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All basic condensed matter physics phenomena and notions mirror in biology – A hypothesis, two examples and a novel prediction

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Abstract. A few billion years of evolutionary time and the complex process of 'selection' has given biology an opportunity to explore a variety of condensed matter phenomena and situations, some of which have been discovered by humans in the laboratory, that too only in extreme non-biological conditions such as low temperatures, high purity, high pressure etc., in the last centuries. Biology, at some level, is a complex and self-regulated condensed matter system compared to the 'inanimate' condensed matter systems such as liquid ^{4}He, liquid water or a piece of graphite. In this article I propose a hypothesis that 'all basic condensed matter physics phenomena and notions (already known and ones yet to be discovered) mirror in biology'. I explain this hypothesis by considering the idea of 'Bose condensation' or 'momentum space order' and discuss two known example of quantum magnetism encountered in biology. I also provide some new and rather speculative possibility, from light harvesting in biological photosynthesis, of mesoscopic exciton condensation related phenomena at room temperature.

Keywords. Condensed matter physics; magnetic crystals in biology; excitons and photosynthesis.

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1. Introduction

The world we live in is made mostly of inanimate matter; and a small fraction of it is the biological matter. The air, the water, the earth with all its rocks and minerals hardly change. Their dynamics is slow. The biological matter such as the tiniest of life, an amoeba, is alive and active, at all length scales – from atomic dimensions to microns, at all time scales – from femtoseconds to seconds. In some sense the inanimate matter is stuck or frozen in some finite region of phase space. The energy input to a living biological system with its profoundly complex genetic and protein machinery keeps it alive and active – some estimates tell us that every atom in a cell wall is replaced by about 5 times a day! In biology nothing is at rest, even the gene sequences are changing through mutations etc. The dynamics of biological system is exploratory and evolutionary, over time scales that range from femtoseconds to billion years.

A systematic understanding of matter with its constituents, and how quantum mechanics puts them together to make a variety of condensed matter systems with innumerable physical and chemical properties, has given us a variety of 'basic phenomena' in condensed

matter science. Many of them are experimental discoveries under unusual (non-biological) conditions, such as very low temperatures or large magnetic fields etc., and some of them are theoretical predictions. An interplay of advances in material science, technology, our ability to model, use of quantum mechanics and statistical mechanics has been mostly responsible for the birth of the new field of condensed matter physics in the last century.

2. A hypothesis

It is in the light of the statements I made in the introduction, I make the following hypothesis: 'All basic condensed matter physics phenomena and notions (already known and ones yet to be discovered) mirror in biology'. Perhaps this hypothesis is self-evident to trained eyes; perhaps it is a tautology in the sense if biology is a complex condensed matter, it should obviously contain condensed matter phenomena etc. But, like every hypothesis, when spelt out with support it can guide us, focus our thinking in some useful fashion and sometimes it can have useful consequences. In my own attempt to comprehend bits and pieces of biology, in non-traditional fashion, I found this hypothesis very useful. A word of caution however: *biology is 'more and different' from condensed matter physics* [1].

This hypothesis can also help us in two ways. The first use is not so obvious and very interesting: *biology revealing to us key ideas, fundamental notions, condensed matter phenomenon or 'laws of physics' that we have failed to discover in non-biological contexts so far*. This could be ideas such as statistical mechanics of regulated systems, intelligent materials, complimentary pairing in self-assembly as suggested by DNA, negative entropy etc. Secondly we can make a conscious search in biology for the phenomena and notions known to us in physics. Such findings can help us to make rapid progress in some corners of biology through the use of our insights and experiences gained in condensed matter physics.

Our hypothesis essentially states that nature is a wise user of available resources in unimaginable fashions and seems to have explored in its evolution most possible phenomena, to be only constrained by the laws of physics and chemistry.

