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ABSTRACT

The present work was undertaken in order to analyze electric resistivity (R) at different ambient temperatures (T) between 300 to 10 K in the frog sciatic nerves. When the electrical contacts were embedded into the sciatic nerve of a frog, a linear decrease of the sciatic nerve resistivity is observed for 240 K < T < 300 K and a rise of electrical conductivity is apparent below 240 K. This dependence is generally associated with a metal-like behavior. Then, once the sciatic nerve temperature is driven below 240 K, the resistivity decreases abruptly and then at temperatures lower than 234 K, it remains constant and close to one tenth of its ambient temperature value. On the other hand, when the electrical wires are just leaned on the sciatic nerve, the nerve resistivity increases with temperature and reach a maximum relative value close to 1.5 at a temperature close to 250 K. Such dependence is generally associated with a semi-conducting behavior. The nerve resistivity decreases also abruptly at temperature lower than 250 K, to reach a low relative resistivity close to 0.1. Thus, for the first time we report the existence of a new form of electric conductivity in the sciatic nerve at low ambient temperature, which in turn has many electric similarities with inorganic or organic superconductors. Topological Geometrodynamics (TGD) based model for the effective superconductivity relying on the notion of many-sheeted space-time is discussed. The model allows to understand the experimental findings and makes several testable predictions.

Keywords: Electric conductivity, sciatic nerve, cold, superconductor.

1. INTRODUCTION

The evolution of the nervous system has been an important factor in the adaptation of animal to their environment [1]**.** It might therefore be expected that natural selection on nerve or neuron conduction could have caused several structural and functional changes [1]. Interestingly, Abdelmelek et al [1] demonstrated the improvement of superconductor-like behavior during evolution can be correlated with the degree of myelinisation. Electrical activity is of major importance in the function of nerve cells, playing a fundamental role in the transmission of signals and in the processing of information in the nervous system. The generation of electric potential across the cell membrane is brought about and controlled by the flow of specific ions through channels implanted in the membrane. The temperature affects the conduction velocity and electric potential amplitude, both locally at the recording site and generally along the nerve [2]. The conduction velocity is also dependent on temperature, the axonal diameter, the presence of myelin and the properties of the membrane [3, 4, 5]. Under cold environment, previous study showed a modulation effect of cold on the spinal cord monoaminergic system in ducklings [6]. In addition, sciatic nerves isolated from frogs frozen at 265.5 K were refractory to electrical stimulation. By contrast, frogs surviving at 270.5 K or 268 K generally exhibited normal characteristics of compound action potentials [7].

The mechanism behind the propagation of the nerve pulse at low temperature is not well understood. Indirect evidence suggests that electron tunnelling may occur across junctions between micro regions in living systems [1]. It was proposed that in living system electric behaviour could be understood in terms of “superconductivity” [1, 8]. The aim of this study were primarily to perform experimental approach to determine the temperature dependence of resistance in the sciatic nerves between 10-300 K in poikilotherm; the frog. Secondly, we defined a model in order to understand the experimental findings and make several testable predictions.

2. METHODS

Sciatic nerve samples were obtained by decapitation of frogs (*Rona esculenta*) with light anaesthesia (Halothane 2.5% in air). Animals were cared for, under the Tunisian code of practice for the Care and Use of Animals for Scientific Purposes. The experimental protocols were approved by the Faculty Ethics Committee (Faculté des Sciences de Bizerte, Tunisia). Sciatic nerves were conserved in Ringer-buffer during 1 to 5 min. Then, the electrical resistivity variations of the sciatic nerve with varying temperature were investigated by employing the four-probe technique. The temperature variation was achieved using a Helium exchange gas filled cryostat. Temperature was measured using a calibrated Si-diode sensor with an accuracy of 0.1 K and was varied from 300 K to 10 K. No previous measurements of conductivity in biological systems were driven at such low temperatures. The four electrical contacts were made using gold wires that were embedded into the nerve. The two external wires were used as current leads and the other two as the voltage leads to record potential differences. The value of the current used for the resistivity measurements was 10 µA [1].

