Naive Attempt of Quantum Mechanics: Axonal Membrane

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Abstract: Quantum mechanics -by using what we know about the system now- provides us information about the future of the system. Quantum physics and biology have been regarded as unrelated disciplines, describing nature at the inanimate micro level on the one hand and living species on the other hand. However, currently it is known that quantum mechanics is necessary in the description and understanding of natural phenomena. In fact, phenomena, which occur on a very small scale, cannot be explained outside the framework of quantum physics. It leads naturally to the question: Can quantum mechanics play a role in biology? In many ways it is clear that it already does.

The concept of tunneling is as old as quantum mechanics. The electrons have a finite probability of tunneling through the insulator without having enough energy to mount it. Although quantum effects are subtle, quantum mechanical tunneling may be important in understanding many membrane processes. This paper is a naive attempt to understand the potassium current characteristics from the quantum mechanical point of view.

Keywords: Axonal membrane, Electron tunneling, p-n junctions, Quantum mechanics, Tunneling diodes.

INTRODUCTION

Quantum theory is the notional basis of modern physics that explains not only the nature and behavior of matter but also the energy on the atomic and subatomic level. Both the nature and the behavior of the matter and energy at that level are sometimes designated as quantum physics and quantum mechanics.

The fact that there is even the probability of a functional role for quantum mechanics in nearly the entire field of biology is entering into a new stage. There can be many more examples of functional quantum behavior waiting to be naked. Additionally, there are number of obvious and common questions that arise: Can we learn from nature's example and build up some bio-mimetic quantum technologies? Do all quantum effects are destroyed or limited by the warm and wet biological environment?

Scientists all through the past century have balked at the implications of quantum theory. The theory's doctrine has repeatedly been supported by experimentation, even when the scientists were trying to contradict them. Quantum theory and Einstein's theory of relativity is the outward appearance for the modern physics. The principles of quantum physics recently are being applied in an increasing number of areas, including optics, chemistry, computing, and cryptography.

Quantum Biology

Quantum physics and biology have been regarded as unrelated disciplines, describing nature at the inanimate micro level on the one hand and living species on the other hand [1]. However, currently it is known that quantum mechanics is necessary in the description and understanding of natural phenomena. In fact, phenomena, which occur on a very small scale, cannot be explained outside the framework of quantum physics [2]. It leads naturally to the question: Can quantum mechanics play a role in biology? In many ways it is clear that it already does [3]. It is reported that quantum effects are observed in photosynthesis [4, 5], magnetoreception [6, 7], olfaction [8], vision [9, 10], and enzyme catalysis [11]. However, still quantum mechanics is an alien concept to biology.

Axonal Membrane

Like all the other cells, neurons are surrounded by a cell membrane. Besides it's complexities of the metabolic and structural apparatus both the inside and the outside filled with saline (*i.e*., water with ions dissolved in it).

In its simplest form all cell membranes are phospholipid bilayer, *i.e*. a layer which is only two phospholipid molecules thick. Due to the lowest-energy state possible principle parts of these molecules have different properties (phosphate group hydrophilic whereas the hydrocarbon chain part is hydrophobic). The lipid bilayer is very thin compared to its lateral dimensions. The thickness of the typical mammalian cell is around 4.8 nm (1-1.3 nm head and 2.5-3.5 nm chain).

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What we know about the artificial membranes is that the phospholipid bilayers are quite good insulators (this is not surprising: there are no free ions in the membrane so there are no carriers to transport charges). Their specific conductance per unit area is only about $g_{pure}=10^{-13}\Omega^{-1}m^{-2}$ [12]. However, due to the reason that there are many kinds of ion channels and other pores penetrating the membrane and allowing additional currents to flow, the conductance's of the biological membranes are several orders of magnitude of high even at rest. Indeed, these currents that make cells behave in a complex and interesting manner.

The free ions -electrical charges- constitute quite a good conductor in both ends of the phospholipid bilayers separated by an insulator ($c\approx10^{-2}Fm^{-2}$). This makes it possible to have different amounts of electrical charges inside and outside the cell. The capacitance, unlike the conductance, is very little influenced by all the complexities of biology. So the specific capacitance of biological membranes is very close to what is obtained simply from the dielectric constant of lipids and the thickness of the bilayer [13].

