Ontological Status of Molecular Structure

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Abstract: Molecular structure (MS) has been treated as a convention or an epiphenomenon by physicists and quantum chemists interpreting the mathematical formalism of quantum mechanics as the essential reality criterion in the submicroscopic world (R2 world). This paper argues that, (a) even in the R2 world there is a class of entities which are real *per se*, even though they cannot be separated from their material support, and MS may belong to that class; (b) MS actualizes a particular molecule from the many potentialities of a given set of nuclei and electrons, all present in the same Schrödinger equation; (c) MS is a fact established in the XIXth century, albeit as a result of circumstantial evidence (because of its belonging to the R2 world); (d) the fact that MS is known, as all objects of the atomic world, in terms of analogies with macroscopic models, is not valid grounds for questioning its reality; (e) MS is a set of topological as well as geometrical relations. All along the discussion, observability according to Bohr, Heisenberg, Feynman is taken as the essential criterion of reality in the R2 world. On its basis, quantum mechanics is by no means in conflict with the reality of molecular structure and shape. On the other hand, the question of the minimum lifetime required for a MS proper to exist should be left open, pending a detailed analysis of measurement techniques.

Keywords: *ontology, molecular structure, quantum mechanics, analogy, observability.*

Introduction

Tradition has it that Paul Dirac, after casting quantum mechanics into his well known formalism, echoed Shakespeare by saying: “the rest is chemistry.” He apparently thought that chemistry is only a sort of scientific cuisine. Also Werner Heisenberg, though a man of great culture, was mistaken about the program and field of inquiry of chemistry, for he suggested that chemistry had merged with physics into quantum mechanics by bringing the atom to the latter;[1] the mistake being, of course, that if chemistry has anything to do with atoms, it is because they are the building blocks of molecules.

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Other founding fathers of quantum mechanics certainly knew better: in particular, Born and Oppenheimer considered it extremely important for the validation of the new-born quantum mechanics that it should be proven that, despite the uncertainty principle, the new theory was perfectly compatible with the empirically founded notion of chemical structure. Also the work of Heitler, Hückel, Slater, Pauling, Hund, and others was aimed at finding out if quantum mechanics could account for the known building rules of molecules and possibly extend their scope. This was done by introducing special, *ad hoc* assumptions into a quantum mechanical perturbational treatment.[2]

However, curiously enough, in later years the belief spread, especially among chemists, that, in the world of atoms and molecules, real is what is explicitly contained in the equations of quantum mechanics. It is not surprising, therefore, that ideas (probably inspired by theories of atomic nuclei) according to which the chemical bond is a convention, and molecular structure is merely a property of chemical formulas were received with indifference: the great battle against such conventionalists as the great chemists Ian Berzelius and Wilhelm Ostwald seemed to have been won in vain.

Yet, after almost a century of hard work and debates, by about 1900 the organic chemists had reached the conclusion that structure is the fundamental fact of the world of molecules; in the long run, therefore, further progress in our understanding of the physical world might be seriously hindered by the existing uncertainty about the epistemological and ontological status of molecular structure and related concepts.

This situation has prompted the reflections presented in this paper, which is intended as a contribution towards the re-establishment of consistency with historical facts and a critical analysis of the reasons why even the founders of quantum mechanics considered molecular structure, bonds, valence as ascertained properties of matter.

Our exposition will be divided into four parts. In part A we shall consider judgments of existence on things which cannot be isolated from their material support (second class entities); in part B we shall look at the status of the latter in the picture of the physical world suggested by recent advances of science; in part C we shall pause on the history of molecular structure, to show how it came to be considered a fact before quantum mechanics; in part D we shall see on what grounds and in what sense molecular structure is more than ever a second class entity whose presence in molecules is a fact which characterizes molecules as distinct from atom clusters and other particle aggregates. The last part will demand a brief tour into the quantum-mechanical theory of time-dependent states.

Part A: Ontological status of relational entities

A.1 Foundations

We accept the strong-realism axiom, according to which there are things, events and processes independent of our own existence and will, and they can be individually known by us, within limits imposed by our senses and brain, as existing and distinct from other objects.

We also accept the classical view that ordinary intuitive existence judgments can be taken as starting points for a critical analysis, needed anyway to determine, as the case may be, either what precisely an existence judgment applies to, or why it is mistaken.

As is well known, realism was challenged by philosophers since the birth of philosophy.[3] In modern science a sort of idealistic approach to what science studies has been built on the difficulties quantum mechanics has with the role of the observer in experiments. Actually, there is much to say in favor of the possibility that a careful distinction between 'observer' and 'perceiving subject' would remove the reality issue from the overfull epistemological agenda of theoretical physics. However that may be, the neopositivistic view of science was very popular for a time. However, inconsistencies turned out, and it would now seem that scientists prefer to believe that what they study is reality.

A double classification of real entities is essential for our study. The first one is that between *first class (FC) entities*,[4] *i.e.* objects existing *per se* (say, a tree or a molecule), and *second class (SC) entities* (say, the psyche of a dog or a man), which presuppose a 'carrier', even though they can be treated, within certain limits, as if they were FC entities.[5] The second distinction is between entities directly and indirectly accessible to sensible experience – which Schummer[6], following Harré, calls R1 and R2 entities, respectively. In this paper, R1 is used for entities which can be perceived as such, R2 for entities believed to exist because of analogical and logical evidence similar in nature to that by which a judge may condemn a man as the author of a crime.

A.2 Aspects of existence judgments

A few examples of entities on which a judgment of existence is made are listed below to attract attention to points relevant to the chemical structure problem. They are given in pairs: the latter member of each pair is similar to the former but involves R2 entities.

1a: *A quartz crystal & a benzene crystal.*

1b: *Flour & the chemical substance benzene.*

- Example 1a compares a standard reality judgment with one still bearing on directly perceived objects but partly based on indirect evidence, possibly in the form of reports accepted by general consensus.
- Example 1b is parallel to 1a, but refers to entities whose existence no one would deny, and yet are partly abstract, for they can be experienced as pieces with a variety of shapes and sizes, not isolated 'in the laboratory' as such.

