Great Experiments in Physics

2. Tunneling in Superconductors: The Josephson Effect

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Tunneling between two superconductors was first predicted theoretically and then observed experimentally. The discovery of this effect has led to measurements of extremely tiny magnetic fields, new standard measurements of volt amongst other things. The experiments in which Josephson effect was first observed is described.

Introduction

Tunneling is the name given to the penetration of a particle through a region which is classically impossible for the particle to enter, from energy considerations. Imagine a ping-pong ball being thrown repeatedly at a brick wall. We would always see the ball bounce back and would not believe our eyes if it went through the wall without breaking the wall. But if the ball is replaced by an electron and the wall by an energy barrier like a thin insulator layer on a metal surface, we would observe the electron go through the barrier some times if the experiment is repeated a large number of times. The penetration of such energy barriers is essentially a quantum mechanical phenomenon. Familiar examples of such barrier penetration occur in the alpha decay of a nucleus, field emission of electrons from metals, flow of nutrients across cell membranes in biological systems, etc.. It has long been known that an electric current can flow between two metals separated by a thin insulating film when a voltage is applied across the barrier because of this tunnel effect. For metals, the thickness of such insulating films should be few tens of Angstroms or less for such tunneling to be observed. Similar tunneling currents would flow if either or both metals are replaced by superconductors. This single electron tunneling was used as a probe for studying the superconducting energy gap by Ivar Giaevar in 1959. In 1961, Brian D Josephson, then a

Previous article in this series – 1. Discovery of Transistor Effect that changed the Communication World. *Resonance*, Vol. 3, No. 9 1998.

graduate student at Cambridge, made the startling prediction that not only single electrons but also pairs of electrons (Cooper pairs) can tunnel through sufficiently thin insulating gaps between two superconductors. This would give rise to tunneling currents even when the voltage across the barrier is put to zero. He had definite predictions for the tunneling current for dc and ac bias across the junction. Josephson's own efforts to verify his predictions were unsuccessful but P W Anderson, a scientist from Bell Laboratories, who was lecturing at Cambridge when Josephson got this idea came back to USA and set to work along with J M Rowell to verify Josephson's predictions. Their efforts fructified in a short while and the Josephson effect went on to provide the then most accurate determination of the fine structure constant 'α', the standard of voltage measurement and one of the most sensitive devices to measure weak magnetic fields, the Superconducting QUantum Interference Device (SQUID).

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Anderson realised that Josephson's efforts at Cambridge failed as his specimens had too high resistances leading to higher noise which masked the effect. His colleague J M Rowell at Bell Laboratories prepared a low resistance (0.4 Ω) junction of size 0.025 × 0.065 cm^2 by sandwiching a tin oxide layer (<2 nm) between evaporated layers of tin and lead films each approximately 200 nm thick. A sketch of the junction is shown in *Figure 1*. Tin was evaporated first and the oxide layer was thermally grown on it before depositing the layer of lead film. The junction was cooled to ~1.5K, well below the superconducting transition temperature of both lead and tin by pumping on liquid helium. They applied a voltage to two arms of the junction from a 1 kW potentiometer and measured the resulting current flow by recording the voltage across a series resistor of 10 Ω. The voltage appearing across the barrier was measured directly from the other two arms of the junction. The current was found to increase upto a value of 0.3 mA with no voltage appearing across the barrier. Such a current could also be due to small superconducting shorts or bridges across

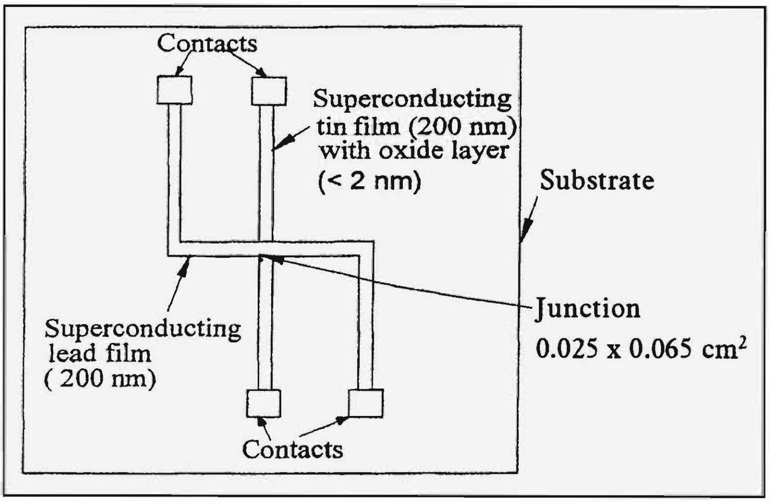


Figure 1. Type of junction used by Anderson and Rowell to observe the Josephson effect.

