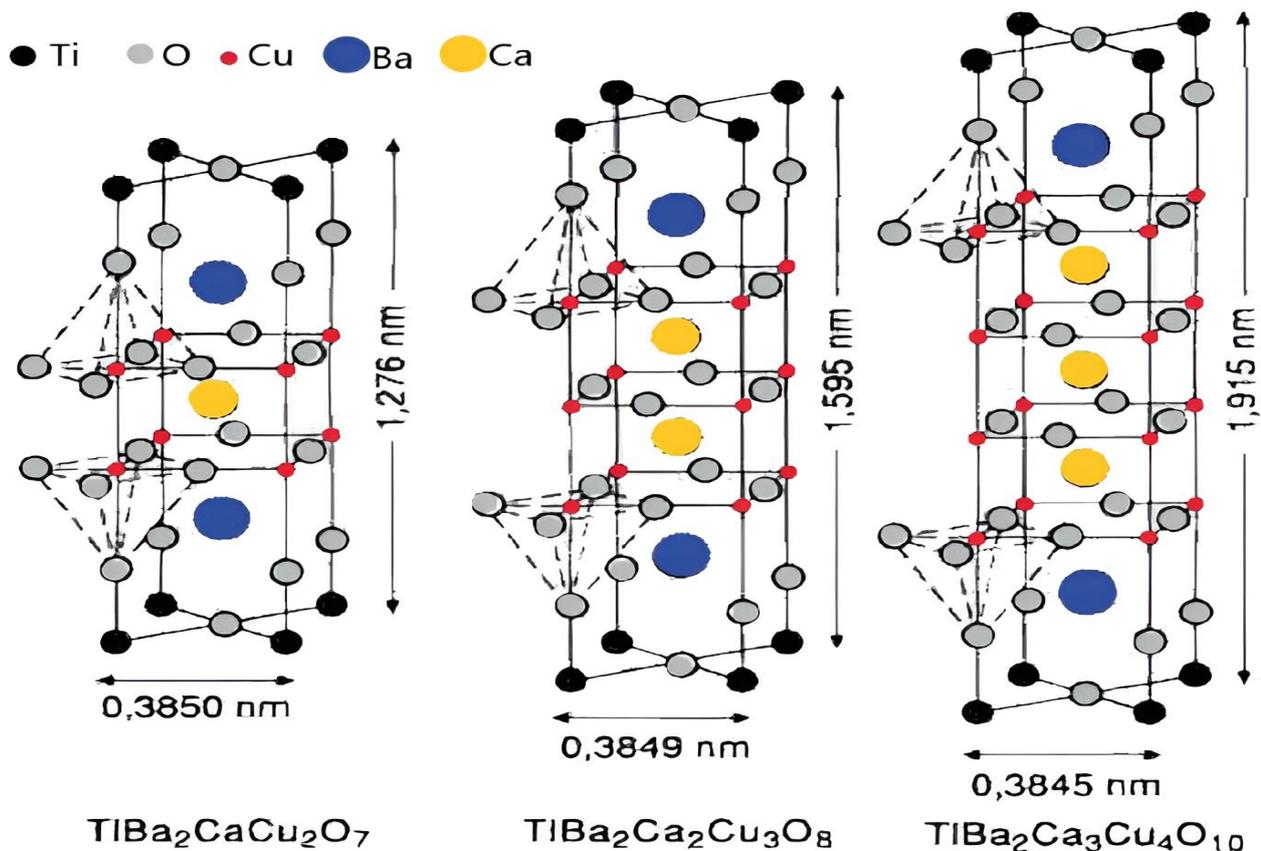


Figure 5.1. Crystal structure Tl-based cuprates.

§ 6. Hg-Based Cuprates

Figure 6.1 shows the crystal structure of three representatives of the Hg-family cuprates.

Consequently, the Hg-family of compounds, whose general chemical formula reads $\text{HgBa}_2\text{Ca}_{n-1}\text{Cu}_n\text{O}_{2n+2+\delta}$, has received considerable attention. Here, n indicates the number of CuO_2 layers in the simple tetragonal primitive

cell, and δ indicates the concentration of oxygen in the Hg-O layer. The maximal value of T_c , fully optimized

