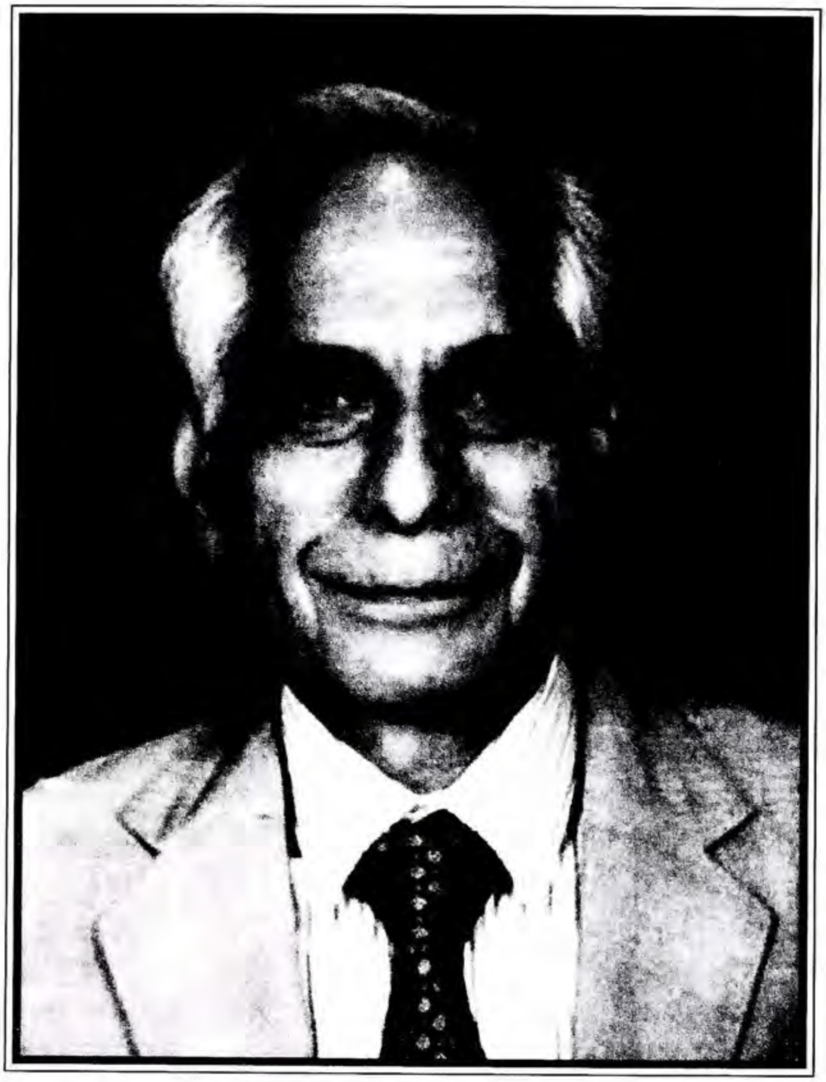
AJIT RAM VERMA

21 September 1921 – 4 March 2009

Biog. Mem. Fell. INSA, New Delhi **39** (2011) 29-55



AJIT RAM VERMA

1921–2009

Elected Fellow 1963

FAMILY BACKGROUND AND EARLY EDUCATION

AJIT RAM VERMA was born on 21 September 1921 at Dalmau in Pratapgarh Division of Uttar Pradesh. He often quoted his father that he was born on equinox day i.e. 23 September. His family originally belonged to Naushehra in Punjab and his grandfather Shri Daulat Ram Verma had left that place due to a family issue and started working in Indian Railways. He had passed middle class and could easily get a job in the Railways. Later, his father, Shri Hans Raj Verma had also served the Indian Railways all his life and rose to be a Station Master. He had many exceptional qualities. He was well versed with herbs and would treat people who approached him for the same. He was reputed for his astrological predictions. Verma had a strong influence of his mother Smt. Rani Devi all his life.

A.R. Verma had his primary education at Pratapgarh in a school, which was not recognized. Therefore, his father sent him to Allahabad with one of his assistants who arranged his admission in a recognized school there and also arranged his stay with a family of a railway employee. It is remarkable that this family at that time did not have a child but after his short stay with them they were blessed with a child. Verma did his high school from CAB Higher Secondary School at Meerut Cantt. It is a peculiar co-incidence that 20 years later, the author also passed his high school from the same school. His university education was entirely at Allahabad University, Allahabad. Professor K.S. Krishnan was Head of the Physics Department. He stood first is his M.Sc. (Physics) examination and for some time worked with Professor K.S. Krishnan on experimental study of reflection spectra of crystals in the ultra-violet wavelength region. It may be mentioned that his father was keen that he may take up a job in the Railways after he had graduated. He had a throughout first class career and it was felt that this will fetch him a respectable position. In this context, Shri Jagjit Singh, former member of Railway Board and well known popular science writer had recalled that once on an inspection tour of the railway station where Professor Verma's father Shri Hans Raj Verma was a Station Master, he had met young Ajit Ram, who had just passed his B.Sc. with first class. His father had introduced him to Shri Jagjit Singh and sought his blessings for a suitable job. After speaking to the young person for a short time, Jagjit Singh ji realized his strong inclination for further studies and his high potential for the same. He strongly recommended that Ajit Ram should do his Masters' at Allahabad and then decide about his career.

TEACHING AND RESEARCH CAREER

A.R. Verma was appointed as Lecturer in Physics at University of Delhi in 1947. It was through Professor D.S. Kothari's initiative that three outstanding scientists, A.R. Verma, R.P. Bambah and K.S. Singhvi, were appointed as Lecturers in the same interview. It is here that Verma came in close contact with Professor Kothari and developed life long association with him. He often mentioned that for him Professor Kothari was a real friend, philosopher and guide, a true mentor. While working as a Lecturer in Physics, Verma was awarded in 1950 a British Council scholarship for research in UK. Professor Kothari consulted famous physicist Professor P.M.S. Blackett (Nobel Laureate), who happened to be in Delhi at that time, regarding the most appropriate research group in Britain for Verma to pursue his research. They both felt that Professor S. Tolansky's group in Royal Holloway College, London University, which was very well known for their contributions in high resolution optics particularly in multiple beam interferometry would be the most appropriate place. As a result, Verma joined Professor Tolansky's group.

Ph. D. Work: *Landmark observation of growth spirals on silicon carbide crystal surfaces and measurements of step heights*

On joining his laboratory, Professor Tolansky suggested to Verma that he should take up study of metal surfaces, which would ensure him a Ph. D. degree in about two years time, the duration of the British Council Fellowship. However, Verma had taken with him some crystals from India like those of haematite and silicon carbide, which had flat and shining surfaces. He was keen to study these by high resolution optical techniques available in Professor Tolansky's laboratory. Finally, Professor Tolansky agreed that if he was very keen "he can play with his crystals for some time".

In late 1940s there was considerable interest in the study of crystal growth and lattice imperfections. It was well known that the morphology of crystal surfaces holds the key to understand the mechanism of crystal growth. The predominant theory of crystal growth from the vapour phase was based on two-dimensional nucleation leading to layer by layer growth. Since all the atoms are expected to occupy positions on a perfect periodic network in each layer, no defect is anticipated in the crystals. However, the mathematical model evolved by F.C. Frank and his co-workers showed that the probability of formation of a two dimensional nucleus which will remain stable is negligibly small when the supersaturation is low. This meant that crystals will take infinitely long time to grow to millimetric sizes, which are observed to exist. In laboratories crystals of millimetric dimensions are known to grow at finite rates even at low supersaturations. Frank and co-workers introduced the concept of screw dislocation in crystal growth to explain the experimentally observed rates of crystal growth. According to this mechanism, if a screw dislocation emerges on a crystal surface it will provide unending steps and will accelerate the crystal growth substantially. One important consequence of crystal grown by this mechanism is that the surfaces of crystals will not be molecularly flat. There should be a spiral in the form of stepped pyramid on the surface of the crystal grown by this mechanism. The step heights of the spirals will be directly related to the size of the unit cell of the crystals in that direction and the shape of the spiral will be governed by the symmetry of the crystal surface. Therefore, if experimentally it was possible to observe the growth spirals and their step heights were measured and correlated with crystallographic unit cell dimensions, it would have been a direct proof for the screw dislocation theory for crystal growth. Verma was fascinated with the silicon carbide crystals whose surfaces appeared to be optically flat and were known to be very stable. Therefore, these were eminently suited for high resolution optical interferometric studies.

Verma selected phase contrast microscopy technique for investigation of silicon carbide crystals. This technique was developed by Professor Frits Zernicke in 1930 and was used widely for examination of biological materials. It did not gain much popularity in study of inorganic materials. Professor Tolansky's laboratory had a phase contrast microscope attachment with the Vickers Projection Microscope, which was not in much demand. He mastered this technique and after considerable efforts succeeded in seeing a faint spiral-like feature on one of his SiC crystals. The contrast around the observed image was very low. His fellow students could not "see" and confirm this observation and suggested to him to photograph this feature to convince everybody. Of course, a photograph of the spiral proved Verma right and there was a lot of excitement about this observation.

