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ICMAB INSTITUT DE CIÈNCIA DE MATERIALS DE BARCELONA EXCELENCIA SEVERO OCHOA

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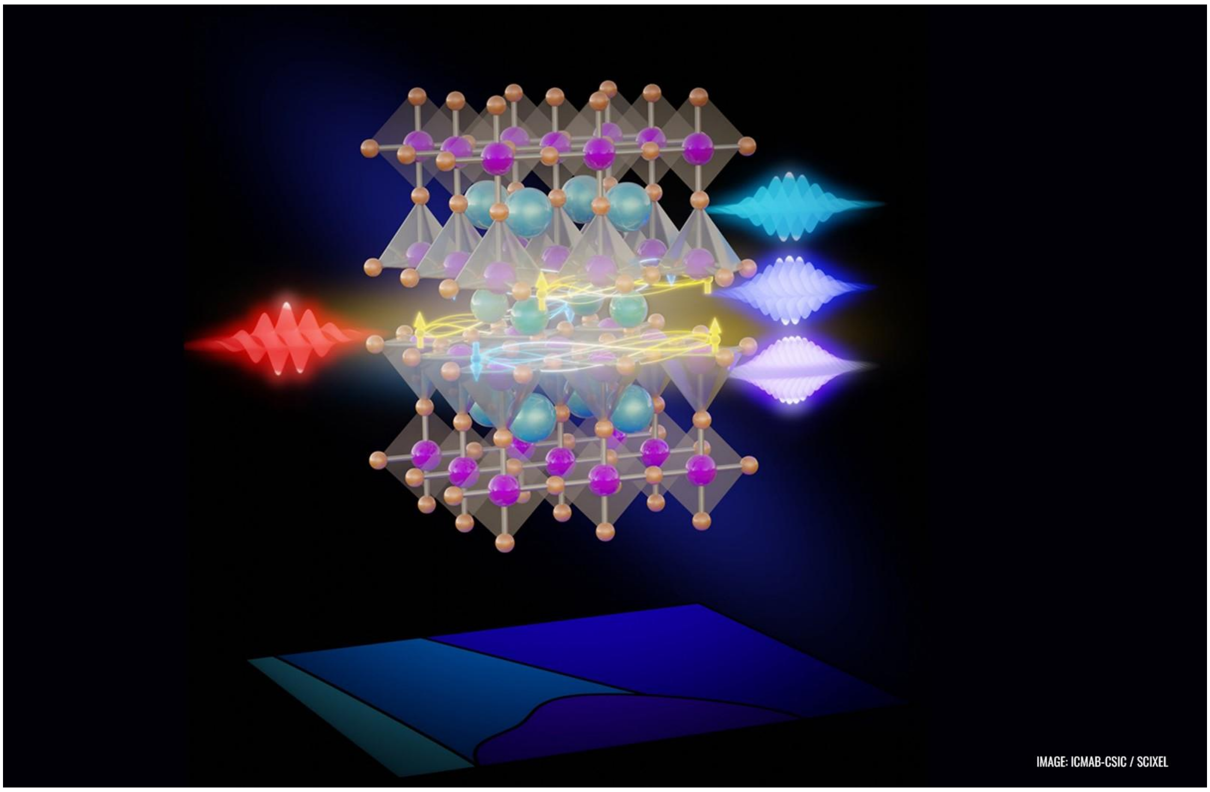
High Harmonic spectroscopy unveils the phase transitions of high-temperature superconductors

Researchers from ICFO, ICMAB-CSIC and Guangdong Technion-Israel Institute of Technology have developed a new methodology to investigate and measure the quantum phase transitions of a high-temperature superconductor by using High Harmonic spectroscopy.



Crystal structure of superconducting $YBa_2Cu_3O_{7-d}$ (YBCO) illuminated by strong laser light (red pulse). The induced ultrafast electronic processes in the material lead to radiation of light at high frequencies (purple pulse), predominantly at multiples of the laser frequency. This effect, known as high-harmonic generation, is used to probe the dynamic evolution of quantum phase transitions in these compound and provide novel insight into the underlying microscopic dynamics of Cooper pair formation.

