Quantitative analysis of the frequency spectrum of the radiation emitted by cytochrome oxidase enzymes

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A physical model is proposed that provides a quantitative analysis of the energy emitted by proton flows through mitochondrial walls. The model developed is based on biochemical and biophysical properties of the enzyme cytochrome oxidase and in particular the embedded heme groups that are involved in the electron ferrying mechanism. The estimates of the energies at approximately 1.1 eV and corresponding wavelengths of the near infrared radiation generated, with a peak close to 900 nm, agree extremely well with experimental values. The basic idea in the mechanism proposed is that the passage of a proton through the mitochondrial wall's gate is linked with the creation of a virtual proton-electron pair in an excited state of a hydrogen atom. The electron is temporarily removed from the enzyme when the proton arrives at the gate and is subsequently deposited back at the enzyme's acceptor site when the proton leaves the gate.

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I. INTRODUCTION

All living systems spontaneously emit biophotons [1] in a broad range from thermal radiation in the infrared through visible up to ultraviolet. The intensity of biophotons has been detected to range from a few (photons/s)/cm^2 up to several hundred (photons/s)/cm^2. In most cases the spectral distribution is broad and rather flat except in special situations such as cell division. The origin of biophoton research can be traced back to the pioneering work of Gurwitsch [2] and can be linked to the electromagnetic theory of life proposed by Burr and Northrop [3]. In 1955 Colli *et al.* [4] succeeding in proving the existence of biophoton emission in the visible region between 390 and 650 nm.

Today, bioluminescence is a well documented phenomenon that can be traced to bacteria whose light emissions can be visible to the naked eye. Various higher organisms such as squid, jelly fish, and fireflies emit light using the enzyme luciferase. We note that for fireflies and fishes, this luminescence serves interorganism communication purposes. Colli's experiments were later supported by the results of Veselovskii *et al.* [5], Ruth and Popp [6], Tarasov *et al.* [7], all of whom studied different organisms. Significantly, for the purpose, Vladimirov and L'vova [8] detected emissions from isolated mitochondria of rat liver that occurred most intensely when conditions were optimum for oxidative phosphorylation. Zhuravlev *et al.* [9] worked with isolated rat liver mitochondria, finding that mitochondrial luminescence requires ammonium dihydrogen phosphate (ADP) and oxygen, and that uncoupled electron transport (nonphosphorylating) can contribute to the observed luminescence. Since photons are emitted when electrons jump from molecular excited states to lower energy levels, it should not be too surprising to find that photons are emitted from mitochondria, where oxidative phosphorylation and electron transport can provide the energetic pathways to boost electrons into excited states [10]. Interestingly, the last part of Ref. [10] comments on the source of bioluminescence in eukaryotic cells in the following way: ''Unlike bacteria and other organisms displaying macroscopic bioluminescence, however, precise mechanisms for weak eukaryotic photon emissions remain to be discovered.'' It is our intention in this paper to provide an insight into this question.

In a series of studies, spanning a period of some 25 years of research Albrecht-Buehler (AB) demonstrated that living cells possess a spatial orientation mechanism located in the centriole [11–13]. This is based on an intricate arrangement of microtubule filaments in two sets of nine triplets each of which are perpendicular to each other. This arrangement provides the cell with a primitive ''eye'' that allows it to locate the position of other cells within a 2°–3° accuracy in the azimuthal plane and with respect to the axis perpendicular to it. He further showed that electromagnetic signals are the triggers for the cells' repositioning. It is still largely a mystery how the reception of electromagnetic radiation is accomplished by the centriole. Another mystery related to these observations is the origin of the electromagnetic radiation emitted by a living cell. Using pulsating infrared signals scattered off plastic beads AB mimicked the effects of the presence of another living cell in the neighborhood. The question that still remains, which we wish to address in this paper is the source of infrared (IR) radiation speculated by AB to originate in the mitochondria. Mitochondria are the organelles that produce the energy in the form of ATP molecules each of which carries approximately 0.5 eV stored in the high energy phosphate group part of which is due to the electrostatic repulsion between the oxygens in the phosphate group. The synthesis of ATP in the mitochondria is a multiple step process relying on the transfer of protons across the mitochondria wall and creating a pH gradient. The explanation of how this works brought Mitchell a Nobel Prize in

