History of X-ray Crystallography and Early Indian Contributions

Talk delivered at the

University of Hyderabad
8-September-2014

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National Centre for Cell Science
Pune

Science


Crystallography at 100

Dazzling History

Over the past century, x-ray crystallography has transformed scientists' understanding of the structure and behavior of materials

REPORTED AND WRITTEN BY THOMAS SUMNER

PREHISTORY

1611 Johannes Kepler speculates that **snowflakes** are **hexagonal grids** of water particles—a hypothesis that cannot be tested for centuries to come.

1895 1901 Physics
Wilhelm Röntgen produces and measures **x-rays**.

1912 1914 Physics
Max von Laue creates a **diffraction pattern** by firing x-rays at a crystal of copper sulfate but cannot interpret it.

$n\lambda = 2d \sin\Theta$

1912 1915 Physics
William Henry Bragg and his son **William Lawrence Bragg** publish **Bragg's law**, the key to using diffraction to infer crystal structure.

1913 Braggs determine crystal structure of **diamond**.

1916 Powder diffraction analysis makes it possible to study small crystals.

1924 **John Desmond Bernal** determines structure of **graphite**.

1937 1946 Chemistry
James Sumner demonstrates that any protein can be **crystallized**.

1945 1964 Chemistry
Dorothy Hodgkin and colleagues determine structure of **penicillin**, the first complex molecule solved by x-rays.

1946 1994 Physics
First **neutron diffraction** experiments; the technique provides **3D structures** and other details that x-rays cannot.

1952 **Rosalind Franklin** uses x-ray diffraction to image **DNA** and suggests it has a helical structure.
1962 Physiology or Medicine
F. Crick, J. Watson, and M. Wilkins

Science

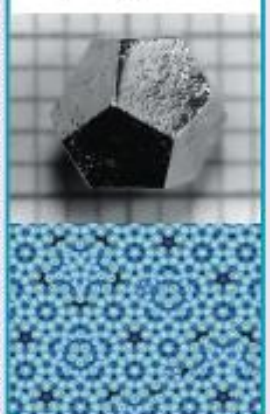
1952
Grazing-incidence optics paves way for modern x-ray studies.

1958 1962 Chemistry
John Kendrew and Max Perutz determine first protein structures, of **myoglobin and hemoglobin**.

1970 The first **synchrotron x-ray** sources open, producing brilliant x-rays for detailed crystallography research.

1978 **Tomato bushy stunt virus** is imaged—the first viral structure mapped at atomic level.

1982 2011 Chemistry
Scientists observe first **quasicrystals**, strange materials whose atoms follow an **ordered but nonrepeating pattern**.



1984 1988 Chemistry
Researchers solve structure of **photosynthesis reaction site**.

1989
Time-resolved crystallography reveals action mechanisms of rapidly changing molecules.

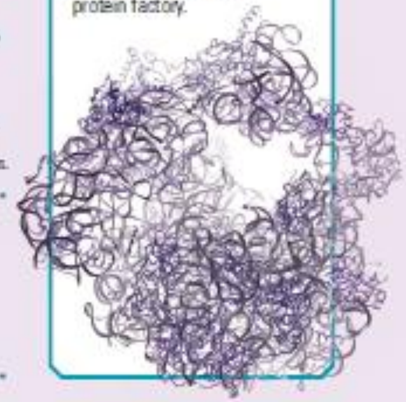
1990s
Automated protein crystallization. Number of structures in the Protein Data Bank grows from 507 in 1990 to 97,980 in 2014.

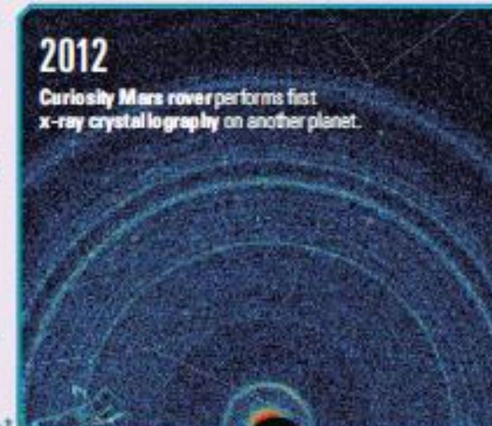
2000
Protein Structure Initiative begins (see News Focus, in this issue).

2001
"Robotic beamlines" start to speed sample analysis at x-ray sources.

2002
Microfluidic chips promise to boost automated protein-crystal growing.

2000 2009 Chemistry
Scientists solve structure of a **ribosome**, cells' protein factory.





2012
Curiosity Mars rover performs first **x-ray crystallography** on another planet.

2013
Crystallography yields a detailed picture of the protein that **HIV** uses to **invade immune cells**.

Nobel Prize awarded for work

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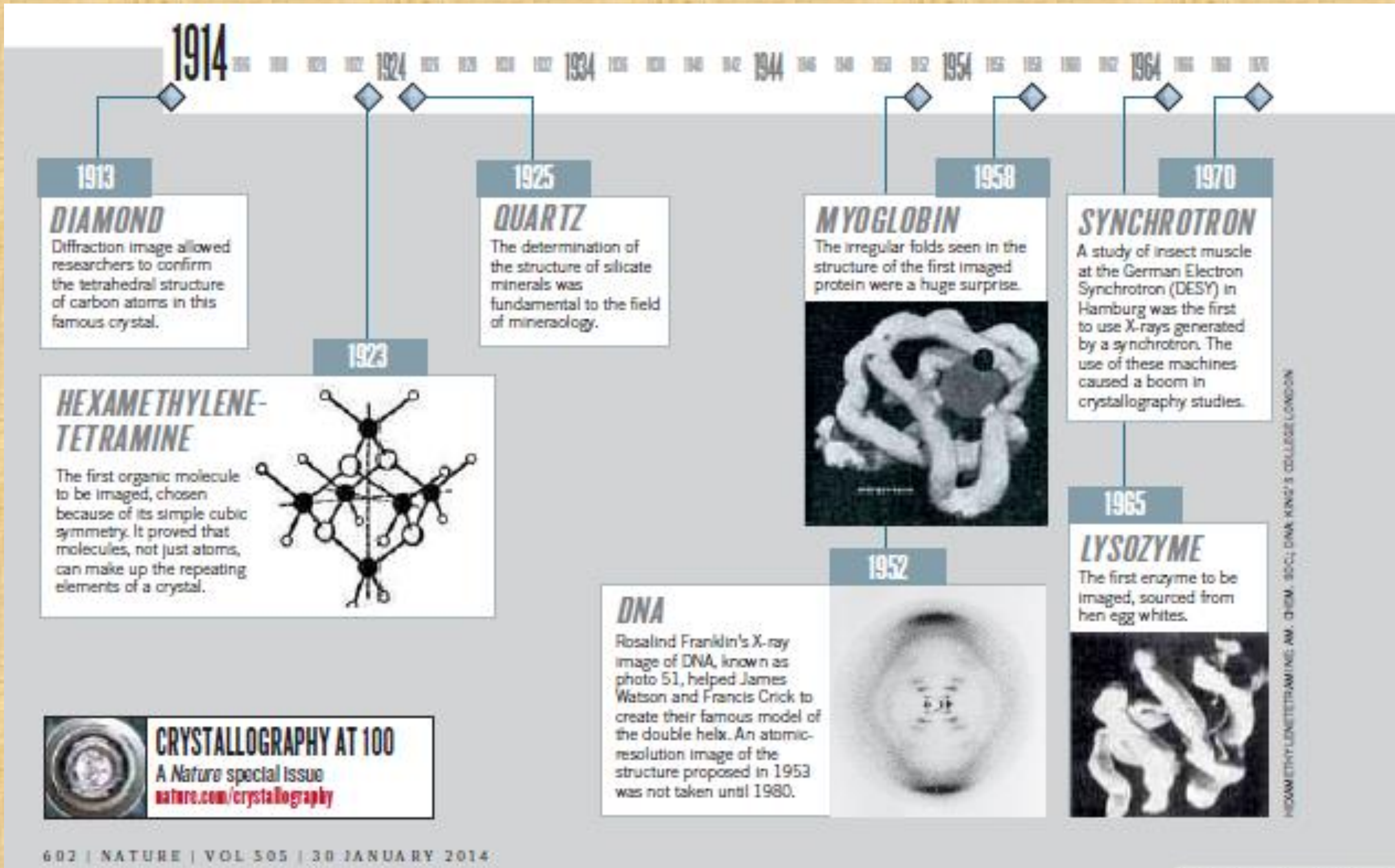
Nature



1914 1924 1934 1944 1954 1964

1913
DIAMOND
Diffraction image allowed researchers to confirm the tetrahedral structure of carbon atoms in this famous crystal.

1923
HEXAMETHYLENE-TETRAMINE
The first organic molecule to be imaged, chosen because of its simple cubic symmetry. It proved that molecules, not just atoms, can make up the repeating elements of a crystal.

1925
QUARTZ
The determination of the structure of silicate minerals was fundamental to the field of mineralogy.

1958
MYOGLOBIN
The irregular folds seen in the structure of the first imaged protein were a huge surprise.

1952
DNA
Rosalind Franklin's X-ray image of DNA, known as photo 51, helped James Watson and Francis Crick to create their famous model of the double helix. An atomic-resolution image of the structure proposed in 1953 was not taken until 1980.

1970
SYNCHROTRON
A study of insect muscle at the German Electron Synchrotron (DESY) in Hamburg was the first to use X-rays generated by a synchrotron. The use of these machines caused a boom in crystallography studies.