In this paper we elaborate how biology mirrors some basic notions and phenomena in its own wet biological environment. In Anderson's book [2], many basic notions and ideas in condensed matter physics are spelt out: some of them are, spontaneous symmetry breaking, generalized rigidity, topological defects, adiabatic continuity, Fermi and Bose liquids, localization, scaling, renormalization etc. A basic notion is a key idea that underlies and unifies diverse phenomenon. Depending on its universality and generality it may be even elevated to a law or a principle.

For example, the notion of 'Bose condensation', 'order in momentum space' or 'momentum space rigidity' underlies diverse phenomena such as superfluidity in liquid ^{4}He, superconductivity, quantum Hall effect, spin density wave, laser and recently matter laser from atomic Bose condensates etc. Here 'order in momentum space' is a key idea, that is independent of conditions such as low temperatures, high purity, or large magnetic fields or low dimensionalities, under which condensed matter physicists discovered the above phenomenon.

As far as we know, biology does not exhibit fractional quantum Hall effect or superconductivity. However, it exhibits 'momentum space order', the key idea underlying these phenomena. It may even exhibit 'room temperature superfluidity' under some conditions,

as we will speculate in this paper. In this paper we will take only one notion, the idea of 'momentum space order' and see how biology mirrors it in unexpected places.

I do not want my limited hypothesis to mean *that 'human mind', believed to be a product of 'biology' can comprehend, conceive, and possibly discover only what is contained in its body/biological system!* I am clearly out of my depths in these and epistemological issues. I limit myself to condensed matter phases, concepts and phenomenon, such as ferromagnetism, Kondo effect, Peierl's instability, entropy, Josephson effect etc.

2.1 *When do new notions emerge?*

Basic condensed matter physics notions and phenomena are many. It includes phenomena, concepts, notions, phases, methodologies etc. Examples of very simple and yet fundamental phenomena and notions are liquid–gas co-existence, critical point or critical opalescence in binary liquids etc. The idea of spin glasses, broken ergodicity, frustration etc., arose from the study of spin susceptibility of gold when alloyed in a controlled fashion with parts per million of Mn atoms. While there are many ways in which new understanding arises with the growth of science, *new notions often emerge in a natural fashion in new contexts and situations*: quantum number fractionization in the study of polyacetylene, cuprates, fractional quantized Hall system, 'exclusion statistics' in the context of strongly correlated electron systems, fractals in the context of aggregation phenomenon, topological defects and use of homotopy theory in the study of symmetry broken phases, renormalization group idea in the context of Kondo effect or phase transitions, soft mode and Bose condensation in the context of structural or ferroelectric phase transitions etc.

The world of biology has much more contexts and situations than those created by humans in the laboratory. That is why one expects in biology an evolution from down-to-earth condensed matter type to an unending hierarchy of notions, hypothesis, concepts and phenomena.

3. Bose condensation in biology: Single domain quantum magnetism

Condensation in momentum space or the phenomenon of Bose–Einstein type condensation is the corner stone in quantum condensed matter physics. As mentioned earlier, it is at the heart of diverse special systems such as superfluid ^{4}He, superconductors, fractional quantized Hall effect, quantum antiferromagnets, laser and most recently matter laser. Even though these phenomena manifest themselves in profound fashions in terms of different desirable physical properties, in their mathematical descriptions, notions such as anomalous averages, Goldstone modes, Bogoliubov type of theories, diagonal and off-diagonal long range order etc. unify all the above (table 1). For the reader not familiar with fractional quantum Hall effect, this novel quantum state may also be considered as a Bose condensed state of composite bosons – a composite of an electron and three flux quanta in the case of the famous $\frac{1}{3}$ quantum Hall state.

The above phenomena are not known to occur in biological systems; however, the unifying notion of 'condensation in momentum space' is beautifully realized in the case of quantum magnetism, which is what we will briefly describe. It is important to recall that

Table 1. Some states of condensed matter and their order parameters.

