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Dedicated to Professor Ionel Haiduc
on the occasion of his 65th birthday

A CHALLENGE FOR CHEMISTRY: VERY LARGE INORGANIC MOLECULES PENETRATE THE MESOSCOPIC REALM

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ABSTRACT. The paper aims to denominate and present the largest synthesized and structurally characterized molecules.

To begin with, the terms chemical compound and molecule are analyzed and differentiated. Two types of very large/giant molecules are defined: a) collective large molecules, generated through an inflationary multiplication (in one, two or three dimensions) of one or several species of smaller discrete molecules and b) discrete/individual large molecules, constructed by actual synthesis through the assembly of appropriate building blocks.

The candidates for the title of the largest molecule are sought among the discrete giant molecules.

Reviewed are very large molecules synthesized over the past 30 years, starting with the classical molecular polyoxometalate clusters $[As_4W_{40}]$ and $[P_8W_{48}]$ and continuing with the new supramolecular polyoxometalate clusters, such as $[Mo_{57}M_6]$, $[Mo_{132}]$, $[Mo_{72}Fe_{30}]$, $[Mo_{102}]$, $[Mo_{154}]$, $[Mo_{176}]$, $[Mo_{248}]$ and $[Ln_{16}As_{12}W_{148}]$. The $[Mo_{368}]$ cluster, currently the largest synthesized and structurally characterized molecule, concludes the presentation.

The possibility of synthesizing even larger molecules is also envisaged.

1. INTRODUCTION

According to a frequent simple definition, chemistry is the discipline that studies the composition, structure, properties and transformations/reactions of chemical substances. The definition underlines that the object of study, i.e. the prime matter of chemistry, is represented by chemical substances that can be conventionally divided into chemical elements and chemical compounds.

One of the criteria of evaluation of the development and progress of chemistry is also the continual diversification of its objects of study. The discovery and later the "creation" in laboratory of new elements, with an ever higher atomic number and atomic mass, has always been immediately popularized. The discoverers of new chemical elements enjoy general recognition in the scientific community and certain elements are even named after them. But the number of chemical elements, which is currently of 113 (a previous number of 115 elements (in 1999) was reduced to 113 (in 2001), because the existence of elements 116 and 118 now seems to be suspect after which subsequent experiments failed to reproduce the original data of the authors which had announced their discovery) [1], seems to approach a limit that is rather physical than experimental in nature.

On the other hand, the problem of chemical compounds is much more confusing. Due to the fact that the possibility of combination of the elements seems to be limitless, obtaining new chemical compounds is pursued in a frenzy and represents the favorite occupation, almost a “hobby-horse”, of chemists today. Chemists tend to turn into “laboratory robots” running in a rat race to discover, list and characterize an ever increasing number of chemical compounds, basically molecules often with no clearly defined purpose. Due to the joint effort of chemists all over the world, the number of registered organic and inorganic substances/compounds is of 20,120,922, to which 21,479,781 biosequence substances can also be added, thus increasing the total number of registered chemical substances/compounds to 41,600,703, according to the statistics offered by **Chemical Abstracts Service** (as of August 13, 2002) [2]. Thus, the words of Berthelot that “*chemistry creates its own object”* are more topical than ever. Developing this idea we can also characterize our discipline by the following statement: “*Chemistry is a natural science which creates and diversifies its object of study by the activity of its practitioners who construct in laboratory ever new molecules”*.

Within the efforts of chemists to obtain more or less surprising and expected new chemical compounds/molecules, the activity of those who construct ever larger molecules, with high symmetry and aesthetic qualities, has a pride of place and it represents the starting point of this paper. In essence, the topic of the paper is the presentation of the largest molecules synthesized by chemists and the evolution of the record in the field, a subject that has never really been satisfactorily treated in literature up to now.

Before discussing these aspects, we will try to throw light upon the terms of chemical compound and molecule that seem more complex and complicated than they might appear at first sight.

2. CHEMICAL COMPOUNDS AND MOLECULES

Almost automatically we identify chemical compounds with molecules, in the sense that chemical compounds would be constructed of molecules, if not actual at least conventional ones. We calculate for every chemical compound a molecular mass taken to be the mass of an (actual or conventional) molecule of the respective compound.

In fact, chemical compounds represent complex systems of atoms and/or ions, which are electrically neutral and have a well-defined composition and structure. This somewhat ambiguous and vague definition is due to the high diversity of chemical compounds.

According to the defining structural unit, chemical compounds can be divided into molecular and ionic compounds.

The actual chemical compounds are the molecular ones and they are by far the most numerous. The molecular compounds are in fact molecular species with clearly defined constituents and structure.

The molecule, as the structural unit of molecular compounds, is a system of atoms linked by covalent bonds (to which can also be added noncovalent bonds).

On the other hand, ionic compounds are systems of ions with opposite charges, kept together by electrostatic forces. The ions with opposite charges generate an ionic crystal, in which they are arranged tridimensionally in a crystalline lattice. In the case of ionic compounds the notion of molecule is practically meaningless. That is why ionic compounds should rather be considered ionic aggregates or ionic substances than actual chemical compounds.

But the classification of chemical compounds into ionic and molecular is not always sufficient and satisfactory. Thus, certain ionic compounds which form ionic crystalline lattices also contain a molecular unit and cannot be reduced to pure ionic compounds. For example, the lattice of sodium carbonate, i.e. Na_2CO_3 is composed of Na^+ and CO_3^{2-} ions, but the CO_3^{2-} anion is in fact a molecular anion (anionic molecule) with covalent bonds between carbon and oxygen atoms. In their turn coordination compounds, which are characterized by a great number of coordinative and covalent bonds are not, with the exception of the electroneutral ones, pure molecular compounds. So, the first characterized heteropolyoxometallic acid, i.e. $H_3[PW_{12}O_{40}] \cdot 6H_2O$ with the structure determined by Keggin, has as a main constituent a molecular unit, namely the $[PW_{12}O_{40}]^{3-}$ molecular anion (anionic molecule). But between the molecular anion and the acidic H^+ there are only electrostatic interactions (i.e. ionic bonds) and the crystal water is linked to the compound only through noncovalent bonds (i.e. hydrogen bonds).

Consequently, the concept of chemical compound remains somewhat conventional and confusing. On the other hand, the concept of molecule seems to be relatively straightforward and unambiguous; it is independent of the electrical charge and, as a result, there are neutral molecules, cationic molecules (molecular cations) and anionic molecules (molecular anions). Only in the particular case of certain neutral molecules can the chemical compound and the corresponding molecule be mixed up.

However, for the moment we shall forbear to ask the following delicate question: In the case of densely packed metal-atom arrangements, where does the molecule (the molecular state) end and when does the solid-state bulk metal begin?

We also mention the case where a certain molecule, even with complex structure and high symmetry, does not belong/correspond to a chemical compound proper. Thus, the famous C_{60} neutral molecule, the so-called *buckyball* or fullerene, is not an actual chemical compound but rather it is an allotrope state of carbon distinct from diamond and graphite.

One may well ask oneself what is the sense and especially the accuracy of the notion of molecular mass, which is usually calculated for every chemical compound.

The attempt to clarify the exact status of molecules and why they cannot be identified with the corresponding chemical compounds is an important but not sufficient step in the search for the largest synthesized molecules.

The next step involves the identification and nominalization of the researched molecules by a previous selection of various kinds of species.

Our intention is to eliminate from the beginning the giant molecules resulting from an excessive multiplication of one or more smaller molecules or fragments, such as for instance common polymers. In this type of molecules, the degree of multiplication is sometimes so high, that it is undetermined or even cannot be determined and is formally taken to be infinite. It is obvious that such types of molecules, resulting from a simple photocopying multiplication (in one, two or three dimensions), do not belong to the species looked for by us.

Our attention has been focused on giant molecules generated by actual synthesis and built up through successive assemblies, which can be considered discrete or individual molecules.

But the differentiation and especially the pinpointing of the distinctions between the two types of molecules is far from being simple and easy, all the more so since both are made up of smaller (actual or formal) molecules and/or fragments. The differences obtain especially concerning their production and usually their symmetry. The development of supramolecular chemistry, with its by now famous supramolecules, further complicates the attempts at general classification of giant molecules and molecular buildings.

With the above mentioned reservations, we shall name and define the two types of very large and giant molecules (which are obtained/prepared in laboratory), as follows:

> a) *collective large molecules*, generated through an inflationary multiplication of one or several smaller species of discrete molecules or molecular fragments, in one, two or three dimensions, with formation of chains (1D), layers (2D) or networks (3D).
>
> The multiplication process occurs through reactions of addition and/or condensation and presupposes necessarily covalent bonds between units. The existence of noncovalent intermolecular interactions beside the covalent ones, as well as of linkers/spacers is also allowed and sometimes possible. Usually, collective large molecules have low symmetry or at least low local symmetry and are qualitatively a molecular assembly of smaller molecules/molecular units/fragments expanded in one, two or three dimensions. The most widely known collective molecules are the classical/common polymers and copolymers.
>
> b) *discrete/individual large molecules*, constructed by actual synthesis through the assembly of appropriate building blocks which are molecular units/moieties/fragments.

> The bonds between the molecular units are necessary (and) covalent. The existence of noncovalent intermolecular interactions, in addition to the covalent ones, as well as of certain linkers/spacers, heretoatoms and other small molecules, is allowed and relatively frequent. Discrete large molecules usually have high or very high symmetry and are qualitatively different from the building blocks/molecular units out of which they have been assembled.

When the bonds between molecular units are exclusively covalent, it is the case of classical discrete molecules, which belong to molecular chemistry. But the largest and more spectacular discrete molecules belong to supramolecular chemistry and represent supramolecular discrete molecules. Supramolecules are characterized by a cooperative action among the composing entities which act as building blocks in the assembly process (self-assembly and even self-organization) and also the mandatory presence of noncovalent bonds (hydrogen bonds, ionic/electrostatic interactions, π bonding interactions, secondary bonds (soft-soft interactions), week interactions (i.e. van der Waals forces) etc.) [3, 4].

Thus, the differences between the two types of large molecules remain ones concerning their production, to which qualitative elements are also added. In the case of collective molecules, the original molecular species act(s) as a unit or pattern/matrix for multiplication. On the other hand, in the case of discrete/individual molecules, the original molecular species acts as building blocks in the assembly and organization (sometimes self-assembly and self-organization) processes. If in the first case the result is more or less a molecule which is a conglomerate of molecules, in the second case the product is a distinctly individual molecule with high symmetry.

Nevertheless, certain additional remarks are necessary. In some cases, certain discrete large molecules, including supramolecules, can further condense, generating chains, layers or networks. The final product is a giant collective molecule made up of large discrete molecules.

