

28

“Tunnelling”-junctions and superconduction

The more enlightened our houses are, the more their walls ooze ghosts.

Italo Calvino: The Literature Machine

28.1 Measuring “tunnelling”

There have been experiments reported in the scientific literature, and Nobel Prizes have been awarded, where “tunnelling” has been measured from a superconductor, as well as into a superconductor, through an insulating-layer: For example, through a superconductor-insulator-superconductor (SIS-structure) consisting of an insulating-layer (I-layer) flanked by two superconducting layers (SC-layers): See Fig. 28-1. “Tunnelling” from a normal conductor (N-layer), through an I-layer, into an SC-layer (or from an SC-layer through an I-layer into an N-layer) will not be considered here.

In order to simplify the discussion, it will be assumed that the two SC-layers flanking the I-layer are identical and perfect: In terms of the BCS-model the two phases must have the same density of Cooper pairs and the same order-parameters. In terms of Wigner-orbitals this mandates that the distances R between the orbitals in the direction of the current are all identical, and that the ionisation-energy ΔE_S is the same for each orbital.

The circuit external to the SIS-sandwich has a resistance, R_{ext} , so that the voltage which appears across the SIS-sandwich is not the same as the “internal” voltage V of the power-supply (see Fig. 28-1). Since the voltages across the two superconductors must be zero when a superconducting-current is flowing, it is argued in the mainstream literature that the measured voltage V_J must always only manifest across the insulating-layer. It would have been preferable if this voltage could have been measured directly across the I-layer to confirm that this assumption is correct under all circumstances: But these layers are so thin that it is not practically possible to do so. It might thus be possible, and, as will be seen in this section, is most probably

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a fact, that the measured voltage V_J could, especially under conditions when no current is flowing, be substantial across the whole SIS-structure: Not just the insulating-junction.

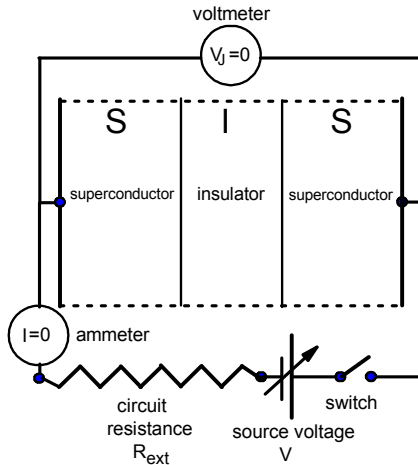


Figure 28-1: Schematic illustration of an experimental set-up to measure a current flowing through a superconductor-insulator-superconductor sandwich (SIS-sandwich). The current I flowing around the circuit is measured as a function of the voltage V_J which is assumed in the mainstream scientific literature to be only present across the insulating-layer. In this diagram no current is flowing since the switch is open.

“Tunnelling” between two superconducting phases has, and is being modelled (in the mainstream physics journals) in terms of the traditional interpretation, according to which this physics-phenomenon is a result of the wave-intensity acting as a “probability-distribution”: i.e. it is assumed that it occurs when the “tunnelling-tail” of the relevant wave has a presence within the insulating-layer so that the “particle” it represents has a “probability” to find itself “within” this layer and thus move “through” this layer: This aspect has already been discussed in section 9.3.

Also in the same latter section, it was argued that the traditional explanation in terms of a probability-amplitude might be wrong. It was thus proposed that there is not any “tunnelling of a particle” owing to the non-zero intensity of a wave-function within an energy-barrier, but that this process is caused by a pseudo-“particle” (or better described as a localised electron-wave; which can be either a wave-packet or a localised orbital) scaling such an energy-barrier by means of “barrier-jumping”. As proposed in section 23, it is also this same mechanism that enables superconduction to occur.

Future experiments will have to serve as the final arbiter in deciding which one of these two mechanisms is the correct one: Or at least which one

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is more “probable” than the other mechanism. In my opinion, it is compelling that the jumping mechanism is less Voodoo than the movement of a particle with mass through an energy-barrier which requires from it to have a negative kinetic energy: The latter mechanism most probably violates Pauli’s exclusion principle.

In this section of this book, “tunnelling” from one superconductor (SC-layer) to another superconductor (SC-layer) through an insulating-layer (I-layer) is modelled in terms of barrier-jumping and compared to the conventional models based on “tunnelling-tails” within the barrier. Since this entails new physics which has not yet been proposed elsewhere, mathematics is used a bit more generously.

28.2 Josephson’s prediction

Brian Josephson predicted in 1962, by using the complicated mathematics of quantum field theory, that Cooper pairs should be able to “tunnel” as “single entities” through an insulating-layer. John Bardeen, of transistor- and BCS-fame, publicly dismissed Josephson’s derivation because *“pairing does not extend into the barrier, so there can be no such superfluid flow”*. It is indeed found that insulating layers through which normal wave-packets can “tunnel” with ease, do not allow superconducting charge-carriers to “tunnel” through them. But when the insulating-layer becomes extremely thin, it is found that superconducting charge-carriers can actually move through such an I-layer; but when this happens normal charge-carriers cannot move through the same I-layer simultaneously.

But does this experimental observation really prove that the charge-carriers are Cooper pairs? As already mentioned above, it is argued in the conventional scientific literature that for “tunnelling” to occur the relevant waves must have “tunnelling”-tails within the insulating-layer. It is thus a mystery why the “tunnelling-tails” of the free wave-packets can be responsible for “tunnelling” while the “tunnelling”-tails of the superconducting charge-carriers do not allow any simultaneous tunnelling whatsoever of the superconducting charge-carriers when the layer is too thick. It is even more of a mystery why the normal charge-carriers are not simultaneously flowing through the thinner I-layer when the superconducting charge-carriers can.

One would expect that when both types of charge-carriers are present, they should both have “tunnelling tails” within the insulating-layer and should thus, according to the traditional model for “tunnelling”, both be able to “tunnel” at the same time: i.e. when the insulating-layer is thin enough to allow normal wave-packets to “tunnel”, it should surely also allow superconducting charge-carriers to “tunnel”: But this is not what is experimentally measured.

