Supercurrent without a spatially varying phase or a vector potential from time-reversal and inversion symmetries breaking in superconductors.

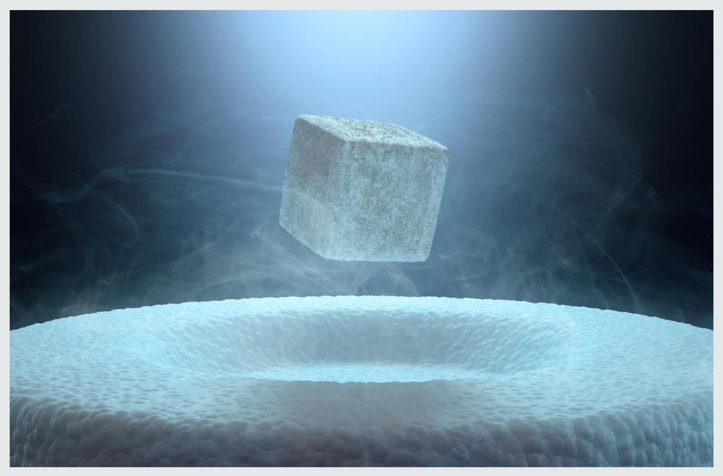
Daniel Palacios[1], Pavan Hosur[1,2]
[1]Department of Physics, University of Houston, Houston, TX.
[2]Texas Center for Superconductivity, University of Houston, Houston, TX

UNIVERSITY of HOUSTON
TEXAS CENTER FOR SUPERCONDUCTIVITY

UNIVERSITY of HOUSTON
DEPARTMENT OF PHYSICS

What is superconductivity?

- When electrons travel to materials, energy is dissipated in form of heat due to electrical resistance.
- If some materials are cool down enough, they can lose the electrical resistance and become superconductors where electrons can flow perfectly without heat lost.
- Superconductors exclude all magnetic field lines –Meissner effect (figure 1A).
- These materials are useful to make MRI machines and super fast trains (figure 1B)



Magnetic Levitation of a Superconductor. School of Engineering. (n.d.). Retrieved August 20, 2020, from https://www.eng.ed.ac.uk/research/themes/applied-superconductivity

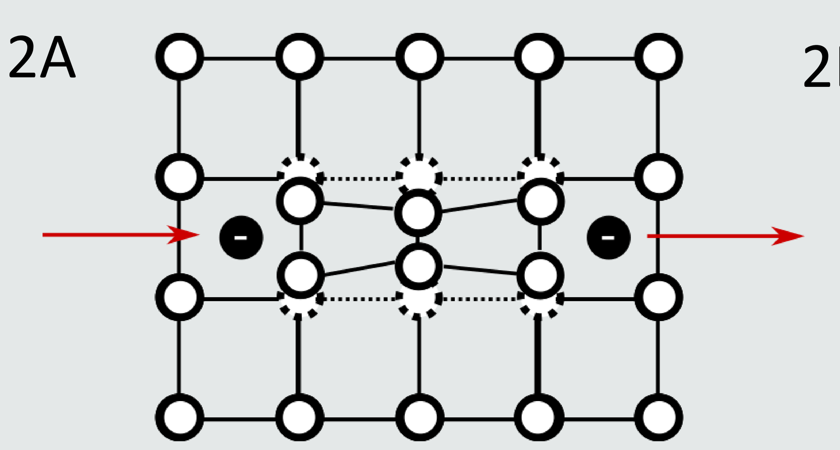
Maglev Train. Travel.Earth. (2019, August 09). China unveils 600km/h high-speed Maglev Train Prototype. Retrieved August 20, 2020, from https://medium.com/@Travel.Earth/china-unveils-600km-h-high-speed-maglev-train-prototype-463b0035b4c6

1A. A magnet levitates on top of a superconductor because of the repulsion force from the surface currents generated by the superconductor to oppose the magnetic field of the magnet. **2A**. Chinese Maglev Train prototype which will reach speeds up to 600 kilometers per hour (272 miles per hour).