Due to its insulating properties, lipid bilayer is modeled as a capacitor. Since the total charge cumulated on the capacitor is the multiplication of capacitance and voltage, capacitive current can be written as

$$I=\frac{dq}{dt}=\frac{\partial(CV)}{\partial t}=V\frac{\partial C}{\partial t}=C\frac{\partial V}{\partial t} \qquad (1)$$

where C is the capacitance of the membrane and V is the applied voltage. For simplicity Hodgkin & Huxley [14] assumed capacitance of the membrane constant, which is independent of the sign, and the value of voltage, so the first term in the RHS of the equation (1) is zero. On the other hand, in the same paper they reported the small effect of the time course of the voltage on the capacitance of the membrane.

Conversly, It is stated by Heimburg [15] that not only electrical properties, but also membrane dimensions and thus the capacitance of the membrane changes during an action potential.

The concept of the flow of electrons through sufficiently thin insulating film arises from the theory of quantum mechanics. Classically, if the energy of the particle is less than the height of the barrier, a particle can never pass through it. However, if the barrier is sufficiently thin (< 30 Å) and if a potential difference V is applied between the electrodes, the metal wave function can extend on the barrier, and thus, electron passes from one metal to the other.

Although quantum effects are subtle, quantum mechanical tunneling may be important in many membrane processes. Attempt to understand axonal membrane from the quantum mechanical point of view.

Quantum Tunneling: Theory

Quantum tunneling or simply tunneling refers to the quantum mechanical phenomenon where a particle tunnels through a barrier. Let's consider two metals with work function ϕ, and barrier thickness s, at zero temperature (Figure **1**). The metal can be assumed as free electrons of mass moving in one dimension. It is viewed as a finite square-well, filled up to the Fermi level E_F. All states above E_F are empty. If $V = 0$, there will be no current flow, since the electrons on one side cannot find any available states to occupy. When a potential V is applied across the barrier, this causes the Fermi levels in the two metals to be separated by an energy eV. Hence, the electrons on one side can find empty states on the other side to occupy.

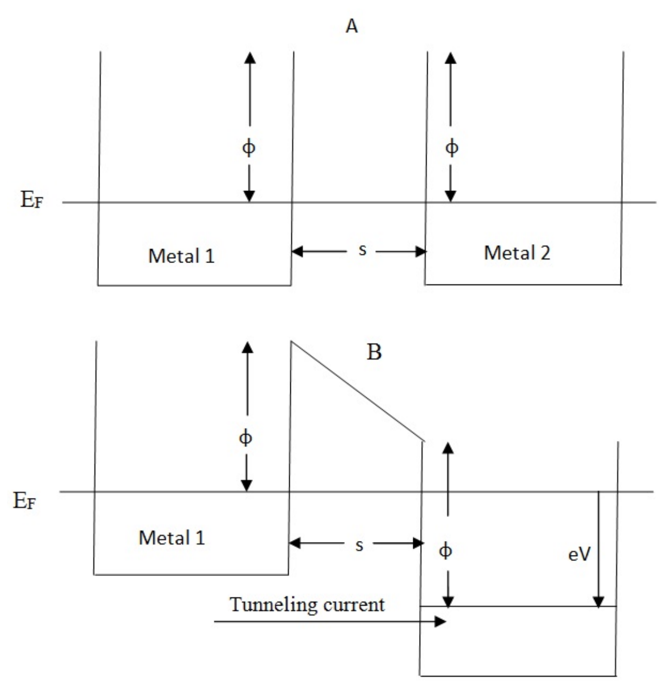

Figure 1: Schematic representation of an electron tunneling between the metals. Energy diagram for two identical metals separated by an insulator of thickness s. E_F refers the Fermi level. In A No voltage applied whereas in B Voltage V (eV) applied. Cursor in B shows the direction of electrons tunneling.

The transmission coefficient of a tunneling electron depends exponentially onto the thickness of the barrier and onto the square root of the work function. If small biases are applied to the metals, the tunneling current is given in equation (2) [16].

$$I \approx V e^{\frac{-2s}{h}\sqrt{2m\phi}} \tag{2}$$

If small biases are applied between two metals in their normal state the tunneling current I, through insulating film is approximately linear with the applied voltage, as long as the work fuction ϕ and the density of electron states are essentially constant, and the number of electrons which can flow proportionally increases with the voltage. As the bias further increases, the effective barrier decreases and thus the current increases exponentially. At biases greater than $eV = \phi$ the barrier width at $E=E_F$ starts to decrease with increasing bias and the current increases faster.