the insulating barrier. Many workers in this field had observed these annoying shorts appearing in the junctions prepared by them. In fact in 1960, Nicol, Shapiro and Smith had published a paper in which such a current was observed, but as Josephson's theory did not exist at that time, the observations were explained as a characteristic feature of a negative resistance region. Of course, real shorts could exist due to pinholes in the insulating layer. So great care is required in preparing good junctions. Anderson and Rowell were armed with the knowledge of Josephson's theory and they proceeded to check the current at zero voltage by subjecting the junction to different values of magnetic fields, since the Josephson current would be extremely sensitive to small values of magnetic fields whereas the shorts would not be. The junction was carefully shielded by a mu-metal (a very high permeability material) container with a measured interior field of 6×10^{-3} gauss. The zero voltage current increased from 0.3 mA to 0.65 mA and when a field of 20 gauss was applied, this current disappeared. The I-V curve obtained by them is sketched in *Figure 2*. Additional observations which supported the explanation of tunneling current were: (i) the effect occurred only if both the metals were superconducting, (ii) the value of the conductivity of the junction was much lower than could be attributed to shorts and (iii) that all attempts to burn out the 'shorts' by passing large currents across the

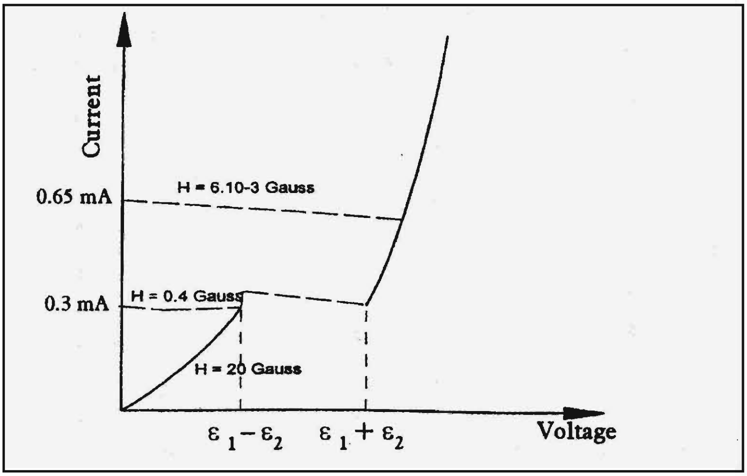


Figure 2. The current-voltage (I-V) characteristics observed by Anderson and Rowell showing the effect of magnetic field on the zero voltage current. In the earth's magnetic field (~ 0.4 Gauss) the current was 0.3 mA which increased to 0.65 mA when the junction was shielded by a mu-metal container. Also shown in the figure by the solid line is the curve when 20 Gauss field destroys the effect.

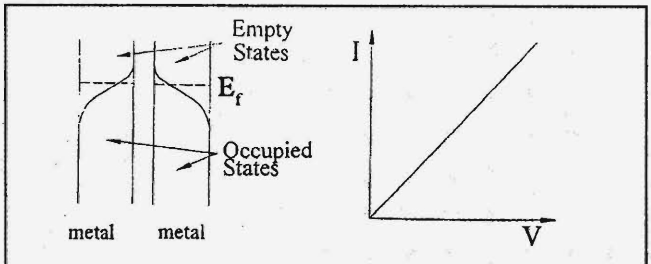
junction failed to change the zero voltage current until sufficiently high voltages destroyed the whole junction.