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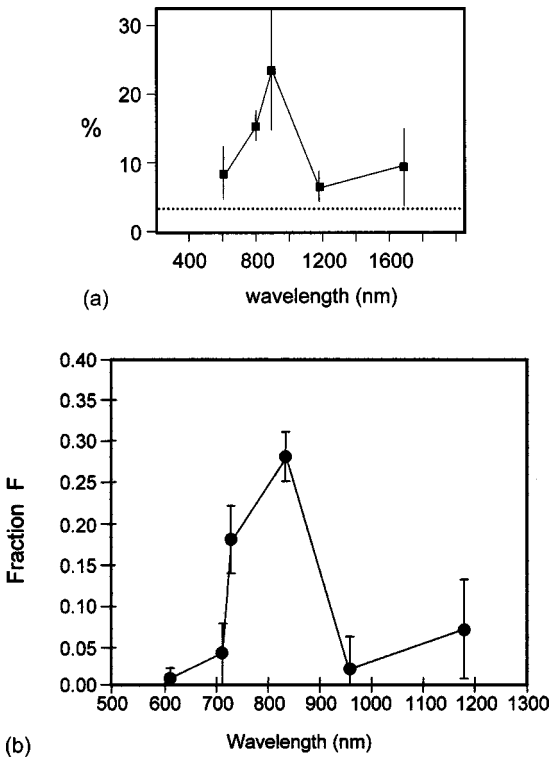

FIG. 1. (a) The percentage of cells that removed the light scattering particle as a function of wavelength. The most ''attractive'' wavelength was between 800 and 900 nm, (http://www.basic.nwu.edu/g-buehler/irvision.htm). (b) The fraction F of cells that remove the light scattering particles.

1971 [14]. At the center of this mechanism is the functioning of proton pumps embedded in the mitochondrial wall. Broadly speaking, these pumps are intricately built with an active moveable part consisting of an enzyme called cytochrome oxidase that opens and closes a channel through which individual H^+ ions enter the mitochondria. A living cell is a noneqilibrium physical system that requires a continuous energy input to sustain its activities. In animal cells energy production involves breakdown of nutrients and a subsequent production of ATP molecules that are the universal currency of energy in cells. The production of ATP molecules in turn is directly linked to the regular functioning of the mitochondrial pumps. It is therefore logical that one of the signatures of a living cell would be related to the oscillatory (pulsating) effect of mitochondrial proton flow. AB did suggest that the mitochondria are the best candidates for the explanation of infrared emission effects. He even pointed in the direction of the porphyrin containing proteins, i.e., the cytochromes. It is our intention in this paper to provide a quantitative account of how the structure of the porphyrin molecule results in the spectrum of emitted IR radiation observed in AB's experiments. Based on statistical analysis of a culture of 800 cells AB found a response function to the wavelength of electromagnetic radiation found below. The peak in Fig. 1 appears to coincide with 850 nm that is in the near IR and in the following pages we propose a detailed quantitative mechanism explaining such an emission spectrum.

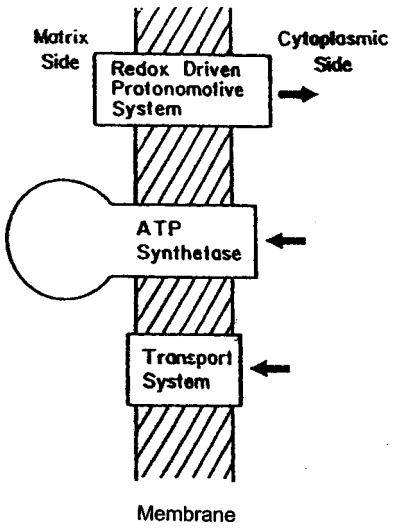

FIG. 2. A model of the transducing components located on the inner side of the mitochondrial membrane.

The effects of biophoton emission and absorption in living cells cover a very large body of literature, as we have shown above, some of which provides corroborative, albeit indirect, evidence for studies of Albrecht Buehler.

