Condensed Matter Physics - Biology Resonance

G. Baskaran[‡]
Institute of Mathematical Sciences
C I T Campus
Madras 600 113, India

The field of condensed matter physics had its genesis this century and it has had a remarkable evolution. A closer look at its growth reveals a hidden aim in the collective consciousness of the field - a part of the development this century is a kind of warm up exercise to understand the nature of living condensed matter, namely the field of biology, by a growing new breed of scientists in the coming century. Through some examples the vitality of this interaction will be pointed out.

I. INTRODUCTION

'Condensed Matter Physics' (CMP) is a clever name for the study of any form of matter that is condensed - liquids, solids, gels, cells, superfluid He4, quantum Hall liquid etc etc. The folklore is that the name 'Condensed Matter Theory' was coined in Cambridge in the 60's in the solid state group that involved people like V. Heine and P.W. Anderson. Of course, before this field was christened it existed, on its own right as solid state physics and related fields with very many significant developments to its credit - the new name gave it an added identity and perhaps a new purpose.

Physics, a part of Natural Science, is an experimental science. It gains its strength from experiments, observations, theorizing, and impact on technology and society. CMP has a special place in physics because of its closeness to a multitude of feasible and often novel experiments. This feasibility is intimately tied with the wealth of matter and associated phenomena around as well as the development in the field of material science and in turn technology - both low and high tech. Elegant concepts from quantum physics, statistical mechanics, mathematics are combined alive so that it continues to produce surprises and new phenomena and new concepts. This field is also a source for innovative new experimental methods that has extended human 'senses' to atomic scale - modern x-ray crystallography, NMR, neutron scattering, spectroscopy, scanning tunneling microscope and so on.

The aim of the present article is to provide a point of view that this field has grown, partly with an aim to address deeper issues in the field of living condensed matter namely biology; and a century of efforts is really a warm up exercise towards this difficult goal. The point of view I am providing is perhaps obvious - my main message is that a true resonance between the two fields is something that is natural and so likely to happen or has already begun.

II. NATURE OF CONDENSED MATTER PHYSICS

CMP is diverse and complex. It addresses issues such as why silicon has a diamond like structure using quantum mechanical considerations, or the growth dynamics of snow flakes, or the electrical conduction in carbon nanotubes. There is CMP in the field effect transistor, modern computer chips and the sensitive SQUID magnetometer that detects the feeble electrical activity that goes on in our restless brain.

The field is messy but rewarding. Quantization of Hall conductance, that won 2 Nobel prizes, occur amidst disorder and interaction. While the field is diverse, there are powerful unifying notions and ideas: spontaneous symmetry breaking, order parameter, renormalization group, complex collective behavior, quantum coherence, chaos etc. The idea of renormalization group is an an example that has grown out of the study of condensed matter systems such as liquid-gas phase transition and Kondo problems - it has far reaching application potential including possibility of understanding some hierarchical structures in biological systems to turbulence in classical fluids.

The field of CMP possesses a deep working knowledge of quantum mechanics, both in theory and experiments. This gives it an unique strength and also makes its relation to biology special. The stability of atoms, the origin of chemical bonds, electron transfer, proton tunneling etc. in biology are truly quantum mechanical. However, it is fair to say that some mysterious leaking of quantum effects to some unexpected aspects and domains of biology (such as the origin of consciousness), apart from the above obvious ones. are distinct perhaps remote possibilities. CM physicists will not accept such suggestions uncritically, but will have a natural edge in unraveling those which turn out to be meaningful.

Physics gains its predictive power and becomes a quantitative science because of the powerful use of mathematics - analysis and approximations intertwined with physical insights, order or magnitude estimates, dimensional analysis and many modern mathematical ideas such as homotopy theory, group theory, algebraic geometry, functions of many complex variables etc. In view of the remarkable developments in computers computational CMP is becoming very popular and powerful. Often you can do a computer simulation or experiment and create situations that you find it hard to create in the laboratory, or study analytically.

I alluded to the complexity of the study of condensed matter. This gives it a remarkable ability to suggest new paradigms through its emergent character [1], that could be helpful elsewhere. The last several decades have seen some of them: i) spin glass and neural network, and ii) self organized criticality, power laws etc. These notions may not have solved the real problem of biology - but they are some new windows for physicists to look at this totally new world of biology. The wealth of phenomena in condensed matter is sure to provide seeds of new paradigms provided we look for them and and develop a sensitivity to abstract them.