The clinching evidence of Josephson tunneling came from further experiments by Rowell who used several lead-insulator-lead junctions and subjected them to a magnetic field whose magnitude he could vary in a controlled manner. The junctions were immersed in liquid helium at 4.2K or at 1.3K. The magnetic field was provided by a copper wound solenoid surrounded by a mu-metal container both immersed in the liquid helium bath. The mu-metal shield reduced the magnetic field at the sample from other sources to $<10^{-2}$ gauss. As the magnetic field was first increased, Rowell observed the zero voltage current to decrease by a factor of 600 at a field of 6.5 gauss. On increasing the field further, the current first increased and then again went through minima at 13.0 and 19.5 gauss with successively decreasing maxima in between as shown in *Figure 3*. The value of 6.5 gauss between the successive minima has a special significance. Considering the area of the junction containing the flux this value of the field gives a value of 2.0×10^{-7} gauss-cm^2 for the flux in the junction, which is indeed the flux unit.

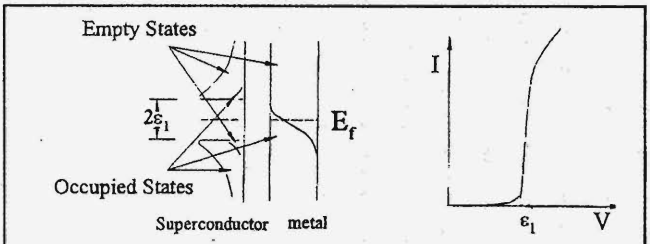
We understand the behaviour of superconductors in terms of transport of coupled electron pairs or 'Cooper pairs'. The coupling is provided by the interaction of the electrons with the

Box 1

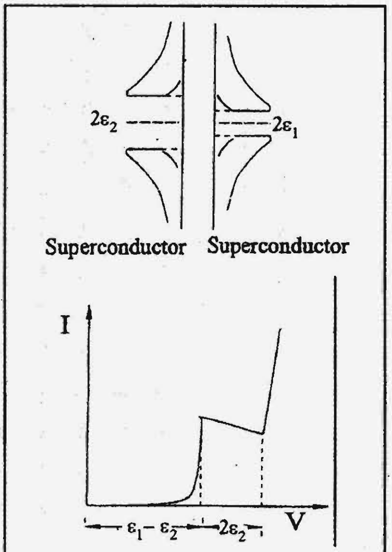
The current-voltage characteristics for single electron tunneling between two metals separated by a thin insulating layer can be understood if we use the concept of density of states. In a metal, the energy levels are filled with electrons upto the Fermi level (E_f) at $T = 0$. For finite temperatures, thermally excited electrons occupy higher levels and the I-V curve is a straight line as shown in *Figure a*. When one metal is a superconductor as shown in *Figure b*, the electron density of states for the superconductor has an energy gap centred at the Fermi level and the I-V curve is shown on the right. At $T = 0$, no current can flow until the applied voltage corresponds to half the energy gap, beyond which the current rapidly increases and approaches that for normal metals. For finite T, a small current can flow even for the smallest voltages due to the presence of electrons above the gap region. When both metals are superconducting as is the case in *Figure c*, no current can flow at $T = 0$ till the voltage is equal to half the sum of energy gaps on two sides. But for finite T, a current will flow at the smallest voltages and will increase till the voltage is equal to half the difference in energy gaps. As the voltage is increased further, the number of electrons taking part in the tunneling process remains the same but the density of states goes down and the current will decrease till the voltage reaches half the value of the sum of the energy gaps, beyond which again there is a rapid rise as in the case of normal metals.



(a) both metals in normal state



(b) superconductor – metal junction



(c) both metal superconductors

I–V characteristics for the tunneling current between (a) two metals (b) superconductor-metal and (c) two superconductors separated by a thin layer of insulator.