It is well known that silicon carbide is a polytypic material, which has different polytypic structures. The most common variety of this material is a 6H polytype, which is hexagonal in structure and the value of unit cell dimension c is 15.1 Å. Therefore, the heights of the steps on the spiral observed on the basal plane were expected to be about 15Å. Verma used the high resolution multiple beam interferometry and took it to its limit to make these measurements. After considerable efforts he measured the spiral step heights as 15 ± 2 Å. The results were published in Nature as a leading note. It was interesting to note that in the same issue of Nature, Amelinckx had also published a paper on observation of growth spirals on silicon carbide crystal surfaces. He had used bright field method and had found the spirals' step heights to be up to 35Å. However, no exact measurement was reported in Amelinckx's paper. The same year, Dawson and Vand had investigated basal planes of n-paraffin crystals ($C_{36}H_{74}$) by employing electron microscopy and had reported step height of 43 ± 5 Å. However, phase contrast microscopy employed by Verma proved to be very effective in observing the molecular features on crystal surfaces and when it was combined with high resolution multiple beam interferometry step heights of only about 15 Å could be measured.

The results on SiC crystals reported above were immediately taken note of at global level and received high appreciation for A.R. Verma and those who were connected with these investigations directly or indirectly. Professor Zernicke who had developed the phase contrast microscopy technique in 1930 was awarded Noble Prize in Physics in 1953 and in his citation, it was mentioned, "…In this connection, Zernicke's phase plate serves an indicator which locates and measures small surface irregularities to a fraction of light wavelength. The sharpness of depth is so great that it penetrates to the point at which the atomic structure of the substance begins to become manifest…" Professor Tolansky was elected as a Fellow of the Royal Society soon after the work was published. Verma was able to present these new results during the next Congress of Crystallography even though a formal abstract had not been submitted. He often recalled that he was invited by Max von Laue for breakfast (Früstück) together with several distinguished scientists.

The spiral features observed by Verma had a strong impact on crystal physics and many textbooks have reproduced these like the well known book, *Introduction to Solid State Physics* by C. Kittel. Also, in the famous book on Science in History by J.D. Bernal photograph of a growth spiral is one of the two photographs. Fig. 1 shows a spiral observed by Verma. In September 1957 Professor Linus Pauling had contacted Dr. Verma and had remarked: "I have been interested to read your paper on dislocations in silicon carbide crystals, in the Proceedings of the Royal Society for 16 July 1957. This paper seems to me to be an important contribution to our understanding of the structure and growth of crystals."

Dear Dr. Verma:

I have been interested to read your paper on dislocations in silicon carbide crystals, in the Proceedings of the Royal Society for 16 July 1957. This paper seems to me to be an important contribution to our understanding of the structure and growth of crystals.

A.R. Verma was awarded Ph.D. degree in a period of 2 years' time by the London University. He had extended his work to different polytypes of silicon carbide in addition to the 6H variety with which he had started. These included: rhombohedral polytypes like 15R and 33R. The step heights of the spirals in the case of rhombohedral polytypes were equal to the length of the side of the rhombohedral unit cell.

During his investigations at the Royal Holloway College, Verma visited University of Bristol and showed his results to Professor F.C. Frank who was very excited about this experimental work. On a mutual agreement, they both sent papers to Philosophical Magazine, which were published in the same issue. Frank had given interpretation of several growth features reported by Verma. Frank extended his ideas of crystal growth to develop a theory of polytypism on the basis of screw dislocations having different Burgers vectors.

A growth spiral on the surface of silicon carbide crystal

It may be mentioned that Professor J.D. Bernal was Ph.D. examiner of Verma and he had asked several questions during viva-voce examination on the correlation between the experimentally measured step heights of growth spirals and the relevant unit cell dimension determined by X-ray diffraction. Due to limitations of the facilities at Holloway College, X-ray diffraction experiments had been conducted on silicon carbide specimens, which were different from those on which optical measurements were made. As a consequence, Professor Bernal readily offered Verma the facilities of his laboratory at Birkbeck College. In the meanwhile, he was selected for the prestigious ICI Research Fellowship of London University and could work for three years at Birkbeck College as well as Royal Holloway College. It is during this period that he learnt crystallography from such distinguished authorities as Professors J.D. Bernal and Kathleen Lonsdale. Professor Verma often mentioned as to how Kathleen Lonsdale would explain intricate details of crystallography in his notebook. He correlated the results of X-ray and optical investigations of silicon carbide crystals and also, identified anomalies when he tried to correlate the step heights and the lattice spacing in the c direction. Several of the polytypes had shown unresolved disorder. Also, there were some polytypes in which the measured step heights were sub-multiples of the relevant dimensions of the unit cell. In the case of rhombohedral structures, the step height and the value of c did not show direct correlation. These findings had established that more in-depth investigations were required to understand the phenomenon of polytypism. The research work reported above was consolidated by Verma in the form of a book, Crystal Growth and Dislocations, published by Butterworth, London in 1953.

During his research career Professor A. R. Verma had established three schools of crystallography, one each at University of Delhi, Delhi; Banaras Hindu University, Varanasi; and National Physical Laboratory, New Delhi. His major contributions at the three centres are described in the following.

Contributions at the First School of Crystallography

In 1955, Dr. A.R. Verma returned to University of Delhi from London University and laid the foundation of the first School of Crystallography. It may be mentioned that he was promoted as Reader in Physics on his return. G.C. Trigunayat was the first research scholar who joined his group. The research work undertaken was essentially an extension of the investigations he had started at Birkbeck College and Royal Holloway College at London. He started with the investigation of solution grown cadmium iodide single crystals. Cadmium Iodide crystals had been investigated by A.J. Forty and R.S. Mitchel. Forty had observed several growth spirals on the basal planes of the crystals and had reported that the step heights of these spirals measured by internal interference fringes could be expressed as integral multiples of the thickness of the minimal sandwich of cadmium iodide. It is on this basis that he had predicted that CdI_2 was a polytypic material. Mitchel had investigated cadmium iodide crystals by employing X-ray diffraction and he had reported that 20 polytypes in his studies could be related with the spiral heights reported by Forty. However, the correlation between the measured step heights and the unit cell dimensions obtained by X-ray diffraction investigations was done on two different sets of samples used in the two techniques. Therefore, Verma together with Trigunayat initiated a study of CdI_2 crystals, which involved growth from the aqueous solution and their investigation by X-ray diffraction and optical interferometry techniques. Cadmium iodide is a very soft material unlike silicon carbide and therefore these crystals needed careful handling. These were grown on glass micro slides. The optical measurements were carried out in-situ and step heights could be deduced from the internal interference fringes and these specimens were then isolated for X-ray diffraction work. It may be mentioned that Verma established a Vicker's Projection microscope, a 12" diameter Edwards Vacuum coating unit and a Philips X-ray generator with a 3 cm cylindrical oscillation camera in his laboratory. The surprising result of these investigations was that practically all the crystals showed no correlation between the step heights of the growth spirals and the unit cell dimensions obtained by X-ray diffraction. This result showed that the screw dislocation theory could not be used to understand polytypism in these crystals. However, several new polytypes were discovered and Trigunayat and Verma for the first time reported two rhombohedral polytypes whose formation could not be understood on the basis of screw dislocation theory. This formed the Ph. D. thesis of G.C. Trigunayat. During this period, several original research papers and review articles were published in reputed journals.

After Verma left University of Delhi to join BHU, Varanasi, G.C. Trigunayat continued studies of polytypism and other physical phenomena. He and his co-workers extended this work further on CdI_2 crystals grown from the vapour phase. They found that the growth of their crystals could be understood in terms of Jagodzinski's theory, which was based on thermodynamical considerations. Phase transitions induced by heating the cadmium iodide crystals have also been investigated in detail. The crystal structure of over 80 polytypes has been worked out. A special feature of this work was the discovery of the first found actual examples of homometric structures, which were theoretically envisaged by Patterson in 1944.

Establishment of Second School of Crystallography: Banaras Hindu University, Varanasi

In September 1959, Dr. A.R. Verma was appointed as Professor and Head of the Physics Department of Banaras Hindu University, Varanasi. He made concerted efforts for all round growth of the Department including the fields of spectroscopy, nuclear physics, theoretical physics and crystallography. The facilities available for crystallographic work to begin with consisted of a Philips X-ray diffraction unit and oscillation and Weissenberg cameras. Here again, Verma decided to work on polytypism but in greater details to tackle some of the unsolved problems. For example, at Birkbeck College, London, he had mostly focused on determination of the size of the unit cells of polytype crystals and tried to correlate the measured step heights of the growth spirals with the c lattice parameter by making both the measurements on the same silicon carbide crystals. However, no detailed structural investigation of the specimen crystals had been carried out. This was taken up as a research problem in the new laboratory at Varanasi. At this time, P. Krishna who had done his M. Sc. from University of Delhi joined Professor Verma. It is interesting to mention that at Delhi University, Krishna was advised by friends and well-wishers to join any of the groups on theoretical physics, which were very well established and reputed so that he could be ensured of a good job after his Ph.D. However, Krishna, as M.Sc. student had been fascinated by Prof. Verma as a teacher and as a wonderful person at University of Delhi. He had made up his mind to join him as a research scholar. He had to silence his well wishers by saying that he would be happy to get a job of a school teacher after his Ph.D. in experimental physics under the guidance of Professor Verma if he could not find a proper job in a university or a college. Of course, it is well known that Krishna has made a mark with his investigations in polytypism and his work has been recognized in different centres of the world and subsequently he got elected as a Fellow of INSA.