III. NATURE OF BIOLOGY AS A SCIENCE

Like physics, biology is truly an experimental science. Most of the problems in biology are far too complex, at the moment, to be analyzed threadbare, the way we do in physics with some problems, using our existing knowledge and concepts of physics, chemistry and mathematics. However, after the revolutionary beginning of the field of molecular biology [2] at the middle of this century, biology has taken a new shape, and looks comfortable even for a physicist to look at from a distance. Very general principles like Darwin's natural selection to very specific structure and function relations in DNA, proteins, etc. are dominating the field currently. There are also many dogmas, hard earned hypothesis and working principles that pervade this truly diverse field - protein structure, signal transduction, brain function to name a few. Thanks to the experimental tools like x-ray crystallography, electron microscopy, NMR imaging, ATM, STM, optical tweezers and so on, that actually came from physics, the field is undergoing revolutionary development.

The urgent problem facing a hard core biologist is often very different from what a physicist, genuinely interested in biology, is capable of solving in a short time period. This is the reason many biologists sincerely feel that physicists can not solve the mysteries of biology. On the other hand, physicists like Schroedinger, Max Dellbruke, Crick, Hopfield and others have made truly original contributions and opened up new directions. It is becoming clear that physics is not just providing experimental tools to other fields such as biology, it is evolving capabilities and insights to understand the spirit of biology.

IV. SOME EXAMPLES

Having made several general remarks let me indicate some examples, based on my one decade of a distant admiration for biology - it is so distant that biology does not know that I am dreaming of her !

Brain

A brain would naturally like to think about how it thinks; why grey matter-a large piece of condensed matter possesses consciousness, self awareness, minds eye-I etc. Physicists have no clues as to how the laws of quantum mechanics, thermodynamics or even quantum gravity for that matter, leads to these profound properties in a living state of condensed matter. After listening to an illuminating talk by John Hopfield on neural network and associative memory [3] in the fall of 1987 at Princeton, I thought, in a moment of weakness, that I understood the physics of the mind ! - soon to realize it is far from it.

It is becoming increasingly clear that all our understanding of spin glass physics, that came from partly the study of a dilute concentration of magnetic impurities in an otherwise pure gold, has only landed us somewhere at the plains of the Himalayan range, we have to scale Mount Everest. The concept of network, basin of attraction, possible hierarchical or ultra metric organization of attractors, are all but words in constructing a long poem. This became clear to me, when I participated in an Institute of Theoretical Physics, Santa Barbara workshop on 'Neurobiology for physicists' in the fall of 1987, where neurobiologists humbled us with mind boggling biological and clinical facts about the brain. But, at the same time, our successful understanding of the neural network of sea slug, an organism that has few hundred neurons, gives us hope that perhaps one day we can understand mammalian brain, with all its complexities and hierarchies. It is clear that all our efforts so far has been a warm up exercise.

Gene

The next example is from DNA. I was surprised, like my colleagues, by the findings of some physicists [4] that DNA of various living organisms possess some kind of long range or power law correlation in its nucleotide sequence - that is, the probability that two nucleotides separated by n bases in a strand of DNA, will be both adenine for example, is $\approx \frac{1}{n^\alpha}$. It was claimed that the exponent α is species dependent - a one parameter characterization of a species at the level of nucleotide sequence in DNA !

Soon it became clear that things are much more complicated - there are introns, the non coding genes, tandem repeats and so on that make this long range correlation not very meaningful or insightful. However, it gave an opportunity to many physicists like me, to get a glimpse of the world of biology with problems that are even more challenging than the power law correlation in the nucleotide sequence. Genetics is full of many surprises - gene replication, gene repair, translation, gene regulation etc. All my initial enthusiasm to model the DNA as a one dimensional 4 state Potts model with long range interaction and frustration soon gave way to other glamours of biology.

Gene regulation is a fascinating subject. This is what controls the shape of a blue whale or a butterfly, in its growth, by a profound regulation of the production of various proteins, at various cell at different times starting from the first zygote (formed by the union of a sperm and an egg) cell. It is a network that is very different from the neural network or immune network or the spin glass or glass. At the same time it is a network that should posses some general characteristics of any large networks - this is what prompted Kaufman, for example, to invent a Boolean net to model gene regulation [5].

