Early Developments in Crystallography

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It has been more than 100 years since the discovery of X-ray diffraction by crystals. The evolution of this technique has transformed our understanding of Nature very profoundly. In India, the early proponents of this area of research were Kedareshwar Banerjee, A R Verma, S Ramaseshan and G N Ramachandran, etc. In this article, contributions of some of them are highlighted.

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Importance of Geometric Relationships between Atoms within a Molecule

"*The properties of the metals must depend, in the first place, on the properties of the individual atoms, and, in the second place, on the atomic arrangement, which is in effect the state of crystallization,*" wrote William Henry Bragg in 1925 in his book *Concerning the Nature of Things*, the title borrowed from a 2000-year-old treatise of Lucretius. By 1925, Bragg and his prodigious son, William Lawrence Bragg, had pioneered the use of X-ray crystallography in determining three-dimensional arrangements of atoms in many organic and inorganic materials. The father and son duo had developed the technique based on the discovery of X-ray diffraction by Max Von Laue, Walter Friedrich and Paul Knipping earlier in the year. Little did the Braggs and Laue realize that use of the technique of X-ray crystallography would unfold such unprecedented advancement of knowledge in the following 100 years that it could be used to make designer molecules to treat different diseases, make materials of desired properties and attempt to understand unknown territories far away from the Earth such as the exploration of the surface of Mars. In this article, we will try to trace the early historical events in the development of X-ray crystallography, and the Indian contributions to these events.

Keywords
X-ray diffraction, crystals, molecular structure

Discovery of X-rays

Wilhelm Roentgen accidently discovered X-rays in 1895, while he was building upon the work of Philipp Lenard, Jean Baptiste Perrin and J J Thomson to study the effect of cathode rays on low-pressure gases. He published three seminal papers between December 1895 and March 1897, in which he described many properties of X-rays such as that they travelled in straight lines, they made an impression on photographic plates, and one of the most profound discoveries for mankind, that bones can be imaged using X-rays. However, one aspect that Roentgen pursued vigorously but was not able to find, was diffraction by X-rays. He noted in the third of his highly influential papers in March 1897:

> "*I have not succeeded to register a single experiment from which I could gain a conviction of the existence of diffraction by X-rays with certainty which satisfies me.*"

Wave–Particle Duality

The raging debate in the early part of the last century, much before the wave–particle duality principle was accepted, was whether light (including X-rays) consists of waves or particles. In this debate, two of the towering scientists of the day – Charles Barkla and William Henry Bragg – from opposite parts of the world, UK and Australia, found themselves on opposite ends. Roentgen's discovery of X-rays had already caused a great deal of sensation in the scientific world, but the debate now focused on the wave or particle nature of X-rays. Bragg was particularly fond of the corpuscular theory of X-rays. He proposed that ionization of gases by X-rays arose from the transfer of energy by photoelectric effect, totally unaware of Einstein's discovery of the photoelectric effect a few years earlier. He promoted the idea of X-rays being made up of a stream of neutral particles, or doublets of ± charge. The debate was carried in the journal *Nature*, but finally brought to an end by the Editor's note in *Nature* on 19th November, 1908 with a comment, "*As there are few opportunities in Australia for an investigator to place his views quickly before a scientific public,* *we print the above letter, but with it the correspondence must cease. The subject is more suitable for discussion in special journals devoted to physics than within our columns*". Later the news of Laue's X-ray diffraction influenced Bragg to change his views.