Krishna, under the guidance of A.R. Verma used Weissenberg and oscillation cameras to investigate silicon carbide crystals. He solved crystal structure of a number of polytypes of SiC. These structures were solved by recording specially the 10.1 row of diffraction spots. They keenly observed the intensities of different X-ray reflections and from the missing reflections and variations in intensities of other reflections, the structure of these polytypes were determined. Some of the results showed that a polytype like 36H could contain two structures of the same period within one crystal piece. These detailed investigations showed that deduction of earlier polytype structures from screw dislocations in the basic phases had two drawbacks namely, (i) they employed Zhadanov symbols instead of the actual ABC sequence of layers and (ii) it was assumed that every screw dislocation ledge could wind over itself without any slip. Verma and Krishna showed that the rhombohedral structures would result when the first and the last layer of the exposed ledge were in the same orientation A, B or C and accordingly they deduced all possible polytypes structures that could result from theoretical screw dislocation in the basic phases using the ABC notation. Their investigations revealed that there were several polytypes such as 36H, 54H, 66H and 90R, which had a unit cell height that was an integral multiple of c-parameter of the basic structure. There were many others which contained faults in the middle of the unit cell in addition to those at the end and the origin of such polytypes which could not be understood in terms of spiral growth around single screw dislocations. Their growth would require a complicated set of cooperating dislocations of which there was no direct evidence on crystal surfaces. Such structures were termed as anomalous. This study showed that spiral growth did not determine the structure of polytypes but rather followed it. The surface features appeared in later growth of these crystals. The details of the investigations on polytypism were published as a book, *Polymorphism and Polytypism in Crystals*, by A.R. Verma and P. Krishna, published by John Wiley in 1966.

After obtaining his Ph.D., P. Krishna established his own research group and had done many interesting investigations with his students and co-workers on solid state transformations in silicon carbide and zinc sulphide crystals and they have developed a faulted matrix model for anomalous polytype structures and giant screw dislocations in platelet crystals.

Govind Singh joined as a Ph.D. student and Professor Verma assigned him the problem of determining detailed crystallographic structure of anomalous polytypes of SiC and understand their structure in relation to Frank's theory. He undertook investigation of structures of 126R and 54H on which some preliminary work had already been done. The polytype 126R showed two spirals of equal step height of about 106 Å but of opposite hand. To understand the observed X-ray intensities of different diffraction spots about 160 probable structures were tried but none of these proved to be satisfactory. A reasonable fit between the calculated and the observed intensities was obtained for the structure $[(33)_3\ 43433223]_3R$, which had been corrected later on. The polytype 54H appeared to be based on 6H and its structure was found to be $(33)_6$ or 323334. The spirals on the growth face had a step height equal to half of the c-periodicity of the hexagonal cell. Thus, the internal structure and the surfaces of both the crystals did not support Frank's theory of screw dislocation for formation of polytypes. Two new polytypes, 105R and 99R were discovered and their structures were determined. The polytype 105R was one of the undiscovered members of the rhombohedral series while structure of polytype 99R could be explained on the basis of three cooperating screw dislocations. Govind Singh undertook a detailed electron density mapping of 6H and 15R polytypes whose structures were well known. These results indicated that the spacing between the h and K layers in the 6H unit cell is not exactly the same as between the k layers in the hkk structure. This investigation showed that binding energies of polytype structures are not identical and the bonds could be strained near the faults. Later, Govind Singh and his students and co-workers had pursued study of extremely large period polytypes. They have also used lattice imaging technique in electron microscopy which helped them to reveal the stacking sequences in their specimen polytypes.

O.N. Srivastava joined Professor A.R. Verma in 1962 and he was asked to study cadmium iodide crystals in detail by using X-ray diffraction techniques. Earlier G. C. Trigunayat had correlated spiral step heights with unit cell dimensions in CdI_2 crystals. However, detailed crystallographic structures of CdI_2 polytypes had not been determined. Using critical analysis of different X-ray reflections, O.N. Srivastava and A.R. Verma determined structures of the polytypes of CdI_2: 22H, 26H and 28H. It was also found that the observed structures could not be explained in terms of screw dislocation ledges, which may form stable growth nuclei in the parent 4H structure. For investigation of large period polytypes, it was important to improve the resolution of the X-ray diffraction experiment and for this purpose, a fine focus X-ray source was employed. With this arrangement it was possible to resolve X-ray diffraction spots even from large period polytypes like 50H CdI_2 polytypes. Subsequently, O.N. Srivastava established his own active group and investigated variation of electronic band active gap of layered semiconductors as a function of their periodicity and dielectric properties were correlated with the structure of these materials. He also had investigated phase transformations in MX_2 type layered polytypes (like CdI_2 and PbI_2). Presently, Professor O. N. Srivastava is actively engaged in investigating hydrogen storage materials, high temperature superconductors, carbon nano tubes and other nano materials. He is well known for his contributions and is a Fellow of INSA.

The combination of multiple beam optical interferometry and X-ray diffraction techniques was used by A.R. Verma together with Vinod Kumar Srivastava, a Ph.D. scholar at BHU, Varanasi to investigate molecular films. An equipment based on the principle of Blodgett-Langmuir was constructed to prepare monomolecular films and transfer the same on to solid substrates. A variety of materials like barium palmitate, barium margarate, barium stearate and barium behenate on a plain glass slide were investigated. The thicknesses of the films transferred on to plain glass slides were measured by multiple beam interferometry. A lot of experimental ingenuity was needed to prepare and measure thicknesses of these monomolecular layers, which were independent of the refractive index of the film. The substrate glass slides were carefully selected keeping in view their high quality flatness. A thin layer of silver was deposited on the slides by thermal vacuum evaporation, which served as a clean hydropholic surface for deposition of films to be studied. On a large area of the silvered glass slide, a suitable number of layers of barium palmitate and similar materials were deposited to form a base layer. The Blodgett-Langmuir technique was employed for this purpose. On a part of this base layer, a second film of required number of layers (2, 4 and 7) was deposited which produced a step on the surface. A thin layer of pure silver (about 1000 Å thick) was then deposited over the region covering the step and the surrounding area. A reference optical flat was also coated with a low absorption coating having about 80% reflectivity. The specimen film was matched at a small angle against the reference flat and this system was illuminated with normal incident parallel white light to obtain fringes of equal chromatic order (FECO). This experiment gave high accuracy in measurement of thickness and difference in thickness of homologues series of fatty acids. With this set-up chain length interval of only 1.5 Å could be distinguished.

For X-ray diffraction experiments a micro focus X-ray source with copper Kα radiation was used to obtain diffraction spectra on a Bragg-Muller spectrograph. With this arrangement very beautiful X-ray diffraction patterns from multiple layers of barium stearate and similar materials could be recorded. The agreement between the measured thickness by optical means and X-ray diffraction experiments proved the monomolecular nature of all the films. These experiments also showed that the molecules in the layers transferred on glass substrates were oriented with hydrocarbon chains almost at right angles to the substrates.

Professor V.K. Srivastava after completing his Ph.D. at BHU established an active group at Roorkee University, Roorkee presently, IIT, Roorkee. He also investigated the optical and dielectric properties of these films. His group investigated the phenomenon of internal fields in these films. He has investigated in great depth, the physical properties and structure of a variety of monomolecular films. In the recent times, Blodgett-Langmuir layers are finding wide applications in bio-molecular sensors and other devices.

Contributions as Director, National Physical Laboratory, New Delhi & Establishment of the Third School of Crystallography

In 1965, Professor A.R. Verma was appointed Director of National Physical Laboratory, New Delhi, a prestigious national laboratory with high visibility. It had been headed by Professor K.S. Krishnan since its inception in 1947 till 1961, when Professor Krishnan died suddenly. It was followed by a short period of Directorship of Professor P.K. Kichlu. As mentioned above, Professor Krishnan was Professor Verma's teacher at Allahabad and he had worked with him on study of reflection from crystal surfaces at ultra-violet wavelengths just after his M. Sc. He had kept good contact with Prof. Krishnan and during his five years stay at London, he sometimes met him during his visits to UK. In one of these visits, they together took a three hours boat trip on the river Thames where Krishnan shared with him many of his experiences including the work with Professor C.V. Raman, which led to the discovery of the Raman Effect and his researches on magnetism on the basis of which he was elected as a Fellow of the Royal Society. Professor Verma occasionally reminisced about this interaction and it revealed many interesting features of human nature. Dr. Verma also had a very cordial and close relationship with Professor Kichlu, which developed during his affiliation with the Department of Physics and Astrophysics at University of Delhi. There was a gap between appointments of Professor Kichlu as Director, NPL and the unexpected passing away of Professor Krishnan. Similarly, there was a gap between the joining of Professor Verma and the resignation of Professor Kichlu in 1964. The laboratory had passed through a turbulent period. Also, in between, Government had requested famous physicist, Professor P.M.S. Blackett to look at the working of NPL and submit a report, which is often referred to as Blackett Report.