II. THE BIOCHEMICAL STRUCTURE AND FUNCTION OF THE CYTOCHROMES

The mechanisms involved in the process of proton gradients are illustrated in Fig. 2. To convert the energy of redox reactions of photoredox processes into a movement of protons from the left- to the right-hand side of the membrane, the redox driven protonmotive system is postulated. The separation of protons and anions across the membrane holds the energy and the stored potential energy is utilized in two ways. When there is a right-to-left flow of protons through the ATP, synthetase is coupled to the energy requiring synthesis of ATP from ADP and inorganic phosphate. This latter flow is coupled to active transport of biochemical components. The reverse flow involves the hydrolysis of ATP on the left side accompanied by the left-to-right proton flow.

ATP synthetases are located asymmetrically in membranes that are driven by the electrochemical potential of the protons and have a H^+/P stoichiometry characterizing it. The major subunits are shown in Fig. 3. To the left cytochrome-*c*-oxidase and to the right the quinol oxidase. In both cases the motif of a single heme plus heme/copper bi-

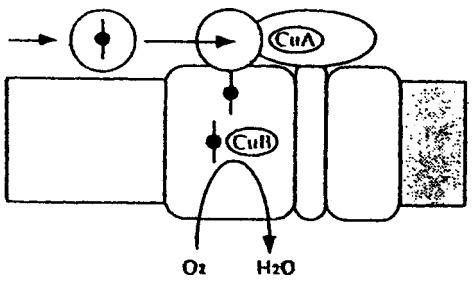

FIG. 3. A schematic diagram of cytochrome *c* oxidase (cyt.aa3).

nuclear center is evident. An analogy may be drawn, despite the fact that the enzymes differ in the nature of their electron entry sites, between electron donation from cytochrome *c* to the Cu_a/cytochrome *a* sites and from quinol (QH_2) to heme. The oxidation system in mitochondria is made up, principally, of the membrane associated with the electron transport chain.

The oxidation of reduced NAD, the reduction of O_2 to water that accompanies it, and the storage of energy are the overall function of this system. It is assumed in the chemiosmotic hypothesis that the intermediate form is created by transporting hydrogen ions from the inner mitochondrial matrix to the exterior of the inner mitochondrial membrane. A representation of the process in the mitochondria can be schematically illustrated by the following reactions:

$$\mathrm{NADH}+\mathrm{H}^{+}+\frac{1}{2}\mathrm{O}_2 \leftrightarrows \mathrm{NAD}^{+}+\mathrm{H}_2\mathrm{O}+\mathrm{ESE}, \qquad (2.1)$$

$$\mathrm{ADP}+P+\mathrm{ESE} \rightleftarrows \mathrm{ATP}. \qquad (2.2)$$

The electrochemically stored energy is represented by ESE. The reaction in Eq. (2.1) describes the oxidation subsystem and ESE is associated with the membrane. The process in Eq. (2.2) describes the transduction system. Available models have restrictions placed upon them by experimental features. The reactions in Eqs. (2.1) and (2.2) can be thought of as reversible since, in the presence of excess ATP and an appropriate electron source other than water, the reactions can be run backwards leading to such high energy reduced intermediates as NADH. This mechanism seems to be possible in many systems and a normal pathway in others. A second reason for reversibility is that respiratory control of the rate of oxygen utilization by ADP suggests a near-to-equilibrium distribution of the products of the first reaction. By a utilization of ESE the reaction is shifted to the right. Clearly the reversible and near-to-equilibrium features suggest that equilibrium thermodynamics can be used. We may assume that for Eq. (2.2) the actual sites for the corresponding processes are the ATP synthetase complexes of the inner mitochondrial membrane.

As a super family of metalloenzymes, the terminal oxidases share the basic function of catalyzing, by a four electron process, the complete reduction of oxygen to water. For our purposes it is important to emphasize that a proton electrochemical gradient is established across the membrane by the terminal oxidases. This is achieved by taking up the required protons to produce water from one side of the membrane only. These latter oxidases have also been shown to pump protons across the membrane. This occurs in a process that implies a coupling, against the diffusion gradient, between endergonic proton translocation and an exergonic electron transfer process. The terminal oxidases, therefore, contribute significantly to the maintenance of a transmembrane proton electrochemical gradient. Crystallographic structures of cytochrome oxidase enzymes have been established and we show one example below in Fig. 4.