2. RESULTS

When the electrical contacts were embedded into the sciatic nerve of a frog, a linear decrease of the sciatic nerve resistivity was observed for 240 K < T < 300 K and an abrupt rise of conductivity was shown below 240 K (see Fig. 1). This dependence is generally associated with a metal-like behaviour (linear in T) in the normal state of materials. Then, once the sciatic nerve temperature is driven below 240 K, the resistivity decreases abruptly.
At temperatures lower than 234 K, the resistivity of the nerve remains constant and close to one tenth of its ambient temperature value. On the other hand, when the electrical wires were just leaned on the sciatic nerve, the nerve resistivity increases with temperature and reaches a maximum relative value close to 1.5 at a temperature of about 250 K (see Fig. 2).
Such dependence could be associated with a semi-conducting behaviour in the normal state of materials. The nerve resistivity then, decreases abruptly at temperatures lower than 250 K, to stabilize at a low relative values close to 0.1. In both cases, the R-T curve at 250 K show a markedly fall of resistivity without reaching the zero point.

3. DISCUSSION OF EXPERIMENTAL RESULTS

Our main interest lies in the properties of large-scale nerve networks at low temperature (250 K), and which are responsible for such nervous system functions in frog. Understanding these complex functions requires a multidisciplinary approach. The present study on the sciatic nerve revealed a temperature dependency of the electric resistivity and indicate that low temperatures (<250 K) induce a striking decrease of resistivity with a width of transition of about ΔT=10K.? ? Recent results have shown that organic elements, such as tetracene and pentacene, present a normal state semi-conducting behaviour[9, 10]. By contrast, sciatic nerves collected from frogs frozen at 265.5 K were refractory to electrical stimulation [7]. This result can be explained by the presence of a skin resistance response to constant stimuli as indicator of the strength of nerve traffic [11].

The frog's resistance to cold depends perhaps on the state of activity of the nervous system in various tissues at low temperature. According to our findings, the marked decrease of resistivity at low ambient temperature (250 K) can be mediated by a mechanism, which has many similarities with inorganic and organic superconductors [9]. At cold environment, periods of intense heat loss are occurring in all the tissues of the body. That's why animals have to develop a mechanism of energy management. Thus, the decrease or increase of temperature has a proportional effect on the sciatic nerve resistivity.

Furthermore, our data suggest the existence of a new electrical conductivity mechanism, which gives the nervous system a real potential to function at low temperature of about 250 K. In this case, low resistivity of sciatic nerve can be understood as an adaptive behaviour of the nervous system in order to control the energy loss of frogs. Knowledge of changes in frog sciatic nerve conductivity under cold environment is still limited. The difference between endotherms (rabbit, Tc: 300 K; H. Abdelmelek et al [1]) and poikilotherms (frog, Tc: 250 K) could be explained by fundamental anatomical and functional nerves properties related to the development of metabolic function and the development of myelin. Peripheral nerves are made of bundles of nerve fibres, which can be regarded as living wires. The fastest conducting nerve fibres are like wires and have their own insulating sheaths [4]. Nerve fibres conduct nerve impulses very quickly because the myelin sheath has gaps, which allows the nerve impulse to jump from gap to gap and travel faster [4]. The temperature transition (Tc) in the sciatic nerves of frog remains constant and reproducible at 250 K. This result has many similarities with inorganic and organic superconductors. If we assume the existence of "superconductivity" behaviour of the nerve, there is an increasing evidence to attribute this superconductivity to myelin sheaths. Interestingly, numerous studies are dealing with the relationship between structure of the living matter and physical properties as superconductors [8, 9, 10, 11].

In conclusion, our present results show, for the first time to the best of our knowledge, the frog sciatic nerve resistivity can be markedly decreased at low temperature (250 K). The mechanism underlying the decrease of resistivity after cold exposure remains to be investigated and suggests the presence of adaptive mechanisms of the poikilotherm nerve involving a new form of electric conductivity, may be superconductor-like behaviour, at ambient temperature (250 K).