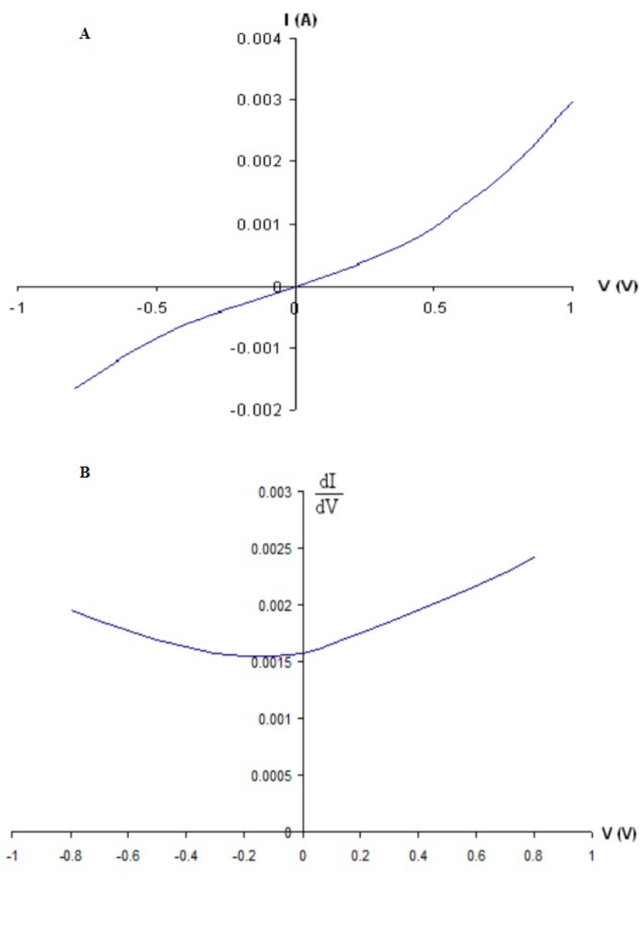

Figure 2: Typical curve shapes for electron tunneling. **A** shows the Current-Voltage while **B** shows the Conductance-Voltage relationship (Adapted from MS Thesis of YANARDAG SB.) [18].

The tunneling resistance at low voltages can be written as [16],

$$R_T = \exp\left[\left(\frac{2s}{h}\right)(2m\phi)^{\frac{1}{2}}\right] \approx \exp\left(-t\phi^{\frac{1}{2}}\right) \tag{3}$$

where m is the electron mass, h is Planck's constant, s is the separation distance between two electrodes, and ϕ is the work function. If the work function is about 4 eV, 1 Å change in separation distance, changes the resistance by an order of magnitude [17]. For low voltages the resistivity is constant; at higher voltages the resistivity decreases with the increasing voltage. The curves of tunneling current I, conductance $G = \frac{dI}{dV}$ as a function of voltage are given in Figure **2**.

Tunneling Diode

A tunnel diode -or Esaki Diode- is a p-n junction device [19], which is associated with quantum tunneling. With the help of degenerate -heavily doped-semiconductors, in the equilibrium Fermi level is kept constant through the junction (Figure **3**). Application of reverse or forward bias results in an electron flow from p to n or vice versa. A typical I-V characteristic of a tunneling diode is given in Figure **4**. It can be seen from the figure that diode exhibits a negative resistance in a region. After that region, it behaves like a conventional diode. Application of positive voltage raises the energy level of n-type material with respect to p-type and electron tunneling occurs from n to p. As the bands pass each other, current across the diode decreases, at the end of the negative resistance region the barrier is too large for tunneling, it behaves like a conventional diode, electrons travel by conduction. Due to N-like shape of its I-V characteristic it is called as N-shaped characteristics.

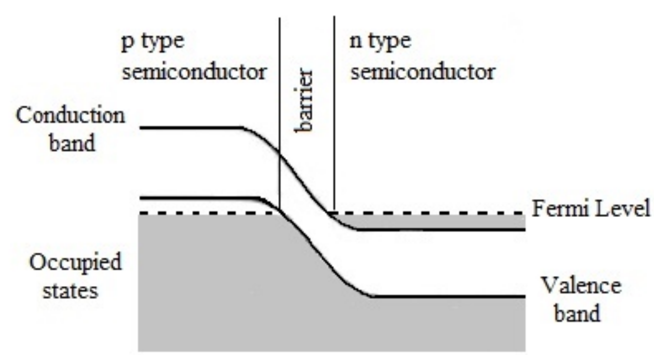

Figure 3: Zero bias (equilibrium) tunnel diode band diagram (no net tunneling).