Phenomenon	Order parameter
Bose–Einstein condensation	$\langle b_0^\dagger \rangle$
Superconductivity	$\langle C_{k\uparrow}^\dagger C_{-k\downarrow}^\dagger \rangle$
Charge density wave	$\langle C_k^\dagger C_{k+Q} \rangle$
Antiferromagnetism	$\langle S_Q^+ \rangle$
Fractional quantum Hall state	$\left\langle \int \mathrm{d}x\mathrm{d}y \psi^\dagger(z) \mathrm{e}^{m \int \mathrm{d}x' \mathrm{d}y' \log(z-z') \psi^\dagger(z') \psi(z')} \right\rangle$

Frohlich [3] has often emphasized and suggested the possibility of Bose type of condensation in biological systems, crudely speaking in a system of interacting dipoles; and their role in the activities of enzymes [4]. Interacting dipole moments are ubiquitous in biology, at various length scales and relaxation time scales – water, proteins, charged DNA, microtubles etc. Frohlich called them coherent excitations of polar modes, a type of $k = 0$ giant dipole oscillations at the frequency range 10^{11}–10^{12} s^{-1}. These dipole systems are complex and needs to be investigated further; they will perhaps give novel ideas to condensed matter physics. However, there are some relatively simple quantum magnetic system in biology which mirrors some of the condensed matter ideas in a more transparent fashion.

The phenomenon of magnetism, particularly ferromagnetism is old. The origin of magnetism in solids and the key role played by quantum mechanics in establishing atomic magnetic moments and a long range co-operative order through 'exchange interaction' etc., gave birth to the field of magnetism in solids. It is a matured field with a lot of technological applications. Scientists have been working hard to produce single crystals to understand the magnetic properties in a detailed fashion. Even in single crystals, the long range dipolar forces and the magneto-crystalline anisotropy inevitably produce magnetic domains and the physics is complicated and rich.

Magnetism is intrinsically quantum mechanical, in spite of a classical flavor that is attached to it in our education. In particular the phenomenon of quantum antiferromagnetism is a genuine Bose condensation of magnons and also illustrates some of the subtleties of spontaneous symmetry breaking in quantum systems in a powerful fashion.

Biology manages to 'grow' monodomain magnetic single crystals, at least in two different contexts: (i) ferritin, an iron storage system, very important for human beings and (ii) magnetotactic bacteria.

Let us consider ferritin. It became popular among condensed matter physicists recently [5] in the context of a claim of macroscopic quantum tunneling of the residual ferromagnetic moment of this finite system. Ferritin is a multi (24) protein complex that sequesters iron inside the 2 nm thick protein coat. The iron atoms are in the ferric (Fe^{3+}) state as a hydrous ferric oxide phosphate mineral (structure similar to that of ferrihydrate). The single crystal can have a dimension of about 3 – 7.5 nm and hold a maximum of about 4500 Fe atoms.

Since Fe^{3+} is an $L = 0$ state with $S = \frac{5}{2}$, it is a nearly isotropic system with smaller spin-orbit coupling effects. The iron spin-$\frac{5}{2}$ moments in ferritin are antiferromagnetically coupled through superexchange interactions. Ferritin is large enough so that it can easily support long range antiferromagnetic order in laboratory time scales. Further, the size of

the ferritin magnetic crystals are larger than the domain size that is dictated by magneto crystalline anisotropy and dipolar interactions. It is an antiferromagnet with Neel temperature $T_N \approx 240$ K. Being a finite system with particular shape and surface area, the two sublattice magnetic moments do not cancel each other. There is a resultant ferromagnetic magnetic moment of the order of tens of Bohr magnetons, which can undergo collective quantum tunneling, exhibit even-odd effect etc. Partly as a spin-off from the study of ferritin, a biological system, condensed matter physicists and chemists are studying quantum spin dynamics in molecular magnets such as Mn_{12}-acetate and Fe_8 high spin molecule; it is an active field [6] where many issues of quantum dissipation, macroscopic quantum tunneling etc. are discussed both experimentally and theoretically.

