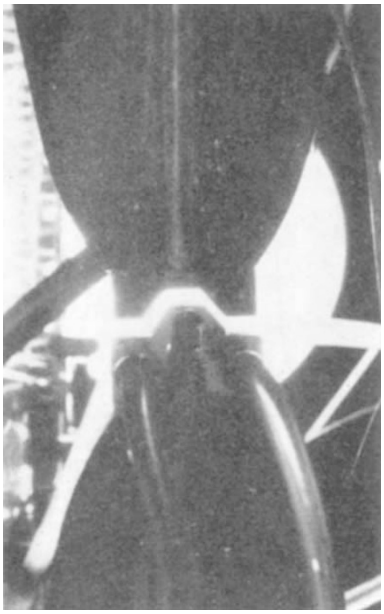

Fig. 2. Holder between shaped pole pieces. Apparent asymmetry is due to camera angle. Meniscus of water is just visible.

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Electron Tunnelling in Biological Structures

DEVAULT *et al.*[1] have proposed that electron transfer through biological structures over distances of a few tens of Ångstroms occurs by tunnelling, the height of the energy barrier stipulated being 1 eV. Similarly, Wei[2] has suggested that electron tunnelling through the nerve membrane is involved in producing the N-shaped current voltage characteristics observed in, for example, squid axons[3] and other membranes[4]. The question of the relative probability of the electron going over instead of through the barrier—in other words, electron transfer by hopping—has, however, not yet been resolved.

This question may be decided by calculating the Christov[5] characteristic temperature T_{Ch} for a somewhat idealized barrier—the temperature at which the probabilities of tunnelling and hopping are equal. Below T_{Ch} electron transport is predominantly by tunnelling while hopping is the prevalent mode of transport above T_{Ch}. The values of T_{Ch} depend critically on the rate of curvature at the top of the barrier, as well as on its height and width. It can be assumed, however, that the actual shape of the barrier will fall somewhere in between two extremes: the rather steep Eckart[6] barrier and the rather flat parabolic barrier. Using the equations derived by Christov[5] for these extremes,

$$T_{\mathrm{Ch}} = 0{\cdot}28\,\frac{h\,E_0^{1/2}}{k\,l\,(2m)^{1/2}} \qquad \text{for the Eckart barrier}$$

and

$$T_{\mathrm{Ch}} = \frac{h\,E_0^{1/2}}{(12)^{1/2}\,\pi\,k\,l\,(2m)^{1/2}} \quad \text{for the parabolic barrier}$$

T_{Ch} has a value between 1,950° K (Eckart) and 640° K (parabolic barrier) for a 1 eV barrier 40 Å wide. Here k is Boltzmann's constant, h Planck's constant, m the mass of the carrier here taken as that of the free electron; l stands for the half-width and E_0 for the height of the barrier.

This treatment tacitly assumes a resonance condition, in that there is an exact alignment between the highest occupied and the lowest vacant energy levels on both sides of the barrier. Moreover, it takes no account of the spin un-pairing which may have to precede the tunnelling, nor of any phonon interactions. The resulting Christov characteristic temperatures are so much higher than the biological range, however, that electron transport at and near room temperatures must occur almost entirely by tunnelling, as envisaged by DeVault *et al.*[1] and by Wei[2], irrespective of the shape of the potential barrier.

This is not the case for proton tunnelling: assuming a 1 eV barrier and a Christov characteristic temperature of 400° K, a barrier width $2l$ of 4·6 Å results for the case of an Eckart barrier and 1·5 Å for a parabolic barrier. Thus, at least in some cases, proton tunnelling will critically depend on details of the shape of the potential barrier.

The tunnelling resistance per cm² area of a membrane can be estimated by considering the aqueous phases on both sides as providing an electron source and sink; in other words, acting as a Redox system, as suggested, *inter alia*, by Wei[2]. If the voltage V across the membrane barrier is small, so that $V \ll E_0$ (within the ohmic range), then the tunnelling current density J can be written[7]

$$J = 3{\cdot}16\times 10^{10}\,(E_0)^{1/2}\,\frac{V}{2\,l}\,\exp\left(-2{\cdot}05\,l\,(E_0)^{1/2}\right)\ \mathrm{A\ cm^{-2}}$$

The tunnel resistance per cm² area, V/J, for a 40 Å wide membrane involving a potential barrier of 1 eV is then about 10^9 Ω/cm². Typical membrane resistances[8] are of the order of 10^7–10^8 Ω/cm², so charge transfer through such membranes must occur predominantly either by means of an ionic mechanism or by the formation of charge transfer complexes as envisaged by Rosenberg *et al.*[9–11] and others[12]. It is of interest, however, to note that cholesterol membranes[13,14] do exhibit resistances of about 10^9 Ω/cm²; these values might be explained by electron tunnelling.

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