What is found is that either the superconducting charge-carriers “tunnel” or the normal charge-carriers “tunnel”: Never both simultaneously. This is very strange indeed, since the wave which represents a Cooper pair is larger

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than a normal wave-packet one expects that it should have longer tunnelling tails: If this is the case, then, according to the overlap-model, it should make it easier for a Cooper pair to tunnel under all conditions through any insulating-layer (thick or thin) than it should be for a normal charge-carrier. In contrast, when modelling “tunnelling” in terms of barrier-jumping (as will be done below), it becomes clear why, when normal charge-carriers can “tunnel”, superconducting charge-carriers cannot, and why, when superconducting charge-carriers can “tunnel”, normal charge-carriers cannot.

John Bardeen apologised to Brian Josephson at a conference. Maybe he should not have done so: The other possibility is that the experimental verification of “tunnelling” between two superconductors is proof that Cooper pairs do not exist at all; since such entities, if they do exist, will, most probably, not be able to “tunnel” for exactly the reason that Bardeen had pointed out.

Bardeen might thus not have been wrong at all! But if he at that time proved that Cooper pairs are not the charge-carriers responsible for superconduction, he would not have won a second Nobel Prize. This does of course not imply in any way that he deliberately blocked any suggestion that Cooper pairs are not responsible for superconduction in order to win the Nobel Prize: But it does imply that Josephson’s model could be wrong since it is not Cooper pairs that are “tunnelling”: Would Josephson then have won a Nobel Prize for his model as he did?

28.3 Conventional models

28.3.1 Thick insulating-layer:

“Tunnelling”-currents are measured by switching on the power-source in Fig. 28-1 and increasing the source-voltage V , while measuring the electron-current I flowing around the circuit as a function of the measured voltage V_J across the SIS-sandwich. The voltage V_J is, whether a current is flowing or not flowing, non-zero when the insulating-layer is too thick to allow superconducting charge-carriers to “tunnel”.

It is found that for the low temperature metal-superconductors (which will be solely considered in this section), at very low temperatures above absolute zero (so that SC-layers on both sides of the I-layer consist primarily of superconducting charge-carriers) there is only a small leakage-current caused by the residual normal charge-carriers that is flowing at low voltages V_J until a critical voltage V_{JC} is reached; whence the current increases rapidly and becomes completely normal metallic-conduction. Extrapolation shows that at absolute zero temperature, when there should be no normal charge-carriers left at all, there will not be any current: Not even a leakage current until V_{JC} is reached and exceeded.

At the voltage V_{JC} , the superconducting phases, constituting the SC-layers, must thus suddenly change into normal-metal conductors: Normal char-

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ge-carriers must now be the majority charge-carriers present within the SC-layers: A normal current then flows through the whole SIS-sandwich and increases with a further increase in the measured voltage $V_J > V_{JC}$: Just as any normal current must do. This behaviour mandates that the voltage V_{JC} must be the thumbprint of an insulator-to-metal transition. This, in turn, mandates that the voltage V_J must manifest across the whole SIS-sandwich and not only across the insulating-layer (I-layer): However, this does not mean that the voltage across the I-layer cannot be larger than the concomitant voltages across the SC-layers. In the mainstream literature it is, however, assumed that the total voltage must always be only across the insulating-junction. If this could have been so, the normal charge-carriers would not be accelerated to move through the SC-layers.

The current-voltage (IV) curve which is measured for a thick insulating-layer is illustrated in an ideal format in Fig. 28-2(a): Here it is assumed that the measurement has been made at absolute zero temperature so that there is no leakage-current by normal charge-carriers whatsoever when $V_J \leq V_{JC}$. If there were only normal charge-carriers from the start, the current would have increased along the dashed line. Thus the inverse-slope of the dashed line is the normal resistance R_{SIS} of the SIS-sandwich.

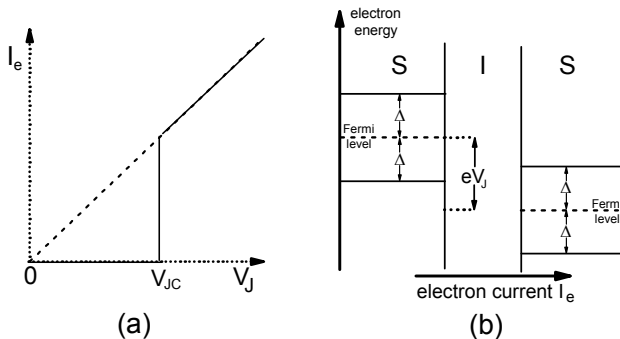


Figure 28-2: (a) An idealised representation of the current I flowing around a circuit (having an SIS-sandwich as an element) at absolute zero temperature, as a function of the voltage V_J measured across the SIS-structure: In this case the insulating-layer is too thick to allow superconducting charge-carriers to transfer a current through the SIS; (b) The proposed electron-energy diagram modelling this current-voltage behaviour in terms of the BCS model: It is assumed that V_J is only present across the insulating-layer: This is obviously impossible when there is no current flowing for voltages between zero and V_{JC} .

According to the BCS-model, the binding-energy 2Δ (of the Cooper pairs) forms an energy gap within the electron-energy spectrum around the

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Fermi-level: i.e. the upper edge of the energy-gap lies at energy Δ above the Fermi-level, and the lower edge of the gap at an energy Δ below the Fermi-level. When applying a voltage across the SIS-sandwich, the voltage-drop V_J is supposedly only present across the insulating-layer; even when there is no current flowing at all: This supposedly causes the energy levels on both sides of the insulator to move relative to one another by an amount eV_J as shown in Fig. 28-2(b): Note that e , the magnitude of the electron's charge, converts volt into electron-volt.

According to Fig. 28-2(b), the electrons below the gap, on the one side of the insulating-layer (left-hand side), can “tunnel” through the insulating-layer into the allowed energy-states above the gap on the other side (right-hand side) of the insulating-layer, as soon as $eV_J = 2\Delta$: According to the BCS-model, it is for this reason why the critical voltage V_{JC} manifests. Thus, it is argued in the mainstream scientific literature that one measures directly the “binding-energy $2\Delta = eV_{JC}$ of the Cooper pairs”. As can be seen in this energy diagram, whether a current is flowing or whether it is not flowing, the voltages across the SC-layers are totally ignored. But while a current is not flowing, the SC-layers must act as insulators (see section 23), and therefore the voltage across each of them cannot be neglected as being zero.