The next example is the magnetotactic bacteria [7]; magnetotaxis refers to propulsion or motion along lines of magnetic field. A magnetotactic bacteria precisely does that. It has built-in magnetic compasses, a collection of (often well-faceted) single crystals of Fe_3O_4 (magnetite). The single crystals have dimensions that range from 30 to 120 nm and they are encapsulated by lipid membranes. Each family of bacteria chooses its own number of magnetic crystals, sizes and shapes. These single crystals are monodomain ferrimagnets with a magnetic transition temperature $T_c \approx 850$ K. In this system with a spinel structure Fe^{2+} and Fe^{3+} occur in the ratio 1 : 2. In the ordered state the spin-$\frac{5}{2}$ moments of Fe^{3+} order antiferromagnetically and the spin-2 moments of Fe^{2+} order ferromagnetically and one observes a moment of $4\mu_B$ per formula unit.

In the spin wave theory for quantum antiferromagnetism as well as ferromagnetism there is a Bose condensation of spin reversals at a finite wave vector $\mathbf{Q}$ in momentum space $\langle S^+_{\mathbf{Q}} \rangle \neq 0$. We will not go into the mathematics of this and refer any young reader to books such as Quantum theory of solids by Kittel [8]. It is fair to say that nature has achieved Bose condensation of magnons in biological systems under biological conditions. And not only that, some room temperature quantum coherent behavior involving collective moment type variables are perhaps at work as part of some biological processes!

4. Speculations on mesoscopic exciton condensation in photobiology

Now I wish to speculate on the possibility of Bose condensation in finite geometries, of neutral particles, namely excitons, in biological systems. The field of photobiology is very vast – from the study of pigments in biology of vision to the study of photosynthesis in the simplest of bacteria. These diverse systems have remarkable unity at various levels. The light absorbing pigments are all $p\pi$ conjugated double bonded molecules: examples are the family of chlorophyll, carotenoid and retinene. The light absorbing pigments are spatially organized as symmetrical mesoscopic systems such as circular or linear arrays. I wish to discuss one of the simplest of the systems, light harvesting system in purple bacteria, an active area [9] in photosynthesis. This remarkable bacteria, that is really starved of light in its dark and anaerobic environs at the bottom of muddy waters, harvests the faint light available in a most fascinating fashion with high efficiency and uses it to initiate an important bio-chemical electron transfer reaction across cell membranes.

Significant recent advances [10,11] using protein X-ray crystallography, electron microscopy and molecular modeling, have revealed the detailed protein structure along with the complex and symmetrical arrangements of the pigments in the light harvesting system. There are very nice articles and review articles and web sites [12,13] that give great details

about the structure of this complex system. This simple bacterial system is believed to be a representative system, as far as arrangements of pigment molecules are concerned, even for higher organisms such as plants.

The light harvesting system is a *two-dimensional array* of light harvesting complexes denoted as LH1 and LH2 that are embedded and exposed to light in the bacterial cellular membranes. LH1 and LH2 are integral membrane proteins in which the light absorbing bacteriochlorophylls (BChl's) and carotenoid (Car's) pigments are non-covalently bonded and organized in a circular fashion (figure 1). The reaction center is surrounded by the LH1 complex, whereas the LH2 complexes are arranged around the perimeter of the LH1 ring in a 2d structure. At the center of LH1 is the reaction center (RC). There are about 300 BChl molecules per reaction center. For every LH1 unit there are about 8 – 10 LH2 units.

LH2 comprises of 27 BChl and 18 Car molecules. The BChl molecules are organized in two concentric rings. One ring, referred to as B800, features a group of 9 well-separated BChl molecules with an absorption band at $\sim$800 nm. The other ring, referred to as B850, consists of 18 closely interacting BChl molecules with an absorption band at $\sim$860 nm. It is believed that the B800 and Car molecules are essentially feeders to the B850 ring. LH1 is similar but bigger, containing a B875 ring containing 32 closely interacting BChl molecules and similar number of feeder Car molecules.

