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Charge-injection into a Superconductor

It was as if a superconducting wire were like a bucket brigade that could deliver water up to speeds to, say, 10 buckets a minute, but could be pushed no faster.

Bruce Schechter: The Path of No Resistance

27.1 Injection rate

When a normal electric-current is flowing around a circuit, the applied source-voltage V causes an applied electric-field E around the whole circuit. If the circuit, however, contains a superconducting element through which an equilibrium-current is flowing, then there is no electric-field within this element, but only within the circuitry external to the superconducting element, which, as illustrated by the dashed box in Fig. 27-1, solely determines the magnitude of the current I that flows through the superconducting element.

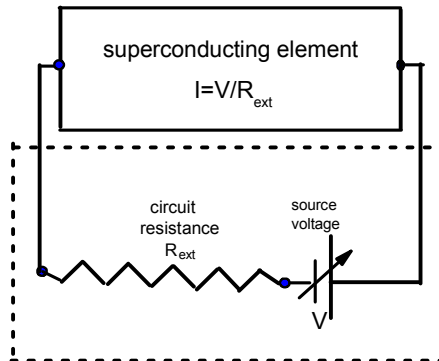


Figure 27-1: A superconducting element within a circuit: The circuitry external to the superconducting element (enclosed by the dashed box) solely determines the current I which flows through the superconductor

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In other words, even though the electric-field can only exist externally to the superconductor, it still drives the current around the whole circuit (including the superconducting element), by only accelerating-and-scattering the charge-carriers within the circuit external to the superconductor. If the external circuitry responds according to Ohm's law, the current through the superconductor increases proportionally to an increase of the electric-field within the external circuit: i.e. proportional to the source-voltage V . For a total resistance R_{ext} , external to the superconducting element (which includes the resistance of the source-voltage element), the current I through the superconductor can be written as:

$$I = \frac{V}{R_{\text{ext}}} \quad (27.1)$$

Note that there is no physical property of the superconductor itself that determines the magnitude of this current. There is, however, an upper limit to the magnitude of this current, which is solely determined by the superconductor; and this behaviour will be explained in this section.

When the source-voltage V is increased, the rate at which charge-carriers move along the external circuit, through an interface normal to the direction in which the current flows, increases in proportion to the external resistance as determined by Eq. 27.1. Thus, the applied electric-field, caused by the source-voltage, within the injection-contact to the superconductor, solely determines how many charge-carriers are being injected per unit time into the superconductor.

27.2 Transit-time of an injected charge-carrier

Since there is no electric-field within the superconducting element itself, the speed with which an injected charge-carrier moves through the superconductor, all the way from the injection contact until it reaches the target contact, is now not determined by acceleration-scattering within the superconductor, as is the case for a normal conductor, but by the time-interval Δt_i which elapses from the instant after a charge-carrier replaces a resident orbital until after it has moved on and replaced the next orbital. This time-interval is thus equal to the time interval for which the orbital remained at the first site (which will be termed the dwell-time Δt_{dw}) plus the time interval Δt needed to jump and replace the next orbital. One thus has that:

$$\Delta t_i = \Delta t_{\text{dw}} + \Delta t \quad (27.2)$$

As had already been shown in Fig. 23-2, for a given binding-energy ΔE_s , the actual jump-time Δt of any orbital from one anchor-site to the next is solely determined by the distance R between the orbitals.

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In order to simplify the discussion, we will now consider a hypothetical superconductor consisting of a single string of Wigner-orbitals where the orbitals are spaced at the same inter-orbital distances R apart. Some of the possibilities inside such a single-string superconductor are shown in Fig. 27-2:

(a) When a solitary charge-carrier is injected (see Fig. 27-2(a)), it sets in motion successive barrier-jumps of the orbitals from one anchor-point to the next: Each jump requires a time interval Δt as determined by Heisenberg's relationship for energy and time. If there are N_{ORB} residential orbitals between the two contacts, where the latter are spaced a distance L_S apart from each other, the injected charge will reach the target-contact after a time-interval ΔT where:

$$\Delta T = N_{\text{ORB}} \Delta t = \left(\frac{L_S}{R} \right) \Delta t \quad (27.3)$$

But this is not the originally injected charge-carrier itself that moved all the way from the injection contact to the target contact: The original charge-carrier remains trapped at the site of the first orbital it replaced. Its dwell-time Δt_{dw} is thus infinitely long; unless another charge is subsequently injected to replace the first injected charge-carrier. In contrast, the speed v_q with which a charge is relayed and ejected at the target-contact, after a single charge-carrier has been injected at the injection-contact is given by:

$$v_q = \frac{L_S}{\Delta T} = \frac{R}{\Delta t} \quad (27.4)$$

(b) When a second orbital is injected, the situation could be as shown in Fig. 27-2(b) where the barrier-jumping, initiated by the first injected charge-carrier, is well spaced from the barrier-jumping that is now being initiated by the second injected charge-carrier. In this case the second charge is injected at the same time that the first injected orbital has already caused two relay-jumps to have occurred; so that the relay-jump caused by the first injected charge-carrier is occurring from orbital position 3 to orbital position 4, while simultaneously the relay jump initiated by the second injected charge-carrier is occurring from orbital 1 to orbital 2. Thus, the dwell-time of the first injected charge at the first anchor-site of the orbital it replaced, is now $\Delta t_{\text{dw}} = 2\Delta t$.