2: *A microscopic mite & a benzene molecule*.

- A molecule is a typical example of what Harré and Schummer call R2 entities; a microscopic mite is an intermediate example, which differs from a molecule inasmuch as it finds an immediate model by analogy with direct experience.

3a: *A computer program in general & a computer program for the benzene normal modes.*

3b: *Organization & a benzene-producing organization.*

- A computer program is an SC entity which can be 'transferred' from one computer to another, and can be stored on all sorts of material supports.
- Organization is a property of a whole which cannot be reduced to the properties of its parts, for the behavior of each part depends on those of the others *and* on the aims of the whole. The very special nature of organization is recognized from linguistic usage, which treats 'an organization' as an entity *per se*.
- Both a program and an organization pattern are cases of information, but it remains to be seen if organization is transferable, as is the case in general with information.

4a: *A pattern in a carpet & partly miscible liquid layers.*

4b: *A solid-state radio set & crystal structure.*

- SC entities come into existence ('emerge') as a result of the arrangement or interconnection of certain parts of a whole, but are not the parts, even though they can be traced back to specially situated or connected R1 or R2 entities;
- important SC entities of this type are associated to wholes whose behavior results from special relations among many interacting parts, ranging from tight dynamical cooperation of the parts (case of a radio set) to persistent ordering due to weak pairwise interactions (case of a crystal structure).

Part B: Levels of reality and the role of analogies

B.1 The nature of the physical world

The traditional expression 'physical world' covers all that can be detected directly or indirectly by our five senses. The above examples show that the claim that the whole physical world is nothing but 'atoms and quanta' is as untenable as the claim that airplanes, tractors, cars, trains, bridges, etc., are but the materials of which they are made. That is to say, a given collection of atoms and quanta – or indeed of fundamental particles – can in general form an incredibly large number of different physical systems, each with its own identity and specific properties.

In principle, the possible existence and properties of those systems can be quantitatively *predicted* from the properties of the constituent particles. To that end, however, the physical conditions which correspond to existence and the nature of the properties must be known or guessed, unless they are simply sums of corresponding properties of the parts; moreover, the collection of particles from which a system arises contains part of information about that system only potentially. In other words, *information about possible wholes is partly either latent or not uniquely specified* in the constituents, meaning by 'latent' that the problem remains of knowing which global properties are possible that are not sums of the properties of the parts, and by 'not uniquely specified' the fact that a specific system of *n* given particles is formed by selection out of many possibilities.

A chemical example of such a selection process is the sequence of operations by which one isomer is selected out of many. For example, given six carbon atoms and six hydrogen atoms, the rules of valency predict 217 different molecules (and hence 217 different chemical substances) formed with the same atoms ('isomers'). Although a much greater number of aggregates of the same number and species of atoms can be imagined, no chemist has any doubt that those 217 and only those 217 can be synthesized, the reserves being that some of the possible molecules can be relatively unstable because of steric hindrance or bond bending, and therefore they might have to be isolated under very special conditions, say, very low temperatures; and some isomers may be equivalent forms of the same molecule (*cf.* our comment on the Kekulé structures at the end of Sect. D.4).

Starting from the 42 electrons and the 12 nuclei of benzene, the only way to predict theoretically the possible 'existence' of those substances consists in:

(a) declaring that there is a molecule when there is a chemically stable configuration, *i.e.* one corresponding to a free-energy minimum such that its lifetime with respect to spontaneous isomerization is sufficiently long for chemical observation;[7]

(b) writing down the Hamiltonian operator for the given nuclei and electrons;
(c) trying to solve the Schrödinger equation by a numerical quantum mechanical exploration of the whole 162-dimensional energy hypersurface defined by the 42 electrons and 12 nuclei, with the vibrational analysis required for entropy computations.

Such a procedure is possible in principle with a sufficiently powerful computer, but it is conceptually similar to (and not as reliable as) an empirical search for the isomers of benzene not guided by the laws of valency; moreover, since the information contained in the chemical formula according to the theory of valency also concerns chemical reactivity, further *ad hoc* criteria would be necessary.

In conclusion, the criteria of existence of molecules are provided by the building laws formulated in the theory of valency quite independently of the fact that quantum mechanical computations lead to the same molecules if the right input data and definitions are provided.

B.2 Two examples of complex systems

What we have seen so far seems strongly to suggest that the aporias and limitations of physicalistic reductionism ('the world is nothing but atoms and quanta') require the adoption of a new general picture of the physical world as a system made of (sub-)systems of different orders of size and degrees of complexity. The subsystems in question range from tightly integrated ones to weakly interacting ones which still have an identity of their own.

A molecule and a cell provide two concrete reference examples for our further reflections.

a) A molecule

A molecule *is* a collection of electrons and nuclei, and can be described as such. However, as seen on the case of benzene, a description at this level leaves a large number of possibilities open, because – at variance with a plasma or an atom cluster – the way in which the electrons and nuclei are put together matters, and the 'connections' (chemical bonds) determine the properties of the whole. Moreover, at variance with the physicists' liquid-drop model, a molecule appears to be a persistent entity, whose demolition requires *ad hoc* conditions or processes.

The boom of research on molecules of the fullerene class after their discovery in 1985 was due precisely to the fact that, thought at first to be just amorphous clusters of carbon atoms, on closer inspection they turned out to have properties not explicable by the liquid-drop model or by analogy with a tiny crystal, but explicable if they had a quasi-rigid structure.