By doing measurements at different temperatures it has been found that the measured critical voltage V_{JC} decreases when the temperature increases; and that it increases to a maximum value when the temperature approaches absolute zero. This behaviour is (at present) taken as proof that electron-pairs are being “glued” together by phonon-interactions; and that they must therefore be Cooper pairs: As the temperature decreases, the phonon “coupling-strength” supposedly increases and therefore the binding-energy increases; so that the gap-energy 2Δ increases.

28.3.2 Thin insulating-layer:

When the insulating-layer is thin, it is found that when switching on the power supply and increasing the output voltage V of this power supply, a current immediately flows, but now no voltage V_J can be measured across the SIS-sandwich when increasing the voltage V of the power supply in order to increase the current through the circuit (see Fig 28-3(a)).

By increasing the source-voltage V , and thus the rate at which charge-carriers are being injected at the injection-contact, this current, for $V_J = 0$, increases, until at a critical magnitude I_0 , it suddenly disappears completely, and only then a non-zero voltage $V_{JN} \leq V_{JC}$ immediately appears: See the dotted line in Fig. 28-3(a) which connects the maximum current I_0 with the voltage V_{JN} . Thus V_{JN} is the voltage that would have been required to cause a normal current I_0 to flow through the SIS-structure: Therefore V_{JN} can be written in terms of the normal electrical resistance R_{SIS} of the SIS-sandwich as:

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$$V_{JN} = I_0 R_{SIS} \quad (28.1)$$

It is not clearly pointed out in the mainstream literature that the current, for zero V_J , does not flow at all when the output voltage of the power supply is switched off; and that when switched on, the voltage V must be non-zero in order to inject charge-carriers into the SIS-structure. Thus, as already pointed out in section 27, there is a voltage V involved which drives charge-carriers into the SIS-sandwich and then drives them further after they exit the SIS-sandwich; even though there is no voltage V_J across the whole SIS-sandwich itself when a superconducting-current is flowing.

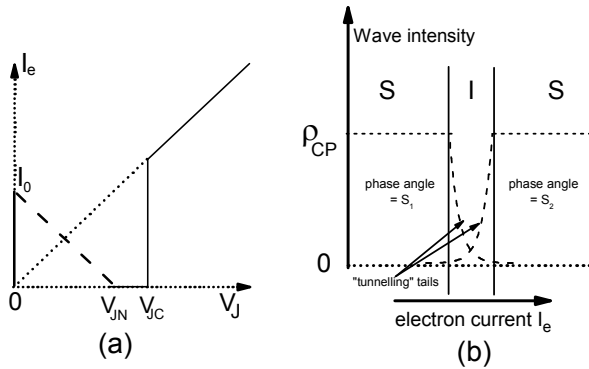


Figure 28-3: (a) An idealised representation of the current I_e flowing at absolute zero temperature through a suitably thin insulating-layer of an SIS-sandwich without any voltage V_J appearing across the SIS-sandwich until the current reaches a maximum value I_0 . (b) The macro-wave intensity-diagram which is used to model the current-voltage behaviour shown in (a) in terms of two superconducting order-parameters within the SC-layers.

At and above the critical voltage V_{JC} , the behaviour is exactly the same as for a thicker insulating-layer (see Fig. 28-2(a) for comparison). Thus also in this case an insulator-to-metal transition occurs at this voltage.

28.3.3 “Phase-slipping”

Since Josephson’s theoretical derivation is too complicated for most human beings, and even the majority of physicists to understand (most probably all of them, including Josephson), “Josephson-tunnelling” is modelled in text books and scientific publications by a derivation due to Feynman. Similar to Josephson’s approach, it is assumed that there are two superconducting macro-waves (order-parameters), one on each side of the insulating-layer. The supposed intensities of these order-parameters are illustrated in Fig. 28-3(b).

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Within these superconducting phases, the intensity is supposedly equal to the density of Cooper pairs and each wave has a phase-angle S . On the injection side of the insulating-layer, the phase-angle is supposedly S_1 , and on the other side the angle is supposedly S_2 . Why they should be different when the two superconducting phases are exactly the same, is quite strange and not explained anywhere; except in a hand-waving manner (see Feynman's argument below). The two order-parameters Ψ_1 and Ψ_2 are then written in mathematical format as:

$$\Psi_1 = \sqrt{\rho_1} \exp(iS_1) \quad (28.2a)$$

And

$$\Psi_2 = \sqrt{\rho_2} \exp(iS_2) \quad (28.2b)$$

where ρ_1 and ρ_2 are the densities of the Cooper pairs on the two sides. Why the densities of the Cooper pairs should be different for identical superconducting phases is just as strange; and is also not explained in terms of real physics.

It is then further argued that these two macro-waves decay in intensity when entering the insulating-layer; as illustrated in Fig. 28-3(b). How two waves, each of which must have a constant intensity everywhere within infinite space (see section 7.5), can do this, constitutes another major mystery. It is then argued that as long as these two decaying tails overlap, they “couple” quantum-mechanically: This “coupling” of the two waves supposedly enables Cooper pairs to “tunnel through” the insulating-layer and this allows a superconducting-current to flow through the SIS-structure. The latter current which flows through the I-layer is then supposedly given by a sinusoidal-function of the so called “phase-slip” S_s where the phase-slip is given by $S_s = S_1 - S_2$: i.e.

$$I = I_0 \sin(S_1 - S_2) = I_0 \sin(S_s) \quad (28.3)$$

The fact is, however, that this derivation actually gives two such currents flowing equally into opposite directions: i.e. for every charge-carrier that flows from the one side into the other side, another charge-carrier must flow back: In other words, there are two opposite currents, each described by its own identical equation, which flow along both directions and therefore the resultant current must be zero: Zero current is exactly what the situation always must be when two phases, which have the exact same Fermi-levels, are interacting across a thin insulating-layer. There is thus no physics-reason whatsoever why a current will only flow along a single direction through the I-layer! Feynman, however, argued that one should only choose one of the two equations as the sole current flowing through the SIS-structure.