It has been firmly established that there is a near-zero activation energy in oxidation of reduced cytochrome *c* by ferricyanide. The uptake of an electron at the iron center or the energy for release may come from the vibrational energy of the protein. Furthermore, for our purposes in this paper, it would seem quite probable that conformational mobility of the protein may assist in the electron-transfer process and the control of the gating process itself. The removal of sites for binding ferricyanide and elimination of surface positive charges via modification of lysine residues, does not affect the activation energy that remains near zero. The treatment of the protein with 4M guanidine hydrochloride (which relaxes the binding of ferrocyanide to the reduced molecule) does not affect the electron transfer rate. The notion that conformational changes are important in the electron transfer function of cytochrome *c* is supported by the above evidence.

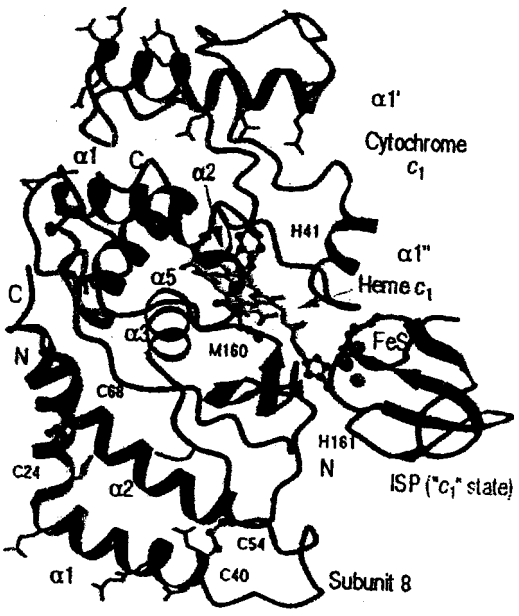

FIG. 4. A view from the mitochondria intermembrane space down the membrane normal: a stereoview of cytochrome *c*, subunit 8, and the metalcluster binding fold of the ISP at the ''c_1'' state. The disulphide bonds in subunit 8 are shown and ligands of heme c_1, His^{161} of ISP.

At the center of the enzyme one always finds an all important heme group that plays a cardinal functional role. The heme group, which is essentially a network of 36 conjugated bonds arranged in a flat disc, is derived from porphyrin molecules. Below we show the basic structure of the heme group in Fig. 5(a) as well as a specific example in Fig. 5(b). Iwata *et al.* [15] pointed out that the structure of the cytochrome bc_1 complex, especially the iron-sulphur complex suggests the existence of a new electron transport mechanism of the enzyme. The importance of electroconformational coupling, i.e., the influence of oscillating electric fields for the enzymes cellular energy production has been demonstrated by Tsong *et al.* [16] within a physical framework. The heme group and related molecules often contain a metal ion at their center. One can imagine that such systems of conjugated bonds will exhibit physical properties that are somewhere ''between'' those produced by the energy levels of single ions and the continuous energy band structure of solid state

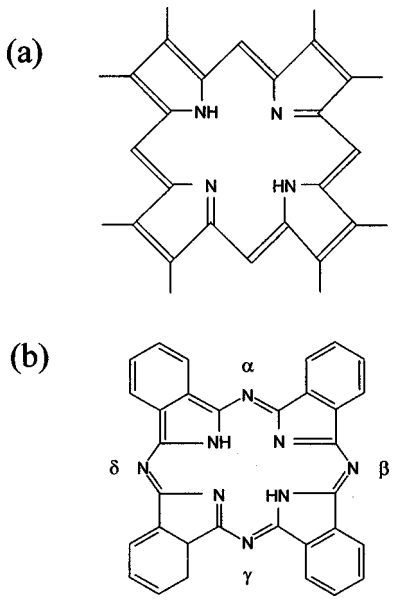

FIG. 5. (a) Basic molecular structure of porphyrins without the side chains being specified. (b) H_2 phthalocyanine (for H_2 porphyrin omit peripheral benzene rings and replace $\alpha,\beta,\gamma,\delta$,—N═ by —CH═.

crystals. The electronic structure generated by the charge of the metal ion when it interacts with its environment will be considerably modified. Some of the states may lie close to each other not allowing transitions to take place because of selection rules arising from conservation of momentum and spin. It is possible, therefore, that they may store energy in the form of infrared photons being well protected from the thermal chaos of the cellular world until a very specific trigger discharges them. These discharges may release photons of higher energy than the single electrons that built up the charge. They may also generate sudden electrical conductivity of the molecule because electrons in higher energy levels may have energies comparable to the energies of the conduction bands of the crystal in which they are embedded. Thus the porphyrin molecule could serve as a powerful amplification mechanism even though the absorbed photons have relatively small energies. In the next section we present a very simplified picture of the lowest states of the divalent ferrous ion in the center of a heme group.