In both cases under discussion, only the molecular units integrated in the assembly exclusively or inclusively by covalent bonds belong to the giant molecule. When the assembly also contains components integrated exclusively through noncovalent bonds, the whole assembly is no longer identical with the giant molecule and can be defined as a supramolecular array [3, 4].

To round off the topic, we must also mention that over the last decades a high number of so-called (ligand-stabilized) metal clusters have been reported. They consist of a “core” of a certain number of metal atoms surrounded by a “shell” of organic ligands which stabilize the metal core and inhibit nucleation to metal bulk. The metal-atom core, composed of a central atom and concentric shells of densely packed atoms, contains occasionally a huge number (up to hundreds and even over one thousand) of metal atoms. But usually, structural analysis is not possible due to the lack of crystalline samples. On the other hand, these metal clusters should rather be considered intermediates between molecules and the bulk metal than actual molecules. For all these reasons, we shall neglect the metal clusters in our search for the largest molecule.

3. VERY LARGE SYNTHESIZED AND STRUCTURALLY CHARACTERIZED MOLECULES

After the qualitative identification of the researched candidates for the title of the largest molecule, i.e. discrete giant molecules constructed by the assembly of building blocks, it is necessary to select them following a quantitative criterion.

In this sense, the following criteria/parametres can be used:

- the (total) number of metal centres (=a);
- the (total) number of heavy atoms (=b);
- the number of non-hydrogen atoms (=c);
- the relative molecular mass (=M);
- the linear dimensions, e.g. the diametre (=d).

A number of observations are in order. The first two criteria/parametres are inoperative in the case of organic molecules. The number of heavy atoms and metal centres is not necessarily equal, not even in the case of clusters, for example when they contain heavy non-metal atoms. The last criterion is also relative, because huge molecules usually have one or more internal cavities.

The literature shows that the largest discrete molecules belong to inorganic chemistry, while organic chemistry is remarkable especially for large collective molecules. That is why we shall use the first parametre, i.e. the number of metal centres, as the main criterion to differentiate the largest molecules; mention will however be made of the values of the other parametres.

Over the last decades, the largest synthesized and structurally characterized molecules were the polyoxometalates (POMs). POMs are metal oxide-based clusters and represent the polyoxoanions of the early transition metals/elements, especially Mo, W and V, constructed of linked MO_n units (usually MO_6 octahedra). The M metal centres, which may belong to one or more atomic species, are named addenda [5].

In the case of POMs, we shall consider that the number of metal centres is equal to the number of actual addenda (to which may be added other metal atoms that occupy the place of some absent/missing addenda). On the other hand, by heavy atoms we mean metal centres (including those replacing absent/missing addenda), to which are added, as the case may be, other heavy atoms acting as linkers/spacers (between building blocks) and heteroatoms. Thus, heavy atoms are atoms (exclusively or inclusively) coordinated by ligands.

For every POM cluster/molecule a complete formula, which notes all the atoms, and an abridged/short formula, which notes only the heavy atoms, can be written.

3.1. CLASSICAL MOLECULAR POLYOXOMETALATES

After decades of heated controversy concerning the accurate formulation of POMs, Keggin first determined in 1933 the structure which was to bear his name, by investigating the $[PW_{12}0_{40}]^{3-}$ molecular anion [6]. In the following years, the structure of numerous classical POMs, which belong to molecular chemistry, was determined.

We shall present only two of them, which at the very moment of their characterization were at the top of the list of the largest molecules with determined structure.

$[As_4W_{40}]$ and derivatives

The first molecule with a minimum of 40 metal centres, the $[As^{III}{}_4W_{40}O_{140}]^{28-}$ POM cluster, abridged as $[As^{III}{}_4W_{40}]$, was reported in 1974 [7]. The $[As_4W_{40}]$ cluster was shown to bind two additional transition metal cations. The first structure determination was only performed in 1980 by Robert, Leyre and Hervé [8] on the complex with Co(II) having the formula $[|NH_4|As^{III}{}_4W_{40}O_{140}Co^{II}{}_2(H_2O)_2]^{23-}$ or $[As^{III}{}_4W_{40}Co^{II}{}_2]$ (a=42, b=46, c=189, M=10065.18).

The structure determination revealed that the parent cyclic $[As_4W_{40}]$ unsaturated cluster is built up from four α-B-$[As^{III}W_9O_{33}]^{9-} \equiv [AsW_9]$ trilacunary Keggin fragments/units, linked together by four bridging cis-$[WO_2]^{2+}$ groups (Fig. 1).

The $[As_4W_{40}]$ cluster, with D_{4h} symmetry, is a cryptand and has a central cryptate site (S_1) and four lacunary sites (S_2). The S_1 site can be occupied by alkali, alkali-like, alkaline earth and lanthanide ions, with the formation of stable cryptates. Two of the four S_2 sites can be occupied by di- or trivalent metal ions, which have a single terminal H_2O ligand. Only Ag^I can occupy all four S_2 sites.

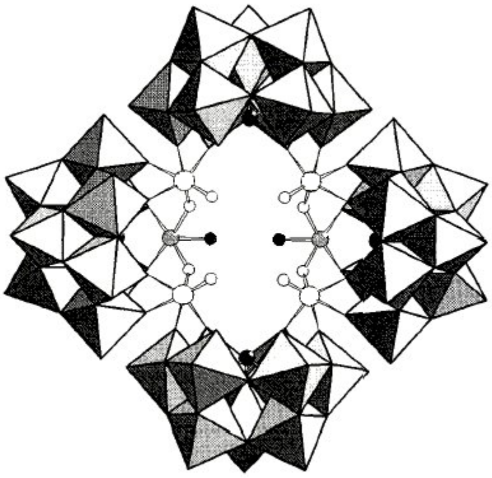


Fig. 1. Structure of the $[|NH_4|As^{III}{}_4W_{40}O_{140}Co^{II}{}_2(H_2O)_2]^{23-} \equiv [As^{III}{}_4W_{40}Co^{II}{}_2]$ POM cluster. The four $[AsW_9]$ units are shown in polyhedral representation, while the four cis-$[WO_2]^{2+}$ groups (W large white spheres; O small white spheres) and the two $[Co^{II}(H_2O)]^{2+}$ groups (Co small gray spheres; H_2O small black spheres) are figured in ball-and-stick representation. The encapsulated NH_4^+ ion has been omitted.

[P_8W_{48}]

In 1985, Contant and Tézé [9] synthesized and determined the structure of an even larger POM, namely [$P^V_8W_{48}O_{184}]^{40-}$ or [P_8W_{48}] (a=48, b=56, c=240, M=12016.05).

The very massive [P_8W_{48}] ring, having a high symmetry (D_{4h}), is built up from four $[H_2P_2W_{12}O_{48}]^{12-}$ ≡ [P_2W_{12}] units. The [P_2W_{12}] unit is the hexalacunary fragment of the $[P_2W_{18}O_{62}]^{6-}$ Dawson anion, resulting from the removal of an enormous block of six lengthwise adjacent W atoms, i.e. six WO_6 octahedra, sharing edges and corners (Fig. 2).

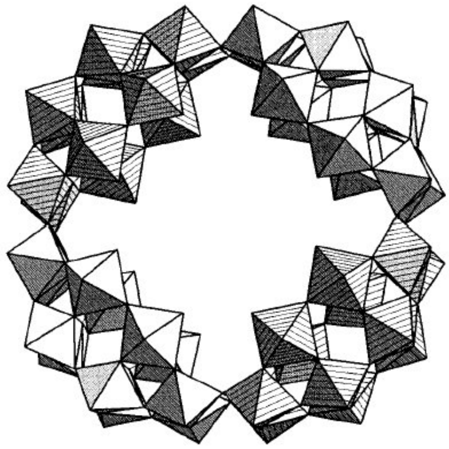


Fig. 2. Structure of the $[P^V_8W_{48}O_{184}]^{40-}$ ≡ [P_8W_{48}] POM cluster in polyhedral representation, as a cyclic assembly of four lacunary [P_2W_{12}] groups. The internal [PO_4] tetrahedra of the latter have been omitted and only the [WO_6] octahedra are figured.

3.2. THE NEW GENERATION OF VERY LARGE SUPRAMOLECULAR POLYOXOMETALATES

Starting in the 1990s, the development of supramolecular chemistry and especially the activity of Achim Müller and his research team from Bielefeld University (Germany) opened a new chapter in the synthesis of exceptionally large inorganic molecules.

Currently, chemists construct more complex and large molecules in a step-wise manner through a time-consuming and hard-work sequential synthesis, isolation and purification of each intermediate, following the logic of retrosynthesis. But recent developments in supramolecular chemistry brought a very different approach for the synthesis of giant molecules, which is characterized more by “intelligence” than by hard-work and is not time-consuming.

The so-called bottom-up method uses a type of unit construction under a multicomponent one-pot synthesis. The novel synthesis strategy allows on the basis of a number of simple combinatory linkable building blocks/ units at the disposition, the obtaining, by successive and rapid processes of self-assembly, self-organization and molecular growth, of a huge variety of very large molecules. This is the starting point of a new type of chemistry, which is directed by geometrical and topological rules.

The basic chemical principles for the new strategy provide a number of features that offer excellent prerequisites for the synthesis of giant molecular species.

Müller [10-13] mentions the following conditions/parametres that favour the emergence of molecular complexity and the obtaining of very large molecules:

1. *Abundance of transferable building blocks.* This concept does not only refer to the geometrical/structural decomposition into smaller entities/units/motifs/building blocks, but reflects also their well-defined reactivities determining the unit-specific local matching rules according to which these building blocks can be linked.
2. *Versatile redox chemistry.* Different degrees of reduction of a number of metal centres to obtain mixed-valence species offer the possibility to tune the electron density of the cluster.
3. *Integration of hetero elements and exchange of ligands.* This allows altering reactivity, functionality and the physical properties, such as the magnetism of the final resulting cluster.
4. *Tunable charge/size ratio.* The charge of the growing molecular fragment can be modified by the exchange of ligands, inclusion of hetero elements, exchange of some metal centres or an optimal reduction of the existing metal centres using an adequate reducing agent. An increased absolute (negative) charge, while keeping the charge density constant of the intermediates in solution, guarantees a good solubility that is necessary for the ongoing molecular growth and prevents possible degradations by hydrolysis.
5. *Template functionality.* The formation of very large molecules is in special cases facilitated by supramolecular-type interaction between the growing fragments and other species present in the reaction solution, for instance those which can act as templates.

These conditions can only be optimally fulfilled in POM systems, especially molybdenum oxide-based POMs, which possess the relevant variety of molecular and electronic structures/configurations.

