80^{th} Birthday Anniversary of Brian D. Josephson

To honor professor Brian.D. Josephson on the occasion of his 80th birthday anniversary, I want to describe in a simply way his theoretical discovery and highlight some of its consequences.

In 1962 B. Josephson published a theoretical paper predicting the existence of two effects: the existence of Superconducting Currents in tunnel junctions and the Josephson Radiation or high frequency electromagnetic radiation, which were soon verified experimentally. The term Weak Superconductivity or Josephson Effect is related to a situation in which two superconductors are coupled together by a Weak Link. This WK can be produced by a tunnel junction or some constriction in the cross section of a thin film (a weak contact between two superconductors can be produced by an isolator, a normal metal or some other situation where the contact between superconductors is somehow weakened).

The effects of weak superconductivity have their origin in the quantum nature of the superconducting state. It is known that the basis of the superconducting state is the existence of the Bose condensate, i, e., all the electron pairs in the superconducting state occupy the same quantum level and are described by a single wavefunction common to all of them. They are coherent.

In order to understand it, suppose we have two bulk pieces of the same superconductor at the same temperature isolated from each other. When both pieces are in the superconducting state, the superconducting electrons have their own superconducting wavefunction. Since the temperature and the superconductors are identical the amplitudes of the wavefunctions must also be the same, but the phases are arbitrary. If now we stablish a weak contact between them (a contact that not change radically the electron states of the two pieces, but that can be taken as a perturbation), a new wavefunction will emerge for the superconductor as a whole, which can be considered as a result of the interference between the wavefunctions of the two pieces. The amplitude of the wavefunction was the same even before the weak link was formed, but not their phases, then the phase coherence (the coherent behavior of superconducting electrons) is a direct result of stablishing the weak link.

There are two Josephson Effects: stationary or dc JE or non stationary or ac JE.

The first effect can be produced when a small current is applied through a weak link or Josephson Junction. If the current is sufficiently small ($I < Ic$), where Ic is a critical value, it passes through the WL without resistance even if the material of the WL is not superconductor (for example an insulator in a tunnel junction).

The ac JE is produced when the current through the WL is increased until a finite voltage appears across the junction ($I > Ic$). The voltage have an ac component of angular frequency ω, so that $h\omega/2\pi = 2eV$, in addition to a dc component V. This is the so called Josephson Radiation i,e,. the electromagnetic radiation emited by a Josephson Junction [1].

Theoretical discovery of Josephson effects has brought great consequences for science and economy, and in the future promises more benefits for public health. The strongest impact, has been the use of Josephson devices and circuits. The Superconductor Quantum Interferometers Devices (SQUID) have opened new horizons in low temperature measurements techniques [2].

A SQUID is essentially a superconducting ring containing either one or two Josephson Junctions and it is considered a flux to voltage transducer, so it can be used to measure magnetic flux, changes in flux, current or voltage. Many SQUID based instruments are unique in their sensitivity: SQUID magnetometers are able to resolve flux increments of $\sim 10^{-10}$ G and precision voltmeters with the sensitivity of $\sim 10^{-15}$ V.

"There are two types of SQUIDs.

- A dc SQUID, contains two Josephson Junctions in a superconducting ring and is operated by dc current. The critical current in the SQUID oscillates as a function of the externally applied flux (ϕ) with a period of a flux quantum (ϕ_0). If the SQUID is biased with constant current, the voltage across the SQUID is also periodic in ϕ.

- An rf SQUID, contains only one Josephson junction in the superconducting ring, which is coupled to a tank circuit and is operated by rf current. The rf voltage across the tank circuit is also periodic in ϕ." [3]

The Superconducting Quantum Interferometers Devices have the following applications:

- Magnetic resonance imaging for medical diagnostics (e.g. activities of brain).

- Sensing geological changes deep within the earth crust (for ore deposits).

- Prospecting to submarine hunting.

- Measurements of magnetic properties of materials.

- In the future, they will be used probably to predict earthquake periods by magnetically monitoring strain build up deep beneath the earth [3].

Finally, it is worth to mention that additionally to the many applications of the Josephson Effect, in the future the understanding of the superconductivity in HTS, and the development of a perfect Josephson junction operating at high temperatures would be the key, between others, to improve qubit performances[4].

If anyone want to read the original paper from B.D. Josephson, see the reference [5].

References

[1] V.V. Schmidt. *The Physics of Superconductors: Introduction to Fundamentals and Applications*, Springer (2013) pp. 74-80.

[2] A. I. Braginski, Consequences of Brian Josephson's Theoretical

Discovery, J Supercond Nov Magn **34**, 1597-1600 (2021). https://doi.org/10.1007/s10948-020-05772-z

[3] Ajay Kumar Saxena. *High-Temperature Superconductors* Vol 125, Springer Series in Materials Science (2009) pp. 166-172.

[4] F. Tafuri, Introduction: the Josephson Effect and Its Role in Physics. J Supercond Nov Magn **34**, 1581–1586 (2021). https://doi.org/10.1007/s10948-020-05775-w

[5] B.D. Josephson, Possible new effects in superconductive tunnelling, Physics Letters **1**, 7 251-253 (1962). https://www.sciencedirect.com/science/article/pii/0031916362913690

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