III. A SIMPLIFIED MODEL CALCULATION

We suppose that we have a structure made up of N carbon atoms in a plane and arranged in a circle with an Fe^{2+} ion at its center having an incomplete d shell containing six electrons and all other ion states are filled. The presence of a ferrous or ferric ion in the cytochrome molecule is a reasonable presumption since it undergoes a redox reaction by hydrogenase whereby

$$\text{ferricytochrome } c_3(4\text{Fe}^{3+})+2\text{H}_2 \rightleftarrows \text{ferrocytochrome } c_3(4\text{Fe}^{2+})+4\text{H}^+.$$

We choose to examine the divalent variety and how its environment modifies its orbital states since its ground term has an orbital angular momentum, $L=2$ (a high angular momentum state), whereas the ferric variety is an S-state ion that is not significantly affected by charges in its environment. If a is the radius of the first co-ordination circle, the carbon atoms will be at positions $[x=a\cos((2\pi/N)m),\ y=a\sin((2\pi/N)m),\ z=0]$ where the integer, m, takes the values $m=1,2,\ldots,N$.

We consider one of the $3d$ electrons for simplicity at the position $x=r\sin(\theta)\cos(\phi)$ $y=r\sin(\theta)\sin(\phi)$, $z=r\cos(\theta)$. If $-q|e|$ is the charge on any one carbon atom, the potential energy, V, of one $3d$ electron will be

$$V=\frac{q|e|^2}{\sqrt{r^2+a^2-2ar\sin(\theta)\left[\cos\left(2\frac{\pi}{N}m\right)\cos(\varphi)+\sin\left(\frac{2\pi}{N}m\right)\sin(\varphi)\right]}}, \tag{3.1}$$

obtained by writing the squared distance between the carbon atom and a $3d$ electron as

$$\left(x-a\cos\frac{2\pi}{N}m\right)^2+\left(y-a\sin\left(\frac{2\pi}{N}m\right)\right)^2+z^2, \tag{3.2}$$

Rewriting Eq. (3.1), V becomes

$$V=\frac{q|e|^2}{\sqrt{r^2+a^2-2ar\sin(\theta)\cos\left(2\frac{\pi}{N}m-\phi\right)}}$$

$$=\frac{q|e|^2}{a\sqrt{1+\frac{r^2}{a^2}-\frac{2r}{a}\sin(\theta)\cos(\overline{\theta})}}, \tag{3.3}$$

where

$$\overline{\theta}=\frac{2\pi}{N}m-\phi. \tag{3.4}$$

By assuming $r \ll a$ we may expand the square root so that Eq. (3.3) becomes

$$V=\frac{q|e|^2}{a}\sum_{n=0}^{\infty}\left(\frac{r}{a}\right)^n P_n(\sin(\theta)\cos(\overline{\theta})), \tag{3.5}$$

where the P_n are the nth Legendre polynomials. More explicitly, to the $n=4$ term

$$\begin{aligned}V=\frac{q|e|^2}{a}\Bigg\{1&+\frac{r}{a}\sin(\theta)\cos(\overline{\theta})+\frac{r^2}{a^2}\frac{1}{2}\\&\times[3\sin^2(\theta)\cos^2(\overline{\theta})-1]+\frac{r^3}{a^3}\frac{1}{2}\\&\times[5\sin^3(\theta)\cos^3(\overline{\theta})-3\sin(\theta)\cos(\overline{\theta})]\\&+\frac{r^4}{a^4}[35\cos^4(\overline{\theta})\sin^4(\theta)-3\cos^2(\overline{\theta})\sin^2(\theta)+3]+\cdots\Bigg\}.\end{aligned} \tag{3.6}$$

