V. *The Bakerian Lecture. On the elementary Particles of certain Crystals. By* William Hyde Wollaston, *M. D. Sec. R. S.*

Read November 26, 1812.

Among the known forms of crystallized bodies, there is no one common to a greater number of substances than the regular octohedron, and no one in which a corresponding difficulty has occurred with regard to determining which modification of its form is to be considered as primitive; since in all these substances the tetrahedron appears to have equal claim to be received as the original from which all their other modifications are to be derived.

The relations of these solids to each other is most distinctly exhibited to those who are not much conversant with crystallography, by assuming the tetrahedron as primitive, for this may immediately be converted into an octohedron by the removal of four smaller tetrahedrons from its solid angles. (Fig. 1.)

The substance which most readily admits of division by fracture into these forms is fluor spar; and there is no difficulty in obtaining a sufficient quantity for such experiments. But it is not, in fact, either the tetrahedron or the octohedron, which first presents itself as the apparent primitive form obtained by fracture.

If we form a plate of uniform thickness by two successive divisions of the spar, parallel to each other, we shall find the plate divisible into prismatic rods, the section of which is a rhomb of 70° 32′ and 109° 28′ nearly; and if we again split these rods transversely, we shall obtain a number of regular acute rhomboids, all similar to each other, having their superficial angles 60° and 120°, and presenting an appearance of primitive molecule, from which all the other modifications of such crystals might very simply be derived. And we find, moreover, that the whole mass of fluor might be divided into, and conceived to consist of, these acute rhomboids alone, which may be put together so as to fit each other without any intervening vacuity.

But, since the solid thus obtained (as represented fig. 2.) may be again split by natural fractures at right angles to its axis (fig. 3.), so that a regular tetrahedron may be detached from each extremity, while the remaining portion assumes the form of a regular octohedron; and, since every rhomboid, that can be obtained, must admit of the same division into one octohedron and two tetrahedrons, the rhomboid can no longer be regarded as the primitive form; and since the parts into which it is divisible are dissimilar, we are left in doubt which of them is to have precedence as primitive.

In the examination of this question, whether we adopt the octohedron or the tetrahedron as the primitive form, since neither of them can fill space without leaving vacuities, there is a difficulty in conceiving any arrangement in which the particles will remain at rest: for, whether we suppose, with the Abbé HAÜY, that the particles are tetrahedral with octohedral cavities, or, on the contrary, octohedral particles regularly arranged with tetrahedral cavities, in each case the mutual contact of adjacent particles is only at their edges; and although in such an arrangement it must be admitted that there may be an equilibrium, it is evidently unstable, and ill adapted to form the basis of any permanent crystal.

More than three years have now elapsed since a very simple explanation of this difficulty occurred to me. As in the course of that time I had not discovered it to be liable to any crystallographical objection, and as it had appeared satisfactory to various mathematical and philosophical friends to whom I proposed it, I had engaged to make this the subject of the Bakerian Lecture of the present year, hoping that some further speculations, connected with the same theory, might lead to more correct notions than are at present entertained of crystallization in general.

At the time when I made this engagement, I flattered myself that the conception might be deserving of attention from its novelty. But I have since found, that it is not altogether so new as I had then supposed it to be; for by the kindness of a friend, I have been referred to Dr. Hooke's Micrographia, in which is contained, most clearly, one essential part of the same theory.

However, since the office of a lecturer is properly to diffuse knowledge already acquired, rather than to make known new discoveries in science, and since these hints of Dr. Hooke have been totally overlooked, from having been thrown out at a time when crystallography, as a branch of science, was wholly unknown, and consequently not applied by him to the extent which they may now admit, I have no hesitation in treating the subject as I had before designed. And when I have so done, I shall quote the passage from Dr. Hooke, to shew how exactly the views which I have taken have, to a certain extent, corresponded with his; and I shall hope that, by the assistance of such authority, they may meet with a more favourable reception.