If a complete description of the nuclei and electrons of a molecule is not a complete description of the molecule (*cf.* Sect. B.1), for the whole reality of a molecule *as distinct from everything else* includes 'emergent properties', then clearly a picture of the physical world only granting reality to the ultimate constituents of matter falls short of accounting for factual evidence.

b) A cell

In a cell, as in a molecule, something becomes actual and uniquely specified that is only one possibility, selected in the course of its formation out of the many possibilities compatible with the nature of its constituents. But it differs dramatically from a molecule in at least three ways. First, it is far more complicated than a molecule. Secondly, it is what it is, not because it corresponds to a metastable configuration of the atoms and electrons which constitute it, but because its coordinated activity ('entelechy') is finalized, aimed at holding it alive in a particular (normal) state. Thirdly, it can be divided into significant constituents of at least two different sorts: either comparatively large parts (membrane, lysosomes, nucleus, mitochondria, etc.), or the macromolecules and the media in which they operate, which are its building blocks from the point of view of molecular biology.[8]

Is there really such an object as a cell? Every biologist would answer this question by an emphatical 'yes'. More or less as the microscopic mite mentioned above, it is midway between an R2 entity and an R1 entity, for there are cells which are directly accessible to plain observation (the eggs of birds, reptiles, etc.). If any given cell exists, the question 'what-is-it' (Aristotle's famous '*to ti en*') is justified. Within the frame of molecular biology the answer might be: it is a collection of water, biologically active molecules and enzymes, *as well as* a single entity with properties which cannot be attributed to any single component or group of components.

Of course, a cell is also a collection of molecules and macromolecules in the chemical sense, a collection of nuclei and electrons, and so on down and down to the ultimate particles.

B.3 Complexity levels

Thus, far from being void of meaning, as the anti-essentialists claim, the questions "what is a molecule? What is a cell?" can be answered in a multiplicity of ways, all true, but all different in the load of 'actual' information they carry. One can express this in terms of 'complexity levels'. A complexity level of a thing is the reality of that thing seen as a collection of wholes of a certain degree of complexity, treated as indivisible building blocks (which might be called, *faute de mieux*, the 'elementary objects' of that level),[9] from which that thing emerges as a whole by successive (spontaneous and environment-conditioned) appearance of order, structure, organization. A reference analogy might by a many-storey pyramidal building: at the foundation, there is a shapeless, structureless assemblage of countless particles (say, the fundamental particles) with an extremely small number of properties each. Above it there might be (depending on the particular thing under consideration) the same particles already grouped into simple wholes (say, atomic nuclei); and the number of elementary objects which are parts of the given thing at the top would then be smaller, but the number of properties of each larger. In the next storey, those elementary objects would combine in groups to form structured wholes, which are the elementary objects of the new level (say, molecules), *viz.* new wholes with even more properties – although some of those of the lower level become unobservable or irrelevant – but fewer in number. Up and up the scale one would find the elementary objects of molecular biology, the corpuscles and media in a cell, and finally the cell itself, if that is the complex system whose reality one is trying to grasp. If one had a living organism in mind, then the pyramid would continue up to organs, the psyche, and the organism itself.

The storeys of the pyramid represent what we have called 'complexity levels'; and we may therefore speak of a 'complexity pyramid'. In most scientific approaches the levels come in pairs: that at which the system to be analyzed is an elementary object, and another, usually the immediately underlying one, provides the parts out of which it results. Theoretical physics tends to ignore the intermediate storeys, and tries to represent all systems as consisting of elementary particles (or of quasi-elementary ones). Since originally the elementary particles were the atomic nuclei and electrons, theoretical physics accounts for 'ordinary matter' by the Schrödinger equation, as already discussed. The reality of complex systems, whether metastable (like molecules) or steady-state ones (like cells), is actualized by selecting certain sets of quantum states out of those of the general system of nuclei and electrons, in which all actual systems are potentially contained that are compatible with the number of the electrons and the number and species of the nuclei (see below).

Perhaps even groups of particles lasting less than a femtosecond (if, as it is claimed, that is a feasible observation time) might be treated as a real physical system; but they do not define complexity levels, because the latter are defined with reference to objects which persist long enough to interact as such with their environment. This remark shows that there is a relation between existence, entities, observability, and lifetime; we shall return to it presently.

The most important point in the complexity level view, which eliminates for one thing the aporia between physics and biology, is that, on the one hand, the collection of all the levels lying below that at which a given thing appears as a unit is essential for a complete description of its reality, while, on the other hand, at each lower level the information actual in the given object is partly latent and indeterminate; so that the reality of the upper levels cannot be completely predicted, unless the process by which the elementary objects (the 'parts') are put together and the nature of the emergent properties are known. Moreover, at each higher level the nature of the individual constituents of the elementary objects is irrelevant as such, for it melts into the overall properties. This is not in contrast with the existence of additive properties, although they are a case where consideration of the complexity levels is merely academic: suffice it to mention that even the weight of the whole, though a typically additive property, does not tell anything about the nature of the parts.

B.4 Size levels and the direct-access level.

Size is related to complexity because there is a rough parallelism between size and degree of complexity of a physical system, whether nonliving or living. However, the epistemological import of size is quite different, because it operates a three-fold partition among objects of the world in which any given living being capable of knowledge, albeit rudimentary, is immersed. There are objects whose sizes lie within the range of the bodily senses – which can be entirely touched and seen (or detected by smelling, hearing, or possibly tasting) without the help of instruments. In the case of a human 'perceiver' those objects have sizes ranging from not more than that of a man to those of things at the limit of vision. They belong to a 'size level' which we shall call the 'direct-access level' (DAL). The DAL is the size level of our ordinary experience, on which immediate and usually reliable reality judgments are based.

Then there are objects which we think we know directly – say, the Earth, or even just a mountain – but actually that is not the case, because what we perceive of them at the DAL is either a remote, intangible image, or parts of them, from which we reconstruct the whole. Similarly, but the other way round, we think we know directly that a powder is made of extremely tiny grains, but as a matter of fact we only see the powder. These examples are actually simple examples of a procedure which modern science has systematically applied since the time of Galileo: with the help of the telescope and the microscope, it has extended the range of the DAL by entrusting reality judgments to indirect sight and inference by analogy, as already mentioned on the example of a microscopic mite. Whenever the analogy is immediate (the Earth with a sphere, the mite with other *Acari*), the reality judgment is assumed to have the same validity as one made within the DAL. We can therefore speak of an extended direct-access level (EDAL).