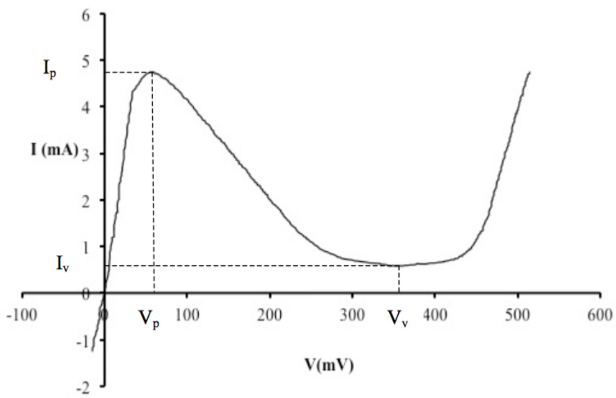

Figure 4: I-V characteristic of tunneling diode. The peak tunneling (I_p) current and valley current (I_v) determines the negative resistance slope of the diode.

This N shaped I-V characteristic of the system attracts the attention of the researches for the explanation of the axonal membranes nature. Spyropoulos [20] observed N-shaped I-V characteristics of super cooled (-5 °C) axon of the Loligo vulgaris. Moore's [21] observations were similar at higher temperatures with higher extracellular potassium concentration. Negative resistance was observed also by Mueller and Rudin in a reconstituted lipid membrane, and in the marine algae by Blinks [22]. Since the axon membrane is thin enough for tunneling and extra- intracellular matrices are the electron providers it seems logical to visualize the membrane as a p-n junction like tunneling diode. P-n-p junction analogy has no connection p-n-p transistor where p (positively charged) stands for excess hole and n (negatively charged) for excess electron.

It is well known phenomenon that during axonal conduction - formation of action potential- for the nerve axon the major current carriers are the positive ions. Specifically for the axonal action potential these ions are sodium and potassium among which the former is responsible for the depolarization and the later is responsible for the repolarization phases.

Since the I-V characteristics of the axon membrane has N-shaped, the axoplasm and extracellular matrix can be assumed as p type material, whereas the membrane can be assumed as n-type material, thus there are two junctions in the nerve axon.

I-V characteristic of a p-n junction is given in Figure **5**, total current of the p-n junction has two components: Drift and generation. The former is the diffusion of the major carriers from one side to the other in the presence of the forward bias and the later is the diffusion of the thermally excited minor carriers near the junction.

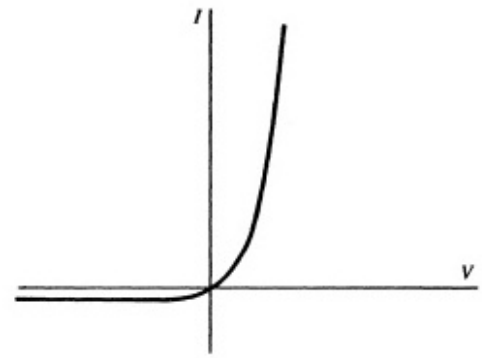

Figure 5: Typical I-V characteristic of an p-n junction.

In resting state the junction between the extracellular matrix and membrane is forward biased and the other is reversed. The ions at the forward biased side have an advantage on the ions of the other side and flow on this side is easier. It may explain the steepness of the rising phase of the sodium current however, may be due to the presence of its inactivation phase this model cannot explain the rest. On the other hand, this model suits well on the potassium channels. During an action potential as the membrane potential increases axoplasm -forward biased side- gets the advantage, movement of potassium ions from axoplasm to the extracellular matrix is observed. Otherwise, when reverse bias is present only a leak current is measured, which is similar to generation current in p-n junctions.

CONCLUSION

Tunneling diodes are capable of fast operations, including high-speed switching like the ones that we see in the axonal conduction events. In an evolutionary manner for faster responses it is necessary to have the advantage of the forward bias on the motion of the major current. Although the current topic seems to be complex still it is obvious that it can be a useful tool for understanding of the electrophysiological behavior of the neuronal axon (especially the behavior of the K ion channels) besides other techniques. This charming topic needs further investigations.

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