Superconductors are materials that exhibit the ability to conduct electricity without any resistance. This phenomenon is observed in materials when they are cooled below the so-called superconductor transition temperature, often at very low temperatures (a few degrees above the absolute 0). Among these materials, there are the so-called high-temperature superconductors, which behave as superconductors at temperatures above 77K (the boiling point of liquid nitrogen).

These materials are showing to be essential in the development of new electronic and information processing devices as well as optical quantum computers and even for improving the efficiency of electrical transmission lines.

However, high-temperature superconductivity has been seen to be closely linked to the control of their microscopic dynamics. So far, the detection of the different microscopic quantum phases in these complex materials has resulted quite challenging. Not only are the physical processes of these dynamic states still incomplete due to their wide array of quantum states, but the current methods used to explore their dynamics at microscopic scales are lagging sensitivity. Therefore, new tools to better understand the dynamic evolution of these types of superconductors are needed.

Now, in an international study, ICFO researchers Utso Bhattacharya, Ugaitz Elu, Tobias Grass, Piotr T. Grochowski, Themistoklis Sidiropoulos, Tobias Steinle, and Igor Tyulnev, led by ICREA Professors Jens Biegert and Maciej Lewenstein, in collaboration with ICMAB-CSIC researchers Jordi Alcalà and Anna Palau, and Marcelo Ciappina, from the Guangdong Technion-Israel Institute of Technology, propose a new methodology based on the use of High Harmonic spectroscopy (HHS) to investigate the transitions between the different phases of YBCO, a copper oxide cuprate material which is a well-known high-temperature superconductor. This study represents a major scientific breakthrough since it is the first time that highly non-linear and non-perturbative diagnostics/detection methodology is used to understand the behavior of strongly correlated materials.

In view of the experimental results obtained, the researchers have also gone beyond and present a new theoretical model to identify the connection between the measured optical spectra and the transition between the different quantum states of the YBCO: strange metal, pseudogap, and superconductor. The study has been recently published in the journal PNAS.

In their experiment, the researchers used 100nm thick films of YBCO mounted on a micro-refrigerator. Firstly, they characterized the superconducting properties of the YBCO films and confirmed their quality. Then, by using ultra-short infrared laser pulses the authors of the study induced high harmonics generation in the material samples, which were placed inside a vacuum chamber and cooled to a temperature of 77K.

High Harmonics are the high-energy photons emitted by the electrons of a system when it is placed in a strong laser field. These emitted photons have a frequency many times that of the driving laser field.

When they hit the surface, they recorded the reflected radiation with a spectrograph to study the harmonic spectrum, which contains the imprints of this nonlinear optical response, and was found to have a connection with the phase transitions.

Seeing these experimental results in the lab and the lack of a theory that could explain what was being observed, the researchers developed a new strong-field quasi-Hubbard model to shed light on the connections between the measured high harmonics and the formation of Cooper pairs, that is, the paired electrons that are responsible for the superconducting phase.

When using this new theoretical model, the theoretical calculations of the high harmonic spectra obtained matched the experimental data. "The model faithfully reproduces the functional form of the measurement data over the entire temperature range and for several orders of magnitude of harmonic amplitude", the authors highlighted.

This new approach, as they noted, has permitted a theoretical connection between the measurements and the underlying microscope dynamics providing a "powerful new methodology to study the quantum phase transitions" in correlated materials.

Finally, the team highlights that their work provides a "first striking example" of how High Harmonic Spectroscopy can be used to distinguish correlated phases of matter. They also consider that it paves the way toward a "refined understanding of the physical processes that occur inside high-temperature superconductors”.

ICFO Communication

Original paper

High harmonic spectroscopy of quantum phase transitions in a high-Tc superconductor
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Campus de la Universitat Autònoma de Barcelona
08193 Bellaterra, Catalunya, Espanya
Telf.: +34 935 801 853
Fax.: +34 935 805 729