Laue's Discovery of Diffraction of X-rays by Crystals

During January of 1912, a young doctoral student, P P Ewald, sought an appointment with Max von Laue to discuss the action of light waves in a lattice of polarizable atoms. From the autobiographical notes of both Laue and Ewald, it is now known that the idea that crystals would act as a grating to X-rays, and if irradiated with X-rays, might produce diffraction, were sown during a post-dinner conversation between the two. It was known to scientists even in the early part of the twentieth century that crystals are made up of repetitive arrangements of molecules in three-dimensional space. During the conversation between the two, Laue recognized that if atoms really formed a lattice upon irradiation of crystals with X-rays, a phenomenon similar to interference of light by optical gratings might be observed. Indeed a few months later, with the help of Friedrich and Knipping, Laue observed definitive evidence of diffraction of X-rays by crystals. It is important to note that many people prior to Laue had irradiated crystals with X-rays however, their observations were limited only to measuring the intensity of X-rays after passing through crystals, which was found to be somewhat diminished. Laue was delighted to present his results on 8th June, 1912 from the same platform where Max Planck had presented his results on radiation and quantum theory 12 years earlier.

The news of the Laue photographs reached the father and son Braggs in UK while they were on a vacation in summer 1912. A letter dated 26th June 1912 was written by Lars Vegard, stating that he had heard a lecture by Laue showing a very intriguing photograph and was perplexed by its explanation. The photograph was of an image obtained by irradiating a crystal of copper sulphate with X-rays which showed that there was significant deviation of

X-rays from their direct path in certain directions (*Figure* 1). The letter set off the Braggs' interest, and intense academic discussions followed about the diffraction of X-rays by crystals. Soon, when William Lawrence Bragg returned to Cambridge, he derived the famous law named after him. Lawrence Bragg published his paper, 'Diffraction of short electromagnetic waves by a crystal' on 11th November, 1912.

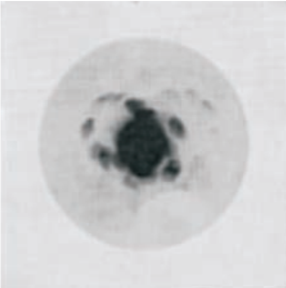

Figure 1. Image of the first X-ray diffraction experiment. Friedrich, Knipping and Laue exposed the crystal of copper sulphate to X-rays, and placed a photographic plate behind the crystal to obtain this image.

When Laue first observed the diffraction of X-rays by crystals in 1912, he proposed an explanation based on the interference of waves in three-dimensional space giving rise to sharp diffraction maxima. He observed that the long-range periodicity of the molecules acts as a three-dimensional grating for X-rays giving rise to the diffraction pattern. William Lawrence Bragg gave a much simpler explanation of the phenomenon that this may be considered as a reflection of X-rays by parallel planes of atoms, with the interplanar distances (d) and glancing angle (θ) satisfying the relationship $2d\sin\theta = n\lambda$, λ being the wavelength of the incident radiation (*Figure* 2). This equation has come to be known as Bragg's law. Although the two explanations appear to be different superficially, they can be shown to be equivalent. The diffraction maxima therefore occur in directions defined by Bragg's law, and these maxima possess all the information regarding atomic arrangements within the crystals.

The photographs published by Laue and colleagues were also obtained from the diffraction of zinc blende (*Figure* 3). Laue assumed that the molecules of ZnS occupy the corners of a cube and with this assumption, went on to explain the observed

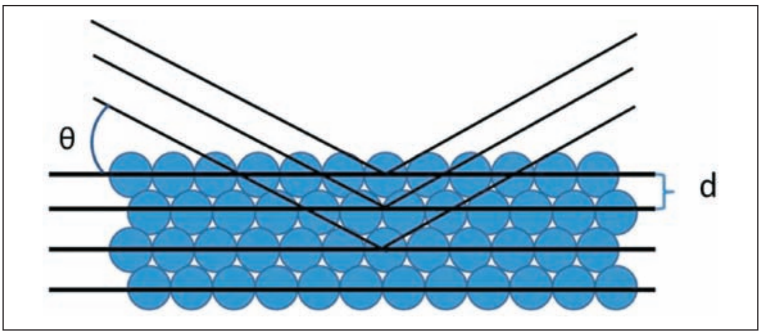

Figure 2. Imaginary parallel planes as conceptualized by Lawrence Bragg. The family of parallel planes with interplanar distance 'd' satisfies the relationship with glancing angle of X-rays 'θ' such that $2d\sin\theta = n\lambda$. Only if this relationship is satisfied that the diffraction maxima are observed in the direction specified by θ.

