

$F_1 = -Y$) of a given polyhedron, the X value remains unchanged. Examples have been shown in Charts VII and VIII.

Polyhedral Holes and Condensed Polyhedra. It is possible to invoke the concept of "polyhedral holes" in place of face-sharing "fused (or condensed) polyhedra". Rule 6 applies to both concepts.⁴⁶ One example is the truncated ν_2 (frequency two, meaning that each edge corresponds to two metal-metal bonds) trigonal bipyramid (49), shown in Chart XVI, which has two octahedral holes and three trigonal-bipyramidal holes. If each octahedral hole contributes $X = 1$ (rule 4) and each trigonal-bipyramidal hole contributes $X = 2$ (rule 4), with three "hidden edges" (inner triangle of the center layer), $X = -3$ (rule 7), a net X value of 5 can be calculated. The predicted electron count is thus 166e as is indeed observed in the $[\text{Ni}_{12}(\text{CO})_{21}\text{H}_{4-\pi}]^{n-}$ anions.⁴⁷ We note that the interlayer metal-metal distances are longer than the intralayer metal-metal bonds, in accord with the use of the X value of 2 for each of the three trigonal-bipyramidal holes. We predict that an electron count of 160e is more appropriate for a similar structure with more or less equal inter- and intralayer metal-metal distances.

Cage Size. It is evident from eq 5b that for a given number of vertices (V), as the number of faces (F) decreases, the cage size increases and hence the number of electrons (N) that can be "stored" in the cage increases. The cage may reach a size big enough to completely "encapsulate" a metal atom of approximately the same size for 12-vertex polyhedra or above.

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Notable examples include the icosahedron, cuboctahedron or twinned cuboctahedron, bicapped pentagonal prism, etc. Besides, the cage size must be more or less spherical (and of the right dimension) to completely incorporate atoms such as carbide, nitride, sulfide, or metal atoms. Two examples of the nonspherical cage are those within the dodecadeltahedron (which is ellipsoidal) and within the pentagonal bipyramid (which is disklike).

Conclusion

In summary, we have developed in this paper a new topological electron-counting theory based on Euler's theorem and the effective atomic number rule. Each polyhedron (of given numbers of vertices and faces), be it simple, capped, or condensed (via vertex, edge, or face sharing), is characterized by a parameter X , which can be determined from a set of simple rules. This simple scheme can also be used to predict the electron counts as well as to correlate the structures of a wide range of metal clusters of varying nuclearity (cf. following paper), thereby enabling one to achieve a better understanding of the interrelationships between the various cluster geometries.

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Applications of Topological Electron-Counting Theory to Polyhedral Metal Clusters¹

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The simple topological electron-counting theory developed in the previous paper is applied to a wide range of transition-metal and post-transition-metal clusters of varying nuclearity. The results are in excellent agreement with experimental observations. This simple electron-counting scheme provides an alternative to the skeletal electron pair theory in that it can be used to correlate the known as well as to predict the yet unknown polyhedral structures of a general nature. The theory also provides a better understanding of the interrelationships between different cluster geometries.

Introduction

The last decade or two has witnessed a dramatic increase in interest in metal cluster chemistry. Principles underlying the stereochemistry and bonding of metal cluster compounds are generally well established through synthetic, structural, spectroscopic, and theoretical studies.² On the one hand, simple electron-counting schemes such as the effective atomic number (EAN) and the skeletal electron pair (SEP)^{3,4} rules, which result from these systematic studies, are extremely useful in correlating the structures of a vast number of clusters to their electron counts. On the other hand, more insight can be gained through more elaborate treatments such as graph theory,⁵ perturbed spherical shell theory,⁶ isolobal concept,^{3,4,7,8} and the extended Hückel molecular orbital (EHMO),⁷⁻¹¹ Fenske-Hall approximate Hartree-Fock,^{12,13} and SCF- $X\alpha$ -

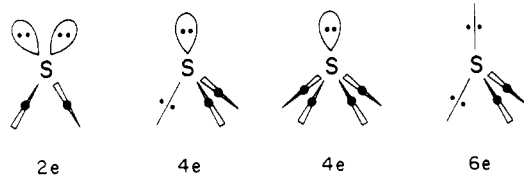
SW calculations¹⁴⁻¹⁶ (in the order of increasing calculational complexity).

