2014

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2014 - International Year of Crystallography

Un'introduzione storica alla diffrazione, di M. von Laue

1. HISTORICAL INTRODUCTION

by M. VON LAUE

THE science which the *International Tables* are intended to serve is concerned primarily with the atomic theory of crystals, and secondarily with optical theory as applied to the short wavelengths of X-radiation. Moreover, now that we know of electron and neutron diffraction by crystals, it must include quantum mechanical wave theory, which is also, as it happens, of importance in the branch of optics already mentioned. This introduction has to deal, therefore, with the history of these three branches of physics. Let us begin with the most important and the oldest branch, the theory of crystals.

We may take as a beginning the small pamphlet written in the year 1611 by the great astronomer Johannes Kepler, which bears the title *Strena seu de nive sexangula*, or in translation ''A New Year's present; on hexagonal snow.'' It is dedicated to one of his patrons at the court of the Emperor Rudolph II, whose friendship Kepler enjoyed during his stay in Prague. Kepler's astronomical works show that throughout his life he believed that the material world was the creation of a Spirit delighting in harmony and mathematical order. Had he not tried in his youth to deduce the radii of the planetary orbits from the dimensions of certain regular polyhedra, and did not his principal work (1619) bear the title *Harmonice Mundi*? It need not surprise us, therefore, that it was the appearance of these regular and beautifully shaped snowflakes rather than the appearance of the crystals of the mineral world that inspired Kepler with the idea that this regularity might be due to the regular geometrical arrangement of minute and equal brick-like units. Thus he was led to think of close-packed spheres, and, although he did not coin the expression ''space-lattice'' and although his development of these ideas is not always correct, we can find among his illustrations the first pictures of space-lattices.

Nevertheless Kepler felt uneasy about these speculations. He realised, quite correctly, that his way would lead to an atomic theory; yet the idea of the atom, as handed down from the ancient Greeks, lacked an empirical foundation and therefore has often been the subject of excessively fanciful speculation even until well into the nineteenth century. Hence it was not without reason that the natural scientist in Kepler mistrusted this idea and would not take it seriously. He toyed with the double meaning of the word ''nix,'' which in Latin means snow but in German dialect ''nichts''—nothing. And so from beginning to end he repeatedly explained the whole idea away as a mere ''nothing.''

In these circumstances the little pamphlet, even though it was printed, naturally made no deep impression on his contemporaries, and was gradually forgotten. Crystallography took another direction, that of the description of the external form of crystals, after Niels Stensen had in 1669 pointed out the existence of characteristic angles between crystal faces. By devious ways this led eventually to the Millerian indexing of faces (1839), to the laws of symmetry and to the classification of crystals in 32 classes, which was accomplished in 1830 by Johann Friedrich Christian Hessel and in 1867, independently and rather more simply, by Alex Gadolin.

This consistently phenomenological approach was not abandoned, even though the crystal-optical discoveries made early in the nineteenth century by such men as Baptiste Biot, David Brewster, Augustin Fresnel and Frederick William Herschel had led to the development of the important idea that the same laws of symmetry which were valid for the positions of crystal faces also controlled the physical events inside the crystal. This was first made clear by Franz Neumann in 1833.

Apart from these trends of thought, however, ideas about the internal structure of crystals continued to appear. Thus Christiaan Huygens' fundamental work on the wave theory of optics, *Traité de la lumière*, which was published in 1690, contains among other things a wave-theoretical explanation of birefringence, and ascribes to calcite a structure made up of ellipsoidal particles; the threefold periodicity of this arrangement characterises it as a space-lattice, although Huygens, like Kepler, did not define it as such. It was the cleavage along three planes which led him to this idea. Like Kepler's pamphlet, however, this part of the otherwise famous work was soon forgotten. Independently of Huygens, crystal cleavage in general led Torbern Bergman in 1773 and René Just Haüy in 1782 to suppose that all crystals consist of a kind of masonry of equal, parallelepipedal building bricks. That these ''molécules soustractives''

were often supposed to consist of ''molécules intégrantes'' of other shapes need not concern us here. A structure of this kind involves a space lattice, and Haüy could therefore easily go on from this idea to deduce the laws governing the geometry of crystal faces, already empirically known. But it would be premature to describe this as an atomic theory of crystals. No wonder! For the scientific theory of atoms had yet to be created, in its own good time, by the great chemists of the eighteenth century. The theorem that a lattice may be divided into unit cells, as we should say today, in an infinite number of different ways would have made no physical sense whatever to Haüy (although he would have admitted, of course, its geometrical correctness), since the shape of the ''molécules soustractives'' was fixed unambiguously by Nature.

Thus the true beginning of the atomic theory of crystals must be dated from a paper published in the year 1824 by Ludwig August Seeber, physicist in Freiburg, in Gilbert's *Annalen der Physik*, vol. 16, page 229. Seeber, who certainly knew of Haüy's works but probably did not know the part we have quoted from Huygens', was trying to find an explanation of the thermal expansion and the elasticity of solids, of which he quite rightly believed crystals to be the normal type. He found the bricklike structure unsuitable for his purpose, since, he argued, the only view compatible with this picture would be that the single bricks themselves possess these physical properties, which does not solve the problem but only pushes it one step farther back. Seeber, whose outlook was essentially modern, introduced instead the idea of a structure consisting of chemical atoms or molecules (at the time these two concepts were not strictly differentiated), whose mutual distances are determined by the balance of attractive and repulsive forces, thus forming a system of stable equilibrium. External disturbances cause certain changes of position—this is his explanation of elasticity—and possibly also elastic vibrations about the equilibrium positions. Seeber, of course, did not visualise thermal vibration: he explained thermal expansion in terms of the temperature dependence of the attractive and repulsive forces. In order to retain the sound parts of Haüy's postulate, Seeber placed each of his molecules, assumed by him to be spherical, at the midpoint of the cell which would have formed one of Haüy's ''molécules soustractives''; he thus arrived at a ''parallelepipedal arrangement of the indivisible parts of matter,'' as he describes it at the end of his paper. In our language such an arrangement implies a primitive translation lattice, and it is not far from this concept to the idea that each unit cell of the space lattice is occupied by several atoms.

This was the earliest application of the scientific atomic theory to a purely physical problem. The kinetic theory of gases, which is usually regarded as the beginning of atomic theory in physics, did not appear until thirty-two years later. Seeber was therefore far ahead of his time, and it was no wonder that his contemporary physicists failed to respond to his ideas, which were forgotten until Sohncke revived them in 1879. But at least one mathematical problem had been raised—the number of geometrically possible space lattices that correspond to the 32 crystal classes and to their symmetry operations. Moritz Ludwig Frankenheim and Auguste Bravais took up this problem, and in 1850 Bravais described the 14 pure translation lattices which have been named after him. Incidentally, his papers also contain the concept of the reciprocal lattice, which was later rediscovered and used in connection with the study of interference effects from crystals. This purely group-theoretical investigation was extended by Leonhard Sohncke in 1879 through the introduction of further symmetry operations, thus arriving at 65 different ''space groups.'' The complete solution of the problem, taking into account *all* possible symmetry operations on a lattice, was given simultaneously in the year 1890 by Evgraph Stepanovitsch Fedorov and by Artur Schoenflies. They derived the 230 space groups which are used in modern structural research.