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His argument is as follows: “*These equations are not the whole story. They say what the changes in ρ_1 and ρ_2 would be if there would be no extra electric forces due to an unbalance between the electron fluid and the background of positive ions.*” But there cannot be such an unbalance when the Fermi-levels are the same and when there is no voltage across the whole SIS-structure. The experimental data compellingly prove that there is not a voltage anywhere across any part of the SIS-device when a superconducting-current is flowing through it. So where does Feynman’s “*extra electric forces*” come from? If there are such forces, a voltage must be measured, and the current can then not be a superconducting-current at all: It will then have to be a normal current. The latter inescapable fact demands that, within Eqs. 28.2, one must have that $\rho_1 = \rho_2$ and that $S_1 = S_2$. It is thus impossible that Eq. 28.3 can model a superconducting-current flowing through a SIS-sandwich.

Nonetheless, it is argued in the mainstream physics-literature that when the phase-slip is zero, there is no “tunnelling-current” flowing, and when it is $\pi/2$ (90°), the maximum “tunnelling-current” must be flowing; where the magnitude of the latter, maximum current is supposedly determined by the strength of the “coupling” between the “overlapping waves” within the insulating layer. Why the phase-slip, under equilibrium conditions, can be anything else but exactly zero is not explained at all: It is just assumed that this is caused by the “magic” of quantum mechanics which is manifesting on a “macro-scale”.

The following double-speak can be found in the accepted scientific literature: “*In practice, a given current I is passed through the junction and for $I < I_0$ the phase-slip S_s adapts so that the current passes without a voltage appearing*”. What an intelligent phase-slip! Wow!!! And they call this physics?

28.4 Wigner-orbitals separated by an insulating-layer

Let us now look at the alternative model for superconduction proposed in this book: Assume that within the two superconductors (SC-layers), separated by an insulating-layer (of thickness δ) the Wigner-orbitals have a binding-energy ΔE_s and are at distances R apart: If the insulator presents a barrier-energy of ΔE_B , which must be larger than ΔE_s , a Wigner-orbital must borrow the required energy given by $\Delta E_B + T_K$ to move through a distance $R_B \geq \delta$ from one side of the insulating-barrier to the other side (see Figs. 28-4(a) and 28-5(a)) for the thick layer and for the thin layer respectively).

28.4.1 A thick insulating-layer

Consider the experimentally-established situation when the insulating-layer of thickness δ does not allow superconducting charge-carriers to “tunnel”, but is thin enough to allow normal, free wave-packets to “tunnel”.

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The electron-energy diagram, within the SIS-sandwich at a temperature T less than T_c (but above absolute zero) after a voltage V_J has been generated across the SIS-structure, is shown in Fig. 28-4(a). Since there is not a superconducting current flowing at all through the SIS-structure, there must be an electric-field within the whole SIS-structure caused by the voltage V_J across the whole SIS-structure. Therefore, the energy levels must be sloped everywhere within the SIS-sandwich.

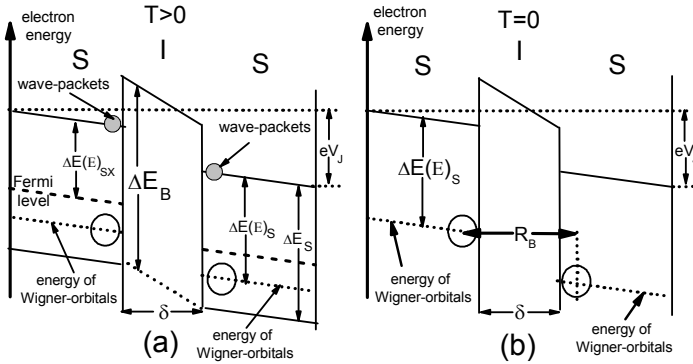


Figure 28-4: (a) Schematic equilibrium electron-energy diagram of a SIS-sandwich with a thick insulating-layer when there are Wigner-orbitals, and after a voltage drop V_J has been applied at a temperature higher than absolute zero. (b) The corresponding electron-energy diagram at absolute zero temperature after a voltage V_J has been applied across the sandwich.

Note that, within the SC-layers depicted in Fig. 28-4a, the sloped Fermi-level is above the sloped energy-level of the Wigner-orbitals: There are thus, in addition to the Wigner-orbitals, also wave-packets present. It has been assumed that the insulating-layer is thin enough so that these wave-packets can barrier-jump through it: To do this they must be able to scale a barrier-height of ΔE_{WP} which can be calculated to be: $\Delta E_{WP} = \Delta E_B - E_S$.

One might now want to argue that the slope of the energy-levels should, under these conditions, be very small within the SC-layers since the leakage current represents “normal” metallic-conduction through the SC-layers: But the latter is not the case. Even though there are normal charge-carriers which can barrier-jump, and thus cause a small, metal-like current to flow from one contact to the next through the SIS-sandwich, the SC-layers are in essence insulators: This is so since a metal-insulator transition occurred when the Fermi-level moved into the energy-gap ΔE_S at the critical temperature T_c : Thus, the remaining normal charge-carriers are too few for the SC-layers to be real metal-conductors. The slope of the Fermi-level within the

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SC-layers will thus be substantial and essentially the same as one would expect if there were no normal charge-carriers present at all within these layers.

Since δ is large, a Wigner-orbital on one side of the layer cannot borrow enough energy to scale the insulating barrier with energy ΔE_B and move through the distance R_B in order to replace the next orbital on the other side of the insulating-layer. This means that according to Eq. 23.5 one has that $R_B > g\hbar / \sqrt{2m\Delta E_B}$: It is for this reason that “tunnelling” of Wigner-orbitals does not manifest at all when δ is large, and why only the few remaining, normal charge-carriers can constitute a small leakage-current for voltages V_J between zero and V_{JC} .