Physicists have come across some networks and learned some general principles - network of dislocation that controls the mechanical properties of solids under stress, shape memory alloys, glasses and spin glasses. Thanks to experiments that guides the theoretical developments hand in hand, we have gained some insight and useful notions have been developed [7]. Erstwhile Condensed matter physicists, and my ex collaborator Shoudan Liang is deep into genetic net and Stan Leibler and Naama Barkai are deep into biochemical nets apart from other involvements. But all our insights from CMP are truly warm up exercises at the base camp.

Electron and exciton transport in biological systems

Szent-Gyorgyi, an eminent biochemist, speculated on the importance of electron transport in biological systems including DNA. He along with others have speculated that it could hold some of the the secret of carcinogenesis. Possible connection to cancer apparently got a lot of (unjustifiable ?) funds - that is a different story. The point is that the lightest of charged particles in biology, namely electron, is involved in too many vital activities. Within proteins electron transport is well studied in biology for the last many decades. There are reaction centers, typically a prosthetic group such as a porphyrine complexing a metal ion, embedded in protein. On absorbing a light quanta the reaction center releases an electron that tunnels through a couple of tens of angstrom distance through the folded protein before it is absorbed by another special complex, just to trigger another reaction; then it continues sometimes ending up in an ion transfer across the membrane, if it were a membrane bound protein.

Electron transfer in biological system, even though it takes place at room temperature, is clearly a quantum mechanical phenomenon. The theory of Marcus and its generalizations have been used for quantitative estimates of the reaction rates. Our experiences with electronic conduction in semiconductors, metals or in general crystalline materials, where Bloch's theory applies is only a warm up exercise to handle this special disordered system. Condensed matter systems such as amorphous materials where Anderson theory of localization applies looks too simple and less structured compared to the mesoscopic biological proteins. We have a disordered peptide bond skeleton along with the amino acid side groups that have considerable number of π electrons, where the electron correlations are important. That is there is more structure including some significant vibrionic couplings and electron correlation effects. Most of the present theoretical efforts I have seen are one electron type that are computer intensive. Are we missing some subtle effects, including the correlation effect in the π electron pool of the porphyrine rings ? I think only experiments have to give an answer to these questions through possible anomalies. It is interesting that even a diamagnetic response of a pool of π electrons of planar aromatic ring compounds show interesting surprises through correlation effects, a subject that worried people like Pauling, London [6], K S Krishnan and some in the recent times.

One hears of new experiments where electron transfer along the DNA double helix has been seen [8] indirectly in some experiments. Its possible relevance in biological functions is an obvious next question. Physicists with their warm up exercise and training in condensed matter can hope to scale the mountain after knowing many biological details and with help from future experiments.

Structure and function are catch words in biology often used at the level of DNA or enzyme functions. In a different context, in bacterial photo synthesis certain geometrical arrangement of porphyrine complexes have given new insights into mechanism of energy transport by exciton. The structure of the basic unit of the so called light harvesting complex has been deciphered a couple of years ago [9]. There are two types of ring complexes one containing one concentric circle of 18 porphyrine molecules that are stacked in a circle like slides in a circular slide box. The other contains two concentric rings with the reaction center complex at the center. These ring complexes are organized on the surface of the cell in some quasi periodic fashion. The incident photon is absorbed by the porphyrine to create an exciton which propagates to end up in the reaction center to activate an electron transfer reaction. To this complex geometrical arrangement one can apply, as Ramakrishna and myself attempted among others [10], our knowledge of exciton transport in molecular crystals. Already there are many surprises - one always felt that the exciton transport is an incoherent hopping process at the physiological temperatures. But within the ring complex the exciton transport has been shown to be coherent experimentally and theoretically. Our feeling is that between the ring complex also , through Forster mechanism, there is some coherence and possibility of new physics.

What is remarkable is that the photo synthetic apparatus of the purple bacteria, is probably the simplest of the lot. When we come to even simple algae and plant leaves, the photo synthetic apparatus is much more complex and structured, with light guides and so on. In many of these cases we do not know in detail the basic structural units and their organizations - apart from circular complexes there are cylindrical complexes and light guides. What we have learned in CMP as exciton transport in semiconductors or molecular crystals is truly a warm up exercise when we come to this very complex photo synthetic apparatus.

Regulated self assembly

Periodic structures are very dear to condensed matter physicists. We study how these structures change when we heat a solid or how a beautiful sugar crystal grows from a tiny nucleus in a concentrated sugar solutions. There is plenty of physics and statistical mechanics. Some times there are even quantum effects like in the case of Helium solids or solids of light elements such as Li.

