Name	Symbol	Name	Symbol	Name	Symbol
Actinium	Ac	Hafnium	Hf	Praseodymium	Pr
Aluminum	Al	Helium	He	Promethium	Pm
Americium	Am	Holmium	Ho	Protactinium	Pa
Antimony	Sb	Hydrogen	H	Radium	Ra
Argon	Ar	Indium	In	Radon	Rn
Arsenic	As	Iodine	I	Rhenium	Re
Astatine	At	Iridium	Ir	Rhodium	Rh
Barium	Ba	Iron	Fe	Rubidium	Rb
Berkelium	Bk	Krypton	Kr	Ruthenium	Ru
Beryllium	Be	Lanthanum	La	Samarium	Sm
Bismuth	Bi	Lawrencium	Lr	Scandium	Sc
Boron	B	Lead	Pb	Selenium	Se
Bromine	Br	Lithium	Li	Silicon	Si
Cadmium	Cd	Lutetium	Lu	Silver	Ag
Calcium	Ca	Magnesium	Mg	Sodium	Na
Californium	Cf	Manganese	Mn	Strontium	Sr
Carbon	C	Mendelevium	Md	Sulfur	S
Cerium	Ce	Mercury	Hg	Tantalum	Ta
Cesium	Cs	Molybdenum	Mo	Technetium	Tc
Chlorine	Cl	Neodymium	Nd	Tellurium	Te
Chromium	Cr	Neon	Ne	Terbium	Tb
Cobalt	Co	Neptunium	Np	Thallium	Tl
Copper	Cu	Nickel	Ni	Thorium	Th
Curium	Cm	Niobium	Nb	Thulium	Tm
Dysprosium	Dy	Nitrogen	N	Tin	Sn
Einsteinium	Es	Nobelium	No	Titanium	Ti
Erbium	Er	Osmium	Os	Tungsten	W
Europium	Eu	Oxygen	O	Uranium	U
Fermium	Fm	Palladium	Pd	Vanadium	V
Fluorine	F	Phosphorus	P	Xenon	Xe
Francium	Fr	Platinum	Pt	Ytterbium	Yb
Gadolinium	Gd	Plutonium	Pu	Yttrium	Y
Gallium	Ga	Polonium	Po	Zinc	Zn
Germanium	Ge	Potassium	K	Zirconium	Zr
Gold	Au				

Periodic Table, with the Outer Electron Configurations of Neutral Atoms in Their Ground States

The notation used to describe the electronic configuration of atoms and ions is discussed in all textbooks of introductory atomic physics. The letters s, p, d, . . . signify electrons having orbital angular momentum 0, 1, 2, . . . in units $\hbar$; the number to the left of the letter denotes the principal quantum number of one orbit, and the superscript to the right denotes the number of electrons in the orbit.

H^{1} $1s$																	He^{2} $1s^2$
Li^{3} $2s$	Be^{4} $2s^2$											B^{5} $2s^22p$	C^{6} $2s^22p^2$	N^{7} $2s^22p^3$	O^{8} $2s^22p^4$	F^{9} $2s^22p^5$	Ne^{10} $2s^22p^6$
Na^{11} $3s$	Mg^{12} $3s^2$											Al^{13} $3s^23p$	Si^{14} $3s^23p^2$	P^{15} $3s^23p^3$	S^{16} $3s^23p^4$	Cl^{17} $3s^23p^5$	Ar^{18} $3s^23p^6$
K^{19} $4s$	Ca^{20} $4s^2$	Sc^{21} $3d$ $4s^2$	Ti^{22} $3d^2$ $4s^2$	V^{23} $3d^3$ $4s^2$	Cr^{24} $3d^5$ $4s$	Mn^{25} $3d^5$ $4s^2$	Fe^{26} $3d^6$ $4s^2$	Co^{27} $3d^7$ $4s^2$	Ni^{28} $3d^8$ $4s^2$	Cu^{29} $3d^{10}$ $4s$	Zn^{30} $3d^{10}$ $4s^2$	Ga^{31} $4s^24p$	Ge^{32} $4s^24p^2$	As^{33} $4s^24p^3$	Se^{34} $4s^24p^4$	Br^{35} $4s^24p^5$	Kr^{36} $4s^24p^6$
Rb^{37} $5s$	Sr^{38} $5s^2$	Y^{39} $4d$ $5s^2$	Zr^{40} $4d^2$ $5s^2$	Nb^{41} $4d^4$ $5s$	Mo^{42} $4d^5$ $5s$	Tc^{43} $4d^6$ $5s$	Ru^{44} $4d^7$ $5s$	Rh^{45} $4d^8$ $5s$	Pd^{46} $4d^{10}$ –	Ag^{47} $4d^{10}$ $5s$	Cd^{48} $4d^{10}$ $5s^2$	In^{49} $5s^25p$	Sn^{50} $5s^25p^2$	Sb^{51} $5s^25p^3$	Te^{52} $5s^25p^4$	I^{53} $5s^25p^5$	Xe^{54} $5s^25p^6$
Cs^{55} $6s$	Ba^{56} $6s^2$	La^{57} $5d$ $6s^2$	Hf^{72} $4f^{14}$ $5d^2$ $6s^2$	Ta^{73} $5d^3$ $6s^2$	W^{74} $5d^4$ $6s^2$	Re^{75} $5d^5$ $6s^2$	Os^{76} $5d^6$ $6s^2$	Ir^{77} $5d^9$ –	Pt^{78} $5d^9$ $6s$	Au^{79} $5d^{10}$ $6s$	Hg^{80} $5d^{10}$ $6s^2$	Tl^{81} $6s^26p$	Pb^{82} $6s^26p^2$	Bi^{83} $6s^26p^3$	Po^{84} $6s^26p^4$	At^{85} $6s^26p^5$	Rn^{86} $6s^26p^6$
Fr^{87} $7s$	Ra^{88} $7s^2$	Ac^{89} $6d$ $7s^2$															

Ce^{58} $4f^2$ $6s^2$	Pr^{59} $4f^3$ $6s^2$	Nd^{60} $4f^4$ $6s^2$	Pm^{61} $4f^6$ $6s^2$	Sm^{62} $4f^6$ $6s^2$	Eu^{63} $4f^7$ $6s^2$	Gd^{64} $4f^7$ $5d$ $6s^2$	Tb^{65} $4f^8$ $5d$ $6s^2$	Dy^{66} $4f^{10}$ $6s^2$	Ho^{67} $4f^{11}$ $6s^2$	Er^{68} $4f^{12}$ $6s^2$	Tm^{69} $4f^{13}$ $6s^2$	Yb^{70} $4f^{14}$ $6s^2$	Lu^{71} $4f^{14}$ $5d$ $6s^2$
Th^{90} – $6d^2$ $7s^2$	Pa^{91} $5f^2$ $6d$ $7s^2$	U^{92} $5f^3$ $6d$ $7s^2$	Np^{93} $5f^5$ $7s^2$	Pu^{94} $5f^6$ $7s^2$	Am^{95} $5f^7$ $7s^2$	Cm^{96} $5f^7$ $6d$ $7s^2$	Bk^{97}	Cf^{98}	Es^{99}	Fm^{100}	Md^{101}	No^{102}	Lr^{103}

CHARLES KITTEL

Introduction to Solid State Physics

SEVENTH EDITION

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Brisbane, Toronto, Singapore

About the Author

Charles Kittel taught solid state physics at Berkeley from 1951 to 1978; earlier he was a member of the solid state group at the Bell Laboratories. His undergraduate work was at M.I.T. and at Cambridge University, followed by graduate work at the University of Wisconsin. He is a member of the National Academy of Science and of the American Academy of Arts and Sciences.

His research in solids began with studies of ferromagnetic, antiferromagnetic, and paramagnetic resonance, along with work on magnetic domains, spin waves, and domain boundaries in ferromagnets and ferroelectrics. His work on the single domain structure of fine particles has had broad application in magnetic recording, geomagnetism, and biomagnetism. Along with collaborators at Berkeley he did the first work on cyclotron resonance in semiconductors, which led to the understanding of the band structure of silicon, germanium, and indium antimonide, together with the theory of their impurity states. He also worked on the interpretation of magnetoplasma resonance in semiconductors and of Alfvén resonance in electron-hole drops in germanium.

The first edition of *ISSP* integrated the elementary aspects of solid state physics for study by seniors and beginning graduate students. Now in its seventh edition, *ISSP* plays the same part for the current generation of students.

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Preface

This book is the seventh edition of an elementary text on solid state physics for senior and beginning graduate students of physical science and engineering. The book is an update of the sixth edition of 1986 and includes additions, improvements, and corrections made in that edition in 13 successive printings—which it was time to pull together—and a number of new topics besides. Significant advances in the field have been added or discussed more fully: thus high temperature superconductors are treated, and results of scanning tunneling microscopy are displayed; the treatment of fiber optics is expanded. There are discussions, among other topics, of nanostructures, superlattices, Bloch/Wannier levels, Zener tunneling, light-emitting diodes, and new magnetic materials. The additions have been made within a boundary condition intended to keep the text within one volume and at a reasonable price.

The theoretical level of the text itself has not been changed. There is more discussion of useful materials. The treatment of elastic constants and elastic waves which was dropped after the fourth edition has now been returned because, as many have pointed out, the matter is useful and not easily accessible elsewhere. The treatment of superconductors is much more extensive than is usual in a text at this level: either you do it or you don't.

Solid state physics is concerned with the properties, often astonishing and often of great utility, that result from the distribution of electrons in metals, semiconductors, and insulators. The book also tells how the excitations and imperfections of real solids can be understood with simple models whose power and scope are now firmly established. The subject matter supports a profitable interplay of experiment, application, and theory. The book, in English and in many translations, has helped give several generations of students a picture of the process. Students also find the field attractive because of the frequent possibility of working in small groups.

Instructors will use the book as the foundation of a course in their own way, yet there are two general patterns to the introduction, selection and order of the basic material. If students have a significant preparation in elementary quantum mecha s, they will like to begin with the quantum theory of elec-

trons in one-dimensional solids, starting with the free electron gas in Chapter 6 and energy bands in Chapter 7. One will need to treat the reciprocal lattice in three dimensions (Chapter 2) before plunging into semiconductors (Chapter 8) and Fermi surfaces (Chapter 9). Crystal structures, crystal binding, and phonons could be considered as recreational reading. In a more gradual approach, the first eight chapters through the physics of semiconductors are read consecutively as a one-semester introduction to the field.

What about the necessary statistical mechanics? A vague discomfort at the thought of the chemical potential is still characteristic of a physics education. This intellectual gap is due to the obscurity of the writings of J. Willard Gibbs, who discovered and understood the matter 100 years ago. Herbert Kroemer and I have clarified the physics of the chemical potential in the early chapters of our book on thermal physics.

Review series give excellent extended treatments of all the subjects treated in this book and many more besides; thus with good conscience I give few references to original papers. In these omissions no lack of honor is intended to those who first set sail on these seas.

The crystallographic notation conforms with current usage in physics. Important equations are repeated in SI and CGS-Gaussian units, where these differ. Exceptions are figure captions, chapter summaries, some problems, and any long section of text where a single indicated substitution will translate from CGS to SI. Chapter Contents pages discuss conventions adopted to make parallel usage simple. The dual usage in this book has been found useful and acceptable.

Tables are in conventional units. The symbol e denotes the charge on the proton and is positive. The notation (18) refers to Equation (18) of the current chapter, but (3.18) refers to Equation 18 of Chapter 3. A caret $\hat{}$ over a vector refers to a unit vector. Few of the problems are exactly easy; most were devised to carry forward the subject of the chapter. With a few exceptions, the problems are those of the original sixth edition.

This edition owes much to the advice of Professor Steven G. Louie. For collected corrections, data, and illustrations I am grateful to P. Allen, M. Beasley, D. Chemla, T.-C. Chiang, M. L. Cohen, M. G. Craford, A. E. Curzon, D. Eigler, L. M. Falicov, R. B. Frankel, J. Friedel, T. H. Geballe, D. M. Ginsberg, C. Herring, H. F. Hess, N. Holonyak, Jr., M. Jacob, J. Mamin, P. McEuen, J. G. Mullen, J. C. Phillips, D. E. Prober, Marta Puebla, D. S. Rokhsar, L. Takacs, Tingye Li, M. A. Van Hove, E. R. Weber, R. M. White, J. P. Wolfe, and A. Zettl. Of the Wiley staff I have particularly great debts to Clifford Mills for publication supervision, to Cathy Donovan for her ingenuity in processing the additions between the thirteen successive printings, and to Suzanne Ingrao of Ingrao Associates for her skill and understanding during the editorial process.

Corrections and suggestions will be gratefully received and may be addressed to the author at the Department of Physics, University of California, Berkeley, CA 94720-7300; by email to kittel@uclink4.Berkeley.edu; and by fax to (510) 643-9473.

C. Kittel

An Instructor's Manual is available for this revision; several problems have been added (to Chapter 3 and Chapter 6); one dropped (from Chapter 4), and several corrections made. Instructors who have adopted the text for classroom use should direct a request on departmental letterhead to John Wiley & Sons, Inc., 605 Third Avenue, New York, NY 10158-0012. Limited requests for permission to copy figures or other material should be addressed to the Permissions Editor at this address.

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Review series

F. Seitz and others, *Solid state physics, advances in research and applications*, Vols. 1–⟨48⟩, plus supplements. This valuable continuing series is often cataloged as a serial, as if it were a journal, and is cited here as Solid state physics.

Literature guides

There are many good databases, library and organizational; this is the way to go for monograph and journal searches.

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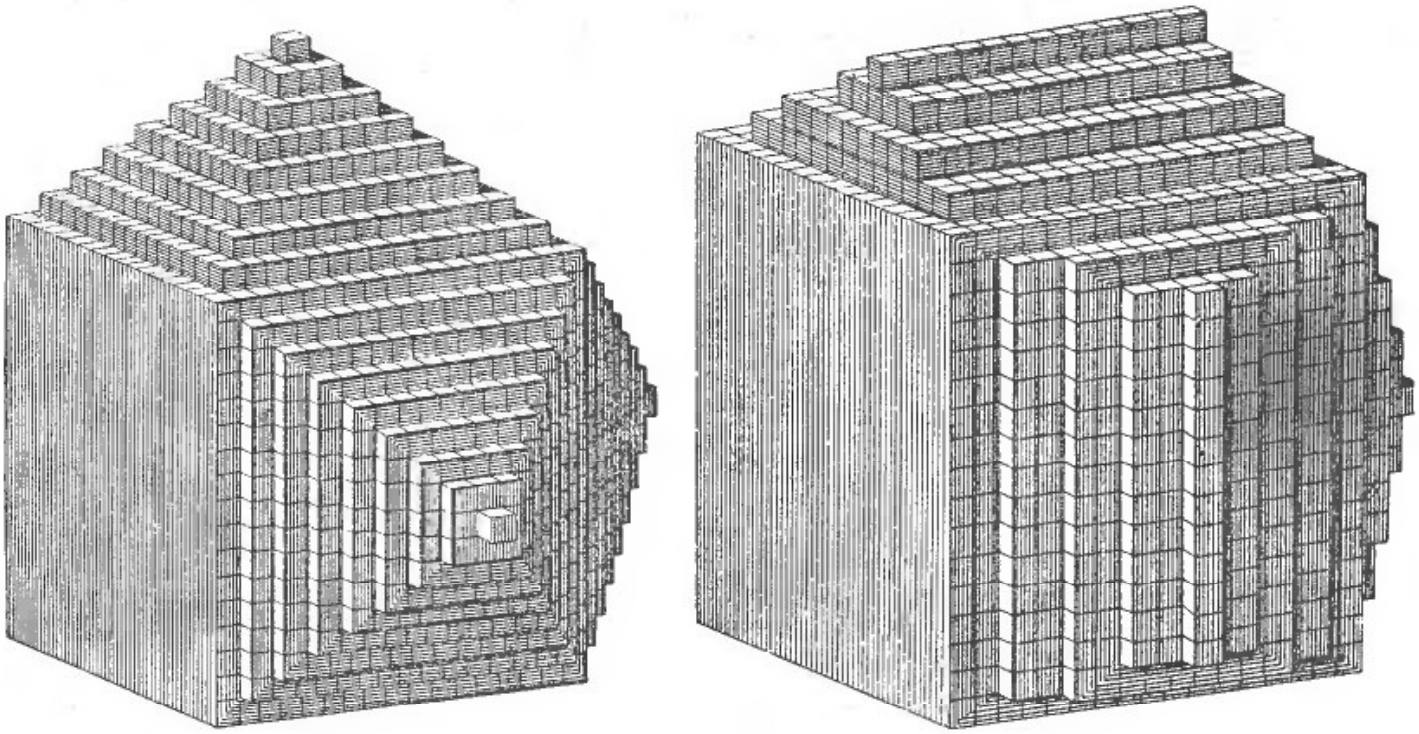
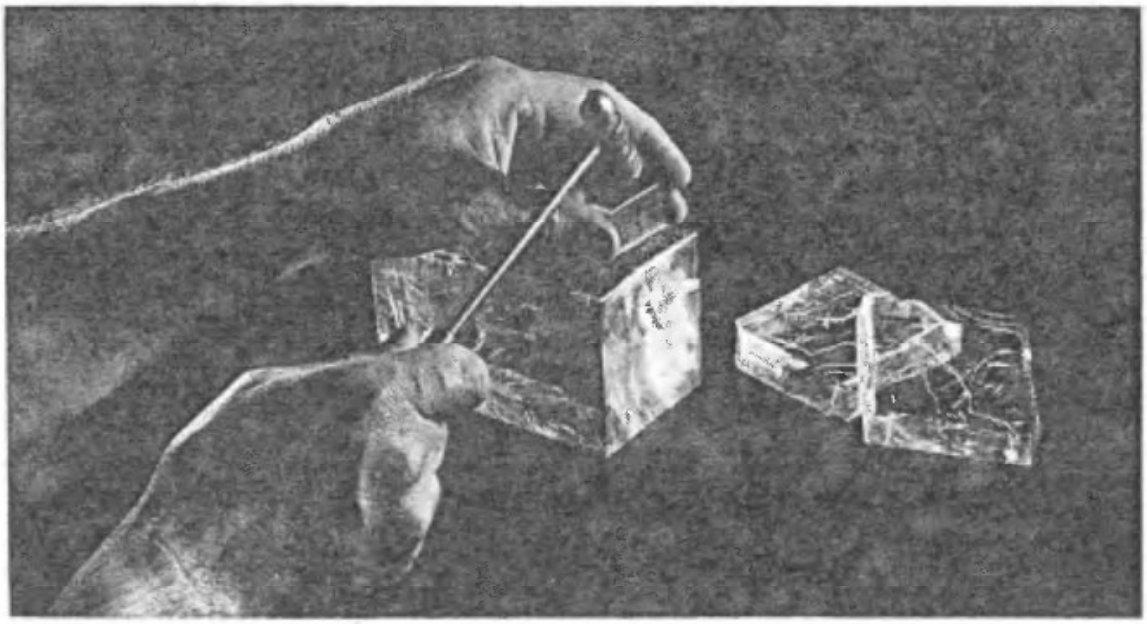
UNITS: 1 Å = 1 angstrom = 10^{-8} cm = 0.1 nm = 10^{-10} m.



(a) (b)



(c)

Figure 1 Relation of the external form of crystals to the form of the elementary building blocks. The building blocks are identical in (a) and (b), but different crystal faces are developed. (c) Cleaving a crystal of rocksalt.

CHAPTER 1: CRYSTAL STRUCTURE

Solid state physics is largely concerned with crystals and electrons in crystals. The study of solid state physics began in the early years of this century following the discovery of x-ray diffraction by crystals and the publication of a series of simple calculations and successful predictions of the properties of crystals.

When a crystal grows in a constant environment, the form develops as if identical building blocks were added continuously (Fig. 1). The building blocks are atoms or groups of atoms, so that a crystal is a three-dimensional periodic array of atoms.

This was known in the 18th century when mineralogists discovered that the index numbers of the directions of all faces of a crystal are exact integers. Only the arrangement of identical particles in a periodic array can account for the law of integral indices,[1] as discussed below.

In 1912 a paper entitled "Interference effects with Röntgen rays" was presented to the Bavarian Academy of Sciences in Munich. In the first part of the paper, Laue developed an elementary theory of the diffraction of x-rays by a periodic array. In the second part, Friedrich and Knipping reported the first experimental observations of x-ray diffraction by crystals.[2]

The work proved decisively that crystals are composed of a periodic array of atoms. With an established atomic model of a crystal, physicists now could think much further. The studies have been extended to include amorphous or noncrystalline solids, glasses, and liquids. The wider field is known as condensed matter physics, and it is now the largest and probably the most vigorous area of physics.

PERIODIC ARRAYS OF ATOMS

An ideal crystal is constructed by the infinite repetition of identical structural units in space. In the simplest crystals the structural unit is a single atom, as in copper, silver, gold, iron, aluminum, and the alkali metals. But the smallest structural unit may comprise many atoms or molecules.

The structure of all crystals can be described in terms of a lattice, with a group of atoms attached to every lattice point. The group of atoms is called the basis; when repeated in space it forms the crystal structure.

[1] R. J. Haüy, *Essai d'une théorie sur la structure des cristaux*, Paris, 1784; *Traité de cristallographie*, Paris, 1801.

[2] For personal accounts of the early years of x-ray diffraction studies of crystals, see P. P. Ewald, ed., *Fifty years of x-ray diffraction*, A. Oosthoek's Uitgeversmij., Utrecht, 1962.

Lattice Translation Vectors

The lattice is defined by three fundamental translation vectors $\mathbf{a}_1$, $\mathbf{a}_2$, $\mathbf{a}_3$ such that the atomic arrangement looks the same in every respect when viewed from the point $\mathbf{r}$ as when viewed from the point

$$\mathbf{r}' = \mathbf{r} + u_1\mathbf{a}_1 + u_2\mathbf{a}_2 + u_3\mathbf{a}_3 \ , \tag{1}$$

where u_1, u_2, u_3 are arbitrary integers. The set of points $\mathbf{r}'$ defined by (1) for all u_1, u_2, u_3 defines a **lattice**.

A lattice is a regular periodic array of points in space. (The analog in two dimensions is called a net, as in Chapter 18.) A lattice is a mathematical abstraction; the crystal structure is formed when a basis of atoms is attached identically to every lattice point. The logical relation is

$$\textbf{lattice} + \textbf{basis} = \textbf{crystal structure} \ . \tag{2}$$

The lattice and the translation vectors $\mathbf{a}_1$, $\mathbf{a}_2$, $\mathbf{a}_3$ are said to be primitive if any two points $\mathbf{r}$, $\mathbf{r}'$ from which the atomic arrangement looks the same always satisfy (1) with a suitable choice of the integers u_1, u_2, u_3. With this definition of the **primitive translation vectors**, there is no cell of smaller volume that can serve as a building block for the crystal structure.

We often use primitive translation vectors to define the crystal axes. However, nonprimitive crystal axes are often used when they have a simpler relation to the symmetry of the structure. The crystal axes $\mathbf{a}_1$, $\mathbf{a}_2$, $\mathbf{a}_3$ form three adjacent edges of a parallelepiped. If there are lattice points only at the corners, then it is a primitive parallelepiped.

A lattice translation operation is defined as the displacement of a crystal by a crystal translation vector

$$\mathbf{T} = u_1\mathbf{a}_1 + u_2\mathbf{a}_2 + u_3\mathbf{a}_3 \ . \tag{3}$$

Any two lattice points are connected by a vector of this form.

To describe a crystal structure, there are three important questions to answer: What is the lattice? What choice of $\mathbf{a}_1$, $\mathbf{a}_2$, $\mathbf{a}_3$ do we wish to make? What is the basis?

More than one lattice is always possible for a given structure, and more than one set of axes is always possible for a given lattice. The basis is identified once these choices have been made. Everything (including the x-ray diffraction pattern) works out correctly in the end provided that (3) has been satisfied.

The symmetry operations of a crystal carry the crystal structure into itself. These include the lattice translation operations. Further, there are rotation and reflection operations, called **point operations**. About lattice points or certain special points within an elementary parallelpiped it may be possible to apply rotations and reflections that carry the crystal into itself.

