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SOLID STATE PHYSICS: 1900-1980

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In the international scene, the first major steps in solid state physics after 1900 were Einstein's explanation of the data on photoelectric effect and his theory of specific heat. Subsequent important developments were: X-ray crystallography: thermionic emission and the vacuum tube; application of quantum mechanics to solid state physics problems; invention of the television, the transistor and the computer; neutron diffraction; solid state electronics for space science; theories of superfluidity and superconductivity; materials science, specially of amorphous materials; microelectronics; solid state lasers and fibre optics; ultrahigh vacuum and ultralow temperature.

We review the corresponding Indian developments. The time scale of the growth in Indian science and technology is examined. While the lag in scientific studies with respect to the developed countries is generally diminishing, that in technology, especially high technology, is not. Some reasons are discussed.

It is perhaps no exaggeration to say that solid state technology – the radio using the vacuum tubes and later the transistor and the television, now with colour – is crucial in generating social consciousness. The computer revolution already under way and the revolution in communication based on fibre optics are going to transform the cultural ethos of the people even more in the foreseeable future.

The standard of life is determined by the prevalent technology which must have a large component of matter in solid and condensed states. The empirical foundations of solid state physics are lost in the mists of early history. The science, however, is new, as the understanding of matter in condensed state requires development of ideas and methods of the quantum many-body problem. Professor N.F. Mott organised, under the auspices of the Royal Society of London, a meeting on the beginnings of solid state physics[1] and it is found that many of the pioneers are still alive.

I. THE INTERNATIONAL SCENE: 1900-1980

The year 1900 saw the introduction of the idea of the 'quantum' by Planck[2,3]. Using the quantum hypothesis, Einstein[4] explained the photoelectric data of Lenard (1905). The verification of Einstein's photoelectric equation by Millikan[5] emphasized the importance of good surface preparation and vacuum techniques. Electron diffraction was introduced by Davisson and Germer[6] and Thomson[7] (1928), but surface physics could not be developed until much later when ultrahigh vacuum[8] could be produced.

In the paper on the explanation of the specific heat of solids, Einstein[9] used the quantum hypothesis again (1907). His ideas were developed further by Debye[10] and Born and von Karman[11]. Born and his students also developed the study of ionic crystals and lattice dynamics of solids in general. Specific heat measurements were done with great accuracy when the adiabatic vacuum calorimeter was developed[12]. Measurements at low temperature down to 1°K or lower were made possible by the liquefaction of helium at Leyden by Onnes (1908)[13] and the development of adiabatic demagnetization method of Debye[14] and Giauque[15] (1935).

X-ray crystallography was started from the discovery of X-ray diffraction by Laue, Friedrich and Knipping[16] (1912). The technique of crystal structure determination, that is, finding out quantitatively the periodic arrangement of atoms, ions or molecules in a crystal, was introduced by W.H. Bragg and W.L. Bragg[17]. More and more complex structures were solved. The determination of protein structure required patient work over decades. Sometimes, as in the structure determination of deoxyribonucleic acid (DNA), an entire new science – molecular biology – was created[18]. The instrumental technique has improved over the years, and X-rays are used routinely in metallurgy, fibre processing and medicine.

S.N. Bose's work[19] introduced quantum statistics in 1924 and Einstein, applying it to a gas, showed the intriguing possibility of gas degeneracy and the Bose-Einstein condensation[20]. Superconductivity was discovered in 1911 by Onnes[13]: superfluidity in liquid helium was found by Kapitza[21] (1938). But further understanding came much later.

The year 1925 saw the birth of quantum mechanics[22]. Pauli[23] made the first application of new mechanics and the Fermi-Dirac[24] statistics to explain paramagnetism of metals. Heisenberg discovered the quantum mechanical exchange phenomena and started the quantum mechanical theory of ferromagnetism[22]. Bloch[25], who had worked with both Heisenberg and Pauli, studied the motion of electrons in a periodic potential such as would exist in a crystal and founded the modern solid state physics. He developed the theory of conductivity in metals and of the excitation spectra of magnets. Wigner[26] and Bethe[27] studied group theory as applied to solids. The famous Handbuch article of Sommerfeld and Bethe[28] made the knowledge of the energy bands in solids well known. Wilson[29] proposed the band theoretic classification of solids into metals, semiconductors and insulators. In 1932, Bethe solved a genuine many-body problem in quantum mechanics by the now celebrated Bethe Ansatz[30]. Wigner and Seitz[31] analyzed the problem of cohesion in solids, and together with Slater[32], Wannier and Herring, they laid the foundation of accurate computation of the properties of solids.

During the second world war, on 2 December 1942, the nuclear reactor was constructed at Chicago by Fermi and his group[33]. Neutrons from the thermal column were soon used by Shull and Wollan for neutron diffraction work[34]. The magnetic scattering of neutrons made the determination of magnetic structure possible.