Utilizing trigonometric multiple angle formulas (3.6) [17], becomes

$$\begin{aligned}V=\frac{q|e|^2}{a}\Bigg\{1&+\frac{r}{a}\sin(\theta)\cos(\overline{\theta})+\frac{r^2}{4a^2}\\&\times[3\sin^2(\theta)[\cos(2\overline{\theta})+1]-2]+\frac{r^3}{8a^3}\\&\times\{5\sin^3(\theta)[\cos(3\overline{\theta})+3\cos(\overline{\theta})]-12\sin(\theta)\cos(\overline{\theta})\}\\&+\frac{r^4}{64a^4}\{35\sin^4(\theta)[\cos(4\overline{\theta})+4\cos(2\overline{\theta})+3]\\&-120\sin^2(\theta)[\cos(2\overline{\theta})+1]+24\}+\cdots\Bigg\}.\end{aligned} \tag{3.7}$$

Summing over all the carbon atoms, i.e., m from 1 to N, the contributions from $\cos(\overline{\theta})\cos(2\overline{\theta})$, $\cos(3\overline{\theta})$, and $\cos(4\overline{\theta})$ vanish leaving the potential energy of *one* electron due to N carbon atoms, $\overline{V}$, as

$$\begin{aligned}\overline{V}=\frac{q|e|^2}{a}N\Bigg\{1&+\frac{r^2}{4a^2}[3\sin^2(\theta)-2]+\frac{r^4}{64a^4}\\&\times[105\sin^4(\theta)-120\sin^2(\theta)+24]+\cdots\Bigg\}.\end{aligned} \tag{3.8}$$

When $\overline{V}$ is summed over all six electrons, retaining only the first two terms of $\overline{V}$, and using operator equivalents we find

$$\overline{V}=\frac{q|e|^2}{a}N\left\{6+\frac{\langle r^2\rangle\alpha}{4a^2}[L(L+1)-3L_z^2]+\cdots\right\}, \tag{3.9}$$

where the average of r^2 for $3d^6Fe^{2+}$ is $\langle r^2\rangle=2.026a_0^2$, a_0 being the radius of the first Bohr orbit of hydrogen. The constant $\alpha=-2/21$ and L is the total orbital angular momentum of Fe^{2+} for its ground term that by Hund's rules is $L=2$. We drop the first constant term in Eq. (3.9) as this merely shifts all levels up or down in energy depending on its sign.

In order to estimate the range of acceptable values for $\overline{V}$ in Eq. (3.9) we rewrite this expression as

$$\overline{V}=\frac{\Delta EqN}{x^3}(-4800)\ \ \mathrm{cm}^{-1}, \tag{3.10}$$

where we have used the facts that $e^2/a_0\simeq 10^5\ \mathrm{cm}^{-1}$ and $1\ \mathrm{eV}\simeq 8000\ \ \mathrm{cm}^{-1}$, ΔE is the energy separation in dimensionless units from $L(L+1)-3L_z^2$ when the component of orbital angular momentum takes the values ∓ 2 ∓ 1, and 0. Thus positive values of ΔE can be 9, 12, and 3. The parameter q represents the valence of the carbon atoms that can lie between 2 and 4 and N is the total number of carbon atoms in the ring that we estimate can range between 30 and 36. Here, x represents the multiple of a_0 that makes up the radius of the circle, i.e., $a=xa_0$. We believe x can vary approximately between $x=10$ and $x=20$. The largest positive value of $\overline{V}$ is, therefore,

$$\overline{V}\simeq\frac{12\times 4\times 36}{1000}\times 4800=8294.4\ \ \mathrm{cm}^{-1}=1.04\ \ \mathrm{eV}. \tag{3.11}$$

The energy corresponds to a wavelength that is almost 1200 nm and lies approximately in the middle of the range shown in Fig. 1 stretching from 600 to 1700 nm. The values above 1200 nm correspond to lower energies and are easy to account for due to the possibility of a larger ring size, smaller valence or smaller values of ΔE. We envisage, as we see later, a proton in close proximity to the ring that will then become distorted preferentially on one side only. Thus the effective radius, a, of the ring for a percentage of the carbon atoms on one side of it will become less. As the quantity a appears as a^{-3} in expression (3.9) or (3.10), this distortion will have the effect of increasing the magnitude of $\overline{V}$ in Eq. (3.10). This increase will clearly depend on the number of carbon atoms affected and the average fractional decrease in a, i.e., $-3\delta a/a$. We estimate that for $|\delta a/a|\sim 5/100$ then the value of $\overline{V}$ in Eq. (3.11) will be increased, for half the carbon atoms affected, by approximately 6%. This is quite sufficient to bring $\overline{V}$ close to 1.10 eV in agreement with experiment. In order to explain the peak below 1200 nm one needs to revisit the structure of the ring. The trivalent nitrogen tends to be closer to the center of the ring and could also easily increase the energy of the transition.