(c) In Fig. 27-2(c) the dwell-time is zero so that the time that elapses after injecting the second charge-carrier is now $\Delta t_i = \Delta t$.

It should be clear that the time-interval Δt_i is completely determined by the rate at which charges are being injected. It is for this reason that the sub-

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script “i” has been used from the start. The faster the rate, the smaller Δt_i becomes and therefore also the smaller the dwell-time Δt_{dw} becomes. The jump-time Δt is obviously not affected by the rate at which charge-carriers are being injected since this time-interval is fixed by the binding-energy ΔE_S of the orbitals and the distances R between them.

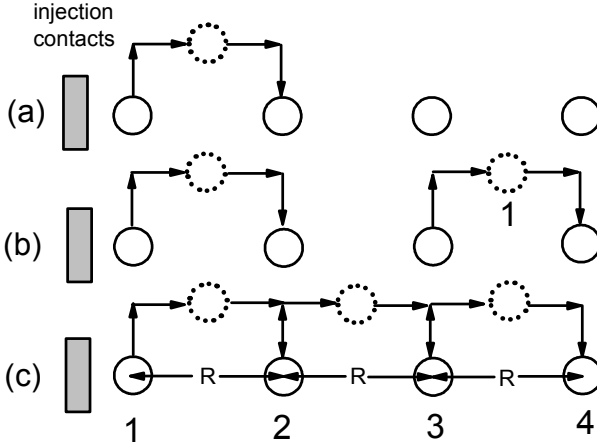


Figure 27-2: Injecting charges into one-dimensional arrays of Wigner-orbitals: (a) A single charge is injected causing an orbital to barrier-jump from position 1 to position 2 and then proceeding further. (b) Two charges sequentially injected so that an orbital is moving from position 3 to position 4, while an orbital moves from position 1 to 2: (c) Three charges injected soon after one another so that the orbitals follow each other with sequential jumps.

27.3 Injection-limited maximum current flow

One might want to argue that when injecting a single charge-carrier into such a string of orbitals, this initiates a current I which flows through the string for a time interval ΔT given by:

$$I = \frac{qR}{\Delta t} \quad (27.5)$$

But this is not an equilibrium-current: In order to have an equilibrium-current flowing through the string, one must keep on injecting charge-carriers into the string at a constant rate. Assume that charge-carriers are injected at time intervals Δt_i apart: Sequential, relayed charges will then pass any point along the string with the same time-interval Δt_i between them: The electric current I along the string must then be:

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$$I = \frac{q}{\Delta t_i} = \frac{q}{\Delta t_{dw} + \Delta t} \quad (27.6)$$

Since Δt is fixed by the binding-energy ΔE_S and the distance R between the orbitals, there is an upper limit Δt_{i0} to the time-rate at which charge-carriers can be injected: This limit is reached when $\Delta t_{dw} = 0$: i.e. when $\Delta t_i = \Delta t_{i0} = \Delta t$. The current through the string then reaches a maximum value I_0 beyond which it cannot increase any further.

27.4 Single-link limitation to current-flow

For orbitals along a string, which all have the same binding-energy ΔE_S but not the exact same length R between all of them, the shortest distance between two consecutive orbitals will be responsible for determining the maximum current I_0 that can flow along the string. It is weird to find that the shortest distance between two orbitals causes the longest jump-time Δt_{long} from one anchor-site to the next: But, as already pointed out above (see section 23), this is how it is when Heisenberg's relationship for energy and time applies.

Since the actual jump-time Δt_{long} (through such a shortest distance) is longer than for the other inter-orbital distances along the string, the concomitant dwell-time $\Delta t_{dwshort}$ is shorter: This is so since, independent of the distances between the orbitals, the sum of the dwell-time and jump-time must remain equal to the injection-time Δt_i for as long as an equilibrium-current is flowing along the string: Thus, also for the shortest distance one must have that:

$$\Delta t_{dwshort} + \Delta t_{long} \equiv \Delta t_i \quad (27.7)$$

Therefore, when increasing the injection rate, the dwell-time for the shortest distance becomes zero before the dwell-times for the other distances can do likewise. Thus, even though the other distances can still allow a higher injection frequency, the maximum current I_0 along a superconducting string, is now determined by the shortest distance along the string: i.e. it is reached at the critical injection time-interval $\Delta t_{i0} = \Delta t_{long}$.

Obviously, one can also have other blocking effects between two consecutive orbitals along a string: For example, the energy-barrier that has to be scaled when barrier-jumping from one orbital to the next might for some reason be less than ΔE_S . The jump-time will increase, and this increase will then limit the maximum current that can be reached.