The techniques for producing pure crystals – sometimes of even isotopically pure elements – were improved. As a byproduct of the purification of silicon

Shockley, Bardeen and Brattain invented the transistor[34]. This single invention transformed the entire world of communication. Small power requirement made the instruments operate with batteries and the instruments became portable. Solid state electronics developed rapidly. There were two main driving forces: the electronic computer and the space science.

The phenomenon of thermionic emission was investigated by Richardson[35]. Thermionic valves were used in the radio and associated devices. The electronic computer was developed with thermionic valves by Williams, Turing, von Neumann, Mauchly, Eckert and others[36]. As knowledge of semiconductors and solid state physics advanced, solid state electronics replaced thermionic tubes and grew into microelectronics. The computer became smaller in size, rugged and more powerful. Associated with this was the development of 'software', new forms of mathematics or older forms that are suited to the computer's artificial language and intelligence.

II. The Indian Scene

A. Solid State Experiments

We shall very briefly examine the developments in India against the international background given above. No attempt is made to make the survey extensive or comprehensive. Needless to say, opinions expressed on so recent events may not be entirely balanced.

X-ray crystallography was started quite early in India; the field will be reviewed elsewhere. Several important contributions should be mentioned: the work on polytypes by A.R. Verma[37], the contribution to protein structure by G.N. Ramachandran[38] and the discovery of new ordering in liquid crystals by S. Chandrasekhar[39]. Strong X-ray sources do not exist. A synchrotron proposed[40] and likely to operate around 1990 was expected to bridge a gap. Several centres have now got imported computer-controlled X-ray diffractometers, and work can be done faster on these machines.

Specific heat measurements at low temperatures were done by T.M. Srinivasan and E.S. Rajagopal[41], but these measurements are hard, time-consuming and painstaking. Regrettably, they are not popular and not regularly done anywhere.

Other low temperature measurements down to liquid helium temperature started at the National Physical Laboratory at New Delhi around 1950. There are now many centres with liquid helium facilities. Among them we mention: (i) National Physical Laboratory (NPL), New Delhi; (ii) Solid State Physics Laboratory (SSPL), New Delhi; (iii) Indian Institute of Technology (IIT), Kanpur; (iv) Indian Institute of Technology (IIT), Kharagpur; (v) Indian Institute of Technology (IIT), Madras; (vi) Indian Institute of Science (IISc), Bangalore; (vii) Bhabha Atomic Research Centre (BARC), Trombay, Bombay; (viii) Tata Institute of Fundamental Research (TIFR), Bombay; (ix) Reactor Research Centre (RRC), Kalpakkam; (x) Saha Institute of Nuclear Physics (SINP), Calcutta; (xi) Indian Association for the Cultivation of Science (IACS), Calcutta; (xii) Delhi University, New Delhi; and (xiii) Central University of Hyderabad. Work is mostly concentrated in superconductivity and some measurements in thermophysical and magnetic properties. TIFR has a He^3 dilution refrigerator that goes down to 70 mK and is the only place where work in superconductivity at ultralow temperature can be done. RRC is trying to set up a dilution refrigerator. Liquid nitrogen facilities are more widely available; there are about one hundred liquid nitrogen plants at the educational institutions, and solid state measurements are done at several places, though not as widely as one might expect.

In the field of magnetic measurements, the Indian record has been very good[42]. Magnetic susceptibility measurements by D.M. Bose[43] at Calcutta University (1924-26) established the 'spin-only' magnetism for the 3d transition metals. At IACS, K.S. Krishnan[44] started the magnetic anisotropy measurements and established a school that is still active. Magnetic structure determination can be done at the BARC reactors using neutrons. Since 1960, a group under P.K. Iyengar[33,45] has been utilizing neutrons for this purpose and for the study of lattice dynamics of solids and motion of atoms and molecules in liquids. Magnetic resonance has been studied extensively. SINP and TIFR got two machines quite early and they were quite useful. More is said below.

Production of high purity silicon and germanium is still difficult in India. It has been reported that the Indian space programme initially found the silicon solar cells made in India unacceptable, though improved versions have appeared. A semiconductor laboratory has been set up at Chandigarh, but progress in semiconductor devices or large scale integration (LSI) has been slow. Recently, at the IIT's and IISc, much emphasis has been laid on materials science, production and characterization of new materials.

B. Theoretical Studies in Solid State Physics

The impact of the discovery of quantum dynamics was felt quite late in India in the field of solid state physics. The centre of science at Calcutta was basking in the glory of C.V. Raman's experimental work[46]; spectroscopists continued to collect data. D.M. Bose moved from magnetic studies out into nuclear physics[47]. B.B. Roy, another professor working with X-rays at Calcutta University, did not look kindly at all on the quantum mechanics of Heisenerg, Born and Jordan. He wrote to Bohr (1926): 'I personally shall not be sorry if the whole outburst of Born and Jordan is completely withdrawn and I fear if atomic physics has to progress on the line of Born and Jordan you will find very few people left in the atomic physics circle (quoted in J. Mehra and H. Rechenberg[1], Vol. 4, p. 233). M.N. Saha[48] at Allahabad followed the development of quantum theory keenly. When he joined Calcutta University, K.S. Krishnan succeeded him in Allahabad. Several workers from Allahabad worked in the field of solid state physics: A.B. Bhatia, K.S. Singwi, R.P. Singh, S.S. Mitra, Krishnaji, Vachaspati and S.K. Joshi.