To simplify our discussion it will be assumed that measurements can be made at absolute zero temperature so that there is no residue of normal charge-carriers within the SC-layers whatsoever: The Fermi-level is then at the position of the Wigner-orbitals. When the source-voltage V in Fig. 28-1 is now switched on and increased from zero voltage, no current whatsoever will be able to flow at low voltages $V_J < V_{JC}$: This is so since there are now no wave-packets above the energy gap available (see Fig. 28-4(b)); and, in addition, the width of the insulating-layer is too large to allow the Wigner-orbitals to move through the layer by means of barrier-jumping. Thus, the whole SIS-structure (I-layer and SC-layers) is now a perfect insulator, within which the electron energy-levels are everywhere sloped.

In order to understand what is physically happening when increasing the voltage V_J , we will first assume that there is no SIS-sandwich between the contacts. The two contacts then act as capacitor-plates with an electric-field of magnitude E between them. If the distance between the plates is $D+\delta$, the voltage measured will be:

$$V_{JV} = E(D + \delta) \quad (28.4)$$

Where E is the applied electric-field to which the SIS-sandwich reacts when it is placed between the contacts.

The I-layer need not and do not have the same dielectric constant as the SC-layers: Let us assume a dielectric constant κ_S for the SC-layers and a dielectric constant κ_I for the I-layer. With the SIS-sandwich between the contacts, the voltage across the SIS-sandwich will thus be V_J where:

$$V_J = E \left(\frac{D}{\kappa_S} + \frac{\delta}{\kappa_I} \right) = V_{JSC} + V_{JI} \quad (28-5)$$

The Wigner-orbitals within the SC-layers polarises readily within the applied electric-field E and therefore one expects that the rate at which the voltage will drop with distance across the SC-layers will be less than across the I-

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layer. It is thus possible that $V_{JSC} \ll V_{JI}$: However, it is not zero. This same polarisation of the orbitals within the SC-layers decreases the non-polarised ionisation-energy ΔE_S to be given by $\Delta E(E)_S < \Delta E_S$. Note that this also happens in Fig. 28-4(a) since, even with normal charge-carriers still being present, the material is an insulator as long as the Fermi-level is present within the energy gap.

Thus, by increasing V_J , the electric-field E increases within the SC-layers, and $\Delta E(E)_S$ decreases until it becomes zero: The Wigner-orbitals now have no other choice but to become “normal charge-carriers”: i.e. there is now no binding energy to anchor the Wigner-orbitals at localised sites and they thus transmute into free wave-packets, which can barrier-jump through the insulating-layer. The normal charge-carriers are thus accelerated by the applied electric-field within the SIS-structure so that a normal-current immediately starts to flow all the way through this structure; as illustrated in Fig. 28-2(a). At this point the two SC-layers are not insulators anymore, but real metal conductors. An insulator-to-metal transition thus occurs at the voltage V_{JC} when the Wigner-orbitals morph into wave-packets. Only now does the largest portion of the voltage drop (V_{JC}) manifest across the I-layer.

The polarisation of the Wigner-orbitals, when no current is flowing, can be modelled in terms of a classical spring constant, and therefore one can write that:

$$\Delta E(E)_S = \Delta E_S - \alpha E^2 \quad (28.6)$$

Where α is determined by the spring constant. At the critical electrical field E_C an insulator-to-metal transition is reached since $\Delta E(E_C)_S = 0$. From Eq. 28.5 it thus follows that:

$$E_C = \sqrt{\frac{\Delta E_S}{\alpha}} \quad (28.7)$$

By assuming that one can ignore the much lower voltage drops across the SC-layers, since these layers are now metallic, one can write that $E_C \cong V_{JC} / \delta$: So that in terms of Eq. 28.7, it follows that:

$$V_{JC} \cong \left(\frac{\delta}{\sqrt{\alpha}} \right) \sqrt{\Delta E_S} \quad (28.8)$$

The critical voltage is thus proportional to the square root of the energy gap, and not equal to the energy gap as derived in terms of the BCS-model.

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At temperatures above absolute zero, it becomes more difficult to measure the critical voltage V_{JC} since wave-packets are present even before this voltage is reached: The leakage current that the wave-packets cause cloaks the point at which the critical voltage V_{JC} at the prevailing temperature is reached. For $T > 0$, the latter critical point is obviously reached as soon as the activation-energy $\Delta E(E)_{SX}$ becomes zero: i.e. when the Fermi-level moves out of the gap so that the SC-layers go through an insulator-to-metal transition. Since ΔE_{SX} decreases with increasing temperature, to become zero at the critical temperature T_c , one will measure that V_{JC} does the same; just as is experimentally observed. Thus, V_{JC} correlates with the square root of the activation-energy $\Delta E(E)_{SX}$: Not with the “binding-energy” 2Δ of a Cooper pair.

28.4.2 A thin insulating-layer

When the thickness of the insulating-layer δ becomes small, the situation is reached where the Wigner-orbitals can borrow energy ΔE_B and move through the distance R_B by doing barrier-jumping: i.e. in this case one has that $R_B \leq g\hbar / \sqrt{2m\Delta E_B}$ (see Eq. 23.5).

When now switching on the power supply in Fig. 28-1, and increasing the source-voltage V , the injected charge-carriers can immediately barrier-jump through the insulating-layer. Since charge is now transferred across the I-layer in exactly the same manner as between any two adjacent orbitals within a superconductor, the I-layer becomes an integral part of a single, superconducting phase: The voltage is shorted by the moving Wigner-orbitals since they do not require an electric-field to move from an anchor-site to the next anchor-site, also not when they barrier-jump through the I-layer. The electric-field is therefore totally cancelled within the whole SIS-structure; as illustrated in Fig. 28-5(a).