IV. A PROPOSED MECHANISM

The question of electronic [18–31], protonic [32–35], and ionic [36,37] conduction in biological systems, especially proteins and enzymes, has received considerable attention in the last two decades. Although dry state activation energies for biopolymers have been reported in the range 2.2–3.7 eV [26] this potential barrier can be significantly reduced to the

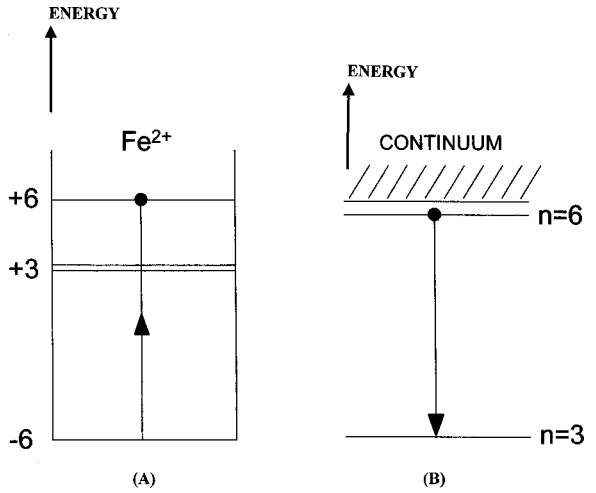

FIG. 6. Excitation of Fe^{+2}, transfer of an electron to a proton, and subsequent descent in energy from the $n=6$ to $n=3$ state of hydrogen. (A) Energy levels of Fe^{2+} labeled with the component of angular momentum. (B) Two energy levels of hydrogen labeled with the principal quantum numbers $n=6$ and $n=3$.

values observed for semiconductors that are 1.1 eV or less [27] as result of hydration which, of course, is the natural state in biological systems. A particular mechanism of electron and proton mobility involves transfer of electrons from donor to acceptor sites via a ferrying process facilitated by protons. We believe that this is indeed the case with a protonic passage through channels in mitochondrial walls.

Gilmanshin and Lazarev [23] claim that the transfer of electrons along a protein is accomplished by a series of redox centres incorporated into the protein structure. This allows for the directionality of electron transfer over distances of 0.3–3.0 nm. The protein-electron carrier system consists of protein, possibly localized within a mitochondrial wall, which has a single redox center. The redox centres are usually prosthetic groups containing molecules of nonproteinous origin that have conjugated orbital systems and often incorporate metal ions. The function of the prosthetic group is several fold. It ensures the fixation of charges and dipoles in its microsurroundings and catalyzes electron transfer. Second, the orientation of the prosthetic group relative to other proteins may enhance recognition of the redox center. Third, the prosthetic group may act to influence the electronic state of associated proteins or vice versa, and result in a degree of isolation from the polar solvent. Finally, it may control electron transport through its oxidation or reaction that alters the carrier concentration. Ichinose and Minato [33] are in general agreement with the statement that electron transfer in biological systems occurs via a redox scheme but are critical of electron tunnelling over distances of 3.0–7.0 nm as some have reported. Instead, Ichinose and Minato propose that protein is an insulator at physiological temperature and that electron transport is mediated by protons.