A mountain and a mite are FC entities, which need no support to exist. As to SC entities, in the direction of decreasing sizes the development of modern science coincided to a large extent (though by no means entirely) with their identification with invisible and intangible FC entities acting as causes; for example, diseases were traced back to the action of specific micro-organisms. The enthusiasm for the applications of that discovery gradually made people forget that those microorganisms are not the disease, but its cause; properly speaking, a disease is today what it was in ancient Greece: an alteration of the normal operation of the body, *i.e.* a modification of the relations among the parts of the body.

In other words, knowledge about things, events and processes at a size level of the R2 type can only be attained and formalized in terms of analogies with the DAL which include both FC and SC entities. This implies in particular that the extension of analogy to the world of molecules is indispensable to make the reality outside the extended direct-access level (EDAL) detectable and treatable at a linguistic level. Coherent sets of relations among the parts of an object which can be thought of independently of their material support (*e.g.* a structure) may therefore be expected to exist by analogy in the submicroscopic world; this is the ontological foundation on which what is often called 'molecular reality', particularly molecular structure, can be understood.

Part C: Molecular structure in the history of chemistry

C.1 The discovery of molecular structure

In the seventeenth century Robert Boyle pointed out that, having accepted the Democritean hypothesis that matter consists of atoms, it would still be convenient to recognize in the world a sort of architectonic principle which operated since the beginning of the Universe.[10] Since he was referring to chemistry, it is clear that he felt that atoms should be arranged into edifices; but it was only two centuries later, after 1858, amidst heated disputes, that molecular structure became a central concept of chemistry – when Kekulé realized that the properties of hydrocarbons could be explained by assuming that their molecules were analogous to chains of carbon atoms.[11]

We are now going to refer to the structure of benzene as a specific reference case for our further considerations. Since, however, confusion may arise, we warn the reader that the term 'structure' is never used here in the symbolic acceptation known from the the quantum-chemical theory of resonance; a short pause on the difference will be made below (Sect. D.3). The history of benzene, extensively treated from a chemist's point of view by Paoloni in 1996,[12] is probably sufficient illustration of the whole ontological import of that notion. Paoloni divided the elaboration of the structural formula of benzene into three stages: representation of chemical properties only (1865-1874); representation of both chemical and spatial characteristics (1874-1913); global representation, with inclusion of X-ray diffraction results (1914-1932).

What interests us here is that Kekulé's original intuition was an analogy with gnomes having one or four arms each, holding one another by their hands. Later, the standard analogy became that of tiny balls having four hooks each for carbon, one hook each for hydrogen. A molecule was assumed to have a spatial configuration determined by the fact that the atoms formed bonds, *i.e.* links similar to the sticks or springs which might hold together the hooked balls just mentioned. Of course, certain features of the structure of the macroscopic would not be transferable to the molecular plane of reality, nor could certain features of its submicroscopic counterpart (especially those connected with reactivity) be placed in correspondence with features of the macroscopic model; but that was part of the game.

In 1866 Kekulé considered for benzene two possible alternatives, presented as follows:[12a]

> 1. The six carbon atoms are connected to one another in a completely symmetric manner […]. The six hydrogen atoms […] occupy completely equivalent position in the molecule. One could therefore represent benzene by a hexagon whose vertices carry hydrogen atoms. By successive substitution of the H atoms by bromine atoms the following isomeric derivatives are possible:
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> | | |
> |---|---|
> | monobromo-benzene | 1 isomer |
> | dibromo-benzene | 3 isomers ab, ac, ad |
> | tribromo-benzene | 3 isomers abc, abd, ace |
> | […] | |
>
> 2. The six hydrogen atoms of benzene form three atomic groups, each constituted by two carbon atoms held together by two valences each. The group appears in itself like a triangle. […] The six hydrogen atoms are therefore alternatively nonequivalent, and benzene could be represented as a triangle. […] Substitution with bromine atoms would then yield the following isomers:
>
> | | |
> |---|---|
> | monobromo-benzene | 2 isomers: a,b |
> | dibromo-benzene | 4 isomers ab, ac, bd, ad |

The story of the structure of benzene continued, a variety of proposals were made, but in 1872 Kekulé concluded as follows:

> It must be accepted that the atoms of a polyatomic molecule are situated in space so as to satisfy as well as possible the attraction forces. [After discussing and proposing a variety of atomic configurations,] I have been led, by considerations of a chemical nature, back to my original idea […]

which was, as is well known, the hexagonal form of benzene with equivalent C-C bonds.

The above quotations present the essential steps in the establishment of the existence of a specific molecular structure and hence of molecular structure in general:

1. the molecular hypothesis;
2. the analogy with a macroscopic model (stick-and-ball model) where valencies are saturated as if they were flanged pipes screwed to one another along the same straight line;
3. the assumption that substitution takes place by cleavage of a terminal bond;
4. the proof, by chemical separation of different isomeric substances, that correct predictions for the number of isomers are obtained by:
   (a) choosing macroscopic models with appropriate structures for the molecules under consideration,
   (b) assuming that they are in a one-to-one correspondence with some otherwise unknown aspect of those molecules;
5. the generalization of point 4, after a careful critical analysis, leading to the principle that all atom groups behaving as single particles in the gas phase or in a solvent (molecules) have a specific, permanent structure;
6. the demonstration that the type of crystals formed by a substance is in correspondence with the supposed structure of its molecules.

Point 4 contains the essential ontological point to be considered here. Let us pause on it.

Reality of molecular structure

It has been admitted since the dawn of philosophy that, even if what we know of a thing is at least part of what the thing really is, our knowledge of it involves a representation made by our mind.[13] Even now that science and technology have taken our knowledge beyond the Ptolemaic limits of the DAL (direct-access level) of reality, our representations are still those of objects in the DA space, and, as mentioned at the end of Sect. B.3, analogies play a fundamental role. When it comes to certain problems, particularly the nature of electrons, it may be necessary to resort to double analogies involving models which would not be compatible at the DA level – particles and waves. Even those partial models are anyway 'analogical' representations of reality in the world of molecules. That sort of reality which can only be grasped by the establishment of a correspondence with some characteristic pattern of passive and active properties of entities of the DA level – a 'principle', as the Ancients would have said. (Note that we have not referred here to 'experimental results', as is customary, because we wish to emphasize again that Heisenberg's uncertainty principle is not limited to human observers, but applies to the response of a quantum system to any perturbation, even in the absence of knowing minds.)