As was the practice at that time, the Committee constituted to select Director, NPL was chaired by Shri M.C. Chhagla, the then Education Minister and Vice President, CSIR Society. During the interview, Professor Verma had stressed about the need for experimental work focused on precision measurements like the one he had developed by using optical techniques. Dr. H.J. Bhabha was also a member of the Selection Committee beside two other members. There was a lot of discussion apparently because Professor Verma was quite young, being only 44 years of age and the Committee wanted to be sure.

Dr. Verma also sometimes recalled the day when Professor K.S. Krishnan had joined as Director of NPL in an office provided by the Department of Physics, University of Delhi, Delhi. He took charge with some money in a safe box handed over by a representative from CSIR headquarters. After the formalities were over, it was lunch time. Professor Krishnan enquired from Dr. Verma, who was a Lecturer there, as to where he takes his lunch. Dr. Verma informed him that a bearer brings lunch for him from his home and would be coming any moment. He said, "Okay, I shall share lunch with you" and they had lunch together.

As is well known, right from its inception NPL had been assigned the responsibility of maintaining the national standards of physical measurements and to conduct research on the same. Keeping in view the need of the Indian society, NPL had been doing applied research on ferrites, piezoelectric ceramics and carbon products and there were two pilot plants functioning at NPL. There was activity on solid state physics including facilities for preparation of single crystals and investigation of their physical properties, electron microscopy, optics and radio propagation studies. NPL also had a research group working on low temperature physics. The emphasis in standards area was on testing and calibration work to meet the needs of the Indian industry and research in standards was very limited. Also, the materials activity had potential for considerable growth. Professor Verma started with enthusiasm and created positive ambience for researchers at all levels to pursue quality research. As mentioned above, there was a Blackett report on the functioning of NPL. In this report, considerable stress had been laid on calibration activities.

Soon after joining NPL, Professor Verma tried to reorganize all the main activities keeping in view the strengths of the laboratory, the needs of the country and the international trends in different areas. In the field of standards, he laid the foundation of quantum metrology. He was deeply involved in the creation of the National Committee on Testing and Calibration Facilities (NCTCF) which later transformed into National Accreditation Board for Testing and Calibration Laboratories (NABL). At international level, he served on the International Committee for Weights and Measures (CIPM). He encouraged the author to plan for preparation of Certified Reference Materials, which later became a successful inter-laboratory project. He helped in reorganizing the industrial materials activity and parts of the solid state physics activities into a Materials Science group and work on advanced materials like semiconductor silicon and silicon solar cells was initiated. Carbon fibers were prepared at NPL, for the first time in the country. This work was also supported by UNDP through a major project. A new group on high pressure high temperature materials like synthetic diamonds was established and facilities for hydro-static intrusion of materials as well as preparation of advanced materials by forging technique was started under a UNDP project. To back up these activities, special stress was laid on analytical techniques and a division of specialized techniques was created. Dr. Verma persuaded several senior people like Professor

V.G. Bhide and Dr. G.C. Jain to join NPL. The group on Radio Sciences expanded under the able leadership of Dr. A.P. Mitra.

Professor Verma encouraged people at all levels and NPL became the only laboratory having four Director Grade Scientists. He often stressed that as a head of the institution, you need to use your head and heart. As a consequence, humanism was one of his great attributes. At times, he would think loudly that in a given situation what would be the strategy of a person like Professor D.S. Kothari. He often cited one of the great Mantra of Professor Kothari, "When in doubt give yourself disadvantage." The author like many others greatly benefitted from this wonderful guide in life.

Under Professor Verma's directorship the reputation of NPL as an eminent centre of research grew significantly in India and abroad. Students from outside India like Bulgaria and Egypt came for their Ph.D. work. One of them, Mrs. S.K. Peneva from University of Sofia did her Ph.D. while working at NPL on growth and study of whisker crystals. It is during this period that the author came in direct contact with Professor Verma.

Professor Verma emphasized on the need for precision measurements and indigenous development of techniques, equipments and materials. He helped in creation of a Specialized Techniques Division, which had facilities to characterize materials regarding chemical composition and structure. In the field of crystal growth and characterization, he got directly associated with the author and encouraged him to grow a full-fledged group. As a result of this effort, the author and his group had developed several advanced equipments including the following:

- An X-ray diffraction topography camera similar to a Lang camera;
- A microfocus X-ray generator;
- A triple crystal X-ray diffractometer;
- A low angle X-ray scattering camera; and
- Two versatile crystal pullers for growth of nearly perfect single crystals by the Czochralski method.

The following advanced techniques were also developed at NPL:

- A high resolution X-ray Laue method for the study of lattice imperfections in needle shaped crystals;
- A technique for measurement of dielectric loss and electrical conductivity of insulators at different temperatures and under different environments;
- X-ray diffraction topographic techniques for evaluation of perfection of single crystals;
- A technique for measurement of dielectric constant of solids;

- High resolution technique for study of diffuse X-ray scattering from single crystals;
- Multicrystal diffractometry for evaluation of perfection of single crystals by recording rocking curves and high resolution topographs; and
- Techniques for growth of single crystals of good perfection by the Czochralski method.

One of the unique features of these efforts was that by employing techniques and equipments developed within the laboratory several fundamental results of considerable significance were obtained. These led to a deeper understanding of mechanism of crystal growth, lattice imperfections in nearly perfect crystals and origin of diffuse X-ray scattering. The important results obtained in these investigations are summarized in the following.

Growth, Morphology and Lattice Imperfections in Whisker Crystals

Mrs. S.K. Peneva of Sophia University, Bulgaria joined NPL as a Visiting Research Scholar in the year 1966. She had opted to work with Professor Verma and wished to investigate growth and morphology of whisker crystals. These crystals had attracted the attention of scientific community for two reasons. Firstly, the rate of growth of vapour grown whiskers at low supersaturation was observed to be very fast and could not be understood in terms of the layer by layer growth mechanism of crystal growth. Secondly, these whiskers were the only materials which exhibited elastic strains of a few percent as expected in the case of ideally perfect crystals. In other words, their mechanical strength was nearly 1000 times that of the normal materials. There were following two main theories to explain the growth of whisker from the vapour phase: (i) the screw dislocation theory proposed by F.C. Frank and (ii) the Vapour Liquid Solid (VLS) mechanism proposed by Wagner and Ellis. According to the screw dislocation mechanism, the ledge of the screw dislocation provides an unending series of growth steps and the crystal would grow at a high rate along the axis of the dislocation and would therefore, exhibit a needle like shape, which is a characteristic of the whisker crystals. Since there is only one imperfection, namely the axial screw dislocation, it is a nearly perfect crystal and can exhibit high mechanical strength. In 1960s, it was considered that this is the most probable mechanism of whisker growth and therefore, all whiskers were expected to contain axial screw dislocations. It was generally thought that if a suitable technique was employed, one would be able to observe the axial dislocation. However, it was not an easy problem. The diameters of the whiskers are very small, a few micrometers and their lengths are also small.

According to the VLS mechanism, a small amount of a suitable impurity can lead to whisker growth. It should be able to form an alloy with the vapours of the materials to be grown as a whisker. When the vapours are allowed to condense on a substrate on which impurity is placed at several locations, the impurity forms an alloy with the incoming vapour and acts as a preferred sink for the vapours. This leads to the formation of droplet of solid solution, which eventually becomes super saturated with the material of the vapour and the excess material precipitates at its bottom in the form of a needle. The droplet remains at the top of the needle. One of the great successes of this mechanism was the growth of silicon whiskers below gold droplets which had served as the impurity. In this mechanism there is no need of a defect to induce the growth at a fast rate. Also, since no defect is expected theoretically, the whiskers can exhibit mechanical properties of ideal crystals.

S.K. Peneva had some experience in growth of whiskers of cadmium from the vapour phase. Also, Sofia had active and known group on crystal growth. She set up a glass based system for preparation of whiskers of materials like cadmium which had low melting point so that growth experiments could be carried out in a pyrex apparatus. This facility was fabricated at NPL with the direct involvement of Mr. F. Kiss, who was instrumental in propagating glass blowing in India. He even got incorporated a NPL made mercury diffusion pump in the system. This set-up allowed baking of growth ampoules under vacuum of $\sim 10^{-6}$ Torr for about 24 hours and repeated distillation of Cd under this high vacuum. The final pyrex ampoule was sealed under vacuum. It contained purified metal at one end and was placed in a thermal gradient furnace to allow transfer of metal vapours at the other end, where whisker growth was observed. Using this facility a number of whiskers were grown under different conditions. Most of the good quality whiskers were very thin, with diameters of only a few micrometers.

The main challenge was to observe and study the axial screw dislocations in vapour grown whiskers like those of cadmium. Dragsdorf and Webb from Cornell University had published a paper on study of α-Al_2O_3 whiskers by X-ray Laue diffraction technique. An axial screw dislocation is expected to produce a twist in the lattice planes belonging to the zone whose axis is along the dislocation line (Eshelby twist). If this axis is aligned along the axis of a cylindrical X-ray camera the equatorial Laue spots would be tilted with respect to the axis of the camera. The experimentally observed tilt is an indication of the axial screw dislocation and even its Burgers vector can be determined from the observed tilt of equatorial spots. Dragsdorf and Webb had published Laue spots of their α-Al_2O_3 whiskers and claimed to have observed axial screw dislocations.