The theory to which I here allude is this, that, with respect to fluor spar and such other substances as assume the octohedral and tetrahedral forms, all difficulty is removed by supposing the elementary particles to be perfect spheres, which by mutual attraction have assumed that arrangement which brings them as near to each other as possible.

The relative position of any number of equal balls in the same plane, when gently pressed together, forming equilateral triangles with each other (as represented perspectively in fig. 4.) is familiar to every one; and it is evident that, if balls so placed were cemented together, and the stratum thus formed were afterwards broken, the straight lines in which they would be disposed to separate would form angles of 60° with each other.

If a single ball were placed any where at rest upon the preceding stratum, it is evident that it would be in contact with three of the lower balls (as in fig. 5.), and that the lines joining the centres of four balls so in contact, or the planes touching their surfaces, would include a regular tetrahedron, having all its sides equilateral triangles.

The construction of an octohedron, by means of spheres alone, is as simple as that of the tetrahedron. For if four balls be placed in contact on the same plane in form of a square, then a single ball resting upon them in the centre, being in contact with each pair of balls, will present a triangular face rising from each side of the square, and the whole together will represent the superior apex of an octohedron; so that a sixth ball similarly placed underneath the square will complete the octohedral group, fig. 6.

There is one observation with regard to these forms that will appear paradoxical, namely, that a structure which in this case was begun upon a square foundation, is really intrinsically the same as that which is begun upon the triangular basis. But if we lay the octohedral group, which consists of six balls, on one of its triangular sides, and consequently with an opposite triangular face uppermost, the two groups, consisting of three balls each, are then situated precisely as they would be found in two adjacent strata of the triangular arrangement. Hence in this position we may readily convert the octohedron into a regular tetrahedron, by addition of four more balls. (fig. 7.) One placed on the top of the three that are uppermost forms the apex; and if the triangular base, on which it rests, be enlarged by addition of three more balls regularly disposed around it, the entire group of ten balls will then be found to represent a regular tetrahedron.

For the purpose of representing the acute rhomboid, two balls must be applied at opposite sides of the smallest octohedral group, as in fig. 9. And if a greater number of balls be placed together, fig. 10 and 11, in the same form, then a complete tetrahedral group may be removed from each extremity, leaving a central octohedron, as may be seen in fig. 11, which corresponds to fig. 3.

The passage of Dr. Hooke, from which I shall quote so much as to connect the sense, is to be found at page 85 of his Micrographia.

" From this I shall proceed to a second considerable phe-
" nomenon, which these diamants (meaning thereby quartz

" crystals) exhibit, and that is the regularity of their figure " ——This I take to proceed from the most simple principle " that any kind of form can come from, next the globular; " for——I think I could make probable, that all these regular " figures arise only from three or four several positions or " postures of globular particles, and those the most plain and " obvious, and necessary conjunctions of such figured particles " that are possible——And this I have *ad oculum* demonstrated " with a company of bullets, so that there was not any regu- " lar figure which I have hitherto met withal of any of those " bodies that I have above named, that I could not with the " composition of bullets or globules imitate almost by shaking " them together.

" Thus, for instance, we find that globular bullets will of " themselves, if put on an inclining plain so that they may " run together, naturally run into a triangular order compos- " ing all the variety of figures that can be imagined out of " equilateral triangles, and such you will find upon trial all the " surfaces of alum to be composed of——

" —nor does it hold only in superficies, but in solidity also; " for it's obvious that a fourth globule laid upon the third in " this texture composes a regular tetrahedron, which is a very " usual figure of the crystals of alum. And there is no one " figure into which alum is observed to be crystallized, but " may by this texture of globules be imitated, and by no " other."

It does not appear in what manner this most ingenious philosopher thought of applying this doctrine to the formation of quartz crystal, of vitriol, of salt-petre, &c. which he names. This remains among the many hints which the peculiar jealousy of his temper left unintelligible at the time they were written, and which, notwithstanding his indefatigable industry, were subsequently lost to the public, for want of being fully developed.

We have seen, that by due application of spheres to each other, all the most simple forms of one species of crystal will be produced, and it is needless to pursue any other modifications of the same form, which must result from a series of decrements produced according to known laws.