1965
LYSOZYME
The first enzyme to be imaged, sourced from hen egg whites.

CRYSTALLOGRAPHY AT 100
A *Nature* special issue
nature.com/crystallography

HEXAMETHYLENETETRAMINE: AM. CHEM. SOC.; DNA: KING'S COLLEGE LONDON

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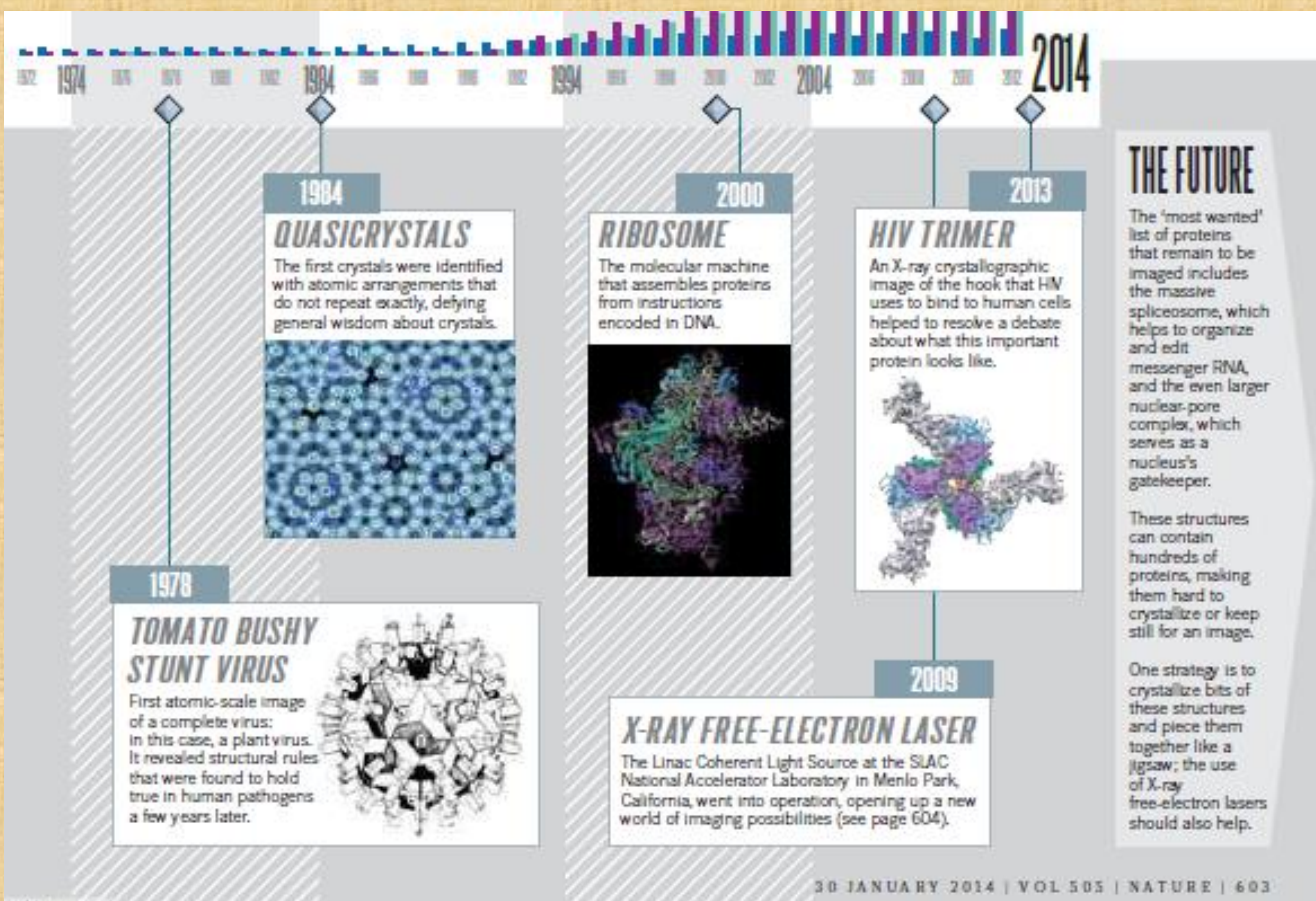
Nature



1974 1984 1994 2004 2014

1978

TOMATO BUSHY STUNT VIRUS

First atomic-scale image of a complete virus: in this case, a plant virus. It revealed structural rules that were found to hold true in human pathogens a few years later.

1984

QUASICRYSTALS

The first crystals were identified with atomic arrangements that do not repeat exactly, defying general wisdom about crystals.

2000

RIBOSOME

The molecular machine that assembles proteins from instructions encoded in DNA.

2009

X-RAY FREE-ELECTRON LASER

The Linac Coherent Light Source at the SLAC National Accelerator Laboratory in Menlo Park, California, went into operation, opening up a new world of imaging possibilities (see page 604).

2013

HIV TRIMER

An X-ray crystallographic image of the hook that HIV uses to bind to human cells helped to resolve a debate about what this important protein looks like.

THE FUTURE

The 'most wanted' list of proteins that remain to be imaged includes the massive spliceosome, which helps to organize and edit messenger RNA, and the even larger nuclear-pore complex, which serves as a nucleus's gatekeeper.

These structures can contain hundreds of proteins, making them hard to crystallize or keep still for an image.

One strategy is to crystallize bits of these structures and piece them together like a jigsaw; the use of X-ray free-electron lasers should also help.

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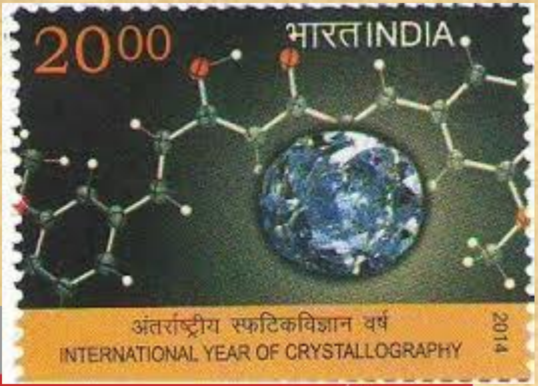
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Virtual Conference on Computational Chemistry
1st Aug 2014 - 31st Aug 2014
India: Virtual
National Science Week
16th Aug 2014 - 24th Aug 2014
Australia: Canberra
Bruker OpenLab Indonesia
June http...
RT @coopallographer: Simon Coles asking an important question. I hope we do. #bca2014 http://t.co/ZfCohnJMgg
#Malaysia celebrates @IYCr2014 at the University of

Discovery of X-rays, 8-Nov-1895

X-rays discovered while studying effect of electric current through gas of extremely low pressure

Building up on the work of Lenard, Perrin and J J Thomson

Recent photograph

Before March 16, 1945

Röentgen and possibility of discovering diffraction, 1897

From W. C. Röntgen's Third Communication, *March 1897:*

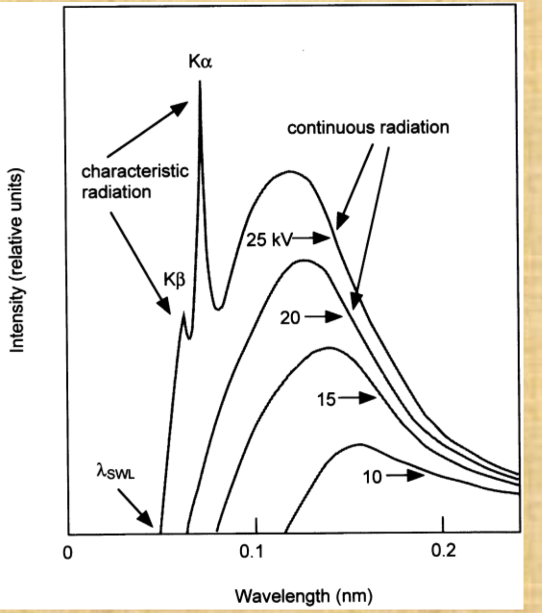
'The experiments on the permeability (for X-rays) of plates of constant thickness cut from the same crystal in different orientations, which were mentioned in my first Communication, have been continued. Plates were cut from calcite, quarz, turmaline, beryl, aragonite, apatite and barytes. Again no influence of the orientation on the transparency could be found.

'Ever since I began working on X-rays, I have repeatedly sought to obtain diffraction with these rays; several times, using narrow slits, I observed phenomena which looked very much like diffraction. But in each case a change of experimental conditions, undertaken for testing the correctness of the explanation, failed to confirm it, and in many cases I was able directly to show that the phenomena had arisen in an entirely different way than by diffraction. I have not succeeded to register a single experiment from which I could gain the conviction of the existence of diffraction of X-rays with a certainty which satisfies me.'

Principle of X-ray generation

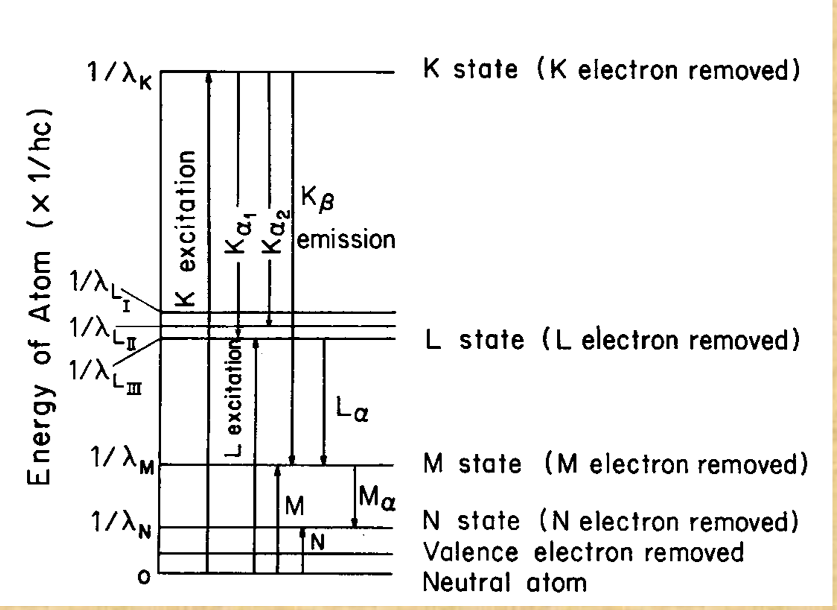
Kaye, Sommerfield, 1909, “Bremsstrahl”

Barkla for characteristic X-rays (called the K-series and the L-series)



X-rays are produced when accelerated electrons collide the target

Loss of kinetic energy of electrons due to impact is manifested as X-rays



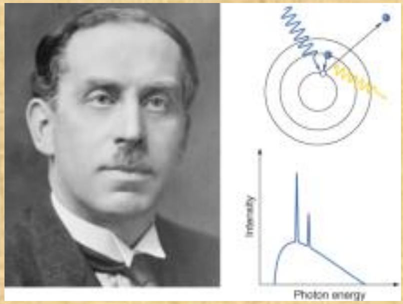
Continuous spectrum arises due to deceleration of electrons within the target

Characteristic spectrum arises due to inner shell electronic transitions

Moseley’s contributions

1911, An Enigma: Waves of Corpuscles?