Alternatively, the barrier height between two consecutive orbitals along a string might for some reason be higher than ΔE_S : Although the jump-time will be shortened by this increase in barrier-height, the maximum distance

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that can be jumped is now shorter, and if this distance is shorter than the actual distance R between the two orbitals, the flow of a current along the string will be totally blocked from even initiating.

27.5 Entanglement along a string of orbitals?

After reaching a maximum current caused by a single link somewhere along the string, how does a charge, being injected into the string ‘knows’ that it cannot cause a relay of charges for the whole length of the string? One is compelled to conclude that under this circumstance it is possible for the orbitals along the string to “know” near-instantaneously (or instantaneously?), that the injection-rate of charges cannot be increased any further.

It seems as if all the orbitals are in “telepathic” contact with one another, provided that all the distances between adjacent orbitals along a string are smaller than a critical distance as determined by Heisenberg’s relationship for energy and time. The latter behaviour seems to be “magic”, but it is commensurate with the deduction in section 23.5 that communication within an entangled wave is not subject to the limitations of Einstein’s special theory of relativity. Thus, one has to conclude that the orbitals along the string are in some manner entangled with one another: This entanglement, however, differs from the macro-wave which forms from electrons which have been extracted from an n-type diamond: In the latter case each “electron-orbital” totally loses its separate existence.

27.6 Holistic coherence?

A superconductor has size: Usually a length L_S and a cross-sectional area A_S . In this case the current is constituted by the total charge that flows per second, perpendicularly through the cross-sectional surface area A_S . For an actual superconducting element within a circuit, one must thus look at the situation when there is more than one string along the direction of current flow: If the density of strings per unit area is N_{SC} , then the total number of strings along the length L_S of the superconductor is $A_S N_{SC}$.

Thus, if all the strings are simultaneously passing a current, the total current that flows through the superconductor, when charges are injected into these strings, follows from Eq. 27.6 as:

$$I = q \left(\frac{N_{SC} A_S}{\Delta t_i} \right) = q \left(\frac{N_{SC} A_S}{\Delta t_{dw} + \Delta t} \right) \quad (27.8)$$

At low injection rates it is possible that only a fraction ϕ of these strings are required to pass the total current. In such a case N_{SC} in Eq. 27.8, must be replaced by ϕN_{SC} .

Since it has been concluded that the orbitals along a single string must be entangled in order to convey a superconducting current, similar cross-en-

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tanglement between parallel strings should also be possible for orbitals within different strings. When this is the case, one expects that the orbitals which move along a “bundle” of parallel strings will do so in step; i.e. by forming coherent “wave-fronts” of orbitals, where the orbitals on such a front, all move simultaneously through the superconductor. This implies that consecutive “wave-fronts” follow each other at consecutive time-intervals equal to the injection time-interval Δt_i ; i.e. they constitute a coherent wave-like motion.

Since the orbitals execute jumps in the direction in which the “wave-fronts” is moving, the motion is akin to a longitudinal wave: However, it is not a “standard” longitudinal wave since, with each cycle, the orbitals do not move to and fro through equilibrium positions like the “particles” which constitute a real longitudinal wave actually do. In contrast, the superconducting orbitals move only forward from one equilibrium position to the next during a single cycle.

It is of course possible that some strings reach the maximum current, which such a string can carry, before other parallel strings reaches their maximum currents. This is probably what happens when one generates a “weak-link” by pushing a sharp point of one superconductor into the surface of another superconductor (see section 28.5).

27.5 Andreev reflection

If one assumes that the BCS-model is correct, one has to explain how a single-electron wave-packet, on entering the superconducting phase at an injection-contact, ends up forming a Cooper pair consisting of two “electrons” of opposite spins; which are bound by an energy 2Δ that supposedly forms a gap with energy Δ below the Fermi-energy and an energy Δ above the Fermi-level.

A Russian scientist, Alexander Andreev, considered the situation when an electron is incident at an energy below the gap-energy 2Δ : Why “below the gap-level” is in itself a mystery, since the free wave-packets within the contact should all be injected at an energy equal to the Fermi-level: i.e. they should all enter at energies which is equal to the midgap-energy of the Cooper pairs. Nonetheless, Andreev concluded that a single-electron wave-packet incident at an energy below the gap-energy will form a Cooper pair within the superconducting phase and this requires a simultaneous “retro-reflection” of a hole of opposite momentum and spin (to the incident electron) from the interface. Retro-reflected holes have since been observed: But these holes are, most probably, not caused by the physical-mechanism proposed by Andreev.

As already pointed out in section 9.1 an image-charge is left behind when an electron is ejected into a vacuum. And near the surface such an image-charge is a real positive charge: i.e. a hole. The vacuum is an insula-

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tor: The same happens when a single-electron wave-packet is ejected from a metal into any other insulator.

A superconductor formed by an array of Wigner-orbitals is a Mott-type insulator: Thus, when injecting an electron wave-packet into it from an injection-contact, a hole must be “retro-reflected” from the interface into the contact material. This behaviour has nothing to do with the formation of a Cooper pair and does not prove the existence of Cooper pairs; as is incorrectly argued in the standard literature on superconduction.