S.K. Peneva started study of X-ray diffraction spots of Cd whiskers. Keeping in view the micrometric thicknesses of whiskers she employed a micro focus X-ray source manufactured by M/s Hilger with a focal spot size of $\sim 40\ \mu m$ on the anode. A Hilger cylindrical camera with radius of 28.6479 mm was used for recording the Laue spots. However, she had no experience of X-ray diffraction and she often interacted with the author, who was at that time working on studies of point defects in alkali halide crystals by dielectric loss measurements, optical absorption, EPR and electrical conduction studies. The author and Peneva found that the formulation of Dragsdorf and Webb was rather approximate. They developed a rigorous theoretical method by which the shapes of the diffracting lattice planes could be determined from the observed shapes of their Laue spots. Using this approach it is possible to not only measure the twist in the planes but also other departures from the ideal state. Professor Verma often used to quote his teacher Professor Kathleen Lonsdale that a Laue spot is the projected image of the lattice plane. This new method was used to analyze the Laue spots published in the paper of Dragsdorf and Webb and it was found that their shapes could not be due to a simple twist in the lattice. Professor Verma wrote to Professor Webb and sought his comments on these results. However, he advised that the new method should be used on the whiskers being grown at NPL. Soon the new method with a few illustrative results was published by the author and Peneva. They also worked out a complementary method with which shapes of Laue spots of ideally perfect crystals were determined and these were compared with those of the Laue spots obtained experimentally. The comparison clearly brought out the extent of defects in the crystals.

A number of cadmium whiskers, grown under different conditions and with different morphologies were investigated by the new X-ray Laue method. However, no twist in the lattice planes and therefore no axial screw dislocation could be detected. Most whiskers showed curvature of lattice planes, which could be due to bending under their own weights. Low angle boundaries were observed in some of the whiskers and their angles of tilt could be determined quantitatively. Thermal annealing was used to remove the boundaries. Attempt was made to see if the Cd whiskers grew by the VLS mechanism. However, it was found that deliberately introduced lead and tin impurities did not promote whisker growth. These were the first detailed investigations which revealed the absence of axial screw dislocations in vapour grown whiskers. S.K. Peneva was awarded Ph.D. by University of Delhi on the basis of the work described above.

Development of Facilities for X-ray Diffraction Topography

In 1970 Professor A.R. Verma encouraged the author to develop facilities for X-ray diffraction topography at NPL. It was an ambitious task. There was no topography system in the country and the author had not yet been abroad and therefore had not seen a working equipment. There were some active international groups like that of Dr. A.R. Lang at the Bristol University in UK. Professor Verma had great fascination for indigenous development of advanced equipment, particularly those which enabled experiments at limits of resolution. A camera for X-ray diffraction topography was this type of system. This system had an immediate application for direct observation of an axial screw dislocation in whisker crystals. Additionally, efforts were being made at NPL to strengthen the broad area of crystal growth and characterization of lattice imperfections.

The author and his young students and co-workers improvised an X-ray diffraction topography system in a few months time in July 1970. He prepared a half meter long collimator out of a glass tube around which a lead sheet was wound. It had an expensive slit made out of a platinum sheet. The more desirable tantalum sheet was not available in NPL at that time. An optical spectrometer was upgraded to provide rotations to the specimen around a vertical axis that was perpendicular to the horizontal plane of diffraction. A standard two arc goniometer was used to provide tilt motion to the specimen crystal. A scintillation counter was fabrication which employed a 13-dynode photomultiplier tube borrowed from Atomic Minerals Division of DAE, which was located at NPL at that time. An Ag activated ZnS phosphor developed at NPL served as a scintillator. A binary counting system meant for Mossbauer Effect experiments was utilized to measure intensity of X-rays. The Hilger microfocus X-ray source served as a high brilliance source with very small source size (~4 μm in the plane of diffraction after foreshortening). First of all Images of defects in LiF single crystals were recorded. This was an exciting success and it followed development and fabrication of a comprehensive system, which comprised of (i) a collimator with carefully prepared slit system out of tantalum sheets; (ii) a turntable which could provide rotations of a few arc sec to the specimen; (iii) a traversing mechanism for translating the specimen and the photographic film/plate across the X-ray beam; (iv) a vertical circle goniometer; (v) a second slit which blocked the residual direct beam and allowed only diffracted X-ray beam to pass through; and (vi) a scintillation counter and a comprehensive counting system used to measure X-ray intensities.

The X-ray diffraction topography system was first used to investigate zinc sulphide whiskers grown from the vapour phase. No axial screw dislocation was observed confirming the earlier results on Cd whiskers obtained by analysis of high resolution Laue spots. Some whiskers of alkali halides also yielded similar results. However a few ZnS whiskers with bends in their bodies showed images of dislocations. Initially, there was reluctance to accept these results on absence of axial screw dislocations in whiskers. But now it is a well established fact.

After the topography camera was developed Professor A.R. Verma strongly suggested to the author to also develop a microfocus X-ray generator at NPL. It is quite challenging to maintain the demountable microfocus sources. During the Ph. D. work of S.K. Peneva the Hilger X-ray generator suffered repeated breakdowns and finally the local Hilger representatives expressed inability to maintain the same. Thereafter the maintenance was done in the research group itself. Several improvements like continuous monitoring of vacuum were introduced. Filaments were also developed in the laboratory. Therefore, the expertise developed in maintaining the commercial equipment was use to successfully develop a demountable microfocus X-ray generator.

The author together with Vijay Kumar investigated defects in α-Al_2O_3 single crystals grown from the vapour phase by the CVD method and those by the Czochralski and the flux growth techniques. It was shown that the CVD grown crystals which were away from the seed-crystal interface were nearly perfect and dislocations in their topographs were well resolved. The degree of perfection of Czochralski grown crystals was rather low. Inclusions could be observed in the flux grown crystals. However, in terms of perfection these were in between the best of the CVD grown crystals and the Czochralski grown specimens. Vijay Kumar was awarded Ph.D. by University of Delhi.

Origin of Diffuse X-ray Scattering and Studies on Nearly Perfect Single Crystals

Professor Verma had a very broad comprehension of crystallography of inorganic materials particularly, the role of X-ray diffraction techniques in revealing the real structure of materials and its correlation with their physical properties. It is well known that there is finite X-ray scattering in close proximity of the well defined X-ray diffraction maxima. This had fascinated crystallographers almost since the time of discovery of diffraction of X-rays. The origin of Diffuse X-ray Scattering (DXS) had been attributed to the elastic thermal vibrations of the lattice because of which finite intensity of X-ray scattering would be expected from regions of reciprocal space around the reciprocal lattice points (relps). DXS measurements had been extensively employed for study of elastic thermal waves and phonons in crystals and the research group of Professor Wooster at Cambridge University had extensively used this method to determine elastic constants of crystals from the observed distribution of diffusely scattered intensities in different directions in the reciprocal space. Professor Verma and the author decided to use the X-ray diffraction topography system developed at NPL for measurement of DXS from crystals. The main idea was that in the conventional techniques, the measurements are made around diffraction maxima having a half width of around 1 arc deg or so. Since the diffraction peaks obtained with the topography system were about 40 arc sec in half width, this was expected to lead to an improvement of about 100 times in the resolution. Also, unexplored region of the reciprocal space close to the reciprocal lattice point (relp) will become available for investigation. Further, the possibility of measurement of elastic constants of whisker crystals in a non-destructive method was very attractive. Therefore, the author together with Bhanu Pratap Singh, who had joined as a research scholar, initiated work on this problem. A second X-ray diffraction topography system was designed and fabricated at NPL with particular emphasis on capabilities for X-ray diffractometry and DXS measurements. With this system changes in glancing angle of about 1 arc sec could be produced and a new simple ingenious optical method for measurement of angle was introduced. This technique has evolved with time and has been used in all the multi-crystal X-ray diffractometers developed by the author and his students and co-workers over the years. It was found that DXS measurements would not be desirable on crystals of ordinary perfections since these produce several peaks in their diffraction curves and what could be considered as a diffuse scattering may actually be usual Bragg diffraction from a mis-oriented region of the crystal. Therefore, to calibrate the new technique, nearly perfect silicon specimens were selected.

The first results with silicon crystals showed that the diffraction maxima due to $K\alpha_1$ and $K\alpha_2$ components of the $K\alpha$ beam were well resolved. DXS measurements were made around more intense $K\alpha_1$ peak that too on the lower angular side, which was away from the $K\alpha_2$ peak. DXS measurements were made along the reciprocal lattice vector **R*** as well as perpendicular to the same so that from the slopes of DXS intensity versus $1/K^{*2}$ plots one should be able to measure the elastic constants. Here **K*** is a vector that joins the elemental volume of the reciprocal space under investigation to the nearest relp. The first results produced a surprise. It was found that the slopes of the lines with **K*** along the reciprocal lattice vector **R*** were much higher than those of the lines for **K*** perpendicular to **R***. This was just opposite of what was expected theoretically if the observed diffuse X-ray scattering was due to elastic thermal vibrations of the crystal lattice. Further, it was observed that in any direction of **K*** there were more than one line with different slopes in the DXS plots. This was a very important result showing that the diffusely scattered intensity close to the relp is not pre-dominantly due to thermal waves. Therefore, a major study was undertaken to establish the true origin of diffuse X-ray scattering.