3. A MODEL FOR THE EFFECTIVE SUPER-CONDUCTIVITY

TGD (Topological GeometroDynamics [13,14]) based model of living matter [15,16] involves a lot of new physics. The basic notions are

a) many-sheeted space-time making possible macroscopic quantum phases;

b) topological field quantization stating that various quantum notions have correlates at the level of space-time topology and meaning that space-time can be regarded as a generalized Feynmann diagram like structure [17];

c) p-adic physics based on p-adic number fields R_p, p prime, which are completions of rational numbers in some aspects analogous but also differing from real numbers together with p-adic length scale hypothesis quantifying the notion of many-sheeted space-time [14, 18];

d) classical Z^0 fields explaining among other things chiral selection in living matter and playing a key role in the generation of nerve pulse [19,20];

e) super-conductivity at magnetic flux tube circuitry providing a template for living organisms and its breaking by the leakage of ions between atomic space-time sheets and magnetic flux tubes [21] serving as the basic mechanism of metabolism [22] and involved also with nerve pulse conduction [20].

It is interesting to find whether the above described experimental findings could be understood in TGD framework. For convenience the units $k_B=1$, $h/2\pi=1$, $c=1$ are used in the sequel.

3.1 Interpretation of the experimental findings

The basic finding is that the resistance of the sciatic nerve is reduced by a factor of about ten below a critical temperature at the lower edge of the range of the physiological temperatures. The reduction of the temperature occurs inside a narrow temperature range ΔT, $\Delta T/T_c \sim .04$. This suggests effective super-conductivity. Furthermore, the critical temperature Tc for the breaking of the effective super-conductivity rises from 240 K to 300 K in the transition from poikiloterms (say frog) to endotherms (say rabbit).

These findings seem to be consistent with the following view.

a) Nerve pulse generation involves a mechanism inducing a flow of ions between axonal interior and exterior and induces at the same time the breaking of super-conductivity [20]. At too low temperatures nerve pulses cannot be generated because the breaking of the super-conductivity is not possible. Therefore the critical temperature must be below the range of physiological temperatures..

b) In myelin sheathed regions the breaking of the effective super conductivity does not occur or the critical temperature is higher and the signal carried by the nerve pulse is transformed to an effective or genuine supra current. A small pulse like perturbation of the membrane potential could propagate still.

c) Poikiloterms can survive only if nerve pulse conduction is possible down to about 240 K which represents lower bound for the temperature of environment. Endotherms can keep the body temperature above 300 K and so that T_c can be as high as 300 K. This is good for survival purposes since high T_c minimizes ohmic losses related to nerve pulse conduction.

3.2 Many-sheeted space-time and connection between thermal de Broglie wavelength and size of the space-time sheet

The concept many-sheeted space-time (see Fig. 3a) is needed to understand super-conductivity and breaking of super-conductivity. Parallel space-time sheets with distance about 10^4 Planck lengths form a hierarchy. Each material object (..., atom, molecule, ..., cell,...) corresponds to this kind of space-time sheet. The p-adic primes $p \cong 2^k$, k prime or power of prime, characterize the size scales of the space-time sheets in the hierarchy. The p-adic length scale L(k) can be expressed in terms of cell membrane thickness as

$$L(k)= 2^{(k-151)/2} \times L(151) \ , \ L(151) \cong 10 \text{ nm}. \qquad (1)$$

These are so called primary p-adic length scales but there are also n-ary p-adic length scales related by a scaling of power of $\sqrt{p}$ to the primary p-adic length scale.
The characteristic temperature scale for particles of mass M in a thermal equilibrium at the space-time sheet characterized by L(k) is given in terms of the zero point kinetic energy associated with the space-time sheet

$$T_c(k) = n\times E_0(k) = n\times n_1\times \pi^2/[2ML^2(k)] \ , \qquad (2)$$

where n and n_1 are numerical constants not far from unity. $T_c(k)$ decreases very rapidly as a function of the p-adic length scale L(k). This equation relates the p-adic prime of space-time sheet to T and M of particles present in the sheets forming join-along-boundaries condensate (Fig. 3b). Of course, the size L of space-time sheet characterized by k can vary in the range $[L(k), L(k_>)]$ and $T \propto 1/L^2$ is an attractive guess for the dependence of the temperature on the size of the space-time sheet. One can interpret $T_c(k)$ as a critical temperature at which the p-adic prime characterizing the space-time sheet changes.