Since then the simplest arrangement of the most simple solid that can be imagined, affords so complete a solution of one of the most difficult questions in crystallography, we are naturally led to inquire what forms would probably occur from the union of other solids most nearly allied to the sphere. And it will appear that by the supposition of elementary particles that are spheroidical, we may frame conjectures as to the origin of other angular solids well known to crystallographers.

The obtuse Rhomboid.

If we suppose the axis of our elementary spheroid to be its shortest dimension, a class of solids will be formed which are numerous in crystallography. It has been remarked above, that by the natural grouping of spherical particles, fig. 10, one resulting solid is an acute rhomboid, similar to that of fig. 2, having certain determinate angles, and its greatest dimension in the direction of its axis. Now, if other particles having the same relative arrangement be supposed to have the form of oblate spheroids, the resulting solid, fig. 12, will still be a regular rhomboid; but the measures of its angles will be different from those of the former, and will be more or less obtuse according to the degree of oblateness of the primitive spheroid.

It is at least possible that carbonate of lime and other substances, of which the forms are derived from regular rhomboids as their primitive form, may, in fact, consist of oblate spheroids as elementary particles.

It deserves to be remarked, that the conjecture to which we are thus led by a natural transition, from consideration of the most simple form of crystals, was long since entertained by HUYGHENS,* when treating of the oblique refraction of Iceland spar, which he so skilfully analysed. The peculiar law observable in the refraction of light by that crystal, he found might be explained on the supposition of spheroidical undulations propagated through the substance of the spar, and these he thought might perhaps be owing to a spheroidical form of its particles, to which the disposition to split into the rhomboidal form might also be ascribed.

By some oversight, however, the proportion of the axes of such an elementary spheroid is erroneously stated to be 1 to 8; but this is probably an error of the press, instead of 1 to 2,8, for I find the proportion to be nearly 1 to 2,87. In fig. 15, F is the apex of a tetrahedron cut from an acute rhomboid similar to fluor spar, and the sections of two spheres are represented round the centres F and C. I is the apex of a corresponding portion cut from the summit of a rhomboid of Iceland spar, as composed of spheroids having the same diameter as the spheres. In the former, the inclination FCT of the edge of the tetrahedron to its base is 54° 44′; in the latter, he inclination ICT is 26° 15′; and the altitudes FT, IT are as

* HUYGHENII Op. Reliq. Tom. I. Tract. de Lumine, p. 70.

the tangents of these angles 1414 to 493 :: 2,87 : 1, which also expresses the ratio of the axis of the sphere to that of the spheroid, or the proportional diameters of the generating ellipse.

Hexagonal Prisms.

If our elementary spheroid be on the contrary oblong, instead of oblate, it is evident that by mutual attraction, their centres will approach nearest to each other when their axes are parallel, and their shortest diameters in the same plane (fig. 13.) The manifest consequence of this structure would be, that a solid so formed would be liable to split into plates at right angles to the axes, and the plates would divide into prisms of three or six sides with all their angles equal, as occurs in phosphate of lime, beryl, &c.

It may further be observed, that the proportion of the height to the base of such a prism must depend on the ratio between the axes of the elementary spheroid.

The Cube.

Although I could not expect that the sole supposition of spherical or spheroidical particles would explain the origin of all the forms observable among the more complicated crystals, still the hypothesis would have appeared defective, if it did not include some view of the mode in which so simple a form as the cube may originate.

A cube may evidently be put together of spherical particles arranged four and four above each other, but we have already seen that this is not the form which simple spheres are naturally disposed to assume, and consequently this hypothesis *alone* is not adequate to its explanation, as Dr. HOOKE had conceived.