As it seems, therefore, within the frame of realism one should accept this conclusion: what we call the 'structure' of a molecule is a principle (an SC entity) inherent to molecular reality, and hence real.

It can be known by analogy through the mediation of a macroscopic model, to which the notion of structure properly applies, certain features not present in the model being added by an operation of logic and imagination.[14]

The geometrical face of molecular structure

This face is at first sight distinct from the chemical one, an impression that has been somehow perpetuated by classical textbooks, despite the unavoidable acceptance of geometrical aspects when considering such topics as Bayer's strain theory, or the mechanism of alkene hydrogenation. Actually, as appears from Kekulé's quotations above, this face was included in the very idea of structure since its first appearance; the view that there were bonds and the bonds were like joining sticks with a precise orientation in space was there even before 1874, when J. H. van't Hoff and A. J. Le Bel made the spatial configuration of molecules a direct subject for reflection. Since then, it was found that not only was the topology described by a written formula or the corresponding graph a representation of reality rather than a mere thinking aid, but it was not even sufficient in the latter capacity. As mentioned above, a merely topological definition of molecular structure related to the notion that structural formulas are just graphs is often adopted, but then the term 'structure' is given a restricted meaning which, as far as our experience goes, is not current among chemists engaged in molecular design and synthetic work: suffice it to think of the use of the word 'structure' in the chemistry of proteins.

One might insist that actually all we have is a macroscopic model, the stick-and-ball or the spring-and-ball model, but then one should answer with scientific rigor and experimental evidence this question: why do all experiments give results in agreement with the claim that molecules have a structure corresponding to that model, in the analogical sense discussed above?

Part D: Quantum mechanics, observability, and chemical formulas

D.1 Molecular structure and quantum mechanics

As mentioned, the founding fathers of quantum mechanics had realized that molecular structure corresponds to a rigid (or quasi-rigid) nuclear framework (called *Kerngerüst* in the German literature), and should be considered a fact in the two senses already discussed:

- topological, *i.e.* as a set of privileged rigid (or quasi-rigid) connections between particular atoms (bonds), forming one or more continuous paths from any given atoms to any other atom;
- geometrical, in the sense that only rotations about pairs of atoms connected by one and not more than one bond are allowed.

As mentioned in the introduction, the existence of a quasi-rigid nuclear framework was the fact on which the approximate schemes for the application of quantum mechanics to molecular problems were developed.[15] However, the factual nature of the nuclear geometrical configuration had already attracted the attention of the physicists, for it was considered necessary to prove that the newborn quantum mechanics was not in conflict with it. This was done by Born and Oppenheimer, as already recalled.[16] They applied a perturbational procedure going back to astronomy and already used by Born and Heisenberg in 1924 in the frame of the Bohr-Sommerfeld semi-classical quantum mechanics[17] to justify an experimental fact: the grouping of molecular spectroscopic terms, which clearly corresponded to the separation of nuclear and electronic motions presupposed by molecular structure in Kekulé's and van't Hoff's sense. With the application to the new quantum mechanics, they actually answered a fundamental question: "If particles are not completely localizable (quantum-mechanical particle-wave dualism), how can quantum mechanics respect the chemists' discovery that molecules have a structure corresponding to fixed relative nuclear positions, and, consequently, a shape?" Their study essentially consisted in a theorem and a corollary:

Theorem: in the frame of quantum mechanics the nuclei of a molecule can be treated as classical particles practically at rest as far as electronic motions are concerned;

Corollary: quantum mechanics is not in conflict with the chemists' model of a molecule as a rigid framework of nuclei held together by shared electrons.

In order to prove their theorem, Born and Oppenheimer (abbr. B-O) showed that the nuclear motions are much slower than those of electrons in equivalent force fields; the displacements of the atoms from their equilibrium positions are very small with respect to the bond distances. For example, the vibration amplitudes of the carbon nuclei of benzene are at most 0.1 Å at room temperature.[18]

The B-O theorem, however, left the possibility open of special quantum effects (now called 'vibronic coupling'), particularly in the case of excited states; therefore, it has become customary to speak of the 'Born-Oppenheimer (B-O) approximation' when a quantum mechanical study of a molecule is carried out under the assumption that its nuclei are fixed point-like sources of an electrostatic field. As a matter of fact, molecular states and their evolution are well described under the B-O approximation, except at intersections of potential-energy hypersurfaces corresponding to different electronic states. At a crossing, the nuclei are 'seen' by the electrons as fixed field sources; but no genuine molecule with the configuration or configurations at which the intersection occurs exists as such (*cf.* Sect. D.5), and vibronic coupling only concerns transitions between two structures.

Despite these considerations, the issue of molecular shape and structure in connection with quantum mechanics, raised in 1978 by a perplexing paper entitled 'Must molecules have a shape?'[19] in 1978, is worth further reflection.

D.2 Existence and observability

So far, we have shown that the question of the existence of molecular structure is distinct from that of the atoms which make up the molecule, for the chemical and physical properties of the latter depend not only on the nature of the atoms, but on the way in which the atoms are connected. Therefore, one should either speak directly of 'properties of molecular structure' or – using a circumlocution more palatable to the modern mind – speak of 'structure dependent properties of a molecule'.

This amounts anyway to admitting that molecular structure is an SC entity having an existence of its own. But what is 'existence' in this case? To put it more precisely, on what grounds do we say that the structure of a molecule exists? The strong realism axiom, stated in section A.1, requires that our perceptions tell us something about what a thing is, at least in principle and after a severe critical analysis. This requirement is what the physicists, led by Einstein and Bohr, have emphasized all along the great advances of physics which took place between 1899 and 1937: what we can accept as real must be *observable*.

There is much to say about what 'observability' means; here we need only emphasize again that scientific observation is often indirect, for it is currently assumed that an observation has been made if there is a unique chain of arguments leading from the actually observed phenomenon (say, the displacement of a pointer) to the value or event under consideration.

