Instrumentation for condensed matter science—Small and large

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In this article I try to focus attention on a few aspects of this vast subject, to the extent that I am aware of. I shall first comment on status of physics instrumentation and therefore experimental technique in India pertaining to condensed matter science and towards the end on some instrumentation for planning future programme in our country.

Condensed matter physics instrumentation

Unlike high energy physics or nuclear physics which are concerned with creation of new particles or reaction products and studying their energetics, condensed matter physics deals with study of different types of response functions from a material to selected probes. Broadly speaking, one can classify the study of the response functions into two categories: one, measurement of bulk response functions and another differential response functions. Stated in a different manner, one is dealing with measurement of macroscopic and microscopic properties of a system. Both studies are essential in the sense that they are complimentary. Nuclear magnetic resonance or muon spin resonance etc. may by considered to belong to the former category; X-ray diffraction, neutron scattering, Mössbauer spectroscopy, etc. belong to the latter category. While one set of studies may relate to, say, study of relaxation times or specific heat or magnetization, the other corresponds to detailed space-time evaluation of the atomic, molecular or electronic constituents of the material under study. The short space-time behaviour is realizable by one type of measurements while the medium or large space-time behaviour can be ascertained by the other. All material properties originate in the atomic structure, dynamics and electronic behaviour at the microscopic level. So, as far as the structural and dynamical behaviour are concerned one can think in terms of a 'small' or 'large' time and space behaviour and total comprehension has to be sought by combination of experimental studies based on widely different principles and techniques.

However, when we think of the experimental techniques or facilities for measurements themselves, one will find that the information comes from instruments which may be very similar or very dissimilar as far as, say, size, cost or infrastructural requirements/facilities are concerned. For example, the magnetometers which can provide data covering magnetization at very low temperatures of the order of liquid helium temperature in presence of high magnetic fields, say, of strength 5–7 tesla or a FTNMR facility or a laser Raman spectrometer that gives data on vibrations of atoms and molecules, a scanning electron microscope that can image at atomic resolution can all be of similar size, cost and need similar infrastructural facilities. On the other hand, an X-ray diffractometer and a neutron diffractometer—both of which give useful information essentially covering atomic disposition in lattices or phase transformation, widely differ in terms of size, cost and infrastructure. One is a 'small' instrument and the other a 'large' instrument backed by a 'large' facility.

Development of instrumentation in the eighties and early nineties world-wide and in India

The tradition of building one's own apparatus or instrument which was very much in vogue in institutes like the Indian Institute of Science in the fifties gave way to large scale import of physics instruments in many institutes in the sixties and thereafter. Equipments like the X-ray diffractometers, UV and IR spectrometers, lasers, NMR machines and electron microscopes could be cited as examples.

The special issue of *Indian Journal of Pure and Applied Physics* to which I refer to later, does not make any reference to these 'imported' equipments but covers the large scale indigenous activities that did take place in the late seventies and eighties, emphasizing once again the instrumentation design and development activities at many places in our country recently. The developments that have influenced instruments for physics research globally in the past two decades arose essentially by some major events: (i) microelectronics, (ii) availability of various types of lasers, (iii) advent of personal computers and related software, (iv) devices based on controlled thin films and coatings-monochromators, sensors and the like.

As a result there was a renaissance in the fields of light scattering studies, X-ray diffraction and practically every other experimental field where automation got coupled with intelligent complex operations. As better intensities and resolutions became available at laser, synchrotron and neutron sources new generation of instruments was ushered in leading to discovery of finer details of structure and dynamics of materials and re-examination and discovery of phenomenon which threw new light on our understanding of materials around us. It is needless for me to mention that these advances have gone hand-in-hand with discovery and syntheses of a variety of new materials like the quasi crystals, high-T_c superconductors, fullerenes and so on. Along with global progress, similar developments have been taking place in India, on a smaller scale, after a certain time lag.

I wish to draw attention to a special issue of *Indian Journal of Pure and Applied Physics* entitled 'Physics Instrumentation in India' (1989, vol. 27, no. 7 & 8), for which I was a Guest Editor, advised by an Advisory Board. This volume details major physics instrumentation designs and developments in our country during this period in the following fields (the numbers in parentheses indicate the number of articles in the specific field):

- Astronomy and Astrophysics (5)
- Condensed Matter Physics (13)
- High Pressure Physics (3)
- Oceanography (1)
- Biophysics (1)
- Laser Physics (1)
- Electronic Instruments (3)
- Reactor Based Research (9)
- Accelerator and Nuclear Physics (8)
- Elementary Particles (2)
- Plasma Physics (1)

The 47 articles were contributed by specialists from various experimental groups in the country. The volume did not cover electronic instruments in any large measure purposely. I am aware that it was not truly comprehensive because it does not contain information concerning physics instrumentation developments in DRDO, ISRO and CSIR laboratories and also of many 'small' instruments. So it is somewhat limited. Therefore, there is scope to publish another compendium to record the current status of physics instrumentation in the country. However, the write-ups that are included in the special issue are still useful because not much has changed in those facilities over the past 5–6 years.