Light in characteristic spectral ranges are strongly absorbed by the BChl's and Car's to produce molecular or Frenkel excitons. The classical picture was that these excitons migrate in an incoherent fashion on the two-dimensional light harvesting area to reach the final reaction center (RC), where the exciton will annihilate itself to release an electron. The RC's are at the centers of LH2's, where a transition metal ion in a prosthetic group in a protein is waiting for light energy to arrive in the form of an exciton so that it can use the energy to excite and release one of its electron and initiate an electron transfer reaction. With the finding of the above crystal structure and spectroscopic experiments, the exciton dynamics is considered to be more quantum mechanical than a classical incoherent random walk process.

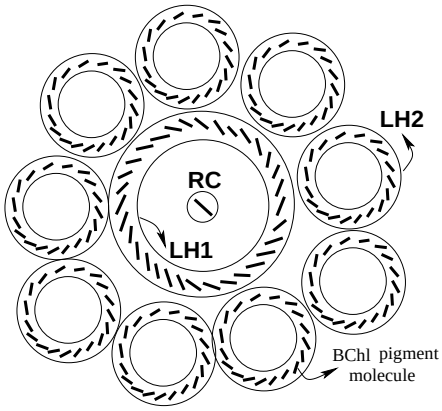

Figure 1. Schematic diagram of the light harvesting complex containing LH1 and LH2 systems and the reaction center (RC). The light absorbing BChl molecules that are strongly coupled in circles alone are indicated. Other feeder BChl, Car molecules and the protein 'substrate' are not shown.

In the simplest model for the exciton dynamics one focuses on one particular excited state of a BChl molecule above the ground state. This is a molecular excitonic state. The exciton can hop to its neighboring BChl molecule either via the Dexter mechanism, an exchange process involving a direct overlap of the relevant ground and excited state molecular orbitals, or the Forster mechanism (electrostatic in origin, interaction between induced fluctuating dipole moments). The largest hopping matrix elements are between neighboring BChl's in B850, $t \sim 40$ meV. There are claims [14] that this could be as large as $t \sim 100$ meV. In our discussion we will focus on B850 system and will not consider the B800 and Car systems, which have their own important roles. The hopping of excitons from one circular LH to another LH is through Forster mechanism and experimentally the corresponding time scale is large $\sim$10 ps.

One is lead to a tight binding model [14] for exciton hopping on a circular array (periodic boundary condition!). The simplified exciton Hamiltonian for the LH system is

$$H_{\mathrm{LH}} = -t \sum_{\langle ij \rangle} b_i^{\dagger} b_j + \mathrm{h.c.} + V \sum_{\langle ij \rangle} n_i n_j. \tag{1}$$

Here b's are the exciton operators and n is an exciton number operator. Since we cannot create the same excited state twice there is a 'hard core repulsion' among the excitons. V represents an effective nearest neighbor repulsion among excitons.

The above Hamiltonian can be trivially diagonalized for a single exciton state. The eigenstates are plane waves on the circular disc. Some experiments show that even at room temperature, in spite of coupling to lattice vibrations and thermal effects, an exciton propagates coherently over the full LH unit [15]! This issue is still debated [15,16] with some claiming a shorter distance for coherent propagation.

4.1 *Are the excitons 'alone' during their short life time?*

Let us look at the characteristic time scales, as determined by recent experiments. The time taken for a photon to be absorbed by a pigment molecule is $\sim$ fms. The hopping time between two neighboring BChl's in B850 are $\sim$30 – 50 fms. The exciton hopping time between two LH's $\sim$10 ps. From LH1 it takes about $\sim$40 ps to reach an open RC center. The total time taken from the time of creation of an exciton to reach the RC by migration is $\sim$100 ps. Excitons have their natural life time for radiative/fluorescent decay in isolation. *However, in the biological environment the fluorescence decay is considerably reduced*. An exciton, instead of emitting a photon, typically hops to a neighboring BChl molecule or relaxes, because of its coupling to other BChl molecules, phonons, and intramolecular electron correlation effects. An exciton may live as long as several nanoseconds in an isolated LH1 circular complex, for example. If an exciton reaches the $k = 0$ state in an isolated LH1 ring it may live even longer, as a radiative transition to ground state is dipole forbidden.