Finally, there may exist compound operations made up of combined translation and point operations. Textbooks on crystallography are largely devoted to

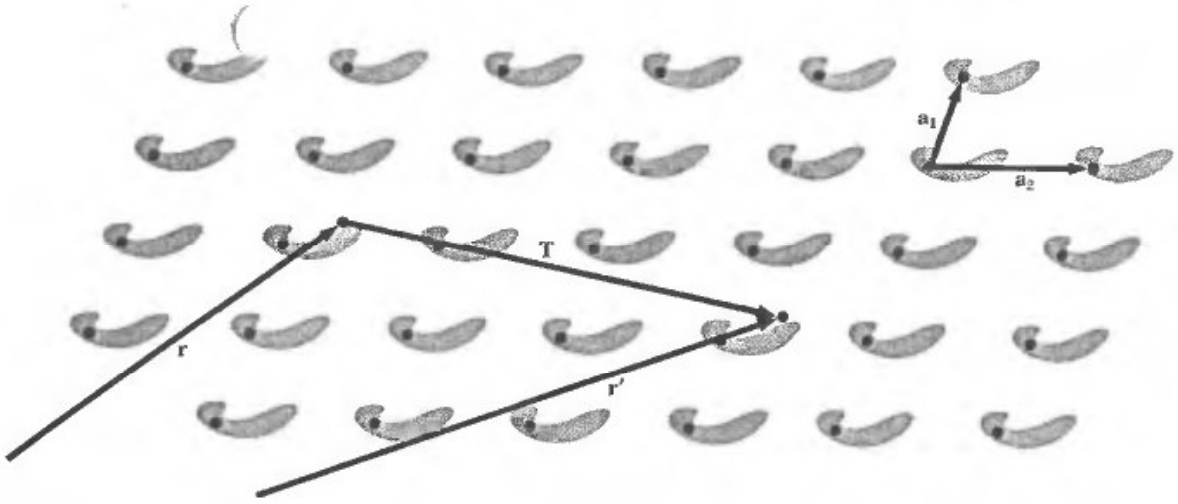


Figure 2 Portion of a crystal of an imaginary protein molecule, in a two-dimensional world. (We picked a protein molecule because it is not likely to have a special symmetry of its own.) The atomic arrangement in the crystal looks exactly the same to an observer at $\mathbf{r}'$ as to an observer at $\mathbf{r}$, provided that the vector $\mathbf{T}$ which connects $\mathbf{r}'$ and $\mathbf{r}$ may be expressed as an integral multiple of the vectors $\mathbf{a}_1$ and $\mathbf{a}_2$. In this illustration, $\mathbf{T} = -\mathbf{a}_1 + 3\mathbf{a}_2$. The vectors $\mathbf{a}_1$ and $\mathbf{a}_2$ are primitive translation vectors of the two-dimensional lattice.

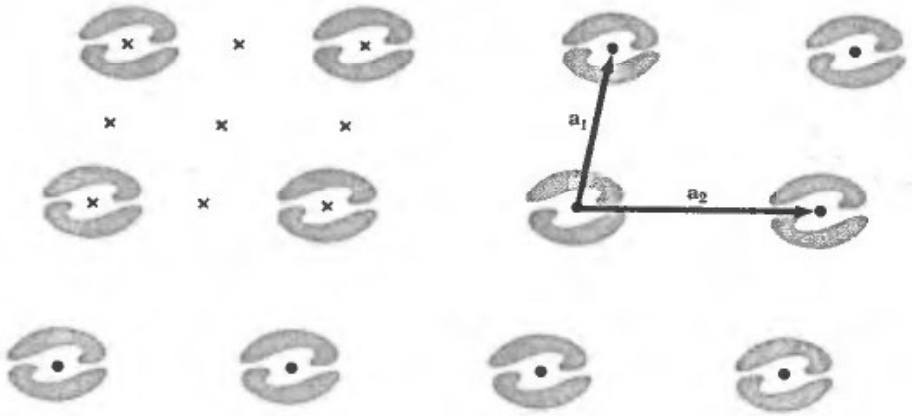


Figure 3 Similar to Fig. 2, but with protein molecules associated in pairs. The crystal translation vectors are $\mathbf{a}_1$ and $\mathbf{a}_2$. A rotation of π radians about any point marked × will carry the crystal into itself. This occurs also for equivalent points in other cells, but we have marked the points × only within one cell.

the description of symmetry operations. The crystal structure of Fig. 2 is drawn to have only translational symmetry operations. The crystal structure of Fig. 3 allows both translational and point symmetry operations.

Basis and the Crystal Structure

A basis of atoms is attached to every lattice point, with every basis identical in composition, arrangement, and orientation. Figure 4 shows how a crystal structure is formed by adding a basis to every lattice point. The lattice is indicated by dots in Figs. 2 and 3, but in Fig. 4c the dots are omitted.

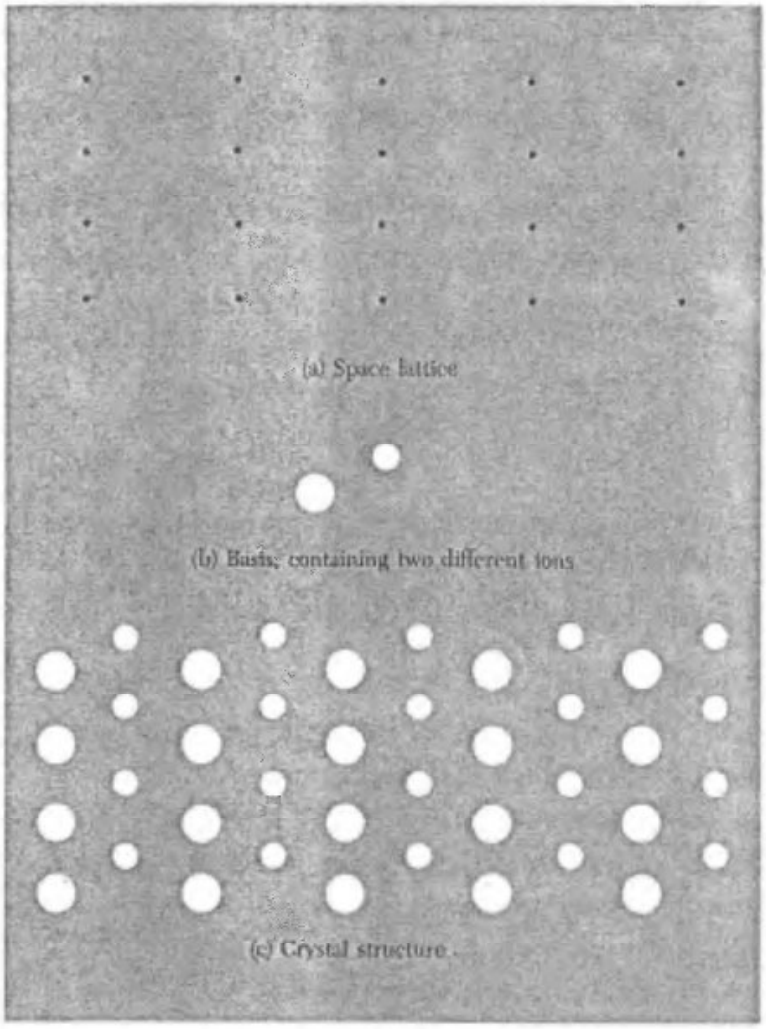


Figure 4 The crystal structure is formed by the addition of the basis (b) to every lattice point of the lattice (a). By looking at (c), you can recognize the basis and then you can abstract the space lattice. It does not matter where the basis is put in relation to a lattice point.

The number of atoms in the basis may be one, or it may be more than one. The position of the center of an atom j of the basis relative to the associated lattice point is

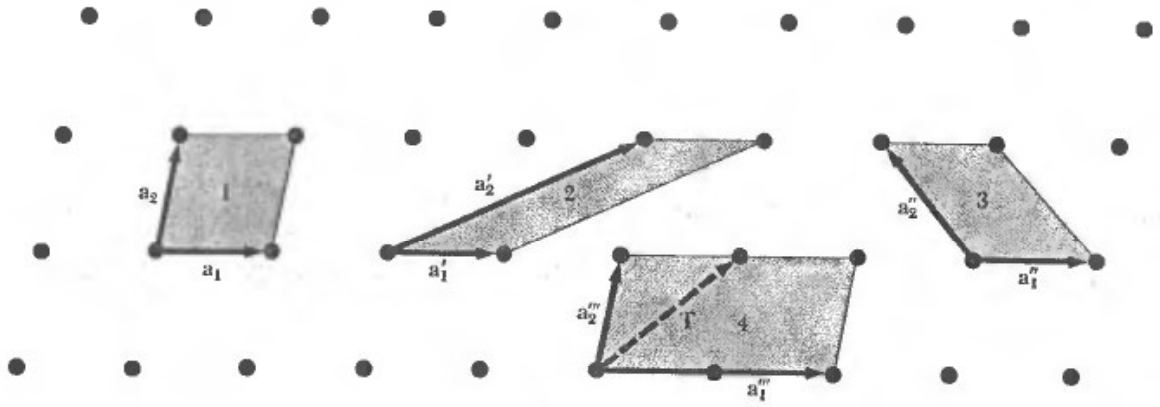
$$\mathbf{r}_j = x_j\mathbf{a}_1 + y_j\mathbf{a}_2 + z_j\mathbf{a}_3 \ . \tag{4}$$

We may arrange the origin, which we have called the associated lattice point, so that $0 \leq x_j,\ y_j,\ z_j \leq 1$.

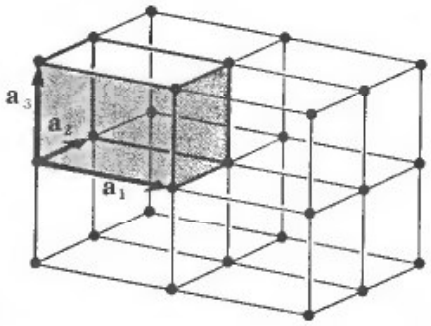
Primitive Lattice Cell

The parallelepiped defined by primitive axes $\mathbf{a}_1$, $\mathbf{a}_2$, $\mathbf{a}_3$ is called a **primitive cell** (Fig. 5b). A primitive cell is a type of cell or unit cell. (The adjective unit is superfluous and not needed.) A cell will fill all space by the repetition of suitable crystal translation operations. A primitive cell is a minimum-volume cell.

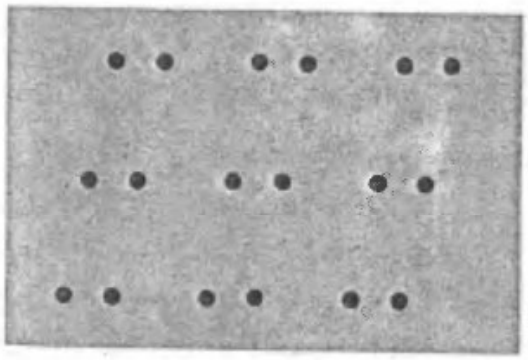
There are many ways of choosing the primitive axes and primitive cell for a given lattice. The number of atoms in a primitive cell or primitive basis is always the same for a given crystal structure.



(a)



(b)



(c)

Figure 5a Lattice points of a space lattice in two dimensions. All pairs of vectors $\mathbf{a}_1$, $\mathbf{a}_2$ are translation vectors of the lattice. But $\mathbf{a}_1'''$, $\mathbf{a}_2'''$ are not primitive translation vectors because we cannot form the lattice translation $\mathbf{T}$ from integral combinations of $\mathbf{a}_1'''$ and $\mathbf{a}_2'''$. All other pairs shown of $\mathbf{a}_1$ and $\mathbf{a}_2$ may be taken as the primitive translation vectors of the lattice. The parallelograms 1, 2, 3 are equal in area and any of them could be taken as the primitive cell. The parallelogram 4 has twice the area of a primitive cell.

Figure 5b Primitive cell of a space lattice in three dimensions.

Figure 5c Suppose these points are identical atoms: sketch in on the figure a set of lattice points, a choice of primitive axes, a primitive cell, and the basis of atoms associated with a lattice point.

There is always one lattice point per primitive cell. If the primitive cell is a parallelepiped with lattice points at each of the eight corners, each lattice point is shared among eight cells, so that the total number of lattice points in the cell is one: $8 \times \frac{1}{8} = 1$.

The volume of a parallelepiped with axes $\mathbf{a}_1$, $\mathbf{a}_2$, $\mathbf{a}_3$ is

$$V_c = |\mathbf{a}_1 \cdot \mathbf{a}_2 \times \mathbf{a}_3| \ , \tag{5}$$

by elementary vector analysis. The basis associated with a primitive cell is called a primitive basis. No basis contains fewer atoms than a primitive basis contains.

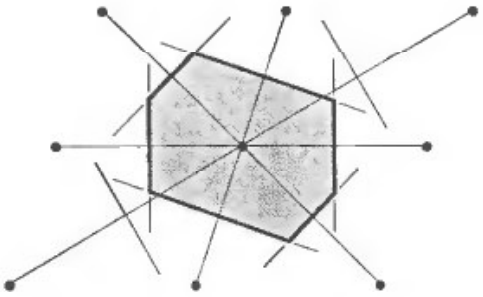


Figure 6 A primitive cell may also be chosen following this procedure: (1) draw lines to connect a given lattice point to all nearby lattice points; (2) at the midpoint and normal to these lines, draw new lines or planes. The smallest volume enclosed in this way is the Wigner-Seitz primitive cell. All space may be filled by these cells, just as by the cells of Fig. 5.

Another way of choosing a primitive cell is shown in Fig. 6. This is known to physicists as a **Wigner-Seitz cell.**

FUNDAMENTAL TYPES OF LATTICES

Crystal lattices can be carried or mapped into themselves by the lattice translations T and by various other symmetry operations. A typical symmetry operation is that of rotation about an axis that passes through a lattice point. Lattices can be found such that one-, two-, three-, four-, and sixfold rotation axes carry the lattice into itself, corresponding to rotations by 2π, $2\pi/2$, $2\pi/3$, $2\pi/4$, and $2\pi/6$ radians and by integral multiples of these rotations. The rotation axes are denoted by the symbols 1, 2, 3, 4, and 6.

We cannot find a lattice that goes into itself under other rotations, such as by $2\pi/7$ radians or $2\pi/5$ radians. A single molecule properly designed can have any degree of rotational symmetry, but an infinite periodic lattice cannot. We can make a crystal from molecules that individually have a fivefold rotation axis, but we should not expect the lattice to have a fivefold rotation axis. In Fig. 7 we show what happens if we try to construct a periodic lattice having fivefold symmetry: the pentagons do not fit together to fill all space, showing that we cannot combine fivefold point symmetry with the required translational periodicity.

By lattice point group we mean the collection of symmetry operations which, applied about a lattice point, carry the lattice into itself. The possible rotations have been listed. We can have mirror reflections m about a plane through a lattice point. The inversion operation is composed of a rotation of π followed by reflection in a plane normal to the rotation axis; the total effect is to replace r by $-$r. The symmetry axes and symmetry planes of a cube are shown in Fig. 8.

Two-Dimensional Lattice Types

There is an unlimited number of possible lattices because there is no natural restriction on the lengths of the lattice translation vectors or on the angle φ between them. The lattice in Fig. 5a was drawn for arbitrary $\mathbf{a}_1$ and $\mathbf{a}_2$. A general lattice such as this is known as an **oblique** lattice and is invariant only under rotation of π and 2π about any lattice point.

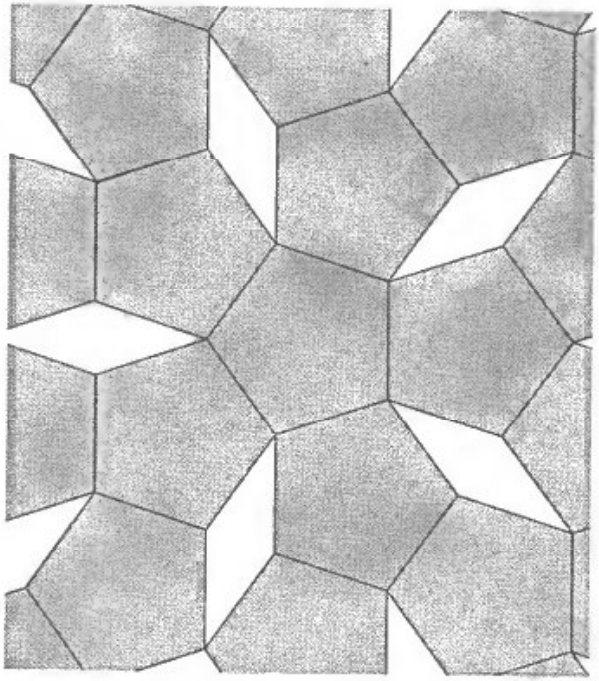


Figure 7 A fivefold axis of symmetry cannot exist in a periodic lattice because it is not possible to fill the area of a plane with a connected array of pentagons. We can, however, fill all the area of a plane with just two distinct designs of "tiles" or elementary polygons. A quasicrystal is a quasiperiodic nonrandom assembly of two types of figures. Quasicrystals are discussed at the end of Chapter 2.

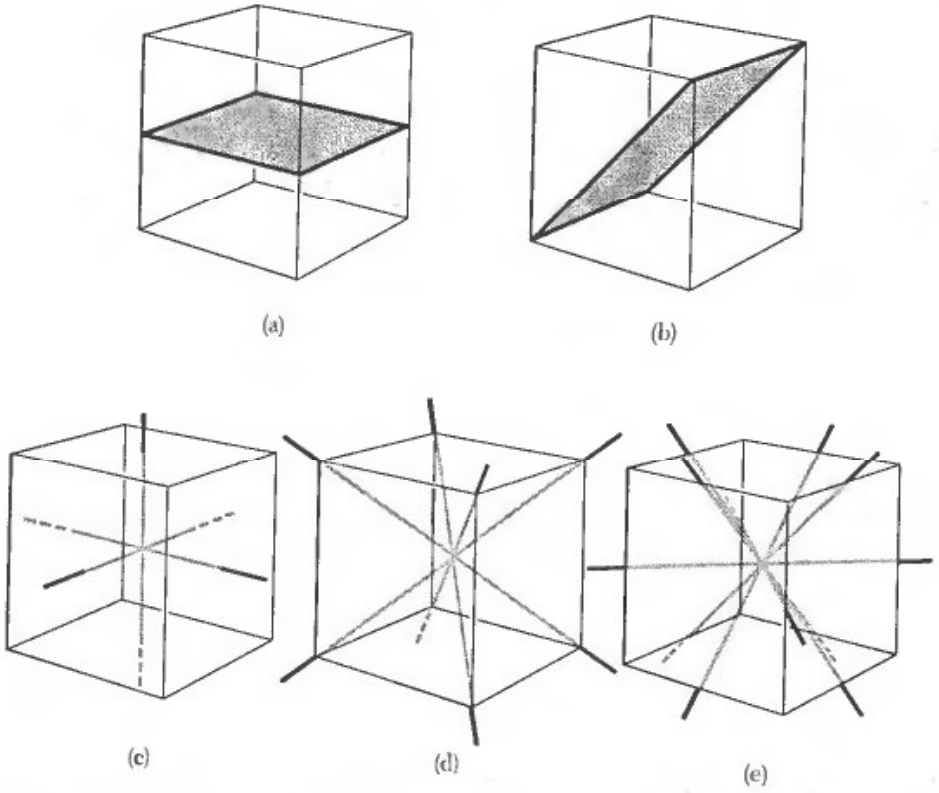


Figure 8 (a) A plane of symmetry parallel to the faces of a cube. (b) A diagonal plane of symmetry in a cube. (c) The three tetrad axes of a cube. (d) The four triad axes of a cube. (e) The six diad axes of a cube.

But special lattices of the oblique type can be invariant under rotation of $2\pi/3$, $2\pi/4$, or $2\pi/6$, or under mirror reflection. We must impose restrictive conditions on a_1 and a_2 if we want to construct a lattice that will be invariant under one or more of these new operations. There are four distinct types of restriction, and each leads to what we may call a special lattice type. Thus there are five distinct lattice types in two dimensions, the oblique lattice and the four special lattices shown in Fig. 9. Bravais lattice is the common phrase for a distinct lattice type; we say that there are five Bravais lattices or nets in two dimensions.

Three-Dimensional Lattice Types

The point symmetry groups in three dimensions require the 14 different lattice types listed in Table 1. The general lattice is triclinic, and there are 13 special lattices. These are grouped for convenience into systems classified according to seven types of cells, which are triclinic, monoclinic, orthorhombic, tetragonal, cubic, trigonal, and hexagonal. The division into systems is expressed in the table in terms of the axial relations that describe the cells.

The cells in Fig. 10 are conventional cells; of these only the sc is a primitive cell. Often a nonprimitive cell has a more obvious relation with the point symmetry operations than has a primitive cell.

Table 1 The 14 lattice types in three dimensions

System	Number of lattices	Restrictions on conventional cell axes and angles
Triclinic	1	$a_1 \neq a_2 \neq a_3$ $\alpha \neq \beta \neq \gamma$
Monoclinic	2	$a_1 \neq a_2 \neq a_3$ $\alpha = \gamma = 90° \neq \beta$
Orthorhombic	4	$a_1 \neq a_2 \neq a_3$ $\alpha = \beta = \gamma = 90°$
Tetragonal	2	$a_1 = a_2 \neq a_3$ $\alpha = \beta = \gamma = 90°$
Cubic	3	$a_1 = a_2 = a_3$ $\alpha = \beta = \gamma = 90°$
Trigonal	1	$a_1 = a_2 = a_3$ $\alpha = \beta = \gamma < 120°, \neq 90°$
Hexagonal	1	$a_1 = a_2 \neq a_3$ $\alpha = \beta = 90°$ $\gamma = 120°$

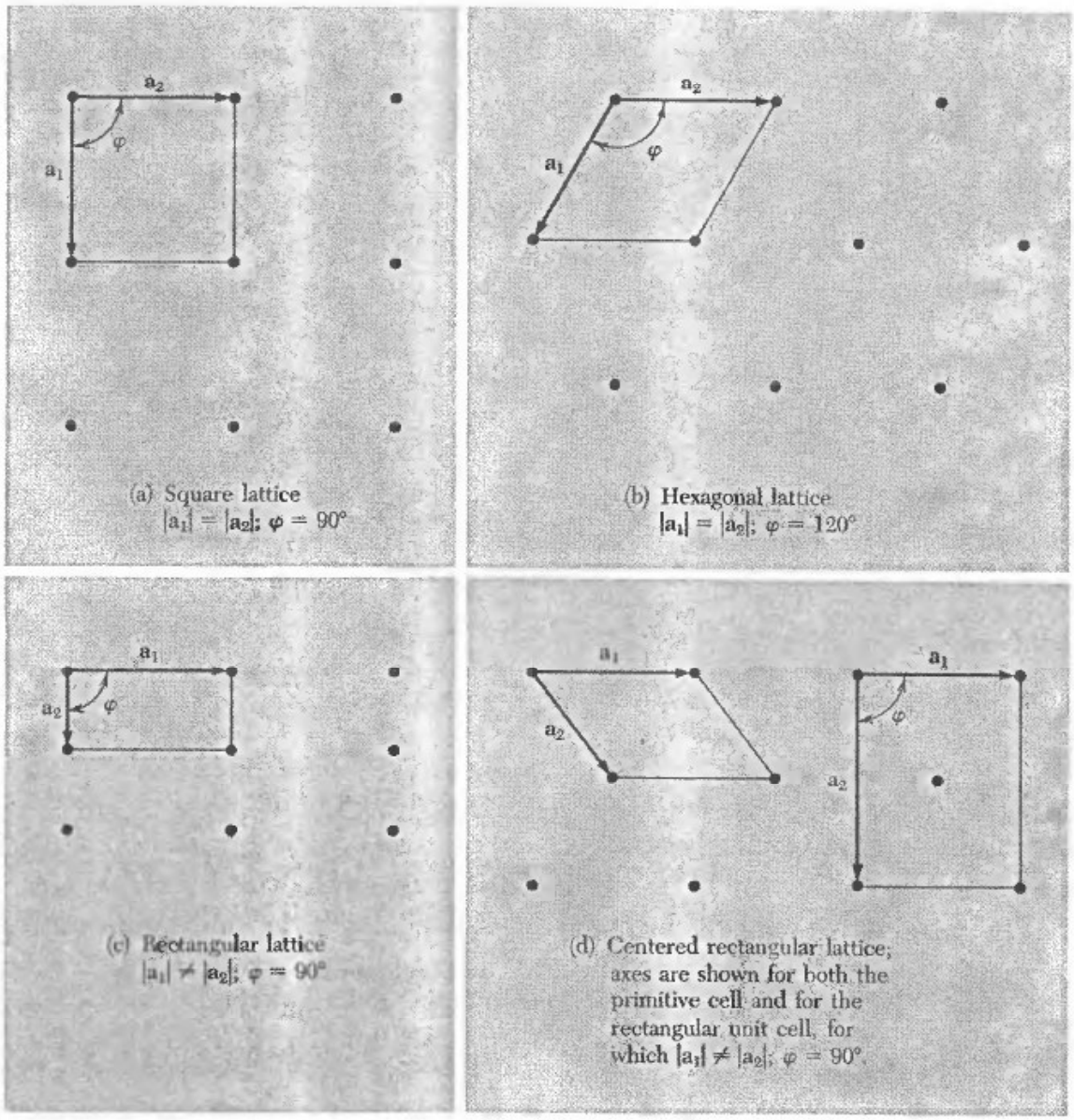


Figure 9

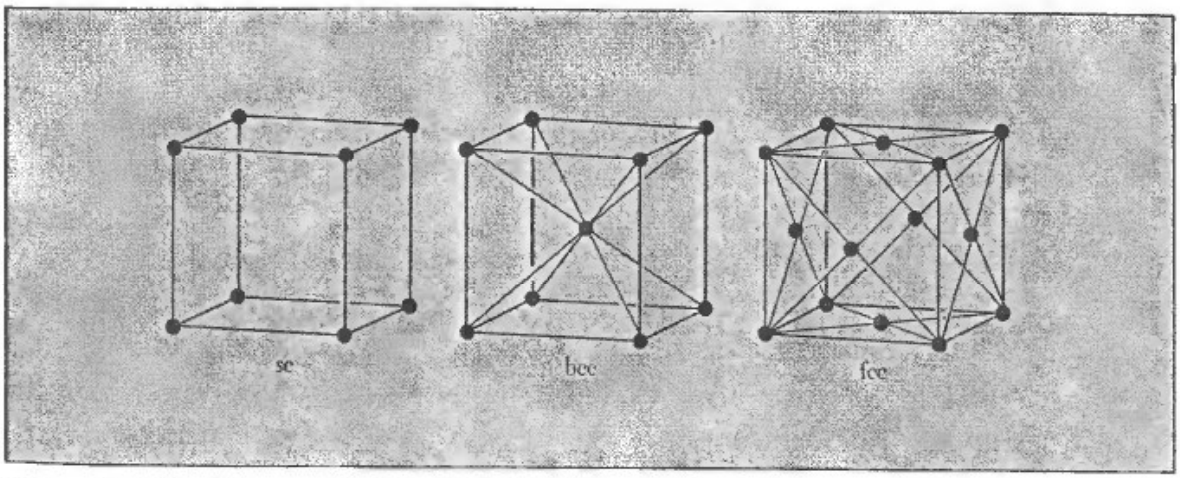


Figure 10 The cubic space lattices. The cells shown are the conventional cells.