When increasing the voltage V on the power supply in Fig. 28-1, the rate at which charge-carriers are being injected increases, and accordingly the current through the superconductor increases in concert. As already discussed in section 27.3, superconduction will stop when the rate at which charges are injected at the injection-contact exceeds a critical value determined by the slowest jump-time between two adjacent orbitals along the direction of motion. This jump-time might be determined by barrier-jumping across the I-layer, or might even be determined by barrier-jumping between two adjacent orbitals within the SC-layers. Assuming that Eq. 23.8 can be used to calculate the jumping speed v_0 through the distances R_0 within the SC-layers at absolute zero temperature, as well as the jumping speed v_B through the distance R_B across the I-layer, the maximum-current I_0 will be determined by the I-layer when:

$$R_B \Delta E_B < R_0 \Delta E_S \quad (28.9)$$

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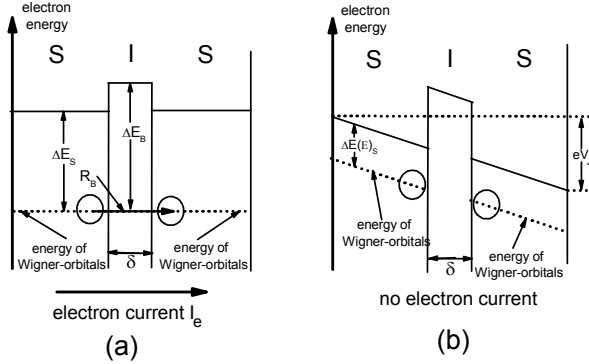


Figure 28-5: Schematic electron-energy diagram at absolute zero temperature of a SIS-sandwich with a thin insulating-layer when invoking the presence of Wigner-orbitals: (a) The insulating-layer is thin enough to form an integral part of it: Therefore a current flows without any voltage appearing across the SIS-sandwich. (b) The corresponding electron-energy diagram at absolute zero temperature after the maximum superconducting-current has been reached: Current-flow stops and a voltage appears across the SIS-structure. A normal current starts to flow as soon as $\Delta E(E)_S$ becomes zero.

If we assume that the relationship in Eq. 28.9 is manifesting, and that there are N_{SC} strings per cross-sectional area (see Eq. 27.8) which all transport a current, the maximum current I_0 for charge-carriers with a charge q per carrier, is reached when the dwell-time for moving through the I-layer becomes zero: i.e. when the injection frequency $\nu_i = (\Delta t_i)^{-1}$ is such that $\Delta t_i = \Delta t_{i0} = \Delta t_B$; where Δt_B is the jump-time of an orbital across the I-layer. The maximum current I_0 then follows (provided Eq. 28.9 is valid) from Eq. 27.8 as:

$$I_0 = q \left(\frac{A_S N_{SC}}{\Delta t_B} \right) = q \left(\frac{A_S N_{SC}}{R_B} \right) V_B \quad (28.10)$$

If the temperature is low enough so that Eq. 23.8 can be used, Eq. 28.10 can be written in terms of the barrier energy ΔE_B as:

$$I_0 = q A_S N_{SC} \left(\frac{\Delta E_B}{g \hbar} \right) \quad (28.11)$$

After reaching the maximum current I_0 , a further increase in the source-voltage V will cause current-flow to stop abruptly, so that the voltage V_{JN} ap-

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pears across the whole SIS-structure as shown in Figs. 28-3(a) and 28-5(b). The electric-field within the SC-layers is now not cancelled anymore; so that the Wigner-orbitals become polarised. Accordingly, as had been pointed out above, the ionisation-energy ΔE_S decreases to become $\Delta E(E)_S$: At absolute zero temperature this occurs without a decrease in the density of the orbitals and a concomitant increase in the spacing R_0 between them.

When now further increasing the source-voltage V , a critical electric-field is eventually reached at which the reduced ionisation-energy $\Delta E(E)_S$ becomes zero: An insulator-to-metal transition occurs so that the majority of Wigner-orbitals are replaced by wave-packets: Normal conduction kicks in at the critical voltage V_{JC} : Just as shown in Fig. 28-3(a).

28.5 The AC-Josephson-effect

It has been claimed by Josephson, and is still advocated in the mainstream literature on superconduction, that when one places a DC-voltage V_J across a thin I-junction of an SIS-sandwich, while the SIS-sandwich is transporting a superconducting-current, the junction will generate an ac-current and emit electromagnetic radiation.

According to Josephson's and Feynman's derivations, any voltage across the junction must cause the phase-slip S_S to become time-dependent: When integrating this time dependence from $t=0$ to $t=t$ one obtains that:

$$S_S = \frac{qV_E}{\hbar} t = \omega t \quad (28.12)$$

The current is then supposedly generated by a trigonometric function of this time-dependent phase-slip (for example, by replacing the phase-slip in Eq. 28.3 with the expression in Eq. 28.12). It is the accepted dogma that for this reason the phase-slip causes an AC-current with frequency $\omega = (qV_J)/\hbar$ that passes to and fro through the I-junction while emitting radiation with a photon-energy of $\hbar\omega = qV_J$.

The logic and experiments used in the mainstream literature as proof that the latter prediction is correct, are very confusing: For example, it is claimed in some publications that after the maximum current I_0 has been reached as shown in Fig. 28-3(a), an AC-current is actually established, but that its amplitude is so small that it cannot be observed. I doubt this very much since there is no physics-reason why the amplitude must be so vanishing-small. Furthermore, the experimental evidence that is used to claim that such an AC-current actually manifests, is based on results which can only be generated when the SIS-sandwich is simultaneously irradiated with electromagnetic waves and then increasing the source voltage V . Resonant, discrete voltage steps ΔV_{JMW} are then generated by the frequency of the electromagnetic field: This is not the same as a continuous increase in the fre-

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quency of an emitted electromagnetic wave with an increase in V_J as Josephson's model predicts (see below).

It is also claimed in the mainstream literature that it has been experimentally verified that when solely placing a DC-voltage across an I-layer, (while superconduction is occurring through the SIS-sandwich) electromagnetic radiation is actually emitted with the frequency predicted by Josephson. But how do you place a DC-voltage V_J across an I-layer while the SIS-structure is still able to pass a DC superconducting-current? It is easy to do this mathematically, as had been done by both Josephson and Feynman, but it cannot be done in reality. As can be seen from Fig. 28-3(a), superconduction must first stop completely before a voltage can at all appear across a SIS-sandwich; and when a voltage does appear, there is clearly not any respectable current for voltages larger than zero and less than V_{JC} . Thus, the claim in the mainstream literature that such radiation is possible when solely placing a DC-voltage across the I-junction of a SIS-sandwich must be completely false!