WH Bragg interpreted ionization of gases as transfer of energy by photoelectric effect (unaware of Einstein's work of 1905). X-rays are a stream of particles of neutral charge, or doublets of ± charged.



Open arguments with Barkla
(upon discovery of polarization of X-rays in 1905)
on the wave or corpuscular nature

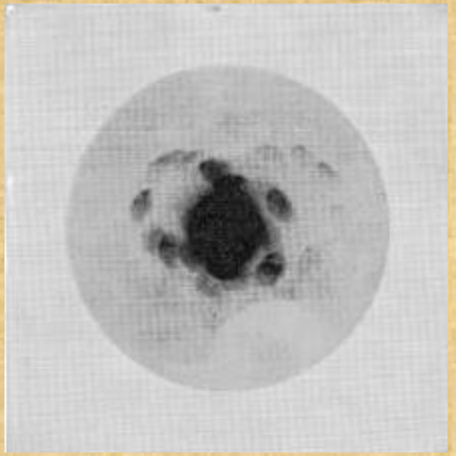
19 Nov 1908 Nature: As there are few opportunities in Australia for an investigator to place his views quickly before a scientific public, we print the above letter, but with it the correspondence must cease. The subject is more suitable for discussion in special journals devoted to physics than in our columns.

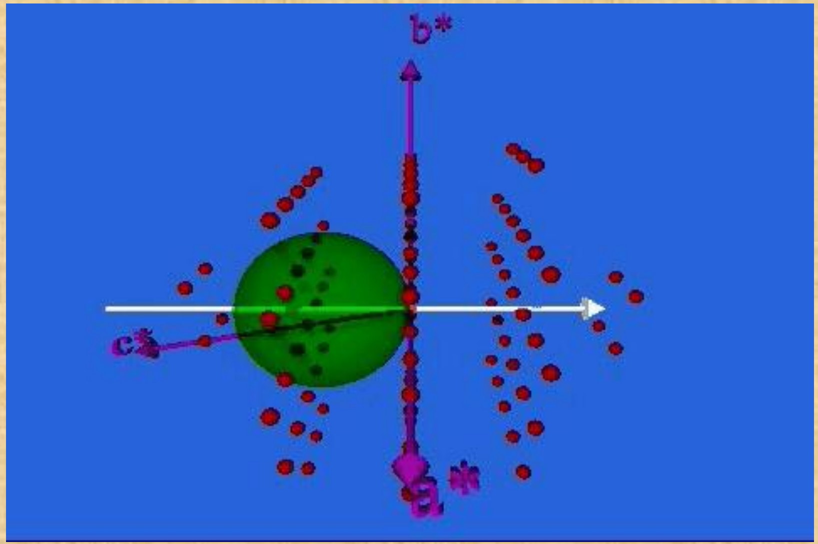
Diffraction by a slit:

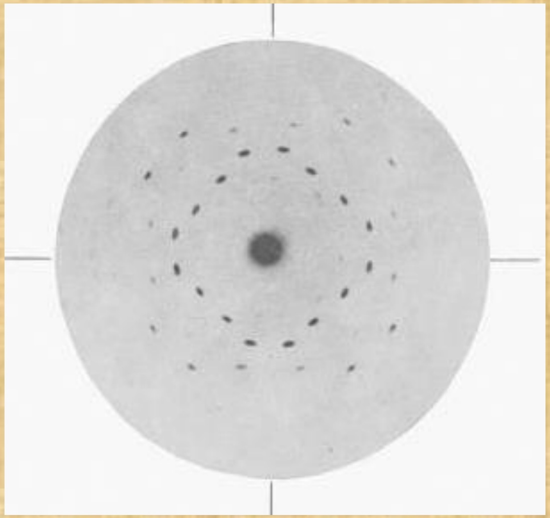
Röentgen, reported unsuccessful attempts, 1897
Sommerfield, fuzziness of fringes due to "diffraction" by a slit caused by considerable spectral range of X-rays.

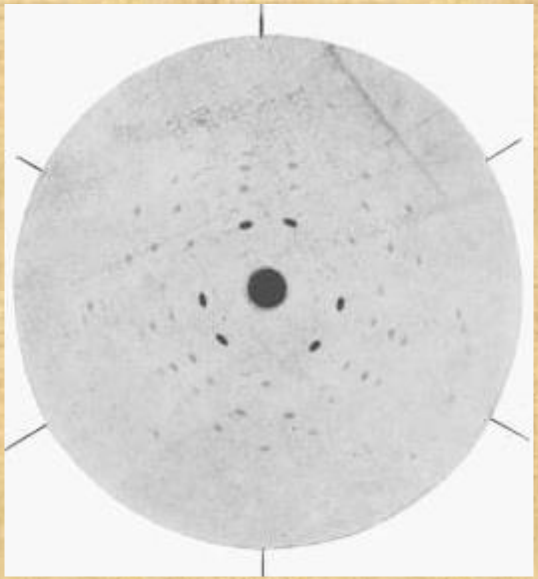
The first photographs, June 1912

Conceptualized possibly during a walk with PP Ewald, January 1912









http://www.xtal.iqfr.csic.es/Cristalografia/parte_05-en.html

Lars Vegard to W. H. Bragg, 26-June, 1912

(1) According to Laue, the diffraction in a grating with regularities in three dimensions is most complicated and there is in such a grating a very little chance that a maximum may occur

(2) The deviated spots seem to be much more distinct than should expected when the points were due to diffraction. It is also very difficult to understand how the scattered points can smaller than the middle point due to the primary rays

(3) It is not easily understood how by diffraction a heterogenous beam can give such sharp maxima- and sharp maxima only. If the scattered rays are all due to diffraction, it must be from some homogenous group of rays which are mixed up with the primary one.

John Jenkin, William and Lawrence Bragg, Father and Son, The most extraordinary collaboration in Science, Oxford University Press

The Diffraction of Short Electromagnetic Waves by a Crystal. By W. L. Bragg, B.A., Trinity College. (Communicated by Professor Sir J. J. Thomson.)

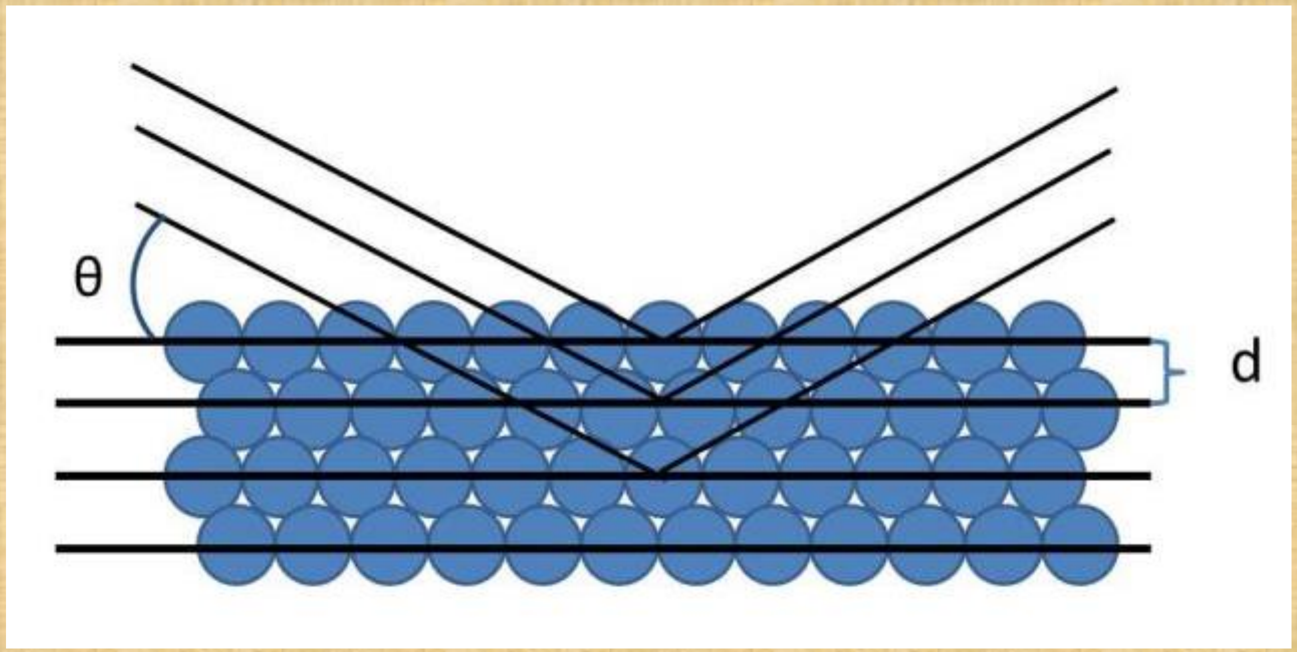
[*Read* 11 November 1912.]

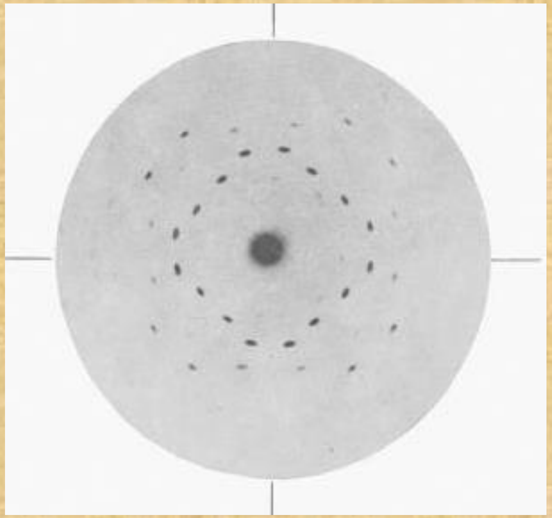
[Plate II.]