3.3 MAGNETIC FLUX TUBES AS EFFECTIVE SUPER-CONDUCTORS AND BREAKING OF SUPER-CONDUCTIVITY

The model for bio-super-conductivity and its breaking relies on the following picture.
a) Magnetic flux tubes of Earth's magnetic field (in particular) characterized by k=169 and having a minimal thickness about 5 μm correspond to tubular space-time sheets. In the absence of both larger and smaller space-time sheets, they can act as 1-D super-conductors since cyclotron energy scale, which by the quantization of the magnetic flux behaves also as $1/L^2(k)$, is larger than de Broglie temperature for sufficiently high values n of the magnetic flux (implying thicker flux tube). More generally, one can consider the possibility of a hierarchy of magnetic flux tubes inside magnetic flux tubes corresponding to the sequence k=169, 167, 163,.... Each of these flux tubes can be a super-conductor. Bio-super-conductivity is assumed to be due to this mechanism. Of course, only space-time sheets corresponding to only some of these p-adic length scales could be present and this would be crucial as far as super-conductivity and its breaking is considered. The study of the effects of external magnetic fields on the axonal conductivity might provide valuable information about the role of magnetic fields.

b) Super-conductivity can be broken by a temporal leakage of the Cooper pairs to larger space-time sheets if present (Fig. 4). These Cooper pairs are kicked back by thermal photons. System is an effective superconductor in the sense that Cooper pairs are not destroyed in the breaking of superconductivity and an effective ohmic conductor in the sense that dissipation is present. Super-conductivity can be also broken by thermal “kicking” of the Cooper pairs to smaller space-time sheets. In this case there is however a restriction posed by the fact that the zero point kinetic energy of the particle increases from $E_0(k)$ to $E_0(k_<)$, where $k_<$ ($k_>$) is the largest (smallest) the prime smaller (larger) than k. Thermal energy is needed to achieve this. For the leakage to occur, one must have

$T > T_c(k) = n \times E_0(k)$. (3)

Some numerical constant n is involved here. Note that the temperature at super-conducting space-time sheets is much lower than the critical temperature and the temperature at atomic space-time sheets.

c) The prediction is that the conductivity decreases in a stepwise manner at temperatures $T=T_c(k)$ as the temperature increases, and that the smallest value of k for current carrying space-time sheets gradually decreases as $k=169\rightarrow 167\rightarrow 163\rightarrow 157\rightarrow 151\rightarrow$.... The behavior of the conductivity in the sciatic nerve seems to represent one particular step of this kind. The primes k=167, 163, 157, 151 are expected to be especially important in living matter since they corresponds to the so called Gaussian Mersennes and p-adic length scales in the range 10 nm-2.56 μm [20].

d) For a space-time sheet having $k=k_0$, the leakage of supra-current is induced by the formation of join along boundaries bonds between space-time sheets with $k= k_0$ and those with $k>k_0$. The leakage to the smaller space-time sheets can be also induced by radiation with frequency corresponding to the increment of the zero point kinetic energy and the transversal electric field involved with radiation can be regarded as inducing the force driving the particles to smaller space-time sheets or back.

e) The strange findings indicating that DNA can behave like a super-conductor [22], an ohmic conductor [23], or an insulator could be perhaps understood in terms of the local architecture of the many-sheeted space-time. If only atomic space-time sheet is present, DNA would behave as insulator. If larger space-time sheets are present DNA behaves as an effective ohmic conductor in the sense that dissipative effects are present. If only single larger space-time sheet is present, super-conductivity is possible so that the manufacturing of super-conductors should reduce to space-time engineering.

3.4. QUANTITATIVE MODEL FOR THE BREAKING OF SUPER-CONDUCTIVITY

The dropping (or leakage) of electronic Cooper pairs from $k=k_0$ (say $k_0=151$ corresponding to cell membrane thickness) space-time sheet to larger space-time sheets possibly present and followed by a thermal kicking back to $k= k_0$ space-time sheet is a good candidate for the mechanism causing the breaking of magnetic super-conductivity (Fig. 4b).
The conductivity as a function $\sigma(k)$ of the p-adic length scale L(k) should characterize the mechanism quantitatively. If the thermal energy $E_{th}=T$ satisfies the condition