A given reaction center, after it absorbs energy from an exciton and starts an electron transfer reaction, takes a finite time $\sim$100 ms, before it is ready for the next electron transfer. This is the time taken to 'recharge' an RC with one electron. During this period, depending upon the photon flux available, an average number of photons are absorbed in the light harvesting planar area, resulting in that many number of excitons. It is also known that a BChl in isolation may absorb a photon from direct sunlight at a rate of 10 Hz and

0.1 Hz at lower intensities. Thus about 300 BChl belonging to a given RC center will absorb photons and produce excitons at a rate of 3000 Hz at high light intensities and 30 Hz at lower intensities [9].

An important question is whether the excitons that are created at various times live long enough to meet other excitons, before they are eaten up by the RC. A search in the literature reveals the prevailing belief that during the period between an exciton creation and annihilation at the RC, an exciton is essentially alone; it does not encounter any other exciton.

We believe that an exciton may stay for time scales much larger than nanoseconds, in the biological environment. We suggest that the *rate limiting step for the disappearance of an exciton is the availability of open RC centers rather than fluorescence and other modes of decay*. Shortly we will give an argument for this. If this be the case it is conceivable that within an LH complex there may be more than one exciton for time intervals as long as $\sim$100 ms.

If we use the exciton production rate of 3000 Hz (at direct sunlight) there can be as many as 30 excitons in a given RC complex in a time interval of $\sim$100 ms. Further, excitons will be funneled down to LH1 complex. So we have the fascinating possibility of coherence arising from the presence of many excitons.

We recently learned of an interesting experiment [17], which, according to us [18], points towards the possibility of anomalous life time enhancement. It has been recently observed that in caratenoids, an exciton decays into two 'triplet excitons', which are in a global spin singlet state but otherwise spatially well separated within a Car chain. This is a remarkable consequence of electron correlations in conjugated systems [19]; it has been observed in some other conjugated systems earlier. It is known that triplet excitons have anomalously long life times, of the orders of seconds and minutes (responsible often for phosphorescence phenomenon); their decay into singlet ground states are forbidden by spin selection rules. And BChl also has a similar number of double bonds as Car; while BChl's are closed, Car are open conjugated 'chains'. Any tendency in BChl, for a singlet exciton to be actually composed of two triplet excitons or two 'spinons' will, to that extent increase the exciton life time.

We will digress a bit and discuss the decay of singlet exciton into two triplet excitons, to view it in the light of some modern development. As correctly observed by Tavan and Shulten [19], for a finite conjugated system such as Car the singlet exciton should be thought of as decaying into two spin-$\frac{1}{2}$ domain walls, rather than two spin-1 excitons. It is a remarkable quantum number fractionization phenomenon, in the modern parlance will mean that this singlet exciton is made up of two non-interacting spinons. Quantum mechanically,

$$|1 \text{ singlet exciton}\rangle \approx \alpha\ |2 \text{ spinons}\rangle + \beta\ |2 \text{ spin 1 excitons}\rangle. \qquad (2)$$

Electron correlations in the conjugated systems makes $|\alpha|^2 \gg |\beta|^2$. The two states on the right hand side should be thought of as weakly coupled two spin– $\frac{1}{2}$ or two spin-1 objects in global spin-singlet states, respectively.

We have another reason for our suggestion/hypothesis of anomalous life time enhancement of exciton and also bunching of excitons: *nature having realized a beautiful geometry, where exciton condensation is so natural and easily possible, should be making good use of it to its advantage during evolution, at least in some of its light harvesting systems!*

4.2 *Bose–Einstein condensation in 'confined systems' and phase rigidity*

Excitonic superfluidity is a phenomenon that has captured the attention of condensed matter physicists for a long time. There has been many attempts to photo-create excitons to such a density that they may undergo BE condensation during the short time they live before radiative recombination. Since excitons of semiconductors have effective masses much lower compared to a ^{4}He atom, the BE condensation temperature could be easily of the order of room temperature. If this condensation could be achieved, it is a superfluidity of excitonic liquid characterized by a phase, as in superfluid ^{4}He. Some experimental difficulty or the other has been preventing experimental observation of excitonic superfluidity in a convincing fashion.