A.B. Bhatia[49] made important contributions to the theory of liquid metals. He worked most of his life abroad. Singhwi[50] worked at the Tata Institute of Fundamental Research (TIFR) and along with L.S. Kothari wrote several well known papers on neutrons. He left for the United States and has continued to be very productive scientifically. T.P. Das[51], who worked at the Saha Institute of Nuclear Physics (SINP) and later at TIFR, and S.S. Mitra[52], also settled in the United States, are both well known for their work in theoretical solid state physics. B. Dayal[53] worked on lattice dynamics. Starting from lattice dynamics, S.K. Joshi[54] moved into various aspects of solid state physics. He settled down in the Roorkee University, built a good school and has been training a large number of workers. Lattice dynamics with neutrons was also pursued at BARC by P.K. Iyengar and G. Vankataraman[55].

From 1966, TIFR has organised under S.S. Jha[56] a small group of enthusiastic young workers in theoretical solid state physics. The group works at the frontiers of modern development: non-linear optics, surface Raman scattering, positron annihilation, phase transition and critical phenomena, renormalization group, percolation problems, liquid helium He^4 and He^3, disordered systems, and general statistical mechanics.

The Indian Institute of Science at Bangalore has also been refurbishing its solid state activities by recruiting a few good theoreticians like K.P. Sinha, N. Kumar[57] and T.V. Ramakrishnan[58]. They work on renormalization group methods, disordered systems and magnetic systems.

Some universities like Banaras Hindu University, Central University of Hyderabad and Panjab University, Chandigarh, and the Indian Institutes of Technology, Bombay, Kanpur and New Delhi, have also active groups in theoretical side. There are several smaller groups elsewhere.

The groups at Bombay, Bangalore and Roorkee have maintained international contacts and have had some impact on the international scene. On the whole, the quality of work has been fair.

III. Time Scale of the Development of Solid State Physics

The rate of growth of solid state physics research in India can be studied in several ways.

A currently fashionable technique is to look at the Citation Index. A good Indian contribution will ultimately be cited. However, average work tends to languish without international notice, particularly from the western world. One may doubt if this technique reflects the growth adequately; it may be an index of 'impact', not of growth.

The Department of Atomic Energy (DAE) runs an annual symposium on Nuclear and Solid State Physics and publishes the proceedings. The number of papers in different branches of solid state physics could be counted, because a continuous series of record is available. We shall use this record occasionally.

We have taken a slightly different approach. We look at fields where a series of international conferences gets established and one of these is held in India. We assume that by the time the conference is held in India, a considerable amount of activity must be current locally and some amount of international recognition is accorded to the activity. It is this measure against international work that makes this more attractive than just a compilation of the DAE records. Nevertheless, the assumption may be questioned. The international conference may not say much about the quality of the Indian science (to emphasise this point one could think of the international soccer tournaments now held in India). The organisers and participating scientists may have been lured by the charms of this ancient land in spite of the well-known physical discomforts of tourists and other political and bureaucratic difficulties (see below[61]). If one takes a pessimistic view, one may argue that the subsequent analysis says nothing or provides at best a lower bound to the time scales involved. With these cautionary remarks let us proceed with the analysis.

A. The Mössbauer Effect

The recoil-free gamma ray emission was discovered by R. Mössbauer in Germany almost accidentally (1958). The international development is well documented, for instance, by Frauenfelder[59]. So is the early Indian attempt to repeat the experiment[60].

The case is interesting from another point of view. Usually the international conferences are dominated by the western bloc. In the Mössbauer effect, the western and the eastern blocs started their developments independently. The two series of conferences converged later in 1977 in Rumania (Table 1).

Notice that the western countries were able to extend and harvest the field of research in six or seven years. The conference proceedings of the third International Conference were published in the *Reviews of Modern Physics*, 1964, and cover 170 pages. The meeting in Japan was 20 years after the discovery and previous to that in India. Israel is another Asian country that held an international conference. The conference proceedings in India were published by INSA for the meeting held in India and ran into 985 pages.

The difficulty of holding an international conference in India also became apparent during the conference in India[61]. Since the government did not issue visas to Israeli scientists or had no clear policy about landing and entry permits for some scientists from certain countries like Israel, Portugal and South Africa, the International Union of Pure and Applied Physics wanted to withdraw their sponsorship. The venue had to be shifted from Kashmir, a hot bed of international politics. However, after strenuous efforts, the Indian scientists got the clearances from the government and managed to hold the conference at Jaipur. They even got encomiums from Israeli scientists who finally did attend the conference[62].