The suitable systems for such research work are solutions of tetrahedral oxoanions of the early transition metals/elements of the MO_4^{n-}-type ($M=W^{VI}$, V^{V} and especially Mo^{VI}). Using the same reaction type, i.e. the acidification of aqueous solutions of these oxoanions, a large variety of discrete giant POM molecules, with amazing structures and properties, can be obtained (essentially through a process which involves successive condensations).

Additional external chemical interventions, e.g. those mentioned above, such as the presence of reducing agents (especially those with the possibility of multi-electron transfer), appropriate templates and hetero elements, lead to an even greater molecular and structural diversity.

It is to mention that the condensation process may continue, leading to chains, layers or networks which have as multiplication units even these discrete nano-sized POM molecules and represent macroscopic solid-state systems (supramolecular arrays).

Consequently, for the first time the possibility to construct in a planned and deliberate way giant molecules, i.e. POM clusters, under one-pot synthesis has become available. The step-wise building process fundamentally entails the existence of adequate linkable building blocks and possibly of different types of linkers/spacers as well as a control parametre, such as the reduction degree (but also the pH value), which influences the kind of successive building blocks formed.

Accordingly, the following question should be addressed: Into what types of structural building blocks can a giant molecule be conventionally reduced, with the possibility of generating a structural and functional hierarchy starting just from these blocks?

Müller [10-13] has done important work in the inventory of the virtual library of building blocks, out of which can be constructed all the molybdenum oxide-based POMs known up to now. These linkable building blocks/units/ fragments/motifs/groups, in the form of Platonic and Archimedean solids, allow the chemist to operate conceptually with a large variety of distinct molecular modules derived from these units.

In essence, all known molecules and structures can be ultimately reduced to $[Mo_1]$ units (containing one Mo atom surrounded by a number of O atoms in different geometries) or to $[Mo_2]$ units (resulted, at least formally, of two $[Mo_1]$ units linked in various ways by edges and/or corners). But the most interesting are the larger building blocks which act as directing molecular modules and may lead to very large molecular systems of higher structural variability and versatility than is possible with arrangements of metal atoms having spherical symmetry. These basic/essential building blocks are the following: $[(Mo)Mo_5]$, $[Mo_8]$, $[Mo_{11}]$ and $[Mo_{17}]$.

A scientist with deep philosophical and aesthetical concerns, Müller [13] gives a special importance to the pentagonal building block/unit/motif. He has noticed the quasi-magical fascination exerted by pentagons over time; these have had an extraordinary role in the cultural and science history of mankind.

The pentagonal $[(Mo)Mo_5]$ building block with C_5 (or C_S when distorted) symmetry, consists of a central MoO_7 pentagonal-bipyramidal unit sharing its equatorial edges with five additional MoO_6 octahedra (Fig.3). Pentagons can be utilized as potential building blocks, especially for constructing spherical clusters of icosahedral symmetry. The icosahedral symmetry (I_h) can be achieved even if the pentagons do not share edges, but are interconnected by appropriate linkers, for instance in the so-called *giant sphere*-type POMs.

The $[Mo_8] \equiv [(Mo_1)[(Mo)Mo_5](Mo_1)]$ building block, characteristically curved, is built up of the densely packed pentagonal $[(Mo)Mo_5]$ unit to which two additional MoO_6 octahedra (sharing only corners) are more weakly connected and can more easily be removed. The $[Mo_8]$ unit makes possible the synthesis of even larger POMs, for instance of the so-called *giant wheel*-type.

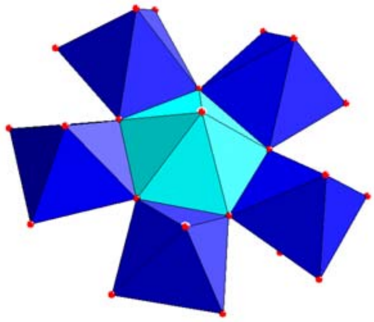


Fig. 3. Structure of the $[(Mo)Mo_5O_{21}]^{6-} \equiv [(Mo)Mo_5]$ building block in polyhedral representation. The central MoO_7 pentagonal bipyramid shares edges with five equatorial MoO_6 octahedra. Color code: MoO_7 unit blue-turquoise; MoO_6 units blue; O red.

The $[Mo_{11}] \equiv [(Mo)^0(Mo_5)^I(Mo_5)^{II}]$ building block has as its central part a pentagonal-bipyramidal MoO_7 unit of $(Mo)^0$-type with a directing function. Five MoO_6 octahedra of $(Mo_5)^I$-type are condensed to the equatorial plane of the central MoO_7 unit sharing edges, while the next five MoO_6 octahedra of $(Mo_5)^{II}$-type share corners with the former octahedra (the superscript 0, I, II indices mention the zero, first or second generation of the building unit) (Fig. 4). $[Mo_{11}]$ is the basic building block for POM molecules which can be formulated as $[Mo_{11}]_n$, i.e. *giant spheres* and *giant wheels*.

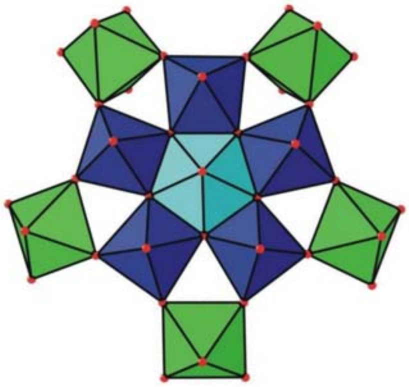


Fig. 4. Structure of the $[Mo_{11}] \equiv [(Mo)^0(Mo_5)^I(Mo_5)^{II}]$ building block in polyhedral representation. The central $MoO_7 \equiv (Mo)^0$ pentagonal bipyramid (zero generation) is connected to five equatorial $MoO_6 \equiv (Mo_5)^I$ octahedra (first generation) by sharing edges to which another five $MoO_6 \equiv (Mo_5)^{II}$ octahedra (second generation) are added by sharing only corners. Color code: $(Mo)^0$ unit blue-turquoise; $(Mo_5)^I$ units blue; $(Mo_5)^{II}$ units green; O red.

Finally, the large $[Mo_{17}] \equiv [(Mo_8)(Mo_1)(Mo_8)] \equiv [(Mo_8)_2(Mo_1)]$ building block can be reduced to two $[Mo_8]$ units fused via eight O atoms and symmetrically linked by an MoO_6 octahedron. The $[Mo_{36}]$ and $[Mo_{57}M_6]$ clusters are made up of two, respectively three such units.

Further, we shall present the largest POM clusters and the fascinating evolution of the record-holding largest synthesized molecule with structure determination.

$[Mo_{57}M_6]$ and derivatives

The three-fragment POM clusters of the $[Mo_{57}M_6]$-type (M=V, Fe) were the first synthesized molecules with over 60 metal centres.

In 1993, Zhang et al. [14], respectively Müller et al. [15] independently reported the synthesis of a large cluster of the $[Mo_{57}M_6]$-type. The molecular formula $[Mo_{57}V_6(NO)_6O_{183}(H_2O)_{18}]^{6-}$ given by the Chinese team was obviously false with respect to its composition, structure and the oxidation numbers of the metal centres. The molecule was structurally analyzed by Müller and coworkers in 1994 [16], who also established the correct formula, namely $[H_3Mo_{57}V_6(NO)_6\text{-}O_{180}(OH)_3(H_2O)_{18}]^{21-}$ or $[[V^{IV}(H_2O)O]_6[Mo^{V}(H_2O)_2(OH)Mo^{V}]_3\text{-}[Mo^{VI}{}_{15}(Mo^{VI}NO)_2O_{58}(H_2O)_2]_3]^{21-}$, abridged as $[Mo_{57}V_6]$ or $[Mo^{VI}{}_{51}Mo^{V}{}_6V^{IV}{}_6]$ (a=b=63; c=276; M=9212.54; d=2.2nm).

The $[Mo_{57}V_6]$ molecule, with 63 metal centres and 276 non-hydrogen atoms, has a high symmetry (D_{3h}) and contains three large $[Mo^{VI}{}_{17}]$ building blocks linked by six V^{IV} centres and three $[Mo^{V}{}_2]$ units (Fig.6a). More precisely, the doughnut-shaped cluster (which corresponds to an ellipsoid with the dimensions 2.2 x 2.2 x 1.0 nm) consists of three highly negatively charged $[Mo^{VI}{}_{15}(Mo^{VI}NO)_2O_{58}(H_2O)_2]^{20-}$ units, connected by six $[V^{IV}(H_2O)O]^{2+}$ groups and three dinuclear $[Mo^{V}(H_2O)_2(OH)Mo^{V}]^{9+}$ units.

In 1995, Müller and his team [17] also synthesized and characterized the analogous cluster with M=Fe, having the formula $[Mo_{57}Fe_6(NO)_6O_{174}(OH)_3(H_2O)_{24}]^{15-}$ $\equiv [[Fe^{III}(H_2O)_2]_6[Mo^{V}(H_2O)_2(OH)Mo^{V}]_3\text{-}\ [Mo^{VI}{}_{15}(Mo^{VI}NO)_2O_{58}(H_2O)_2]_3]^{21-}$, abridged as $[Mo_{57}Fe_6]$ or $[Mo^{VI}{}_{51}Mo^{V}{}_6Fe^{III}{}_6]$ (a=b=63; c=276; M=9251.09; d=2.2nm). The structure is similar to the previous cluster, with the difference that six Fe^{III} centres occupy the place of the six V^{IV} centres, more precisely the molecule has six $[Fe^{III}(H_2O)_2]^{3+}$ instead of six $[V^{IV}(H_2O)O]^{2+}$ units (Fig. 5).

The relatively large cavity inside the $[Mo_{57}M_6]$ molecular anions is formally accessible through two openings in the cluster shell. The cavity (with a diametre perpendicular to the S_3 axis of ≈ 0.9 nm and parallel to it of ≈ 0.5 nm) is delimited by a central $[O_{33}]$ polyhedron. The two openings are delimited by two alternating Mo-O-M-O 12-membered rings.

An interesting structural feature is the presence of six rather large cavities on the outher sphere between the $[Mo_{17}]$ units. These cavities are accessible to the coordination of further electrophyllic metal-oxygen fragments, i.e. $[MoO]^{4+}$ units. As a consequence, in aqueous solutions under strong reducing conditions and in excess of molybdate(VI) may undergo a step-by-step molecular growth process, which enables all $[Mo_{57+x}M_6]$ (x=0-6) species to be formed. Each $[MoO]^{4+}$ unit binds to three O atoms (two terminal) of the $[Mo_{57}M_6]$ core, resulting in a tetrahedral coordination of the incorporated additional Mo atoms. The degree of occupation of the cavities (the x value) can be correlated with the reduction degree of the $[Mo_{57}M_6]$ cluster. Reduction increases the nucleophilicity of the core-cluster and initiates a growth process in which up to as many six electrophilic units can be incorporated.