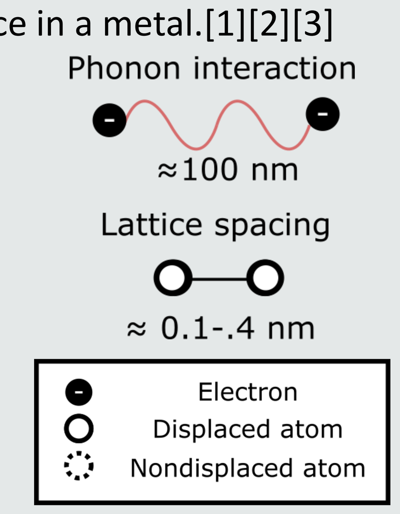
Bardeen–Cooper–Schrieffer theory

- Electrons form Cooper pairs by phonon interactions with the metal lattice at extremely low temperatures.
- Pairs of electrons behave differently and condense into the same energy level.
- This state allows electrons flow without any resistance in a metal.[1][2][3]

2A



2B

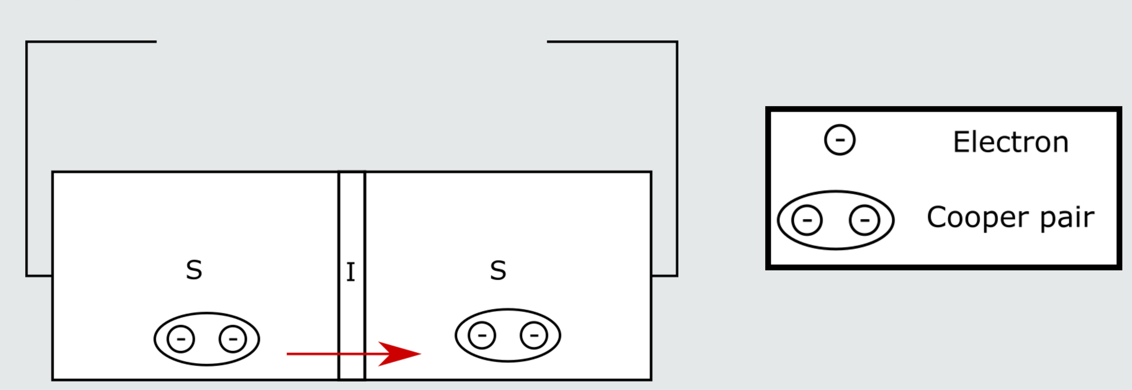


2A. Cooper pairs are form from moving electrons in a lattice attracts the positive ions, another electron far away is attracted to the collective motion of the positive charged lattice (phonon). **2B**. Net attraction between cooper pairs is very weak, and small thermal agitation is needed to convert them back to normal electrons.

Josephson Junction

- Consists in two pieces of superconductors separated by a thin insulator.
- Cooper pairs can quantum tunnel the insulator barrier.
- Useful in digital logic circuitry and can be constructed to measure extremely small magnetic fields – SQUID.[4][5][6]

3A



3A. Classic Josephson junction (SIS) consists in a Superconductor-Insulator-Superconductor configuration Cooper pairs quantum tunnel through the insulator to generate a supercurrent.

References

[1] Pierre-Gilles De Gennes. Superconductivity of metals and alloys. CRC Press, 2018.
[2] Takafumi Kita. Statistical Mechanics of Superconductivity. Springer, 2015.
[3] Hiroyasu Koizumi. Theory of supercurrent generation in bcs superconductors. arXiv preprint arXiv:1810.12508, 2018.
[4] Philippe Mangin and R´emi Kahn. Superconductivity: an introduction. Springer, 2016.
[5] Manfred Sigrist. Introduction to unconventional superconductivity in noncentrosymmetric metals. In AIP Conference Proceedings, volume 1162, pages 55–96. American Institute of Physics, 2009.
[6] D Singh, PK Biswas, AD Hillier, RP Singh, et al. Superconducting properties of the noncentrosymmetric superconductor laptge. Physical Review B, 98(21):214505, 2018.
[7] D Singh, KP Sajilesh, S Marik, AD Hillier, and RP Singh. Superconducting properties of the noncentrosymmetric superconductor taos. Superconductor Science and Technology, 30(12):125003, 2017.
[8] Carsten Timm. Theory of superconductivity. Institute of theoretical Physics Dresden, 2012.
[9] Michael Tinkham. Introduction to superconductivity. Courier Corporation, 2004.