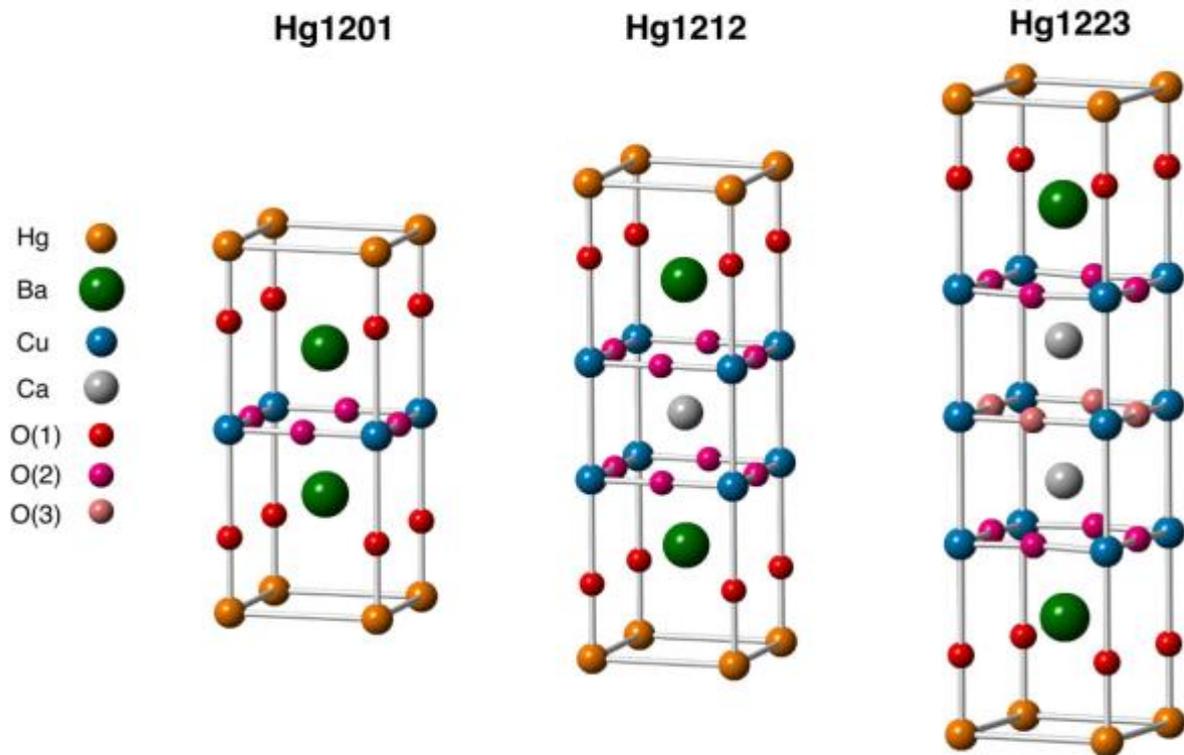


Figure 6.1. Schematic comparison of the crystal structures of the first three members of the Hg-family of cuprates.

as a function of δ , depends on n : it increases from 97 K ($n=1$) to 127 K ($n=2$) to 134 K ($n=3$), and then decreases again even larger n ¹.

Figure 6.2 shows the variation of the critical conductivity temperature of Hg-based cuprates as a function of the denotes the ordinal number of the homologue's series member, as reported in the work of Dmitry Pavlov².

¹Lichen Wang and Xiangpeng Luo and Jiarui Li and Junbang Zeng and Min Cheng and Jacob Freyermuth and Yang Tang and Biqiong Yu and Guichuan Yu and Martin Greven and Yuan Li. Growth and characterization of $\text{HgBa}_2\text{CaCu}_2\text{O}_{6+\delta}$ and $\text{HgBa}_2\text{Ca}_2\text{Cu}_3\text{O}_{8+\delta}$ crystals. Physical Review Materials 2,123401 2018. <https://doi.org/10.1103/PhysRevMaterials.2.123401>

² Dmitry A. Pavlov. Synthesis and properties of substituted Hg-based superconductors - PhD Thesis (2004).