In the case of molecular structure this condition is satisfied by a large number and variety of observations, which essentially reduce to statements of the type: "if the molecule of the substance J under study contains a bond connecting atoms X and Y, which in turn are connected to the other atoms by certain bonds, then a certain laboratory procedure will yield a substance K; otherwise there will be no reaction or another substance will result." Of course, failure to obtain an expected substance may be just due to experimental difficulties; but the number and variety of successful tests of this kind, plus the application of similar lines of reasoning to physical properties (rotation of the polarization plane of light waves, molecular refraction, dielectric constants, X-ray diffraction, etc.) give that overwhelming evidence as was already available when quantum mechanics appeared.

To sum up our conclusion, unless the very notion of molecule in the sense of Dalton and Avogadro is rejected, molecular structure and the rules of directed valency are facts of nature, belonging to the complexity level where the 'elementary objects' (building blocks, *cf.* Sect. B.2) are the atoms of the periodic table.

D.3 Observability and time

We have mentioned in Sect. D.1 doubts about molecular shape – which, if valid, imply that molecular structure is at best of a topological nature. Those doubts are shown to be in general unjustified by the B-O theorem recalled in Sect. D.1, but, as mentioned, they raise an interesting issue in connection with the time evolution of molecular states.

We shall now briefly discuss that issue, with reference to molecular ground states.[20]

In principle, the different isomers obtained from a given collection of atoms – an indeterminate system Σ – are just forms of Σ corresponding to sets of states very weakly coupled to all other states. They give rise to distinct substances because, at least at temperatures not much higher than ordinary ones, they persist for a significant time, often for longer than a human lifetime.[21] Because of this, Σ in a state belonging to one of those sets is considered as a separate system – a molecule M unless, of course, its states are products of the states of individual atoms or groups of atoms.

That this is legitimate is clear from the consideration that, strictly speaking, the only isolated system in the Universe is the Universe itself, and a change in a single object is a change of state of the whole Universe. This holds even for the change in position of a hydrogen atom traveling alone in the background radiation field; but, because the parameters other than the velocity vector of that hydrogen atom remain constant, the latter can be treated as if it were alone.[22] But a philosophical difficulty arises. When we say that a set χ of (bound) states such that a very strong perturbation is required for them to go into states of Σ not belonging to χ *may be considered as* the set of all the states of a *molecule* M, *i.e.* a particular system resulting from Σ by imposing to it a particular structure, is that enough for the claim that those states belong to a system existing on its own right? The answer is positive, that is to say, M exists. In fact, the existence of M is implicit in the existence (observability) of its states χ in virtue of the following general axioms:

- reality exists and can be known;
- observation (direct or indirect) of the states of a system provides knowledge of its existence, and of its 'what-is-it', *i.e.* of what characterizes it with respect to other systems as perceived by the human mind;
- observed properties are characteristic of the given system in interactions with other systems, even in the absence of a human observer – *e.g.* the wave-particle dualism applies to a collision between a photon and an electron even in the absence of an observation.

The set χ is the 'what-is-it' of M, and M differs from other molecules or clusters that may be formed with the same atoms. If M is normally in the ground state and the other states can easily decay into it, then the nuclear configuration in the ground state determines M with respect to Σ, and the determining principle is the SC entity called 'structure'.

The possible objection that external perturbations (interaction with a photon, collision with another particle) can make M change into an isomeric molecule, or dissociate into one or more parts; that, indeed, such a change might take place spontaneously, can be met by a question: is my dog Argos not a being in all respects, only because it is bound to change one day into a carcass, as a result of external agents or age? More explicitly: for the entity M, resulting from the 'information' of Σ through a structure, to exist and persist as such it is not necessary that it should have an infinite lifetime.[23]

A serious problem arises, on the other hand, when the *minimum* lifetime of a structure is considered. The indeterminate system Σ might give rise to clusters having an extremely small or even a zero lifetime, corresponding to temporary aggregates of, say, two distinct molecules formed with its atoms, as in a transition state. Even granting that such a state exists as a determination of Σ, meaning that its existence is a necessary condition for certain observed events, one cannot say that it is a molecule, for it does not last long enough to be observable as such. Strictly speaking, a chemist would accept a determination of Σ as a molecule only if the corresponding pure substance could be prepared and isolated. A current softening of this condition consists in accepting that a molecule exists if the corresponding substance can be detected as such at least by fast analytical techniques in solution or in the gas phase.

This criterion implies that the lifetime of the individual molecules must be longer by a few orders of magnitude than the mean collision time (a couple of picoseconds, 10^{-12} s, for ammonia in the vacuum at room temperature). This means that the states χ(M) of a molecule M are quasi stationary states which will not go into states of Σ corresponding to other structures faster that a few picoseconds.[24]

This remark provides a clear-cut answer also to the question of molecular shape recalled in Sect. D.1. Although that is seldom the case, it might happen that two equivalent (or even isomeric) structures A and B of Σ have ground states separated by a rather low energy barrier, so that the sets of states χ(A) and χ(B) of Σ are actually coupled to a significant degree and A changes periodically into B. Is it right to say that χ(A) and χ(B) correspond to two distinct structures?

The doubt thus raised becomes more puzzling when it is considered that quantum mechanically this situation may be represented as one where there are stationary states in Bohr's sense (*i.e.* states extremely weakly coupled in the absence of external perturbations) which are linear combinations of states corresponding to both structures. One might be tempted to claim that in such cases quantum mechanics is not compatible with the geometrical face of molecular structure. There is a flaw in the line of reasoning leading to this conclusion which can be illustrated on the case of the ammonia molecule.[25]