In the experiments performed with X-ray diffraction topography set up, it was observed that the diffraction maxima were very narrow with half widths of about 40 arc sec as compared to the usual peaks with width of about 1 arc deg, leading to is an improvement of about 100 times. However, even this half width was nearly 8 to 10 times of that expected theoretically. The reason was obvious. The X-ray beam from the micro-focus source was collimated with the help of a long collimator fitted with a narrow slit. The specimen crystal itself resolved the $K\alpha_1$ and $K\alpha_2$ peaks and served as a monochromator. To obtain curves which have half widths close to those expected theoretically, it was decided to improve the experimental set up further. The author together with Bhanu Pratap Singh developed a three crystal X-ray diffractometer within the laboratory. A set of two monochromators made out of nearly perfect silicon boule as per the arrangement of Bonse and Hart were employed to produce a nearly parallel and monochromated X-ray beam. This arrangement helped to take the resolution to the state-of-the-art level at that time. The diffraction peak for (111) lattice planes of a silicon crystal recorded with Mo $K\alpha_1$ radiation had a half width of only 5 arc sec. The key achievement in this equipment was that the monochromators resolved $K\alpha_1$ and $K\alpha_2$ components of the $K\alpha$ beam and a special slit was introduced to isolate the $K\alpha_1$ beam which was used as the exploring radiation. It may be mentioned that the theoretical half width of the diffraction curve under consideration is only about 4 arc sec for these experimental conditions. This was a major breakthrough and the DXS measurements were made by using this arrangement. This new technique was also published by Lal and Singh.

The high resolution DXS measurement technique around the diffraction maxima having nearly theoretical half widths proved to be very effective in establishing the origin of the diffuse X-ray scattering from crystals. This was the first time ever that DXS measurements were made so close to the reciprocal lattice points with unprecedented resolution. The results of experiments with silicon crystals had clearly shown that the slopes of the lines with **K*** along **R*** were higher than those of the lines obtained for **K*** perpendicular to **R***, similar to the results obtained with X-ray diffraction topography set up described above. This clearly showed that the observed diffuse X-ray scattering cannot be explained on the basis of phonons or thermal vibrations of the lattice. Further, in this case, the reciprocal space was mapped along at least four directions around the relps and an asymmetry was observed in DXS intensities when results of measurements made along a direction of **K*** and an opposite direction was compared for the same values of **K***. Also, experiments performed with different relps showed similar results. Some experiments were performed by heating silicon crystals at different high temperatures. The thermal part of DXS became manifest when the temperature of the crystal was raised close to the Debye temperature (640 K for Si). Experiments were also performed with nearly perfect crystals of alkali halides, which have low Debye temperatures. As will be described in the following, the author and co-workers had developed new indigenous equipments for growth of nearly perfect crystals by the Czochralski method. These facilities had enabled growth of nearly perfect crystals of KCl, KBr and NaCl. The Debye temperatures of these crystals were considerably lower than that of silicon. In the case of KBr crystals, it is even below the room temperature. Even these results were more or less similar to those obtained on silicon.

The results described above clearly showed that DXS close to the relps is not due to thermal vibrations of the lattice at and around the room temperature. The other source could be the defects. Subsequent detailed research work by the author and co-workers established that this is indeed so. Crystals with different thermal histories like alkali halide crystals cooled to room temperatures at different rates after growth showed very different distribution of DXS intensities. Phenomenological models had been used to determine the size and shapes of point defect clusters from DXS measurements. Also, the distinction between scattering from isolated point defects and their clusters was established. In later years, the author and his group have used this technique to investigate point defects and their clusters in ion implanted crystals and crystals of bismuth germinate and similar materials.

Investigation of Dynamical Diffraction Phenomena and Diamond Crystals

In 1940s, there were intense activities on studies related to X-ray diffraction from natural diamond crystals. It is well-known that diamonds are classified as type I and type II. The type I diamonds exhibit prominent infrared absorption around 7.8 μm. Type II variety are transparent in this region. Professor C.V. Raman had a large group working on different aspects of diamonds at that time and he had proposed four structures for diamonds based on possible vibrations in the diamond lattice and the symmetry considerations. The British school of crystallographers including Professor Kathleen Lonsdale did not agree with this approach. An intense research activity on studies on diamond crystals took place and a whole volume of Proceedings of Royal Society is devoted to this issue. Professor Verma was aware of these activities. Several peculiar diffraction features from natural diamond crystals had also been reported including the forbidden 222 reflection. Later experiments at Bell Labs had established that presence of nitrogen in type I diamonds gave strong absorption in type I variety diamonds. Type II diamond were almost free of nitrogen. Subsequently other impurities had been investigated in diamond crystals.

An analysis of previous work on X-ray diffraction studies on diamond crystals showed that the resolution of the techniques available at that time was not sufficiently high. Professor Verma and the author decided to examine natural diamond crystals by using the high resolution X-ray diffraction techniques developed at NPL. It was possible to borrow a number of diamond crystals from the famous collection of late Professor C.V. Raman from the Raman Research Institute through the courtesy of Professor J. Radhakrishnan, the then Director and Professor S. Ramaseshan. Investigations on diamond crystals by high resolution X-ray diffraction techniques clearly showed that the peak intensities of diffraction peaks of the type II variety crystals were considerably higher than those of the type I variety, whereas the degree of perfection of type I was much higher than that of the type II variety. These results showed some peculiar structural differences between the two types of diamond crystals.

During the investigations described above an interesting result was the observation of a forward diffracted X-ray beam when the diamond crystals were oriented for Laue diffraction. A forward diffracted beam is only expected on the basis of dynamical theory of X-ray diffraction. As is well known, this theory is applicable to nearly perfect crystals which are 'thick' meaning that the value of μt is about 10 or even more. Here μ is the absorption coefficient and t is the thickness of the specimen. Also, under these conditions, a loss in absorption of X-ray is to be expected at and around the Laue peaks (Borrmann Effect). The diamond crystals brought from the collection of Professor C.V. Raman were about 1.5 mm thick and for Mo $K\alpha_1$ radiation, the μt values were much less than 1, typically about 0.3. Therefore, even the nearly perfect diamond crystals having μt of less than 1 were not expected to exhibit any dynamical features like the forward diffracted beam. However, careful experiments with highly collimated and monochromated $K\alpha_1$ exploring made it possible to observe the forward diffracted X-ray beam even with these 'thin' crystals. The dynamical phenomena in diamond crystals were investigated in detail and a new technique was developed to isolate the forward diffracted beam and study its properties. It could be photographed and its diffraction curves could be recorded. Also, it was possible to observe the forward diffracted beam with crystals, which were rather imperfect. Therefore, these investigations showed that the observation of forward diffracted beam is rather general and if the quality of experimental technique is high like that of the one developed at NPL, it is observable even in 'thin' crystals which are not so perfect. Further a loss in absorption was also investigated and demonstrated to exist. A theoretical understanding has been attempted with the collaboration of Professor V.S. Bhasin and G.K. Sapra.

Professor Verma was keenly interested in zeroth order diffraction from single crystals. He felt that if one succeeds in isolating the zeroth order diffracted beam from the direct beam, it will be a very valuable experiment as high quality structural information about crystals could be deduced from such experiments. Some preliminary experiments had been done successfully by the author in collaboration with Niranjana Goswami and Manoj Bhuyan. These experiments have shown the way to isolate the zeroth order diffraction in silicon crystals.

All his life Prof. Verma remained deeply interested in any new developments in science in general and in crystal physics in particular. He was highly impressed with the new experiments established by the author and Peter Thoma first at at Physikalische-Technische Bundesanstalt, Braunschweig, Germany and later by the author and Niranjana Goswami at NPL on direct observation of electric field induced microstructural defects in semiconductors and insulators. Similarly, new techniques for precise measurement of biaxial stress and orientation crystal surfaces and flats were highly appreciated by him. Any experimental set-up with state of the art level capability excited him enormously. For example he was a great admirer and supporter of the Five Crystal X-ray Diffractometer developed by the author. He often called it as a full laboratory for high resolution X-ray diffraction work. He served as a wonderful critic for the research group of the author till the end. Any new development greatly interested him. The recently established high resolution X-ray reflection technique by the author and Goswami deeply interested him and he was keen to see as to whether this technique can image thin films on crystal surfaces with thicknesses of a few nano meters. Of course, this work is in progress but unfortunately, he will not be able to see its culmination.

Even the new directions taken by International bodies like International Council of Science (ICSU) and ICSU Committee on Data for Science & Technology (CODATA) were of keen interest for Professor Verma. He often deliberated with the author as to where CODATA is going and what special he is doing as President, CODATA for making it widely useful organization. It so happened that at the end of February 2009, the author met him a day before leaving for Paris for the Executive Committee meeting of CODATA. He returned on the night of March 3-4 and had been informed by Mrs. Verma that he should proceed to the Rajiv Gandhi Cancer Institute early in the morning of 4 March. It was one hour after he saw him in the ICU that Professor Verma breathed his last.