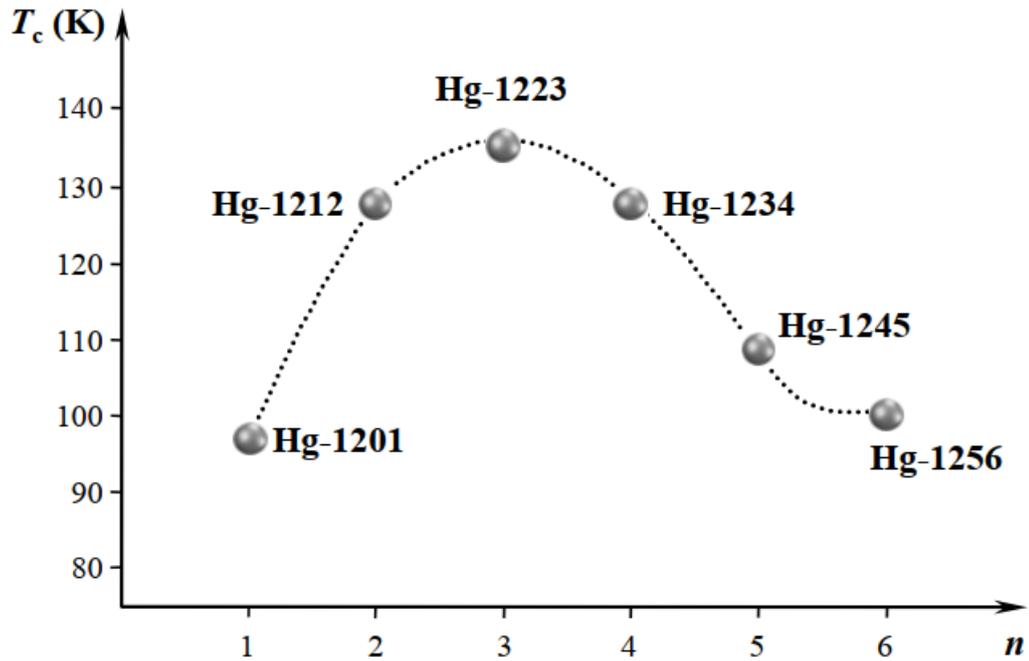


Figure 6.2. The $T_{c, \max}(n)$ diagram (n denotes the ordinal number of the homologues series member).

§7. USING DIGITAL TECHNOLOGY IN TEACHING SUPERCONDUCTIVITY

Various mobile applications, e-books, films, and programs have been created to make the training session interesting and to further improve the teaching methodology. It is a well-known fact that such digital technology tools have a positive effect on increasing the effectiveness of education. In the teaching of physics, through effective use of digital technology tools, it is possible to explain physical laws, various formulas, colorful experiments, and the essence of phenomena in a simple way that students can easily accept. Digital technology tools can be a great assistant to the teacher, especially in cases where it is not possible to fully cover the subject of physics or to carry out an experiment in schools or universities. In particular, when tools and equipment that create lower temperatures and allow demonstrating the

superconducting (SC) properties of the substance is absent in the school and higher education institution the use various tools of digital technologies ensure the achievement of the goal of the training session. This is the case of teaching a course of SC. Among many methods of using digital technology in teaching a course of SC one might use (i) method of deminstarting educational-scientific video-films on the theme of subject and (ii) method of using simulation softwear in explaining different aspects of SC phenomenon.

Regarding the first method, purely subjectively and based on our own experience of teaching a course on superconductivity, we can recommend using the resources of the Youtube.com platform. And in the second method we also give preference to digital educational technology program COMSOL Multiphysics, which provides many useful demonstration and simulation methods for teaching.

§ 7.1 Using “Youtube.com” platform in teaching superconductivity

As there are no films and video-lessons on the physics of SC on the educational portals of our republic, they can be taken and shown from the “Youtube.com” portal of the Internet network. It is worth noting that, according to the research of foreign scientists, the importance of scientific videos posted on the “YouTube” portal in educational processes is increasing¹. As an example, by showing a video clip ² about the high-speed railway "Maglev" train based on the phenomenon of SC, it is possible not only to introduce students to the Meissner effect ³[4], the main property of

¹ S. Richtberg and R. Girwidz. Learning Physics with Interactive Videos – Possibilities, Perception, and Challenges // J.Phys.: Conf. Ser. **1287** (2019) 012057. Doi:10.1088/1742-6596/1287/1/012057

² https://www.youtube.com/watch?v=Hi7tN_B1BT8

³ <https://www.youtube.com/watch?v=HRLvVkkq5GE>

SC, but also to show that SC is currently being used in transport ¹. The useful aspects of "YouTube" videos in the course of the lesson are: (i) they quickly attract the attention of students, help to focus on one place; (ii) the studied process, actions quickly come to the eyes of students and increase the comprehension coefficient; (iii) videos help students understand the relationship between models and reality; (iv) makes learning more interesting and engages students; (v) videos allow students to see experiences that would otherwise be impossible; (vi) the reality that we have to spend hours and days can be quickly understood through shortened videos; (vii) video tutorials remove the noise found in live experience and help learners become more active in their learning. The above-mentioned examples will help make the learning process more interesting. In particular, making educational video lessons on the Internet portal "Youtube" an active part of physics training today and in the future is an urgent methodical and organizational issue and remains on the agenda.