Another obvious supposition is that the cube might be considered as a right angled rhomboid, resulting from the union of eight spheroids having a certain degree of oblateness (2 to 1) from which a rectangular form might be derived. But the cube so formed would not have the properties of the crystallographical cube. It is obvious, that, though all its diagonals would thus be equal, yet one axis parallel to that of the elementary spheroid would probably have properties different from the rest. The modifications of its crystalline form would probably not be alike in all directions as in the usual modifications of the cube, but would be liable to elongation in the direction of its original axis. And if such a crystal were electric, it would have but one pair of poles instead of having four pair, as in the crystals of boracite.

There is, however, an hypothesis which at least has simplicity to recommend it, and if it be not a just representation of the fact, it must be allowed to bear a happy resemblance to truth.

Let a mass of matter be supposed to consist of spherical particles all of the same size, but of two different kinds in equal numbers, represented by black and white balls; and let it be required that in their perfect intermixture every black ball shall be equally distant from all surrounding white balls, and that all adjacent balls of the same denomination shall also be equidistant from each other. I say then, that these conditions will be fulfilled, if the arrangement be cubical, and that the particles will be in equilibrio. Fig. 14 represents a cube so constituted of balls, alternately black and white throughout. The four black balls are all in view. The distances of their centres being every way a superficial diagonal of the cube, they are equidistant, and their configuration represents a regular tetrahedron; and the same is the relative situation of the four white balls. The distances of dissimilar adjacent balls are likewise evidently equal; so that the conditions of their union are complete, as far as appears in the small group: and this is a correct representative of the entire mass, that would be composed of equal and similar cubes.

Since the crystalline form and electric qualities of boracite are perhaps unique, any explanation of properties so peculiar can hardly be expected. It may, however, be remarked, that a possible origin of its four pair of poles may be traced in the structure here represented; for it will be seen that a white ball and a black one are regularly opposed to each other at the extremities of each axis of the cube.

An hypothesis of uniform intermixture of particle with particle, accords so well with the most recent views of binary combination in chemistry, that there can be no necessity, on the present occasion, to enter into any defence of that doctrine, as applied to this subject. And though the existence of ultimate physical atoms absolutely indivisible may require demonstration, their existence is by no means necessary to any hypothesis here advanced, which requires merely mathematical points endued with powers of attraction and repulsion equally on all sides, so that their extent is *virtually* spherical, for from the union of such particles the same solids will result as from the combination of spheres impenetrably hard.