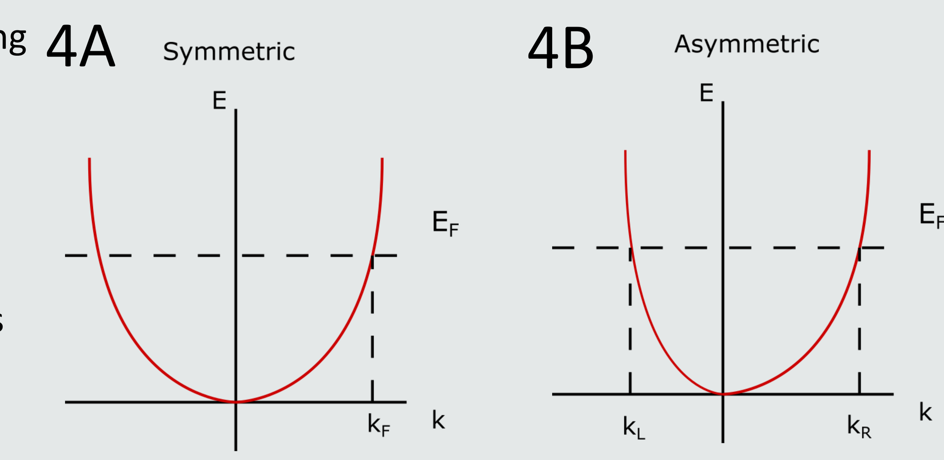
Acknowledgements

The SURF and PURS Programs funded through the Office of Undergraduate Research and Major Awards.

UNIVERSITY of HOUSTON
HONORS COLLEGE
Office of Undergraduate Research and Major Awards

Energy dispersion in asymmetric metals

- Inversion symmetry and time reversal symmetry are required for the formation of Cooper pairs which occurs in symmetrical superconductors. [7]
- The simultaneously breaking of these symmetries leads to the creation of an asymmetric metal. When this metal turns superconducting, the resulting superconductor is an asymmetric superconductor.



4A. Energy dispersion for a symmetric metal, the fermi energy (E_F) corresponds to a fermi momentum (k_F). **4B**. Energy dispersion for an asymmetric metal, here the fermi energy corresponds to two different values of the fermi momentum (left and right fermi momentum - k_L and k_R).

Deriving the Josephson effects of an asymmetric superconductor from the Schrodinger equation.

Consider the following Schrodinger equation of a charged particle in a magnetic field with an asymmetric energy dispersion:

$$i\partial_t\psi = [\frac{(\hat{p}-q\mathbf{A})^2}{2m} - a(\hat{p}-q\mathbf{A}) + q\phi]\psi$$

Solving analytically the previous equation we can find the Supercurrent density phase relation and Energy phase relation.
With energy and supercurrent phase relations we can derive the Josephson effects

- Conventional DC Josephson effect $J = J_c sin(\varphi)$

Supercurrent exist if there is a spatially phase difference across the junction, even in the absence of a potential difference.