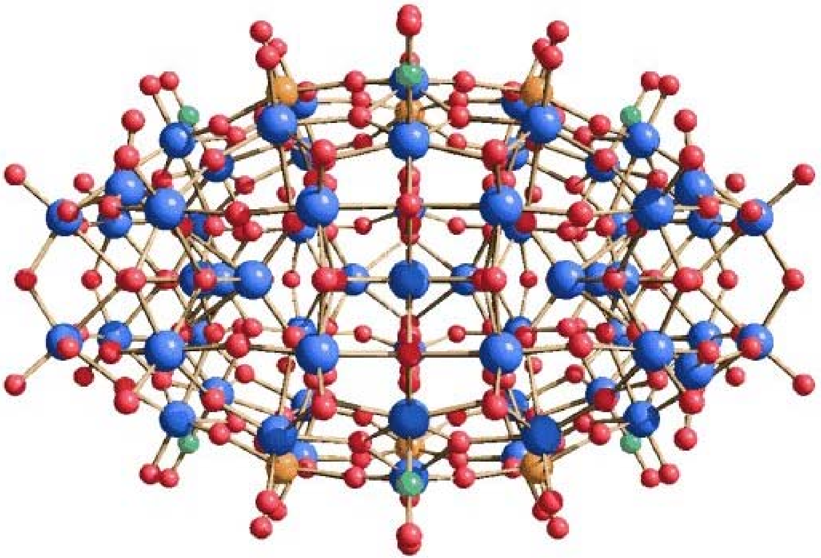


Fig. 5. Ball-and-stick representation of the $[Mo_{57}Fe_6(NO)_6O_{174}(OH)_3(H_2O)_{24}]^{15-} \equiv [Mo_{57}Fe_6]$ POM cluster along one of the $2(C_2)$ axes. Color code: Mo light gray; Fe orange; O red; N green.

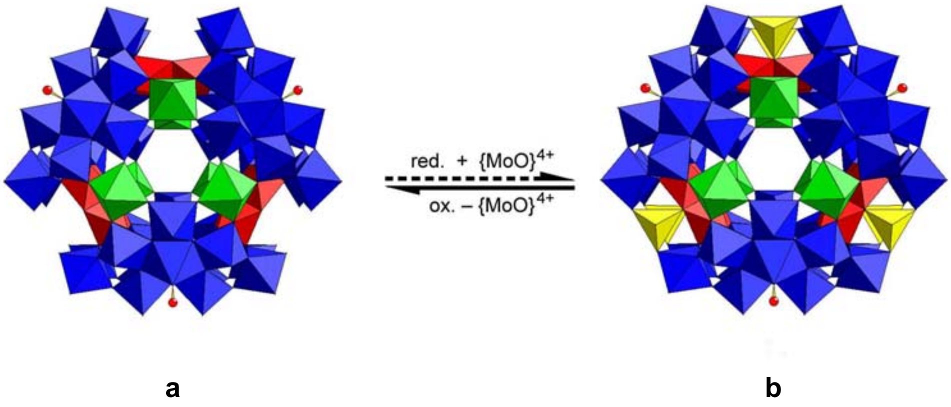


Fig. 6. Quasi-reversible molecular growth within the $[Mo_{57}V_6]$ (a) / $[Mo_{63}V_6]$ (b) POM cluster system. Six $[MoO]^{4+}$ units can be taken up to form the $[Mo_{63}V_6]$ cluster under reducing conditions and can be expelled when the latter is oxidized. Color code: $[Mo_{17}]$ units blue; $[Mo^{V}_{2}]$ linker units red; $[V^{IV}]$ linker units green; additional $[Mo^{VI}O]^{4+}$ units yellow.

Thus in 1998, Müller et al. [18] synthesized under reducing conditions the saturated cluster with six additional Mo^{VI} centres, i.e. $[H_3Mo_{57}V_6(NO)_6O_{189}(H_2O)_{12}(MoO)_6]^{21-}$, abridged as $[Mo_{63}V_6]$ or $[Mo^{VI}_{51}Mo^{V}_{12}V^{IV}_6]$ (a=b=69; c=288; M=9869.07; d≈2.2nm) (Fig. 6b).

In 2000, working with vanadate(V) instead of molybdate(VI), Yang et al. [19] synthesized the analogue cluster with six additional V^V metal centres, i.e. $[H_3Mo_{57}V^{IV}_6(NO)_6O_{189}(H_2O)_{12}(V^VO)_6]^{15-}$, abridged as $[Mo_{57}V_{12}]$ or $[Mo^{VI}_{45}Mo^{V}_{12}V^{IV}_6V^V_6]$.

Giant spheres: $[Mo_{132}]$, $[Mo_{72}Fe_{30}]$ and $[Mo_{102}]$

In spite of the over 100 metal centres, the spherical $[Mo_{132}]$, $[Mo_{72}Fe_{30}]$ and $[Mo_{102}]$ clusters, so-called *giant spheres*, were never at the top of the list of the largest molecules. And because scientific discoveries do not always respect a step-by-step rigorous succession, their synthesis suffered a delay of several years, so that even larger molecules had the chance to be earlier synthesized.

Nevertheless, the spherical clusters of the type $(pentagon)_{12}(linker)_{30}$, with the highest possible symmetry, i.e. icosahedral (I_h), have a special importance in the picture of giant POMs and their presentation is almost mandatory.

In 1999, Müller and his team [20] presented a very large spherical mixed-valence POM cluster, i.e. $[Mo^{VI}_{72}Mo^{V}_{60}O_{372}(CH_3COO)_{30}(H_2O)_{72}]^{42-}$, abridged as $[Mo_{132}]$, $[Mo^{VI}_{72}Mo^{V}_{60}]$ or $[Mo_{11}]_{12}$ (a=b=132; c=696; M=21684.43; d≈2.9nm). The new "dodecameric" (such a term made up of a numeral + the suffix *mer* is specific and adequate for collective molecules, e.g. polymers, and should be use only figuratively in the case of large discrete molecules) cluster was also named *giant ball* (*giant sphere*).

The central Mo^{VI} atoms of the 12 $[(Mo^{VI})Mo^{VI}_5]$ pentagons define the 12 corners, while the 30 $[Mo^V_2]$ linkers, i.e. the $[Mo^V_2O_4]^{2+}$ units, define the 30 edges of an icosahedron. This corresponds to the formulation $[[(Mo^{VI})Mo^{VI}_5O_{21}(H_2O)_6]_{12}[Mo^V_2O_4(CH_3COO)]_{30}]^{42-}$ or $[[(Mo^{VI})Mo^{VI}_5]_{12}\ [Mo^V_2]_{30}] \equiv (pentagon)_{12}(linker)_{30}$. Based on a topological concept, the molecule can also be formulated as $[[(Mo^{VI})^{O}(Mo^{VI}_5)^{I}(Mo^{V}_5)^{II}]_{12}$ or $[Mo_{11}]_{12}$. This formulation takes formally into account that the Mo atoms of each rather stable $[Mo^V_2]$ dumbbell belong to two adjacent $[Mo_{11}]$ groups.

The cluster can be considered as built up of 12 $[Mo_{11}]$ units with central $[MoO_7]$ pentagonal-bipyramidal groups, such that the fivefold symmetry axes are retained in the resulting spherical structure, which shows an overall icosahedral symmetry (I_h) (Fig. 7a, 8a).

The 30 classical $[Mo^V_2]$ dumbbell units span an Archimedean solid of icosahedral symmetry which corresponds to that of the well-known C_{60} fullerene molecule, in the present case a polyhedron with 12 regular pentagons and 20 trigonal hexagons, i.e. the truncated icosahedron (Fig. 7).

Thus, both systems with 60 atoms, i.e. the C_{60} fullerene molecule (d≈0.75 nm; Fig. 9c) and the much larger $[Mo^{V}_{60}]$ fragment (d≈2.5 nm; Fig. 9a) of the $[Mo_{132}]$ molecule, correspond to the Archimedean truncated icosahedron which has the same symmetry as the Platonic icosahedron itself. Therefore, Müller [20] also named the $[Mo_{132}]$ molecule *superfullerene*.

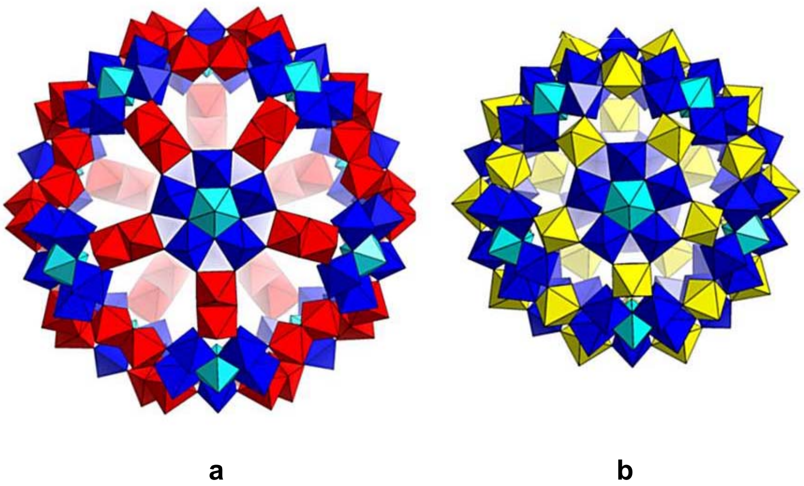


Fig. 7. Structural comparison between the $[Mo_{132}]$ (a) and $[Mo_{72}Fe_{30}]$ (b) clusters in polyhedral representation. Both clusters consists of 12 pentagonal $[(Mo^{VI})Mo^{VI}_{5}]$ building blocks (blue, with the central MoO_7 pentagonal bipyramid in blue-turquoise), but the 30 linker units are different, i.e. $[Mo^{V}_{2}]$ (a) (red) and $[Fe^{III}_{1}]$ (b) (yellow).