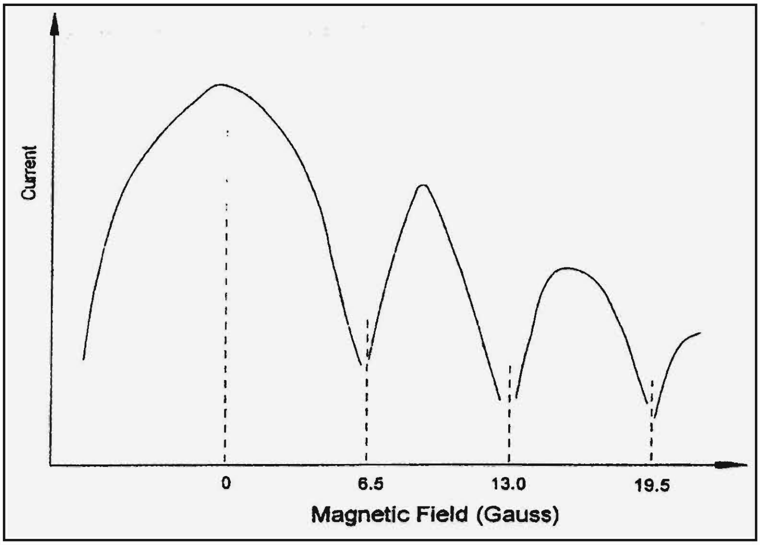


Figure 3. The behaviour of the tunneling current as a function of the magnetic field. The zeros of the current occur at magnetic field values corresponding to multiples of flux unit being contained in the area of the junction.

lattice or in other words electron-phonon interactions. The binding of the electrons into Cooper pairs is extremely weak as revealed by the fact that it is disrupted by thermal disorder at a few degrees K. Because the attraction is weak, the two paired electrons are, on an average, separated by a distance that is thousands of times greater than the distance between lattice ions and hence the wave functions of electrons of each bound pair range over a volume that contains millions of other pairs. The Bardeen–Cooper–Schrieffer theory showed that this gives rise to correlated motion of all the electron pairs. This implies that the waves describing the pairs in a superconductor have the same wavelength and also the same phase. If two superconductors are isolated by a barrier the phases of the wave function, ψ, in each can be altered independently, $\psi = \psi_0 \exp(i\phi)$, where ϕ is the phase.

Now if the barrier is gradually reduced to zero, the properties of the system should go over continuously from those of two isolated superconductors to that of a single superconductor. This would imply that the phases ϕ_1 and ϕ_2 of the waves on two sides would not be independent of each other and would get locked together. The coupling of phases is provided by the tunneling of the pairs of electrons across the barrier. Josephson

The maximum net tunnel current through the junction therefore varies periodically as the magnetic field is increased.

figured out that it should be possible to modify the phase locking which should have observable consequences. His calculation showed that the tunneling current, $\mathcal{J}$, was a sinusoidal function of the phase difference, $\delta = (\phi_1 - \phi_2)$, $\mathcal{J} = \mathcal{J}_0 \sin\delta$ where $\delta = \delta_0 + 4\pi e/\text{h}. Vt$, δ_0 is a constant, e is the electron charge, h is Planck's constant and V is the voltage applied across the barrier. The equation predicts the frequency of the sinusoidal current to be given by $\nu = 2e. V/\text{h}$. Since the value of h is small, the frequency is large and the net current is zero in the presence of a net voltage. But if $V = 0$ then also there is a finite current, $\mathcal{J}_0 \sin\delta_0$. This is the dc Josephson effect.

Now if V contains a high frequency component $V = V_0 + v \text{ Cos } \omega t$ then it is found that the current, $\mathcal{J}$, would increase in magnitude if the frequency ω of the applied voltage satisfies the condition $\omega = n.(4\pi e.V_0/\text{h})$, where n is an integer.