$$E_0(k) - E(k_>) < T < E_0(k_<) - E_0(k) ,$$
$$E_0(k) = n_1\times\pi^2/[4m_eL^2(k)] , \quad (4)$$

one can say that the space-time sheet k is the effective carrier of the current.
The mechanism predicts that the increase of the temperature is accompanied by a sequence of phase transitions in which the value of k characterizing the effective carrier of the current decreases in a stepwise manner: $k=169\rightarrow 167\rightarrow 163\rightarrow 157\rightarrow 151\rightarrow$.... These transitions occur

at temperatures $T_c(k)=n\times E_0(k)$, n a numerical constant. This picture is consistent with the observation that the reduction of resistance occurs in a very short temperature interval ΔT: $\Delta T/T \approx .04$.

A more concrete picture is obtained by decomposing the friction force to a sum of forces resulting from dropping from say k=151 to k=157 163, 167,... and being kicked back. This gives

$$F = K(k)v ,$$
$$K(k) = \sum(k_i > k)\ \kappa(k_i) = \kappa(k_>) + K(k_>) . \qquad (5)$$

The condition F= qE, q=2e, gives for the conductivity defined by $j = nv = \sigma(k)E$, E electric field, the expression

$$1/\sigma(k) = K(k)/[nq] = \kappa(k_>)/[nq] + 1/\sigma(k_>) . \qquad (6)$$

What this means that the space-time sheets correspond effectively to resistors in series.
From the experimental findings for frog, for the transition from k=157 to k=151 the term K(k) (157) must be by about a factor 10 larger than the sum of terms term $\kappa(k)$, k>157. The fractal scaling

$$K(k) \propto 1/L^{\alpha}(k) \propto (2^{-k/2})^{\alpha} \qquad (7)$$

with $\alpha \cong 1.1$, suggests itself.

The standard classical model for the dissipative force implies that the force is inversely proportional to the free path l(k) of the particle and by a naive scaling symmetry l would be naturally proportional to the p-adic length scale $l \propto L(k)$ giving $\alpha=1$. $\alpha>1$ for K(k) means that the free path has a fractal dimension slightly larger than one. This is due to many-sheeted paths. The anomalous dimension of K(k) indeed correctly follows from the higher order terms in its expansion assuming that $\kappa(k)$ has the naïve scaling dimension -1: in the lowest order the model predicts $\sigma(151)/\sigma(157) \cong 1/8- 1/64 \cong .11$ in consistency with the measured reduction of the resistivity. Needless to say, this prediction provides a strong support for the p-adic length scale hypothesis and the notion of many-sheeted space-time.

3.5 Application at axon level

It is interesting to apply the model for the breaking of super-conductivity in the case of axon.

a) Understanding the critical temperature

The model for the nerve pulse generation predicts that "bridges" are formed between $k=k_0 > 151$ (say $k_0=169$) and k=151 space-time sheets making possible the flow of ions between cell interior and exterior. Super conductivity is broken provided that the temperature is sufficiently high. For electron Cooper pairs ($M=2m_e$) the zero point kinetic energy at the cell membrane space-time sheet is from Eq. 4

$$E_0(k=151) = n_1\times 312.25\ K . \qquad (8)$$

n_1 is some numerical constant not too far from unity. n_1=1 corresponds to a temperature 42.25 C. The identification as the critical temperature gives quite satisfactory agreement with the experimental values varying from 240 K to 300 K. Note that the requirement $T>T_c$ for the physiological temperatures means that k=151 cell membrane space-time sheet is the effective current carrier in the presence of larger space-time sheets.

If the join along boundaries bond connecting k=169 and k=151 space-time sheets contains a strong enough transversal electric field, the supra current can flow only in one direction. It seems that in the case of cell membrane the leakage of electronic Cooper pairs to the negatively charged cell interior is forbidden by this mechanism. The absence of the join along boundaries bonds between cell membrane and cell exterior assumed to be generated during the nerve pulse in the TGD based model of nerve pulse [19] in turn implies that the leakage cannot occur to or from k=169 space-time sheets at all. Therefore both k=151 and k=169 space-time sheet might be genuinely super-conducting and only nerve pulse conduction would be accompanied by the breaking of super-conductivity.