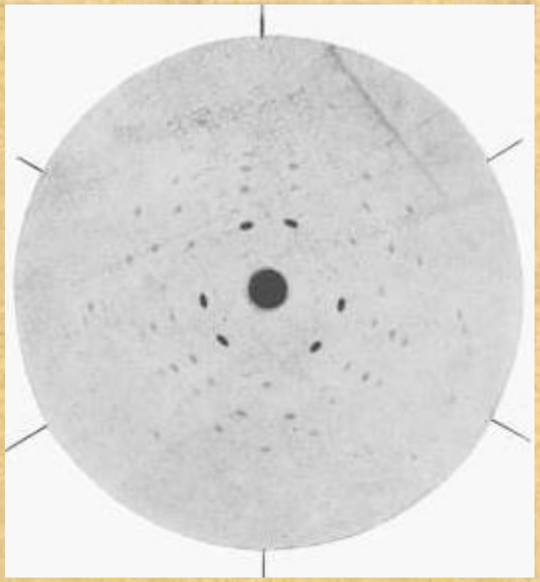
Herren Friedrich, Knipping, and Laue have lately published a paper entitled 'Interference Phenomena with Röntgen Rays*,' the experiments which form the subject of the paper being carried out in the following way. A very narrow pencil of rays from an

strength of a pulse reflected from a single plane will depend on the number of atoms in that plane which conspire in reflecting the beam. When two sets of planes are compared which produce trains of equal wave-length it is to be expected that if in one set of planes twice as many atoms reflect the beam as in the other set, the corresponding spot will be more intense. In what follows

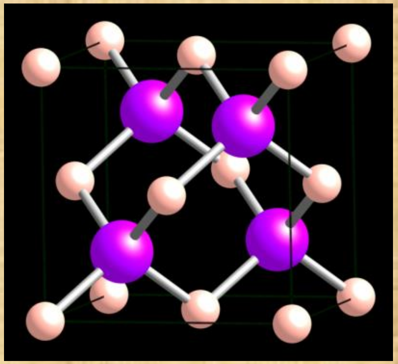
Bragg's law







$$2d\sin\theta = n\lambda$$



p	q	r	s	$\frac{a}{\lambda}$	Intensity	h_1	h_2	h_3
1	1	1	3	2·8	*	1	3	1
1	1	1	5	6·8	✲	1	5	1
1	1	1	7	12·8	*	1	7	1
1	1	1	9	20·8	Invisible	1	9	1
1	3	1	1	2·8	*	3	1	1
1	3	1	3	4·8	*	3	3	1
1	3	1	5	8·8	✲	3	5	1
1	3	1	7	14·8	+	3	7	1
1	3	1	9	22·8	Invisible	3	9	1
1	5	1	1	6·8	✲	5	1	1
1	5	1	3	8·8	✲	5	3	1
1	5	1	5	12·8	*	5	5	1
1	5	1	7	18·8	Invisible	5	7	1
1	7	1	1	12·8	*	7	1	1
1	7	1	3	14·8	+	7	3	1
1	7	1	5	18·8	Invisible	7	5	1
1	9	1	1	20·8	Invisible	9	1	1

Zinc Blende crystals are face centered cubic!

Structure of NaCl

On Pope's suggestions, Bragg took X-ray photographs of NaCl and reported its structure in June 1913

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The Structure of Some Crystals as Indicated by Their Diffraction of X-rays

W. L. Bragg

Proc. R. Soc. Lond. A 1913 **89**, doi: 10.1098/rspa.1913.0083, published 22 September 1913

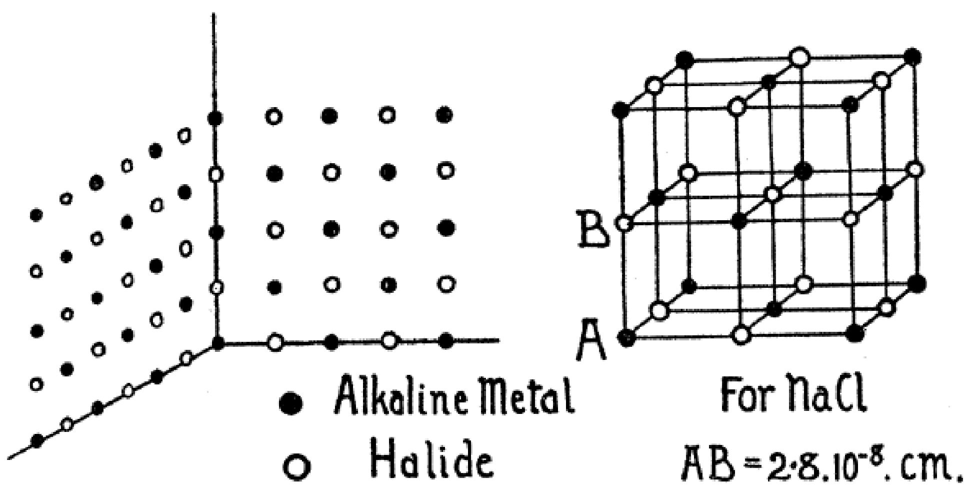
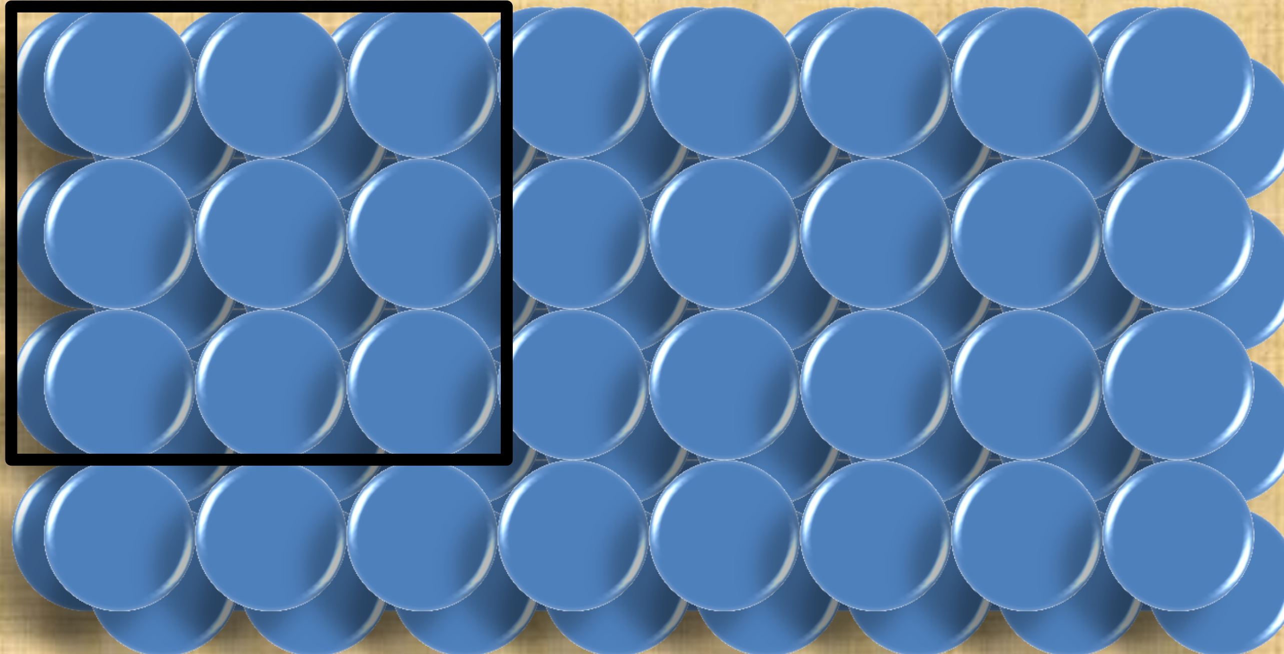
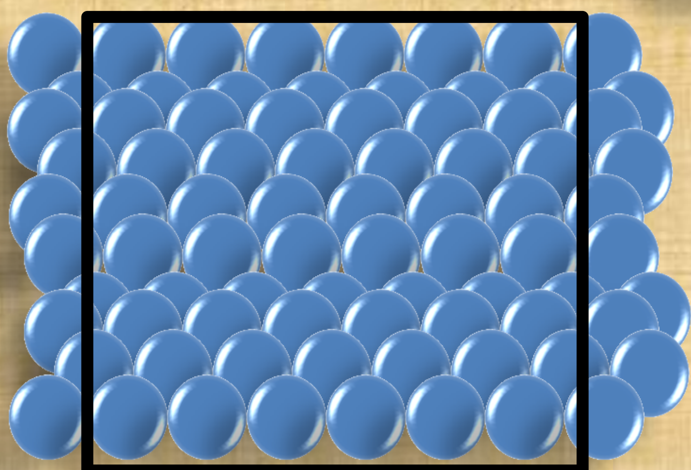


FIG. 10.