As far as I can ascertain, measurements which are claimed to show radiation being emitted, have only been done for so-called weak-link (WL) junctions, which are generated by pressing a sharp point of one superconductor into the flat surface of another superconductor. In this case a constriction is generated: Not an insulating layer. The physics (which will not be done here) is then more complex: For example, the IV-characteristics for such a constriction are not the same as obtained for an actual SIS-structure (see Fig. 28-6(a)).

In the weak-link case, there is no drop to zero current when the maximum current at $V_J=0$ has been reached, even though a voltage appears across the (S-WL-S)-structure. Furthermore, the electromagnetic-radiation, which has supposedly been measured, is emitted with a single frequency at a single voltage (also demonstrated in Fig. 28-6(a)). The emitted frequency does not change continuously when the applied voltage V_J is increased or decreased; as should happen according to Josephson's prediction: Even though there is now not a well-defined I-layer, it is argued that this result confirms Josephson's prediction. I find this highly unlikely.

I have never done any experiments on Josephson-tunnelling myself, and thus foolishly accepted that the experts on superconduction would not mislead one; and that they are therefore actually able to do what they claim in the mainstream literature that they can do: i.e. that they can at will place a DC-voltage across the I-layer of an SIS-sandwich while a superconducting current, which is smaller than the maximum current I_0 in Fig. 28-3(a), is flowing.

Since, according to all other information which I had analysed up to that point, it was compelling that the charge-carriers must be singly-charged, I tried to model why a superconducting charge-carrier with a single electron-charge, moving through an I-layer with a voltage V_J across it, can emit a pho-

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ton as if the charge-carrier is doubly-charged. I had to find out the hard way that this cannot be done at all. I should have realised from the start that it is impossible to directly, without changing any other physical boundary conditions, place (and maintain) a non-zero DC-voltage across an I-layer while a superconducting-current is flowing through a SIS-structure.

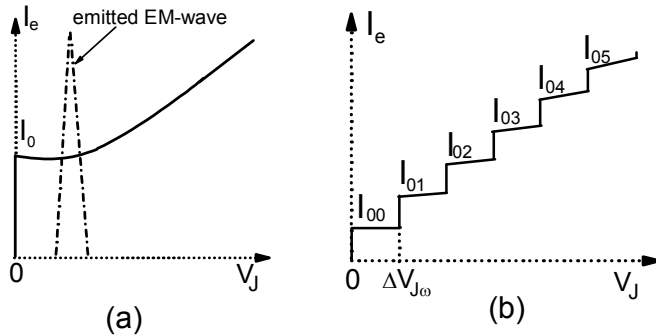


Figure 28-6: (a) Josephson-“tunnelling” through a weak-link: It has been claimed that the emitted electro-magnetic radiation (as shown) occurs when a suitable, single voltage across the weak-link is reached. (b) When irradiating either a suitable weak-link structure or a suitable SIS-sandwich (not all attempts are always successful) with suitable electromagnetic waves, steps can be generated at low voltages.

I thus ended up making a total fool of myself on an internet discussion forum*. Fortunately, my adversaries on this forum, notwithstanding raising some valid arguments, made even bigger fools of themselves. We should all have realised that the original assumption by Josephson that one can (at will) place any voltage V_J across the I-layer while a superconducting-current is flowing through the SIS-sandwich, is a physical impossibility. In the main-stream physics-literature this impossibility is not just assumed to be possible, but also stated as having been proved to be possible; and I, as a novice, unfortunately believed the “experts”.

The way in which the so-called AC Josephson-effect for a SIS-structure has supposedly been proved, has been to irradiate the junction with electro-magnetic waves of a suitable frequency ω_{MW} while increasing the applied DC-voltage from zero to V_{JC} . This is obviously not the same as just placing any DC-voltage at will across an I-layer while not irradiating the junction. Furthermore, most of these experiments have been done on weak-link structures which do not involve I-layers at all.

* Jeff Randi Educational Foundation.

<http://forums.randi.org/showthread.php?t=192121>

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From the main-stream literature it seems that if one is very lucky and succeeds to generate the same effect when applying an electromagnetic field to a SIS-sandwich, the current-free gap between $V_J = 0$ up to $V_J = V_{JC}$ disappears: A current now flows within this gap and this current has a step-wise increase for voltages less than V_{JC} (see Fig. 28-6(b)) at current-levels less than I_0 . These are the famous Shapiro steps named after the first person who measured them. The maximum-current I_0 which now manifests at zero-voltage, when not applying an electro-magnetic field (see Fig. 28-3(a)), is not reached.

Nonetheless, the current, at first, still increases at zero voltage, but now reaches a critical value I_{00} which is lower than I_0 (see Fig. 28-6b). A voltage immediately appears after this critical current has been reached; but this voltage has a lower value ΔV_{JMW} than the voltage V_{JN} in Fig. 28-3(a). Furthermore, the current does now not stop flowing when this voltage appears: The current remains I_{00} within the voltage-interval ΔV_{JMW} , whence another jump in current occurs so that the total current during this jump becomes I_{01} . Then an additional voltage increase appears, apparently of the same magnitude ΔV_{JMW} , while the current now remains at I_{01} ; followed by another current jump to a value I_{02} and so forth. Thus, below V_{JC} , at a voltage of $V_J = n\Delta V_{JMW}$ (where n is an integer) an n^{th} jump to a current of I_{0n} occurs: And this proceeds until the sum of the voltage intervals approaches V_{JC} , whence a normal current proceeds to flow.

These steps are interpreted as proof that the AC Josephson-effect, as modelled by Josephson and also Feynman (and described by Eq. 28.12), is actually occurring: i.e. that the Shapiro steps appear when the charge-carriers radiate energy with the same frequency as the applied electromagnetic field by supposedly jumping to and fro through the I-layer. At each step, the magnitude of the radiated energy supposedly increases by an additional quantum amount $\hbar\omega_{MW}$. Since for a voltage V_J across the I-junction and for a charge-carrier with charge q , this energy is assumed to be qV_J , it is concluded that one must have for the n^{th} step that $qV_J = qn\Delta V_{JMW} = n\hbar\omega_{MW}$; where n is an integer: i.e. each voltage interval ΔV_{JMW} is equal to the energy of an extra photon with frequency ω_{MW} ; thus giving that:

$$q\Delta V_{JMW} = \hbar\omega_{MW} = h\nu_{MW} \quad (28.13)$$

where h is Planck's original constant.