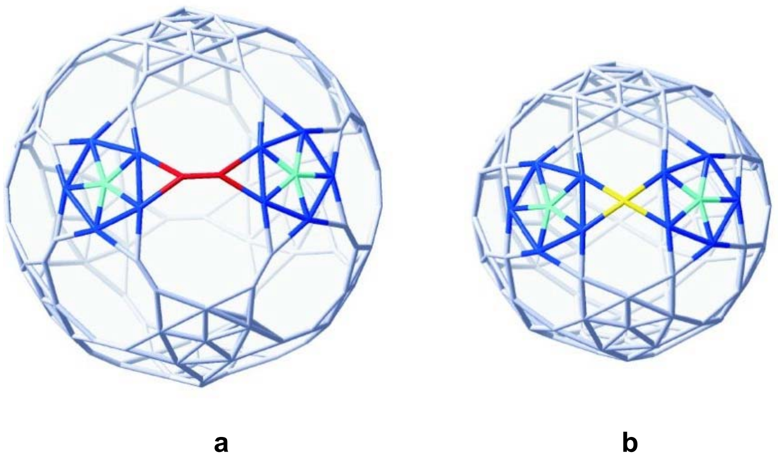


Fig. 8. Structural comparison between the $[Mo_{132}]$ (a) and $[Mo_{72}Fe_{30}]$ (b) clusters in wire-frame representation. Two of the 12 pentagonal $[(Mo^{VI})Mo^{VI}_{5})]$ building blocks (blue, with the central MoO_7 pentagonal bipyramid in blue-turquoise) and one of the 30 linker units, i.e. $[Mo^{V}_{2}]$ (a) (red) and $[Fe^{III}_{1}]$ (b) (yellow), are emphasized.

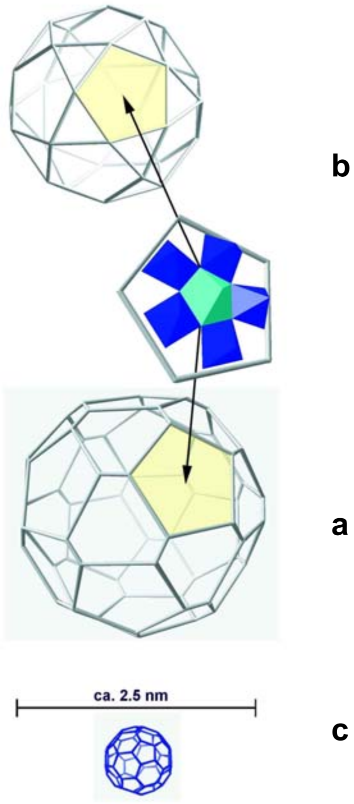


Fig. 9. Structural comparison between the $[Mo^{V}_2]_{30}$ fragment of the $[Mo_{132}]$ cluster (a), the $[Fe^{III}_1]_{30}$ fragment of the $[Mo_{72}Fe_{30}]$ cluster (b) and the C_{60} fullerene (c) in wire-frame representation. The three molecules correspond each to an Archimedean solid, i.e. the truncated icosahedron with 12 regular pentagonal and 20 trigonal hexagonal faces (a and c), respectively the icosidodecahedron with 12 regular pentagons and 20 triangular faces (b). A pentagonal $[(Mo)Mo_5]$ unit occurring in the two clusters is emphasized.

If starting 1985, the almost legendary C_{60} fullerene or *buckyball* was acclaimed as “*the most beautiful molecule”* (this is also the title of a book [21]), there is no question that today the $[Mo_{132}]$ *giant ball* can be considered “*the most aesthetic molecule”* [22].

Müller [20] has also proposed to call the $[Mo_{132}] \equiv [Mo_{11}]_{12}$ molecule a *keplerate*, corresponding to Kepler’s early cosmological model, as described in his magnum opus *Mysterium Cosmographicum*. Kepler believed that the orbits of the planets could be explained if the ratios between successive orbits were designed to be equivalent to the spheres successively circumscribed around and inscribed within the five Platonic solids (i.e. the tetrahedron, cube, octahedron, dodecahedron, icosahedron). By analogy, the $[Mo_{132}]$ cluster correspondingly shows concentric spherical shells of the 132 terminal O and 132 Mo atoms, while the centres of the 12 $[(Mo^{VI})Mo^{VI}_5]$ pentagons, i.e. the 12 Mo atoms of the central $[MoO_7]$ bipyramids, span an icosahedron [11, 13, 20, 22].

The external diametre of the $[Mo_{132}]$ *giant ball* is ≈ 2.9 nm, while the diametre of the large internal cavity is ≈ 2.0 nm.

It is to be noted that the $[Mo_{132}]$ *giant ball* contains only localised reduced metal centres, i.e. Mo^{V} atoms. In the absence of other cromophores, the corresponding compounds have a characteristic brown colour.

In 1999, Müller and coworkers [23] synthesized another molecule of the same class, namely the $[H_4Mo^{VI}_{72}Fe^{III}_{30}O_{252}(CH_3COO)_{12}(H_2O)_{98}]$ cluster, abridged as $[Mo_{72}Fe_{30}]$, $[Mo^{VI}_{72}Fe^{III}_{30}]$ or $[Mo_6Fe_{5/2}]_{12}$ (a=b=102; c=500; M=15089.27; d≈2.5nm). The new molecule, also called *iron ball (iron sphere)*, is no longer an anion but a neutral species and it is a POM any more but only a metal oxide-based cluster, more precisely a molybdenum oxide-based cluster (Fig. 7b, 8b, 10).

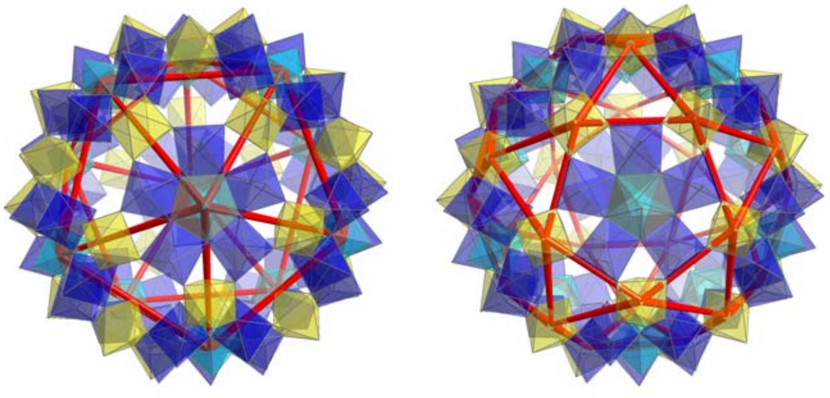
Out of topological reasons, the $[Mo_{72}Fe_{30}]$ neutral cluster can also be formulated as $[[(Mo^{VI})^{O}(Mo^{VI}_{5})^{I}(Fe^{III}_{5/2})^{II}]_{12}$ or $[Mo^{VI}_{6}Fe^{III}_{5/2}]_{12}$, by analogy with the formulation $[Mo_{11}]_{12}$. Another topological formulation, corresponding to $(pentagon)_{12}(linker)_{30}$ is $[[(Mo^{VI})Mo^{VI}_{5}]_{12}[[Fe^{III}_{1}]_{30}]$, more precisely $[[(Mo^{VI})Mo^{VI}_{5}O_{62/3}(OH)_{1/3}(H_2O)_n]_{12}\ [Fe^{III}(H_2O)_2]_{30}]$.

By analogy with the $[Mo_{132}]$ cluster, the central Mo^{VI} atoms of the 12 $[(Mo^{VI})Mo^{VI}_{5}]$ building units define the 12 corners and the 30 $[Fe^{III}_{1}]$ linker units, i.e. the $[Fe^{III}(H_2O)_2]^{3+}$ groups, define the 30 edges of an icosahedron (Fig. 10a). The 30 $[Fe^{III}_{1}]$ linkers also span an Archimedean solid, in this case an icosidodecahedron with 12 pentagonal and 20 triangular faces (Fig.10b). Thus, the $[Mo_{72}Fe_{30}]$ cluster can also be considered a *superfullerene*.

But the special interest of this cluster is due to its magnetochemistry, because $[Mo_{72}Fe_{30}]$ has 30 high-spin Fe^{III} centres (with s=5/2) with a total of 150 unpaired electrons (S=150/2). Thus, $[Mo_{72}Fe_{30}]$ is the discrete molecule with the highest number of paramagnetic centres known up to the present.

The external diametre of the $[Mo_{72}Fe_{30}]$ cluster is ≈ 2.5 nm and of its internal cavity is ≈1.6 nm.

Finally, in 2000, Müller et al. [24] reported another *giant sphere*-type molecule, obtained through sizing the $[Mo_{132}]$ *giant ball*. It is the case of the mixed-valence neutral $[Mo^{VI/V}_{72}Mo^{V}_{30}O_{282}(CH_3COO)_{12}(H_2O)_{78}]$ cluster, abridged as $[Mo_{102}]$ or $[Mo^{VI/V}_{72}Mo^{V}_{30}]$ (with six delocalized Mo^{V} centres), having rather an unusual electronic configuration (a=b=102; c=510; M=16411.55; d≈2.5 nm). The new cluster was also named (only as compared to the $[Mo_{132}]$ *giant ball*) *little ball (little sphere)* (Fig. 11). Unlike the $[Mo_{132}]$ *giant ball,* the $[Mo_{102}]$ *little ball* contains also six delocalized Mo^{V} centres to be found somewhere in the Mo_{72} set.



a **b**

Fig. 10. Structure of the neutral $[H_4Mo^{VI}_{72}Fe^{III}_{30}O_{252}(CH_3COO)_{12}(H_2O)_{98}] \equiv [Mo_{72}Fe_{30}]$ keplerate cluster in transparent polyhedral representation with the two inscribed polyhedra. The icosahedron (a) is defined by the central Mo^{VI} atoms of the 12 $[(Mo^{VI})Mo^{VI}_{5}]$ groups and the icosidodecahedron (b) by the 30 $[Fe^{III}_{1}]$ centres. Color code as in Fig. 7.

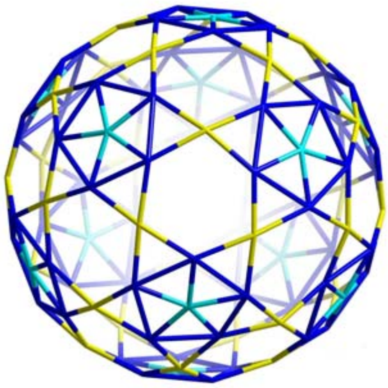


Fig. 11. Structure of the neutral $[Mo^{VI/V}_{72}Mo^{V}_{30}O_{282}(CH_3COO)]_{12}(H_2O)_{78}] \equiv [Mo_{102}]$ cluster in wire-frame representation. The 12 pentagonal $[(Mo^{VI})Mo^{VI}_5]$ building blocks (blue, with the central MoO_7 pentagonal bipyramid in blue-turquoise) are linked by 30 $[Mo^{V}_1]$ units (yellow).