b) *Predictions for the critical temperature and resistance*

Fractality allows to make definite quantitative predictions for the critical temperature.

a) For k=163 conductivity the critical temperature is predicted to be by a factor $2^{157-151}$ = 64 lower than for k=157 conductivity. This gives T_c (163)=4.9 K for T_c (157)=300 K. The upper bound T_c =4 K for the critical temperature for super-conductivity in molecular crystals is reported in [9]. This would correspond to T_c (157) = 240 K measured in the case of frog. The predicted lowering of the resistance at this critical temperature for nerve conduction might be testable.

b) The observation that DNA attached between carbon and rhenium electrodes becomes super-conducting below the critical temperature of about 1 K for rhenium [23] allows the possibility that DNA becomes super-conducting already at about $T_c(163)\approx$ 4-5 K but that the rhenium acts as a weak link in the super-conducting circuit.

c) Cell membrane thickness L might vary and the natural guess is that the critical temperature is inversely proportional to $1/L^2$. If this is the case, the ratio of cell membrane thicknesses for frog and rabbit should be

$$L(frog)/L(rabbit) = [T(rabbit)/T(frog)]^{1/2} \cong 1.12 \qquad (10)$$

for T(rabbit)=300 K and T(frog)=240 K.

d) A further prediction following from the fractal model for the conductance (Eq. 7) is that also the k=157$\rightarrow$ 163 at about 4-5 K involves a 10-fold reduction of resistance. Also this prediction might be testable for nerves.

c) What happens in saltation?

An interesting question is what happens in the saltation over the myelin sheathed portions of the nerve. According to the TGD based model of nerve pulse [20], a Z0 type ME ("mass-less extremal", "topological light ray" moving with effective velocity equal to the conduction velocity of nerve pulse acts as a bridge between cell membrane (k=151) and cell exterior (k=169) space-time sheets and in this manner allows the leakage of ions from cell interior to exterior and vice versa inducing the physiological effects of nerve pulse. Z^0 ME could propagate along the myelin sheath rather than along the axon inside. Therefore nerve pulse would not be generated. The following picture about saltation suggests itself.

a) The transformation of the nerve pulse to an electronic k=151 or k=169 supra current propagating rapidly through the myelin sheathed portion would make possible a rapid signal transmission without physiological effects. Inside myelin sheathed portions of the axon the leakage to k=169 space-time sheets would be impossible by the mechanism described above irrespective of the value of the critical temperature.

b) Nerve pulse conduction involves also communication and interaction between different space-time sheets and therefore necessitates the leakage of electronic Cooper pairs from k=151 cell membrane space-time sheet. Therefore the critical temperature must be below the range of the physiological temperatures. Endotherms have an evolutionary advantage since the higher critical temperature implies that the dissipative effects associated with the nerve pulse conduction are weaker.

Whether electronic supra current in the myelin sheathed portions of the axon propagates along k=151 or k=169 space-time sheet or along both plus possibly along some other space-time sheets, remains unclear. The fact, that cyclotron transitions for ions in the Earth's magnetic field generate ELF radiation in EEG range [17, 20], supports the view that k=169 space-time sheet is involved. Note that the critical temperature in myelin sheathed regions could be higher than the physiological temperature.