Table 2 Characteristics of cubic lattices[a]

	Simple	Body-centered	Face-centered
Volume, conventional cell	a^3	a^3	a^3
Lattice points per cell	1	2	4
Volume, primitive cell	a^3	$\frac{1}{2}a^3$	$\frac{1}{4}a^3$
Lattice points per unit volume	$1/a^3$	$2/a^3$	$4/a^3$
Number of nearest neighbors[a]	6	8	12
Nearest-neighbor distance	a	$3^{1/2}a/2 = 0.866a$	$a/2^{1/2} = 0.707a$
Number of second neighbors	12	6	6
Second neighbor distance	$2^{1/2}a$	a	a
Packing fraction[b]	$\frac{1}{6}\pi$ $=0.524$	$\frac{1}{8}\pi\sqrt{3}$ $=0.680$	$\frac{1}{6}\pi\sqrt{2}$ $=0.740$

[a]Tables of numbers of neighbors and distances in sc, bcc, fcc, hcp, and diamond structures are given on pp. 1037–1039 of J. Hirschfelder, C. F. Curtis and R. B. Bird, *Molecular theory of gases and liquids*, Wiley, 1964.

[b]The packing fraction is the maximum proportion of the available volume that can be filled with hard spheres.

There are three lattices in the cubic system: the simple cubic (sc) lattice, the body-centered cubic (bcc) lattice, and the face-centered cubic (fcc) lattice. The characteristics of the three cubic lattices are summarized in Table 2.

A primitive cell of the bcc lattice is shown in Fig. 11, and the primitive translation vectors are shown in Fig. 12. The primitive translation vectors of the fcc lattice are shown in Fig. 13. Primitive cells by definition contain only one lattice point, but the conventional bcc cell contains two lattice points, and the fcc cell contains four lattice points.

The position of a point in a cell is specified by (4) in terms of the atomic coordinates x, y, z. Here each coordinate is a fraction of the axial length a_1, a_2, a_3 in the direction of the coordinate axis, with the origin taken at one corner of the cell. Thus the coordinates of the body center of a cell are $\frac{1}{2}\frac{1}{2}\frac{1}{2}$, and the face centers include $\frac{1}{2}\frac{1}{2}0$, $0\frac{1}{2}\frac{1}{2}$; $\frac{1}{2}0\frac{1}{2}$.

In the hexagonal system the primitive cell is a right prism based on a rhombus with an included angle of 120°. Figure 14 shows the relationship of the rhombic cell to a hexagonal prism.

INDEX SYSTEM FOR CRYSTAL PLANES

The orientation of a crystal plane is determined by three points in the plane, provided they are not collinear. If each point lay on a different crystal axis, the plane could be specified by giving the coordinates of the points in terms of the lattice constants a_1, a_2, a_3.

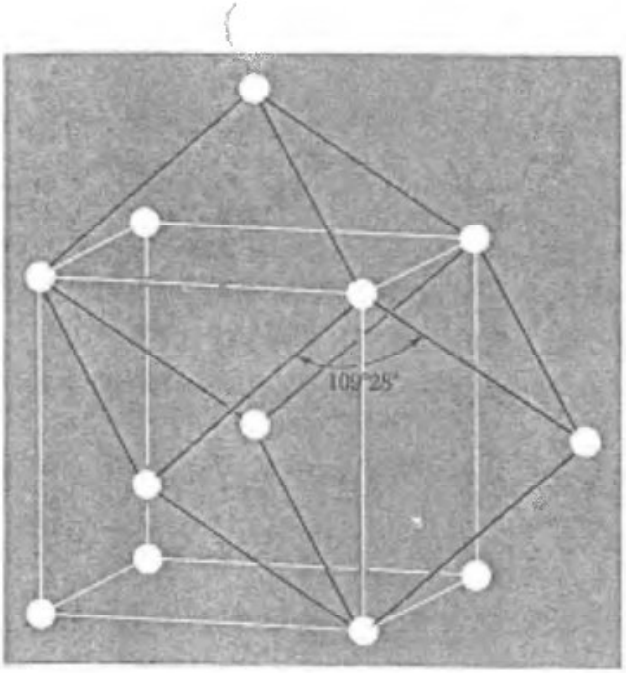


Figure 11 Body-centered cubic lattice, showing a primitive cell. The primitive cell shown is a rhombohedron of edge $\frac{1}{2}\sqrt{3}\,a$, and the angle between adjacent edges is 109°28′.

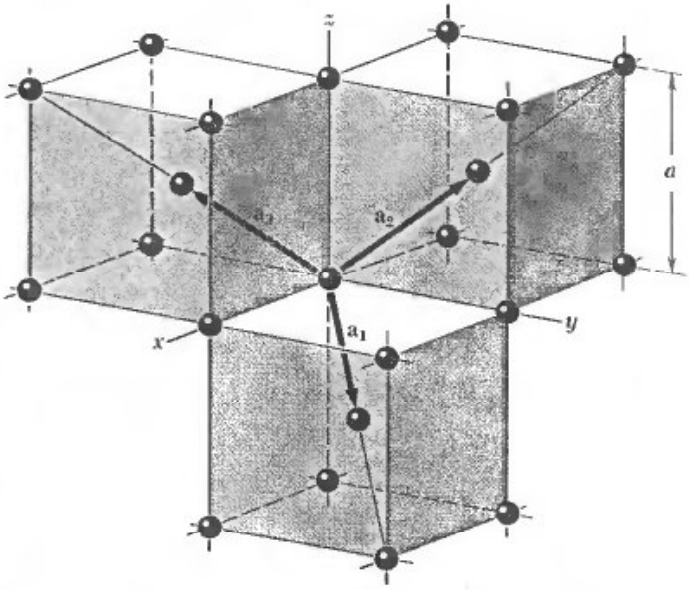


Figure 12 Primitive translation vectors of the body-centered cubic lattice; these vectors connect the lattice point at the origin to lattice points at the body centers. The primitive cell is obtained on completing the rhombohedron. In terms of the cube edge a the primitive translation vectors are

$$\mathbf{a}_1 = \tfrac{1}{2}a(\hat{\mathbf{x}} + \hat{\mathbf{y}} - \hat{\mathbf{z}}) \; ; \qquad \mathbf{a}_2 = \tfrac{1}{2}a(-\hat{\mathbf{x}} + \hat{\mathbf{y}} + \hat{\mathbf{z}}) \; ;$$

$$\mathbf{a}_3 = \tfrac{1}{2}a(\hat{\mathbf{x}} - \hat{\mathbf{y}} + \hat{\mathbf{z}}) \; .$$

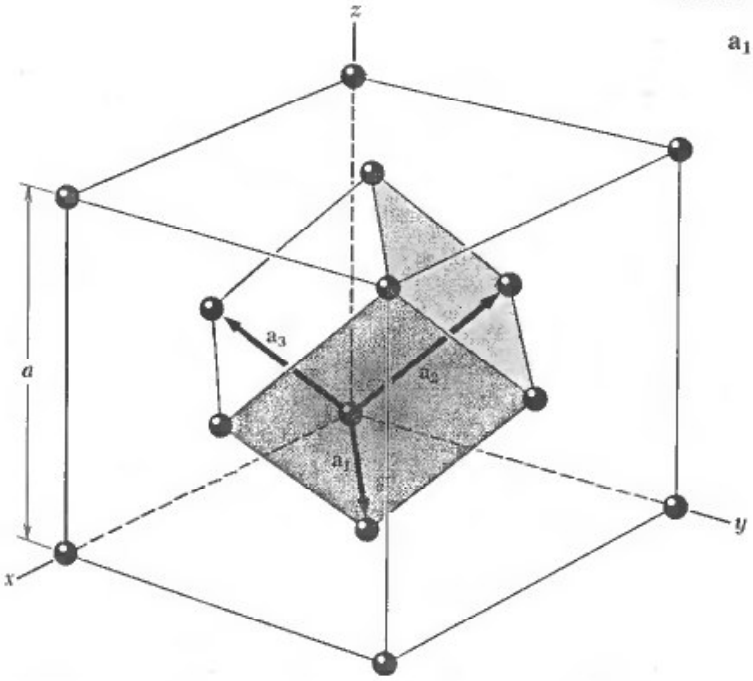


Figure 13 The rhombohedral primitive cell of the face-centered cubic crystal. The primitive translation vectors $\mathbf{a}_1$, $\mathbf{a}_2$, $\mathbf{a}_3$ connect the lattice point at the origin with lattice points at the face centers. As drawn, the primitive vectors are:

$$\mathbf{a}_1 = \tfrac{1}{2}a(\hat{\mathbf{x}} + \hat{\mathbf{y}}) \; ; \qquad \mathbf{a}_2 = \tfrac{1}{2}a(\hat{\mathbf{y}} + \hat{\mathbf{z}}) \; ; \qquad \mathbf{a}_3 = \tfrac{1}{2}a(\hat{\mathbf{z}} + \hat{\mathbf{x}}) \; .$$

The angles between the axes are 60°. Here $\hat{\mathbf{x}}$, $\hat{\mathbf{y}}$, $\hat{\mathbf{z}}$ are the Cartesian unit vectors.

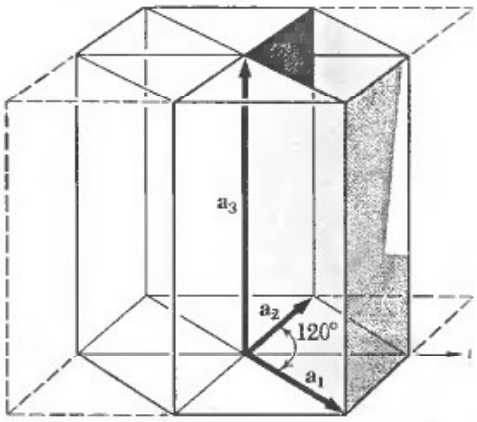


Figure 14 Relation of the primitive cel in the hexagonal system (heavy lines) t a prism of hexagonal symmetry. Her $a_1 = a_2 \neq a_3$.

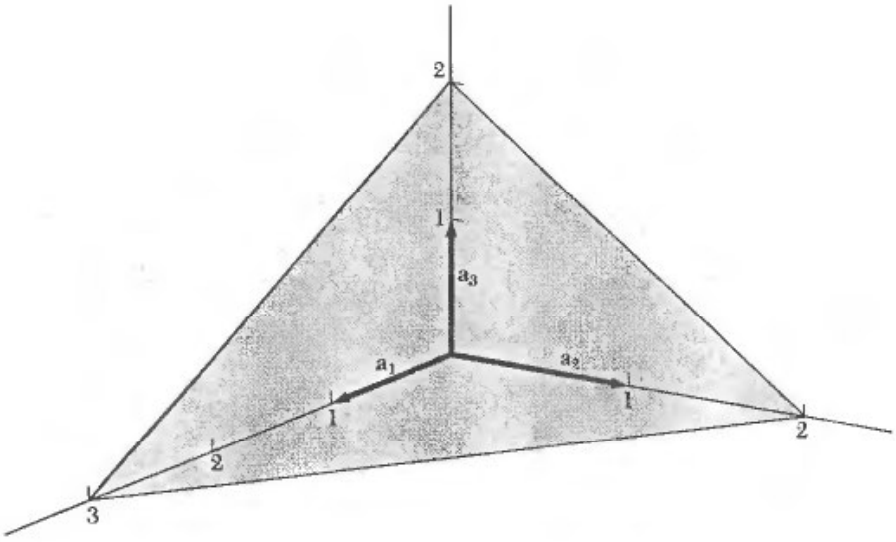


Figure 15 This plane intercepts the a_1, a_2, a_3 axes at $3a_1$, $2a_2$, $2a_3$. The reciprocals of these numbers are $\frac{1}{3}$, $\frac{1}{2}$, $\frac{1}{2}$. The smallest three integers having the same ratio are 2, 3, 3, and thus the indices of the plane are (233).

However, it turns out to be more useful for structure analysis to specify the orientation of a plane by the indices determined by the following rules (Fig. 15).

- Find the intercepts on the axes in terms of the lattice constants a_1, a_2, a_3. The axes may be those of a primitive or nonprimitive cell.
- Take the reciprocals of these numbers and then reduce to three integers having the same ratio, usually the smallest three integers. The result, enclosed in parentheses (*hkl*), is called the index of the plane.

For the plane whose intercepts are 4, 1, 2, the reciprocals are $\frac{1}{4}$, 1, and $\frac{1}{2}$; the smallest three integers having the same ratio are (142). For an intercept at infinity, the corresponding index is zero. The indices of some important planes in a cubic crystal are illustrated by Fig. 16.

The indices (*hkl*) may denote a single plane or a set of parallel planes. If a plane cuts an axis on the negative side of the origin, the corresponding index is negative, indicated by placing a minus sign above the index: $(h\bar{k}l)$. The cube faces of a cubic crystal are (100), (010), (001), $(\bar{1}00)$, $(0\bar{1}0)$, and $(00\bar{1})$. Planes equivalent by symmetry may be denoted by curly brackets (braces) around indices; the set of cube faces is {100}. When we speak of the (200) plane we mean a plane parallel to (100) but cutting the a_1 axis at $\frac{1}{2}a$.

The indices [*uvw*] of a direction in a crystal are the set of the smallest integers that have the ratio of the components of a vector in the desired direction, referred to the axes. The a_1 axis is the [100] direction; the $-a_2$ axis is the

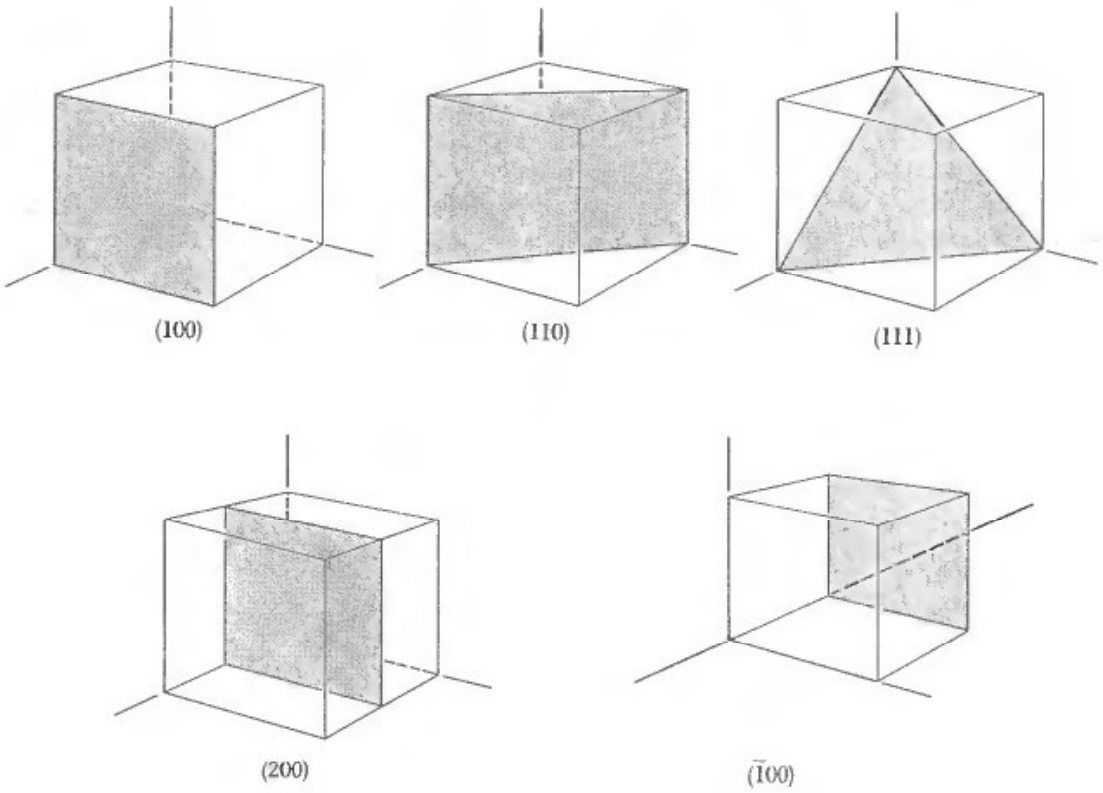


Figure 16 Indices of important planes in a cubic crystal. The plane (200) is parallel to (100) and to ($\bar{1}$00).

[0$\bar{1}$0] direction. In cubic crystals the direction [*hkl*] is perpendicular to a plane (*hkl*) having the same indices, but this is not generally true in other crystal systems.

SIMPLE CRYSTAL STRUCTURES

We discuss simple crystal structures of general interest: the sodium chloride, cesium chloride, hexagonal close-packed, diamond, and cubic zinc sulfide structures.

Sodium Chloride Structure

The sodium chloride, NaCl, structure is shown in Figs. 17 and 18. The lattice is face-centered cubic; the basis consists of one Na atom and one Cl atom separated by one-half the body diagonal of a unit cube. There are four units of NaCl in each unit cube, with atoms in the positions

Cl:	000 ;	$\frac{1}{2}\frac{1}{2}0$;	$\frac{1}{2}0\frac{1}{2}$;	$0\frac{1}{2}\frac{1}{2}$,
Na:	$\frac{1}{2}\frac{1}{2}\frac{1}{2}$;	$00\frac{1}{2}$;	$0\frac{1}{2}0$;	$\frac{1}{2}00$,

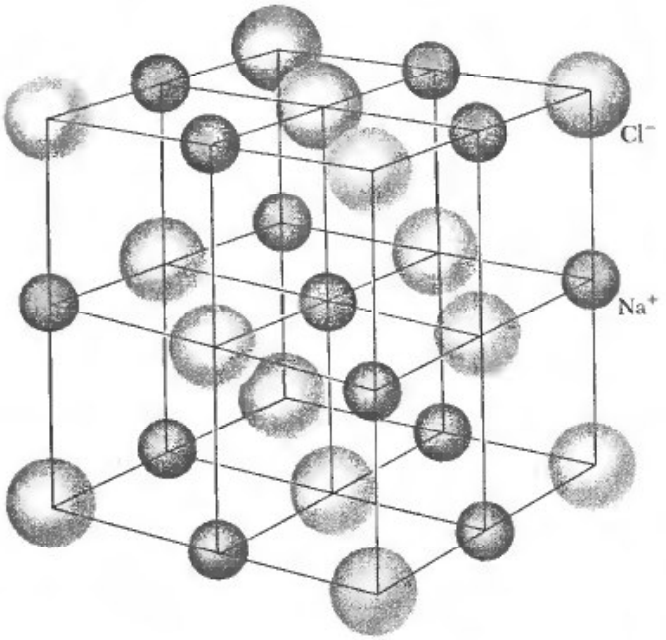


Figure 17 We may construct the sodium chloride crystal structure by arranging Na^+ and Cl^- ions alternately at the lattice points of a simple cubic lattice. In the crystal each ion is surrounded by six nearest neighbors of the opposite charge. The space lattice is fcc, and the basis has one Cl^- ion at 000 and one Na^+ ion at $\frac{111}{222}$. The figure shows one conventional cubic cell. The ionic diameters here are reduced in relation to the cell in order to clarify the spatial arrangement.

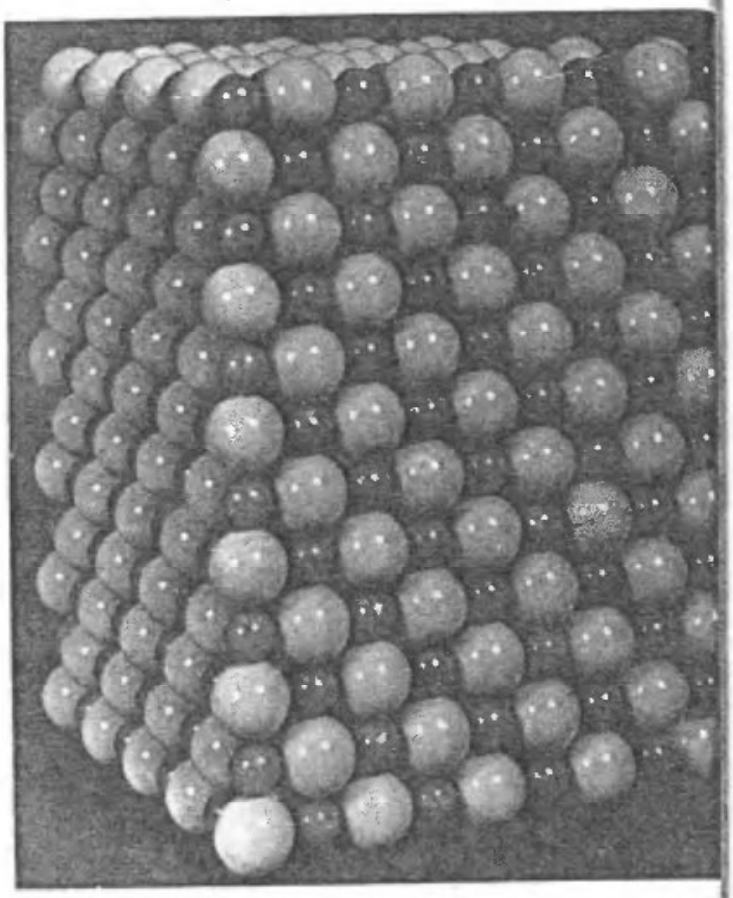


Figure 18 Model of sodium chloride. The sodium ions are smaller than the chlorine ions. (Courtesy of A. N. Holden and P. Singer.)