- Asymmetric DC Josephson effect $J = J_c sin(\varphi) + J_m cos(\varphi) + aqn$

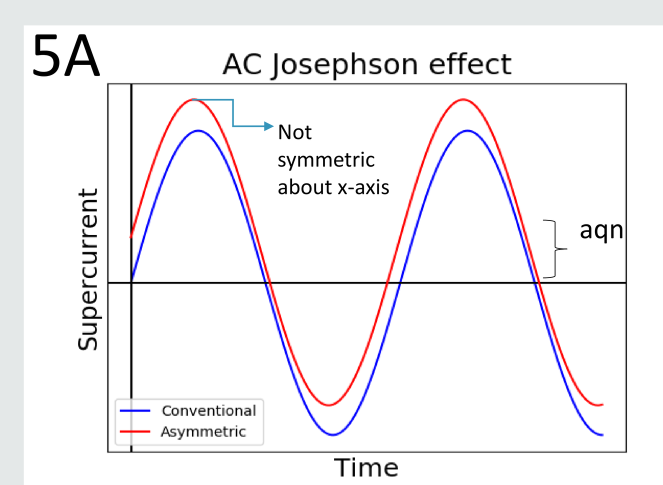
In contrast, for asymmetric superconductors when phase equals 0 we have a nonzero supercurrent.

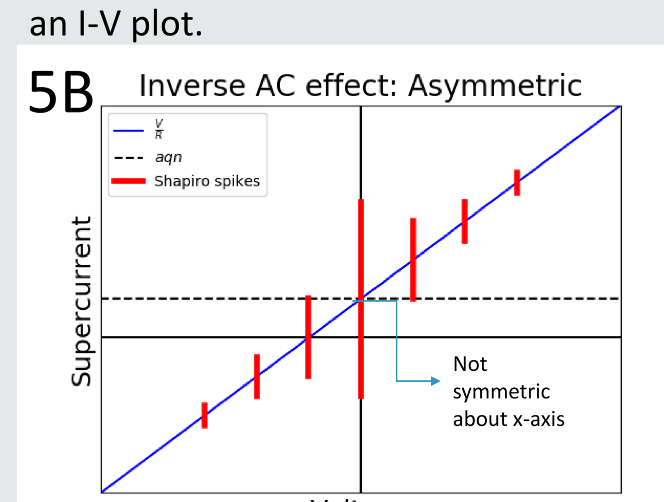
Other main Josephson effect are similar between conventional and asymmetric superconductors.

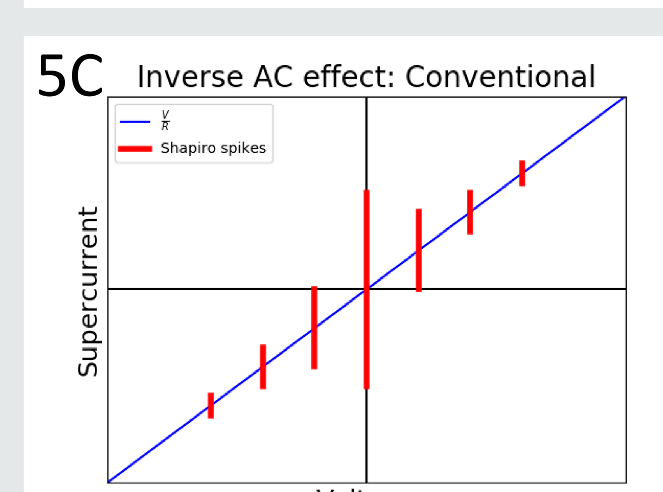
- AC Josephson effect $J(t) = J_c sin(\frac{2\pi}{\Phi_0}Vt) + J_m cos(\frac{2\pi}{\Phi_0}Vt) + aqn$
- Inverse AC Josephson effect

$$I = I_c(\sum_{k=-\infty}^{\infty} J_k(a) sin(\varphi_0 + n\omega t + k\omega t) + I_m(\sum_{k=-\infty}^{\infty} J_k(a) cos(\varphi_0 + n\omega t + k\omega t)) + \alpha q\rho$$

In the AC Josephson effect, a constant voltage is applied, generating an oscillating current. In an asymmetric superconductor the current would be shifted by the asymmetric contribution of the supercurrent. In the inverse AC Josephson effect microwave radiation induces quantized DC voltages. It is expected a similar effect for asymmetric superconductors with a constant shift in an I-V plot.