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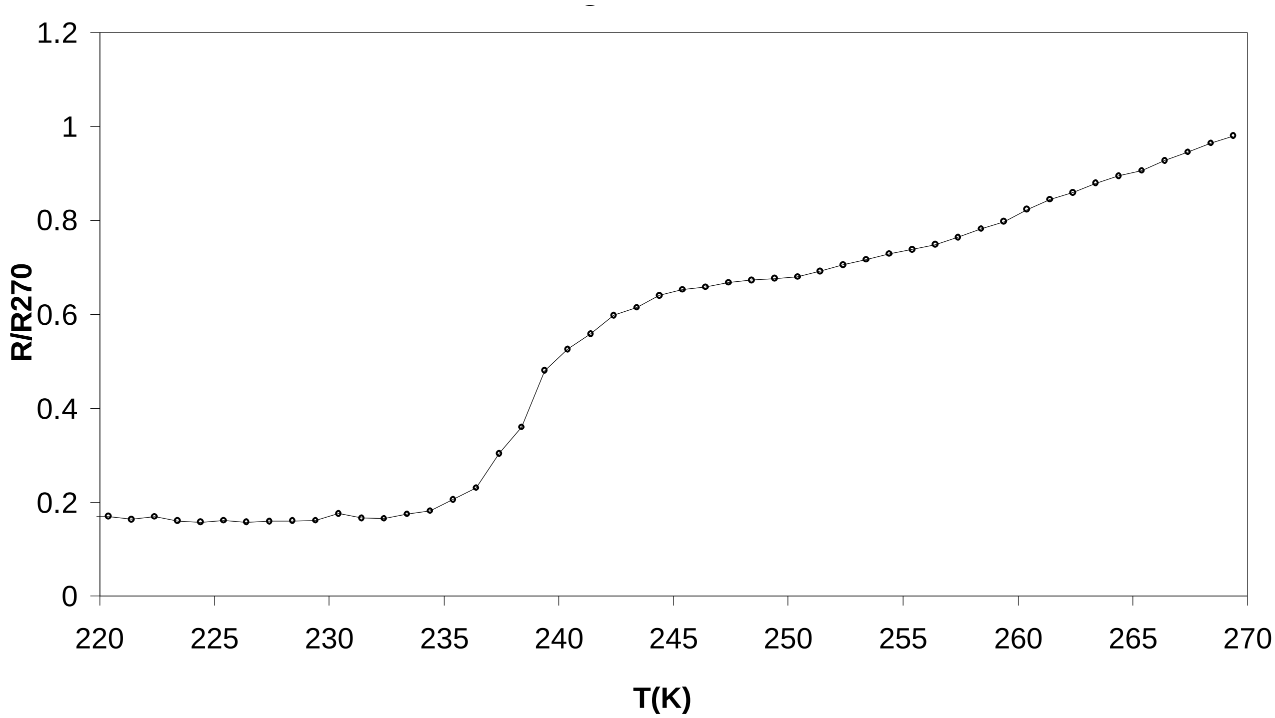

Fig. 1 Resistance of the frog sciatic nerve as a function of temperature. An external recording with the gold past. The resistance decreases with decreasing temperature, the resistance drops to R/Ra=0.35 below 240 K, indicating super-conductive like behaviour.

Fig 2

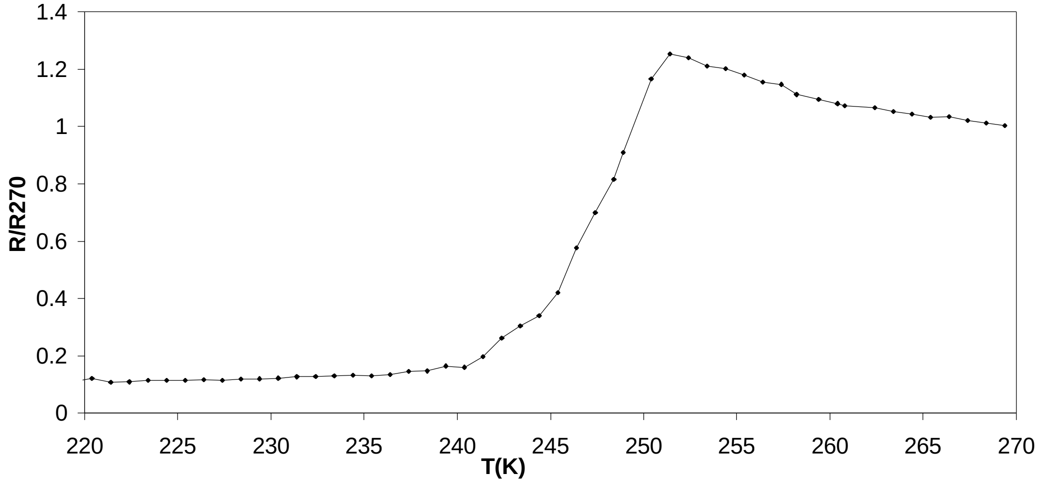

Fig. 2 Resistance of the frog sciatic nerve as a function of temperature. An internal recording with the gold past. The resistance decreases with decreasing temperature, the resistance drops to R/Ra=1.50 below 250 K.