Like the other *giant spheres*, the $[Mo_{102}]$ cluster can also be formulated as $(pentagon)_{12}(linker)_{30} \equiv [[(Mo^{VI})Mo^{VI/V}_5O_{21}(CH_3COO)\text{-}(H_2O)_4]_{12}[Mo^{V}(H_2O)]_{30}] \equiv [[(Mo^{VI})Mo^{VI/V}_5]_{12}[Mo^{V}_1]_{30}]$, respectively $[[(Mo^{VI})^{O}(Mo^{VI/V}_5)^{I}(Mo^{V}_{5/2})^{II}]_{12}$ or $[Mo^{VI/V}_6Mo^{V}_{5/2}]_{12}$.

All three *giant spheres*, namely $[Mo_{132}]$, $[Mo_{72}Fe_{30}]$ and $[Mo_{102}]$, obey the mathematical relation $N=12a+20b+30c+60d$ (where: N= number of metal centres; a, b, c=0 or 1; d=arbitrary integerer) and can be considered *keplerates* [25].

Giant wheels: $[Mo_{154}]$ and $[Mo_{176}]$

Many generations of chemists have tried without success to isolate pure crystalline compounds from the well-known molybdenum blue solutions, obtained by adding an appropriate reducing agent to an acidified aqueous molybdate(VI) (i.e. MoO_4^{2-})-containing solution. Müller and his team have demonstrated that the molybdenum blue solutions mainly contain extremely soluble so-called *giant wheel*-type clusters, i.e. $[Mo_{154}]$ and $[Mo_{176}]$ in proportions that especially depend on the pH value.

The circular $[Mo_{154}]$ and $[Mo_{176}]$ clusters of the *giant wheel*-type are closely related to the spherical clusters of the *giant sphere*-type. Both types contain identical building blocks, namely $[Mo_{11}]$, $[Mo_8]$ and $[(Mo)Mo_5]$.

But in opposition to the $[Mo_{132}]$ *giant ball*, the *giant wheel* and *giant wheel*-derived molecules contain delocalized reduced Mo^{V} metal centres and, as a consequence, the corresponding compounds have an intense blue colour.

The $[Mo_{11}] \equiv [(Mo)^{O}(Mo_5)^{I}(Mo_5)^{II}]$ building blocks of the $[Mo_{132}] \equiv [Mo_{11}]_{12}$ *giant sphere* have a fivefold local symmetry (C_5). But due to the presence of certain reducing agents during synthesis (at pH≈4), all the five peripheral Mo centres of each of the $(Mo_5)^{II}$ units are reduced to Mo^{V}. In exchange, the $[Mo_{11}]$ building blocks of the $[Mo_{154}] \equiv [Mo_{11}]_{14}$ and $[Mo_{176}] \equiv [Mo_{11}]_{16}$ *giant wheels* have a distorted fivefold symmetry (C_s). The *giant wheels* under discussion are prepared in the presence of weaker reducing agents, so that the five peripheral Mo centres are only in part reduced, which determines a non-equivalence between them, generating a perturbation of the local symmetry.

The close relationship of the two $[Mo_{11}]$-type clusters is also provided by the possibility of interconversion by redox processes, such as:

$$\textbf{giant sphere (giant ball)} \underset{\text{reduction}}{\overset{\text{oxidation}}{\rightleftharpoons}} \textbf{giant wheel}$$

(for instance oxidation of $[Mo_{132}]$ to $[Mo_{176}]$, with H_2O_2 in the presence of transition metal cations, such as Mn^{2+}, Co^{2+}, Ni^{2+} and Zn^{2+}) [26].

Chronologically, the “tetradecameric” $[Mo_{11}]_{14} \equiv [Mo_{154}]$-type POM cluster reported by Müller et al. in 1995 [27] having the definitive formula $[Mo^{VI/V}_{154}(NO)_{14}O_{448}H_{14}(H_2O)_{70}]^{28-}$ was the first structurally characterized molecule with over 100 metal centres (a=b=154; c=700; M=23637.93; d≈3.7nm).

Containing 154 metal centres (126 Mo^{VI} and 28 Mo^{V}), 700 non-hydrogen atoms and having a relative molecular mass of 23638, the new molecule (Fig. 12) was named *the (Bielefeld) giant wheel*, instantly rousing the interest and enthusiasm of the scientific community. This lead to the following metaphorical statement in **New Scientist**: “*Big wheels rolls back the molecular frontier”* [28].

Later, Müller also obtained certain other $[Mo_{154}]$-type molecules, with slight ligand modifications, for instance $[Mo^{VI/V}_{154}O_{462}H_{14}(H_2O)_{70}]^{14-}$ [11-13].

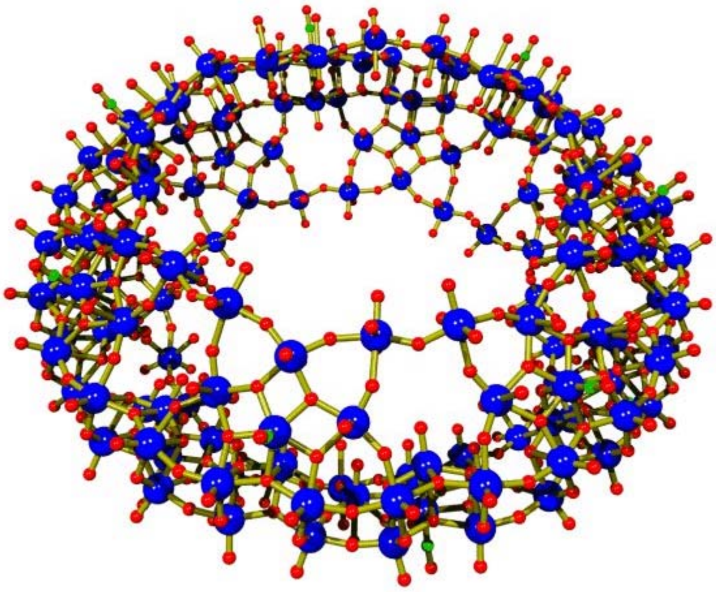


Fig. 12. The structure of the $[Mo_{154}(NO)_{14}O_{448}H_{14}(H_2O)_{70}]^{28-} \equiv [Mo_{154}]$ POM cluster in ball-and-stick representation. Color code: Mo blue; O red; N green.

In a first topological description, the $[Mo_{154}]$-type cluster contains 14 $[Mo_{11}] \equiv 14\ [(Mo)^{O}(Mo_5)^{I}(Mo_5)^{II}] \equiv 14\ [[Mo_2][Mo_8][Mo_1]]$ building blocks. Another description is based on the $[Mo_8]$ unit as a fragment of the $[Mo_{11}]$ building block. Each of the basic $[Mo_8]$ units contains the central pentagonal-bipyramidal MoO_7 polyhedron which is symmetrically connected to five MoO_6 octahedra by sharing edges, resulting in the $[(Mo)Mo_5]$ pentagon. Four of these MoO_6 octahedra are linked to two further MoO_6 octahedra via corners to form the $[Mo_8]$ building block. Starting from the $[Mo_8]$ units the complete $[Mo_{11}]_{14}$-type ring is built up following well-defined rules (Fig. 13a) [12].

The $[Mo_{154}]$-type cluster has a diametre of ≈3.7 nm, a thickness of ≈1.5 nm and a large internal cavity with a diametre of ≈2.0 nm.

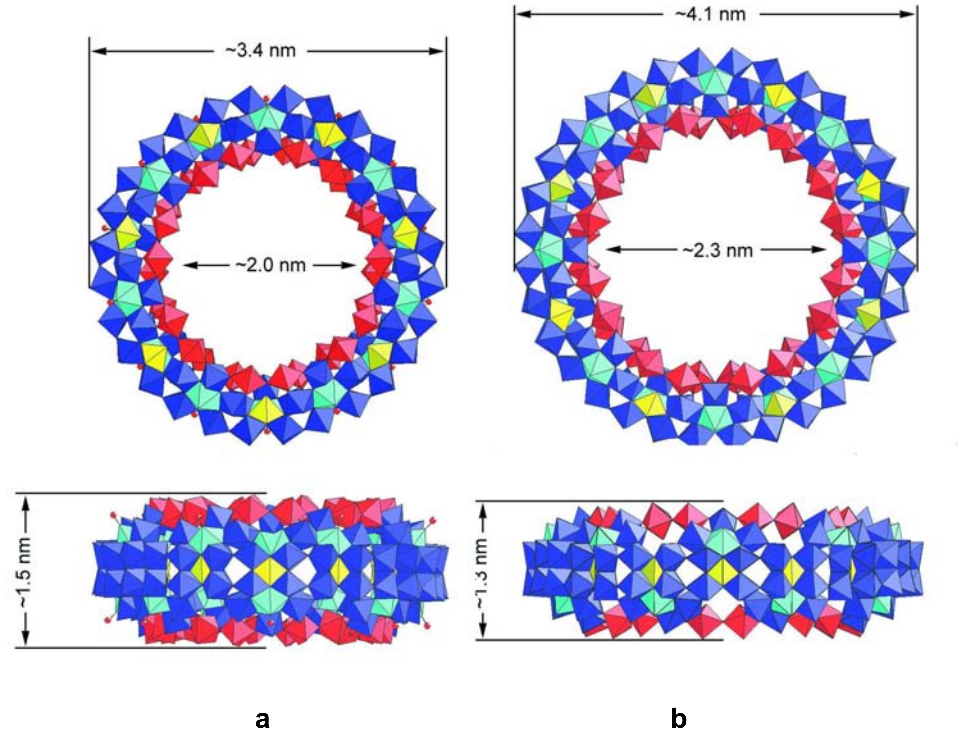


Fig. 13. Polyhedral representation of the $[Mo_{154}] \equiv [Mo_{11}]_{14}$ (a) and $[Mo_{176}] \equiv [Mo_{11}]_{16}$ (b) POM clusters along the C_7 (a) and C_8 (b) axes (top) and perpendicular to them (bottom). The figure shows three different building blocks: the 14(a)/16(b) $[Mo_8]$ units (blue, with the central MoO_7 pentagonal bipyramid in blue-turquoise) which are linked by 14(a)/16(b) $[Mo_2]$ units (red) as well as 14(a)/16(b) $[Mo_1]$ units localized at the equatorial plane (yellow).