The second major effort relates to setting up important new radiation sources. Electron microscopy or laser spectroscopy and related instruments have depended on sources which are mostly acquired commercially. The Centre for Advanced Technology at Indore has been developing a variety of lasers including CW and high power pulsed lasers but to the best of my knowledge they are not being used by condensed matter physicists for any of their own instrumentation. As far as other radiation sources are concerned major developments are related to:

(i) the UV and soft X-ray synchrotron source INDUS-I at CAT, Indore
(ii) the thermal neutron source facility of Dhruva reactor at BARC, Bombay
(iii) the low energy (2–3 MeV) pelletron facility at Institute of Physics at Bhubaneswar
(iv) a low energy tandem accelerator at IGCAR, Kalpakkam.

There are two other facilities which would be of interest to solid state physicists. They are:

(i) the rail-gun facility at BARC for impact-fusion studies at Neutron Physics Division, BARC and
(ii) the gas-gun facility at High Pressure Physics Division BARC for shock-wave experiments extending the scope of static high pressure experiments to dynamic events.

Over the past 6–7 years, the National Board of Superconductivity has also supported various proposals to acquire several experimental facilities to study high-T_c materials. There are 3 or 4 squid magnetometers, high power X-ray diffractometers, vibrating sample magnetometers and the like. In addition, a major facility has been functioning at Indira Gandhi Centre for Atomic Research at Kalpakkam to fabricate squid sensors using microlithographic techniques based on Nb-based conventional hard superconductors.

Utilization of facilities

Setting up a facility or acquisition of equipment is one thing but utilization of these expensive systems within the shortest possible time is another. In this context, although it is not instrumentation *per se*, I wish to draw attention to the establishment of Inter-University Consortium for use of DAE facilities. IUC-DAEF is an important step in the right direction for promoting use of these facilities. Under this collaborative venture between two major agencies namely UGC and DAE, the IUC is currently supporting some 50 projects from all over the country for utilizing Dhruva and VECC which means essentially the synergetic effort of young students participating in material synthesis, characterization and experiments using the large facility is becoming a reality. Taking cue from this successful experiment, DAE scientists are exploring areas where one can have collaborational programme with the Physics Department in this Institute.

Biological macromolecular systems namely the proteins, nucleic acids, lipids and carbohydrates are rarely recognized as part of condensed matter physics although in the current terminology of 'soft matter' these systems (and polymers) are very much a part of condensed matter science. In all cases, structure and the biological function are intimately related. During the process of evolution, these have been selected for specific functions and they exist in a limited number of conformations. High resolution protein crystallography, small angle scattering and low resolution crystallography combined with modern methods of computer modelling and assisted by graphic support have provided copious information concerning the structure and hence on the biological function as well as the interaction with specific drugs. Recognizing these facts, the Department of Science and Technology and the Department of Bio-Technology have funded with the DAE to set up a National Centre for Macromolecular Crystallography at BARC with the view that the facilities at this Centre, namely the biochemical, X-ray and computer graphics facilities are available for research programmes for any institute or university researchers on peer review basis. This will be functional in about a year or so. Hopefully this will lead to exploitation of the neutron sources at BARC also for macromolecular research.

Recent gains and achievements

Experimental research

I shall take a few illustrative examples to be brief: (a) Starting with my own field, namely, neutron beam research, the neutron instrumentation around the Dhruva reactor at Trombay, complete with the inherent design functions of the reactor, have provided us with a variety of neutron spectrometers whose throughputs are 10–30 times more than those of the spectrometers at Cirus. I have no time to go into the details of the spectrometers; suffice it say that over the past 5–6 years we have been able to carry out routinely the following types of measurements which we could not have carried out at Cirus:

- power diffraction from complex materials like high-T_c materials
- thermodiffractograms to study phase transitions
- measurement of phonon density of states in complex geophysical and superconducting systems
- polarization analysis of neutrons scattered from magnetic systems
- structure factor from liquids and amorphous systems over wave vector transfers of order of 20 $Å^{-1}$
- high resolution quasi-elastic scattering.

(b) Facilities at TIFR and IGCAR can provide Josephson junctions, squids and microwave sensors based on high-T_c and low-T_c superconducting materials.

(c) INDUS-I will be operational in about a year. The beam lines that are being set up will help us in carrying out photo-electron spectroscopy using the synchrotron radiation.

(d) The Institute of Plasma Research facility has enabled one to carry out study of plasma interaction with various materials.