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Chart I

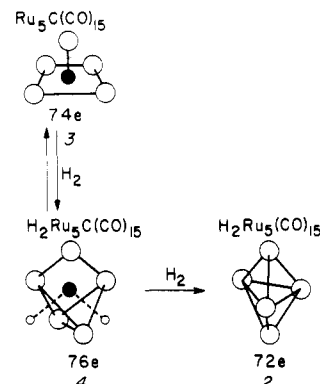


Generally speaking, the structures of transition-metal clusters exhibit a higher degree of complexity and variation than do the main-group element counterparts such as borane and related clusters.¹⁷ While many metal clusters conform to the EAN rule, many others follow the SEP rule. Yet others may adopt structures that cannot be rationalized with either EAN or SEP schemes. In the preceding paper, a new topological electron-counting approach based on Euler's theorem for polyhedra and the effective atomic number rule for transition-metal complexes was developed. In this paper, we will describe application of this electron-counting scheme to a wide variety of metal clusters (containing 4–20 metal atoms), including those that violate either the EAN and/or the SEP rule. As we shall see, this new electron-counting scheme, which requires no theoretical calculations, can provide substantial new insight into the electronic requirements and the interrelationship of various polyhedral cluster structures.

General Remarks

Applications of the topological electron-counting theory to polyhedral structures allow us to predict the number of electrons required for a wide range of transition-metal carbonyl

Chart II



clusters and post-transition-metal naked clusters. Some of the results are tabulated in Table I. While Table I is more or less self-explanatory, the following clarifications may be helpful.

First, the *total electron count*, N , is determined in the usual way by adding up the valence electrons contributed by the metal atoms and the electrons donated to the metals by the ligands. Thus, a cobalt atom has nine valence electrons, a carbonyl ligand (terminal or doubly or triply bridging) is a two-electron donor, a nitride is a five-electron donor, etc. Special attention should be paid to the difference between *surface* and *bulk* ligands. For example, as shown in Chart I, a doubly bridging sulfur atom (with two lone pairs) is a two-electron (2e) donor, a triply or quadruply bridging sulfur (with one lone pair) is a 4e donor, and an encapsulated sulfur is a 6e donor.

Second, though capping the different faces of a polyhedron may give rise to different X values, the resulting electron count remains unchanged. For example, capping the triangular vs. the square face of a trigonal prism gives rise to $X = 0$ and 1, respectively, yet both are 102e systems. The reason is that though capping an n -gonal face causes an increase in X by $n - 3$, the total number of faces increases by the same quantity and hence N remains unchanged (cf. eq 5b of the preceding paper). This observation is analogous to Mingos' capping principle¹⁹ that the number of polyhedral skeletal MOs are unchanged by capping.

Applications

We shall now discuss some of the known polyhedral geometries listed in Table I and their electron counts. The electron counts for many yet-unknown geometries are also predicted in Table I.

Tetrahedral Metal Clusters. The simplest tetrahedral polyhedron of high symmetry is a tetrahedron (1). Many metal clusters possess a completely bonding tetrahedral geometry, with or without bridging ligands. The former is exemplified by $\text{Fe}_4(\text{CO})_4(\eta^5\text{-C}_5\text{H}_5)_4$ ²⁰ and $\text{Fe}_4\text{S}_4(\text{NO})_4$,²¹ and the latter by $\text{Ir}_4(\text{CO})_{12}$ ²² and $\text{Co}_4(\text{CO})_{12}$.²³ A tetrahedron (1) has four vertices, four triangular faces, and an X value of zero (rule 3); the predicted electron count is 60 (cf. Table I), as is indeed observed.