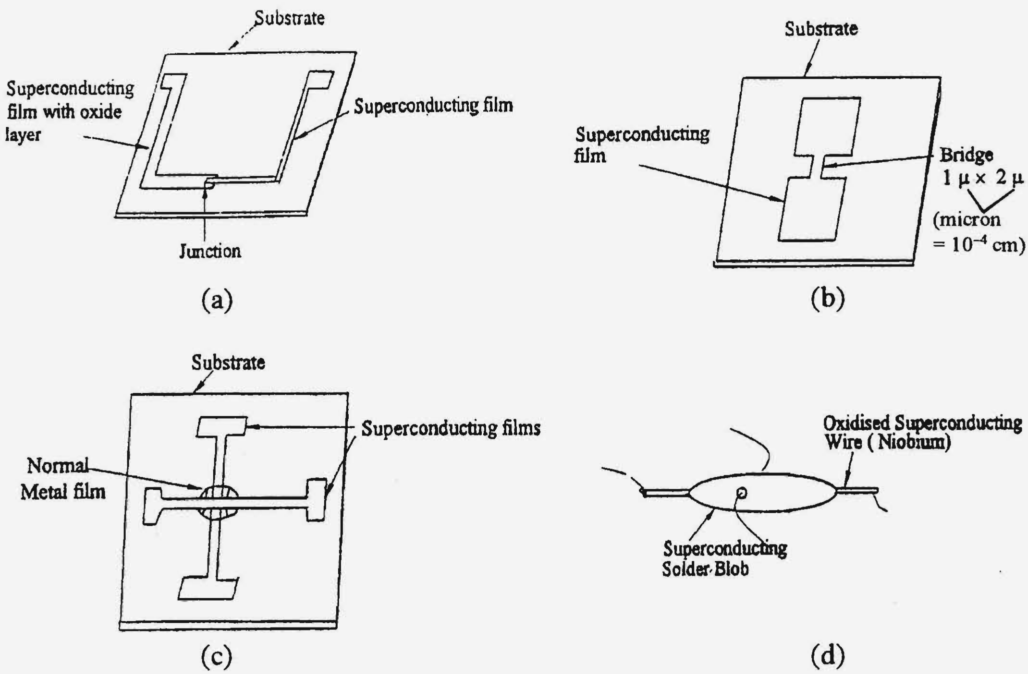
The presence of a magnetic field also would change the phase of the wave associated with the electron pairs. If a tunnel junction is put in a uniform magnetic field in the plane of the barrier, the difference between the pair phases in the two superconductors would increase linearly in the direction at right angles to that of the field and also would be proportional to the value of the magnetic field. Since the current density depends on the phase difference, this results in oscillations of the tunnel current in space and may reverse its direction at several points in the junction depending on the value of the magnetic field. There can thus be interference between the currents from different parts of the junction analogous to the case of diffraction from a single slit. The maximum net tunnel current through the junction therefore varies periodically as the magnetic field is increased.

Just with the observation of tunneling currents, the Josephson effect would have remained an interesting scientific curiosity but for the discovery of the a.c. Josephson effect. The ac manifestation of this effect can be divided into two types, dc biased and RF biased.

In the dc biased case, if two weakly coupled superconductors are maintained at a dc potential difference V, there would exist an alternating supercurrent across the junction with frequency $v = 2eV/h$. In the RF biased case, the application of an RF field across a weakly coupled junction leads to a region of current steps in the dc I-V characteristics at bias voltages which are

Box 2. Tunnel Junctions

Several types of tunnel junctions exist. The superconductor-insulator-superconductor layers deposited in perpendicular directions forming the pattern of a cross was used by Rowell and Anderson and also by Langenberg and collaborators as shown in *Figure a*. A Dayem bridge (*Figure b*) is a weak link junction in which two superconductors are coupled by a narrow constriction. In a variation of this junction, a normal layer of metal is overlaid on the area of the bridge. Josephson originally considered the type shown in *Figure c*. A simple junction which was developed in the early days is the slug (*Figure d*) formed by surrounding an oxidised niobium wire by a blob of ordinary solder which becomes superconducting at low temperatures.



Different types of Josephson tunnel junctions (a) Josephson tunnel junction; (b) Dayem bridge; (c) S-N-S junction; (d) SLUG.

The application of an RF field across a weakly coupled junction leads to a region of current steps in the dc I-V characteristics at bias voltages which are integer multiples of $hf/2e$.

integer multiples of $hf/2e$, where f is the applied radiofrequency. In other words $V_n = nhf/2e, n = 0,1,2,...$