§ 7.2 Using “Comsol Multiphysics” in teaching superconductivity

COMSOL Multiphysics is the platform product for creating physics-based models and simulation applications. COMSOL Multiphysics includes the Model Builder, Application Builder, and Model Manager. The Model Builder contains all the functionality and operations for building, solving, visualizing, and evaluating your models. The Application Builder gives you the tools to build your own simulation apps. The Model Manager is a workspace for managing models and applications². Within COMSOL a server-based application with the name of AURORA is created for simulations with superconductors that might methodically help teachers in

¹ <https://www.youtube.com/watch?v=XjwF-STGtFE>

² <https://www.comsol.com/comsol-multiphysics>

their classes. AURORA is the first developing simulation applications using the Application Builder in the COMSOL Multiphysics software and then making them available using the app-management product COMSOL Server^{1,2}. They AURORA is installed at the Swiss Federal Institute of Technology Lausanne (EPFL)³. Currently, the library of the AURORA has 15 topics for simulation. They are: Coupling Filaments, Critical State Model, Critical current calculation, Critical state model (one step), H Formulation, H-phi formulation, Infinite stack of HTS tapes in external magnetic field, Infinite stack of HTS tapes with transport current, Inhomogeneity 1-D model, Integral equation model with power-law resistivity, Magnet design, Magnetization

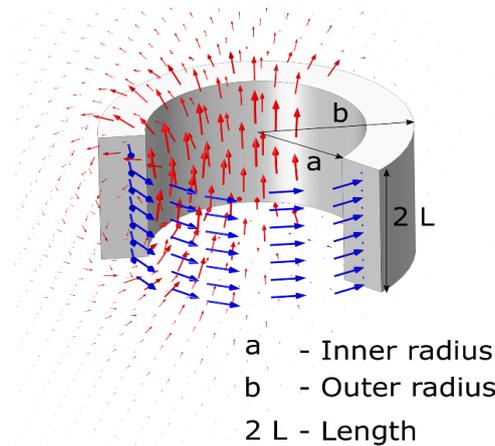


Figure 7.2.1. The magnetic field distribution in solenoid-shaped magnet.

Slab 1D, Superconducting Disk in a Magnetic Field (London's approach), Superconducting fault current limiters (SFCL) and Time dependent Ginzburg-Landau (Type I and Type II). For example, an application "Magnet design" calculates the magnetic field distribution in solenoid-shaped magnet,

¹ N. Riva, F. Grilli and B. Dutoit. AURORA: a public applications server to introduce students to superconductivity // J. Phys. Conf. Ser. **2043**(2021)012005.

<https://dx.doi.org/10.1088/1742-6596/2043/1/012005>

² N. Riva, F. Grilli and B. Dutoit. Superconductors for power applications: an executable and web application to learn about resistive fault current limiters // Eur. J. Phys.

42(2021)045802. <https://dx.doi.org/10.1088/1361-6404/abf0da>

³ <https://aurora.epfl.ch/app-lib>

modeled as a hollow cylinder with the following dimensions inner radius a , outer radius b , length $2L$ (Fig.7.2.1). The user can modify the geometry of the magnet by adjusting the following parameters: $a=b/a$, $\beta=L/a$. Other input parameters are the uniform current density applied to the magnet's cross section and area of the wire's cross section used for the winding.

In conclusion, we can say that today the task of the modern education system is not only to give knowledge to the student, but also to form and develop his creative thinking. In this process, the teacher is required to organize the lessons in an interesting way. The use of COMSOL Multiphysics platform-based AURORA application in SC physics course will help make the learning process more interesting and helps to achieve lessons objectives.

Conclusion

In conclusion, we can say that today the task of the modern education system is not only to give knowledge to the student, but also to form and develop his creative thinking. In this process, the teacher is required to organize the lessons in an interesting way.

This methodological guide has been prepared to enhance students' interest in the physics of superconducting compounds. The guide provides historical information about cuprates, their crystal lattice structure, lattice constants, and the critical temperature of superconductivity.

Additionally, it offers recommendations on using modern technologies in teaching superconductivity, particularly leveraging the "YouTube.com" platform and "Comsol Multiphysics" software.

This guide can serve as supplementary literature for undergraduate students specializing in physics and graduate students pursuing advanced studies. We believe this methodological guide will contribute to increasing interest in the physics of superconductivity to a certain extent. Moreover, it aims to provide initial knowledge to early-career researchers taking their first steps in the scientific field and assist them in finding necessary literature.

List of some review articles and books on HTSC

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Internet resources:

<http://www.superconductors.org/>

<https://www.maglev.net/>

<http://www.ccas-web.org/superconductivity/>

<https://ieeecsc.org/>

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