Investigations pursued by English scientists of the following decade were less systematic and far more hypothetical, but their ideas possessed the advantage that they could be visualised more easily. Inspired by the success of stereochemistry, they devised three-dimensional models of atomic structures based on lattices. Lord Kelvin published a paper on this subject in 1894. Reasoning along these lines was most fully expressed in a series of long papers by W. Barlow in the last decade of the nineteenth century. Barlow took up the idea of close packing, and distinguished for the first time correctly between the cubic and hexagonal forms of packing. He also considered the question of packing of spheres of two or three different sizes and described, for example, the sodium chloride structure, although neither in this nor in any other case did he in these early papers name a substance which might be expected to have one of the proposed structures. This was undoubtedly one of the reasons why the whole of his structure

Notare come von Laue faccia riferimento al suo lavoro mai in prima persona.

theory at first attracted little attention. Moreover, the very reality of atoms was doubted again and again right up to the end of the nineteenth century. Even in the absence of such doubts, and even when collaboration with Pope had given the chemical application of Barlow's theory, there was still no way of bringing the hypothetical structures into relation with experiment. In order to establish structure theory on a firm basis, yet another set of ideas, those of physical optics, had to be brought in.

The diffraction of visible light by gratings, which mostly consisted of lines scratched on glass or metal, had already been described by Grimaldi in the seventeenth century, and again by Joseph Fraunhofer at the beginning of the nineteenth. The relevant theory can be found in the comprehensive treatise by Friedrich Magnus Schwerd: *Die Beugungserscheinungen, aus den Fundamentalgesetzen der Undulationstheorie analytisch entwickelt* (1835). The grating was and still is the most important instrument in spectroscopy. Later physicists engaged in work on optics have often returned to Schwerd's theory. In particular, Lord Rayleigh frequently emphasised that the essential characteristic of a grating is the periodic repetition of its elements and not the nature of those elements. Round about 1910 M. von Laue, in writing an article on wave theory for the *Encyklopädie der mathematischen Wissenschaften*, set himself the task of elaborating, as clearly as possible, this idea of Rayleigh's, and arrived at an equation for the position of the diffraction maxima which could be extended without difficulty to the case of double periodicity as it exists in cross-gratings; in the latter case two such equations had to be formulated.

In the meantime the science of optics had been extended far beyond the limits of the visible spectrum. The farthest extension on the short-wave side had come about in 1895 through Röntgen's discovery of X-rays; soon afterwards (1896) Emil Wiechert and George Gabriel Stokes concluded from the way in which X-rays are produced that they must be short waves consisting of electromagnetic pulses. This was confirmed by the observation of their polarisation, made by C. G. Barkla in 1906. Wilhelm Wien in 1907 estimated their wavelength to be 7×10^{-9} cm. on the basis of their observed photoelectric effect, while A. Sommerfeld in 1912 calculated a value of 4×10^{-9} cm. from their diffraction by a slit. On the other hand, they showed such strong quantum effects that some very eminent physicists held firmly to the corpuscular theory of X-rays.

Both these questions and that of the fine structure of crystals were decided by the researches of W. Friedrich and P. Knipping, which were published in the summer of 1912 in the *Sitzungsberichte der Bayerischen Akademie*. Von Laue's diffraction theory, which had provided the inspiration for these experiments and which had indeed been confirmed by their results, simply consisted of the diffraction conditions for a cross-grating, with the addition of a third condition to take account of the three-dimensional periodicity of a space lattice. Admittedly von Laue had expected, in accordance with the Stokes–Wiechert pulse theory, that many more interference spots would appear on the photographs than were actually observed, and he could only explain their absence by ascribing to the atoms of the crystal a strongly selective scattering power for X-rays: this idea, though it later proved to be mistaken, was not altogether unreasonable in view of the characteristic X-ray emission of the elements which had been found by Barkla. Towards the end of 1913, at the second Solvay Congress, von Laue used the rediscovered reciprocal-lattice theory to extend to the general case of any crystal the geometrical construction for the interference maxima from cubic crystals that had been given by P. P. Ewald. He thus provided the foundation for a simple ''geometrical'' theory of X-ray diffraction.

Meanwhile the experiments of Friedrich and Knipping, and von Laue's interpretation of them, had become known in England, and had inspired much discussion and further investigation, particularly by W. H. and W. L. Bragg. The story of what happened is here continued by Sir Lawrence Bragg:

''In the summer of 1912 my father showed me von Laue's paper, which had aroused his intense interest because of his work on the exciting of cathode rays by X-rays, which pointed to the projectile-like properties of X-rays, and he discussed with me possible alternative explanations for the effects which von Laue had found. I undertook some experiments at Leeds that summer to see whether we could explain von Laue's spots by the shooting of particles down avenues in the crystal lattice rather than by the diffraction of waves, experiments which were of course abortive.

''On returning to Cambridge in the autumn of 1912 I studied von Laue's photographs very intensively, and was very naturally forced to the conclusion that they must be due to diffraction. I also concluded at the same time that one must modify the explanation of them which von Laue had given. Von Laue had remarked that one did not get all the spots one would expect from a simple cubic lattice, but only a selection of the whole range. He ascribed this to the existence in the X-radiation of five characteristic wavelengths chosen so that they approximately satisfied the diffraction conditions for the spots which actually appeared in the photographs. I, on the other hand, concluded that von Laue's spots were due to the diffraction of 'white' X-radiation, representing a continuous band of wavelengths over a certain range. I was led to this first by noting the changing shape of the Laue spots when the distance from the photographic plate to the crystal was altered. This in turn led me to consider the diffraction effect as a reflection of X-ray pulses by the lattice planes of the crystal. I pointed out that this was equivalent to the selection from the continuous spectrum of a wavelength determined by the lattice spacing of the crystal. I tested this by reflecting the X-rays from a mica plate set at a series of angles, getting in every case a spot in the reflected position and so showing, as I believed, that all wavelengths were represented over a certain range in the X-rays. The problem then remained to explain why only certain spots appeared in the Laue photographs, and I ascribed this to the fact that the essential underlying lattice of the crystal was face-centred and not simple cubic. I communicated these results to the Cambridge Philosophical Society in November 1912. The 'Bragg equation' appeared in this paper (p. 46) in the form $\lambda = 2d \cos \theta$, but in later papers θ was defined as the glancing angle and not the angle of incidence.