The ac effect was first observed by S Shapiro in 1963 using Al $-Al_2O_3$-Sn tunnel junction. Two 127μm wide strips of Al were evaporated onto a glass slide and then oxidised in a glow discharge in dry oxygen atmosphere and then 127μm wide cross strip of Sn was evaporated forming two samples on a substrate. A low impedance source was used to drive the loop containing the sample and the current measuring resistor. Most data were taken at a temperature of 0.9K below the transition temperature of Al and Sn. They observed the zero voltage Josephson current and negative resistance switching behaviour towards single particle tunneling as had been seen by Anderson and Rowell previously. Shapiro mounted the samples in a resonant cavity and irradiated the system with microwave at frequencies of 9.3 GHz and 24.85 GHz. With few tens of microwatts applied Shapiro observed that the zero-voltage currents became noisy and gradually vanished resulting in regions of zero slope (or almost zero slope) in which current rose at (or almost at) fixed voltage across the sample as sketched in *Figure 4*. The voltage at which the zero slope regions occurred was equal to $\pm\, hf/2e$, where f is the microwave frequency confirming the ac Josephson effect. As more power was applied, further zero-slope regions appeared at still higher voltages. The interval in voltage from one zero-slope region to the next was not always $hf/2e$, sometimes a step was missing giving the voltage interval of hf/e.

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The effect was utilised by Langenberg, Parker and Taylor at the University of Pennsylvania to measure accurately the value of e/h and thus determine the value of fine structure constant α. It also led to the setting up of a 'standard volt' based on the Josephson effect.

Josephson junctions have in subsequent years found a very important application in the superconducting quantum interference devices (SQUID) as the most sensitive detector of

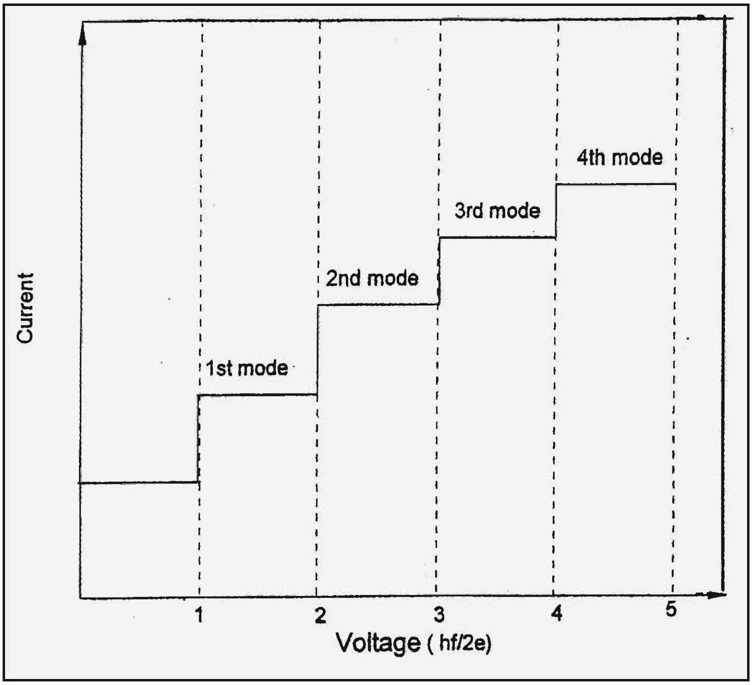

Figure 4. The effect of applying microwave to a Josephson junction. The steps in the I-V curve occur at multiples of (hf/2e), verifying the ac Josephson effect.

magnetic fields. Operated at extremely low temperatures these have been made powerful enough to pick up even the magnetic field generated by electrical activity in the human brain and the human heart. SQUID magnetometers could soon replace the traditional electrocardiograms that doctors use to monitor heart activity. Other uses of Josephson junctions arise from their ability to switch rapidly from the superconducting state to the resistive state in just one or two picoseconds. They can thus be used as components in ultrafast digital circuits.

Suggested Reading

[1] D N Langenberg, D J Scalapino and B N Taylor. The Josephson Effects. *Scientific American*. 214.30–39, 1966.

[2] B D Josephson. Coupled Superconductors. *Reviews of Modern Physics*. 36. 216 –220, 1964.

[3] J Clarke. SQUIDS. *Scientific American*. 271.No 2. 36–42, 1994.

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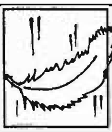

Newton was the greatest genius that ever lived, and the most fortunate, for we cannot find more than once a system of the world to establish

— Lagrange