NOBEL PRIZES

Physics Award for Tunnelling Research

Dr. Brian Josephson, a particularly young winner of the Nobel Prize.

THIS year's award of the Nobel Prize for Physics to Leo Esaki, Ivor Giaever and Brian Josephson recognises the importance of tunnelling phenomena in semiconductors and superconductors. According to the quantum theory, electrons have a small probability of tunnelling through a potential barrier which is impenetrable according to classical theory. The phenomena depend on this probability.

Semi-conductors or super-conductors

The tunnel diode, discovered by Esaki (University of Tokyo) in 1957, is a p-n junction in a semiconductor so heavily doped that both sides are degenerate. The space-charge layer in the junction forms the potential barrier. When a small voltage is applied to bias the junction in the forward direction electrons tunnel from the n side to the valence band on the p side. When the bias voltage is sufficiently great, however, the electrons on the n side will have energies within the energy gap on the p side; since there will be no allowed states to receive the electrons, the current will drop and the diode will have a negative resistance. When the forward bias is sufficiently large the electrons will be able to tunnel across to the conduction band on the p side, and the resistance will become positive again. These properties of the diode enable it to be used in high speed amplifiers and oscillators. Since the electron current is affected by other excitations in the semiconductor, the diode can be also used to study these

Professor G. Rickayzen of the University of Kent at Canterbury describes the research work for which the Nobel Prize for Physics was awarded.

excitations.

Giaever, originally Norwegian and a mechanical engineer, switched to physics on joining the General Electric Research Laboratory, New York. Impressed by the analogy with semiconductors, he used tunnelling to study the superconducting energy gap. In this case, the potential barrier was an insulating layer (usually an oxide) sandwiched between two metals. If one metal is normal and one superconducting (the NIS sandwich) and if the temperature is low, electrons will be able to tunnel from normal metal to superconductor only if the voltage bias is sufficient to carry them over the gap. In 1960 Giaever announced the first observation of the energy gap by this method. Giaever also realised that there is an analogy between the superconductor/insulator/superconductor sandwich and the tunnel diode and that the former should, under suitable conditions, also have a negative resistance characteristic. This he observed and the effect is now being developed in devices. A fuller account of Giaever's discovery has been given by Schmitt in *Physics Today* (14, 38; 1961).

Subsequent theoretical work showed that the characteristic of the NIS sandwich provides a direct measure of the density of electronic states of a superconductor. Because of the effect of other excitations, notably the phonons, on the density of states the tunnelling characteristic can be used to study these other properties. This has helped to confirm the basic theory of superconductivity as well as to yield important information on the phonon spectra of superconductors.

Tunnelling Supercurrents

In 1962, in a two-page letter to *Physics Letters*, Josephson (University of Cambridge), then aged twenty-two, predicted that it would be possible for supercurrents to tunnel between superconductors and that this tunnelling would be accompanied by a number of interesting effects. Essentially, Josephson showed that the whole superconducting sandwich was a single superconductor governed by a single wave

function, and that there were low-lying many-electron states that carried small currents without dissipation. If a large current passed through the sandwich, a voltage V would appear across it and there would be a non-dissipative contribution to the electric current oscillating at the frequency $2eV/h$ independent of the material. If such a junction is placed in a microwave field, this supercurrent leads to steps in the current-voltage characteristic. Josephson also stated (and showed in detail in later papers) that a magnetic field would modulate the phase of the wave function across the junction in a way analogous to that in which the phase of a light wave depends on path length. The result is that the dependence of the maximum Josephson supercurrent through a junction on magnetic field produces a 'Fresnel diffraction pattern'. The story of Josephson's discovery has been told by Anderson in *Physics Today* (23, 23; 1970).

At the time John Bardeen was sceptical that the effect would be as large as Josephson predicted. At an international conference in 1962 there occurred one of those historic moments in physics, the young Josephson defending his theory against the doubts of the 'elder statesman'. Within a few months, experiment had vindicated Josephson.

Since that time many beautiful experiments have been performed that demonstrate the effects of a magnetic field on Josephson tunnelling and which show that the phase of a superconducting wave function is coherent over macroscopic distances (at least of the order of centimetres). The effect is the basis of sensitive devices for measuring magnetic fields, voltages and small currents, and junctions are under development as computer elements.

The a.c. Josephson effect has been detected and used to provide the most accurate value of the fundamental constant e/h ; this, in turn, has led to a reassessment of the values of the other fundamental constants. It is also used to provide a new voltage standard and is being developed for the generation, detection and mixing of electromagnetic waves.