''Professor Pope at Cambridge was very interested in these results, because the close-packed lattices which he and Barlow had devised for atoms which they believed to be of equal size were face-centred cubic. He procured crystals of potassium chloride and sodium chloride for me, and I took their Laue photographs. I showed that these could be explained by an arrangement of alternate scattering centres in two interleaved face-centred lattices, the NaCl structure in fact, and that these centres must be equal in scattering power in KCl but different in scattering power in NaCl.

''This work was done at Cambridge before I collaborated with my father. We worked along divergent lines at first, which came together later. My father was very interested in my explanation of the diffraction effect as a reflection, and he set up at Leeds the first X-ray spectrometer. He was primarily interested in the nature of X-rays. He checked that the reflected rays were really X-rays, a point on which he wished to satisfy himself because of his speculations about the corpuscular nature of X-rays. He found as I did that there appeared to be a continuous spectrum, but his spectrum also showed some peaks superimposed upon this continuous range, and by improving the apparatus he soon narrowed these down so much that it was clear that they were monochromatic components characteristic of the target. Incidentally I think it is not often realised how much work he did on characteristic X-rays before Moseley made his brilliant generalisations. My father constructed tubes with about a dozen different anticathodes and identified Barkla's *K* and *L* radiation, showing that the *K* contained two peaks and the *L* three peaks. He related the wavelengths to the atomic weights of the metals in each anticathode (the idea of atomic number had not yet come to the fore) by a simple law. In fact he gave the first hint of Moseley's relations, and it was his work which inspired Moseley to his broader generalisations.

''My father then examined with his spectrometer crystals of KCl and NaCl such as I had used for my Laue photographs, and found the reflections of the characteristic peaks from the (100), (111) and (110) faces. It was clear at once that the spectrometer was a far more powerful way of investigating crystal structure than the Laue photographs, which I had used. It was only at this stage that we joined forces. In particular, I had been trying to analyse the diamond structure by Laue methods without success, but my father mounted it on the spectrometer and the structure became immediately obvious. We wrote a paper on the diamond structure together, but the results which gave the clue to it were obtained by him. I was able, however, to work along with him with the spectrometer in the summer of 1913, and so to work out the structures of zincblende, fluorspar, pyrites and some of the carbonates, which showed how powerful the spectrometer could be. My father was at first principally interested in X-ray spectra and X-ray absorption edges, but crystal structures also fascinated him, and from that point on we both mainly devoted ourselves to crystal structure analysis.''

These experiments, together with those of Friedrich and Knipping, not only confirmed von Laue's diffraction theory but gave a direct proof of the existence of the space-lattice, and provided a simple expression (the Bragg law) for the relationship between the wavelength of the X-rays used and the lattice spacings of the crystal. The ionisation curves obtained by means of the Bragg spectrometer showed clearly that the ''mirror-image reflection'' postulated by Bragg is selective and is conditioned by multiple interference. The Bragg equation was first published in its usual form in a paper by W. H. and W. L. Bragg in the *Proceedings of the Royal Society*, vol. 88, page 428 (1913). Soon afterwards von Laue [*Physikalische Zeitschrift*, **14,** 421 (1913)] was able to show that this equation was only another way of expressing the results of the geometrical space-lattice theory.

Ionisation spectrometer measurements also revealed another reason for the absence of many of the interference spots at first expected by von Laue. The pulse theory of X-rays predicted much too wide an extension of their spectrum in the short-wave direction. In fact, as W. Duane and F. L. Hunt established in 1915, this spectrum ends abruptly at the short-wavelength limit given by the now well-known quantum rule.

Still further credit is due, however, to W. H. and W. L. Bragg. X-ray diffraction patterns had made it possible to compare the wavelengths of X-rays with the three lattice constants, whose axial ratios were already known. Absolute measurements, however, remained impossible without a knowledge of the absolute value of the lattice constant of at least one substance. It was necessary for this purpose to know the number of atoms in the unit cell, and this was impossible without a knowledge of the structure. The Braggs' measurements, however, had shown that sodium chloride really did possess one of the hypothetical structures postulated by Barlow. Thus it was possible to obtain the absolute value of the lattice constant of this salt; this in turn provided an absolute measure of the wavelengths of X-rays, and hence the absolute lattice constants of all other crystals investigated. Rarely has the value of hypothesis in research been so strikingly demonstrated.

This brings us to the end of the historical introduction as far as X-rays are concerned, since all that has followed is merged into present-day practice. Yet the space lattice has had another most important part to play in physics.

In 1924 L. de Broglie put forward in his *Thèses* the basic idea of wave mechanics. In the summer of 1925 Walter Elsasser, in a letter to the editor of *Naturwissenschaften*, pointed out that the de Broglie waves of electrons must cause space-lattice interference effects, and that experiments by Davisson and Kunzman on the reflection of electrons from a platinum sheet had actually shown maxima of the expected kind. When in 1926 E. Schrödinger published his communications on *Quantisierung als Eigenwertproblem*, C. J. Davisson and L. H. Germer began systematically to look for these effects. In March 1927 they were able to publish a note in *Nature* to say that their efforts, made on a single crystal of nickel, had been crowned with success. In May of the same year G. P. Thomson and A. Reid announced that an electron beam of several thousand volts had, on passing through a celluloid film, produced Debye–Scherrer rings, and G. P. Thomson found the same effect even more clearly with metal foils. Thus Elsasser's prediction was confirmed and the plainest of all proofs had been given of the connection of a wave with the movement of a corpuscle.

Admittedly the geometrical theory of space-lattice interference does not apply so well to electrons as it does to X-rays, especially not to low-energy electrons. But it has enjoyed further triumphs in the diffraction of neutrons, observed first by D. P. Mitchell and P. M. Powers, then since 1946 by W. H. Zinn, E. Fermi, C. Shull and other American physicists using the cyclotron or the uranium pile as a source. Here a new possibility has to be taken into account: the atomic structure factor, which is characteristic for the scattering of single atoms, may be negative as well as positive. This branch of research is, however, still in its infancy. It appears to be capable of great development.

Introduzione storica del secondo volume delle International Tables for X-ray Crystallography, pubblicate dalla International Union of Crystallography

L'introduzione storica è a cura di Max von Laue, premio Nobel per la Fisica 1914 per *his discovery of the diffraction of X-rays by crystals*

Notare che nel testo il ruolo fondamentale dell'autore appare minimizzato mentre è in chiara evidenza il ruolo, di grande importanza, di William Henry Bragg e di suo figlio William Lawrence Bragg, anch'essi premio Nobel per la Fisica 1915 per *their services in the analysis of crystal structure by means of X-rays*. È interessante osservare come nella sua introduzione Max von Laue riporti il suo contributo per mezzo di scritti originali di William Lawrence Bragg che citano espressamente i lavori di Laue sulla diffrazione di raggi-X. Max von Laue dimostra di essere un uomo di grande statura in tutta la sua vita.

William Henry Bragg e suo figlio William Lawrence Bragg, sono l'unico esempio di padre e figlio che abbiano ricevuto insieme un premio Nobel per il medesimo argomento al quale hanno entrambi contribuito in modo diverso e in luoghi diversi.