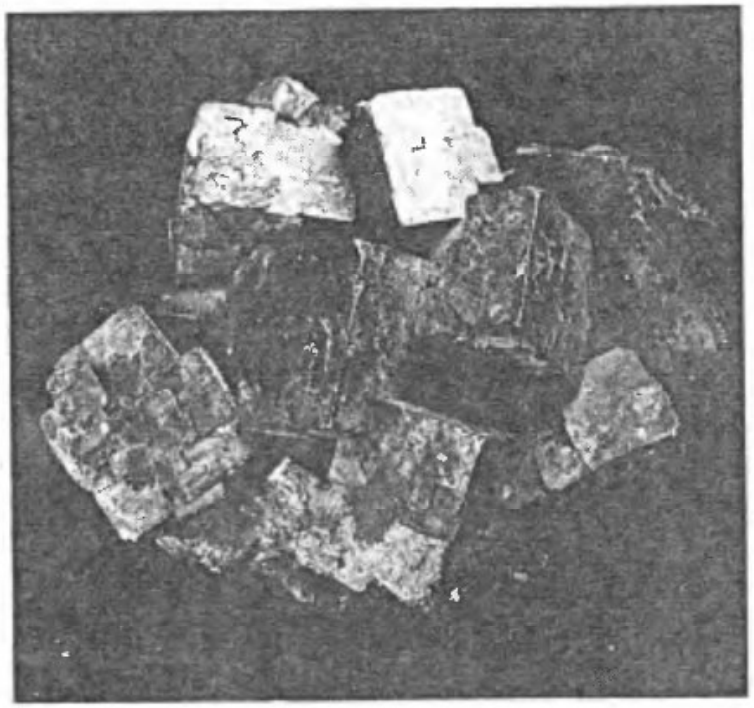


Figure 19 Natural crystals of lead sulfide, PbS, which has the NaCl crystal structure. (Photograph by B. Burleson.)

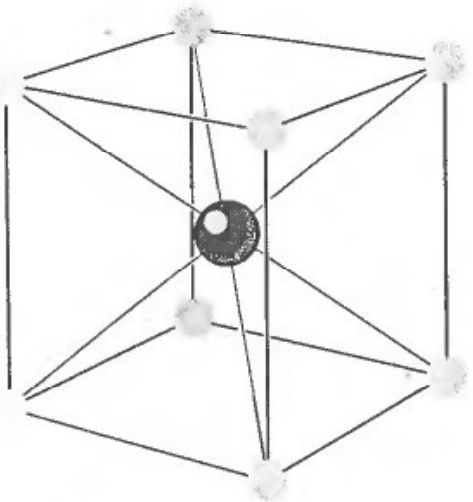


Figure 20 The cesium chloride crystal structure. The space lattice is simple cubic, and the basis has one Cs^+ ion at 000 and one Cl^- ion at $\frac{111}{222}$.

Each atom has as nearest neighbors six atoms of the opposite kind. Representative crystals having the NaCl arrangement include those in the following table. The cube edge a is given in angstroms; 1 Å $\equiv 10^{-8}$ cm $\equiv 10^{-10}$ m $\equiv$ 0.1 nm.

Crystal	a	Crystal	a
LiH	4.08 Å	AgBr	5.77 Å
MgO	4.20	PbS	5.92
MnO	4.43	KCl	6.29
NaCl	5.63	KBr	6.59

Figure 19 is a photograph of crystals of lead sulfide (PbS) from Joplin, Missouri. The Joplin specimens form in beautiful cubes.

Cesium Chloride Structure

The cesium chloride structure is shown in Fig. 20. There is one molecule per primitive cell, with atoms at the corners 000 and body-centered positions $\frac{111}{222}$ of the simple cubic space lattice. Each atom may be viewed as at the center of a cube of atoms of the opposite kind, so that the number of nearest neighbors or coordination number is eight.

Crystal	a	Crystal	a
BeCu	2.70 Å	LiHg	3.29 Å
AlNi	2.88	NH_4Cl	3.87
CuZn (β-brass)	2.94	TlBr	3.97
CuPd	2.99	CsCl	4.11
AgMg	3.28	TlI	4.20

Hexagonal Close-packed Structure (hcp)

There are an infinite number of ways of arranging identical spheres in a regular array that maximizes the packing fraction (Fig. 21). One is the face-centered cubic structure; another is the hexagonal close-packed structure (Fig. 22). The fraction of the total volume occupied by the spheres is 0.74 for both structures. No structure, regular or not, has denser packing.

Spheres are arranged in a single closest-packed layer A by placing each sphere in contact with six others. This layer may serve as either the basal plane of an hcp structure or the (111) plane of the fcc structure. A second similar layer B may be added by placing each sphere of B in contact with three spheres of the bottom layer, as in Fig. 21. A third layer C may be added in two ways. We obtain the fcc structure if the spheres of the third layer are added over the holes in the first layer that are not occupied by B. We obtain the hcp structure when the spheres in the third layer are placed directly over the centers of the spheres in the first layer.

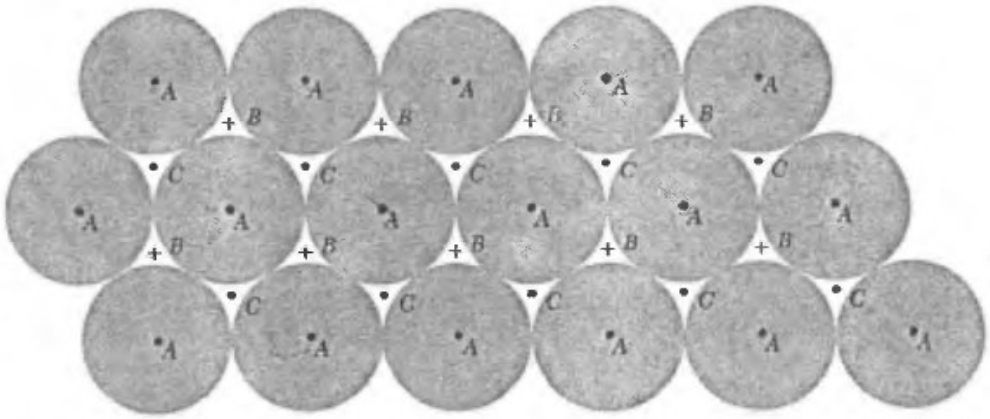


Figure 21 A close-packed layer of spheres is shown, with centers at points marked *A*. A second and identical layer of spheres can be placed on top of this, above and parallel to the plane of the drawing, with centers over the points marked *B*. There are two choices for a third layer. It can go in over *A* or over *C*. If it goes in over *A* the sequence is *ABABAB*. . . and the structure is hexagonal close-packed. If the third layer goes in over *C* the sequence is *ABCABCABC*. . . and the structure is face-centered cubic.

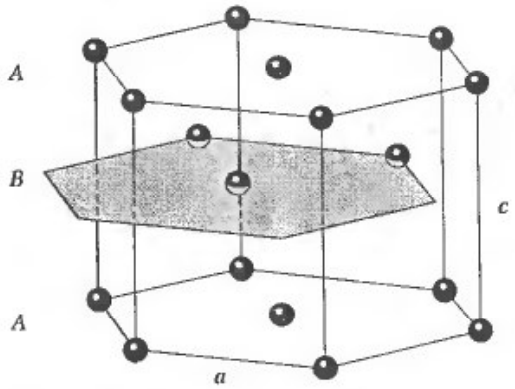


Figure 22 The hexagonal close-packed structure. The atom positions in this structure do not constitute a space lattice. The space lattice is simple hexagonal with a basis of two identical atoms associated with each lattice point. The lattice parameters a and c are indicated, where a is in the basal plane and c is the magnitude of the axis $\mathbf{a}_3$ of Fig. 14.

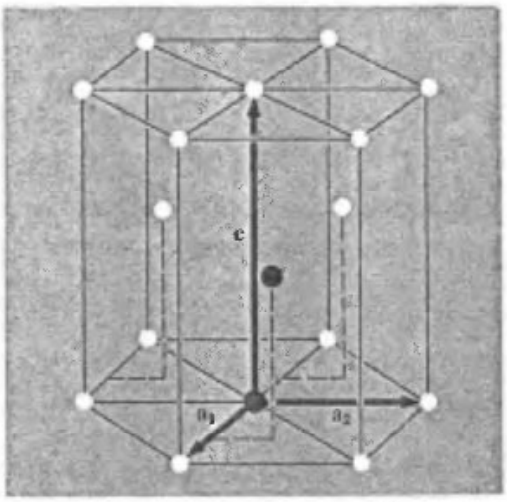


Figure 23 The primitive cell has $a_1 = a_2$, with an included angle of 120°. The c axis (or a_3) is normal to the plane of $\mathbf{a}_1$ and $\mathbf{a}_2$. The ideal hcp structure has $c = 1.633\,a$. The two atoms of one basis are shown as solid circles. One atom of the basis is at the origin; the other atom is at $\frac{2}{3}\frac{1}{3}\frac{1}{2}$, which means at the position $\mathbf{r} = \frac{2}{3}\mathbf{a}_1 + \frac{1}{3}\mathbf{a}_2 + \frac{1}{2}\mathbf{a}_3$.

The hcp structure has the primitive cell of the hexagonal lattice, but with a basis of two atoms (Fig. 23). The fcc primitive cell has a basis of one atom (Fig. 13).

The ratio c/a (or a_3/a_1) for hexagonal closest-packing of spheres has the value $(\frac{8}{3})^{1/2} = 1.633$, as in Problem 3. It is usual to refer to crystals as hcp even if the actual c/a ratio departs somewhat from this theoretical value.

The number of nearest-neighbor atoms is 12 for both hcp and fcc structures. If the binding energy (or free energy) depended only on the number of

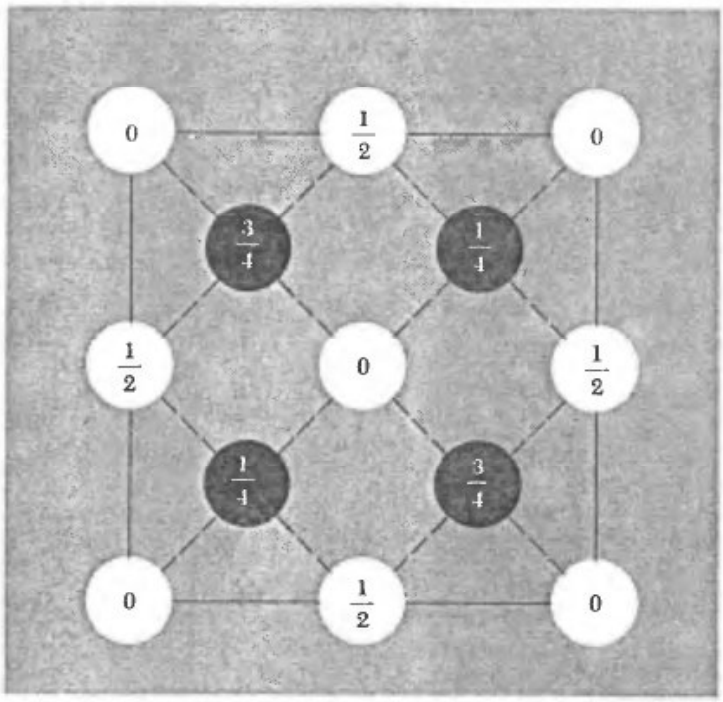


Figure 24 Atomic positions in the cubic cell of the diamond structure projected on a cube face; fractions denote height above the base in units of a cube edge. The points at 0 and $\frac{1}{2}$ are on the fcc lattice; those at $\frac{1}{4}$ and $\frac{3}{4}$ are on a similar lattice displaced along the body diagonal by one-fourth of its length. With a fcc space lattice, the basis consists of two identical atoms at 000; $\frac{111}{444}$.

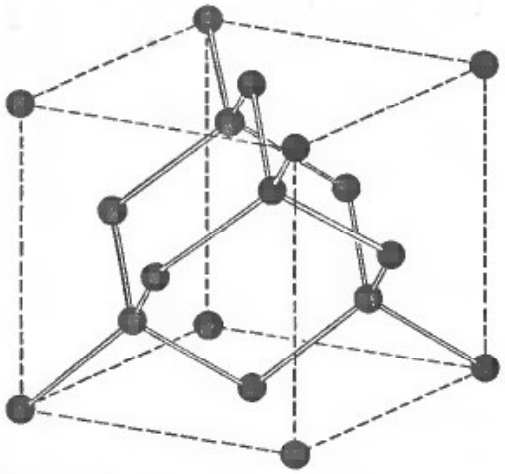


Figure 25 Crystal structure of diamond, showing the tetrahedral bond arrangement.

nearest-neighbor bonds per atom, there would be no difference in energy between the fcc and hcp structures.

Crystal	c/a	Crystal	c/a	Crystal	c/a
He	1.633	Zn	1.861	Zr	1.594
Be	1.581	Cd	1.886	Gd	1.592
Mg	1.623	Co	1.622	Lu	1.586
Ti	1.586	Y	1.570		

Diamond Structure

The space lattice of diamond is fcc. The primitive basis has two identical atoms at 000; $\frac{111}{444}$ associated with each point of the fcc lattice, as in Fig. 24. Thus the conventional unit cube contains eight atoms. There is no way to choose the primitive cell such that the basis of diamond contains only one atom.

The tetrahedral bonding characteristic of the diamond structure is shown in Fig. 25. Each atom has 4 nearest neighbors and 12 next nearest neighbors. The diamond structure is relatively empty: the maximum proportion of the available volume which may be filled by hard spheres is only 0.34, which is 46 percent of the filling factor for a closest-packed structure such as fcc or hcp. The

diamond structure is an example of the directional covalent bonding found in column IV of the periodic table of elements.

Carbon, silicon, germanium, and tin can crystallize in the diamond structure, with lattice constants $a = 3.56$, 5.43, 5.65, and 6.46 Å, respectively. Here a is the edge of the conventional cubic cell.

Cubic Zinc Sulfide Structure

The diamond structure may be viewed as two fcc structures displaced from each other by one-quarter of a body diagonal. The cubic zinc sulfide (zinc blende) structure results when Zn atoms are placed on one fcc lattice and S atoms on the other fcc lattice, as in Fig. 26. The conventional cell is a cube. The coordinates of the Zn atoms are 000; $0\frac{1}{2}\frac{1}{2}$; $\frac{1}{2}0\frac{1}{2}$; $\frac{1}{2}\frac{1}{2}0$; the coordinates of the S atoms are $\frac{1}{4}\frac{1}{4}\frac{1}{4}$; $\frac{1}{4}\frac{3}{4}\frac{3}{4}$; $\frac{3}{4}\frac{1}{4}\frac{3}{4}$; $\frac{3}{4}\frac{3}{4}\frac{1}{4}$. The lattice is fcc. There are four molecules of ZnS per conventional cell. About each atom there are four equally distant atoms of the opposite kind arranged at the corners of a regular tetrahedron.

The diamond structure allows a center-of-inversion symmetry operation at the midpoint of every line between nearest-neighbor atoms. The inversion operation carries an atom at r into an atom at $-\mathbf{r}$. The cubic ZnS structure does not have inversion symmetry. Examples of the cubic zinc sulfide structure are

Crystal	a	Crystal	a
CuF	4.26 Å	ZnSe	5.65 Å
SiC	4.35	GaAs	5.65
CuCl	5.41	AlAs	5.66
ZnS	5.41	CdS	5.82
AlP	5.45	InSb	6.46
GaP	5.45	AgI	6.47

The close equality of several pairs, notably (Al,Ga)P and (Al,Ga)As, makes possible the construction of semiconductor heterojunctions (Chapter 19).

DIRECT IMAGING OF ATOMIC STRUCTURE

Direct images of crystal structure have been produced by transmission electron microscopy. Perhaps the most beautiful images are produced by scanning tunneling microscopy; in STM (Chapter 19) one exploits the large variations in quantum tunneling as a function of the height of a fine metal tip above the surface of a crystal. The image of Figure 27 was produced in this way; see also Figures 12.19 and 19.21. An STM method has been developed that will assemble single atoms into an organized layer nanometer structure on a crystal substrate: see the electron corral in Figure 19.21.

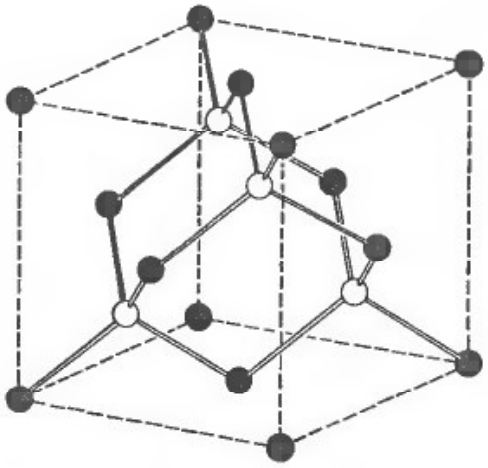


Figure 26 Crystal structure of cubic zinc sulfide.

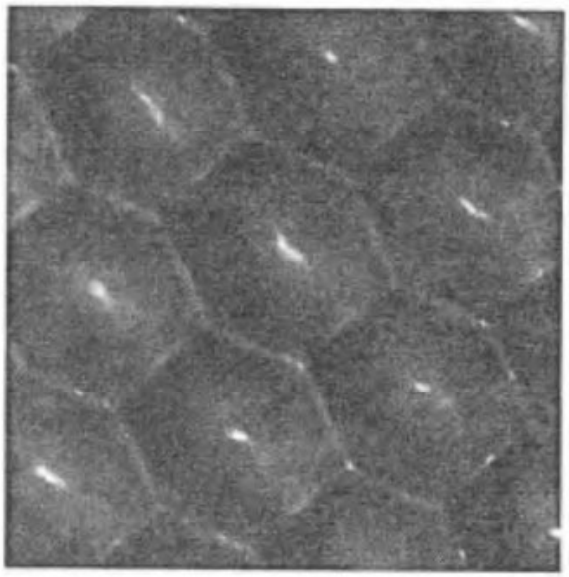


Figure 27 A scanning tunneling microscope image of atoms on a (111) surface of platinum at 4 K. The nearest neighbor spacing is 2.78 Å. (Photo courtesy of D. M. Eigler, IBM Research Division.)

NONIDEAL CRYSTAL STRUCTURES

The ideal crystal of classical crystallographers is formed by the periodic repetition of identical units in space. But no general proof has been given that the ideal crystal is the state of minimum energy of identical atoms at absolute zero. At finite temperatures this is not likely to be true—see the discussion of lattice defects in Chapter 18. Further, it is not always possible for a structure to attain the equilibrium state in a reasonable time—see the discussion of glasses in Chapter 17. Many structures that occur in nature are not entirely periodic; see the quasicrystals treated at the end of Chapter 2. We give some examples here that supplement those in the chapters just cited.

Random Stacking and Polytypism

The fcc and hcp structures are made up of close-packed planes of atoms. The structures differ in the stacking sequence of the planes, fcc having the sequence *ABCABC* . . . and hcp having the sequence *ABABAB* . . . . Structures are known in which the stacking sequence of close-packed planes is random. This is known as random stacking and may be thought of as crystalline in two dimensions and noncrystalline or glasslike in the third.

Polytypism is characterized by a stacking sequence with a long repeat unit along the stacking axis. The best known example is zinc sulfide, ZnS, in which more than 150 polytypes have been identified, with the longest periodicity being 360 layers. Another example is silicon carbide, SiC, which occurs with more than 45 stacking sequences of the close-packed layers. The polytype of SiC known as 393R has a primitive cell with $a = 3.079$ Å and $c = 989.6$ Å. The longest primitive cell observed for SiC has a repeat distance of 594 layers. A given sequence is repeated many times within a single crystal. The mechanism that induces such long-range crystallographic order is not a long-range force as such, but is associated with the presence of spiral steps due to dislocations in the growth nucleus (Chapter 20).

CRYSTAL STRUCTURE DATA

In Table 3 we list the more common crystal structures and lattice structures of the elements. Values of the atomic concentration and the density are given in Table 4.

Many elements occur in several crystal structures and transform from one to the other as the temperature or pressure is varied. Sometimes two structures coexist at the same temperature and pressure, although one may be slightly more stable.

The reader who wishes to look up the crystal structure of a substance may consult the excellent compilation by Wyckoff listed in the references at the end of the chapter. *Structure Reports* and the journals Acta Crystallographica and Zeitschrift für Kristallographie are valuable aids.

Table 3 Crystal structures of the elements

The data given are at room temperature for the most common form, or at the stated temperature in deg K. For further descriptions of the elements see Wyckoff, Vol. 1, Chap. 2. Structures labeled complex are described there.

H^1 4K hcp 3.75 6.12																	He^4 2K hcp 3.57 5.83
Li 78K bcc 3.491	Be hcp 2.27 3.59											B rhomb.	C diamond 3.567	N 20K cubic 5.66 (N_2)	O complex (O_2)	F	Ne 4K fcc 4.46
Na 5K bcc 4.225	Mg hcp 3.21 5.21	← Crystal structure →										Al fcc 4.05	Si diamond 5.430	P complex	S complex	Cl complex (Cl_2)	Ar 4K fcc 5.31
		← a lattice parameter, in A →															
		← c lattice parameter, in A →															
K 5K bcc 5.225	Ca fcc 5.58	Sc hcp 3.31 5.27	Ti hcp 2.95 4.68	V bcc 3.03	Cr bcc 2.88	Mn cubic complex	Fe bcc 2.87	Co hcp 2.51 4.07	Ni fcc 3.52	Cu fcc 3.61	Zn hcp 2.66 4.95	Ga complex	Ge diamond 5.658	As rhomb.	Se hex. chains	Br complex (Br_2)	Kr 4K fcc 5.64
Rb 5K bcc 5.585	Sr fcc 6.08	Y hcp 3.65 5.73	Zr hcp 3.23 5.15	Nb bcc 3.30	Mo bcc 3.15	Tc hcp 2.74 4.40	Ru hcp 2.71 4.28	Rh fcc 3.80	Pd fcc 3.89	Ag fcc 4.09	Cd hcp 2.98 5.62	In tetr. 3.25 4.95	Sn (α) diamond 6.49	Sb rhomb.	Te hex. chains	I complex (I_2)	Xe 4K fcc 6.13
Cs 5K bcc 6.045	Ba bcc 5.02	La hex. 3.77 *ABAC*	Hf hcp 3.19 5.05	Ta bcc 3.30	W bcc 3.16	Re hcp 2.76 4.46	Os hcp 2.74 4.32	Ir fcc 3.84	Pt fcc 3.92	Au fcc 4.08	Hg rhomb.	Tl hcp 3.46 5.52	Pb fcc 4.95	Bi rhomb.	Po sc 3.34	At —	Rn —
Fr —	Ra —	Ac fcc 5.31															

Ce fcc 5.16	Pr hex. 3.67 *ABAC*	Nd hex. 3.66	Pm —	Sm complex	Eu bcc 4.58	Gd hcp 3.63 5.78	Tb hcp 3.60 5.70	Dy hcp 3.59 5.65	Ho hcp 3.58 5.62	Er hcp 3.56 5.59	Tm hcp 3.54 5.56	Yb fcc 5.48	Lu hcp 3.50 5.55
Th fcc 5.08	Pa tetr. 3.92 3.24	U complex	Np complex	Pu complex	Am hex. 3.64 *ABAC*	Cm —	Bk —	Cf —	Es —	Fm —	Md —	No —	Lr —

Table 4 Density and atomic concentration

The data are given at atmospheric pressure and room temperature, or at the stated temperature in deg K. (Crystal modifications as for Table 3.)

