W(h)ither solid state physics?

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The physics of the solid state has grown into that of condensed matter and is now expanding into the study of a bewildering variety of complex systems. After a brief survey of this progression, I enquire into the health of solid state physics; many signs of vitality and growth are found. The Indian scene in this field is briefly sketched, and some suggestions are offered on how to make it more lively.

Background

Till about a generation ago, solid state physics was concerned mainly with crystalline solids, which could be metallic, semiconducting or insulating. They were investigated from many points of view, e.g. for an understanding of different kinds of order such as magnetism, ferroelectricity or superconductivity, or because of the practical importance of semiconductors. Isolated defects such as impurities, vacancies and dislocations were investigated, often because of their drastic effects on electrical, optical and mechanical properties of solids. A number of probes such as X-rays, light scattering and absorption, and nuclear resonance were standard issue. The wealth of new phenomena, materials, experimental techniques, concepts and applications, each driving the other led to an explosion in this field over the fifties and sixties. The field of condensed matter physics, described now as 'the fundamental science of very large number of strongly interacting parts' was born out of this growth, and recognized as the major enterprise in physics about a decade or more ago. This area encompasses the study of solids, liquids, liquid crystals, dense plasmas, glasses, polymers, gels, etc. With other major inputs, e.g. from the theory of nonlinear dynamics, and realization of parallels with phenomena in several other branches of science, a new attitude and a clutch of approaches called the sciences of complexity is emerging.

The above developments can be caricatured in terms of several dichotomies, e.g. quantum vs classical, hard matter vs soft matter or limited domain vs unlimited domain. These, especially the last, have led to a perception that solid state physics is passé, a relic of yesteryear. Such a perception is far from reality, as I point out below by giving many counterexamples.

Some signs of life and growth

High temperature superconductivity

The most spectacular sign that the field of solid state physics holds major surprises comes from the discovery of high temperature superconductivity in an unlikely family of materials. This eight-year-old discovery has led to an unprecedented level of focused work on a single family of systems. The major driving force is clearly the hope of large scale practical applications. But since these applications depend on our control of materials and understanding of their properties, basic science namely chemistry, physics and materials science is a necessity.

It is an indication of the richness of the field that new effects continue to be discovered aplenty in several reaches of it. Just in the subfield of the mixed phase in a magnetic field, many unexpected phenomena, e.g. flux lattice melting, quantum creep, vortex glass, anomalous Hall effect, dimensional crossover, giant low temperature upturn in the higher critical field and columnar defect pinning have been discovered. Many of these are not well understood.

Overshadowing all is the general realization that the cuprate metals are metals qualitatively unlike others. Does this have its origin in strong correlations in oxides and how? What is the connection between the abnormal behaviour of these metals and high temperature superconductivity? These are some of the major unanswered questions in the field. Clearly the answers are difficult to come by. At the most recent conference on high temperature superconductivity in Grenoble (July 1994), there were many new and interesting experimental results, and the general impression was one of progress in the quality of materials and in the experimental questions asked and answers found. However, the various theoretical efforts seem to have reached their peak without a generally accepted comprehensive solution.

Quantum Hall effect

Again in the last decade, the spectacular quantization of the Hall conductance of a very clean degenerate gas of two dimensionally confined electrons in a very strong magnetic field has introduced us to a new state of matter with exotic properties such as fractional statistics excitations. The last few years have seen unusual phenomena such as even denominator QHE and the edge states which behave like a chiral one-dimensional Fermi system. Smouldering in the background are older questions like the effect of strong disorder and the transition from Hall fluid to an insulator at low density.

A number of bold new ideas have been developed to describe the phenomena observed, but there is both a sense of some incompleteness in the description, and of surprises yet to unfold.

Mesoscopic systems

Due to our increasing ability to engineer atomically controlled mesoscopic systems ($l < 200$ Å) and measure their properties, single electron and other quantum behaviour have become quite accessible in the laboratory. Single electron transistors, electron turnstiles, Coulomb blockade, conductance quantization and fluctuations are some of the new observed effects (one family of such systems, namely quantum dots, is discussed by Tapash Chakravarty).

Quasicrystals

This class of solids, discovered a decade ago, was considered surprising because of its very existence. In the last four or so years, after the identification of families of stable quasicrystals such as $Al_{62.5}Cu_{25}Fe_{12.5}$, the intrinsic electrical/electronic properties of clean stable quasicrystals are being studied for the first time, and reveal very strange features. One, for example, is the fact that the cleaner these alloys are, the higher their resistivity! Their low temperature resistivities are orders of magnitude higher than those of any alloy with comparably high electron density, i.e. are much larger than the appropriate Mott maximum metallic resistivities. (These systems, and the Indian work in the field, are reviewed by S. Ranganathan).

Fullerenes

Systems made out of C_{60} and related molecules, discovered five or so years ago, are an unusual family of molecular solids. The intramolecular interactions are stronger than intermolecular ones. On doping with alkali metals, the resulting metals go superconducting at fairly high temperatures. This discovery has again opened up a whole new solid state world, as described by C. N. R. Rao in the meeting.

One could mention other areas such as heavy fermions (reviewed by S. Ramakrishnan and Girish Chandra), low dimensional solids (touched upon by S. V. Subramanyam in his survey of molecular electronics), the fundamental electronic quantum transition from metal to insulator (see A. K. Raychaudhuri's contribution), etc. The main point that emerges is the plenitude of new phenomena and systems. These are indications of what lie ahead as our ability to engineer new materials and structures improves, and as our experimental tools become more powerful. It is also clear that new ideas and theoretical methods are often required. Against this background of vigorous activity in solid state physics, which continues to be a major scientific centre for the physics of condensed and complex systems, where are we?