Vari altri premi Nobel si sono susseguiti nella cristallografia, dalla definizione della struttura del DNA allo studio della struttura delle proteine, informazioni che hanno un'importanza basilare nella moderna tecnologia dei farmaci.

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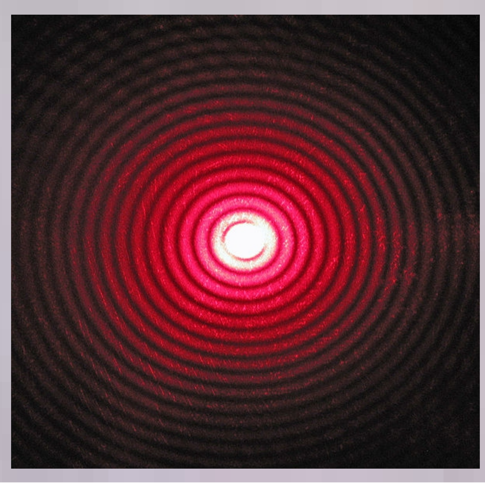
La diffrazione è un fenomeno fisico causato dall'interazione di un'onda con un oggetto di dimensioni opportune



Laser rosso dopo un piccolo foro

La luce delle stelle subisce diffrazione nel telescopio

Nel micro mondo degli atomi ogni oggetto si comporta anche come un'onda quindi si assiste spesso a fenomeni di diffrazione

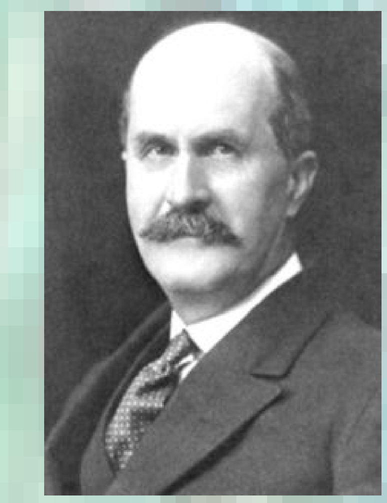
La diffrazione e i premi Nobel per la fisica

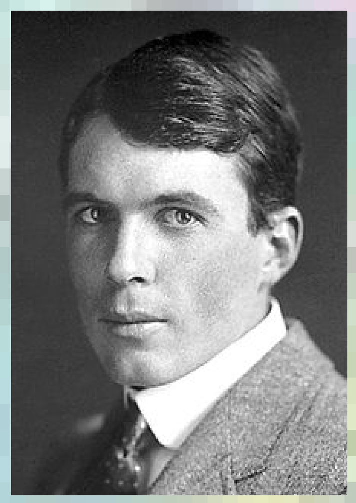
1901 Wilhelm Conrad Röntgen (primo Nobel per la Fisica)

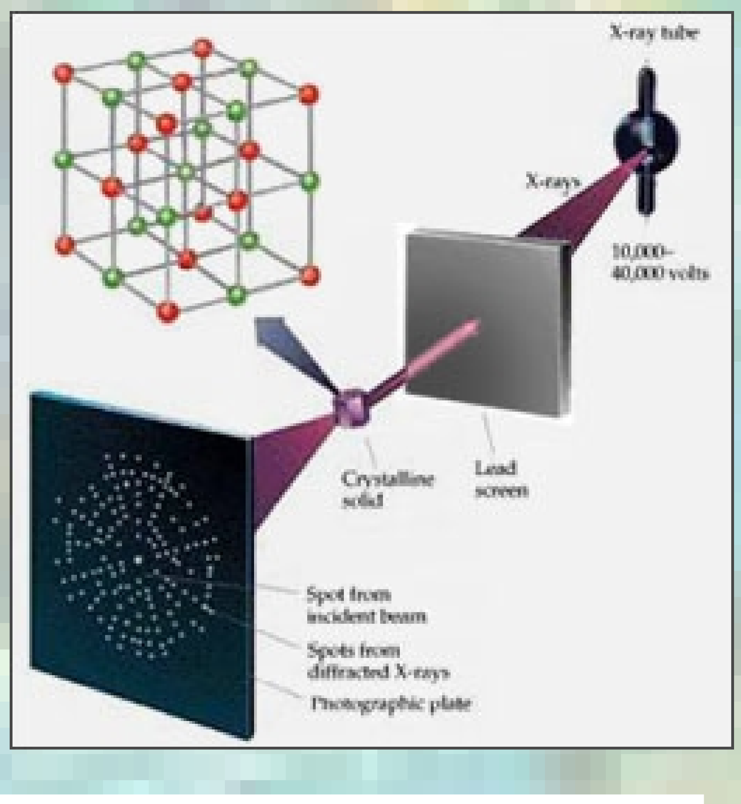
1914 Max von Laue

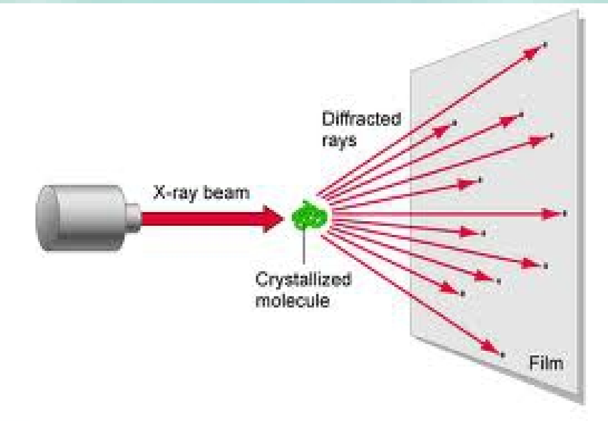
1915 William Henry Bragg

1915 William Lawrence Bragg







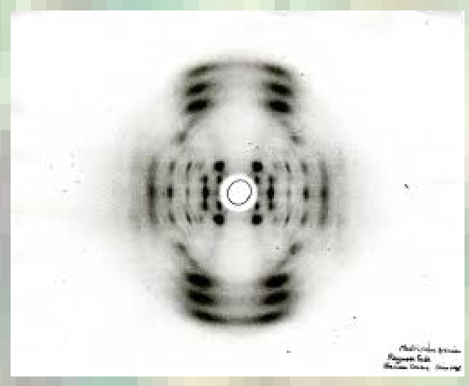


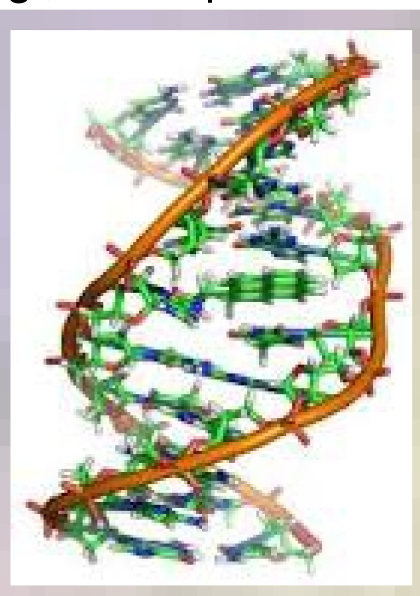
Cristallografia e la materia biologica, gli attori della soluzione della struttura del DNA