We argue that nature offers such a possibility in biological systems at room temperatures, however with some important limitations. The major limitations are effective one-dimensionality of our system and finite size. For example, LH2 is a one-dimensional ring of about 32 BChl molecules. It is a confined system which can hold only a finite number of excitons.

As mentioned earlier, the exciton hopping matrix element is measured to be about 40 meV and some estimates make it as large as 100 meV. This is very interesting from our point of view. If it is of the order of 100 meV then room temperature is well below the 'degeneracy temperature'. Then the condition will be ripe for development of local exciton condensate, provided we have a finite density of excitons.

Further, a simple 1d tight binding system of excitons with nearest neighbor hopping and small nearest neighbor repulsion V, will gain maximum delocalization energy at half filling. The hard core repulsion makes the system essentially a 1d Fermi system which favors half filling in the above model. From this point of view, when the light intensity is high, the excitons will migrate to LH1 and we will have a pool of excitons in a strongly phase coherent state. This can be easily seen from the following discussion.

Our excitons are hard core Bose system in a finite one-dimensional system with a periodic boundary condition. This problem can be mapped onto the 1d spin-$\frac{1}{2}$ XXZ model in a uniform magnetic field, about which we have a wealth of information from Bethe ansatz solution as well as fermionization and bosonization studies. When we have an XY anisotropy in the above system, it has algebraic superfluid order in the ground state and has goldstone mode like 'sound mode' excitations, which gives the ground state a finite phase stiffness.

In the fermionization approach, the hard core boson is converted into interacting fermions, by a Jordan–Wigner transformation and the problem becomes a Luttinger liquid on a finite chain. This description of our exciton systems is also very useful and will be discussed elsewhere.

In general we can say that once we have a possibility of having a finite density of excitons in our light harvesting system the physics of Bose–Einstein condensation in its various forms can manifest itself and lead to some unexpected consequences, which perhaps have important biological functions. When the intensity of incident light has a large variation, pooling of excitons and condensation phenomena could have interesting regulatory roles in photochemical reactions. A very interesting possibility is the entire 2d system of LH complexes behaving like a 2d Josephson lattice – every LH unit has a finite number of coherent excitons and the phases of individual LH units are coupled through Josephson coupling. This could lead to remarkable collective states of the entire light harvesting complex and so on. We hope to elaborate some of these ideas in a forthcoming article.

5. Conclusion

Nature is remarkable. In astrophysical contexts with its myriad stars, galaxies, clusters and black-holes, nature fascinates physicists. It is the study of planetary motions that culminated in the enunciation of Newtons laws of mechanics, universal theory of gravitation etc. While in the down-to-earth situation, we have the living system that fascinates us. We argued that it is a complex condensed matter system and much more. Even a limited recognition or myopic view of living systems, as a complex condensed matter system, gives at once a handle to look at, understand and speculate about biological phenomenon and in turn enrich condensed matter physics. Condensed matter physics – biology resonance [20] is beneficial for science.

As I was finishing this article, a letter [21] entitled 'Snapping shrimp makes flashing bubbles' in a recent issue of *Nature* caught my attention. I did not suspect, in spite of my hypothesis, that 'sonoluminescence', a remarkable condensed matter phenomenon observed in liquids (discovered in the last century), where sound is converted into visible light, is known to biology as long as snapping shrimps ever lived on the earth or elsewhere.

Acknowledgement

It is a pleasure to thank Narendra Kumar who, during my graduate student days enthused me into, among other things, interesting issues in biology, with his characteristic attitudes and inspiring style that removed barriers between physics and biology, and between a student and teacher. I thank Arun Jayannavar, whose perseverence has made the present paper see the light of the day.

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