5A. Current vs Time plot illustrating the AC Josephson effect, in a constant voltage asymmetric and conventional supercurrent oscillate sinusoidally. **5B**. Shapiro spikes for a conventional superconductor, specific voltage values causes a jump in the current . **5C**. Shapiro spikes for an asymmetrical superconductor.

Quantifying asymmetric supercurrent density in a 2D Lattice

Defining the expectation of the supercurrent density as: $\langle j \rangle = tr[U_k P_k U_k^\dagger \hat{J}_k]$

Where, the unitary transformations from a Hamiltonian with superconductivity and Projection operator (diagonal matrix with Fermi-Dirac functions) and Supercurrent matrix operator.

Then, by applying periodic boundary conditions we can show the total supercurrent can be given by: $\langle J \rangle = \frac{1}{V}\sum_{n_x n_y n_z} \langle j_k \rangle$

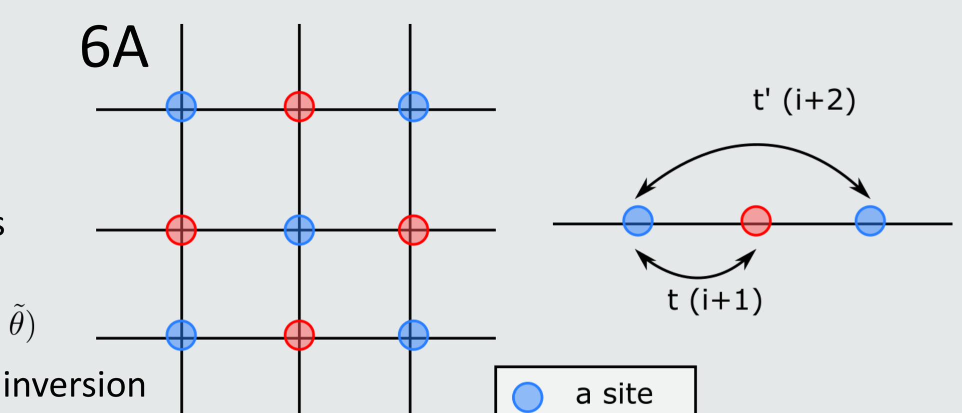
By logic in figure 6A we can derive the following tight-binding Hamiltonian for an asymmetric superconductor.

$$H = -\frac{1}{2}\sum_{i,\sigma}\sum_{\delta}(te^{i\theta}c_{i\sigma}^\dagger c_{i+\delta,\sigma} + te^{-i\theta}c_{i+\delta,\sigma}^\dagger c_{i\sigma} + t'e^{i\varphi}c_{i\sigma}^\dagger c_{i+2\delta,\sigma} + t'e^{-i\varphi}c_{i+2\delta,\sigma}^\dagger c_{i\sigma}) + VN$$

From the Hamiltonian we get the energy dispersion for an asymmetric superconductor. After a Gauge transformation this yields:

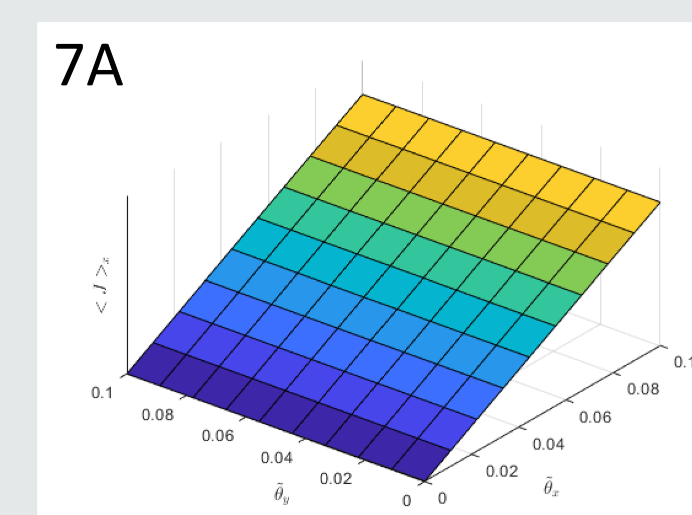
$$\xi_k = t cos(ka) + t' cos(2ka + \tilde{\theta})$$

Where the angle $\tilde{\theta}$ breaks inversion symmetry. The symmetry is recovered when the angles in their respective direction vanish.