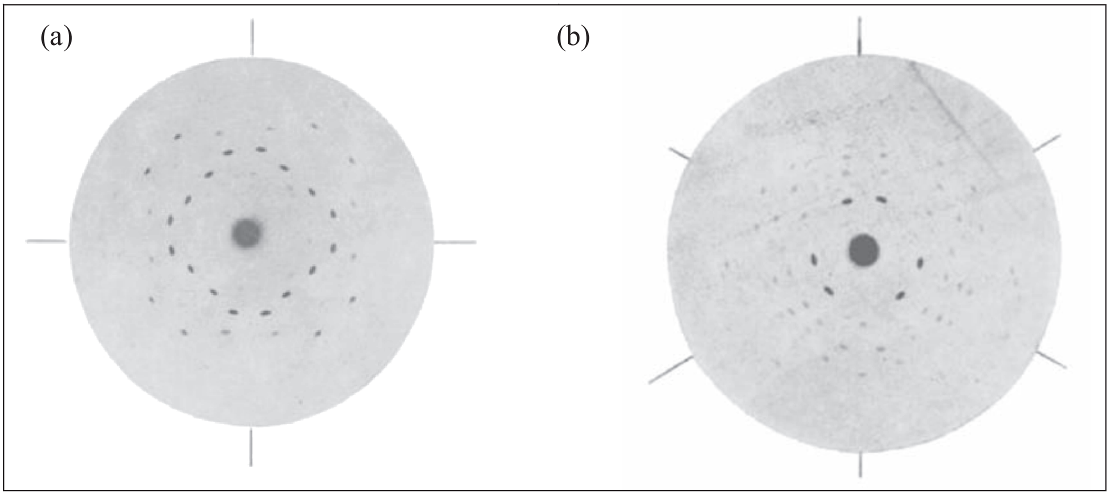

Figure 3. X-ray diffraction photographs of zinc blende crystals obtained by Laue and colleagues (Laue, Friedrich & Knipping, *Sitzungberichte der Königlich Bayerischen Akademie der Wissenschaften,* 8th June, 1912). The photograph (a) clearly shows four-fold symmetry, whereas (b) shows a three-fold symmetry. This is consistent with the cubic symmetry of the zinc blende crystals.

diffraction pattern. However, finding this explanation difficult to accept, Bragg, in his 1912 paper, proposed that instead of the molecules occupying the corners of the cube, the closest packing of ZnS might be obtained by a cube in which the atoms occupied not only the corners but also all the six faces. Bragg also proposed an explanation for the observed differences in intensities of diffraction maxima stating that the strength of the reflected X-ray pulse from each plane would depend upon the number of atoms in that plane. With such an interpretation of X-ray diffraction, Bragg proposed ZnS to be tetrahedral, which was in agreement with the hypothesis of William Pope and William Barlow. Indeed, the so-called 'face-centered cubic' lattice is known to be correct for the diffraction pattern of zinc blende obtained by Laue. Thus, apart from the landmark Bragg's law, this explanation also marked the beginning of analysis of molecular structures with the help of X-ray diffraction.

Early Developments

The Nobel Prize Committee, recognizing the significance of these discoveries, rightly awarded prizes in the following years to the persons involved in different aspects of the field of X-rays and crystallography. Laue was awarded the Nobel Prize in 1914, whereas the Braggs (father and son) were jointly awarded the Nobel Prize in 1915, the only father and son duo to be awarded the

Nobel Prize jointly till date. It is widely believed that while the 1916 Nobel Prize was not awarded to any one, it was meant to be awarded to Moseley, who had pioneered re-writing the periodic table based on characteristic X-ray spectra of atoms and their systematic relationship to atomic numbers. The 1917 Nobel Prize recognized the contributions of Charles Barkla. In the following years, more than two dozen Nobel Prizes have been awarded to people who have used X-rays or crystallography. However, World War I had taken its toll, and when the actual prizes were awarded, the Braggs did not attend the ceremony to receive their Prizes, and William Henry Bragg never delivered the Nobel Lecture. He had lost his other son, Robert, to the War. Similarly, Moseley's brilliant academic career had also been cut down by the War.