Potassium
0.89 g/cm^3



Diamond
3.52 g/cm^3



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 -William Henry Bragg (1925) "*Concerning the Nature of Things*"

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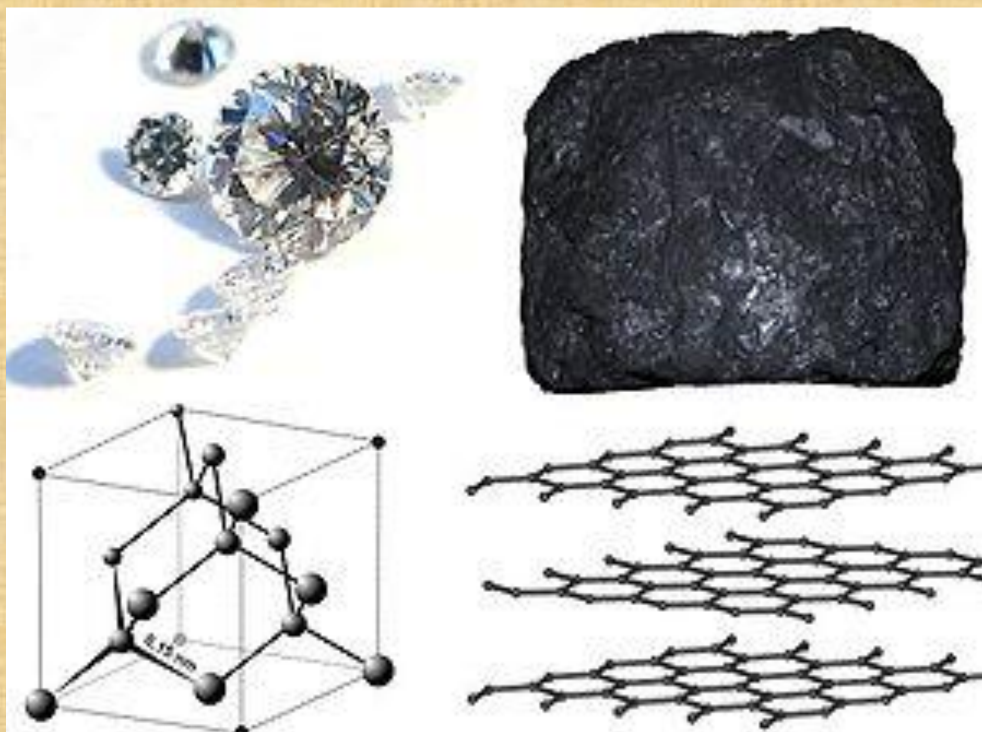
Allotropes of Carbon:

Diamond and Graphite



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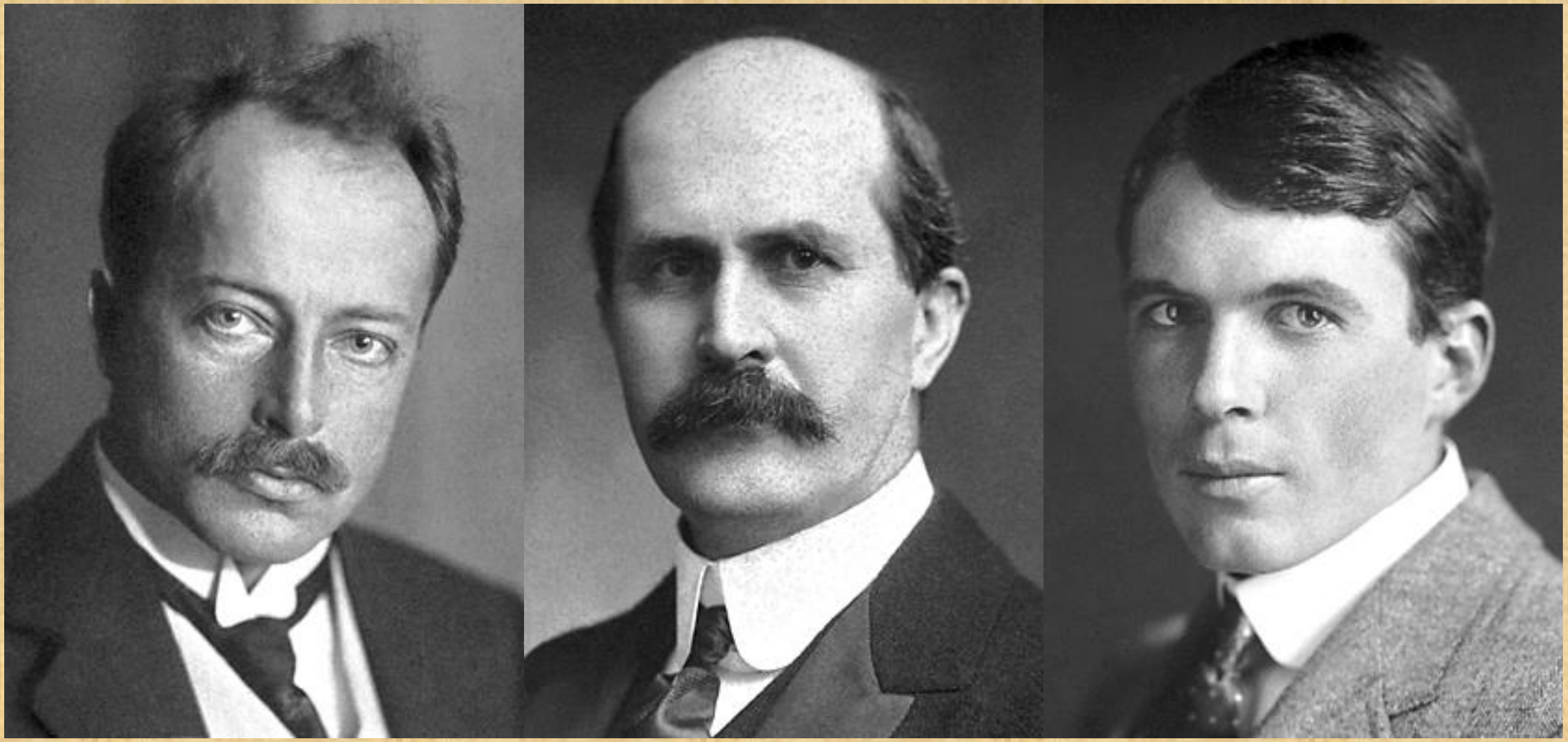
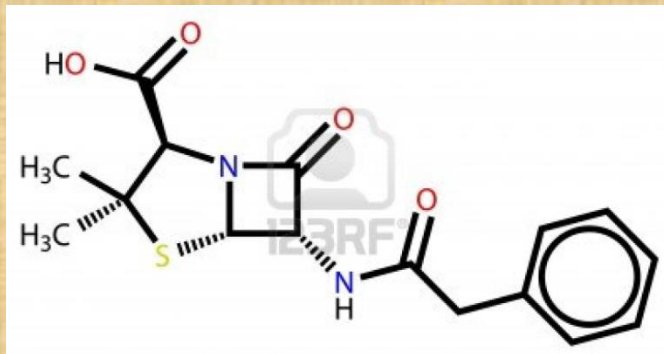
Nobel Prizes of Discovery of X-ray Diffraction



Nobel Prizes, 1914: Laue, 1915: WH Bragg and WL Bragg, 1916: -, 1917: Charles Barkla

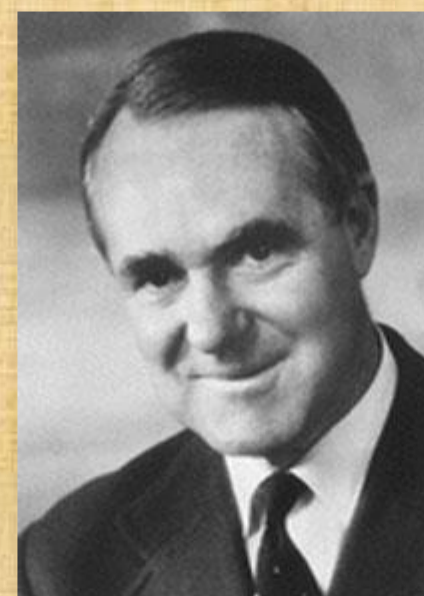
Controversy on Penicillin Structure, 1944

Dorothy Crowfoot Hodgkin



As she later wrote: "I remember sitting on the steps of the Royal Society ... talking to Bernal and I was telling him that we had solved the structure of penicillin. He said 'you will get the Nobel prize for this.' I said 'I would far rather be elected a Fellow of the Royal Society' and he said 'that's more difficult'."

John Cornforth



"If that's the formula of penicillin, I'll give up chemistry and grow mushrooms." Hodgkin was correct, but Cornforth did not become a mushroom farmer.

Pauling's series of 7 papers in PNAS, 1951

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Polypeptide Chain Configurations in Crystalline Proteins

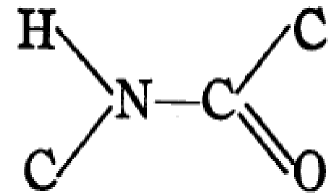
Lawrence Bragg, J. C. Kendrew and M. F. Perutz

Missed the necessity of planar peptide bond unaware of resonance of the peptide group

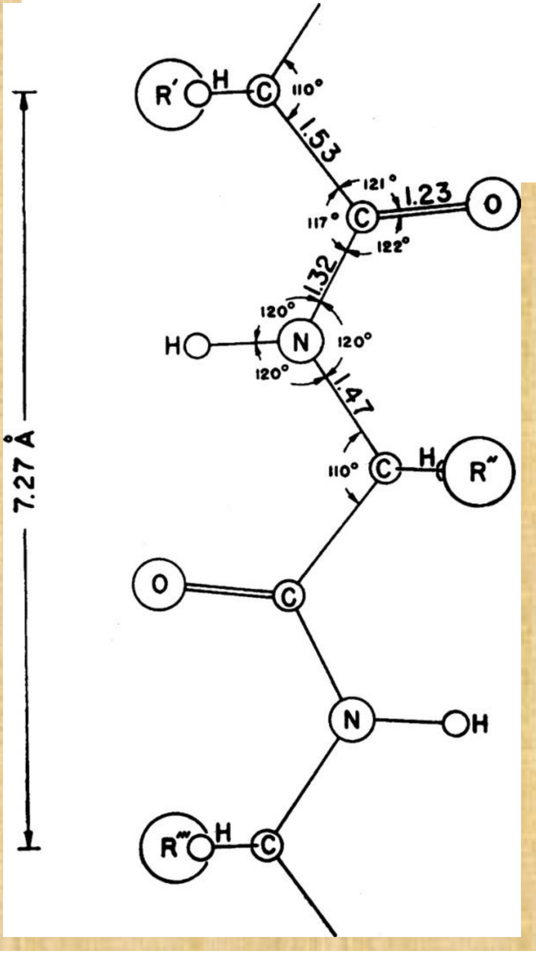
Bragg to Perutz: I wish I had made you angry earlier !