Table 1. Time series of international conferences on Mössbauer effect

80		India	
		Yugoslavia	
1978	(20 years)	Japan	
		Rumania	
76	Greece		
			Poland
74	France		
72	Israel		Czechoslovakia
			DDR (East Germany)
70			
			Hungary
1968			
			Bulgaria
66			
64			
	US (Ithaca, New York)		
62			USSR
	France		Nobel prize to Mössbauer
			1st Indian publication
60	US (Illinois)		
1958	Discovery		

According to R.S. Raghavan[60], the earliest publication in the field is in 1961. From the DAE conference proceedings we find that the number of papers is 12 in 1978, 15 in 1980 and 12 in 1982. Most of the work is with Fe and Sn isotopes, but some rare earth isotopes are also being used. The places active are Aligarh University; Bhabha Atomic Research Centre, Bombay; Bhagalpur University; BNC University, Kurukshetra, Haryana; Hyderabad Central University, Hyderabad; IACS, Calcutta; IISc, Bangalore; IIT, Bombay; IIT, Delhi; IIT, Kanpur; Lucknow University, Lucknow; Madras University, Madras; Osmania University, Hyderabad; Panjab Agricultural University, Ludhiana; Rajasthan University, Jaipur; Reactor Research Centre, Kalpakkam; Roorkee University, Roorkee; Saha Institute of Nuclear Physics, Calcutta; Tata Institute of Fundamental Research, Bombay; and University of Udaipur. There are a few more organisations which have the set-up and carry out the work. The Electronic Corporation of India marketed a Mössbauer spectrometer (MBS 35) and a multichannel analyser in the seventies, but the price is too high by the Indian university standards.

B. Positron Annihilation Studies

We next consider a field in solid state physics which required moderate input, simple instrumentation and not-too-high technology. It is not a fashionable one, but is quite versatile.

Initially, the subject of positrons belonged to particle physics and was very fashionable. Positron was the first antiparticle predicted theoretically and then discovered in cosmic rays[63]. It is a product in artificial radioactivity and can combine with electrons to form short lived hydrogen-like very light positronium atom. The fundamental properties of the positronium atom were soon established experimentally. Since positron annihilates with electron with emission of gamma rays, the annihilation radiation was studied extensively. The early Indian workers in cosmic rays were familiar with the properties of positron.

In solid state physics, positron annihilation became established with the lifetime and the angular correlation measurements of Bell, De Benedetti, Stewart and Berko (1952-57). The first international conference was held at Detroit in 1965. The proceedings ran into 438 pages[64]. The Soviet Union was represented by V. Goldanskii. Only one worker from the Tata Institute of Fundamental Research, Bombay, participated. The seventh international conference ICPA-7 was held in New Delhi. The sixth meeting at Arlington, Texas, USA, already produced a proceedings of 986 pages[65] and the seventh one will be about the same. Notice that Japan once again held an international conference before India.

In Table 2 we have indicated some of the major experimental discoveries in the field. Internationally, the time scale to exploit any idea proposed is about five years. The TIFR theory group had realized the importance of the two-dimensional

Table 2. Time series in Positron Annihilation studies

1985	ICPA 7	New Delhi, India
		(Positron Diffraction experiments)
	ICPA 6	Arlington, Texas, USA Proceedings 986 pages
		(Slow positron beam and QED experiments)
80	ICPA 5	Lake Yamanaka, Japan
		(2 Dim ACAR experiments)
	ICPA 4	Helsingor, Denmark
1975	ICPA 3	Finland (Defect studies)
	ICPA 2	Kingston, Canada (2 Dim, ACAR, London expt. TIFR theory)
		(Effective masss experiment)
65	ICPA 1	Detroit, US (Proceedings 438 pages) (1 participant from India)
		(Fermi Surface experiments)
60		
	Bell, De Benedetti, Stewart, Berko	
1955		
52	Deutsch (Positronium studies)	
	Dumond, Lind and Watson (Discovery of line broadening)	
	Nobel Prize (1948)	
46		
40	Wheeler	
	Nobel Prize (1936)	
34	Nobel Prize (1933)	
	Anderson, Blackett (Discovery)	
1928	Dirac theory	

angular correlation experiments[66] (2D ACAR), but Indian experimentalists could not exploit this advantage. The 2D ACAR experiments were done in several places in the US and Europe and depended on high technology to some extent. A project from Poona University was granted by the Department of Science and Technology and work is in progress. Another project at Calcutta University is delayed by poor administrative handling and has not progressed at all.

There have been at least two national conferences in India at New Delhi[67] and Madras[68]. Both proceedings are available in print. Work in this field is done at Bhabha Atomic Research Centre, Trombay; Delhi University; IIT, Kanpur; Madras University; Poona University; Rajasthan University, Jaipur; Reactor Research Centre, Kalpakkam; Saha Institute of Nuclear Physics, Calcutta; and Tata Institute of Fundamental Research, Bombay.