James Dewey Watson

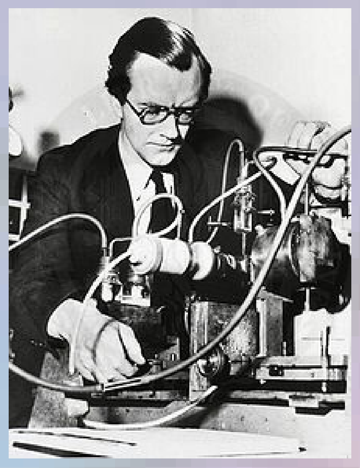
Francis Harry Compton Crick

Biologi, Nobel per la medicina

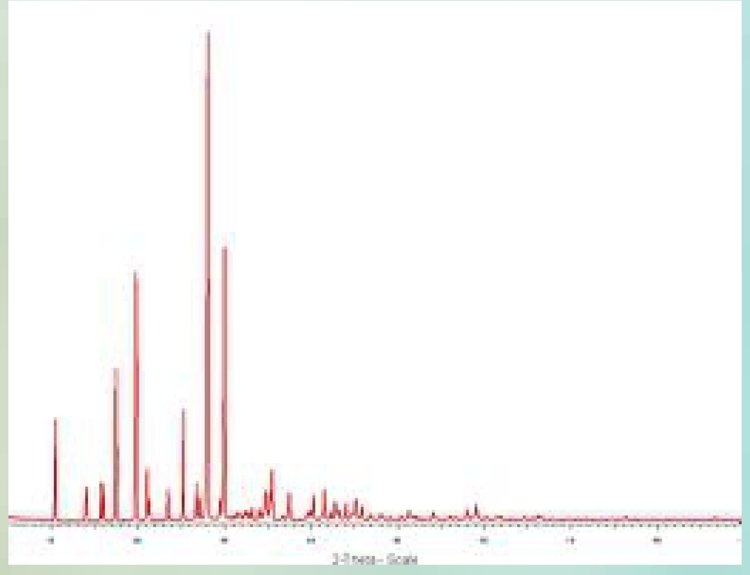


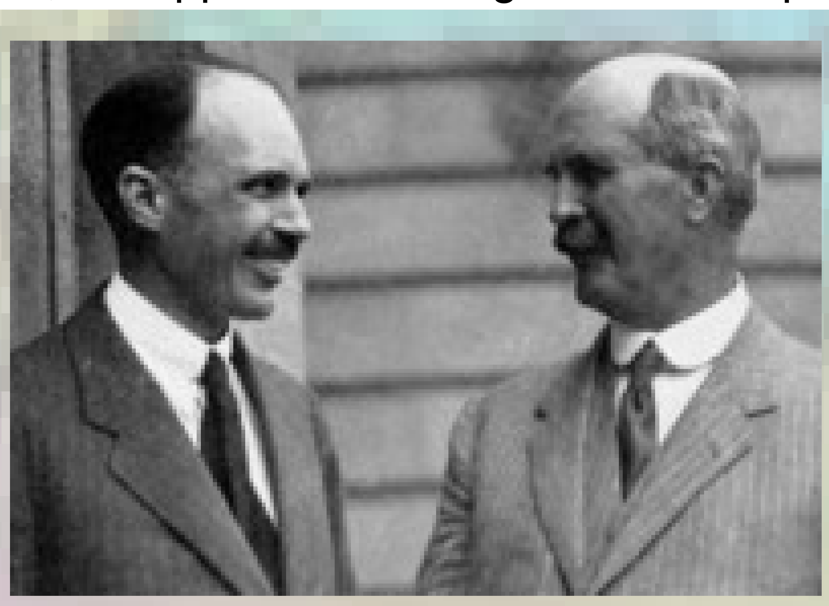


Rosalind Elsie Franklin, diffrazione di raggi-x sul DNA, la doppia elica emerge dai suoi esperimenti



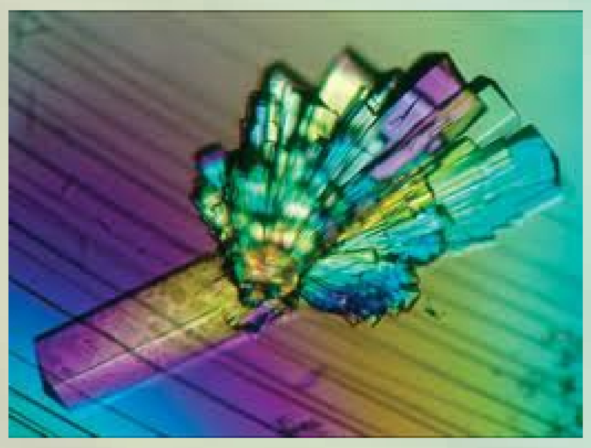
Maurice Hugh Frederick Wilkins, fisico, biologia molecolare, ideatore della struttura a elica, Nobel per la Medicina insieme a Crick e Watson





I Bragg

La cristallografia delle proteine è un procedimento essenziale per la biologia e la farmacologia