The discovery of diffraction of X-rays by crystals in 1912 by Laue and colleagues opened up a completely new world of understanding how individual atoms in molecules are arranged in three-dimensional space. It has since been understood well that the relative juxtapositions of atoms define the physical and chemical properties of molecules. For example, it is well-known today that different allotropic forms of an element, such as diamond and graphite for carbon, have different properties. J D Bernal's structure determination of graphite in 1924, and its comparison to that of Bragg's diamond structure of 1914, are early examples of how atomic arrangements in molecules had the power of explaining these differences. In another elegant example, William Henry Bragg explained in *Concerning the Nature of Things*, that despite individual potassium atoms being three times heavier than carbon atoms, potassium is lighter than water and diamond is three and a half times as heavy. He ascribes this to the potassium atoms being much larger than carbon atoms in size, and the similar packing of potassium and carbon, thus effectively reducing the density of potassium.

The crystallographic measurements enable the determination of atomic positions in materials and therefore precise estimation of bond lengths and angles in complex compounds. The technique is so powerful that the precision of these parameters is in the orders of magnitudes better than a nanometer (1 nm = 10^{-9} m)! This has been apparent even from the early days of studies of X-ray diffraction. J D Bernal was quite remarkably able to propose that C–C bond distances in graphite are smaller than those in diamond by 1/100th of a nanometer. Because of achieving precision of such orders, it has been possible to understand in great detail many fascinating aspects of Nature, such as the mechanisms of catalytic reactions by enzymes, or recognition of foreign material in human body by its immune system.

Among the most complex molecules or processes in Nature are those which occur in living systems. Our understanding of living systems, even in their simplest forms, is grossly incomplete despite great advances. A large part of our understanding of biological systems derives from the knowledge of three-dimensional structure of biological molecules. For example, it was apparent that the mysteries of genetic information would be held in the structure of DNA. Among the few models of DNA structures that were proposed, the one based on diffraction photographs obtained by Rosalind Franklin, and proposed by Watson and Crick, explained the biological properties of DNA most elegantly. One of the greatest proponents of the relationship between atomic positions in molecules, and their correlation to biological properties, was Linus Pauling. Pauling had published landmark papers in 1951 proposing different structural models of proteins. He was awarded the Nobel Prize in 1954, '*for his research into the nature of chemical bond and its application to elucidation of structure of complex substances'*. He made a profound remark in his Nobel Lecture: "*We may, I believe, anticipate that the chemist of the future who is interested in the structures of proteins, nucleic acids, polysaccharides, and other complex substances with higher molecular weights will come to rely upon a new structural Chemistry, involving precise geometrical relationships among the atoms in the molecules and the rigorous application of the new structural principles, and that great progress will be made, through this technique, in the attack, by chemical methods, on the problems of biology and medicine.*"

The Braggs are the only father-son pair to be awarded the Nobel Prize jointly till date. William Henry Bragg did not travel to Stockholm to receive his Nobel Prize, and did not deliver the Nobel Lecture. William Lawrence Bragg travelled to Stockholm to deliver his Lecture, but some years after he had been awarded the prize.

Indeed, in the 60 years since the discovery of the structure of DNA, and Pauling's lecture, great progress has been made in the understanding of many biological principles aided by three-dimensional structures of molecules.