Pentahedral Metal Clusters. The three commonly observed polyhedral geometries for pentametal clusters are the trigonal bipyramid (2), square pyramid (3), and hinged butterfly (4), as tabulated in Table I. For *trigonal bipyramids* (2), the EAN

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rule predicts $N = 72$; our simple rules (rule 4) predict $N = 72, 76$. Indeed, the majority of the trigonal-bipyramidal metal carbonyl clusters known to date are 76e systems, for example, $[\text{Ni}_5(\text{CO})_{12}]^{2-}$,²⁴ $[\text{Rh}_5(\text{CO})_{15}]^-$,²⁵ $[\text{Rh}_5(\text{CO})_{14}]^{2-}$,²⁶ $[\text{Ni}_3\text{M}_2(\text{CO})_{16}]^{2-}$ (M = Cr, Mo, or W), $[\text{RuIr}_4(\text{CO})_{15}]^{2-}$,²⁸ and $[\text{PtRh}_4(\text{CO})_{14}]^{2-}$ —with elongated trigonal-bipyramidal geometry (axial-equatorial > equatorial-equatorial metal-metal distances). Only a few pentametal clusters such as $\text{Os}_5(\text{C}-\text{O})_{16}$,³⁰ $[\text{Os}_5(\text{CO})_{15}]^{2-}$,³¹ and $[\text{PtRh}_4(\text{CO})_{12}]^{2-}$ are known to be 72e systems with more or less regular trigonal-bipyramidal structures. Post-transition-metal clusters are all 72e systems.³²

For square pyramids (3) rule 3 gives $X = 0$ and the electron count is predicted to be $N = 74$ as is observed in, for example, $\text{Ru}_5\text{C}(\text{CO})_{15}$.³³ For the hinged-butterfly C_{2v} geometry (4) with two triangular and two puckered square faces ($F = 4$), $X = 0$ and $N = 76e$ as is observed in $\text{Ru}_5\text{C}(\text{CO})_{16}$ or $\text{H}_2\text{Ru}_5\text{C}(\text{CO})_{15}$.³⁴

Note that in going from trigonal-bipyramidal to square-antiprismatic to hinged-butterfly geometries, the electron count generally increases (from 72 to 74 to 76e) as the number of faces decreases from 6 to 5 to 4. This feature is quite common in polyhedral metal clusters as is evident in Table I. These polyhedral structures can also interconvert as illustrated in Chart II for $\text{H}_2\text{Ru}_5(\text{CO})_{15}$ (trigonal bipyramid, 72e), $\text{Ru}_5\text{C}(\text{CO})_{15}$ (square pyramid, 74e), and $\text{H}_2\text{Ru}_5\text{C}(\text{CO})_{15}$ (hinged butterfly, 76e) as reported by Johnson, Lewis, and co-workers.³⁵

Hexavertex Metal Clusters. Hexametal polyhedral clusters can adopt one of the following structures: *bicapped tetrahedron* (5), *octahedron* (6), *trigonal antiprism* (7), *capped square pyramid* (8), *edge-sharing bitetrahedron* (9), *pentagonal pyramid* (10), or *trigonal prism* (11). The corresponding electron counts are 84, 86 (or less commonly, 84 and 90), 86, 86, 86, 88, and 90e (or less commonly, 86e). The pentagonal pyramid is a yet-unknown geometry in metal cluster chemistry.

The bicapped tetrahedron 5a has $X = 0$ (rules 2 and 3) and $N = 84$ as is indeed observed in $\text{Os}_6(\text{CO})_{18}$ ³⁶ and $\text{Os}_4\text{H}_2(\text{CO})_{12}(\text{AuPPh}_3)_2$.^{37a} The bicapped tetrahedron can also be considered as a capped trigonal bipyramid (5b), and $X = 0$ or 2 or $N = 84$ or 88e is predicted. The observed electron count in $\text{Ni}_3\text{Os}_3(\text{CO})_9\text{Cp}_3$ ^{37b} is 87e.

The majority of *octahedral* metal clusters are 86e systems, as predicted. Examples include $\text{Rh}_6(\text{CO})_{16}$ ³⁸ and $[\text{Fe}_6\text{C}(\text{CO})_{16}]^{2-}$.³⁹ An octahedron can be formed by capping the

Chart III

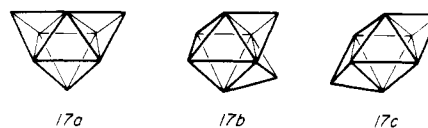
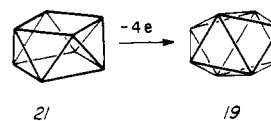