When experimentally measuring the voltage-intervals between Shapiro steps and comparing it to the frequency ν_{MW} of the applied electromagnetic field, it is found that for Eq. 28.13 to be valid, one must have that $q = 2e$: And this is taken as proof that Cooper pairs must be the charge-carriers.

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If the constant currents which remain during each voltage interval are still superconducting-currents, which they must be since the voltage V_{JC} at which the metal-insulator transition occurs has not yet been reached, there can be no voltages across the two SC-layers: The corresponding voltages $V_J = n\Delta V_{JMW}$ must thus be only across the I-layer. Thus, in this respect, the assumptions that had been made by Josephson and Feynman seem to be manifesting. But their models do not explain why this only happens when one applies an electromagnetic field and not when the electromagnetic field is absent.

In terms of the model in this book, when there is no electromagnetic field, the maximum current I_0 is reached when the injection frequency ν_i is such that there is zero dwell-time for the movement of an orbital across the I-layer. But when the electromagnetic field is present, a smaller maximum current I_{00} is reached at $V_J=0$; even before this dwell-time can become zero. Thus, without an applied electromagnetic field, one must have for the injection rate at which I_{00} appears, that the dwell-time is non-zero; so that it is still true that across the insulating layer one has that $\Delta t_{i00} = \Delta t_{dw} + \Delta t_B$. Since the superconducting current experiences its first hiccup at this specific injection frequency ν_{i00} , it is compelling to conclude that I_{00} is caused by a resonant interaction between the injection frequency ν_{i00} and the frequency ν_{MW} of the applied electromagnetic field. This resonance must be responsible for impeding the speed with which an orbital (after arrival at the I-layer) can reach the other side of the I-layer.

Since such an impediment must stop the current from flowing, a smaller critical current I_{00} is reached at a lower injection time-rate Δt_{i00} . This critical current, in turn, demands that a voltage ΔV_{00} must now immediately appear across the whole SIS-sandwich; which is given by:

$$\Delta V_{00} = R_{SIS} I_{00} \quad (28.14)$$

If such a voltage appears, the concomitant voltages across the two SC-layers must polarise the anchored orbitals within these layers. This, in turn, demands that the energies of the anchored orbitals within these layers must increase: But Nature always maintains the lowest energy-state possible; and, in this case, the two SC-layers can maintain their lowest energy superconducting states, provided that these voltages are shifted to only appear across the I-layer. A voltage ΔV_{JMW} thus appears across the I-layer after the critical current I_{00} has been reached.

But since this shift is required to prevent polarisation within the two SC-layers, the situation must be such that a superconducting current keeps on flowing through these layers; or else the orbitals must polarise. In other words, the voltage across the I-layer must be large enough to remove the initial blockage of the current through this layer. This implies that each orbital

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with a charge q , which arrives at the I-layer, is now accelerated through the I-layer to gain energy $q\Delta V_{JMW}$ which is high enough to remove the impediment that had been created by the resonance with the applied electromagnetic field. This acceleration thus allows the orbitals arriving at the I-layer to proceed (after arrival) and to reach the other side of the I-layer within the appropriate time-interval Δt_{i00} . Thus, except for the voltage step ΔV_{JMW} appearing, superconduction through the two SC-layers does not stop.

But what is the initial resonant condition which succeeds in increasing the time-interval between arriving at the I-layer and reaching the other side of the I-layer, so that current-flow momentarily stops at a value of I_{00} ? One's first inclination is to postulate that it must happen when v_{i00} is the same as v_{MW} . But the frequency v_{MW} causes an electric-field that, during one cycle, swings to and fro, while the frequency v_{i00} is a single jump in the forward direction: The charge-carriers do not also jump to and fro through the I-layer as had been predicted by Josephson.

Nonetheless, it should be abundantly clear that for the resonance to occur, which generates the current step I_{00} , the ratio of the critical injection-frequency v_{i00} to the frequency v_{MW} of the electro-magnetic field, must be a rational number. Since the frequency v_{i00} is for unidirectional movement along a single direction (in the direction in which the charge-carriers are moving) while the frequency v_{MW} is for movement which is forwards and backwards, it is compelling to conclude that the first resonance responsible for the current I_{00} occurs when $v_{i00} = (v_{MW} / 2)$. Thus the voltage ΔV_{JMW} , which appears in order to maintain superconduction through the SC-layers must generate a photon per charge-carrier having an energy equal to $\hbar(v_{MW} / 2)$ when such a charge-carrier moves through this voltage. Thus, in terms of the corresponding angular frequency ω_{MW} , one must have after the current I_{00} has appeared and the voltage ΔV_{MW} has manifested across the I-layer, that:

$$q\Delta V_{MW} = \hbar(\omega_{MW} / 2) \quad (28.15)$$

If this is the correct equation, instead of Eq. 28.13, then the experimental results actually prove that the charge-carriers are singly-charged: i.e. that the charge-carriers cannot be Cooper pairs since for each one of them one now has that: $q = e$. This, in turn, implies that the frequencies of the radiation emitted from the I-layer, after the current steps I_{00} , I_{01} , I_{02} , I_{03} , etc., have been reached, must be $(\omega_{MW}/2)$, (ω_{MW}) , $(3\omega_{MW}/2)$, $(2\omega_{MW})$, etc. This is not the same as claiming that the radiation emitted from the I-layer has the same frequency ω_{MW} , since this radiation is supposedly generated by charge-carriers which move to and fro through the junction and thus with every cycle emits a photon of energy $\hbar\omega_{MW}$. A defining experiment will thus be to measure the radiation generated at the I-layer, after each current step: If the frequency of the

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emitted radiation is found to increase by $(\omega_{MW}/2)$ after each current-step, it will be compelling proof that the charge-carriers are not Cooper pairs.