Professor Verma remained deeply attached to NPL and its welfare and achievements remained very close to his heart. Coming to our group and getting involved in deep discussions on some of the latest developments would enthuse him enormously. He often said that these visits serve as real tonic for him and provided him sustenance.

FAMILY LIFE

Professor A.R. Verma entered into wedlock after his return from UK in the year 1956. There were several families who had approached his parents with marriage proposals. Among them was a family from Amritsar who hesitatingly proposed the hand of Km. Shukla. This family was quite apprehensive whether a young, bright person like A.R. Verma who was first class first from Allahabad University in M.Sc. and with Ph.D. degree from London with growing fame at international level would accept their proposal. Many people tried to gauge Dr. Verma's mind at that time but he kept quite and left the choice to his parents. Finally, his mother approved of Shukla as his would be bride. The decision happened in the middle of the day during a discussion with brothers of Shukla. They offered to come back in the evening for a 'Roka' ceremony. However, Dr. Verma's mother pointed to a nearby provision shop and said you can fetch one seer of sugar and put Rs. 1.25 (sawa Rupaiya) on top of it and that is enough for this ceremony.

This very successful marriage provided Dr. Verma stability in life and provided support when he was entrusted with several important duties including Directorship of NPL. After marriage Shukla was named as Sadhana, as per practice in several parts of north India. Once a friend had asked him about the club whose membership Dr. Verma had. He replied that he is a member of 'Sadhana Club' which he remained till the end of his life. Professor Verma and Sadhana have been blessed with three wonderful children. Poonam, the eldest daughter is married to Ravi Khanna and has two offsprings, Pooja and Medha and the younger of the two got married in 2008. Poonam is teaching in a school and Ravi is graduate from IIT Delhi and is into software business. Suman is the second daughter, married to Vivek

Seth, an engineering graduate from Punjab Engineering College, Chandigarh. He is running a successful textile industry. They have two daughters, Divya and Vandini. Atul, their son is an engineer working in IT industry. He is married to Charu, a gifted artist. They have two kids, Amol and Srishti. Dr. Verma was lucky to participate in the wedding of his grand daughter (Poonam's daughter, Pooja) a few months before his demise.

Interest in Spiritual Matters

Professor Verma was keenly interested in Indian spirituality and philosophical thought. His family has Arya Samaj background and he was well versed with performing Havans and reciting Vedic hymns. He practiced hath yoga, pranayama as well as well as meditation regularly. He practiced Reiki in the last part of his life to which he was introduced by his daughter, Poonam. On many occasions, we discussed about the Geeta particularly about the definition of "Sthithpragya" स्थितप्रज्ञ and the meaning of the Shloka 56 of the Second Chapter:

'दुःखेष्वनुद्विग्नमनः सुखेषु विगतस्पृह।

वीतरागभयक्रोधः स्थितधीर्मुनिरूच्यते ।।**56**।। (श्रीमदभ्गवद्गीता द्वितीयोऽध्यायः)

He repeatedly emphasized that pain and sorrow affect all human beings, only we have to develop ourselves to the extent that these do not terribly disturb our mind and the consciousness. Among the medieval period Saints, he was highly impressed by Saint Kabir. The author feels that in the scientific community he was one of the most knowledgeable persons about the thought and message of Sant Kabir. One of his most favourite couplets of Kabir was as follows:

देह धरे का दण्ड है सब काहु को होए ।

ज्ञानी भुगते ज्ञान से मूरख भुगते रोए ।।

The extent to which he had adopted the teachings of Indian spirituality in his life became manifest during the last phase of his life when he suffered from cancer of pancreas and underwent a highly difficult chemotherapy. During this phase also he was always smiling and could laugh about the medical situation and could elaborate about the actions of various medicines. Of course, he often mentioned that the suffering is too much. He was a unique combination of a scientist and a yogi dealing with a tough and often unbearable situation in life. This was always inspiring to see him facing extreme physical suffering with calm and boldness.

Among the contemporary scientists, he had strong influence of his guide, mentor and friend, late Professor Daulat Singh Kothari. He often mentioned that during the last phase of the life of Professor Kothari he always looked forward meet him to gather spiritual knowledge and inspiration. Professor Kothari was a unique synthesis of modern science and the gist of Indian philosophical thought as propounded by the Upnishads, Bhagwad Geeta, essential elements of Buddhism and Jainism.

The Arya Samajist background in the family of Professor Verma had laid great emphasis on education particularly, for the female children. All his sisters were post graduates and even his buas (father's sisters) were well educated and one of the buas served as a Principal in Srinagar. One of his younger sisters was a member of UP Education Commission. He was a wonderful combination of intellectual capability, humility and concern for colleagues from all strata. He practiced ethical values through his personal example. He was one of the key founder members of the Society for Scientific Values.

POPULARIZATION OF SCIENCE

Professor Verma was an excellent teacher and did a lot to popularize science. He always made special efforts to prepare for his formal lectures in class rooms as well as for talks in conferences and popular lectures. He made sure that the matter to be deliberated upon was crystal clear to him to begin with and then he ensured that it was communicated in a language, which the audience will have no difficulty to grasp. Therefore, after such a thorough preparation he could communicate intricate concepts in a simple way. Professor Verma spent considerable efforts on writing research papers. He would write till he was very sure of all its data and its interpretation. He had published only about 100 research papers. However, each paper is respectable and had created impact.

PROFESSOR VERMA, HIS STUDENTS AND COLLEAGUES

Professor Verma's students and co-workers had deep respect for him till his last moment and scientists of all the three schools of Crystallography always looked forward to interact with him and seek his guidance and blessings. At NPL, in 1981, a major international school on Crystal Growth and Materials Characterization was organized by the author and co-workers to felicitate him on the occasion of his 60^{th} birth anniversary. It was sponsored by the Commission of Crystal Growth and Materials Characterization of the International Union of Crystallography. Its proceedings, "Synthesis of Crystal Growth and Characterization" edited by the author and was published by North-Holland in the year 1981 and was dedicated to Professor Verma. A special Issue of Indian Journal of Pure and Applied Physics (Volume 19, September 1981) was also brought out by the author on this occasion. Many eminent scientists, students and close associates of Professor Verma contributed to this volume. These included Professors Alan A. Mackay, W. Bardsley, Jun-ichi Chikawa, Z.G. Pinsker, Peter Thoma, S. Chandrasekhar, S. Ramaseshan, V. G. Bhide, L. S. Kothari, A.R. Patel, G.B. Mitra, N.S. Satya Murthy, G.C. Jain, N.N

Saha, L.M. Pant, P. Krishna, O.N. Srivastava, V.K. Srivastava, G.C. Trigunayat and Krishan Lal.

His wise counsel had been sought by the academic institutions at all levels, from Kendriya Vidyalayas, NCERT to Universities, IITs, IIIT, UGC, AICTE as well as national R&D bodies. He had served as chairman or member of numerous important committees.

AUTHOR AND PROFESSOR VERMA

The author of these Memoirs considers himself fortunate to have worked closely with Professor Verma for more than forty years and developed very strong bonding with him and his family. There was no problem in science, management of R&D, philosophy, spiritual matters, family issues or day to day matters on which we did not have discussions. On a few occasions he tried to define our relationship: teacher-student, father-son, very close friends etc. Finally, he himself exclaimed, "The best description is a true 'Dost', a friend, but let us not constraint our wonderful relationship in narrow boundaries". As mentioned above the author was among the last persons to see him alive, having returned from Paris a few hours before that. Within an hour he passed away. Mrs. Verma's first reaction was he was only waiting for your return.

HONOURS AND AWARDS

Professor Verma earned great respect as a scientist, as a teacher and as a wonderful person. He received several honours and awards during his life. These include:

(i) Fellow of Indian National Science Academy, New Delhi; also served as Treasurer and Foreign Secretary

(ii) Fellow of Indian Academy of Sciences, Bangalore;

(iii) Fellow of National Science Academy, Allahabad;

(iv) Member, Board of Editors – Solid State Communication, Pergamon Press (Charter Member since inception, Retired in 1990);

(v) Elected member of International Committee on Weights and Measures (CIPM) Paris 1966-1982;

(vi) Member, Commission on Symbols, Units and Nomenclature of International Union of Pure & Applied Physics (IUPAP);

(vii) Shanti Swarup Bhatnagar Prize in Physics 1964;

(viii) Honoured by the President of India by the award of Padma Bhushan 1982;

(ix) D.Sc, University of London, London, 1969 on the basis of his published work

(x) D.Sc. (h.c.), Mahatma Gandhi Kashi Vidyapeeth, Varanasi, 1996;

(xi) DSc. (h.c.), Banaras Hindu University, Varanasi, 2000;

(xii) Atma Ram Puraskar in Hindi by Kendriya Sansthan, Agra 1984;

(xiii) British Council Scholarship, Royal Holloway College, University of London, London (1950-52); and

(xiv) I.C.I. Fellowship, University of London, London, (1952-1955).