The next record-holder was the "hexadecameric" $[Mo_{11}]_{16} \equiv [Mo_{176}]$-type *giant wheel*, reported by Müller et al. in 1998 [29], with the definitive formula $[Mo^{VI}_{176}O_{528}H_{16}(H_2O)_{80}]^{16-}$ (a=b=176; c=784; M=26790.67, d≈4.1 nm). The formula is somewhat surprisingly because it does not contain reduced metal centres. Slightly later, the Müller team [30] synthesized by exchanging ligands a mixed-valence $[Mo_{176}]$-type cluster, i.e. $[Mo^{VI/V}{}_{176}O_{528}(H_2O)_{63}(CH_3OH)_{14}H_n]^{(17-n)-}$ (with 144 Mo^{VI} and 32 Mo^{V} centres).

After further period of a few months, Jiang et al. [31] independently reported a mixed-valence neutral cluster, having the formula $[Mo^{VI/V}{}_{176}O_{496}(OH)_{36}(H_2O)_{80}]$.

The structure of the $[Mo_{176}] \equiv [Mo_{11}]_{16}$-type cluster is similar to that of the $[Mo_{154}] \equiv [Mo_{11}]_{14}$ cluster, with a mention of the two additional $[Mo_{11}]$ building blocks (Fig. 13b).

The dimensions of the $[Mo_{176}]$ cluster are also somewhat larger: diametre ≈ 4.1 nm, thickness ≈ 1.3 nm and the internal cavity has a diametre of ≈ 2.3 nm.

$[Mo_{248}]$

In 1998, Müller and his team synthesized a new record-sized molecule, which they presented in early 1999 directly in **Nature** [32]. The huge POM cluster has the formula $[Mo^{VI/V}{}_{248}O_{720}H_{16}(H_2O)_{128}]^{16-} \equiv [[Mo^{VI}{}_2O_5(H_2O)_2]_{16}[Mo^{VI/V}{}_8O_{28}H(H_2O)_3Mo^{VI/V}]_{16}[Mo^{VI}{}_{12}Mo^{V}{}_{24}O_{96}(H_2O)_{24}]_2]^{16-}$, abridged as $[Mo_{248}]$ or $[[Mo_{176}][Mo_{36}]_2] \equiv [[Mo_{11}]_{16}[Mo_{36}]_2] \equiv [[(Mo_2)\ (Mo_8)(Mo_1)]_{12}[Mo_{36}]_2]$ (a=b=248; c=1096; M=37635.05, d≈4.1 nm).

Under special conditions, the $[Mo_{176}]$ *giant wheel* even starts growing with the consequence that two (unstable) $[Mo^{VI}{}_{12}Mo^{V}{}_{24}O_{96}(H_2O)_{24}] \equiv [Mo_{36}]$ neutral fragments cover the cavity of the $[Mo_{176}]$ cluster like hubcaps, thus generating the $[Mo_{248}]$ cluster. The two $[Mo_{36}]$ hubcaps are each connected to eight terminal O atoms of the eight $[Mo_2]$ units on both the upper and the lower parts of the ring (Fig. 14). Consequently, the $[Mo_{248}]$ cluster is not a *giant wheel* proper, but rather a *giant wheel*-derived molecular system.

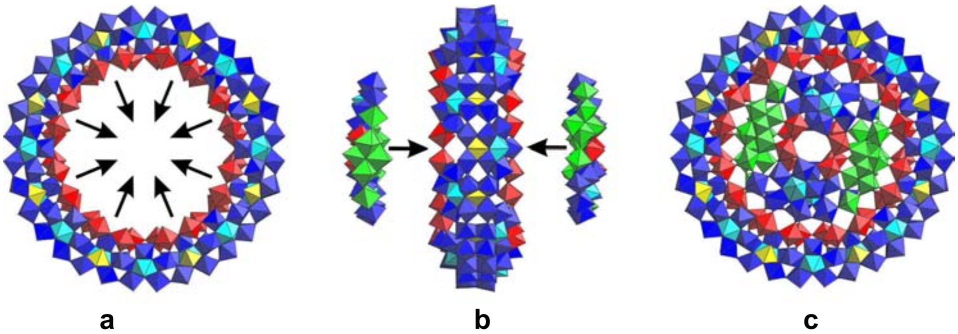


Fig. 14. Schematic view of the relation between the $[Mo_{176}]$ and $[Mo_{248}]$ POM clusters in polyhedral representation. Shown are the $[Mo_{176}]$ cluster viewed from the top (with arrows indicating the pathway of the growth process) (a) and from the side with the two additional $[Mo_{36}]$ fragments acting as hubcaps (b), thus generating the $[Mo_{248}]$ cluster (c). Color code: $[Mo_8]^{*}$ units blue (with the central MoO_7 pentagonal bipyramid in blue-turquoise); $[Mo_8]^{**}$ units green; $[Mo_2]$ units red; $[Mo_1]$ units yellow.

[$Ln_{16}As_{12}W_{148}$]

In 1997, Wassermann, Dickmann and Pope [33] reported the synthesis of an amazing new molecule having the formula [$Ce^{III}{}_{16}As^{III}{}_{12}W_{148}O_{324}(H_2O)_{36}]^{76-}$, abridged as [$Ce^{III}{}_{16}As^{III}{}_{12}W_{148}$] (a=148; b=176; c=536; M=36181.75; d≈4.0 nm).

Because the place of Ce may also be occupied by other lanthanides (Ln=La, Ce, Nd, Sm) it is rather the case of a series of clusters with the [$Ln^{III}{}_{16}As^{III}{}_{12}W_{148}$] short general formula.

The [$Ln_{16}As_{12}W_{148}$]-type molecule is the only known exception within the new generation of supramolecular POM clusters. All other giant POM molecules are molybdenum oxide-based clusters, while the [$Ln_{16}As_{12}W_{148}$]-type molecule is a tungsten oxide-based cluster. Unlike polyoxomolybdates, the synthesis of polyoxotungstates does not have an abundant library of multifunctional building blocks with a large structural and linking versatility, owing especially to the tendency of W to form (too) strong metal-metal bonds.

That is why, the giant polyoxotungstates are constructed through linking of large fragments originating from Keggin or derived from Keggin structures. But the synthesis of a POM with no less than 148 W atoms/centres (the previous record was of 48 W atoms) was considered a general surprise. Its existence confirms that lacunary polyoxotungstate fragments can be linked by transition metal, lanthanide and actinide ions to form water-soluble polyoxotungstate clusters.

The [$Ln_{16}As_{12}W_{148}$]-type cluster (with only unreduced W^{VI} centres) contains an assembly of 12 α-[$As^{III}W_9O_{33}]^{9-}$ ≡ [AsW_9] trilacunary Keggin units, linked by trivalent Ln cations and additional W atoms into a folded structure of D_{3d} symmetry. The structure is further embellished by five [$W_5O_{18}]^{6-}$ lacunary units. The 16 Ln atoms carry a total of 36 H_2O ligands [33, 34] (Fig. 15).

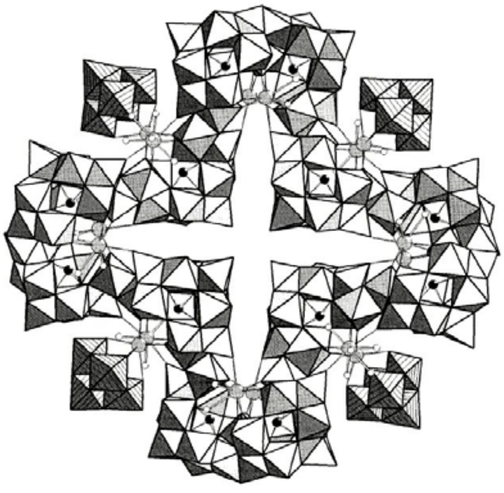


Fig. 15. Structure of the [$Ln^{III}{}_{16}As^{III}{}_{12}W_{148}O_{324}(H_2O)_{36}]^{76-}$ ≡ [$Ln_{16}As_{12}W_{148}$] POM cluster, as a folded cyclic assembly of 12 [AsW_9] groups linked by additional W centres (all shown in polyhedral representation) and four [LnW_5] groups. (Ce(La) large gray spheres; As small black spheres; H_2O small white spheres).

In time, the [$Ce_{16}As_{12}W_{148}$] molecule was reported between the [Mo_{154}] and [Mo_{176}] *giant wheels*. From the point of view of the first criterion selected by us, i.e. the number of metal centres (a=148), the [$Ce_{16}As_{12}W_{148}$] cluster was never the record-holder. On the other hand, at the time, it headed the list according to other mentioned criteria, having a number of 176 heavy atoms, a relative molecular mass of 36182 and a diametre of ≈ 4.0 nm.

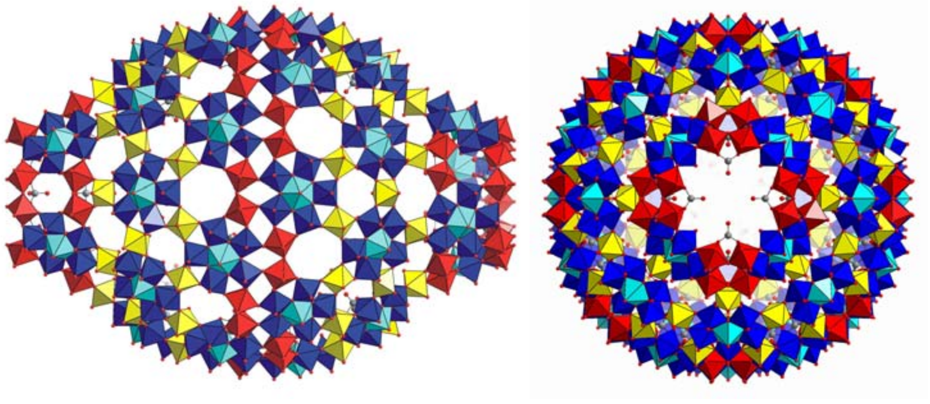
[Mo_{368}]

In November 2001, Müller and his team synthesized and characterized an exceptionally large molecule which was presented to the scientific community a few months later in a paper with the exciting title: *Inorganic Chemistry Goes Protein Size* [35]. The new molecule, with the size of hemoglobine, is a supramolecular POM cluster having the formula $[H_xMo^{VI/V}{}_{368}O_{1032}(H_2O)_{240}(SO_4)_{48}]^{48-}$ ($x \approx 16$), abridged as [Mo_{368}] (a=b=368; c=1880; M=60768.54; d≈6.0 nm). The amazing molecule was also named *nano-hedgehog* or *blue lemon*.

The [Mo_{368}] cluster has been prepared by reducing (with $Na_2S_2O_4$) a molybdate(VI) solution which was acidified with H_2SO_4.