Early Contributions of Indian Crystallographers

The Indian connection to the world of X-ray crystallography begins with a strange story. Robert John Bragg, the father of William Henry Bragg was a sailor, who used to often sail from Liverpool to Kolkata. During one of his trips, the ship that he was sailing was wrecked at the Gangetic Delta near Kolkata in a hurricane on 18th May 1852. Only five people survived, including Robert John Bragg, who were eventually traced on the Sundarban Islands, and were found to be in a state of severe starvation. Robert John Bragg upon his return gave up sailing. William Henry Bragg was born ten years later.

Early interest in crystals and their properties in India began with the work of C V Raman and his group. However, Raman did not undertake the determination and analysis of crystal structures himself; rather one of his illustrious students – Kedareshwar Banerjee – undertook the structural analysis on naphthalene and anthracene. The structures of both these compounds had been published one year prior to Banerjee's analysis, i.e., in 1929 by J M Robertson. Banerjee proposed a new interpretation of these two structures. Most importantly, Banerjee challenged Robertson's ideas that carbon atoms have tetrahedral properties in aromatic structures. Banerjee published his work in the 22nd March 1930 issue of *Nature*, where he proposed that all the carbon atoms in these compounds lie in a single plane. Immediately following Banerjee's paper there appeared a note by J M Robertson that he and Bragg had re-analysed these structures and they found Banerjee's structures to be essentially correct.

Banerjee further went on to publish his seminal paper titled 'Determination of the signs of Fourier terms in complete crystallography structures analysis.' This paper marks the beginning of what are known as the direct methods for crystal structure analysis. The Nobel Prize for these direct methods was shared between Jerome Karle and Herbert Hauptman in 1985, who acknowledged the contributions of Banerjee. More importantly, Banerjee's work paved the way for understanding statistical relationships in the amplitudes of diffracted waves. The contributions of Banerjee were followed by equally profound works by other researchers in India such as S Ramaseshan and G N Ramachandran.

K Banerjee was an illustrious student of Sir C V Raman. He worked at the Indian Association of Cultivation of Science (IACS), Kolkata, Dhaka University and Allahabad University, before retiring from the IACS.

Ramaseshan demonstrated that the phenomenon called anomalous scattering can be effectively used for determination of crystal structures. The phenomenon that amplitudes of diffracted waves from opposite surface of crystals are not equal, is called as anomalous scattering. Anomalous scattering occurs when the frequency of incident radiation is close to the absorption edge of an atom present in the crystals. This phenomenon can be utilized to determine the structures of even highly complex molecules with great precision. For the first time, Ramaseshan showed that by changing the wavelength of incident radiation, but using the same crystals, anomalous scattering can be powerfully used to determine crystal structures. The method was demonstrated to work in the determination of the structure of potassium permanganate with copper, cobalt and iron K*a* radiation. The so-called Multi-wavelength Anomalous Dispersion (MAD) and Single-wavelength Anomalous Dispersion (SAD) methods are extremely popular these days to determine the structures of complex biological molecules.

G N Ramachandran was offered full Professorship at the University of Madras at the young age of 28. He later founded the Molecular Biophysics Unit at the Indian Institute of Science, Bangalore.

Ramachandran made several fundamental contributions in the methods to determine crystal structures, in proposing the structure of collagen, the Ramachandran Map, which is quoted widely in textbooks. Ramachandran recognized brilliantly that since the diffraction maxima are vector quantities, their Fourier transformation to obtain electron density and atomic positions in crystal lattices, would have been influenced by the amplitude of the diffraction waves as well as their phase components. However, it is the phase which appears to dominate the Fourier synthesis, and strangely, a bias in phase information can catastrophically lead to incorrect atomic positions from the Fourier synthesis.

Conclusions

Thus, X-ray crystallographic investigations into the structure of matter have continued to make rapid progress into our understanding of Nature. With recent advancements in instrumentations and computational power, we are on the verge of an exciting era where more and more complex problems in Nature are likely to be addressed. In the context of Indian contributions to this field, it is imperative that substantial infrastructural investments are made into generating resources.

Suggested Reading

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[5] **http://mightyseas.perso.sfr.fr/marhist/workington_harrington / nereids.htm**

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