6A. 2D Square lattice with 2 types of hopping terms. Note a and b sites don't represent different atoms. The odd hopping between a and b sites are represented with t', while even hopping are between a sites are represented with t.

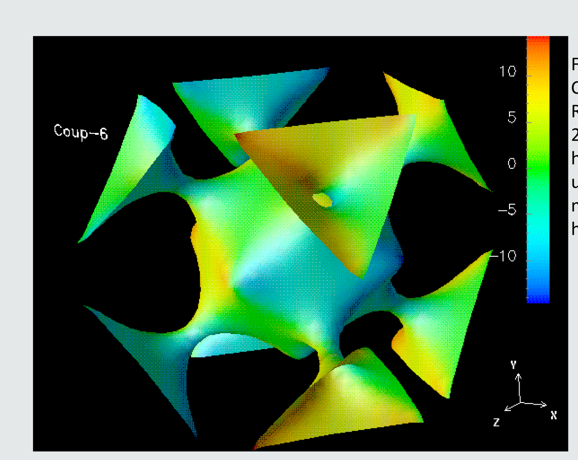
- The model was calculated numerically and tested across several parameters. There is a constant supercurrent across different lattice sizes and a linear relation across small asymmetry angles.
- The supercurrent in the x-direction is plotted as a function of the asymmetry. When the asymmetric angles of the supercurrent are zero, the system recovers symmetry, and the asymmetric contribution of the supercurrent vanishes.
- Similar behavior was obtained from 3D simple cubic lattice.



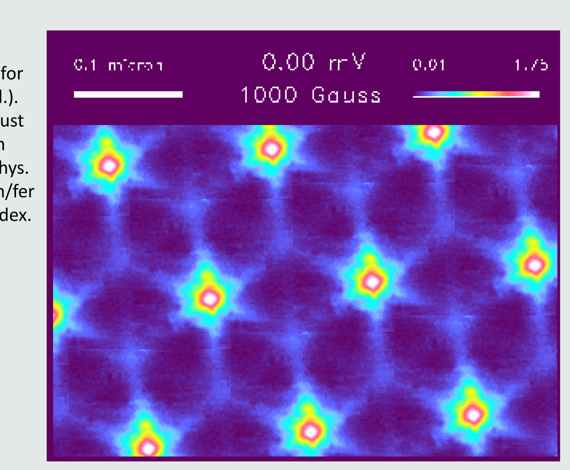
7A. Expectation value of the supercurrent density in the x direction vs. asymmetry angles x and y plot.

Conclusion | Discussion | Future Work

- Inducing an asymmetry on non-centrosymmetric superconductors would allow to have a supercurrent without the need of a spatially varying phase even if we assume a small asymmetry.
- Inducing superconductivity on asymmetric metals turns out to be challenging, one idea is to induce superconductivity extrinsically by putting an asymmetric metal next to a conventional superconductor.
- The model for the calculation of the supercurrent in a 3D lattice showed a non-zero supercurrent across many parameters.
- Explore the structure of Fermi surfaces, vortices and deriving the energy gap of asymmetric superconductors.
- Explore different geometries of asymmetric superconductors to identify how the asymmetric supercurrent would behave. For example, a ring structure.



Fermi surface for Copper-6. (n.d.). Retrieved August 20, 2020, from http://www.phys.ufl.edu/~jchen/fermi_surface/index.html



Vortex bound states. Khurana, A. (1990). STM unravels the vortex core in type II superconductors. *PhT*, *43*(6), 17.