The Electronic Corporation of India Ltd has been selling a coincidence set-up for lifetime measurements but not the angular correlation apparatus. The status of the 2D ACAR projects in India has been discussed above. Internationally there are about ten 2D ACAR machines in operation. The machine from Geneva is commercially available.

C. Magnetic Resonance

The development of magnetic resonance studies started after the second world war with the work of F. Bloch, W.W. Hansen and M. Packard[69] (1946) and E.M. Purcell, H.C. Torrey and R.V. Pound[70] (1946). The field developed rapidly as new sources of microwave power were found and new techniques like the pulse techniques, spin echoes and the electron nuclear double resonance techniques were introduced. The developments led to the Masers and Lasers (microwave or light amplification by stimulated emission of radiation). Resonance techniques gave precise data for chemical systems and revitalized study of complicated molecules or condensed matter systems.

It is a matter of pride that one of the early books in this field was written by A.K. Saha and T.P. Das[71] in Saha Institute of Nuclear Physics, Calcutta. That institute and the Tata Institute of Fundamental Research, Bombay (a group headed by Professor S. Dharmatti and later by R. Vijayaraghavan) set up the nuclear magnetic resonance machines and started work. Over the years, many Indian organisations procured such machines for resonance work in different parts of the electromagnetic spectrum. Invariably they are imported, because the technology of producing the required homogeneity in magnetic field has not been developed in India.

Nevertheless, the Indian work has contributed substantially to this field. The fifth International Magnetic Resonance Conference was held in Bombay and Professor A.K. Saha presided over the opening ceremonies.

The other important magnetism conference, the International Conference in Magnetism, has never been held in India. The field now is dominated by techniques and high technology. This is an example where in spite of good early start in the work of D.M. Bose and Saha and Das, the Indian scientists faded out because of inadequate technological support or, in the current parlance, the lack of infrastructure.

D. Neutron Physics

The story of neutron physics[33] is connected with nuclear reactors and is different in character. The Department of Atomic Energy has been given adequate support by the Indian government and the spectre of the atomic explosion and fear of complete annihilation have always kept the importance of the atomic energy before the public eye.

The neutron was discovered by Chadwick in 1932. Experiments of Fermi on neutron reactions and transuranic elements; the discovery of fission by Hahn, Meitner and Frisch; the realization of the possibility of chain reaction when the neutron yield per fission was found to be more than 2; the identification of U235 as the fissile nucleus; the second world war and the sudden secrecy over the fission work following Sziland's effort; Einstein's letter; the Manhattan Project; Fermi's success with the chain reaction at the Chicago baseball court; the blast at Alamagordo with Oppenheimer reciting the Bhagavad Gita; the destruction of Hiroshima and Nagasaki; arms race; the hydrogen bomb; radiation deaths; radioactive fallout; ban on atomic tests in air; neutron bomb; peace marches – this is the outline of the story of the neutron in the saga of the humanity for the second half of the century.

The atomic age started with Fermi's reactor going critical at Chicago on 2 December 1942. After the second world war, nuclear reactors of various types were developed: light water reactor using enriched uranium, heavy water moderated reactor using natural uranium, high temperature gas reactor, and fast breeder reactors. Stringent safety requirements were imposed, as accidents were thought to lead to catastrophes. Nevertheless, minor accidents took place[72] and the general public reaction has slowed down the development of nuclear reactors and led to the discontinuance of some operating ones.

With the Apsara reactor, India entered the atomic age in 1956. Later, the Indian programme[73] was based on the CANDU type reactors (heavy water moderated natural uranium reactors). Much indigenous development had to take place for the atomic energy programme. There is now a reactor research centre; production of breeder reactors, new types of dense fuels and possibility of a thorium cycle are being actively investigated (Table 3).

Neutron research has been concentrated in Trombay at the CIRUS under P.K. Iyengar. Other Indian groups, for instance, D.C. Khan[74] and his students of the Indian Institute of Technology, Kanpur, have made use of the facilities for work on magnetic substances. Certain international collaborations have fruitfully used the facilities[75,76].

Table 3. Neutron and Development of Neutron Physics

	International	Indian effort
1982 -		R 5 (1985 ?) *
78 -		PURNIMA (1974)
74 -	Neutron interferometers	(PNE at Pokhran)
1972 -		Reactor Research Centre (Kalpakkam)
66 -		
-		Neutron spectrometry at BARC
1962 -		
-	Fermi surface by neutrons (Kohn effect)	CIRUS, Bombay (1960)
58 -		
-	Phonon spectrum by neutrons	APSARA, Bombay (1956)
54 -		Cascade generator, TIFR (1954)
1952 -		
	Neuttron diffraction/scattering and application to magnetism	Neutron cross-section, SINP (1949)
46 -	Transuranic elements (Seaborg, McMillan)	(Ra-Be Source)
1942 -	Nuclear Reactor (Dec. 2, 1942, Fermi)	
38 -	Fission (Hahn, Meitner, Frisch)	
34 -	Transuranic elements (Fermi)	
1932 -	Discovery, Chadwick	

*According to newspaper reports (the *Statesman*, 9 August 1985, Calcutta edition), the reactor now called DHRUVA became critical at 2.42 a.m. on 8 August 1985.