H 4K 0.088																	He 2K 0.205 (at 37 atm)
Li 78K 0.542 4.700 3.023	Be 1.82 12.1 2.22											B 2.47 13.0	C 3.516 17.6 1.54	N 20K 1.03	O	F 1.44	Ne 4K 1.51 4.36 3.16
Na 5K 1.013 2.652 3.659	Mg 1.74 4.30 3.20	← Density in g cm^{-3} (10^3kg m^{-3}) →										Al 2.70 6.02 2.86	Si 2.33 5.00 2.35	P	S	Cl 93K 2.03 2.02	Ar 4K 1.77 2.66 3.76
		← Concentration in 10^{22} cm^{-3} (10^{28} m^{-3}) →															
		← Nearest-neighbor distance, in Å (10^{-10}m) →															
K 5K 0.910 1.402 4.525	Ca 1.53 2.30 3.95	Sc 2.99 4.27 3.25	Ti 4.51 5.66 2.89	V 6.09 7.22 2.62	Cr 7.19 8.33 2.50	Mn 7.47 8.18 2.24	Fe 7.87 8.50 2.48	Co 8.9 8.97 2.50	Ni 8.91 9.14 2.49	Cu 8.93 8.45 2.56	Zn 7.13 6.55 2.66	Ga 5.91 5.10 2.44	Ge 5.32 4.42 2.45	As 5.77 4.65 3.16	Se 4.81 3.67 2.32	Br 123K 4.05 2.36	Kr 4K 3.09 2.17 4.00
Rb 5K 1.629 1.148 4.837	Sr 2.58 1.78 4.30	Y 4.48 3.02 3.55	Zr 6.51 4.29 3.17	Nb 8.58 5.56 2.86	Mo 10.22 6.42 2.72	Tc 11.50 7.04 2.71	Ru 12.36 7.36 2.65	Rh 12.42 7.26 2.69	Pd 12.00 6.80 2.75	Ag 10.50 5.85 2.89	Cd 8.65 4.64 2.98	In 7.29 3.83 3.25	Sn 5.76 2.91 2.81	Sb 6.69 3.31 2.91	Te 6.25 2.94 2.86	I 4.95 2.36 3.54	Xe 4K 3.78 1.64 4.34
Cs 5K 1.997 0.905 5.235	Ba 3.59 1.60 4.35	La 6.17 2.70 3.73	Hf 13.20 4.52 3.13	Ta 16.66 5.55 2.86	W 19.25 6.30 2.74	Re 21.03 6.80 2.74	Os 22.58 7.14 2.68	Ir 22.55 7.06 2.71	Pt 21.47 6.62 2.77	Au 19.28 5.90 2.88	Hg 227 14.26 4.26 3.01	Tl 11.87 3.50 3.46	Pb 11.34 3.30 3.50	Bi 9.80 2.82 3.07	Po 9.31 2.67 3.34	At — 	Rn —
Fr —	Ra —	Ac 10.07 2.66 3.76															

Ce 6.77 2.91 3.65	Pr 6.78 2.92 3.63	Nd 7.00 2.93 3.66	Pm —	Sm 7.54 3.03 3.59	Eu 5.25 2.04 3.96	Gd 7.89 3.02 3.58	Tb 8.27 3.22 3.52	Dy 8.53 3.17 3.51	Ho 8.80 3.22 3.49	Er 9.04 3.26 3.47	Tm 9.32 3.32 3.54	Yb 6.97 3.02 3.88	Lu 9.84 3.39 3.43
Th 11.72 3.04 3.60	Pa 15.37 4.01 3.21	U 19.05 4.80 2.75	Np 20.45 5.20 2.62	Pu 19.81 4.26 3.1	Am 11.87 2.96 3.61	Cm —	Bk —	Cf —	Es —	Fm —	Md —	No —	Lr —

SUMMARY

- A lattice is an array of points related by the lattice translation operator $\mathbf{T} = u_1\mathbf{a}_1 + u_2\mathbf{a}_2 + u_3\mathbf{a}_3$, where u_1, u_2, u_3 are integers and $\mathbf{a}_1$, $\mathbf{a}_2$, $\mathbf{a}_3$ are the crystal axes.
- To form a crystal we attach to every lattice point an identical basis composed of s atoms at the positions $\mathbf{r}_j = x_j\mathbf{a}_1 + y_j\mathbf{a}_2 + z_j\mathbf{a}_3$, with $j = 1, 2, \ldots, s$. Here x, y, z may be selected to have values between 0 and 1.
- The axes $\mathbf{a}_1$, $\mathbf{a}_2$, $\mathbf{a}_3$ are primitive for the minimum cell volume $|\mathbf{a}_1 \cdot \mathbf{a}_2 \times \mathbf{a}_3|$ for which the crystal can be constructed from a lattice translation operator $\mathbf{T}$ and a basis at every lattice point.

Problems

1. ***Tetrahedral angles.*** The angles between the tetrahedral bonds of diamond are the same as the angles between the body diagonals of a cube, as in Fig. 12. Use elementary vector analysis to find the value of the angle.

2. ***Indices of planes.*** Consider the planes with indices (100) and (001); the lattice is fcc, and the indices refer to the conventional cubic cell. What are the indices of these planes when referred to the primitive axes of Fig. 13?

3. ***Hcp structure.*** Show that the c/a ratio for an ideal hexagonal close-packed structure is $(\frac{8}{3})^{1/2} = 1.633$. If c/a is significantly larger than this value, the crystal structure may be thought of as composed of planes of closely packed atoms, the planes being loosely stacked.

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2

Reciprocal Lattice

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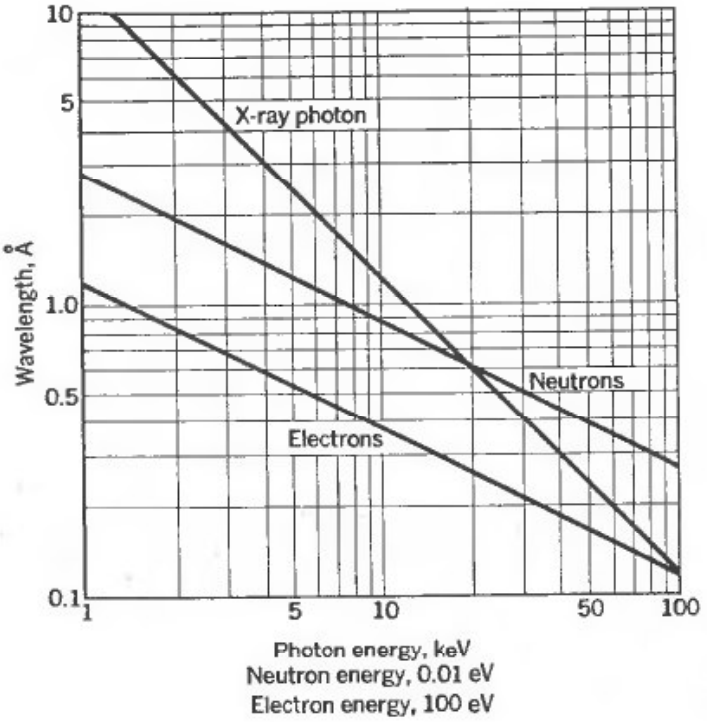

Figure 1 Wavelength versus particle energy, for photons, neutrons, and electrons.

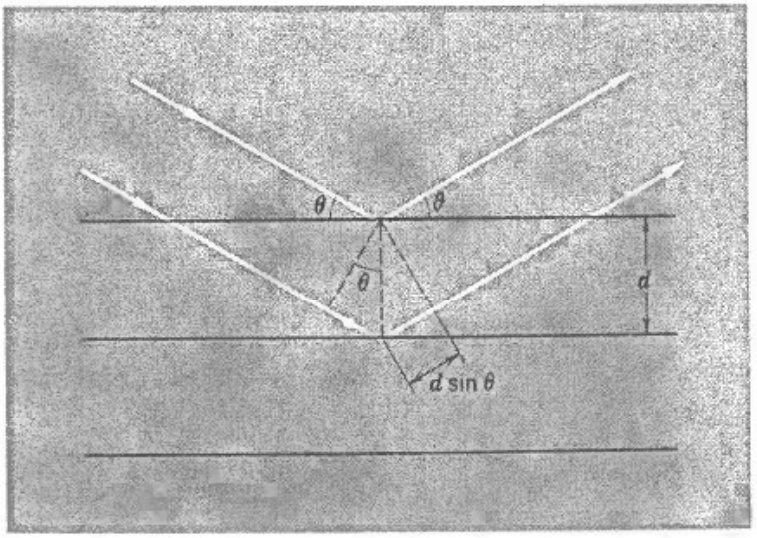

Figure 2 Derivation of the Bragg equation $2d \sin \theta = n\lambda$; here d is the spacing of parallel atomic planes and $2\pi n$ is the difference in phase between reflections from successive planes. The reflecting planes have nothing to do with the surface planes bounding the particular specimen.

DIFFRACTION OF WAVES BY CRYSTALS

Bragg Law

We study crystal structure through the diffraction of photons, neutrons, and electrons (Fig. 1). The diffraction depends on the crystal structure and on the wavelength. At optical wavelengths such as 5000 Å the superposition of the waves scattered elastically by the individual atoms of a crystal results in ordinary optical refraction. When the wavelength of the radiation is comparable with or smaller than the lattice constant, we may find diffracted beams in directions quite different from the incident direction.

W. L. Bragg presented a simple explanation of the diffracted beams from a crystal. The Bragg derivation is simple but is convincing only because it reproduces the correct result. Suppose that the incident waves are reflected specularly from parallel planes of atoms in the crystal, with each plane reflecting only a very small fraction of the radiation, like a lightly silvered mirror. In specular (mirrorlike) reflection the angle of incidence is equal to the angle of reflection. The diffracted beams are found when the reflections from parallel planes of atoms interfere constructively, as in Fig. 2. We treat elastic scattering, in which the energy of the x-ray is not changed on reflection. Inelastic scattering, with excitation of elastic waves, is discussed in Appendix A.

Consider parallel lattice planes spaced d apart. The radiation is incident in the plane of the paper. The path difference for rays reflected from adjacent planes is $2d \sin \theta$, where θ is measured from the plane. Constructive interference of the radiation from successive planes occurs when the path difference is an integral number n of wavelengths λ, so that

$$2d \sin \theta = n\lambda \ . \tag{1}$$

This is the Bragg law. Bragg reflection can occur only for wavelength $\lambda \leq 2d$. This is why we cannot use visible light.

Although the reflection from each plane is specular, for only certain values of θ will the reflections from all parallel planes add up in phase to give a strong reflected beam. If each plane were perfectly reflecting, only the first plane of a parallel set would see the radiation, and any wavelength would be reflected. But each plane reflects 10^{-3} to 10^{-5} of the incident radiation, so that 10^3 to 10^5 planes may contribute to the formation of the Bragg-reflected beam in a perfect crystal. Reflection by a single plane of atoms is treated in Chapter 19 on surface physics.

The Bragg law is a consequence of the periodicity of the lattice. Notice that the law does not refer to the composition of the basis of atoms associated with every lattice point. We shall see, however, that the composition of the basis

determines the relative intensity of the various orders of diffraction (denoted by n above) from a given set of parallel planes. Experimental results for Bragg reflection from single crystals are shown in Figs. 3 and 4, for rotation about a fixed axis.

SCATTERED WAVE AMPLITUDE

The Bragg derivation of the diffraction condition (1) gives a neat statement of the condition for the constructive interference of waves scattered from the lattice points. We need a deeper analysis to determine the scattering intensity from the basis of atoms, which means from the spatial distribution of electrons within each cell.

From (1.3), a crystal is invariant under any translation of the form $\mathbf{T} = u_1\mathbf{a}_1 + u_2\mathbf{a}_2 + u_3\mathbf{a}_3$, where u_1, u_2, u_3 are integers and $\mathbf{a}_1$, $\mathbf{a}_2$, $\mathbf{a}_3$ are the crystal axes. Any local physical property of the crystal is invariant under $\mathbf{T}$, such as the charge concentration, electron number density, or magnetic moment density.

Fourier Analysis

What is most important to us here is that the electron number density $n(\mathbf{r})$ is a periodic function of $\mathbf{r}$, with periods $\mathbf{a}_1$, $\mathbf{a}_2$, $\mathbf{a}_3$ in the directions of the three crystal axes. Thus

$$n(\mathbf{r} + \mathbf{T}) = n(\mathbf{r}) \ . \tag{2}$$

Such periodicity creates an ideal situation for Fourier analysis. The most interesting properties of crystals are directly related to the Fourier components of the electron density.

We consider first a function $n(x)$ with period a in the direction x, in one dimension. We expand $n(x)$ in a Fourier series of sines and cosines:

$$n(x) = n_0 + \sum_{p>0} [C_p \cos(2\pi px/a) + S_p \sin(2\pi px/a)] \ , \tag{3}$$

where the p's are positive integers and C_p, S_p are real constants, called the Fourier coefficients of the expansion. The factor $2\pi/a$ in the arguments ensures that $n(x)$ has the period a:

$$\begin{aligned} n(x + a) &= n_0 + \Sigma[C_p \cos(2\pi px/a + 2\pi p) + S_p \sin(2\pi px/a + 2\pi p)] \\ &= n_0 + \Sigma[C_p \cos(2\pi px/a) + S_p \sin(2\pi px/a)] = n(x) \ . \end{aligned} \tag{4}$$

We say that $2\pi p/a$ is a point in the reciprocal lattice or Fourier space of the crystal. In one dimension these points lie on a line. The reciprocal lattice points tell us the allowed terms in the Fourier series (4) or (5). A term is allowed if it is consistent with the periodicity of the crystal, as in Fig. 5; other points in the reciprocal space are not allowed in the Fourier expansion of a periodic function.

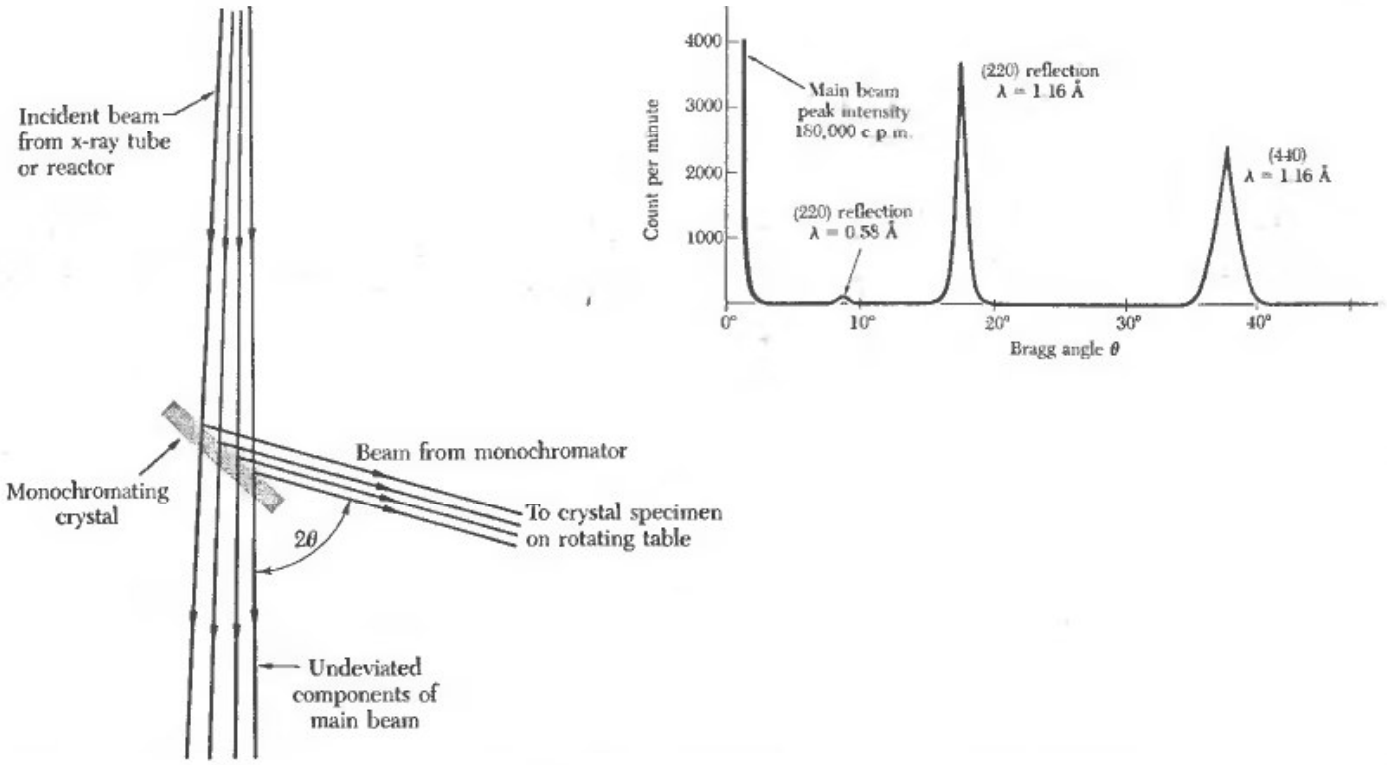

Figure 3 Sketch of a monochromator which by Bragg reflection selects a narrow spectrum of x-ray or neutron wavelengths from a broad spectrum incident beam. The upper part of the figure shows the analysis (obtained by reflection from a second crystal) of the purity of a 1.16 Å beam of neutrons from a calcium fluoride crystal monochromator. The main beam is that not reflected from the second crystal. (After G. Bacon.)

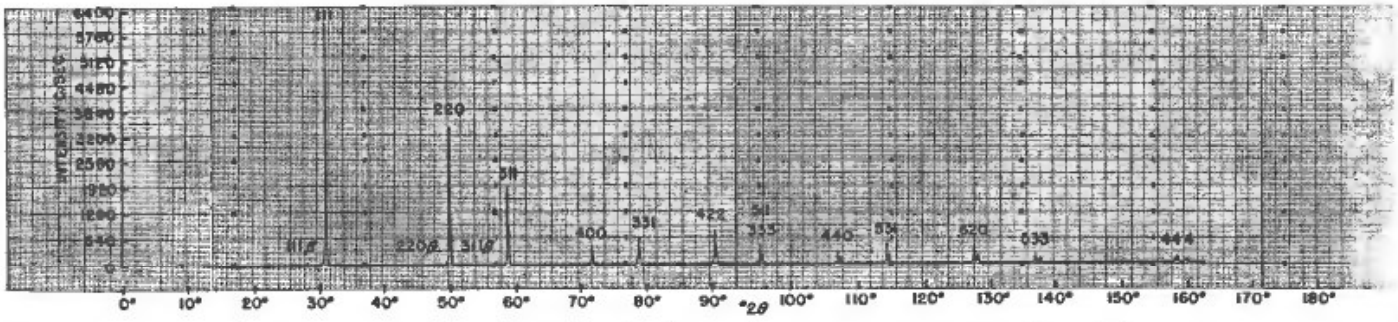

Figure 4 X-ray diffractometer recording of powdered silicon, showing a counter recording of the diffracted beams. (Courtesy of W. Parrish.)

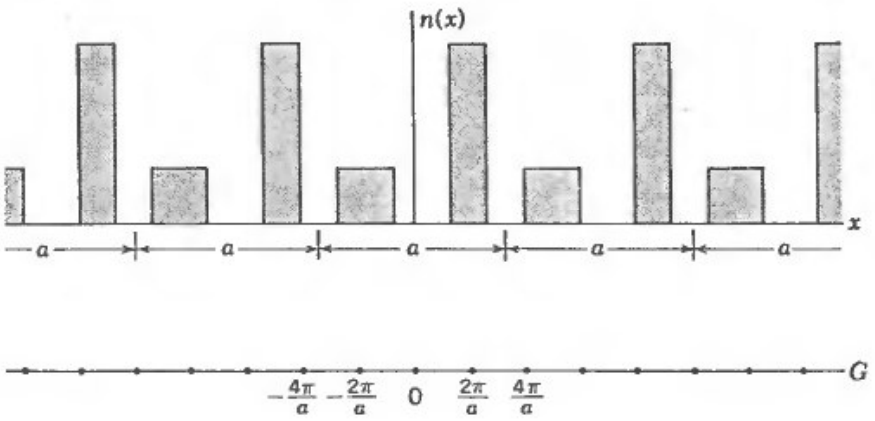

Figure 5 A periodic function $n(x)$ of period a, and the terms $2\pi p/a$ that may appear in the Fourier transform $n(x) = \Sigma\, n_p \exp(i2\pi px/a)$. The magnitudes of the individual terms n_p are not plotted.

It is a great convenience to write the series (4) in the compact form

$$n(x) = \sum_p n_p \exp(i2\pi px/a) \ , \tag{5}$$

where the sum is over all integers p: positive, negative, and zero. The coefficients n_p now are complex numbers. To ensure that $n(x)$ is a real function, we require

$$n^*_{-p} = n_p \ , \tag{6}$$

for then the sum of the terms in p and $-p$ is real. The asterisk on n^*_{-p} denotes the complex conjugate of n_{-p}.

With $\varphi = 2\pi px/a$, the sum of the terms in p and $-p$ in (5) can be shown to be real if (6) is satisfied. The sum is

$$\begin{aligned} n_p(\cos\varphi + i\sin\varphi) + n_{-p}(\cos\varphi - i\sin\varphi) \\ = (n_p + n_{-p})\cos\varphi + i(n_p - n_{-p})\sin\varphi \ , \end{aligned} \tag{7}$$

which in turn is equal to the real function

$$2\mathrm{Re}\{n_p\}\cos\varphi - 2\mathrm{Im}\{n_p\}\sin\varphi \ , \tag{8}$$

if (6) is satisfied. Here $\mathrm{Re}\{n_p\}$ and $\mathrm{Im}\{n_p\}$ denote the real and imaginary parts of n_p. Thus the number density $n(x)$ is a real function, as desired.

The extension of the Fourier analysis to periodic functions $n(\mathbf{r})$ in three dimensions is straightforward. We must find a set of vectors $\mathbf{G}$ such that

$$n(\mathbf{r}) = \sum_{\mathbf{G}} n_{\mathbf{G}} \exp(i\mathbf{G}\cdot\mathbf{r}) \tag{9}$$

is invariant under all crystal translations $\mathbf{T}$ that leave the crystal invariant. It will be shown below that the set of Fourier coefficients $n_{\mathbf{G}}$ determines the x-ray scattering amplitude.

Inversion of Fourier Series. We now show that the Fourier coefficient n_p in the series (5) is given by

$$n_p = a^{-1}\int_0^a dx\ n(x)\exp(-i2\pi px/a) \ . \tag{10}$$

Substitute (5) in (10) to obtain

$$n_p = a^{-1}\sum_{p'} n_{p'}\int_0^a dx\exp[i2\pi(p'-p)x/a] \ . \tag{11}$$

If $p' \neq p$ the value of the integral is

$$\frac{a}{i2\pi(p'-p)}(e^{i2\pi(p'-p)} - 1) = 0 \ ,$$

because $p' - p$ is an integer and $\exp[i2\pi(\text{integer})] = 1$. For the term $p' = p$ the integrand is $\exp(i0) = 1$, and the value of the integral is a, so that $n_p = a^{-1}n_p a = n_p$, which is an identity, so that (10) is an identity.

Similarly, the inversion of (9) gives

$$n_{\mathbf{G}} = V_c^{-1} \int_{\text{cell}} dV\, n(\mathbf{r}) \exp(-i\mathbf{G}\cdot\mathbf{r}) \ . \tag{12}$$

Here V_c is the volume of a cell of the crystal.

Reciprocal Lattice Vectors

To proceed further with the Fourier analysis of the electron concentration we must find the vectors G of the Fourier sum $\Sigma n_{\mathbf{G}} \exp(i\mathbf{G}\cdot\mathbf{r})$ as in (9). There is a powerful, somewhat abstract procedure for doing this. The procedure forms the theoretical basis for much of solid state physics, where Fourier analysis is the order of the day.

We construct the axis vectors $\mathbf{b}_1$, $\mathbf{b}_2$, $\mathbf{b}_3$ of the reciprocal lattice:

$$\mathbf{b}_1 = 2\pi\frac{\mathbf{a}_2 \times \mathbf{a}_3}{\mathbf{a}_1 \cdot \mathbf{a}_2 \times \mathbf{a}_3} \ ; \quad \mathbf{b}_2 = 2\pi\frac{\mathbf{a}_3 \times \mathbf{a}_1}{\mathbf{a}_1 \cdot \mathbf{a}_2 \times \mathbf{a}_3} \ ; \quad \mathbf{b}_3 = 2\pi\frac{\mathbf{a}_1 \times \mathbf{a}_2}{\mathbf{a}_1 \cdot \mathbf{a}_2 \times \mathbf{a}_3} \ . \tag{13}$$

The factors 2π are not used by crystallographers but are convenient in solid state physics.

If $\mathbf{a}_1$, $\mathbf{a}_2$, $\mathbf{a}_3$ are primitive vectors of the crystal lattice, then $\mathbf{b}_1$, $\mathbf{b}_2$, $\mathbf{b}_3$ are primitive vectors of the reciprocal lattice. Each vector defined by (13) is orthogonal to two axis vectors of the crystal lattice. Thus $\mathbf{b}_1$, $\mathbf{b}_2$, $\mathbf{b}_3$ have the property

$$\mathbf{b}_i \cdot \mathbf{a}_j = 2\pi\delta_{ij} \ , \tag{14}$$

where $\delta_{ij} = 1$ if $i = j$ and $\delta_{ij} = 0$ if $i \neq j$.

