Metal–insulator transition: A low temperature perspective

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We discuss briefly some of the basic issues involved in the field of metal–insulator transition. We point out why this area is a profitable area of research. We also suggest certain definite action plan for this area in particular and the area of low temperature solid state physics in general.

The subject of metal–insulator (m–i) transition is definitely a topic of considerable current interest. It is an area of research where in the last three decades a good deal of progress has been made both experimentally and theoretically but the main issues still remain unsolved. It is also an area where one needs expertise from different sub-areas of condensed matter physics and different techniques to look at the phenomena. In one sense the statement of the problem is very simple: how a metal (with extended electronic states) becomes an insulator when some parameter like pressure, temperature or composition is changed. If we exclude such structure-driven transitions like band structure change due to change of crystal symmetry, the phenomenon is an electronic phenomenon. The electronic aspect of the transition can be approached from two sides. We can make a metal an insulator in two distinct but not mutually exclusive ways. We can either make the density of states at the Fermi level ($g(E_f)$) go to zero and open up a gap at the Fermi level (E_f) or we can have a finite density of states at E_f ($g(E_f) \not\subset \neq 0$) but can make the mobility or diffusivity (D) go to zero. It would have been a much better situation if the real world m–i transition can be put into such distinct categories. In reality one finds both $g(E_f) \to 0$ as well as $D \to 0$. This makes the problem difficult but fascinating and that precisely is the challenge in the whole field. In the terminology of the field, one calls such transitions Mott–Anderson transitions, a small tribute to the contribution made by them to bring physics into such a field which otherwise would have been a catalogue of observations which are interesting and complex but at times confusing and misleading. (Another aspect of m–i transition is percolation. It is reemerging in recent years with new perspectives and promise of new understanding.)

This field is rich in phenomena. This is because a number of different but nearly similar energy scales govern the physics. The predominant energy scales are the band width (B), the on site Coulomb repulsion (U), the long range Coulomb interaction (E_r), the magnetic exchange energy (J) and disorder (W). (In addition, in transition metal oxides charge transfer energy (Δ_{ct}) is a relevant scale. Often crystal field splitting (δ_{cf}) is also important because it decides the spin configuration of transition metal ions). The region of particular interest where we think significant new physics can emerge is the so-called critical region where all the relevant energy scales are well balanced and the behaviour of the material is neither of a metal nor of an insulator. This interesting region shows up in a large number of experiments which thus can be used to probe this region.

What is the physical object we are looking at? We are trying to understand the physics of a fairly dense electron gas (electron density $n > 10^{20}$ cm^{-3}) whose diffusivity D is very low. The electrons are strongly interacting with each other. The screening length diverges and the screened Coulomb interaction is giving way to long range Coulomb interactions. Local moments are forming and are making their contributions by spin polarizing the electron clouds around them. There is strong scattering limiting the quasi particle lifetime. In all probability the simple Fermi liquid description of the electrons is either severely modified or ceases to be valid. It is if anything a 'quantum soup'.

Where does low temperature come into the problem? Near the critical region, as pointed out earlier, various energy scales are balanced. On the one hand the kinetic energy is trying to make the system metallic and on the other hand potential energy is trying to localize the electrons. In such a situation if one wants to fine tune the transition and come closer to the critical region, smearing coming from thermal energy has to be reduced to a minimum. In fact if we want to make out if a solid in this region is metallic or insulating we have to study the solid at low temperatures. In fact this area holds immense promise for low temperature experimentalists if they want to do unbiased experiments with no intention to prove or disprove this theory or that. The necessity today is to have well thought of ideas for experiment with a good blend of very interesting physics concepts that have become available in the post high T_c era.

Two questions come up immediately:
(i) Is this an area we should work on?
(ii) If yes what is the reason and what is the action plan?

Before I answer that let me just say in a general context what my criterion of good physics is and what the criterion in the special context of Indian situation is. Good physics should be rich in distinct phenomena with a promise of new concepts. It must have a sense of original thinking. It should lead to good, imaginative and precise experimentation as distinct from mindless measurement of different permutations and combinations of the periodic table. It should throw real challenge at theoretical physicists. In the special context of our country good physics should have a few more crieteria. It should have more experimental aspects to it and should make sure that it leads to growth of experimental techniques. Experiments should be doable in a finite time given all the resources and infrastructure constraints. In other words it should be cost effective so that too much investment is not needed for too little an output.

The area of metal to insulator transition therefore has all the criteria of good physics. Being rich in distinct observable phenomena one need not search for second order effects. Since there are a number of open and fundamental questions one can make significant original contribution. The experiments, even if they have to be done at low temperatures, do not need mega projects. Also they are accessible to at least some laboratories in the country. In addition, there are certain features of this area which make it even more attractive. Since different experimentations are needed, more than one group can work on this problem in tandem leading to a healthy collaborative atmosphere. This may in fact become a part of a well-focused national project on this general area with different groups with varied expertise becoming united on a common physics platform. This will lead to definite and conclusive work and will put a sense of identity and bring in visibility in the international scenario. This will be particularly helpful for smaller groups and young groups trying to establish themselves. Another very strong point for this area is possible availability of first rate support from extremely competent theoretical physicists if they can be oriented to look at experimental results produced by local experimental groups.

We may now think of an action plan for this area. I would list them below:
(i) Identify groups with common interest in this area who can together initiate a focused activity for a period of four to five years. The common point will be the physics of m–i transition and the common work plan will have the goal of utilizing available expertise towards solving certain aspects of this general area.
(ii) Make certain that a reasonable level of funding is available for improving and strengthening these existing groups.
(iii) Set up at least two common facilities in the country where researchers from universities in particular can come and do basic low temperature experiments to temperatures well below 1 K. One of these facilities should have access to high magnetic fields in the range of 15–17 T. This will create a broad experimental awareness in the country in a very vital area and will not limit the participation to only select places. The concrete examples of Nuclear Science Center in New Delhi, Inter University Consortium at Indore and the FT-NMR facility in Bangalore clearly show that such an approach to low temperature solid state physics will go a long way to help the experimentalists of this country. However, we have to be careful that we are not talking of industry. The facilities, if they are set up, have to have a certain set of active researchers in mind who have some immediate problems in hand to solve. It cannot be run in a 'Mail Order' format, because in such a format we cannot have growth of experimental physics. It may degenerate into just data generation, something which we all want to avoid.

We are not talking of a big expenditure but an affordable one which will benefit more than a few groups and can initiate action in experimental areas where we can make visible and original contribution to science. Maybe the time is now to act and act with confidence!