Examining the data given, we note that the Indian scientists were able to make contributions to all the fields in about five years. However, they cannot exploit the possibilities as fast or as thoroughly as the scientists in the western world or of Japan. Here there is a technology gap. The gap is about 15 years for reactor physics and longer, about 20 years, in other fields. When the subject is fashionable or prestigious or somehow connected with the defence of the country, the governmental support pushed the technology along and the gap was narrowed by five years or so. There is very little industrial research in India.

We must point out that the Indian universities lag behind further. The initial work is almost invariably done at the few research institutes or the IIT's. Given the technological backwardness, this is to be expected. Perhaps it has been a good strategy to keep a few well maintained forward-looking research organizations that can compete with the best institutions in the world. But the Indian universities are also unable to bring up a rear in an orderly fashion, either because they are overburdened with too many students or because they are suffering from inadequate financial support. Older reputed universities like Calcutta and Allahabad suffered decline in standards with too many students and political problems. Sometimes there is little realization among the staff that research is an essential part of the university teacher's work. Unless the research activities in the universities are revived with proper orientation and funding, the general decline of standards will spread to the research institutes also. After all, the initial training of the students must take place at the universities. If the initial training is poor, and new talent is not properly motivated to come to science, the research institutes cannot hope to have adequately trained and inspired workers.

IV. Future of Solid State Physics

The present technological revolution in telecommunication requires several new solid state technologies: solid state lasers, fibre optics for optical communications, videophones and low noise satellite communication systems. Some of these, particularly satellite communication to cover remoter regions of India by television, are already seen in India. The technology is mostly imported.

For larger computers, the technology available internationally is similarly imported. But on a smaller scale, the computer technology is growing in India. Internationally, the ability of Indian scientists in computer software is well recognised. But indigenous hardware involving semiconductor technology, large scale and very large scale integration (LSI and VLSI) of multiple components into miniatures is not well developed.

Another area where international and Indian effort is significant is that of non-conventional energy sources. The utilization of low grade but ubiquitous solar energy will go a long way towards meeting the energy needs of the large rural population. While trouble-free nuclear power from fission reactors must be developed for concentrated industrial development and research goes on looking for harnessing fusion power, the energy requirements of the large population must be met for better life. Semiconductors, biotechnology, utilization of biomass, wind, water, geothermal and tidal power – whatever non-conventional sources could be appropriately used in a particular area – must be carefully considered. The present knowledge of solid state physics is just about enough to make a start in all of these.

References

1. The Beginnings of Solid State Physics, *Proc. Roy. Soc.*, **A371**, 1-177, 1980.
2. Planck, M., Zur Theorie des Gesetz der Energieverteilung in Normalspektrum, *Verh. d. Deutsch. Phys. Ges.*, **2**, 237, 1900.
3. Mehra, J. & Rechenberg, H., *The Historical Development of Quantum Theory*, Vols 1 to 4, Springer Verlag, New York, Heidelberg, Berlin, 1980-1982.
4. Einstein, A., *Ann. d. Phys.*, **17**, 132, 1905.
5. Millikan, R.A., *Phys. Rev.*, **7**, 1832, 1916.
6. Davisson, C. & Germer, L.P., *Phys. Rev.*, **30**, 705, 1927.
7. Thomson, G.P. & Reid, A., *Nature*, **119**, 890, 1927.
8. Gihrenbeck, R.K., Electron Diffraction: fifty years ago, *Phys. Today*, **31** (No. 1), 34, Jan 1978; Alpert, D, Ultrahigh Vacuum, *Phys. Today*, **16** (No. 8), 22, August 1963.
9. Einstein, A, *Ann. d. Phys.*, **22**, 180, 1907.
10. Debye, P., *Ann. d. Phys.*, **39**, 789, 1912 and *Collected Papers*, Interscience Pub., New York, 650, 1954.
11. Born, M. & Huang, K. *Dynamical Theory of Crystal Lattice*, Oxford, 1954.
12. Nernst, W., *Sitz ber. Preuss. Akad. Wiss. Berlin*, 262, 1911.
13. Onnes, H.K., *Commun. Phys. Lab. Univ. Leiden*, **108**, 1908 (on liquefaction of helium, the

