Simulation and Discussion of Superconductivity: Cooper Pairing and Beyond

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Background: BCS Theory and Cooper Pairs

When can electrons "attract" each other? In metals, nuclei form a rigid lattice structure while electrons flow freely through this lattice; this is known as metallic bonding. The Bardeen-Cooper-Schrieffer (BCS) theory states that superconductivity arises from Cooper pairs, or pairs of electrons attracted to each other due to temporary positive charges caused by an electron's movement through the lattice. This pairing is not possible at high temperatures due to thermal energy breaking the pairs, but if the temperature is below a critical threshold Tc, the thermal energy is not strong enough to disrupt them. These Cooper pairs behave as composite bosons, which means they can occupy the same quantum ground state and move collectively without resistance, enabling superconductivity.

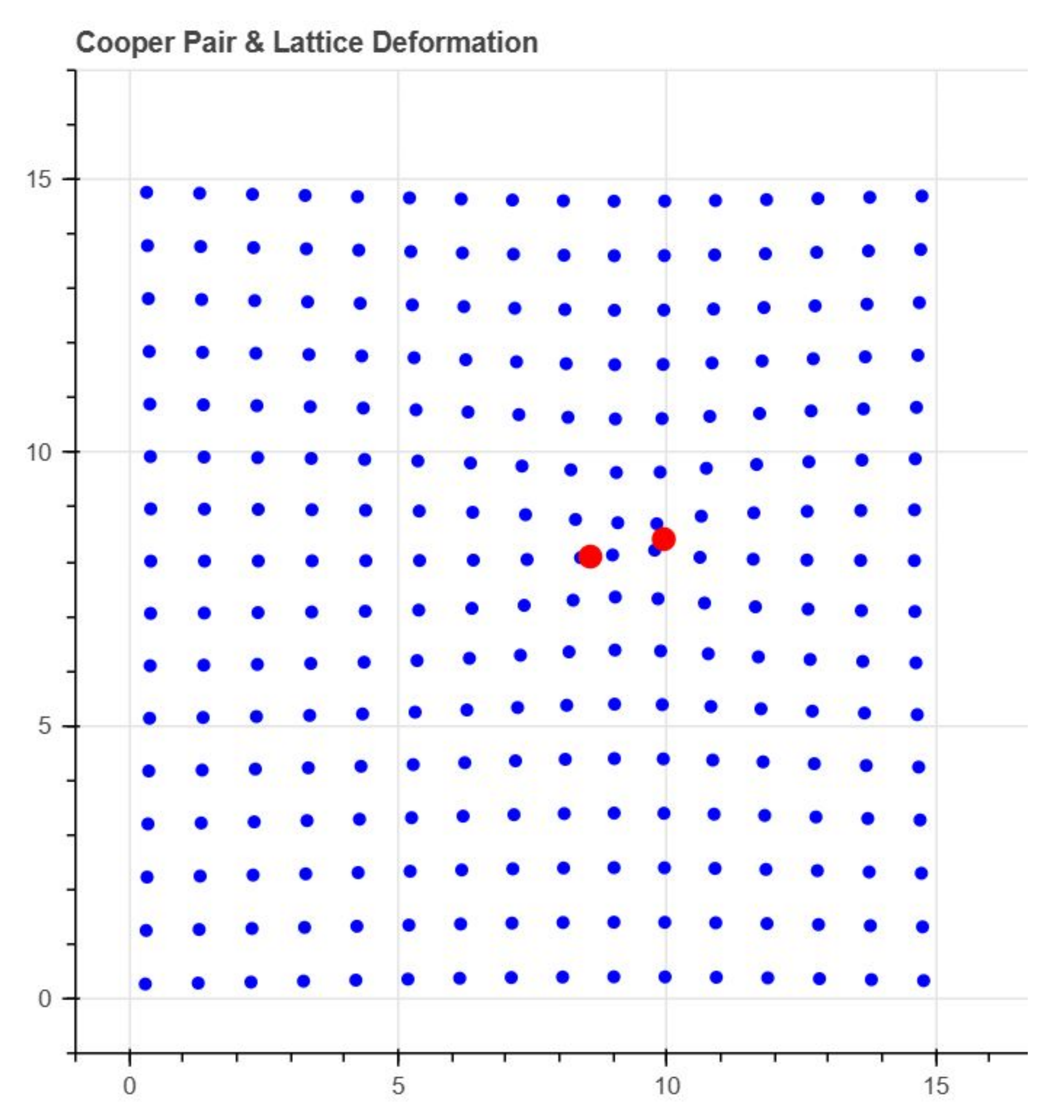
Simulation

We use python to simulate a grid of positive charges (blue) that interact via the coulomb force with negative charges (red)

$$F = k\frac{q_1 q_2}{r^2}$$

At each time-step of the simulation, we use the Bokeh python library to update an animated view of the lattice and the electrons.

At low enough speeds (below Tc) the electrons form a "bound state" (a cooper pair), but at higher speeds (above Tc) the cooper pair will break apart.

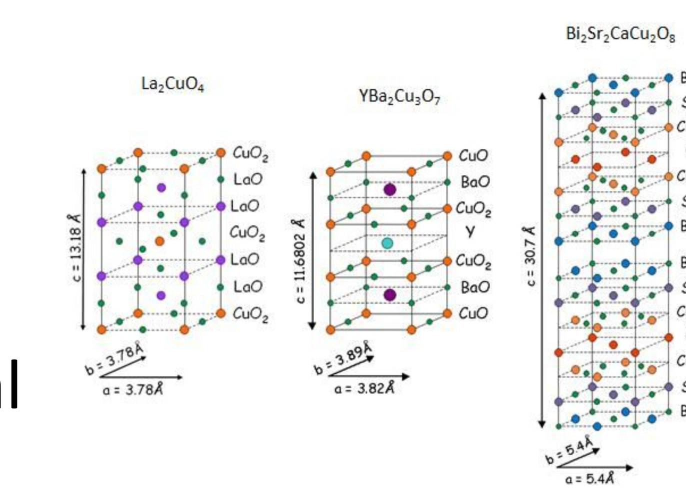


Beyond BCS Theory

Superconductivity is a cutting edge research topic that scientists are still working to understand. BCS theory is an imperfect theory since it cannot explain high-temperature "unconventional" superconductivity.

In general, these unconventional superconductors can be organized into two types:

- Type 1 - superconductivity: Under critical temperature (Tc),the material will resist all the magnetic effects (Meissner effect where B=0 inside of the material);
  - When the magnitude of the outer magnetic field (B) > critical field (Hc), the material loses its Meissner effect and the B-field penetrates through.
- Type 2-superconductivity: Two critical fields (Hc1–Lower critical field, Hc2-Upper critical field)
  - B inside material < Hc1: Meissner Effect
  - Hc1<B<Hc2: partial Meissner Effect ;
  - Hc2<B: loses Meissner Effect



The cuprate family provides examples of Type-II unconventional superconductors. Cuprates are formed with layers of copper oxide sandwiched between ions (like lanthanum, barium, strontium). These ions dope electrons into the copper oxide layer and become Mott insulators themselves.

Applications of Superconductivity

- Magnetic Resonance Imaging (MRI): Superconducting magnets create strong, stable magnetic fields for high-resolution imaging scans in medicine.
- Particle Accelerators: Superconducting magnets are used in accelerators like the Large Hadron Collider to steer and focus particle beams with minimal energy loss.
- Magnetic Levitation (Maglev) Trains: Superconducting magnets enable high-speed, energy-efficient trains with frictionless levitation and propulsion.
- Electric Power Transmission: Superconducting cables can transmit electricity with virtually no losses, improving efficiency in power grids.

Funding Statement: This work was completed as part of the Quantum Engineering Research and You (QuERY) program at Bellaire High School, supported by the Harvard Quantum Initiative and MIT through the Research Laboratory for Electronics and CQE-iQuISE (Center for Quantum Engineering, Interdisciplinary Quantum Information Science and Engineering program).