Piccoli cristalli di proteine al microscopio

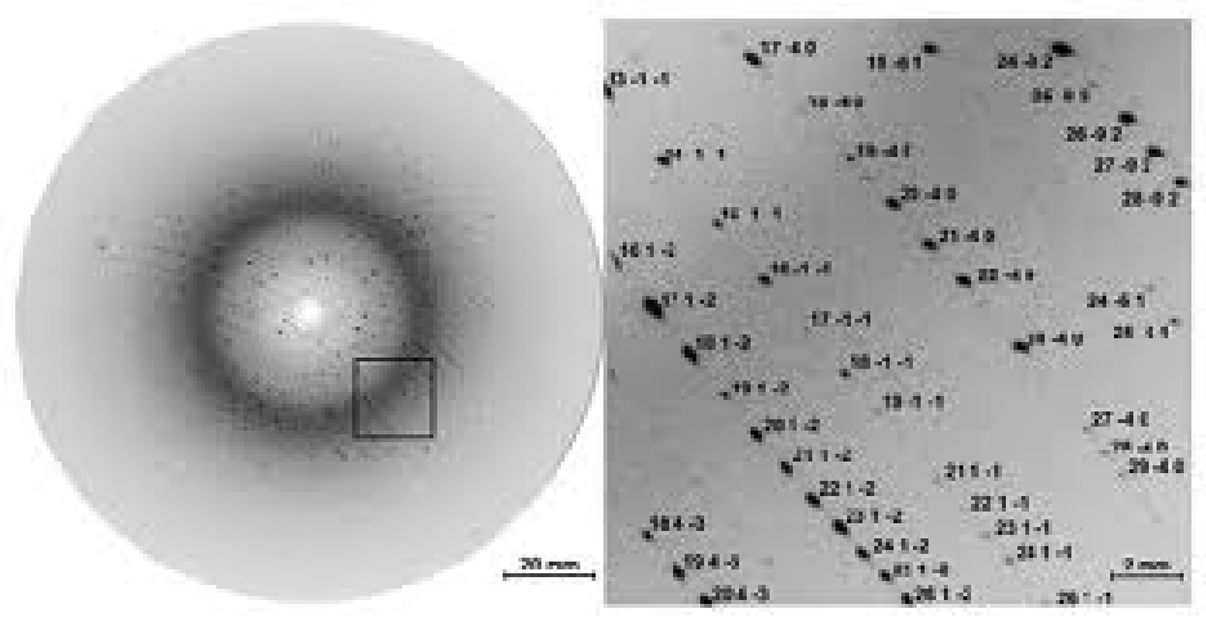
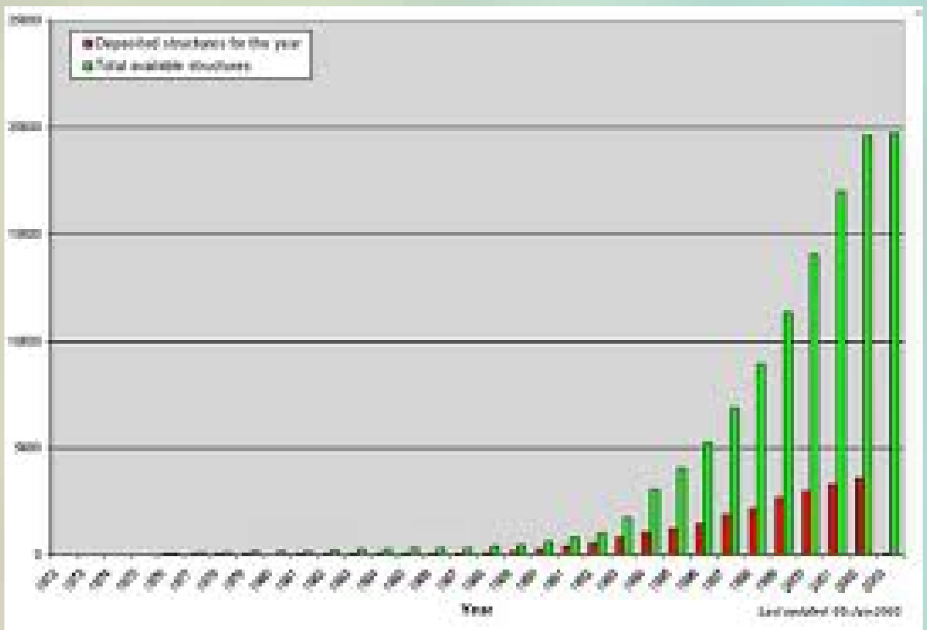


Figura di diffrazione di raggi-X da un cristallo di proteine, il quadrato di lato è un ingrandimento dove si vedono i punti prodotti dalla diffrazione e le terne di numeri (indici di Miller) che li caratterizzano

Protein Data Bank è una raccolta delle strutture dei cristalli di proteine. La crescita del numero di proteine studiate è vertiginosa e continua. Dal 1976 a oggi sono state studiate circa 100.000 proteine, quasi tutte con i raggi-X.



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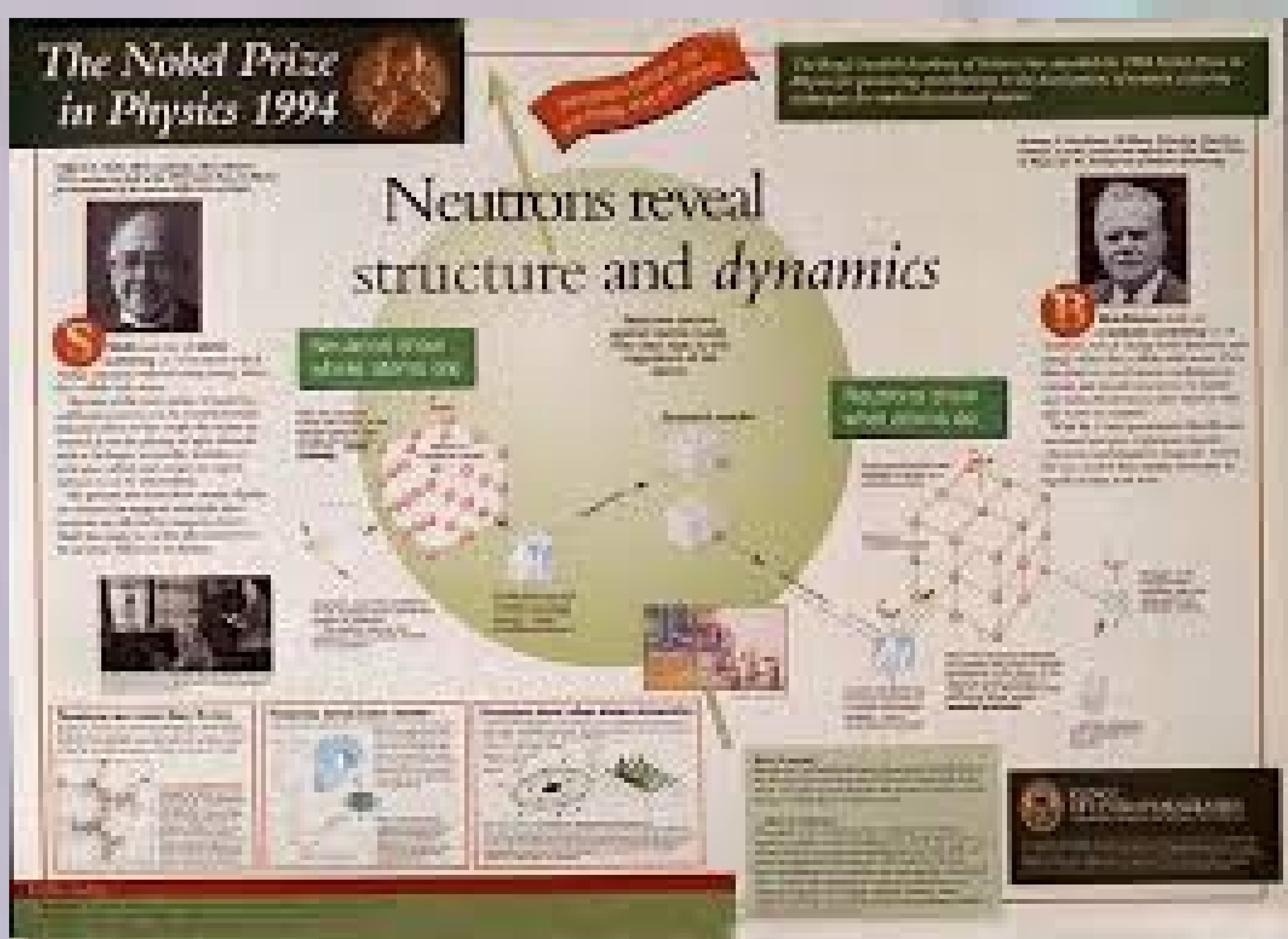
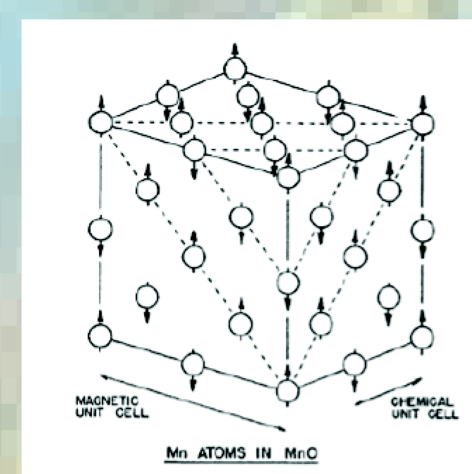
Diffrazione dei neutroni