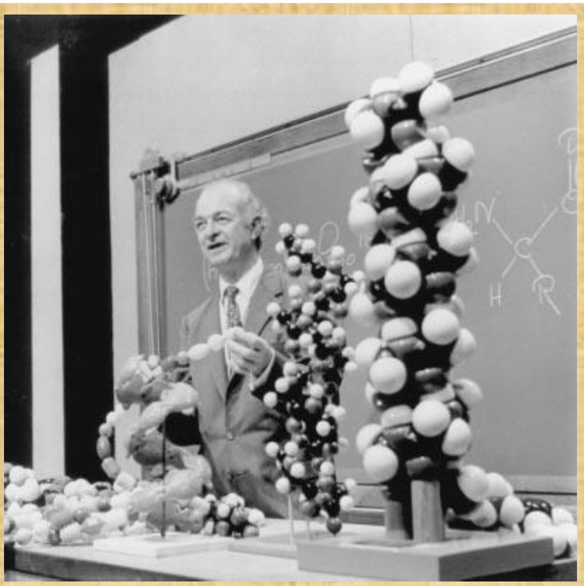
Pauling's series of 7 papers in PNAS, 1951

We assume that, because of the resonance of the double bond between the carbon-oxygen and carbon-nitrogen positions, the configuration of each residue



is planar.





Dimensions of the polypeptide chain.

Pauling L et al. PNAS 1951;37:205-211

Pauling's series of 7 papers in PNAS, 1951

CONFIGURATIONS OF POLYPEPTIDE CHAINS WITH FAVORED ORIENTATIONS AROUND SINGLE BONDS: TWO NEW PLEATED SHEETS

BY LINUS PAULING AND ROBERT B. COREY

GATES AND CRELLIN LABORATORIES OF CHEMISTRY,* CALIFORNIA INSTITUTE OF TECHNOLOGY, PASADENA, CALIFORNIA

Communicated September 4, 1951

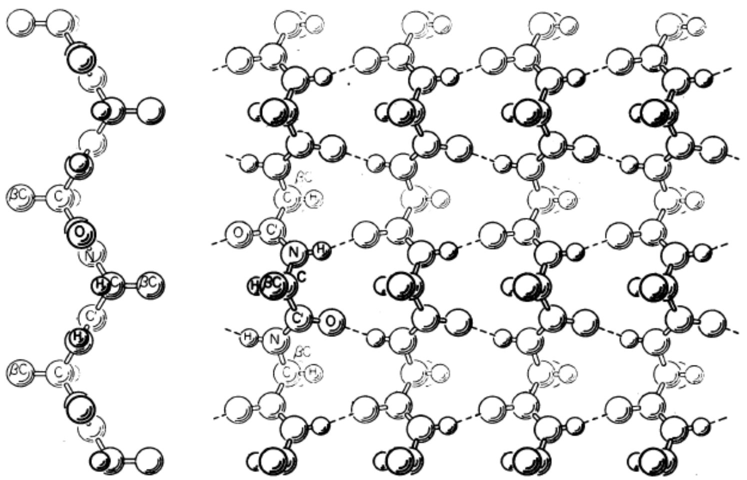


FIGURE 7

Drawing representing the parallel-chain pleated sheet structure.

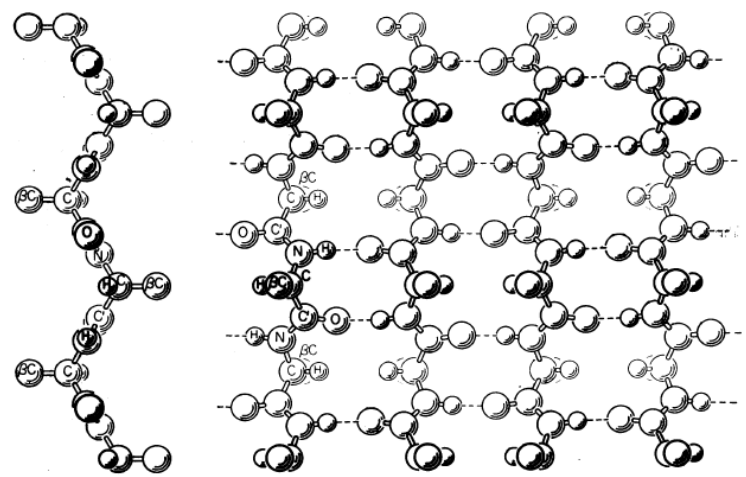


FIGURE 6

Drawing representing the anti-parallel-chain pleated sheet structure.

Structural Models of Collagen

Shekhar C. Mande

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THE STRUCTURE OF FIBROUS PROTEINS OF THE COLLAGEN-GELATIN GROUP

BY LINUS PAULING AND ROBERT B. COREY

GATES AND CRELLIN LABORATORIES OF CHEMISTRY,* CALIFORNIA INSTITUTE OF TECHNOLOGY, PASADENA, CALIFORNIA

Communicated March 31, 1951

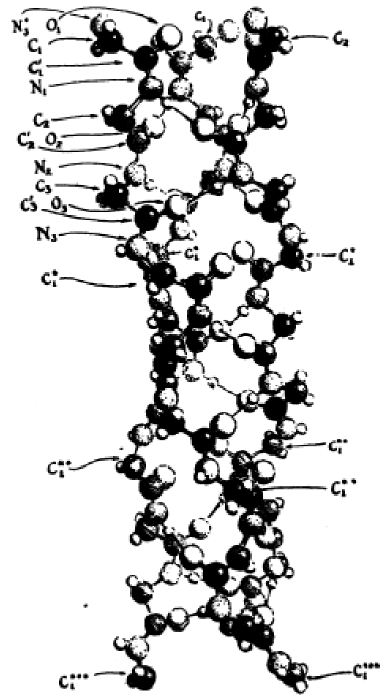
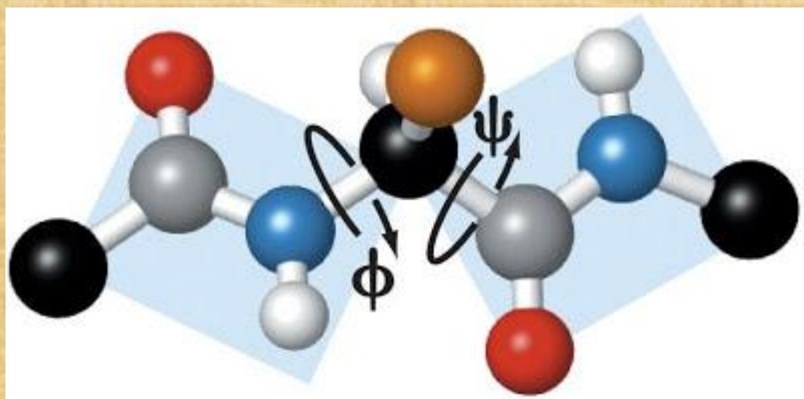
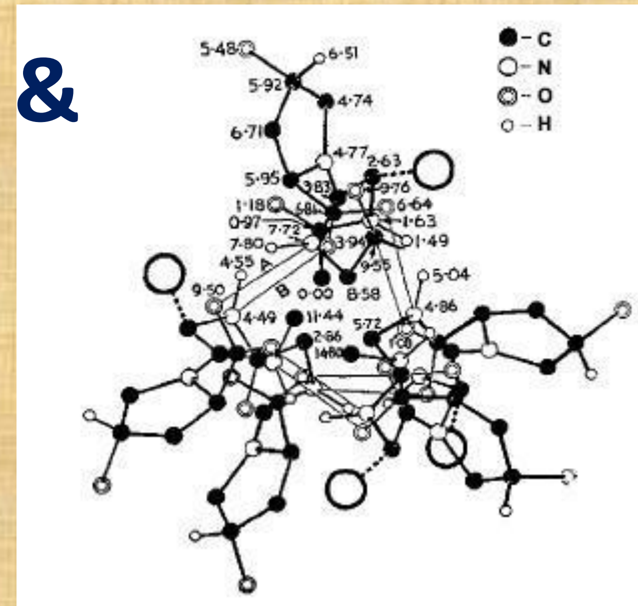
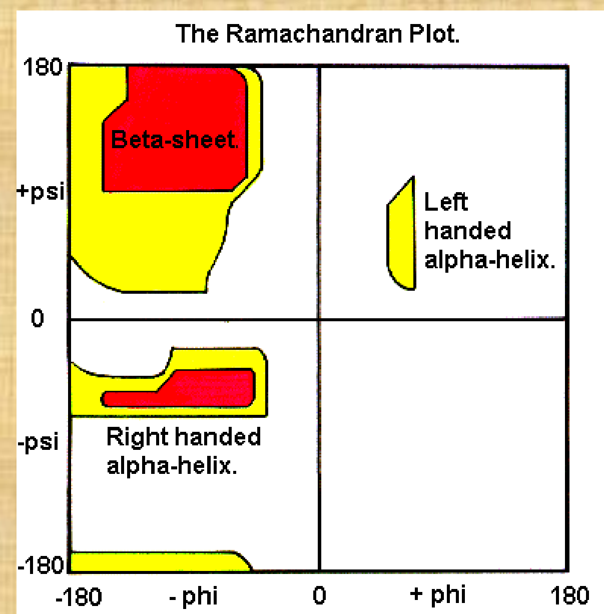


FIGURE 2

Madras model of Collagen & Ramachandran Map







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"She is trying to get real Laue aufnahmen"

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The Structure of the Benzene Ring in C$_{6}$ (CH$_{3}$)$_{6}$

Kathleen Lonsdale

Proc. R. Soc. Lond. A 1929 **123**, doi: 10.1098/rspa.1929.0081, published 6 April 1929

The Structure of the Benzene Ring in $C_6(CH_3)_6$.