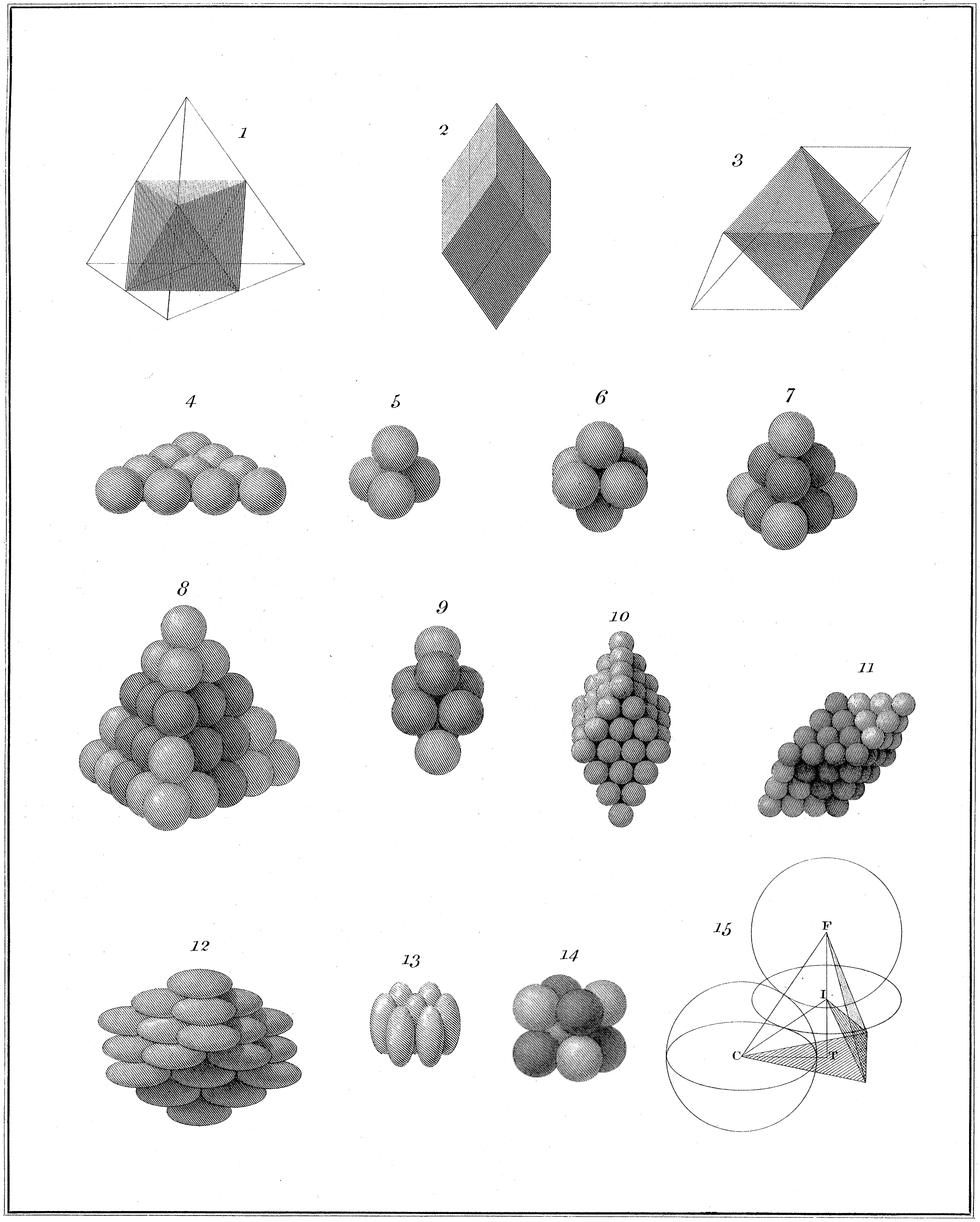
There remains one observation with regard to the spherical form of elementary particles, whether actual or virtual, that must be regarded as favourable to the foregoing hypothesis, namely, that many of those substances, which we have most reason to think simple bodies, as among the class of metals, exhibit this further evidence of their simple nature, that they crystallize in the octohedral form, as they would do if their particles were spherical.

But it must, on the contrary, be acknowledged, that we can at present assign no reason why the same appearance of simplicity should take place in fluor spar, which is presumed to contain at least two elements; and it is evident that any attempts to trace a general correspondence between the crystallographical and supposed chemical elements of bodies must, in the present state of these sciences, be premature.

Note. A theory has lately been advanced * by M. Prechtl, which attempts to account for various crystalline forms from the different degrees of compression that soft spheres may be supposed to undergo in assuming the solid state. It is supposed, that with a certain degree of softness and of relative attraction, the particles will be surrounded each by four others, and will all be tetrahedral, although in fact it be demonstrably impossible that tetrahedrons alone should fill any space.

It is next supposed, that soft spheres less compressed will be surrounded by five others, and will be formed into triangular prisms, comprised under five similar and equal planes. That they should be similar is impossible, and it is further demonstrable, that when the triangular termination of such a

* Journal des Mines, No. 166.



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prism is equal in area to each rectangular side of the prism, so as to present equal resistance, according to the hypothesis, then the triangular faces will be nearer to the centre in the proportion of three to four, so that the attractions will not be equal as the hypothesis would require.

A third hypothesis of M. Prechtl is, that the degree of compressibility may be such that each particle will be surrounded by six others, giving it the form of a cube, which, it must be admitted, is a very possible supposition.

All further application of the same hypothesis is precluded by M. Prechtl, by denying that one particle can be surrounded by more than six others; although in fact it is most evident, that any sphere when not compressed will be surrounded by twice that number, and consequently by a slight degree of compression will be converted into a dodecahedron, according to the most probable hypothesis of simple compression.