Points in the reciprocal lattice are mapped by the set of vectors

$$\mathbf{G} = v_1\mathbf{b}_1 + v_2\mathbf{b}_2 + v_3\mathbf{b}_3 \ , \tag{15}$$

where v_1, v_2, v_3 are integers. A vector G of this form is a **reciprocal lattice vector.**

Every crystal structure has two lattices associated with it, the crystal lattice and the reciprocal lattice. A diffraction pattern of a crystal is, as we shall show, a map of the reciprocal lattice of the crystal. A microscope image, if it could be resolved on a fine enough scale, is a map of the crystal structure in real space. The two lattices are related by the definitions (13). Thus when we rotate a crystal in a holder, we rotate both the direct lattice and the reciprocal lattice.

Vectors in the direct lattice have the dimensions of [length]; vectors in the reciprocal lattice have the dimensions of [1/length]. The reciprocal lattice is a lattice in the Fourier space associated with the crystal. The term is motivated

below. Wavevectors are always drawn in Fourier space, so that every position in Fourier space may have a meaning as a description of a wave, but there is a special significance to the points defined by the set of G's associated with a crystal structure.

The vectors **G** in the Fourier series (9) are just the reciprocal lattice vectors (15), for then the Fourier series representation of the electron density has the desired invariance under any crystal translation $\mathbf{T} = u_1\mathbf{a}_1 + u_2\mathbf{a}_2 + u_3\mathbf{a}_3$ as defined by (1.3). From (9),

$$n(\mathbf{r} + \mathbf{T}) = \sum_{\mathbf{G}} n_{\mathbf{G}} \exp(i\mathbf{G} \cdot \mathbf{r}) \exp(i\mathbf{G} \cdot \mathbf{T}) \ . \tag{16}$$

But $\exp(i\mathbf{G} \cdot \mathbf{T}) = 1$, because

$$\begin{aligned} \exp(i\mathbf{G} \cdot \mathbf{T}) &= \exp[i(v_1\mathbf{b}_1 + v_2\mathbf{b}_2 + v_3\mathbf{b}_3) \cdot (u_1\mathbf{a}_1 + u_2\mathbf{a}_2 + u_3\mathbf{a}_3)] \\ &= \exp[i2\pi(v_1u_1 + v_2u_2 + v_3u_3)] \ . \end{aligned} \tag{17}$$

The argument of the exponential has the form $2\pi i$ times an integer, because $v_1u_1 + v_2u_2 + v_3u_3$ is an integer, being the sum of products of integers. Thus by (9) we have the desired invariance, $n(\mathbf{r} + \mathbf{T}) = n(\mathbf{r})$.

This result proves that the Fourier representation of a function periodic in the crystal lattice can contain components $n_{\mathbf{G}} \exp(i\mathbf{G} \cdot \mathbf{r})$ only at the reciprocal lattice vectors **G** as defined by (15).

Diffraction Conditions

Theorem. The set of reciprocal lattice vectors **G** determines the possible x-ray reflections.

We see in Fig. 6 that the difference in phase factors is $\exp[i(\mathbf{k} - \mathbf{k}') \cdot \mathbf{r}]$ between beams scattered from volume elements **r** apart. The wavevectors of the incoming and outgoing beams are **k** and **k′**. The amplitude of the wave scattered from a volume element is proportional to the local electron concentration $n(\mathbf{r})$. The total amplitude of the scattered wave in the direction of **k′** is proportional to the integral over the crystal of $n(\mathbf{r})\, dV$ times the phase factor $\exp[i(\mathbf{k} - \mathbf{k}') \cdot \mathbf{r}]$.

In other words, the amplitude of the electric or magnetic field vectors in the scattered electromagnetic wave is proportional to the following integral which defines the quantity F that we call the scattering amplitude:

$$F = \int dV\, n(\mathbf{r}) \exp[i(\mathbf{k} - \mathbf{k}') \cdot \mathbf{r}] = \int dV\, n(\mathbf{r}) \exp(-i\Delta\mathbf{k} \cdot \mathbf{r}) \ , \tag{18}$$

where

$$\mathbf{k} + \Delta\mathbf{k} = \mathbf{k}' \ . \tag{19}$$

Here $\Delta\mathbf{k}$ measures the change in wavevector and is called the scattering vector (Fig. 7). We add $\Delta\mathbf{k}$ to **k** to obtain **k′**, the wavevector of the scattered beam.

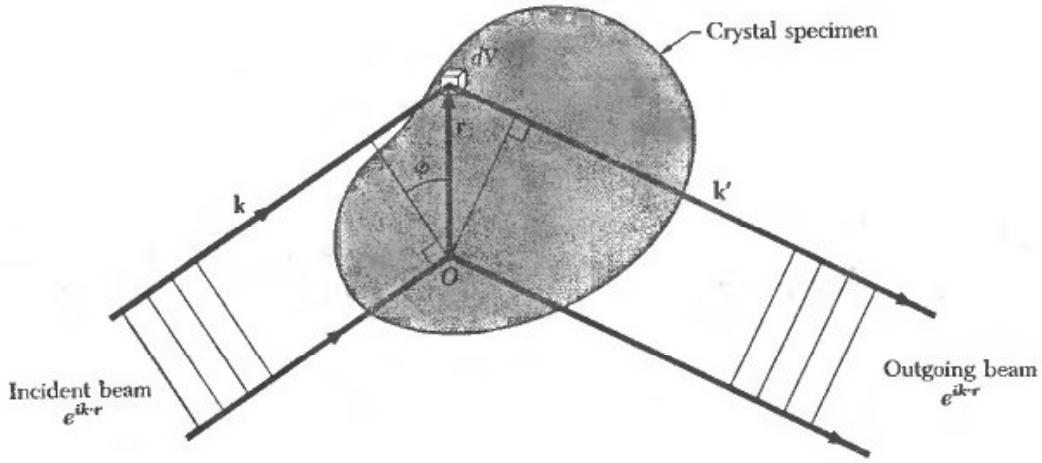

Figure 6 The difference in path length of the incident wave $\mathbf{k}$ at the points O, $\mathbf{r}$ is $r \sin \varphi$, and the difference in phase angle is $(2\pi r \sin \varphi)/\lambda$, which is equal to $\mathbf{k} \cdot \mathbf{r}$. For the diffracted wave the difference in phase angle is $-\mathbf{k}' \cdot \mathbf{r}$. The total difference in phase angle is $(\mathbf{k} - \mathbf{k}') \cdot \mathbf{r}$, and the wave scattered from dV at $\mathbf{r}$ has the phase factor $\exp[i(\mathbf{k} - \mathbf{k}') \cdot \mathbf{r}]$ relative to the wave scattered from a volume element at the origin O.

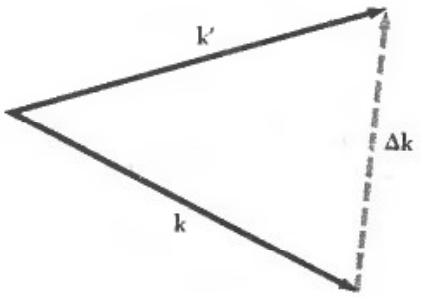

Figure 7 Definition of the scattering vector $\Delta\mathbf{k}$ such that $\mathbf{k} + \Delta\mathbf{k} = \mathbf{k}'$. In elastic scattering the magnitudes satisfy $k' = k$. Further, in Bragg scattering from a periodic lattice any allowed $\Delta\mathbf{k}$ must equal some reciprocal lattice vector $\mathbf{G}$.

We introduce into (18) the Fourier components (9) of $n(\mathbf{r})$ to obtain for the scattering amplitude

$$F = \sum_{\mathbf{G}} \int dV \, n_{\mathbf{G}} \exp[i(\mathbf{G} - \Delta\mathbf{k}) \cdot \mathbf{r}] \ . \tag{20}$$

When the scattering vector $\Delta\mathbf{k}$ is equal to a particular reciprocal lattice vector,

$$\Delta\mathbf{k} = \mathbf{G} \ , \tag{21}$$

the argument of the exponential vanishes and $F = Vn_{\mathbf{G}}$. It is a simple exercise (Problem 4) to show that F is negligibly small when $\Delta\mathbf{k}$ differs significantly from any reciprocal lattice vector.

In elastic scattering of a photon its energy $\hbar\omega$ is conserved, so that the frequency $\omega' = ck'$ of the emergent beam is equal to the frequency of the incident beam. Thus the magnitudes k and k' are equal, and $k^2 = k'^2$, a result that holds also for electron and neutron beams. From (21) we found $\Delta\mathbf{k} = \mathbf{G}$ or

$\mathbf{k} + \mathbf{G} = \mathbf{k}'$, so that the diffraction condition is written as $(\mathbf{k} + \mathbf{G})^2 = k^2$, or

$$2\mathbf{k} \cdot \mathbf{G} + G^2 = 0 \ . \tag{22}$$

This is the central result of the theory of elastic scattering of waves in a periodic lattice. If $\mathbf{G}$ is a reciprocal lattice vector, so is $-\mathbf{G}$, and with this substitution we can write (22) as

$$2\mathbf{k} \cdot \mathbf{G} = G^2 \ . \tag{23}$$

This particular expression is often used as the condition for diffraction.

Equation (23) is another statement of the Bragg condition (1). The result of Problem 1 is that the spacing $d(hkl)$ between parallel lattice planes that are normal to the direction $\mathbf{G} = h\mathbf{b}_1 + k\mathbf{b}_2 + l\mathbf{b}_3$ is $d(hkl) = 2\pi/|\mathbf{G}|$. Thus the result $2\mathbf{k} \cdot \mathbf{G} = G^2$ may be written as

$$2(2\pi/\lambda) \sin \theta = 2\pi/d(hkl) \ ,$$

or $2d(hkl) \sin \theta = \lambda$. Here θ is the angle between the incident beam and the crystal plane.

The integers hkl that define $\mathbf{G}$ are not necessarily identical with the indices of an actual crystal plane, because the hkl may contain a common factor n, whereas in the definition of the indices in Chapter 1 the common factor has been eliminated. We thus obtain the Bragg result:

$$2d \sin \theta = n\lambda \ , \tag{24}$$

where d is the spacing between adjacent parallel planes with indices h/n, k/n, l/n.

Laue Equations

The original result (21) of diffraction theory, namely that $\Delta\mathbf{k} = \mathbf{G}$, may be expressed in another way to give what are called the Laue equations. These are valuable because of their geometrical representation (see Chapter 19).

Take the scalar product of both $\Delta\mathbf{k}$ and $\mathbf{G}$ successively with $\mathbf{a}_1$, $\mathbf{a}_2$, $\mathbf{a}_3$. From (14) and (15) we get

$$\mathbf{a}_1 \cdot \Delta\mathbf{k} = 2\pi v_1 \ ; \qquad \mathbf{a}_2 \cdot \Delta\mathbf{k} = 2\pi v_2 \ ; \qquad \mathbf{a}_3 \cdot \Delta\mathbf{k} = 2\pi v_3 \ . \tag{25}$$

These equations have a simple geometrical interpretation. The first equation $\mathbf{a}_1 \cdot \Delta\mathbf{k} = 2\pi v_1$ tells us that $\Delta\mathbf{k}$ lies on a certain cone about the direction of $\mathbf{a}_1$. The second equation tells us that $\Delta\mathbf{k}$ lies on a cone about $\mathbf{a}_2$ as well, and the third equation requires that $\Delta\mathbf{k}$ lies on a cone about $\mathbf{a}_3$.

Thus, at a reflection $\Delta\mathbf{k}$ must satisfy all three equations; it must lie at the common line of intersection of three cones, which is a severe condition that can be satisfied only by systematic sweeping or searching in wavelength or crystal orientation—or else by sheer accident.

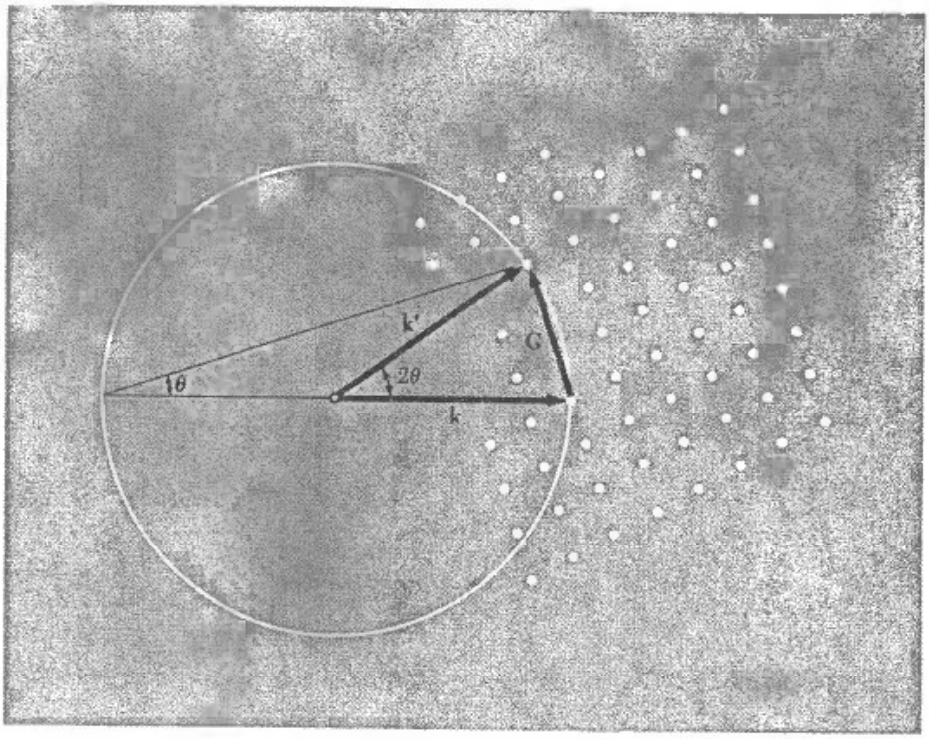

Figure 8 The points on the right-hand side are reciprocal lattice points of the crystal. The vector $\mathbf{k}$ is drawn in the direction of the incident x-ray beam, and the origin is chosen such that $\mathbf{k}$ terminates at any reciprocal lattice point. We draw a sphere of radius $k = 2\pi/\lambda$ about the origin of $\mathbf{k}$. A diffracted beam will be formed if this sphere intersects any other point in the reciprocal lattice. The sphere as drawn intercepts a point connected with the end of $\mathbf{k}$ by a reciprocal lattice vector $\mathbf{G}$. The diffracted x-ray beam is in the direction $\mathbf{k}' = \mathbf{k} + \mathbf{G}$. The angle θ is the Bragg angle of Fig. 2. This construction is due to P. P. Ewald.

A beautiful construction, the Ewald construction, is exhibited in Fig. 8. This helps us visualize the nature of the accident that must occur in order to satisfy the diffraction condition in three dimensions. The condition in two dimensions (diffraction from a surface layer) is treated in Chapter 19.

Reflection from a single plane of atoms takes place in the directions of the lines of intersection of two cones, for example the cones defined by the first two of the Laue equations (25). Now two cones will in general intercept each other provided the wavevector of the particles in the incident beam exceeds some threshold value determined by the first two Laue equations. No accidental coincidence is required, unlike the problem of diffraction in 3D. This matter is of prime importance in the diffraction of low energy electrons from the surface of a crystal.

BRILLOUIN ZONES

Brillouin gave the statement of the diffraction condition that is most widely used in solid state physics, which means in the description of electron energy band theory and of the elementary excitations of other kinds.

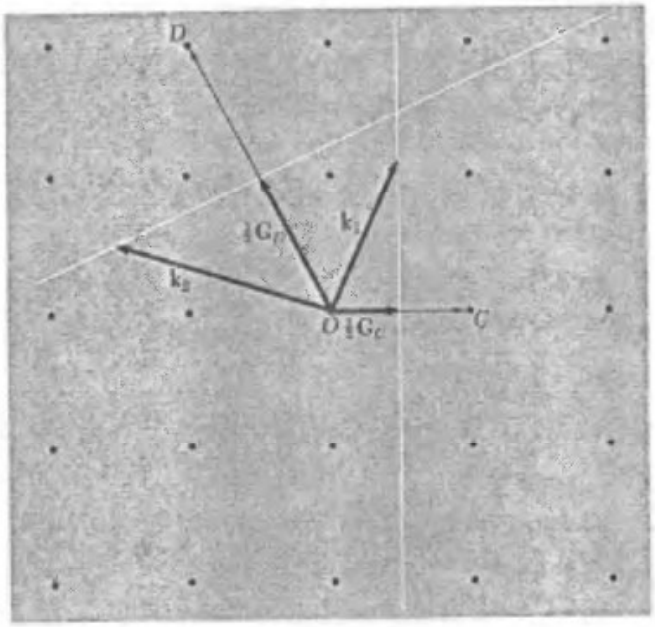

Figure 9a Reciprocal lattice points near the point O at the origin of the reciprocal lattice. The reciprocal lattice vector $\mathbf{G}_C$ connects points OC, and $\mathbf{G}_D$ connects OD. Two planes 1 and 2 are drawn which are the perpendicular bisectors of $\mathbf{G}_C$ and $\mathbf{G}_D$, respectively. Any vector from the origin to the plane 1, such as $\mathbf{k}_1$, will satisfy the diffraction condition $\mathbf{k}_1 \cdot (\frac{1}{2}\mathbf{G}_C) = (\frac{1}{2}\mathbf{G}_C)^2$. Any vector from the origin to the plane 2, such as $\mathbf{k}_2$, will satisfy the diffraction condition $\mathbf{k}_2 \cdot (\frac{1}{2}\mathbf{G}_D) = (\frac{1}{2}\mathbf{G}_D)^2$.

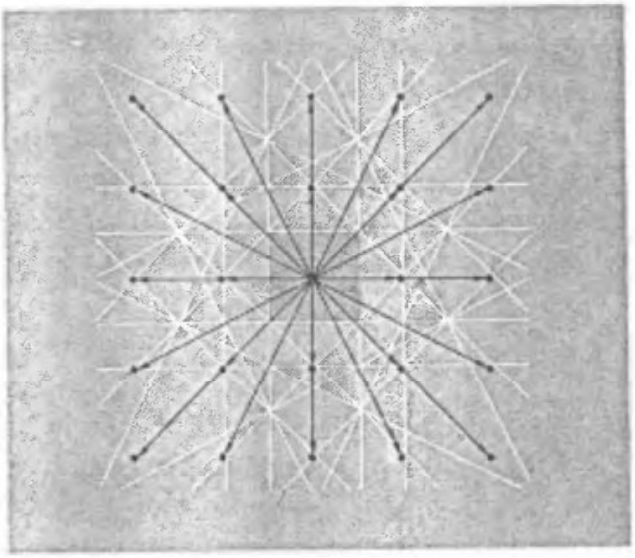

Figure 9b Square reciprocal lattice with reciprocal lattice vectors shown as fine black lines. The lines shown in white are perpendicular bisectors of the reciprocal lattice vectors. The central square is the smallest volume about the origin which is bounded entirely by white lines. The square is the Wigner-Seitz primitive cell of the reciprocal lattice. It is called the first Brillouin zone.

A Brillouin zone is defined as a Wigner-Seitz primitive cell in the reciprocal lattice. (The construction in the direct lattice was shown in Fig. 1.6.) The value of the Brillouin zone is that it gives a vivid geometrical interpretation of the diffraction condition $2\mathbf{k} \cdot \mathbf{G} = G^2$ of Eq. (23). We divide both sides by 4 to obtain

$$\mathbf{k} \cdot (\tfrac{1}{2}\mathbf{G}) = (\tfrac{1}{2}G)^2 \ . \tag{26}$$

We work in reciprocal space, the space of the $\mathbf{k}$'s and $\mathbf{G}$'s. Select a vector $\mathbf{G}$ from the origin to a reciprocal lattice point. Construct a plane normal to this vector $\mathbf{G}$ at its midpoint. This plane forms a part of the zone boundary (Fig. 9a). An x-ray beam in the crystal will be diffracted if its wavevector $\mathbf{k}$ has the magnitude and direction required by (26). The diffracted beam will then be in the direction $\mathbf{k} - \mathbf{G}$, as we see from (19) with $\Delta\mathbf{k} = -\mathbf{G}$. Thus the Brillouin construction exhibits all the wavevectors $\mathbf{k}$ which can be Bragg-reflected by the crystal.

The set of planes that are the perpendicular bisectors of the reciprocal lattice vectors is of general importance in the theory of wave propagation in crystals. A wave whose wavevector drawn from the origin terminates on any of these planes will satisfy the condition for diffraction.

These planes divide the Fourier space of the crystal into fragments, as shown in Fig. 9b for a square lattice. The central square is a primitive cell of the reciprocal lattice. It is a Wigner-Seitz cell of the [illegible]procal lattice.

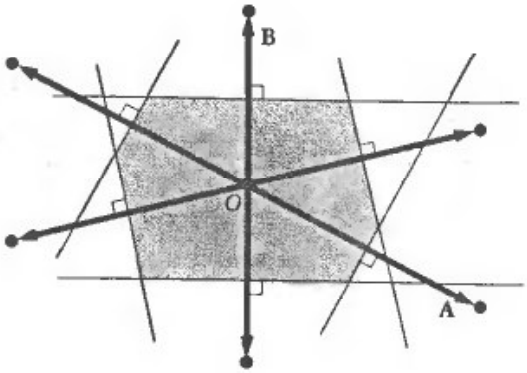

Figure 10 Construction of the first Brillouin zone for an oblique lattice in two dimensions. We first draw a number of vectors from O to nearby points in the reciprocal lattice. Next we construct lines perpendicular to these vectors at their midpoints. The smallest enclosed area is the first Brillouin zone.

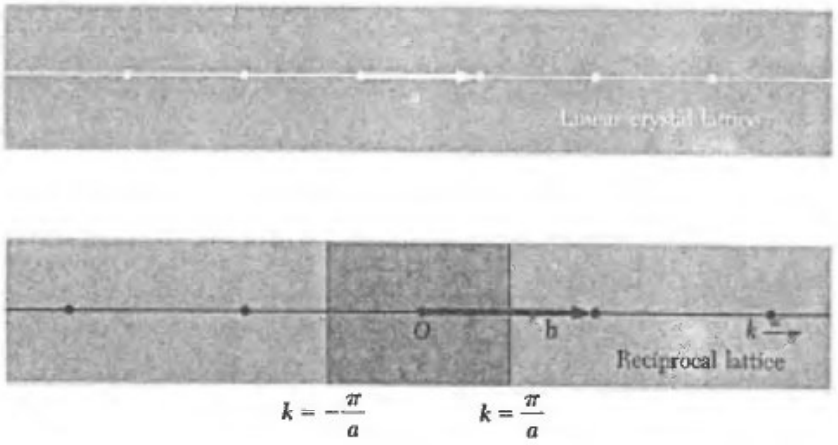

Figure 11 Crystal and reciprocal lattices in one dimension. The basis vector in the reciprocal lattice is b, of length equal to $2\pi/a$. The shortest reciprocal lattice vectors from the origin are b and $-$b. The perpendicular bisectors of these vectors form the boundaries of the first Brillouin zone. The boundaries are at $k = \pm\pi/a$.

The central cell in the reciprocal lattice is of special importance in the theory of solids, and we call it the first Brillouin zone. The first Brillouin zone is the smallest volume entirely enclosed by planes that are the perpendicular bisectors of the reciprocal lattice vectors drawn from the origin.

The first Brillouin zone of an oblique lattice in two dimensions is constructed in Fig. 10 and of a linear lattice in one dimension in Fig. 11. The zone boundaries of the linear lattice are at $k = \pm\pi/a$, where a is the primitive axis of the crystal lattice.

Historically, Brillouin zones are not part of the language of x-ray diffraction analysis of crystal structures, but the zones are an essential part of the analysis of the electronic energy-band structure of crystals. The special utility of the first Brillouin zone is developed in Chapter 9.

Reciprocal Lattice to sc Lattice

The primitive translation vectors of a simple cubic lattice may be taken as the set

$$\mathbf{a}_1 = a\hat{\mathbf{x}} \; ; \qquad \mathbf{a}_2 = a\hat{\mathbf{y}} \; ; \qquad \mathbf{a}_3 = a\hat{\mathbf{z}} \; . \tag{27a}$$

Here $\hat{\mathbf{x}}$, $\hat{\mathbf{y}}$, $\hat{\mathbf{z}}$ are orthogonal vectors of unit length. The volume of the cell is $\mathbf{a}_1 \cdot \mathbf{a}_2 \times \mathbf{a}_3 = a^3$. The primitive translation vectors of the reciprocal lattice are found from the standard prescription (13):

$$\mathbf{b}_1 = (2\pi/a)\hat{\mathbf{x}} \; ; \qquad \mathbf{b}_2 = (2\pi/a)\hat{\mathbf{y}} \; ; \qquad \mathbf{b}_3 = (2\pi/a)\hat{\mathbf{z}} \; . \tag{27b}$$

Here the reciprocal lattice is itself a simple cubic lattice, now of lattice constant $2\pi/a$.