The Indian scene

Here, I shall restrict myself largely to theoretical solid state physics, mainly because the situation in experimental physics has been extensively discussed by a number of colleagues. That condensed matter science is experiment driven needs no emphasis. The following features of solid state theory activity are apparent. There have been several interesting individual contributions. The single area that has seen major activity is the theory of high temperature superconductivity and of strongly correlated electronic systems. In this field, several Indian physicists have done significant and sometimes crucial work. There are, however, no major local initiatives; very few lines of work can be identified as having originated and grown here. There is also weak coupling between theory, and experiment done here (or even elsewhere, in general). Finally, much work in the area of solid state physics seems mired in the past, not just in language, but also in terms of ideas and areas of interest. All the above add up to a somewhat unsatisfactory state of affairs. In what follows, I shall concentrate on two questions, and suggest answers. The first is the problem of inadequate scientific manpower. The second is of scientific emphasis or direction.

Manpower

The problem. One of the most critical problems facing the condensed matter community as a whole in India is the paucity of *quality* manpower both at the level of working professionals and of students entering the field. The number of Indian physicists getting their Ph D at a high level of professional quality (not to speak of imagination and independence) is small both from within the country and without. Thus the human resources available to us are small. They need to be opti- mally used, and to be multiplied. As an illustration (Table 1)

Table 1. Comparison of physics faculty members in major Indian and comparable US universities/institutions

	Period 1967–68		Period 1988–89	
	India	US	India	US
Condensed matter theory	≤ 10	278	~ 45	691
High energy theory	≤ 30	319	~ 85	499

of the problem, I present in Table 1, the number of faculty members at nominally comparable major universities/institutions in two areas of theoretical physics (condensed matter and high energy) at two different times (1967–68, 1988–89) and two different places (India and the US). For India, the numbers are guesses, and for the US they are from an American Institute of Physics report. Several conclusions are obvious. Firstly, that if the numbers in the US reflect 'market' forces, condensed matter is the most promising or fruitful area of theoretical physics. Secondly, that in our country, the slope is good, but the numbers are still far from optimal. There is a real and urgent need to increase condensed matter theory strength in the major research-oriented institutions. Analysing the increase in condensed matter theory faculty strength in more detail, one finds that they have taken place in institutions such as the DAE-supported ones. Universities and IITs with a few exceptions, seem unresponsive to changes. This is really a pity, because the former have at best a small flow of students while the latter have a large multiplier effect due to MSc and PhD students etc.

Another crucial aspect of the manpower problem is the fact (known to all in the field) that the number of students with the right mix of ability, motivation and training opting for research in solid state physics is small. This is clearly a part of the larger problem of undergraduate science education. It may well be the most serious limitation in the long run, and needs to be addressed comprehensively soon by providing attractive, high quality undergraduate science education.

Suggestions. There is an immediate need to increase the number of sizable groups in solid state theory (of size greater than five or so) to something like eight or ten. At present there are perhaps four or so such groups. This expansion is necessary given the spread of the subject. The effect of having a number of *sizeable* groups will be apparent in the quality of intellectual stimulus it provides and in the quality of student training. At least two things should be kept in mind if such a deliberate expansion is attempted. Firstly, one should concentrate one's efforts on a few universities and IITs where such groups can be either grown around existing nuclei, or nucleated. This is obvious because of the multiplier effect via students, but has not been carried out because of practical difficulties. If it is done, physicists who come out of such groups will be a source of locally equilibrated manpower of high quality. It is also mutually advantageous to have theorists as organic part of or as complement to large (new or old) experimental centres or groups.

Without such a conscious and serious active effort (*even more* in experimental solid state than in theory) solid state physics may indeed wither in India. In experimental solid state physics, as pointed out by a number of speakers, in addition to manpower, the crucial issue is lack of comprehensive financial support. Unless stable funding for major areas such as semiconductor physics/optoelectronics, low temperature physics, molecular solid state (in addition to soft condensed matter) is made available, we will not be able to practise in this area of physics.

Whither solid state physics?

The other part of the question in the title, namely, whither solid state physics, is harder to answer. In the introduction, a few areas of activity are mentioned. A number of others have been dwelt upon extensively by other authors. I would like to make a few tentative remarks which may be pertinent for us as a community.

There is a very great need to focus on nonfashionable areas with scientific depth and possible or actual local strength (i.e. *to do your own thing*). One cannot obviously give a list of such problems. Some illustrative examples connected with theoretical materials science are the following. The properties of many solid materials are determined by intermediate level structure, its kinetics and stability. Examples are say the microstructure of steel, or relatedly the martensitic transformation. The existing approaches are either too detailed ('atomistic modelling') or too coarse ('elastic continuum') and in either case too unimaginative. A dynamical theory with just the right degrees of freedom could clear up many long standing mysteries and stimulate observation of new phenomena. Another example is the statistical mechanics of objects with tetrahedral building blocks. Silica, with corner sharing (SiO_4) tetrahedra and many phases, and silicate minerals which are structurally related, are examples of the rich variety possible with such simple units.

An advantage (!) of not being at the centre of the scientific world is that one can try harder problems. Often, in condensed matter theory as elsewhere, problems are shelved, not solved. This has to do with useful levels of description, namely the fact that pressure of experimental results leads to insightful working models which may or may not be comprehensive, or connected with microscopic theory. Thus, in many areas of solid state physics, the remaining questions are often substantive, and not confined to refinements or nitpicking.

Finally, the solid state theorist can do something useful, that is, work closely with experimenters. As experimental activity expands, there is need for a lot of professionally serious theory in areas such as heterostructures, quantum dots, alloy phases.

I believe that given the depth and vitality of the subject, and the sense of reality of its practitioners, solid state physics has a large future in India.