Defining the formal building blocks/units, the [Mo_{368}] cluster can also be formulated as $[H_x[Mo(Mo_5)]^*{}_8[Mo(Mo_5)]^{**}{}_{32}[Mo_2]^*{}_{16}[Mo_2]^{**}{}_8[Mo_2]^{***}{}_8\text{-}[Mo_1]_{64}]^{48-}$ (where: $x \approx 16$; $[Mo(Mo_5)]^* \equiv [Mo_6O_{21}(H_2O)_6]$; $[Mo(Mo_5)]^{**} \equiv [Mo_6O_{21}(H_2O)_3\ (SO_4)]$; $[Mo_2]^* \equiv [Mo_2O_3(H_2O)_2]$; $[Mo_2]^{**} \equiv [Mo_2O_{(t)2}O_{(br)3}(SO_4)]$; $[Mo_2]^{***} \equiv [Mo_2O_{(t)4}O_{(br)}(SO_4)]$; $[Mo_1] \equiv [MoO(H_2O)]$; $O_{(t)}$ = terminal oxygen; $O_{(br)}$ = bridging oxygen).

The molecule, which has approximately D_4 symmetry, contains a central [$Mo_{288}O_{784}(H_2O)_{192}(SO_4)_{32}$] ball-shaped fragment and two [$Mo_{40}O_{124}(H_2O)_{24}(SO_4)_8$] capping units; thus it can also be formulated as [[Mo_{288}] [Mo_{40}]$_2$] (Fig. 16-18).



a b

Fig. 16. Structure of the $[H_xMo_{368}O_{1032}(H_2O)_{240}(SO_4)_{48}]^{48-} \equiv [Mo_{368}]$ POM cluster in polyhedral representation perpendicular to the C_4 axis (a) and along the C_4 axis (b).
Color code: [Mo_1] units yellow, [Mo_2] units red, [(Mo)Mo_5] units blue (with the central MoO_7 pentagonal bipyramid in blue-turquoise).

The $[Mo_{368}]$ cluster can be considered as a giant container, with a huge cavity (diametre ≈ 2.5x4.0 nm at its most extended points), offering space for about 400 H_2O molecules which are encapsulated.

The two types of $[Mo(Mo_5)]$ units differ in the number and coordination type of the SO_4^{2-} ligands. The three types of $[Mo_2]$ units differ concerning the number of bidentate SO_4^{2-} ligands and of terminal and bridging O atoms. The $[Mo_1]$ units, with only Mo^V centres, are classic and contribute to the highly reduction state of the cluster anion. The other formal Mo^V centres are distributed over several parts of the cluster area, which determines a widespread delocalization of the Mo 4d electrons.

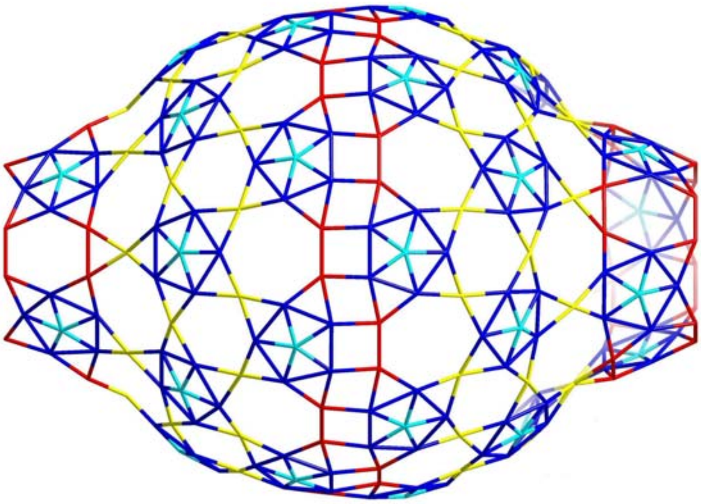


Fig. 17. Structure of the $[H_xMo_{368}O_{1032}(H_2O)_{240}(SO_4)_{48}]^{48-} \equiv [Mo_{368}]$ POM cluster in wire-frame representation perpendicular to the C_4 axis. Color code as in Fig. 16.

The highly reduction state (ca. 256 Mo^{VI} and 112 Mo^V centres) reflects that strong reducing conditions favour molecular growth.

The structure of the $[Mo_{368}]$ POM cluster contains $[Mo(Mo_5)]$ and $[Mo_1]$ units of the $[Mo_{102}]$ *ball*, as well as $[Mo(Mo_5)]$ and $[Mo_2]$ units of the $[Mo_{176}]$ *giant wheel*. Thus, the $[Mo_{368}]$ cluster can be considered a hybrid between the *giant sphere* and *giant wheel*-type clusters.

Having 368 metal centres, no less than 1880 non-hydrogen atoms, a relative molecular mass of 60769 and a diametre of ≈ 6.0 nm, the new $[Mo_{368}]$ POM cluster is the current absolute record-holder in what concerns the largest synthesized molecule with structure determination.

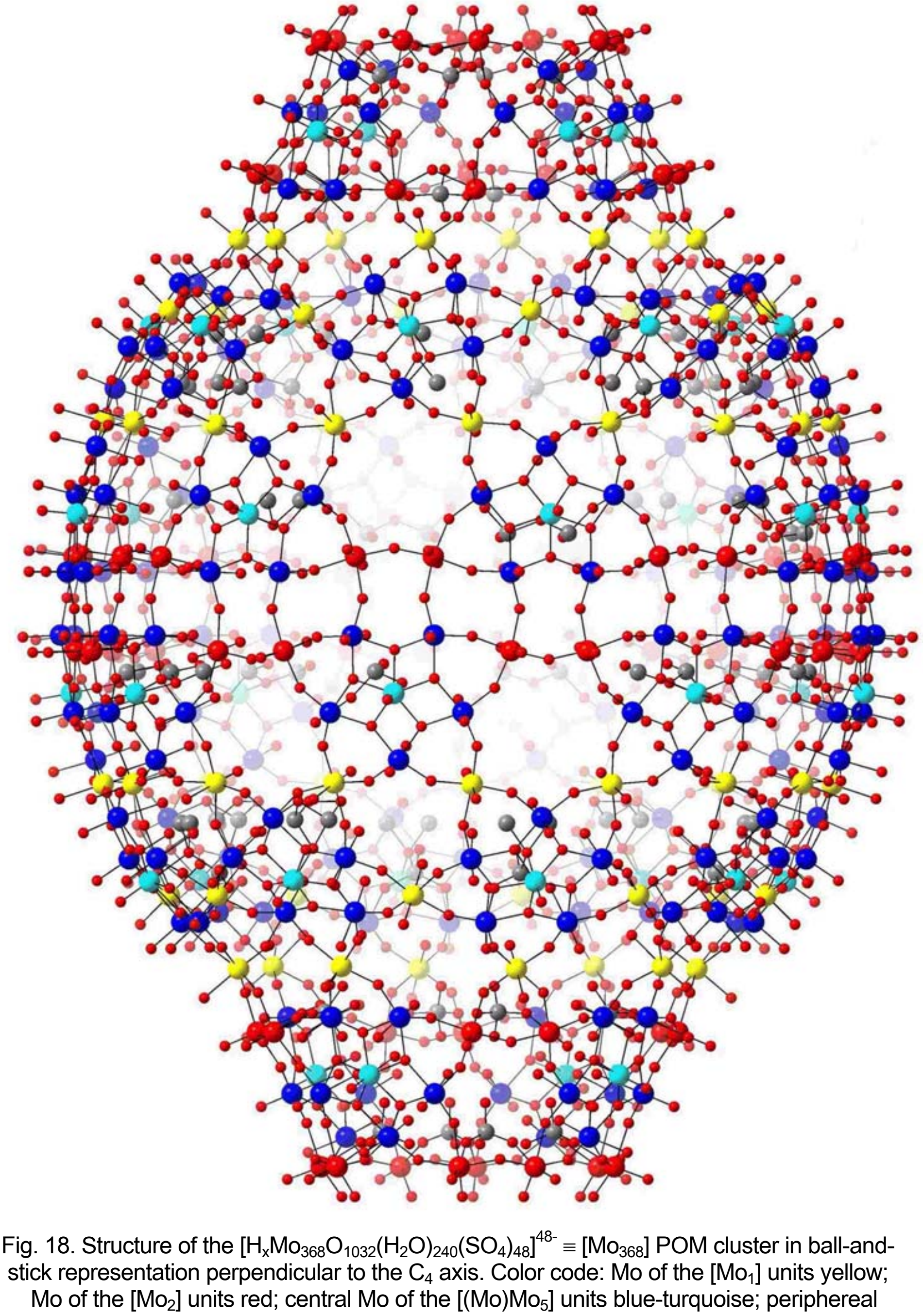


Fig. 18. Structure of the $[H_xMo_{368}O_{1032}(H_2O)_{240}(SO_4)_{48}]^{48-} \equiv [Mo_{368}]$ POM cluster in ball-and-stick representation perpendicular to the C_4 axis. Color code: Mo of the $[Mo_1]$ units yellow; Mo of the $[Mo_2]$ units red; central Mo of the $[(Mo)Mo_5]$ units blue-turquoise; periphereal Mo of the $[(Mo)Mo_5]$ units blue; S grey; O red.

4. CONCLUSIONS

Our survey of the field of the largest synthesized and structurally characterized molecules is almost complete.

The giant molecules, essentially supramolecular POM/metal oxide-type clusters, have reached sizes up to 6 nm, opening new directions and perspectives in a so-called nanoworld.

As a consequence, we have left the domain of classical molecular chemistry and we approach the final limit of supramolecular chemistry, which is localized in a mesocosmic realm, to be found between the micro- and the macroscopic realms. Thus, the new giant POM molecules can be considered true nano-objects of the mesocosmic world.

However, certain questions still need to be addressed: Is the size of such clusters limited or can we construct even larger assemblies? Is the [Mo_{368}] cluster, the current record-holder, the ultimate molecule?

Müller believes that shortly today's record will be surpassed by his research team of Bielefeld or perhaps by another team. He considers that following the novel strategy he has developed molecular growth can continue even farther, up to molecules with over 500 metal centres [36].

The new strategy entails the existence of an adequate library of multi-linkable building blocks which can adapt their shape and size following the boundary conditions, the use of optimal reducing agents and appropriate ligands; this should allow the main fragment to become ever more nucleophile (by increasing the negative charge through reducing metal centres and/or the introduction of negatively charged ligands) thus directing the formation of electrophiles with which it is capped, thereby continuing to grow.

Is Müller's opinion only the expression of the enthusiasm of a very gifted researcher who, carried away like a "sorcerer's apprentice", has obtained results unheard of by chemists 10-20 years ago? Or will the challenge continue and one more time it will be proved that reality is not only beyond what we currently believe, but also beyond what we could imagine?

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