By Kathleen Lonsdale, D.Sc. (London), Amy Lady Tate Scholar.

(Communicated by R. Whiddington, F.R.S.—Received January 25, 1929.)

Since benzene itself is not crystalline at ordinary temperatures the study of the benzene nucleus or ring has had to be referred to certain of its derivatives. The most hopeful line of attack appeared to be in the direction of the fully substituted derivatives, such as C_6Cl_6, or else by way of compounds such as naphthalene and anthracene which contain more than one ring. The results

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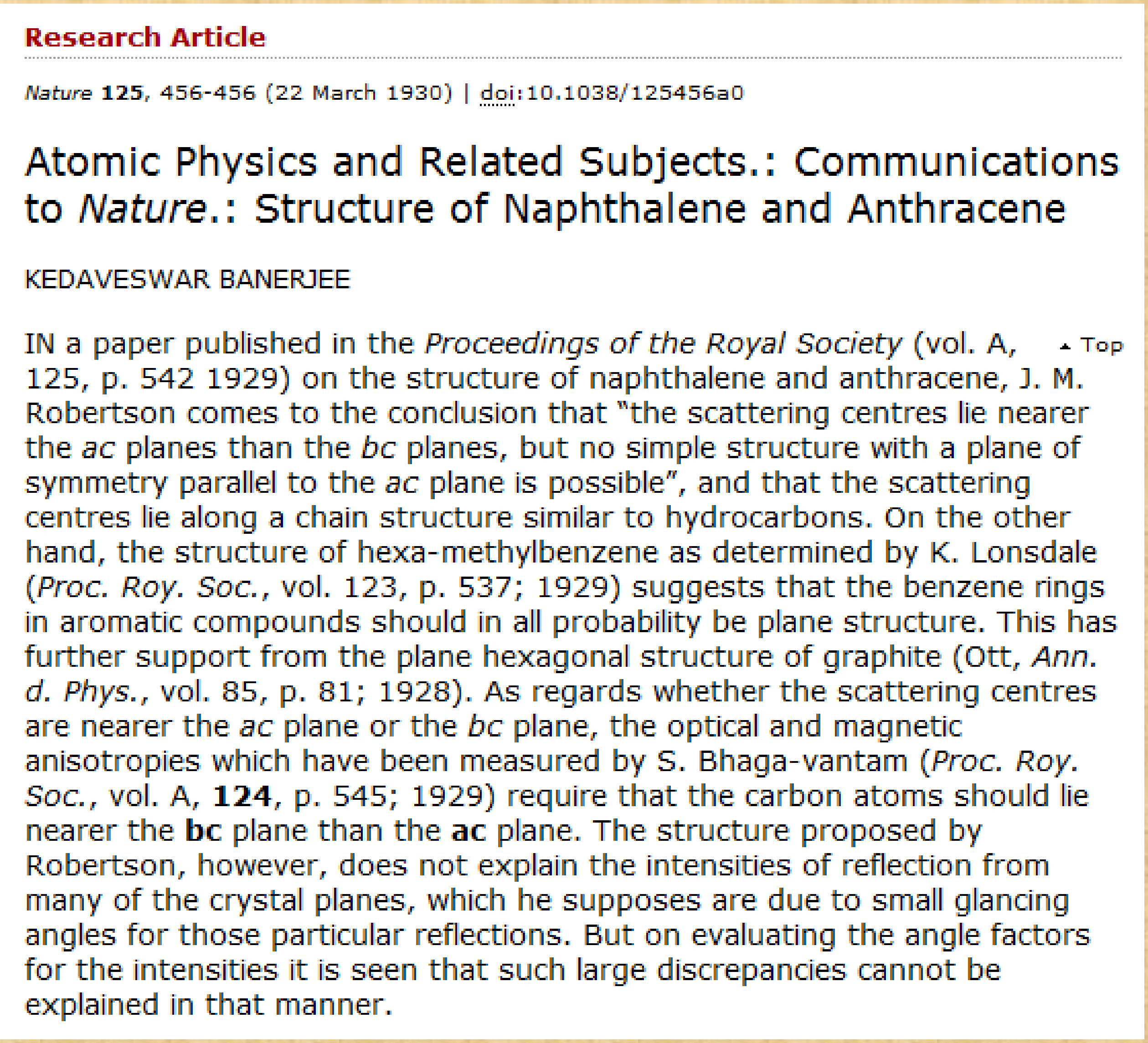
An X-Ray Investigation of the Structure of Naphthalene and Anthracene

J. Monteath Robertson

Proc. R. Soc. Lond. A 1929 **125**, doi: 10.1098/rspa.1929.0185, published 1 October 1929

The close relations between many of the dimensions of the crystal units of naphthalene and anthracene and those of the hydrocarbon $C_{29}H_{60}$ are quite remarkable when we consider how different the substances are in their crystalline form and chemical constitution. These relations seem to afford strong evidence that the tetrahedral properties of the carbon atom are maintained in aromatic structures.



Research Article

Nature **125**, 456-456 (22 March 1930) | doi:10.1038/125456a0

Atomic Physics and Related Subjects.: Communications to *Nature*.: Structure of Naphthalene and Anthracene

KEDAVESWAR BANERJEE

IN a paper published in the *Proceedings of the Royal Society* (vol. A, 125, p. 542 1929) on the structure of naphthalene and anthracene, J. M. Robertson comes to the conclusion that "the scattering centres lie nearer the *ac* planes than the *bc* planes, but no simple structure with a plane of symmetry parallel to the *ac* plane is possible", and that the scattering centres lie along a chain structure similar to hydrocarbons. On the other hand, the structure of hexa-methylbenzene as determined by K. Lonsdale (*Proc. Roy. Soc.*, vol. 123, p. 537; 1929) suggests that the benzene rings in aromatic compounds should in all probability be plane structure. This has further support from the plane hexagonal structure of graphite (Ott, *Ann. d. Phys.*, vol. 85, p. 81; 1928). As regards whether the scattering centres are nearer the *ac* plane or the *bc* plane, the optical and magnetic anisotropies which have been measured by S. Bhaga-vantam (*Proc. Roy. Soc.*, vol. A, **124**, p. 545; 1929) require that the carbon atoms should lie nearer the **bc** plane than the **ac** plane. The structure proposed by Robertson, however, does not explain the intensities of reflection from many of the crystal planes, which he supposes are due to small glancing angles for those particular reflections. But on evaluating the angle factors for the intensities it is seen that such large discrepancies cannot be explained in that manner.

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This precedes Huckel's rules (1931) on separation of sigma and pi orbitals

Research Article

Nature **125**, 456-457 (22 March 1930) | doi:10.1038/125456b0

Atomic Physics and Related Subjects.: Communications to *Nature*.: Structure of Naphthalene and Anthracene

J. M. ROBERTSON

I BELIEVE Dr. Banerjee's structure to be essentially correct. It has been clear to me for some time that the last two sections of my paper to which Dr. Banerjee refers must be amended as regards the distribution of the scattering centres in the *a* and *b* directions. During last summer, Sir William Bragg made 'absolute' measurements of the intensities of the reflections from a number of anthracene planes. These measurements were expressed as ratios between the structure factors actually found, and the structure factor to be expected if all the atoms were in the reflecting planes. It was intended that these results and deductions therefrom should be incorporated with my paper, the publication of which was to be delayed for the purpose: unfortunately, owing to my absence from England, there was some confusion during the revision of the proofs and this was not done. Sir William Bragg's figures lead to a structure resembling Dr. Banerjee's so closely that it is interesting to give the following quotation from a letter which he wrote to me. It is in the form of notes upon a table of structure factors:

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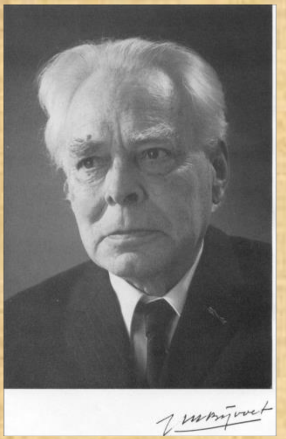
PROCEEDINGS OF THE ROYAL SOCIETY A | MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Determinations of the Signs of the Fourier Terms in Complete Crystal Structure Analysis

K. Banerjee

Proc. R. Soc. Lond. A 1933 **141**, 188-193
doi: 10.1098/rspa.1933.0111



Article

Nature **168**, 271-272 (18 August 1951) | doi:10.1038/168271a0

Determination of the Absolute Configuration of Optically Active Compounds by Means of X-Rays

, PROF.J. M. BIJVOET, A. F. PEERDEMAN & A. J. van BOMMEL

1. van 't Hoff Laboratory, University of Utrecht

THE USE OF ANOMALOUS SCATTERING FOR THE DETERMINATION OF CRYSTAL STRUCTURES—$KMnO_4$

By S. Ramaseshan, F.A.Sc., K. Venkatesan and N. V. Mani

(Department of Physics, Indian Institute of Science, Bangalore-3)

Received May 10, 1957

S. Ramaseshan speaking as Vice-President of the International Union of Crystallography at the Hamburg Congress in 1984.

$\Delta f'$ and $\Delta f''$ for manganese for CuKα, CoKα and FeKα
f_0 for Mn is 25. The K-absorption edge of Mn......1·895 Å

Radiation	λ_i	λ_i/λ_k	$-\Delta f'$	$\Delta f''$
CuKα ..	1·541 Å	0·813	0·789	2·63
CoKα ..	1·789	0·944	2·62	3·34
FeKα ..	1·936	1·021	4·21	0·00

PHYSICS

An Apparent Paradox in Crystal Structure Analysis

A COMMONLY used test for the correctness of a crystal structure deduced from X-ray diffraction data is to perform a Fourier synthesis using the observed structure amplitudes ($|F_o|$) and the calculated phases (α_c) in the Fourier coefficients (namely $|F_o| \exp i\alpha_c$) and to verify that this diagram gives peaks of the right magnitudes at the assumed positions of atoms and none elsewhere. It was thought worth while examining what would happen if the amplitudes and the phases that are fed in belong to different structures. The tests that were carried out are briefly described here, together with an explanation of the results observed and their relation to the methods of structure analysis.