experiment was done on 10 July 1908); **119, 120, 122** (1911) (on superconductivity). For a good popular account see Wilson, D., *Supercold*, Faben and Faber, London and Boston, 1979.
14. Debye, P., *Ann. d. Phys.*, **81**, 1154, 1926; *Collected Papers*, Interscience Pub., New York, 620, 1954.
15. Giauque, W.F., *J. Am. chem. Soc.*, **49**, 1964, 1927.
16. Friedrich, W., Knipping, P. & Laue M., *Ann. d. Phys.*, **41**, 971, 1913 (the experiment was performed on 21 April 1912).
17. Bragg, W.H. & Bragg, W.L., *Nature*, **91**, 1913; and Bragg, W.L., *Proc. Roy. Soc. London*, **A 89**, 248, 1913.
18. Watson, J.D., *The Double Helix a personal account of the discovery of DNA*, London, Weidenfeld and Nicolson, pp. 226, 1969.
19. Bose, S.N., *Z. Phys.*, **26**, 178, 1924, English translation published in *Phys. News*, **5** (2) 40, 42, June 1974.
20. Einstein, A., *Sitz. ber. Preuss. Akad Wiss. Berlin*, 241, 1924; 3, 1925 and 18, 1925, English translation published in *Phys. News*, **14** (1), 10, March 1983.
21. Kapitza, P., *Nature*, **141**, 74,1938 (coined the term superfluidity).
22. Heisenberg, W., *Z. Phys*, **33**, 879, 1925 (quantum mechanics), *Z. Phys.*, **49**, 619, 1928 (ferromagnetism).
23. Pauli, W., *Z. Phys.*, **41**, 81, 1926.
24. Fermi, E., *Z. Phys.*, **36**, 902, 1926; Dirac, P.A.M., *Proc Roy Soc.*, **A112**, 66, 1925.
25. Bloch, F., *Z. Phys.*, **52**, 555; 1928; Electronentheorie der Metalle, *Handbuch d. Radiologie*, VI/2, Leipzig, 226, 1933.
26. Wigner, E.P., *Group theory and its application to the Quantum Mechanics of Atomic Spectra*, Acad Press; translation by J.J. Griffin (Ist edition in 1931), 1959.
27. Bethe, H., *Ann. d. Phys.*, **2**, 133, 1929.
28. Sommerfeld, A. & Bethe, H., *Handbuch d. Phys.*, **24/2**, 333, 1933.
29. Wilson, A.H., *Proc. Roy. Soc*, **A 133**, 458, 1931; **A134**, 277, 1931. (semiconductor).
30. Bethe, H., *Z. Phys.*, **71**, 205, 1931.
31. Wigner, E. & Seitz, F., *Phys. Rev.*, **43**, 804, 1933.
32. Slater, J.C., *Quantum Theory of Molecules and Solids, Vol. 1. Electronic structure of molecules*, 1963; *Vol. 2. Symmetry and energy bands in crystals*, 1965, *Vol 3. Insulators, semiconductors and solids*, 1967; *Vol. 4. The Self-consistent field for molecules and solids*, 1974, McGraw Hill Publishing Co. New York.
33. See the compendium *The Golden Book of Neutrons*, Vols I and II, compiled at BARC, Bombay, 1982.
34. Shockley, W., *Electrons and Holes in Semiconductors*, New York, 1950.
35. Richardson, O.W., *The Electron Theory of Matter* (2nd ed. Cambridge, England) Cambridge Univ. Press, 1916.
36. Goldstine, H., *Phys. Today*, **36** (12), 86, December 1983; Mauchly, J.W. & Eckert, J.P. (Edvac), 1946; Burks, A.N., Goldstine, H.H. & Von Neumann, J., Institute of Advanced Study, 1945, Preliminary discussion of the logical design of an electronic computing instrument Edvac, 1950. The Institute of Advanced Study machine was completed in 1952.
37. Verma, A.R. & Krishna, P., *Polymorphism and Polytypism in crystals*, Wiley, 1966.
38. Ramachandran, G.N., Ramakrishnan, C. & Sasisekharan, N., *J. Molec. Biol.*, **95**, 1962.
39. Chandrasekhar, S., Sadashivan, B.K., Suresh, K.A., Madhusudana, N.V., Kumar, S., Shashidhar, R. & Venkatesh, G., *J. Phys. (Paris)*, **40**, c3, 1979.
40. *Synchrotron Radiation Sources*, Proceedings of Meeting at Poona on 29-30 September 1980, edited by Gowarikar, R. and Chidambaram, R.
41. Rajagopal, E.S., *Specific heat at low temperature*, Plenum Press, New York, 1967.
42. Majumdar, C.K., Magnetism Past, Present and Future, in *Current Trends in Magnetism*, edited by N.S. Satya Murthy and L. Madhav Rao, Indian Physics Association, Bombay, June 1981.
43. Bose, D.M., *Z. Phys*, **35**, 212, 219, 1926.
44. Krishnan, K.S., Chakraborty, N.C. & Banerjee, S., *Phil. Trans. Roy Soc (London)*, **232**, 99, 1933.
45. Iyengar, P.K., *Trombay Multiarm Spectrometer*, Symposium on inelastic scattering of neutrons by condensed system held at Brookhaven National Laboratory BNL 940, (c. 45) 179, 1965.
46. Raman, C.V. & Krishnan, K.S., *Phil Mag.*, **3**, 713, 1927.
47. Bose, D.M. & Chaudhuri, B., *Nature*, **147**, 240, 1941; 148, 251, 1941; **149**, 303, 1942.