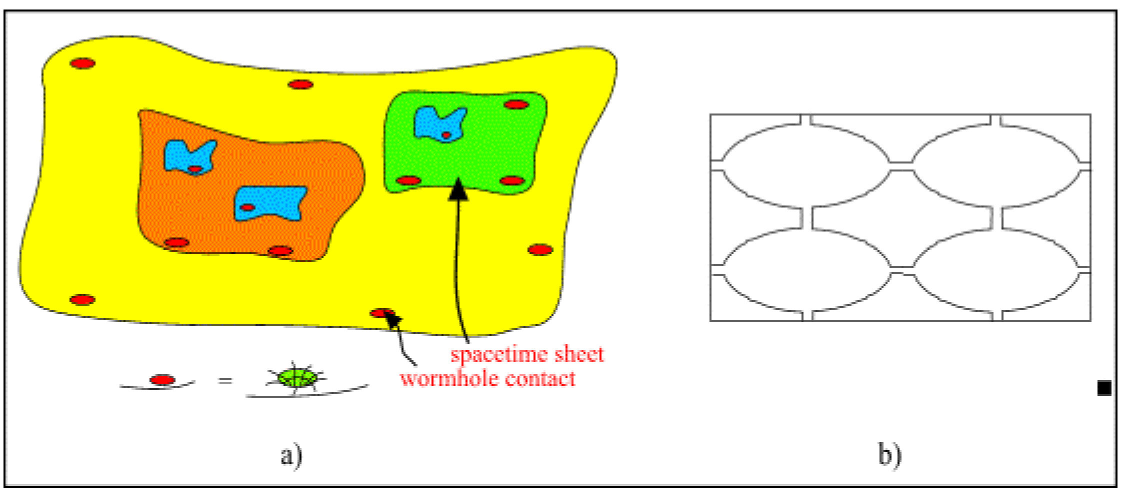

Fig 3: A 2-D illustration of a) many-sheeted 3-space/space-time, b) join-along-boundaries condensate.

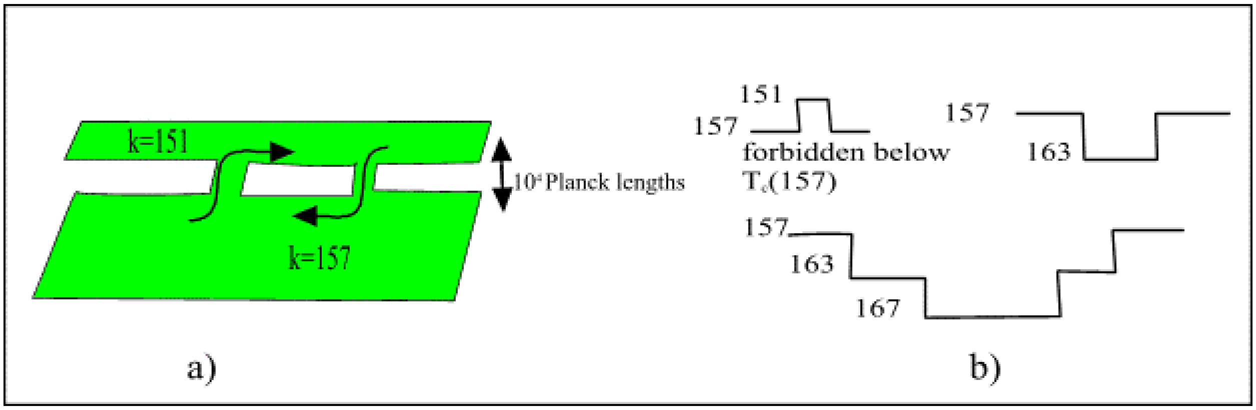

Fig. 4. a) A 2-D illustration of the leakage mechanism of the supra-currents between different space-time sheets. The “bridges” along which the leakage occurs could correspond to thermal photons or to “topological light rays” serving as the space-time correlate for coherent light . b) The mechanism of effective super-conductivity. The leakage of Cooper pairs occurs to larger space-time sheets and back, but its occurrence to smaller space-time sheets is energetically forbidden below critical temperature.