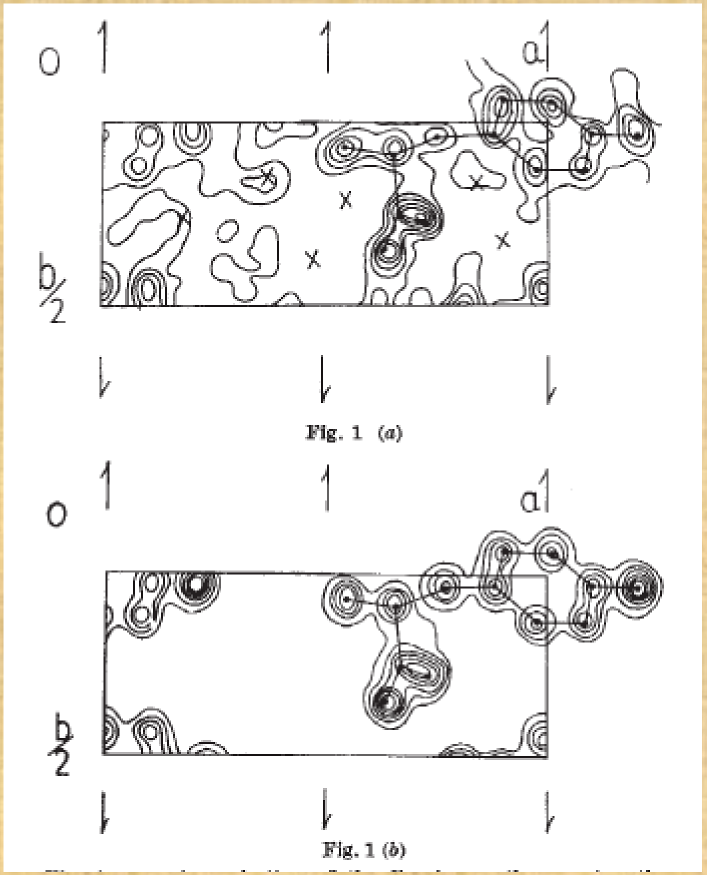


Fig. 1 (a)

Fig. 1 (b)

GN Ramachandran and R Srinivasan, Nature (1961)

Utility of structures in understanding complexity of Nature

Shekhar C. Mande
NCCS, Pune

Sickle Cell Anemia caused by One Mutation

- Sickle cell anemia is caused by a point mutation in hemoglobin b chain (a is unaffected)

val-his-leu-thr-pro-**glu**-glu … normal individual
val-his-leu-thr-pro-**val**-glu … affected individual

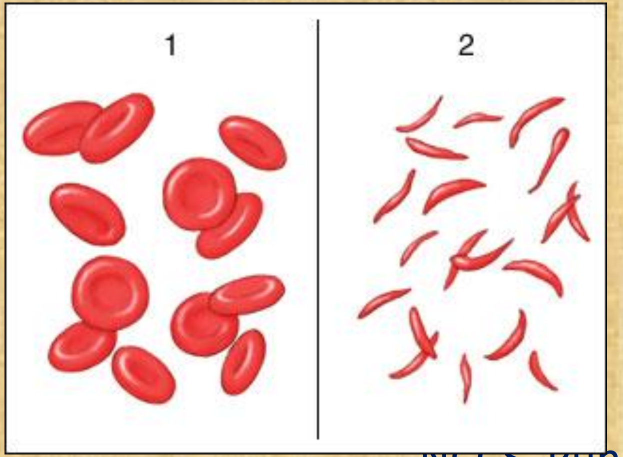
- Only one amino acid is change in the entire sequence of the protein

glutamic acid side chain	$-CH_2-CH_2-COO^-$	acidic side chain
valine side chain	$-CH-(CH_3)_2$	nonpolar side chain

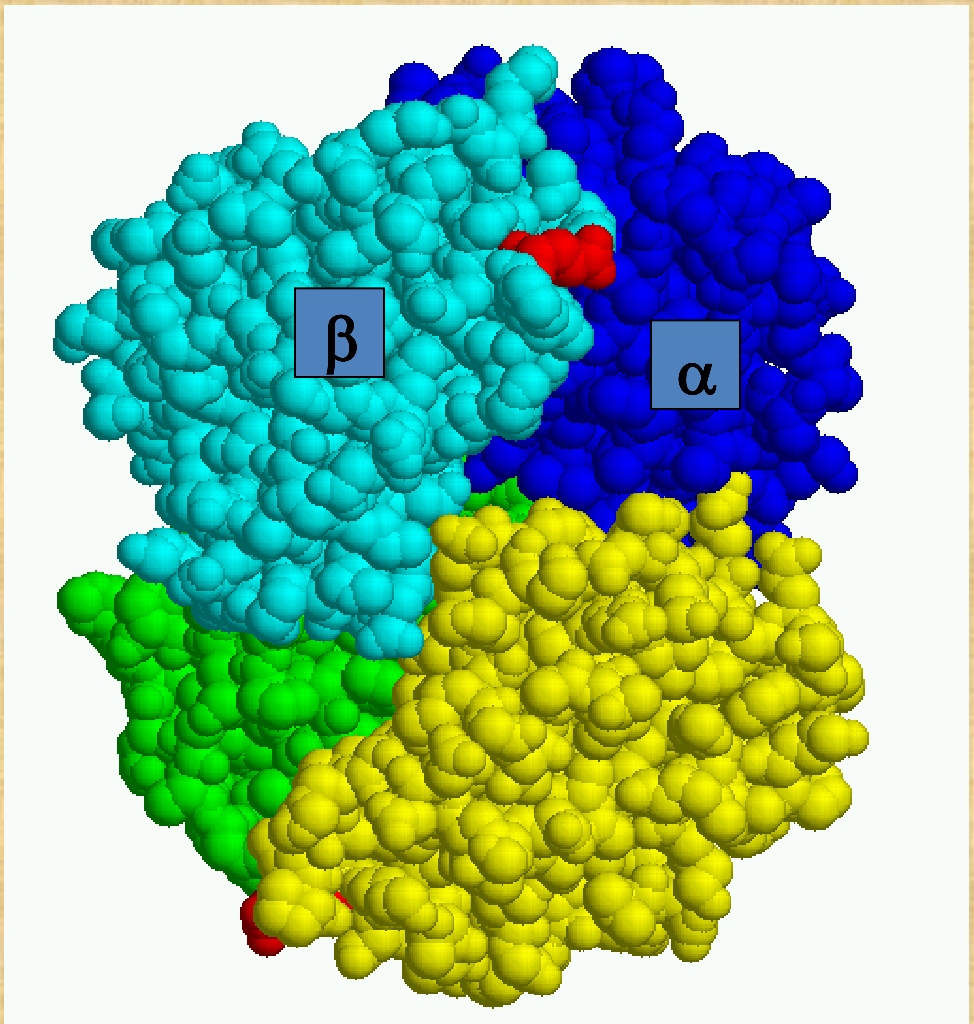
- The hemoglobin molecule folds up and functions (binds oxygen)

- The mutation caused the protein to clump up in the cells

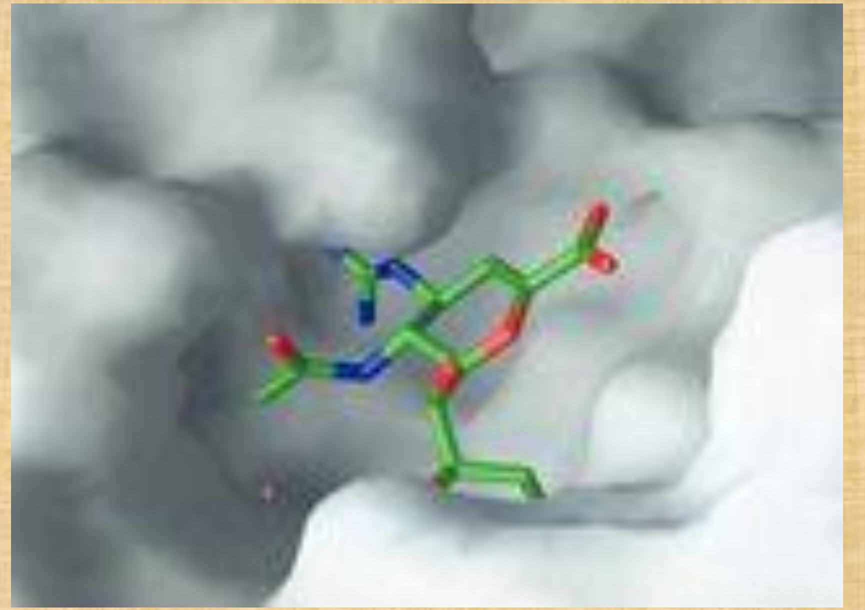
- The clumping up distorts the cell shape and makes them architecturally weaker



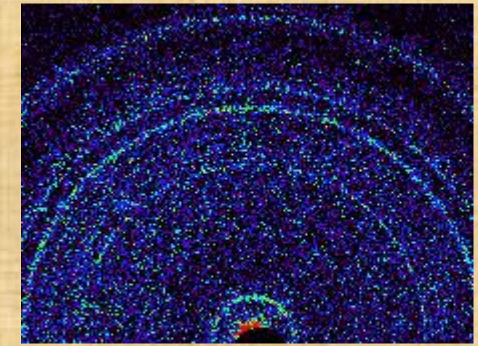
Sickle Cell Anemia caused by One Mutation



- The surface of the protein has side chains sticking out.
- Polar and charged side chains help the protein stay dissolved in water
- The glutamic acid to valine mutation is a surface mutation



Crystal structure of Zanamivir: neuraminidase structure



Future Challenges

- Addressing fundamental problems in biology through understanding structures of many more molecules
- Understanding structure and assembly of large molecular complexes
- Ability to design compounds complementary to defined targets
- Ability to design potential vaccines
- Evolution of molecules that clean up the environment

Thank you!