In terms of the energies and individual mechanisms for the electronic transitions in the cytochrome oxidase we propose that the first step in the process involves the excitation of the ferrous ion. This is most likely caused by a kinetic energy transfer from the decelerating proton approaching a

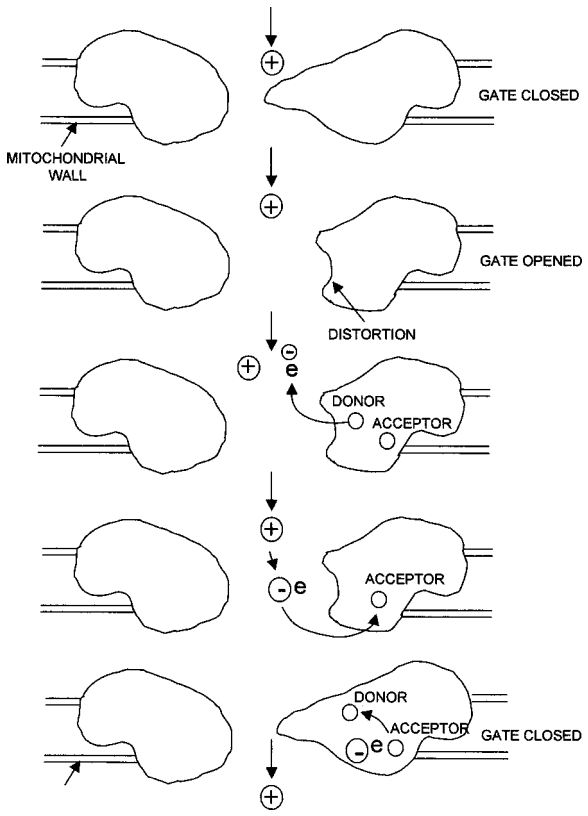

FIG. 7. The passage of a proton through an opening in the mitochondrial wall ferrying an electron between donor and acceptor sites. The proton ''opens the gate'' by distortion of the heme group, accepts a loosely bound electron, freely diffuses to the acceptor site where it then donates the electron. Donor and acceptor relax to their initial state and the ''gate closes.''

positively charged heme group. It would only require a slow down of the proton from a velocity seven times greater than the rms value to the thermal average. Once the ferrous ion is sufficiently excited an electron can tunnel through a potential barrier to become loosely bound to the proton as illustrated in Fig. 6. The virtual weakly bound hydrogenic system formed may then relax from an $n=6$ state to an $n=3$ state to emit IR radiation of 1.13 eV. The iron remaining in the heme group will be a ferric ion, in an *S*-state ground state, which will not couple strongly to its immediate ring of carbon atoms. The loosely bound hydrogen electron, when the proton moves past the heme group, would then be transferred to a local acceptor site, so that when donor and acceptor relax, the iron is restored to its Fe^{2+} valence state with six electrons and the process begins again as the proton moves further through the mitochondrial membrane (see Fig. 7).

V. CONCLUSIONS

In this paper we have discussed a specific model of a physical mechanism intended to explain quantitatively the origins of cell-cell communication by the emission of infrared radiation. The motivation for this analysis was given by the experimental observation made over the past two decades by AB who established that neighboring cells perceive each

other's presence through signals emitted most likely by the mitochondria. The experimental evidence gathered by AB strongly suggests that infrared radiation is produced by the proton pump in the mitochondrial wall. We have followed up on this hint and developed a quantitative model that would fully account for and corroborate AB's suggestions. The process that we envisage is consistent with the biochemical structure and function of the enzyme. In the first step of the process a cytoplasmic proton impinges upon the wall and decelerates, transferring some of its kinetic energy into the gate. This energy is then utilized to excite the heme group and also causes a conformational change in the enzyme resulting in the opening of the gate. The excitation in the heme group facilitates the subsequent tunneling of one of its valence electrons that forms a virtual pair with the proton. The pair, with no net charge, freely passes through the gate, upon which the electron is reabsorbed into the protein at the interior acceptor site. It is subsequently recycled back into the donor site through a process of thermally activated migration. The gate closes and the process repeats itself cyclically with the arrival of a new proton outside the gate. The electromagnetic radiation is emitted when the electron is deexcited from the conduction band to a valence state and has an energy, approximately in agreement with experiment, and in the vicinity of 1 eV that corresponds to the near infrared region in accordance with AB's work.

Although in this paper we have elucidated how the infrared signal is produced by the mitochondria there is still an important aspect of cell-cell communication that remains to be explained. This is the complementary aspect of how the signal is absorbed by the centriole, and how it is processed in a cascade of events orchestrating the cells motility. We intend to develop a physical theory of the centriole's role in directing the cell's movements in a future publication.

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