The boundaries of the first Brillouin zones are the planes normal to the six reciprocal lattice vectors $\pm\mathbf{b}_1$, $\pm\mathbf{b}_2$, $\pm\mathbf{b}_3$ at their midpoints:

$$\pm\tfrac{1}{2}\mathbf{b}_1 = \pm(\pi/a)\hat{\mathbf{x}} \; ; \qquad \pm\tfrac{1}{2}\mathbf{b}_2 = \pm(\pi/a)\hat{\mathbf{y}} \; ; \qquad \pm\tfrac{1}{2}\mathbf{b}_3 = \pm(\pi/a)\hat{\mathbf{z}} \; .$$

The six planes bound a cube of edge $2\pi/a$ and of volume $(2\pi/a)^3$; this cube is the first Brillouin zone of the sc crystal lattice.

Reciprocal Lattice to bcc Lattice

The primitive translation vectors of the bcc lattice (Fig. 12) are

$$\mathbf{a}_1 = \tfrac{1}{2}a(-\hat{\mathbf{x}} + \hat{\mathbf{y}} + \hat{\mathbf{z}}) \; ; \qquad \mathbf{a}_2 = \tfrac{1}{2}a(\hat{\mathbf{x}} - \hat{\mathbf{y}} + \hat{\mathbf{z}}) \; ; \qquad \mathbf{a}_3 = \tfrac{1}{2}a(\hat{\mathbf{x}} + \hat{\mathbf{y}} - \hat{\mathbf{z}}) \; , \tag{28}$$

where a is the side of the conventional cube and $\hat{\mathbf{x}}$, $\hat{\mathbf{y}}$, $\hat{\mathbf{z}}$ are orthogonal unit vectors parallel to the cube edges. The volume of the primitive cell is

$$V = |\mathbf{a}_1 \cdot \mathbf{a}_2 \times \mathbf{a}_3| = \tfrac{1}{2}a^3 \; . \tag{29}$$

The primitive translations of the reciprocal lattice are defined by (13). We have, using (28),

$$\mathbf{b}_1 = (2\pi/a)(\hat{\mathbf{y}} + \hat{\mathbf{z}}) \; ; \qquad \mathbf{b}_2 = (2\pi/a)(\hat{\mathbf{x}} + \hat{\mathbf{z}}) \; ; \qquad \mathbf{b}_3 = (2\pi/a)(\hat{\mathbf{x}} + \hat{\mathbf{y}}) \; . \tag{30}$$

Note by comparison with Fig. 14 (p. 42) that these are just the primitive vectors of an fcc lattice, so that an fcc lattice is the reciprocal lattice of the bcc lattice.

The general reciprocal lattice vector is, for integral v_1, v_2, v_3,

$$\mathbf{G} = v_1\mathbf{b}_1 + v_2\mathbf{b}_2 + v_3\mathbf{b}_3 = (2\pi/\mathrm{a})[(v_2 + v_3)\hat{\mathbf{x}} + (v_1 + v_3)\hat{\mathbf{y}} + (v_1 + v_2)\hat{\mathbf{z}}] \; . \tag{31}$$

The shortest $\mathbf{G}$'s are the following 12 vectors, where all choices of sign are independent:

$$(2\pi/a)(\pm\hat{\mathbf{y}} \pm \hat{\mathbf{z}}) \; ; \qquad (2\pi/a)(\pm\hat{\mathbf{x}} \pm \hat{\mathbf{z}}) \; ; \qquad (2\pi/a)(\pm\hat{\mathbf{x}} \pm \hat{\mathbf{y}}) \; . \tag{32}$$

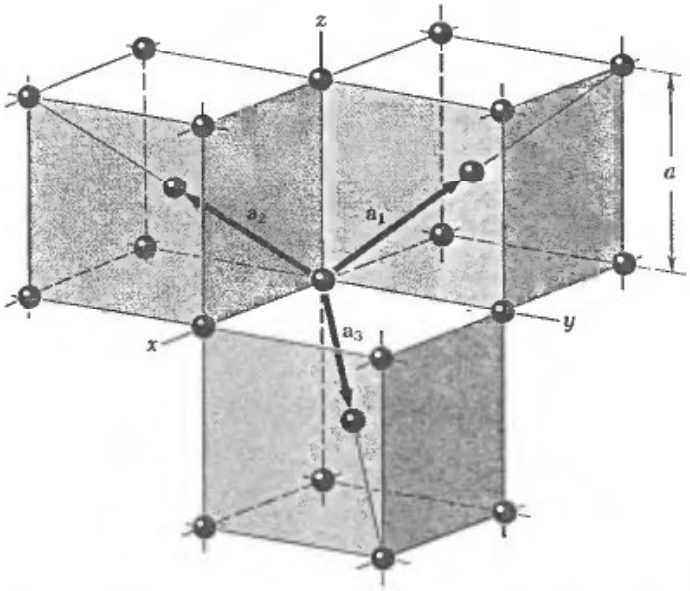

Figure 12 Primitive basis vectors of the body-centered cubic lattice.

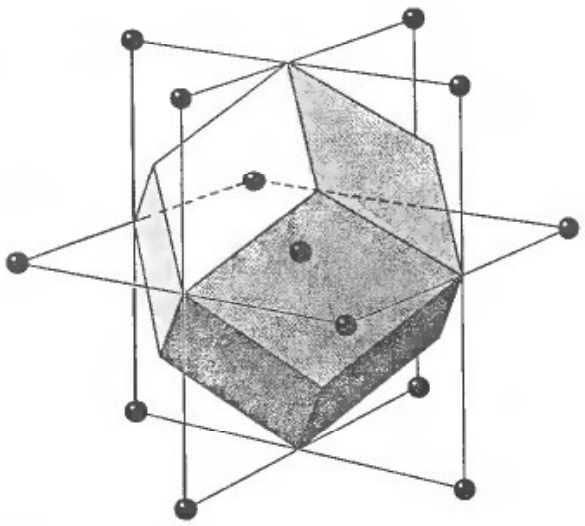

Figure 13 First Brillouin zone of the body-centered cubic lattice. The figure is a regular rhombic dodecahedron.

The primitive cell of the reciprocal lattice is the parallelepiped described by the $\mathbf{b}_1$, $\mathbf{b}_2$, $\mathbf{b}_3$ defined by (30). The volume of this cell in reciprocal space is $\mathbf{b}_1 \cdot \mathbf{b}_2 \times \mathbf{b}_3 = 2(2\pi/a)^3$. The cell contains one reciprocal lattice point, because each of the eight corner points is shared among eight parallelepipeds. Each parallelepiped contains one-eighth of each of eight corner points.

In solid state physics we take the central (Wigner-Seitz) cell of the reciprocal lattice as the first Brillouin zone. Each such cell contains one lattice point at the central point of the cell. This zone (for the bcc lattice) is bounded by the planes normal to the 12 vectors of Eq. (32) at their midpoints. The zone is a regular 12-faced solid, a rhombic dodecahedron, as shown in Fig. 13. The vectors from the origin to the center of each face are

$$(\pi/a)(\pm\hat{\mathbf{y}} \pm \hat{\mathbf{z}}) \; ; \qquad (\pi/a)(\pm\hat{\mathbf{x}} \pm \hat{\mathbf{z}}) \; ; \qquad (\pi/a)(\pm\hat{\mathbf{x}} \pm \hat{\mathbf{y}}) \; . \tag{33}$$

All choices of sign are independent, giving 12 vectors.

Reciprocal Lattice to fcc Lattice

The primitive translation vectors of the fcc lattice of Fig. 14 are

$$\mathbf{a}_1 = \frac{1}{2}a(\hat{\mathbf{y}} + \hat{\mathbf{z}}); \quad \mathbf{a}_2 = \frac{1}{2}a(\hat{\mathbf{x}} + \hat{\mathbf{z}}) \; ; \quad \mathbf{a}_3 = \frac{1}{2}a(\hat{\mathbf{x}} + \hat{\mathbf{y}}) \; . \tag{34}$$

The volume of the primitive cell is

$$V = |\mathbf{a}_1 \cdot \mathbf{a}_2 \times \mathbf{a}_3| = \frac{1}{4}a^3 \tag{35}$$

The primitive translation vectors of the lattice reciprocal to the fcc lattice are

$$\mathbf{b}_1 = (2\pi/a)(-\hat{\mathbf{x}} + \hat{\mathbf{y}} + \hat{\mathbf{z}}) \; ; \qquad \mathbf{b}_2 = (2\pi/a)(\hat{\mathbf{x}} - \hat{\mathbf{y}} + \hat{\mathbf{z}}) \; ;$$
$$\mathbf{b}_3 = (2\pi/a)(\hat{\mathbf{x}} + \hat{\mathbf{y}} - \hat{\mathbf{z}}) \; . \tag{36}$$

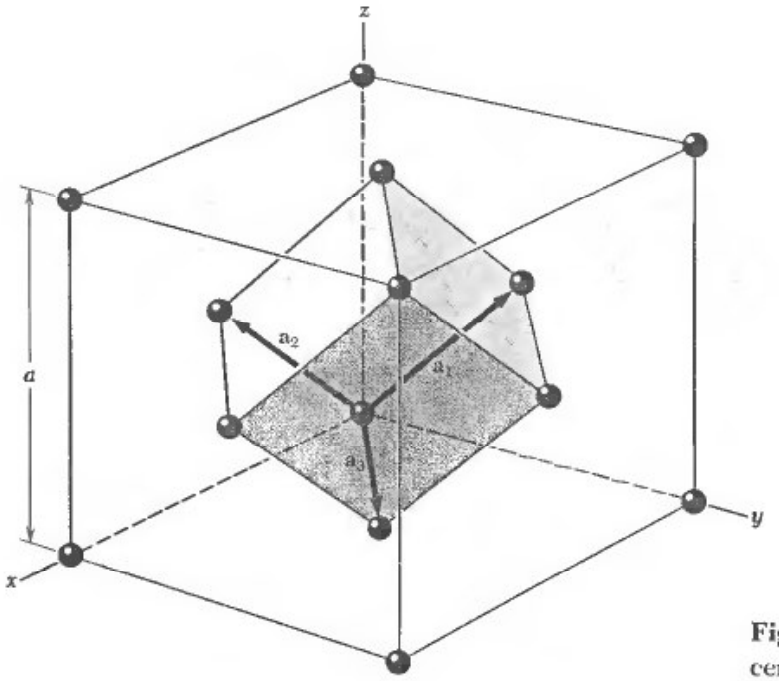

Figure 14 Primitive basis vectors of the face-centered cubic lattice.

These are primitive translation vectors of a bcc lattice, so that the bcc lattice is reciprocal to the fcc lattice. The volume of the primitive cell of the reciprocal lattice is $4(2\pi/a)^3$.

The shortest **G**'s are the eight vectors:

$$(2\pi/a)(\pm\hat{\mathbf{x}} \pm \hat{\mathbf{y}} \pm \hat{\mathbf{z}}) \ . \tag{37}$$

The boundaries of the central cell in the reciprocal lattice are determined for the most part by the eight planes normal to these vectors at their midpoints. But the corners of the octahedron thus formed are cut by the planes that are the perpendicular bisectors of six other reciprocal lattice vectors:

$$(2\pi/a)(\pm 2\hat{\mathbf{x}}) \ ; \qquad (2\pi/a)(\pm 2\hat{\mathbf{y}}) \ ; \qquad (2\pi/a)(\pm 2\hat{\mathbf{z}}) \ . \tag{38}$$

Note that $(2\pi/a)(2\hat{\mathbf{x}})$ is a reciprocal lattice vector because it is equal to $\mathbf{b}_2 + \mathbf{b}_3$. The first Brillouin zone is the smallest bounded volume about the origin, the truncated octahedron shown in Fig. 15. The six planes bound a cube of edge $4\pi/a$ and (before truncation) of volume $(4\pi/a)^3$.

FOURIER ANALYSIS OF THE BASIS

When the diffraction condition $\Delta\mathbf{k} = \mathbf{G}$ of Eq. (21) is satisfied, the scattering amplitude is determined by (18), which for a crystal of N cells may be written as

$$F_{\mathbf{G}} = N\int_{cell} dV \, n(\mathbf{r}) \exp(-i\mathbf{G}\cdot\mathbf{r}) = NS_{\mathbf{G}} \tag{39}$$

The quantity $S_{\mathbf{G}}$ is called the **structure factor** and is defined as an integral over a single cell, with $\mathbf{r} = 0$ at one corner.

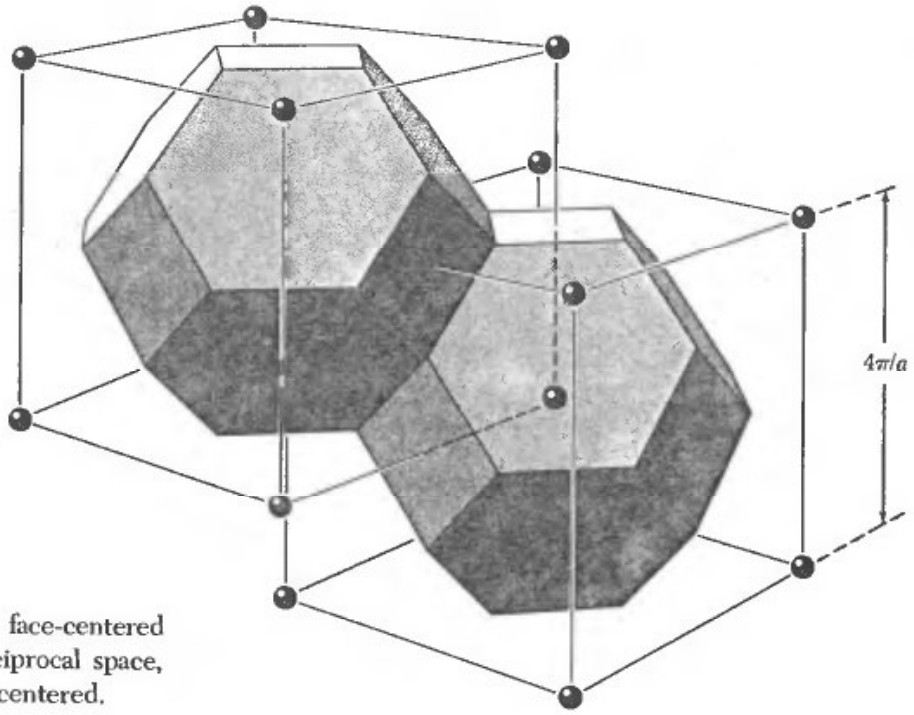

Figure 15 Brillouin zones of the face-centered cubic lattice. The cells are in reciprocal space, and the reciprocal lattice is body centered.

Often it is useful to write the electron concentration $n(\mathbf{r})$ as the superposition of electron concentration functions n_j associated with each atom j of the cell. If $\mathbf{r}_j$ is the vector to the center of atom j, then the function $n_j(\mathbf{r} - \mathbf{r}_j)$ defines the contribution of that atom to the electron concentration at $\mathbf{r}$. The total electron concentration at $\mathbf{r}$ due to all atoms in the cell is the sum

$$n(\mathbf{r}) = \sum_{j=1}^{s} n_j(\mathbf{r} - \mathbf{r}_j) \tag{40}$$

over the s atoms of the basis. The decomposition of $n(\mathbf{r})$ is not unique, for we cannot always say how much charge is associated with each atom. This is not an important difficulty.

The structure factor defined by (39) may now be written as integrals over the s atoms of a cell:

$$S_{\mathbf{G}} = \sum_j \int dV\, n_j(\mathbf{r} - \mathbf{r}_j) \exp(-i\mathbf{G}\cdot\mathbf{r}) = \sum_j \exp(-i\mathbf{G}\cdot\mathbf{r}_j) \int dV\, n_j(\boldsymbol{\rho}) \exp(-i\mathbf{G}\cdot\boldsymbol{\rho}) \ , \tag{41}$$

where $\boldsymbol{\rho} \equiv \mathbf{r} - \mathbf{r}_j$.

We now define the atomic form factor as

$$f_j = \int dV\, n_j(\boldsymbol{\rho}) \exp(-i\mathbf{G}\cdot\boldsymbol{\rho}), \tag{42}$$

integrated over all space. If $n_j(\boldsymbol{\rho})$ is an atomic property, f_j is an atomic property.

We combine (41) and (42) to obtain the structure factor of the basis in the form

$$S_G = \sum_j f_j \exp(-i\mathbf{G}\cdot\mathbf{r}_j) \ . \tag{43}$$

The usual form of this result follows on writing for atom j:

$$\mathbf{r}_j = x_j\mathbf{a}_1 + y_j\mathbf{a}_2 + z_j\mathbf{a}_3 \ , \tag{44}$$

as in (1.4). Then, for the reflection labelled by v_1, v_2, v_3 we have

$$\begin{aligned} \mathbf{G}\cdot\mathbf{r}_j &= (v_1\mathbf{b}_1 + v_2\mathbf{b}_2 + v_3\mathbf{b}_3)\cdot(x_j\mathbf{a}_1 + y_j\mathbf{a}_2 + z_j\mathbf{a}_3) \\ &= 2\pi(v_1x_j + v_2y_j + v_3z_j) \ , \end{aligned} \tag{45}$$

so that (43) becomes

$$S_G(v_1v_2v_3) = \sum_j f_j \exp[-i2\pi(v_1x_j + v_2y_j + v_3z_j)] \ . \tag{46}$$

The structure factor S need not be real because the scattered intensity will involve S*S, where S* is the complex conjugate of S so that S*S is real.

At a zero of S_G the scattered intensity will be zero, even though G is a perfectly good reciprocal lattice vector. What happens if we choose the cell in another way, as a conventional cell instead of a primitive cell, for example? The basis is changed, but in such a way that the physical scattering is unchanged. Thus for two choices, 1 and 2, it is not hard to satisfy yourself from (39) that

$$N_1(\text{cell}) \times S_1(\text{basis}) = N_2(\text{cell}) \times S_2(\text{basis}) \ .$$

Structure Factor of the bcc Lattice

The bcc basis referred to the cubic cell has identical atoms at $x_1 = y_1 = z_1 = 0$ and at $x_2 = y_2 = z_2 = \frac{1}{2}$. Thus (46) becomes

$$S(v_1v_2v_3) = f\{1 + \exp[-i\pi(v_1 + v_2 + v_3)]\} \ , \tag{47}$$

where f is the form factor of an atom. The value of S is zero whenever the exponential has the value -1, which is whenever the argument is $-i\pi \times$ (odd integer). Thus we have

$$\begin{aligned} S &= 0 \quad \text{when } v_1 + v_2 + v_3 = \text{odd integer} \ ; \\ S &= 2f \quad \text{when } v_1 + v_2 + v_3 = \text{even integer} \ . \end{aligned}$$

Metallic sodium has a bcc structure. The diffraction pattern does not contain lines such as (100), (300), (111), or (221), but lines such as (200), (110), and (222) will be present; here the indices $(v_1v_2v_3)$ are referred to a cubic cell. What is the physical interpretation of the result that the (100) reflection vanishes?

The (100) reflection normally occurs when reflections from the planes that bound the cubic cell differ in phase by 2π. In the bcc lattice there is an intervening plane (Fig. 16) of atoms, labeled the second plane in the figure, which is

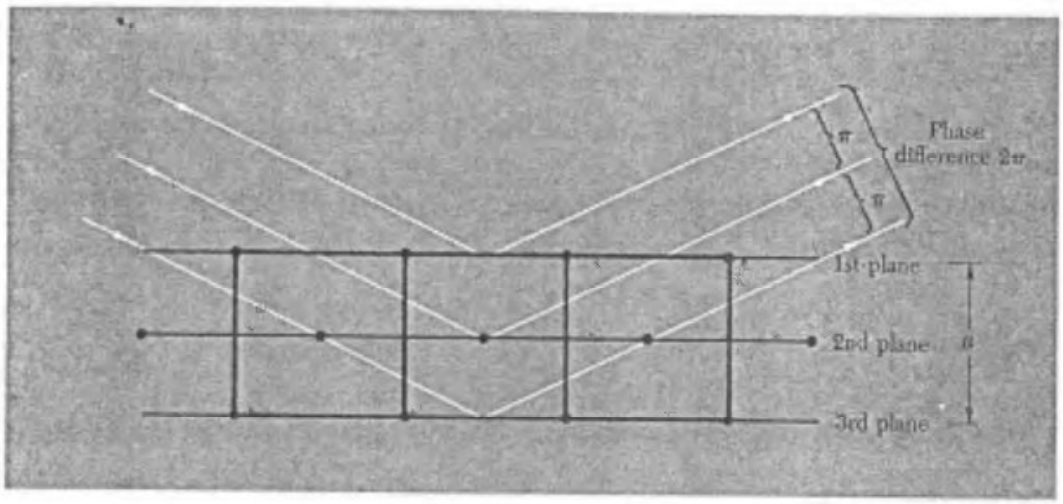

Figure 16 Explanation of the absence of a (100) reflection from a body-centered cubic lattice. The phase difference between successive planes is π, so that the reflected amplitude from two adjacent planes is $1 + e^{-i\pi} = 1 - 1 = 0$.

equal in scattering power to the other planes. Situated midway between them, it gives a reflection retarded in phase by π with respect to the first plane, thereby canceling the contribution from that plane. The cancellation of the (100) reflection occurs in the bcc lattice because the planes are identical in composition. A similar cancellation can easily be found in the hcp structure.

Structure Factor of the fcc Lattice

The basis of the fcc structure referred to the cubic cell has identical atoms at 000; $0\frac{1}{2}\frac{1}{2}$; $\frac{1}{2}0\frac{1}{2}$; $\frac{1}{2}\frac{1}{2}0$. Thus (46) becomes

$$S(\upsilon_1\upsilon_2\upsilon_3) = f\{1 + \exp[-i\pi(\upsilon_2 + \upsilon_3)] + \exp[-i\pi(\upsilon_1 + \upsilon_3)] + \exp[-i\pi(\upsilon_1 + \upsilon_2)]\} . \quad (48)$$

If all indices are even integers, $S = 4f$; similarly if all indices are odd integers. But if only one of the integers is even, two of the exponents will be odd multiples of $-i\pi$ and S will vanish. If only one of the integers is odd, the same argument applies and S will also vanish.

Thus in the fcc lattice no reflections can occur for which the indices are partly even and partly odd. The point is beautifully illustrated by Fig. 17: both KCl and KBr have an fcc lattice, but KCl simulates an sc lattice because the K^+ and Cl^- ions have equal numbers of electrons.

Atomic Form Factor

In the expression (46) for the structure factor, there occurs the quantity f_j, which is a measure of the scattering power of the jth atom in the unit cell. The value of f involves the number and distribution of atomic electrons, and the wavelength and angle of scattering of the radiation. We now give a classical calculation of the scattering factor.