La diffrazione dai cristalli è stata scoperta per mezzo dei raggi-X e la teoria è stata sviluppata per questa tecnica. Nella prima metà del XX secolo, l'avvento della Meccanica Quantistica ha portato a comprendere che i fenomeni di diffrazione possono avvenire con qualunque tipo di particelle microscopiche: elettroni, atomi, protoni e neutroni. I neutroni si sono affermati come tecnica standard grazie all'assenza di carica elettrica che li rende preziosi per investigare materiali di ogni genere anche perché i neutroni sono in grado di *vedere* gli atomi leggeri che i raggi-X hanno difficoltà ad evidenziare.



1994, premio Nobel per la Fisica



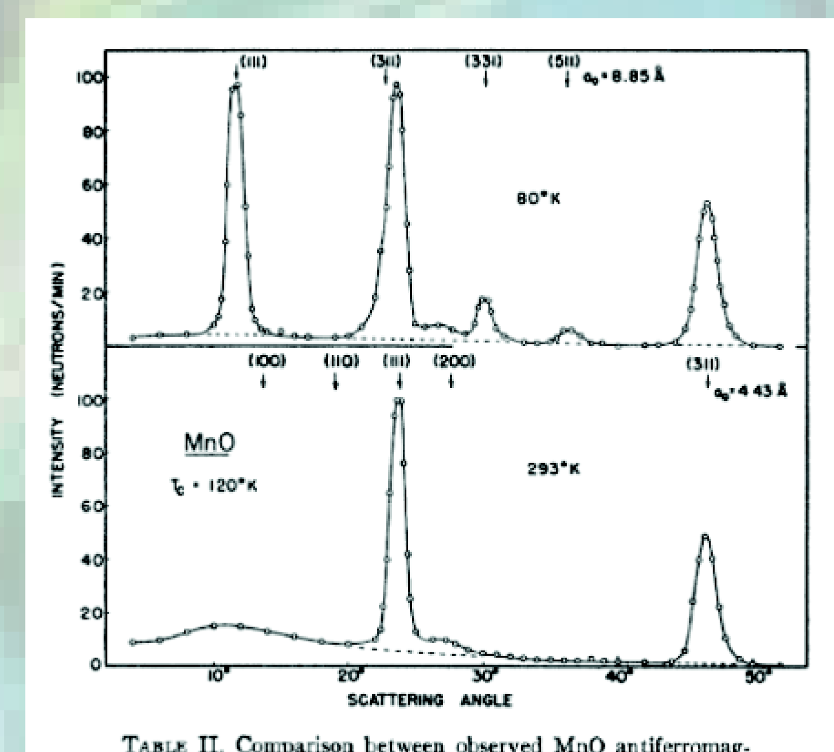
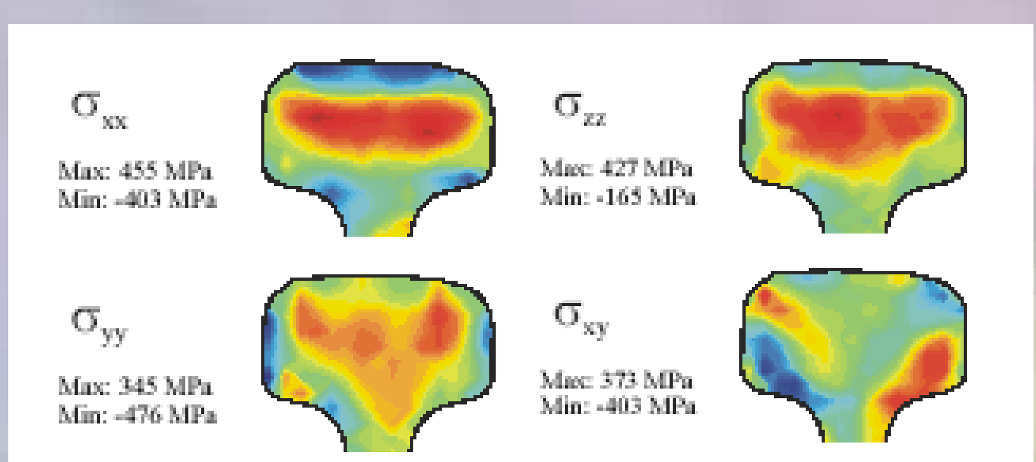
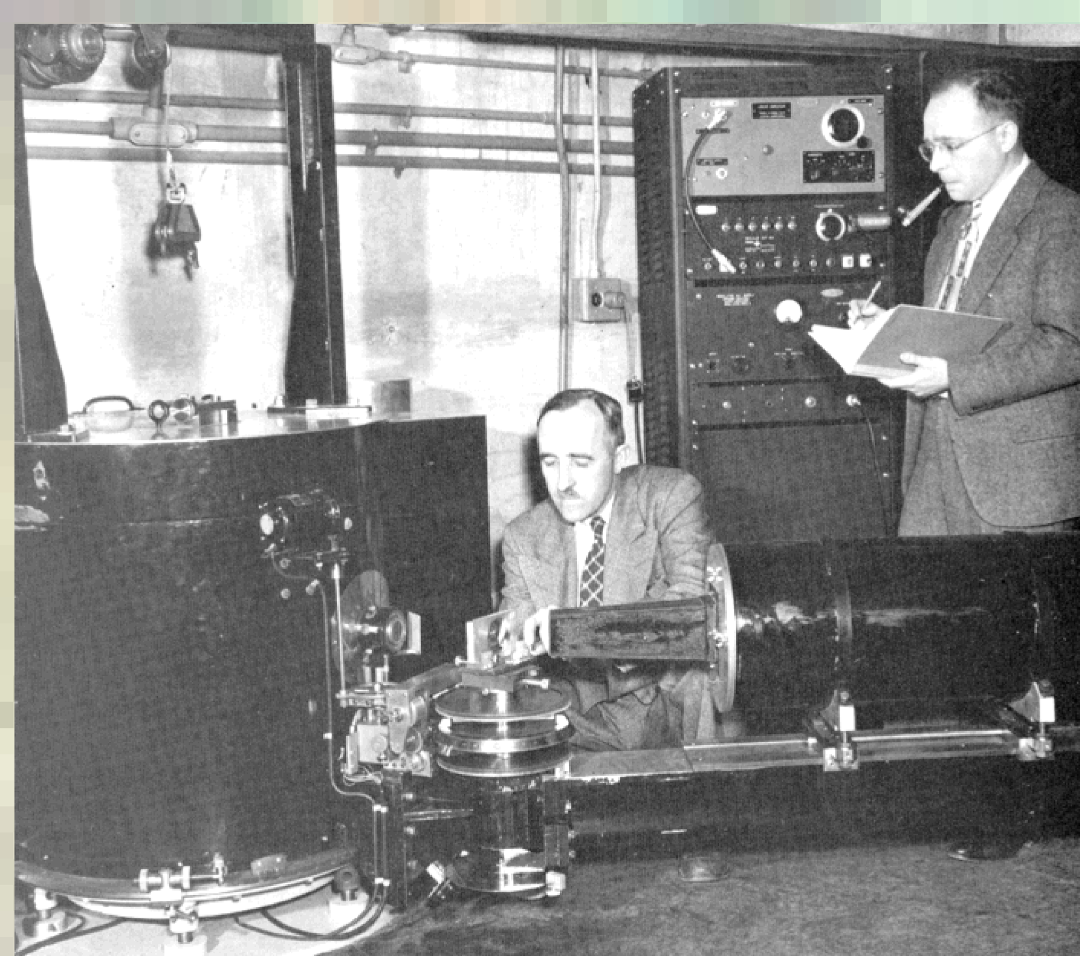