48. Saha, M.N., *Collected Works of Meghnad Saha*, edited by S. Chatterjee, Orient Longman, 190, 1982.
49. Bhatia, A.B. & Krishnan, K.S., *Proc. Roy. Soc.*, **A194**, 185, 1948; Bhatia's obituary was published in *Phys. Today*, **38** (2), 96, February 1985.
50. Singwi, K.S. & Kothari L.S., *Phys Rev.*, **76**, 305, 1949; Singwi, K.S., *Phys. Rev.*, **87**, 504, 1044, 1952, Kothari, L.S. & Singwi, K.S., *Proc., Roy Soc. (London)*, **A231**, 293, 1955.
51. Das, T.P. & Hahn E.L., *Nuclear Quadrupole Resonance Spectroscopy*, Academic Press Pub., New York, 1958.
52. Mitra, S.S., Vibration spectra of solids, *Solid State Physics*, **13**, 1, 1962.
53. Dayal, B. & Tripathi, B.B., *Proc. Roy. Soc., London*, **A 266**, 122, 1962.
54. Joshi, S.K. & Rajagopal, A.K., Lattice Dynamics of Metals, in *Solid State Physics*, **22**, 152, 1968.
55. Venkataraman, G. & Sahni, V., *Rev. Mod Phys.*, **42**. 409, 1970.
56. Jha, S.S., Inelastic light scattering in solids in *A short course in Solid State Physics*, Vols 1 and 2, edited by F.C. Auluck, sponsored by the Centre of Advanced Study, Univ. of Delhi, Thomson Press India Ltd., New Delhi, 1972.
57. Sinha, K.P., Coexistence of Magnetism and Superconductivity: Theoretical Studies in Current Trends in Magnetism, op. cit.; Kumar, N., *Physics of Disordered Solids*, edited by P. Shukla, Mittal Pub., Delhi, 1982; *Phys Rev.*, **B31**, 5513, 1985.
58. Ramakrishnan, T.V., *Phys. Rev.*, **B10**, 4014, 1974; Ramakrishnan, T.V. & Yussouff, M, *Phys. Rev.*, **B19**, 2775, 1978 (First principles order parameter theory of freezing).
59. Frauenfelder, H., *The Mössbauer effect*, W.A. Beniamin, Inc., New York, 1962.
60. Raghavan, R.S., *Phys. Today*, **37** (2), 38, February 1984, *Proc. Indian Acad Sci*, **53A**, 265, 1961.
61. Gladstone, D, No Israeli Visas for India Meeting, *Phys. Today*, **34** (2), 54, September 1981.
62. Bauminger, E.R. & Cohen, S.G., *Phys. Today*, **35** (4), 97, April 1982.
63. Sieghahn, K., (editor), *Beta and Gamma Ray Spectroscopy*, edited by K. Sieghahn, North Holland Pub. Co., Amsterdam, 672-696, 1955.
64. Stewart, A.T. & Roellig, L.O., Positron Annihilation, *Proc. International Conference at Detroit*, Academic Press, New York, 1967.
65. Positron Annihilation, *Proc. 6th Intl. Conf. at Arlington*, Texas, USA; edited by G. Coleman, S.C. Sharma and L.M. Diana, North Holland, Amsterdam, 1982.
66. Majumdar, C.K., *Phys. Rev.*, **B4**, 2111, 1971.
67. Positron Annihilation, edited by P.C. Jain and R.M. Singru, South Asian Publishers, New Delhi, 1980.
68. Positron Annihilation Spectroscopy, *Proc. 2nd National Symposium*, Madras, 5-12 Feb. 1982, Madras Univ., Vol 45, No. 3, Dec. 1982, edited by V. Devanathan, and K.P. Gopinathan.
69. Block F., Hansen, W.W. & Packard, M., *Phys Rev.*, **69**, 127, 1946.
70. Purcell, E.M., Torrey, H.C. & Pound, R.V., *Phys. Rev.*, **69**, 37, 1946.
71. Saha, A.K. & Das, T.P., *Theory and Application of Nuclear Induction*, Saha Institute of Nuclear Physics, Calcutta, 1957.
72. The most discussed incident is the 'Three Mile Island' accident, *Phys Today*, 77, June 1979, and *Phys Today*, 89, February 1980.
73. The Indian programme is publicised in the bulletin *Nuclear India* published by the Department of Atomic Energy running Vol. 23 in 1985.
74. Khan, D.C., Types of Exchange Interactions and Magnetic structures, in *Current Trends in Magnetism*, op. cit.
75. The Bhabha Atomic Research Centre (BARC), Bombay fabricated a novel neutron spectrometer which has been installed at the Rutherford-Appleton Laboratory, UK.
76. Dr. S.K. Sinha, an Indian scientist settled in the USA, has been a prominent collaborator at BARC.