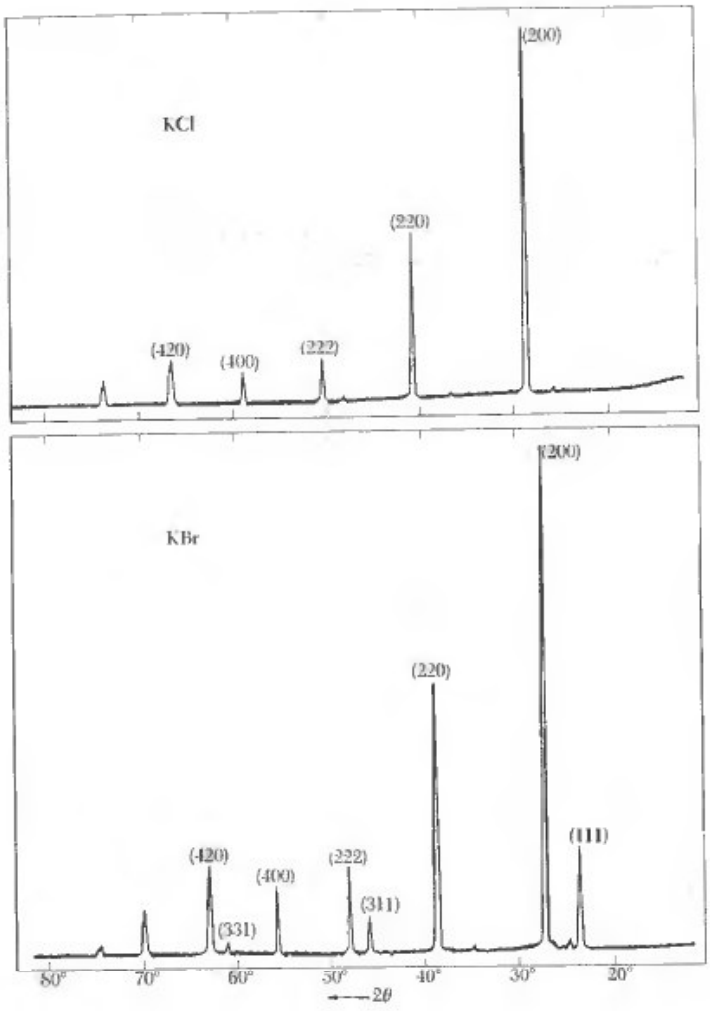

Figure 17 Comparison of x-ray reflections from KCl and KBr powders. In KCl the numbers of electrons of K^+ and Cl^- ions are equal. The scattering amplitudes $f(K^+)$ and $f(Cl^-)$ are almost exactly equal, so that the crystal looks to x-rays as if it were a monatomic simple cubic lattice of lattice constant $a/2$. Only even integers occur in the reflection indices when these are based on a cubic lattice of lattice constant a. In KBr the form factor of Br^- is quite different than that of K^+, and all reflections of the fcc lattice are present. (Courtesy of R. van Nordstrand.)

The scattered radiation from a single atom takes account of interference effects within the atom. We defined the form factor in (42):

$$f_j = \int dV\, n_j(\mathbf{r}) \exp(-i\mathbf{G}\cdot\mathbf{r}) \,, \tag{49}$$

with the integral extended over the electron concentration associated with a single atom. Let $\mathbf{r}$ make an angle α with $\mathbf{G}$; then $\mathbf{G}\cdot\mathbf{r} = Gr\cos\alpha$. If the electron distribution is spherically symmetric about the origin, then

$$\begin{aligned} f_j &\equiv 2\pi \int dr\, r^2\, d(\cos\alpha)\, n_j(r) \exp(-iGr\cos\alpha) \\ &= 2\pi \int dr\, r^2 n_j(r) \cdot \frac{e^{iGr} - e^{-iGr}}{iGr} \,, \end{aligned}$$

after integration over $d(\cos\alpha)$ between -1 and 1. Thus the form factor is given by

$$f_j = 4\pi \int dr\, n_j(r) r^2 \frac{\sin Gr}{Gr} \,. \tag{50}$$

If the same total electron density were concentrated at $r = 0$, only $Gr = 0$ would contribute to the integrand. In this limit $(\sin Gr)/Gr = 1$, and

$$f_j = 4\pi \int dr\, n_j(r) r^2 = Z \,, \tag{51}$$

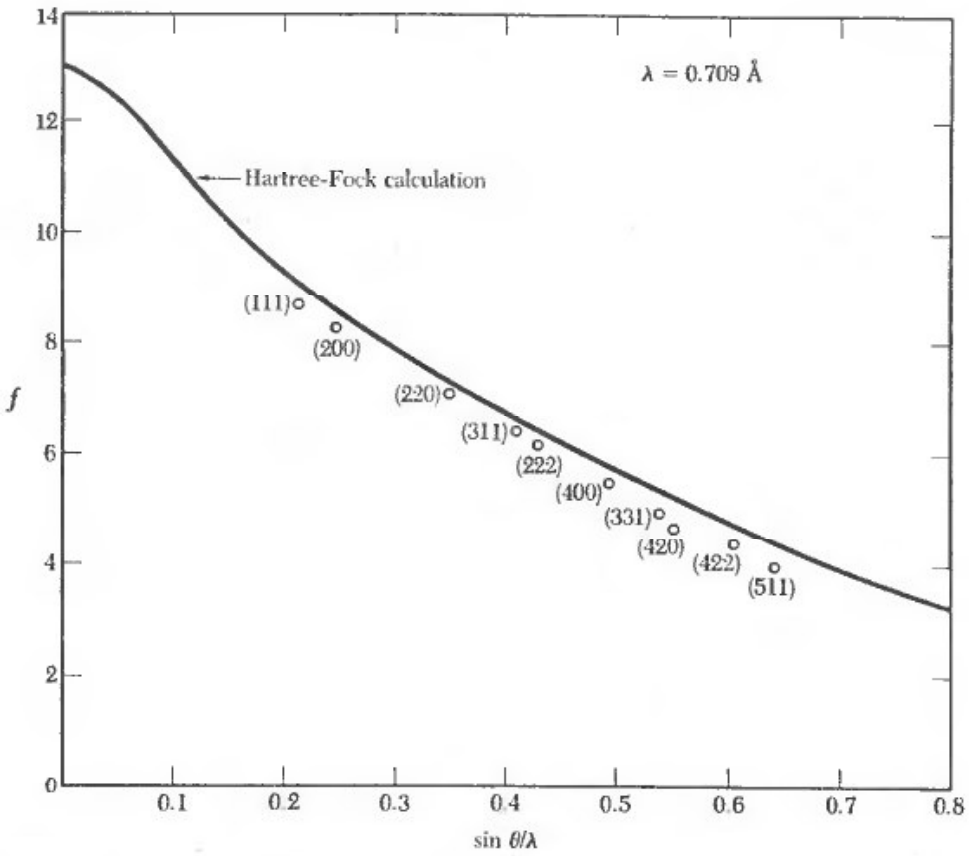

Figure 18 Absolute experimental atomic scattering factors for metallic aluminum, after Batterman, Chipman, and DeMarco. Each observed reflection is labeled. No reflections occur for indices partly even and partly odd, as predicted for an fcc crystal.

the number of atomic electrons. Therefore f is the ratio of the radiation amplitude scattered by the actual electron distribution in an atom to that scattered by one electron localized at a point.

In the forward direction $G = 0$, and f reduces again to the value Z. Values of the atomic form factor f for atoms may be found in the *International tables for x-ray crystallography*, Vol. 3.

The overall electron distribution in a solid as seen in x-ray diffraction is fairly close to that of the appropriate free atoms. This statement does not mean that the outermost or valence electrons are not redistributed in forming the solid; it means only that the x-ray reflection intensities are represented well by the free atom values of the form factors and are not very sensitive to small redistributions of the electrons.

As an example, Batterman and co-workers find agreement within 1 percent in a comparison of the x-ray intensities of Bragg reflections of metallic iron, copper, and aluminum with the theoretical free atom values from wavefunction calculations. The results for aluminum are shown in Fig. 18.

There have been many attempts to obtain direct x-ray evidence about the actual electron distribution in a covalent chemical bond, particularly in crystals having the diamond structure. The question now lies within the limits of what can be explored by(ıy diffraction methods. In silicon at a point midway

between two nearest-neighbor atoms, there is an appreciable increase in electron concentration over what is expected from the overlap of the electron densities calculated for two free atoms.

Scattering from crystal surfaces is treated in Chapter 19. It is shown in Appendix A that thermal motion does not broaden a diffraction line, but only reduces the intensity. The lost intensity reappears as long, low wings about the position of the diffraction line.

QUASICRYSTALS

In 1984 quasicrystals were first observed;[1] these are structures which cannot be indexed to any Bravais lattice and "which have symmetries intermediate between a crystal and a liquid." They were first observed in grains of size 2 μm in an alloy of Al with 14 at pct Mn. The smaller Mn atoms are each surrounded by 12 Al atoms arranged at the corners of an icosahedron. The structure is made up of parallel icosahedra attached at their edges. Crystals cannot exhibit the fivefold symmetry of an icosahedron, but a crystal can be constructed by nucleation at a center cell, followed by outward growth from there. All of the space of a nodule cannot be filled by repeating the basic unit (see Figures 19 and 1.7 for the picture in two dimensions), although the "parallel" part of the specification does give a long-range orientational order to the structure. It is perhaps surprising that the x-ray diffraction pattern of such a structure can have fivefold symmetry; that is how they were first observed.

The known quasicrystals are intermetallic alloys and are very poor electrical conductors; they are nearly insulators with a somewhat well-defined band gap (Chapter 7) at the Fermi level. They are of great interest intellectually in expanding the definition of crystal lattice.

A distinctly different crystal diffraction pattern results from an almost periodic structure, one that is neither rigorously periodic nor simply amorphous (as for a glass, Chapter 17). An almost periodic structure can be expressed in one dimension if we are given the electron charge density wave:

$$\rho(x) = \Sigma[C_n \cos[2\pi n(1 + \tau)x/a] \ , \qquad (52)$$

where τ is an irrational fraction. The terms in $2\pi n/a$ by themselves give the usual lattice with translational periodicity a. When the terms in τ are added, the charge density is almost periodic; that is, the period $(1 + \tau)a$ is not an integral multiple of the period a, because τ is irrational. The period gives a long-range nonrandom order to the structure, and the long-range order gives a diffraction pattern, which appears split off from the pattern defined by the short-range order. This is dominated by the reciprocal lattice points in n_1, but

[1]D. Levine and P. J. Steinhardt, Phys. Rev. Lett. 53, 2477 (1984); Phys. Rev. B34, 596 (1986); D. S. Schechtman and others, Phys. Rev. Lett. 53, 1951 (1984).

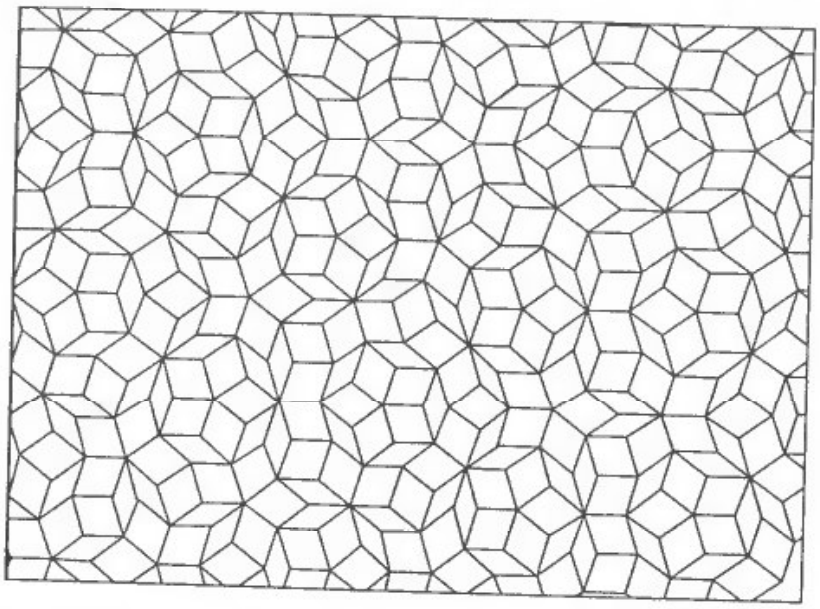

Figure 19 A quasicrystal tiling in two dimensions, after the work of Penrose. The long-range orientational order and the long-range nonperiodic order are shown.

will appear to be clustered and spread out (broadened). The diffraction pattern of a three-dimensional quasicrystal is quite different, however; the pattern is well defined and can have the fivefold symmetry by which quasicrystals were first discovered. A computer-generated diffraction pattern with fivefold symmetry is shown in Figure 20.

SUMMARY

- Various statements of the Bragg condition:

$$2d \sin\theta = n\lambda \; ; \qquad \Delta\mathbf{k} = \mathbf{G}. \; ; \qquad 2\mathbf{k}\cdot\mathbf{G} = \mathbf{G}^2 \; .$$

- Laue conditions:

$$\mathbf{a}_1\cdot\Delta\mathbf{k} = 2\pi v_1 \; ; \qquad \mathbf{a}_2\cdot\Delta\mathbf{k} = 2\pi v_2 \; ; \qquad \mathbf{a}_3\cdot\Delta\mathbf{k} = 2\pi v_3 \; .$$

- The primitive translation vectors of the reciprocal lattice are

$$\mathbf{b}_1 = 2\pi\frac{\mathbf{a}_2\times\mathbf{a}_3}{\mathbf{a}_1\cdot\mathbf{a}_2\times\mathbf{a}_3} \; ; \qquad \mathbf{b}_2 = 2\pi\frac{\mathbf{a}_3\times\mathbf{a}_1}{\mathbf{a}_1\cdot\mathbf{a}_2\times\mathbf{a}_3} \; ; \qquad \mathbf{b}_3 = 2\pi\frac{\mathbf{a}_1\times\mathbf{a}_2}{\mathbf{a}_1\cdot\mathbf{a}_2\times\mathbf{a}_3} \; .$$

  Here $\mathbf{a}_1$, $\mathbf{a}_2$, $\mathbf{a}_3$ are the primitive translation vectors of the crystal lattice.

- A reciprocal lattice vector has the form

$$\mathbf{G} = v_1\mathbf{b}_1 + v_2\mathbf{b}_2 + v_3\mathbf{b}_3 \; ,$$

  where v_1, v_2, v_3 are integers or zero.

- The scattered amplitude in the direction $\mathbf{k}' = \mathbf{k} + \Delta\mathbf{k} = \mathbf{k} + \mathbf{G}$ is proportional to the geometrical structure factor:

$$S_{\mathbf{G}} \equiv \Sigma f_j \exp(-i\mathbf{r}_j \cdot \mathbf{G}) = \Sigma f_j \exp[-i2\pi(x_j v_1 + y_j v_2 + z_j v_3)] \ ,$$

where j runs over the s atoms of the basis, and f_j is the atomic form factor (49) of the jth atom of the basis. The expression on the right-hand side is written for a reflection $(v_1 v_2 v_3)$, for which $\mathbf{G} = v_1\mathbf{b}_1 + v_2\mathbf{b}_2 + v_3\mathbf{b}_3$.

- Any function invariant under a lattice translation $\mathbf{T}$ may be expanded in a Fourier series of the form

$$n(\mathbf{r}) = \sum_{\mathbf{G}} n_{\mathbf{G}} \exp(i\mathbf{G} \cdot \mathbf{r}) \ .$$

- The first Brillouin zone is the Wigner-Seitz primitive cell of the reciprocal lattice. Only waves whose wavevector k drawn from the origin terminates on a surface of the Brillouin zone can be diffracted by the crystal.

• *Crystal lattice*	*First Brillouin zone*
Simple cubic	Cube
Body-centered cubic	Rhombic dodecahedron (Fig. 13)
Face-centered cubic	Truncated octahedron (Fig. 15)

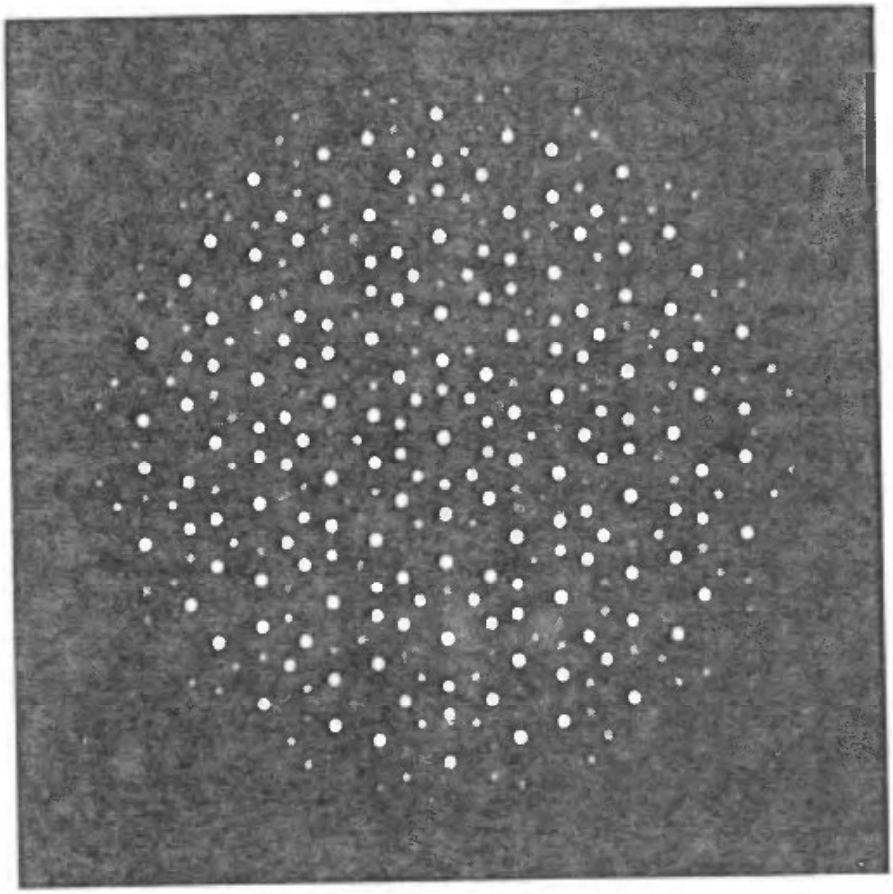

Figure 20 Photograph of the calculated Fourier transform (diffraction pattern) of an icosahedral quasicrystal along one of the fivefold axes, illustrating the fivefold symmetry. The transform is calculated from a theoretical computer-generated model, by(hael Jacob.

Problems

1. ***Interplanar separation.*** Consider a plane hkl in a crystal lattice. (a) Prove that the reciprocal lattice vector $\mathbf{G} = h\mathbf{b}_1 + k\mathbf{b}_2 + l\mathbf{b}_3$ is perpendicular to this plane. (b) Prove that the distance between two adjacent parallel planes of the lattice is $d(hkl) = 2\pi/|\mathbf{G}|$. (c) Show for a simple cubic lattice that $d^2 = a^2/(h^2 + k^2 + l^2)$.

2. ***Hexagonal space lattice.*** The primitive translation vectors of the hexagonal space lattice may be taken as

$$\mathbf{a}_1 = (3^{1/2}a/2)\hat{\mathbf{x}} + (a/2)\hat{\mathbf{y}} \; ; \qquad \mathbf{a}_2 = -(3^{1/2}a/2)\hat{\mathbf{x}} + (a/2)\hat{\mathbf{y}} \; ; \qquad \mathbf{a}_3 = c\hat{\mathbf{z}} \; .$$

   (a) Show that the volume of the primitive cell is $(3^{1/2}/2)a^2c$.
   (b) Show that the primitive translations of the reciprocal lattice are

$$\mathbf{b}_1 = (2\pi/3^{1/2}a)\hat{\mathbf{x}} + (2\pi/a)\hat{\mathbf{y}} \; ; \qquad \mathbf{b}_2 = -(2\pi/3^{1/2}a)\hat{\mathbf{x}} + (2\pi/a)\hat{\mathbf{y}} \; ; \qquad \mathbf{b}_3 = (2\pi/c)\hat{\mathbf{z}} \; ,$$

   so that the lattice is its own reciprocal, but with a rotation of axes.
   (c) Describe and sketch the first Brillouin zone of the hexagonal space lattice.

3. ***Volume of Brillouin zone.*** Show that the volume of the first Brillouin zone is $(2\pi)^3/V_c$, where V_c is the volume of a crystal primitive cell. Hint: The volume of a Brillouin zone is equal to the volume of the primitive parallelepiped in Fourier space. Recall the vector identity $(\mathbf{c} \times \mathbf{a}) \times (\mathbf{a} \times \mathbf{b}) = (\mathbf{c} \cdot \mathbf{a} \times \mathbf{b})\mathbf{a}$.

4. ***Width of diffraction maximum.*** We suppose that in a linear crystal there are identical point scattering centers at every lattice point $\boldsymbol{\rho}_m = m\mathbf{a}$, where m is an integer. By analogy with (20) the total scattered radiation amplitude will be proportional to $F = \Sigma \exp[-im\mathbf{a} \cdot \Delta\mathbf{k}]$. The sum over M lattice points is

$$F = \frac{1 - \exp[-iM(\mathbf{a} \cdot \Delta\mathbf{k})]}{1 - \exp[-i(\mathbf{a} \cdot \Delta\mathbf{k})]} ,$$

   by the use of the series

$$\sum_{m=0}^{M-1} x^m = \frac{1 - x^M}{1 - x} \; .$$

   (a) The scattered intensity is proportional to $|F|^2$. Show that

$$|F|^2 \equiv F^*F = \frac{\sin^2 \tfrac{1}{2}M(\mathbf{a} \cdot \Delta\mathbf{k})}{\sin^2 \tfrac{1}{2}(\mathbf{a} \cdot \Delta\mathbf{k})} \; .$$

   (b) We know that a diffraction maximum appears when $\mathbf{a} \cdot \Delta\mathbf{k} = 2\pi h$, where h is an integer. We change $\Delta\mathbf{k}$ slightly and define ϵ in $\mathbf{a} \cdot \Delta\mathbf{k} = 2\pi h + \epsilon$ such that ϵ gives the position of the first zero in $\sin \tfrac{1}{2}M(\mathbf{a} \cdot \Delta\mathbf{k})$. Show that $\epsilon = 2\pi/M$, so that the width of the diffraction maximum is proportional to $1/M$ and can be extremely narrow for macroscopic values of M. The same result holds true for a three-dimensional crystal.

5. ***Structure factor of diamond.*** The crystal structure of diamond is described in Chapter 1. The basis consists of eight atoms if the cell is taken as the conventional cube.

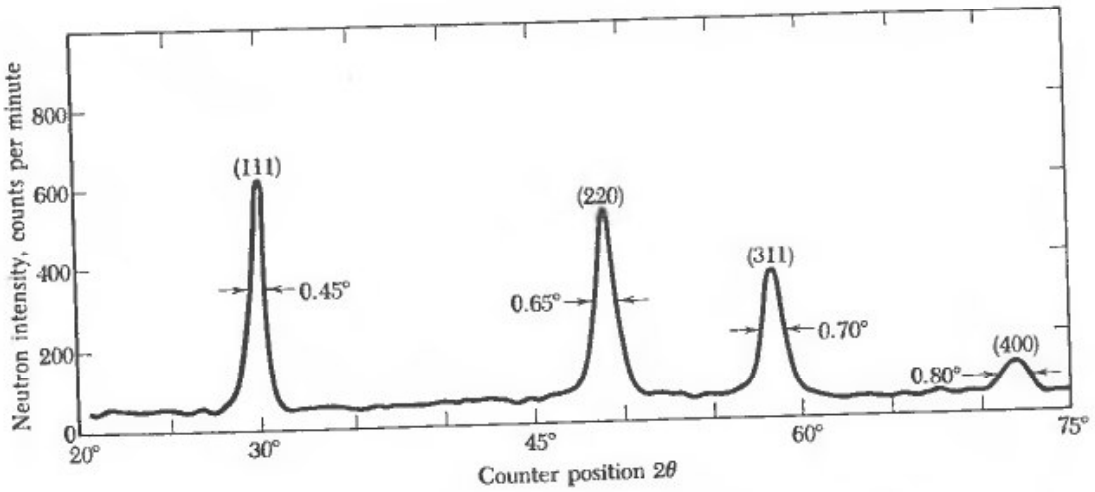

Figure 21 Neutron diffraction pattern for powdered diamond. (After G. Bacon.)

(a) Find the structure factor S of this basis. (b) Find the zeros of S and show that the allowed reflections of the diamond structure satisfy $\upsilon_1 + \upsilon_2 + \upsilon_3 = 4n$, where all indices are even and n is any integer, or else all indices are odd (Fig. 21). (Notice that h, k, l may be written for υ_1, υ_2, υ_3 and this is often done.)

6. ***Form factor of atomic hydrogen.*** For the hydrogen atom in its ground state, the number density is $n(r) = (\pi a_0^3)^{-1} \exp(-2r/a_0)$, where a_0 is the Bohr radius. Show that the form factor is $f_C = 16/(4 + G^2 a_0^2)^2$.

7. ***Diatomic line.*** Consider a line of atoms $ABAB \ldots AB$, with an A—B bond length of $\frac{1}{2}a$. The form factors are f_A, f_B for atoms A, B, respectively. The incident beam of x-rays is perpendicular to the line of atoms. (a) Show that the interference condition is $n\lambda = a \cos\theta$, where θ is the angle between the diffracted beam and the line of atoms. (b) Show that the intensity of the diffracted beam is proportional to $|f_A - f_B|^2$ for n odd, and to $|f_A + f_B|^2$ for n even. (c) Explain what happens if $f_A = f_B$.

References

X-RAY DIFFRACTION

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