In biology very rarely do we come across periodic structures. Since the structure of proteins and DNA imply important functions, evolution has not chosen structures that are manifestly periodic. However, there are remarkable regular, sometimes symmetric and hierarchies of structures. For example if we look at the virus T4, there are a few types of basic proteins that make up the so called pro head - a complex of proteins that has icosahedral symmetry that encapsulates the viral DNA. Then there is a neck, again made up of protein complexes and a body (that looks like a bit of micro tubule) - a cylinder made up of proteins and the legs made of proteins. This tiny little 'robot' is different from a periodic crystal. However there is some regularity in its making.

And condensed matter physicist is tempted to wonder about the assembly of this complicated macromolecular robot. The physics is not exactly that of the growth of a sugar crystal. It is a self assembly that is regulated. It is non equilibrium statistical mechanics that is embedded in a signaling network.

The regulated self assembly is a new notion that is very unique to and ubiquitous in biology. The above is only an example of the many hierarchical structural organizations that one comes across in biology - morphogenesis, micro tubules, myosin complex, collagen fibers, fibrils etc.

In fact I learned about this notion of regulated self assembly during my sabbatical at Princeton in 1996, in a Cell Biology course organized by Stan Leibler and Frank Wilczek. It became clear in that course, that had distinguished attendees like Curtis Callan, Stephen Adler and others, that there are many challenging and profound problems. We physicists returned spell bound at the end of every class on learning new wonders in cell biology and felt the need for serious investigations by many physicists.

Finally a word about some macro molecular structural changes in biology. Structural rearrangements in biology are in plenty. A heme protein, as soon as it gets an oxygen, undergoes a conformational change so that it can bind the second oxygen more easily and so on. An allosteric protein like the motor protein, once it gets an ATP undergoes a massive conformational or structural change, that is like an elementary step in walking. Our well known notions such as soft modes or anharmonic interactions that we are used to in structural changes in simple solids, are far from sufficient to understand even the simplest macro molecular structural change - we have to think afresh. People like Frauenfelder, Austin, Stein, Wolynes and others have made a start at this.

V. CONCLUSION

The trend of many condensed matter physicists taking a serious look at biology is visible for a long time. One also hears of new Institutes and ventures like Santa Fe Institute which catalyses new kind of activities and exchanges. In a special section devoted to 'Complexity Science', a recent issue of Science [11] enumerates about a dozen Universities and Labs in the United States trying to set up new across the disciplinary ventures involving physics and biology departments, just at the turn of this century. This has started happening in a natural fashion in developed nations like the US or Europe. The developing countries will do well to recognize this and participate and contribute to this resonance and redefinition among disciplines in science.

When the condensed matter physics - biology resonance touches the spirit of biology, the nature of progress will be substantial.

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‡ Baskaran@imsc.ernet.in

[1] P.W. Anderson, Science **177** 393 (1972)

[2] see for example, J.D. Watson et al. Molecular Biology of the Gene (Benjamin/Cummings Publishing Co. 1987); B. Alberts et al. Molecular Biology of the Cell (Garland Publishing Inc., 1994)

[3] J. J. Hopfield, Proc. Nat. Acad. Sc. (USA) **79** 2554 (82); G. L. Shaw and R. Vasudevan, Mathematical Biosciences **12** 207 (1974); W.A. Little, Mathematical Biosciences **12** 101 (1974)

[4] C.-K. Peng et al. Nature **356** 168 (92); R. Voss, Phys. Rev. Lett. **68** 3805 (92); Maria de Sousa Vieiera, cond-mat/9905074

[5] S. Kaufman, The Origin of Order (Oxford University Press, 93)

[6] F. London, Phys. Radium **8** 397 (1937); see for some modern works, Y. Anusooya and Z.G. Soos, Current Science **75** 1233 (1998)

[7] Dynamical Networks in Physics and Biology, Les Houches School, Ed. D. Beysens and G. Forgacs (Springer 97)

[8] Hans Werner Fink and C.Schonenberger, Nature **398** 407 (99)

[9] M.Z. Rapiz et al. Trends in Plant Sciences, **1** 198 (96)

[10] V.I. Novoderezhkin and A.P. Rajivin, Chme. Phys. **211** 201 (96); Ivan Barvik et al., Chem. Phys. **194** 117 (95) and a preprint; S. Ramakrishna and G. Baskaran, unpublished

[11] Special section on Complex system Science, Science **284** 79 - 107 (1999); S. Arunachalam, Current Science **76** 1191 (99)