Classically, the ammonia molecule NH_3 is endowed with an inversion vibration, *i.e.* oscillation between two pyramidal configurations having the nitrogen atom on either side of the basis, formed by the three hydrogen atoms. Quantum-mechanically, this means that the quantum states of ammonia come in pairs of weakly coupled degenerate components |Nupâ and |Ndownâ. After they have been prepared *e.g.* by making NH_3 molecules pass through a strongly non-homogeneous electric field, there is a periodically changing probability that a successive observation will find in a state |Ndownâ a molecule originally in |Nupâ, and conversely. The period is precisely the classical inversion period (0.035 ps). Now, according to the preceding remark, Bohr's quasi-stationary states can be built by combining |Nupâ and |Ndownâ with equal weights. This transforms each degenerate pair into a doublet of closely lying states corresponding to a planar symmetry. *Ergo*, one might say, the ammonia molecule, which the chemists expect to be pyramidal, is actually planar; the only way out from this aporia is to admit that it has no shape. Here is the answer. As shown by Feynman, even a slight perturbation would make either of the stationary states collapse into either |Nupâ or |Ndownâ which correspond to pyramidal shapes associated with angular momentum quantization; quantum mechanics says that no intermediate configuration is 'allowed'. Therefore, whenever it is observed or interacts with any other particle, the ammonia molecule always behaves as a pyramidal structure; the planar stationary states are useful mathematical intermediates, and could be attributed a physical meaning only when time periods far longer than the inversion period are considered, as when a microwave photon is emitted or absorbed.[26] Note that the potential energy profile for ammonia inversion is a double well, with energy minima corresponding to the two pyramidal configurations.

The case of the Kekulé 'structures' of benzene introduced in the chemical resonance theory should be mentioned, because confusion may arise from the fact that there the term 'structure' stands for 'bond arrangement', the nuclear frame being ignored. As such, those structures correspond to degenerate *electronic* states associated to the same nuclear configuration. In that sense they are crude approximations of structures predicted by the chemical theory of molecular structure, which should have alternating short and long bonds. If thus redefined, they show the real nature of the major contribution of quantum mechanics to the theory of chemistry: the two degenerate structures, at variance with the case of ammonia, do not correspond to energy minima, and it is their 50–50 linear combination which does so; consequently, out of the 217 isomers mentioned above, at least the two corresponding to a distorted hexagon alternating (long) single and (short) double bonds are only realized as extremes of a vibration; therefore, in accordance with the above analysis, they cannot be treated as representations of a genuine molecule. Even a perturbation would not normally stabilize them – at variance with the case of ammonia –, because the energy required is large.

In sum, doubts about the existence of molecular structure and molecular shape (except as regards resonance of electronic structures) seem to be due to a misunderstanding: it is not the mathematics of quantum mechanics that determines what exists and what does not exist in the world of FC and SC R2 entities, but their experimental observability. This point, as it seems, should be taken as a starting point for reflections on molecules and their structure, in full agreement with Bohr's *Kopenhagener Geist der Quantentheorie*. As to its implications for the ontology of the world of molecules, the above discussion is only a first exploration, which should be followed by quite a subtle and intricate technical discussion.

D.4 Status of molecular structure and bonds

Apart from our last remark, we have reached a general conclusion which can be summarized as follows:

> Molecular structure is a static topological and geometrical order principle which belongs to the reality of a molecule, indeed is what distinguishes a particular molecule from all other clusters and molecules consisting of the same

> atoms. It is a 'principle' in the following sense: it is a unitary SC entity to which a variety of observable molecular properties belong; it can only be observed, as any other entity, through properties which depend on it; indeed, the latter belong to it, in the sense that, (a), they are inseparable, (b) they vanish as soon as the structure disappears, (c), they all change more or less dramatically if the structure changes.

What is the status of molecular structure from the complexity viewpoint? This question arises from the analysis of example 4b of Sect. A.2, where we have suggested that what makes a whole a whole may range from a set of essentially additive properties to something entirely new with respect to the parts, having properties of its own (organization). It would seem that it has already something in common with organization; to be sure, it is not related to actual exchange of information, but it makes a molecule behave as a whole, as is shown immediately by the remark that, at variance with a crystal, cleavage of a bond yields molecules (radicals or ions, in general) having completely different properties. This is the reason why it is a 'principle'; and the qualification 'static' used above is a concise way of telling that it does not correspond, as the organization of a cell (example b, Sect. B.2), to an internal activity capable of adaptation to a changing environment.

This consideration completes as it were the evidence in favor of the claim that, far from being a property of symbolic diagrams, molecular structure is a real SC entity which cannot be reduced to 'atoms and quanta'. There remain, of course, many subordinate questions, the most important one being the existence of the chemical bond. To answer this question in detail it would be necessary to retread the path followed for structure; we only recall here that, as the analogy by which structure becomes intelligible to us is that with the stick-and-ball, or, better, spring-and-ball model of a molecule, so also a bond as an SC entity must be defined by means of an analogy (a privileged connection analogous to a quasi-rigid spring but, for one thing, not isolable) to which corrections and reservations are added.

D.5 Structures and formulas

In the work already cited, Schummer pointed out that structural formulas may be looked at as analogical representations (which stand for molecules in virtue of an analogy) helping chemists to keep track of the static and dynamic properties of molecules.[27] This view has its merits, for it emphasizes that the chemists do not work with mathematical symbols, as the physicists do, but with schematic topological and geometrical representations of molecules. It might be misleading, however, to think that structural formulas are only a reminder of molecular properties. Indeed, since the beginning there was great emphasis on their faithfulness to the spatial arrangement of atoms and bonds. Nowadays, the formula as a simplified but essentially correct representation of a molecule in space is the tool for designing new, strange molecules ('supermolecules')[28] and for understanding the role of configurations in biochemical processes.

Apart from the great historical events (such as the discovery of the biochemical significance of protein and DNA conformations), suffice it to mention that in a single issue of *Nature*, chosen at random from a bookshelf, we found formulas used both to represent schematically the conformations of immunoglobulin[29] and to show how certain supermolecules could be obtained by inserting two independent cyclic molecules one into the other (as chain rings, 'catenanes').[30] We add that geometry-dependent features like Bayer strains characterize molecules which are comparatively unstable and/or highly reactive: *e.g.* (in today's formulas) a hydrocarbon molecule represented by a triangle on paper is more 'strained' than one represented by a pentagon, because the angles are 60° instead of 108°.