Importance of drawing upon inter-institutional resources

One of the most important inputs to some of these activities is that, we are able to draw upon the infrastructure and expertise available at many places for establishing new instruments and facilities. In this context, as an example from personal experience, I wish to relate our efforts in development of neutron guides which are now installed at Dhruva reactor to transport cold neutron beams from the reactor to an adjoining laboratory for specific experiments. This was possible because we had access to:

- production of uniform thin nickel wires from MIDHANI
- development of tungsten filament wires of various designs for coating nickel on glass from Central Electronics Ltd., UP
- the vacuum coating plant at the optical observatory at Kovalur
- advanced telemetric survey devices at CAT
- large machine shops at BARC for fabrication of various large and small components of the system.

So also, on the experimental front we have been able to draw on resources such as the high-pressure resistivity measurement apparatus at IGCAR, NMR at Bangalore for liquid crystal studies or photoluminiscence studies at TIFR as complimentary tools to neutron scattering, X-ray diffraction or Raman scattering to study materials like tetracyanoethylene, various model membranes and silicon quantum structures respectively. Whenever we needed to supplement our neutron data from other advanced neutron facilities, we have also been using facilities, say, at Rutherford Appleton Lab in UK or Argonne National Lab, Brookhaven National Lab or University of Missouri reactor in USA and so on where we send experimentalists for specific experiments.

Future programmes and perspectives: A scenario

I now describe some very useful techniques in which there are no experimental activities in our country to the best of my knowledge. Particularly since this

Discussion Meeting is dealing with Condensed Matter Science and not Condensed Matter Physics this becomes all the more pertinent. Over the past 40 years or so, a period in which neutron scattering, which from 'looming over the horizon' became an indispensable tool, we find there are other techniques which are yet to be exploited. Some of these are:

(a) electron energy loss spectroscopy
(b) helium atom scattering (HAS)
(c) atomic optics
(d) synchrotron applications
(e) a few important detectors and other developments.

One may enlarge or replace this list by one's own inclinations and expertise.

These are all techniques related to surface studies especially of the nature of excitations of surfaces, not so much of the structure of surfaces as revealed by scanning electron microscopy or scanning tunelling microscopy, surface electron diffraction and the like.

In helium atom scattering (HAS), inelastic effects with energy resolutions of 0.5 meV are measurable. The ranges of beam energies and wavelengths of helium atoms are very similar to those of thermal neutrons. However, helium atoms cannot penetrate bulk matter and are reflected by even very weak electron densities. 'HAS is the only diffraction probe which is exclusively sensitive to outermost surface layers, is entirely non-destructive and universally applicable to insulators, semiconductors and metals.' Since the atoms are insensitive to space and surface charge, operation of HAS is said to be much less demanding than say LEED-EELS apparatus. The technique is also used for studying phenomena such as chemisorption, surface reactions, etc. There are as many as 20–25 groups all over the world using this technique for various applications and none in India. As far as inelastic scattering is concerned, HAS is used for studying the dynamics of surface layers in, say, metal surfaces as a function of temperature to study features related to surface vs bulk modes or reconstructive phase transition or to study dynamics of thin *in-situ* epitaxially grown films etc. There is an excellent book entitled *Helium Atom Scattering from surfaces* by E. Hulpke (Springer Verlag 1992).

Entirely new and novel techniques are underway involving neutral atomic beams to study fundamental and applied physics (*Physics World*, 1993) via 'atomic optics'. Optical elements for atomic optics have recently come into vogue. Unlike photons which get refracted through materials, or electrons in electric and magnetic fields or neutrons in crystal structures, the optical elements for thermal atomic beams are based on free-standing structures based on microfabrication and manipulation of the beam which depends on momentum transfer to atoms from tunable lasers. Interaction of atomic beams with transverse optical standing waves leads to spatial focusing of such beams. Similarly interaction of atoms with, say, high gradient evanescent light fields, leads to reflection useful for 'atomic mirrors'. This field which needs support from a variety of high technologies is only in its infancy (Special issue of *Applied Physics*, 1992, **B54** (5)).

It is desirable that the type of new experimental programmes as illustrated above be initiated in an existing university or one of the existing Centers for Advanced Research where adequate infrastructure exists. In my opinion, creation of new centers at this stage of our progress is not necessary as funding would go into creating administrative set-ups and other avoidable expenditure. Adequate technical staff and young experienced research leaders are essential for ushering in new programmes.

The XUV synchrotron INDUS-I at CAT, Indore is likely to operate by the end of this year and the X-ray synchrotron INDUS-II by 1997 or thereabout. These are, therefore, periods of unique opportunities in our country to carry out experiments using synchrotrons that have not been possible so far by us in this country. Back-scattering X-ray optics is being used for magnetic and dynamical determinations. Construction of such major facilities demanding a variety of technical skills and competence will have to be met by equally demanding inputs by the condensed matter science community to design, develop, commission and use the physics instruments. Instrumentation, far from being treated as a 'dirty job' should occupy centre stage in order that the physics/science community in this country finds its place among other nations. It is just in the spirit of things that flourished in this department some 60 years ago.