TABLE II. Comparison between observed MnO antiferromagnetic intensities and those calculated for various models of magnetic orientation with respect to crystallographic axes.

Louis Néel, premio Nobel in Fisica nel 1970 per *fundamental work and discoveries concerning antiferromagnetism and ferrimagnetism which have led to important applications in solid state physics*. La dimostrazione dell'esistenza dell'antiferromagnetismo e del ferrimagnetismo è stata possibile con la diffrazione magnetica dei neutroni.

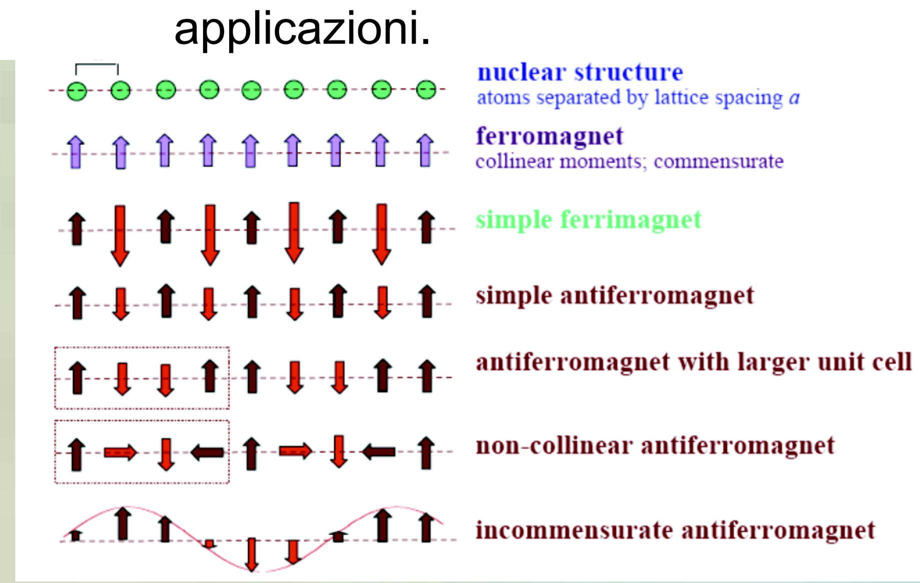


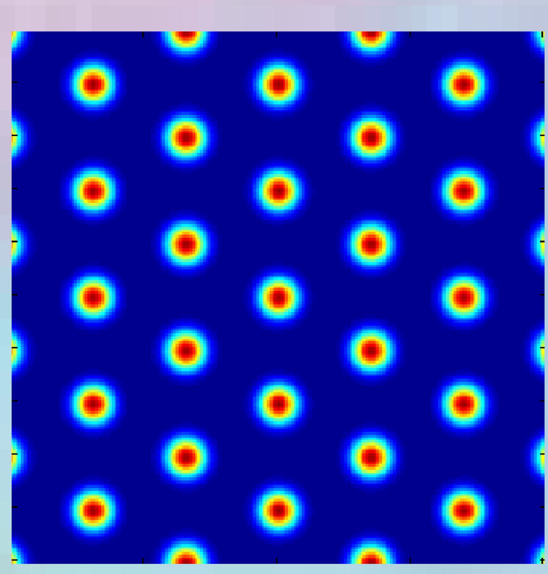
La diffrazione dei neutroni è molto efficace nello studio degli sforzi residui in parti di apparati industriali. Un esempio importante è quello di componenti soggetti a usura per poter controllare e sostituire i componenti prima che lo sforzo a fatica diventi critico.



Shull (premio nobel 1994, in piedi con la caratteristica pipa) e Wollan nel 1947 al primo diffrattometro per neutroni a Oak Ridge. Notare che si trovano nel laboratorio in giacca e cravatta vicinissimi al fascio di neutroni monocromatici (tutti con la stessa velocità) in uscita dal moncormatore.

Il magnetismo è un fenomeno complesso che si sviluppa in un numero considerevole di forme schematizzate qui in una sola dimensione. Nei casi reali a tre dimensioni si sviluppano anche distribuzioni a elica e la coesistenza del magnetismo e della superconduttività sono materia di studio in quanto il magnetismo tende a sopprimere la superconduttività. La diffrazione di neutroni è uno dei modi più efficaci per comprendere la natura microscopica di questi fenomeni e governarli anche in prospettiva delle applicazioni.





Il campo magnetico non penetra liberamente nei superconduttori ma si organizza in linee dette *flussoidi*. I neutroni permettono di osservare direttamente i flussoidi che sono le zone dove rimane campo magnetico. Il reticolo di flussoidi nel Niobio (uno dei superconduttori più impiegato per produrre i grandi campi magnetici usati ad esempio in diagnostica medica) è qui mostrato come osservato con i neutroni. La zona blu è superconduttrice mentre nelle zone rosse, che sono allo stato normale, c'è il campo magnetico.