Thus, a structural formula can be interpreted as a representation of a molecule with its structure in the same way as a drawing of a person can be used to discuss the difference in profile between that person and another. As said, this consideration is not in contrast with the use of chemical formulas as 'thinking aids', but it should be kept in mind in order not to fall into traps like misunderstanding the meaning and epistemological status of the Born-Oppenheimer approximation (Sect. D.1).

Notes

[1] W. Heisenberg, *Physics and Philosophy*, Harpers & Bros., New York 1958.

[2] See Sect. D.1 for references.

[3] The literature on this point is next to infinite; suffice it to recall two books which we consider representative of the situation of ontology today: W.O. Quine, *From a logical point of view*, Harvard Univ. Press, Harvard/Mass 1953, 1961; H. Putnam, *The many faces of Realism*, Open Court, La Salle/Ill. 1987. A critical study of realism in science with emphasis on chemistry has been given by J. Schummer, *Realismus und Chemie*, Königshausen & Neumann, Würzburg 1996.

[4] Called *substances* in the Aristotelian tradition.

[5] The ontological status of entities like a pure number or an idea will not be explicitly considered here.

[6] *Op. cit.*, p. 13.

[7] An energy barrier with walls higher than about 150 kJ/mole will usually do. By 'energy' one means here one of the thermodynamical functions $E-TS$ or $H-TS$, *viz.* internal energy E or enthalpy H minus the temperature T times the entropy S, because they represent the energy which matters for chemical reactions. For a recent discussion and references *cf.* 'A controversy about the Gibbs function', in: *Journal of Chemical Education*, 73 (1996), 384-412.

[8] As is well known, except in borderline cases molecular biologists do not consider the molecular nature of enzymes as part of their subject, for their problems always bear on how the enzymes interact, cooperate and maybe change into one another or form new enzymes to perform certain tasks in a cell.

[9] Schummer rightly calls these objects *Bausteine*, building blocks, although he adopts an essentially topological definition of molecular structure (*op. cit.*, pp. 254, 268).

[10] Robert Boyle: *The sceptical chymist* (1661), chap. 6.

[11] *Cf.* F.A.v. Kekulé: *Berichte der Deutschen Chemischen Gesellschaft*, **23** (1890), 1302. Trans. into English by O.T. Benfey, *Journal of Chemical Education*, **35** (1958), 21-23.

[12] L. Paoloni: 'I contesti della scoperta della struttura molecolare. IV. Un caso esemplare: la rappresentazione del benzene 1865-1932. – *Contexts of the discovery of molecular structure. IV. An exemplary case: the representation of benzene 1865-1932*' (in Italian), in: P. Riani and G. Villani (eds.), *Lecture notes for the Summer School on the methodological and epistemological foundations, history and teaching of chemistry*, ICQEM-CNR, Pisa 1996. For copies contact Istituto di Chimica Quantistica ed Energetica Molecolare, via Risorgimento 35, I-56126 Pisa, Italy. Also the preceding lectures by Paoloni, in the same book, are of the greatest interest.

[12a] Both quotations are reported by Paoloni, *loc. cit.*, Note 12.

[13] We are not taking here a precise position, but we are inclined to agree with the analysis made by C. Fabro, *Percezione e Pensiero – Perception and Thought,* Morcelliana, Brescia 1962, chap. 1, where he compares W. Köhler's *Gestalttheorie* with the Aristotelian view about knowledge of sensible reality.

[14] *Cf.* Schummer, *op. cit.*, p. 246f.

[15] A review can be found in the famous paper by F. Hund, *Zeitschrift für Physik*, **73** (1932), 1-30.

[16] M. Born & J.R. Oppenheimer, *Annalen der Physik*, **84** (1927), 457. A slightly different presentation is given by J.C. Slater, *Quantum Theory of Molecules and Solids*, McGraw-Hill, New York 1963, Vol. 1, App. 2. Slater correctly speaks of the B-O approximation as a 'theorem'. A more detailed presentation is given by A. Messiah, *Mécanique Quantique*, Dunod, Paris 1959.

[17] M. Born & W. Heisenberg, *Annalen der Physik*, **74** (1924), 1.

[18] This value applies to the maximum-amplitude (the γ-mode of the ring at 405 cm^{-1}), excited with one quantum (7.4% probability at room temperature); the majority of the atoms are in the vibrational ground state, with a maximum uncertainty of 0.06 Å on their positions. The bond lengths are 1.40 and 1.00 Å for CC and CH, respectively. Although computed from the harmonic oscillator wavefunctions, this illustrates the general B-O theorem, according to which the amplitude of the nuclear motions about their equilibrium positions in the first vibrational excited state is ca. 1/10 of bond distances or less; in the ground vibrational state it is far smaller, of course.

[19] R. G. Woolley, *Journal of the American Chemical Society*, **100** (1978), 1073-1078. *Cf.* Schummer, *op. cit.*, p. 164.

[20] For excited states molecular structure is not yet easily observable, but there is already sufficient experimental evidence to prove that the same notion applies; anyway an extension of the considerations given below is possible.

[21] Certain organic molecules are found in coal, and are likely to have persisted since the Carboniferous, millions of years ago.

[22] This is a crude way of stating the famous Mach principle in quantum mechanical language.

[23] This remark is not superfluous, because such popular philosophers of science as K. R. Popper apparently saw in continuous change an argument for claiming that what is real is only events and processes.

[24] We shall discuss elsewhere the problem posed by the fact that the lifetime as defined here is temperature and environment dependent.

[25] The essential points are given by R. Feynman, *Lectures in Physics*, Eddison-Wesley, Reading/Mass. 1963, part III, chap. 8, in his treatment of the ammonia maser.

[26] This point is related to the general epistemological framework of quantum mechanics. A brief but masterful discussion is to be found in W. Heisenberg's *The physical principles of quantum theory* (translation from German), Univ. of Chicago Press, Chicago 1930, chap. IV, p. 65.

[27] Schummer, *op. cit.*, p. 243ff.

[28] *Cf.* V. Balzani, F. Scandola: *Supramolecular Photochemistry*, Ellis-Horwood, New York-London 1991.

[29] C. Chothia *et al.*, *Nature*, **342** (1989), 877-883.

[30] R. Pease, *ibid.* pp. 859-60.

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