His passing away on 4 March 2009 strongly impacted all those close to him in the family and in professional sector. A large number of top scientists conveyed their sentiments. At NPL a meeting was organized the next day and besides many scientists from NPL several senior scientists paid their tributes with emotions. Professor M.G.K. Menon recalled his very long association of nearly six decades. He was a witness to the impact of Professor Verma's work on direct observation and study of spirals on SiC crystals and the excitement and appreciation of top scientists like F.C. Frank. He recounted his long close association including the time of open heart surgery of Mrs. Verma and Professor Menon's involvement in arranging the best possible medical treatment. Some parts of the messages received from senior scientists and students are reproduced below.

Professor M. Vijayan, Former President of Indian National Science Academy

I was close to him and he was indulgent in his affection to me. He was a respected and admired member of the scientific community and fellowship of INSA. We deeply mourn his passing away.

Dr. R. Mashelkar, Former President, INSA and Former DG, CSIR

I was very sad to hear about the sad demise of Professor Ajit Ram Verma. I vividly recollect my last meeting with him in INSA. He was such a wonderful human being.

Professor S.K. Brahmachari, Director General, CSIR

Dr. Verma was not only an eminent scientist but also a fine human being. His contributions to the growth of National Physical Laboratory are always gratefully acknowledged. I pray to the Almighty that his Soul may rest in peace. The entire CSIR family joins me in offering heartfelt condolences to you and your family.

Professor L.S. Kothari

Dr. Verma will long be remembered as a great teacher and a lovable human being. He never believed in preaching - his life was an example to learn from. He was extremely honest and straight forward in his behavior and always helpful. I learnt that once when he was going to attend an official meeting in an official car, Mrs. Verma asked him to drop her at her friend's place on his way. Dr. Verma declined to do this as he was going in an official car. (It is lucky for most of our families that we have forgetting the difference between personal and official work.) Dr. Verma will always remain a model for all those who knew him.

Professor R.P. Rastogi

Sudden demise of Prof. A.R. Verma is a great personal loss for me. Besides being a great scientist, his ethical principles were of a very high order. In Committees, he would act as tower of strength for those whose integrity was unquestionable. I remember he was a member of Executive Council of B.H.U. during my tenure as V.C. He would always support me without reservation when he was convinced about my honest intentions and administrative attitude. Thus he acted as a source of strength for me. This quality was rare amongst senior scientists in those days.

Prof. S. Ranganathan

For the last four decades, I held him in deep admiration. I learned about his seminal contribution to the direct observation of dislocations using interferometry. In turn it influenced me to derive the contrast from dislocations in field-ion images. I understand that these helices of Frank-Verma-Amelinckx influenced Watson on his discovery of the double helix.

Prof. P. Ramachandra Rao

He has been a guiding spirit for many a young scientists and I have always appreciated the interactions I had with him from my research student days.

Prof. M.S. Sodha

We are shocked and grieved to learn of our loosing Professor Verma, friend, philosopher and guide to many like me.

Prof. M.D. Tiwari

Prof. Verma has been one of the main architects who conceived, established and helped run the Indian Institute of Information Technology, Allahabad since its inception. His wisdom and guidance has been the main source of inspiration for all of us.

Prof. P. Krishna

"He was an outstanding teacher with a very dignified and charming personality and remarkable clarity of thought and expression. Very difficult concepts would become crystal clear after listening to his lectures and he acted as a great source of inspiration to all his students. In the experimental work he demanded the highest precision and was himself a perfectionist. The photographs he produced both in X-ray diffraction and in microscopy/ interferometry were of the highest international quality and often better than those from foreign laboratories who had access to superior facilities."

"Despite his international stature and training as a scientist, he led a life of great simplicity and humility. All his sub-ordinates including class IV staff loved him as he was always very kind and friendly with them. He was almost Gandhian in his large-heartedness and his affection for his students and colleagues."

"As a research guide he never used his students as merely an assistant producing data or mechanically performing experiments/calculations for him. He insisted that a research fellow should know more than the guide on his topic of research and come up with suggestions for new experiments. He would then act as a sounding board and give his opinion whether those experiments were worth doing."..." The result was that every student who completed his Ph.D. with him became an independent researcher capable of guiding others and tackling new problems."

"I consider it one of the greatest privileges of my life to have had a friend, philosopher and guide of his calibre in science and even more so in life."

Prof. O.N. Srivastava

"I was amazed to see the intensity and clarity with which he taught us the difficult topic of crystallography which among other things required lots of imagination and conceptualization."

"I planned to meet him to request to take me as research scholar under his supervision. I had become late in meeting him since I came from a poor family and my father could give me money for travel to Varanasi only after he received his salary. When I finally met him in first week of August 1961, other M.Sc. students have already talked him for research and there was no seat vacant under him. However, when I told him that I had obtained first position in Solid State and that I became late since enough money for traveling was not available, he got moved and he said that he will do something. After about two weeks he informed me that university has agreed to get me registered under him. Based on this and later other similar incidents I realized that he has great respect for merit".

"Around 1962 he established excellent collaboration with the group of Prof. T.R. Anantharaman of Metallurgy where several physicists (metallurgists) like Prof. P. Rama Rao, Prof. P. Ramachandra Rao, Prof. S. Lele and some others have started doing research on metals/alloys/amorphous-glassy metals (alloys). Several of these used the facilities including X-ray diffractometer which Prof. Verma has established. Later these collaborations through the efforts of Prof. S. Ranganathan fructified into the development of discipline of "Materials Science" at BHU."

Finally my last visit and interaction with Prof. Verma was somewhere in February 2009 (he breathed is lost on 4 March 2009) when I met him at his house in New Delhi. During about 40 minutes time through which I interacted with him, he talked about scientific/medical pros and cons of the illness he was suffering from, and the direction of education and research which we may pursue in Hydrogen Energy and Nanoscience and Technology in the coming years.

Prof. G.C. Trigunayat

"An obvious and striking quality he possessed was his clarity of expression both in speech and in writing. It was a pleasure for anybody to talk to him or listening to his lecture. While delivering a lecture his articulation was simply superb. He had the knack of rendering even the most difficult concept to appear simple. He used to speak with passion and intensity, too. The same is true for his writings. In the Foreword to his famous book CRYSTAL GROWTH AND DISSLOCATIONS, Prof. Tolansky wrote "In reading the manuscript I have been struck by the clarity and ease by which the author illuminates what are indeed quite obscure aspects of crystal growth". Anybody who has consulted this book will agree one hundred percent with Tolansky. The introductory chapters of the book, dealing with the fundamentals of crystal growth, are still being employed for teaching the rather complex subject of growth of crystals to graduate students.

He was a man of simple habits. In fact, he was an epitome of "plain living and high thinking". He was a very disciplined person, endowed with all essential human qualities. He paid due regard and affection to all, including the junior-most, and was ever keen to help anyone seeking his guidance or help. His ever smiling face will never be forgotten. He was also very versatile and witty and possessed a strong sense of humour. Behind his simple frame, he possessed a great vitality and fearlessness, which amply manifested in the initiatives and the actions taken by him all through his life.

In a nutshell, Dr. Verma was a phenomenon and an institution in himself. His memory will continue to inspire and guide us. With these words, I pay my homage to the great departed soul."

Professor V.K. Srivastava

I have had the privilege of being a student of the great Professor Verma. He was a source of inspiration to us and he regarded failure in work as a useful experience. In my very long association with him I never saw him losing temper on anybody even under most provocative situation, thus raising him to the level of Gautam Buddha or our ancient 'rishis'. He had conquered two of the greatest failings of human nature - hatred and bitterness. He used to deal with institutional politics, not by politics, but by goodness and dignity, thus winning hearts of his opponents. He helped many people at crucial stages of their career, without bias though some of them later turned against him and his students under the influence of a powerful group. May Professor Verma's soul rest in peace.

Dr. P.N. Tiwari

I have read with respect your very good write up about Dr Verma in June 10 issue of Current Science. You are quite write in saying that he was strongly influenced by Geeta, Upanishads and Kabir. In fact he played the role of Krishna of Geeta in the formation and working of SSV.

Dr. B.P. Singh

Professor A.R. Verma was one person who commanded respect from all. He was an extremely humble, simple in nature and a broad minded person with a great vision.

In addition, several important organizations organized Condolence Meetings and formally conveyed their strong feelings. These included National Physical Laboratory, New Delhi; NPL Former Scientists Forum; Department of Physics & Astrophysics, University of Delhi, Delhi; Indian Institute of Information Technology, Allahabad, whose condolence meeting was widely reported in local media including The Hindustan Times, Allahabad; Aaj; Hindustan; The Pioneer, Allahabad; The Northern India Patrika; and United Bharat; Indian Institute of Technology Delhi (Hindi Kaksha); Indian Association of Physics Teachers, Delhi; and several social organizations with whom Prof. Verma was associated such as Uttar Pradesh Samaj Co-operative House Building Society Limited, Delhi; Varishth Nagrik Satsang Sabha, Saraswati Vihar, Delhi and Satsang Sabha, Deepali, Delhi.

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(ii) on Diamonds in Hindi; received National Award

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