Chart IV



square face of a square pyramid; thus rule 2 predicts $X = 1$. Alternatively, it can be considered as a special trigonal antiprism with twelve edges of equal length; rule 5 again predicts $X = 1$. A third route to an octahedron is to demand all 12 edges of a tetragonal bipyramid be equal; rule 4 predicts $X = 1$ or 3. The latter, however, is less common because there are only two octahedral clusters, $\text{Ni}_6(\eta^5\text{-C}_5\text{H}_5)_6$ ⁴⁰ and $[\text{Fe}_6\text{S}_8(\text{PEt}_3)_6]^{2+}$ ⁴¹ known to have 90 electrons ($X = 3$). In this context, they are more appropriately considered as "exceptions" in that they have four extra electrons in the energetically low-lying molecular orbitals that may be substantially *metal-ligand antibonding* in character. Early-transition-metal clusters often have less electron counts. One typical example is $[\text{Mo}_6\text{Cl}_{14}]^{2-}$ ⁴² an octahedral cluster with 84e ($X = 0$). This case ($X = 0$) should again be considered as an "exception".

A trigonal-antiprismatic cluster is predicted to have $X = 1$ and $N = 86e$; one example is the $[\text{Ni}_6(\text{CO})_{12}]^{2-}$ dianion.⁴³

The capped (Δ) square pyramid 8 (cf. Chart VIII in the preceding paper) has $X = 0$ (rules 2 and 3) and $N = 86e$ as is observed in $\text{Os}_6\text{H}_2(\text{CO})_{18}$.^{44a}

The edge-sharing bitetrahedral geometry 9 with $X = 1$ is predicted to have $N = 86e$. The observed electron count in $\text{Os}_4\text{H}_2(\text{CO})_{12}(\text{AuPPh}_3)_2$ ^{44b} is 84e.

The trigonal prisms have $X = 0$ (rule 1) and $N = 90e$ as observed in, for example, the $[\text{Rh}_6\text{C}(\text{CO})_{15}]^{2-}$ dianion⁴⁵ and the $[\text{Co}_6\text{N}(\text{CO})_{15}]^-$ anion.⁴⁶ One exception is the $[\text{Pt}_6(\text{CO})_{12}]^{2-}$ dianion,⁴⁷ which has 86e. As we shall see later in this paper, the platinum carbonyl clusters often exhibit electron counts lower than expected (cf. footnotes *b* and *c* of Table I) due in part to the tendency to form a 16- rather than 18-electron count for platinum.

Heptavertex Metal Clusters. There are fewer examples of heptametal polyhedral clusters. The two known geometries are (1) a tricapped tetrahedron (12a) with 10 faces and 96-electron count as exemplified by $\text{Au}_3\text{Ru}_4(\text{CO})_{12}(\text{PPh}_3)_3\text{H}$ ⁴⁷ and $\text{Au}_3\text{CoRu}_3(\text{CO})_{12}(\text{PPh}_3)_3$ ⁴⁸ and (2) capped octahedron

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Table 1. Electron Counting in Transition-Metal Cluster Systems

no.	polyhedron	predicted				obsd		example
		<i>V</i>	<i>F</i>	<i>X</i>	<i>N</i>	<i>N</i>		
1	tetrahedron	4	4	0	60	60	Ir ₄ (CO) ₁₂ , ²² Co ₄ (CO) ₁₂ ²³	
2	trigonal bipyramid (hexadeltahedron)	5	6	0	72	72	Os ₅ (CO) ₁₆ , ³⁰ Sn ₅ ²⁻ , Pb ₅ ²⁻ ³²	
				2	76	76	[Ni ₅ (CO) ₁₂] ²⁻ , ²⁴ [Rh ₅ (CO) ₁₄ I] ²⁻ ²⁶	
3	square pyramid	5	5	0	74	74	Ru ₅ C(CO) ₁₅ ³³	
4	hinged butterfly ^a	5	4	0	76	76	Ru ₅ C(CO) ₁₆ , H ₂ Ru ₅ C(CO) ₁₅ ³⁴	
5a	bicapped tetrahedron	6	8	0	84	84	Os ₆ (CO) ₁₈ , ³⁶ Os ₆ H ₂ (CO) ₁₂ (AuPPh ₃) ₂ ^{37a}	
5b	capped trigonal bipyramid	6	8	2	88	87	Ni ₃ Os ₃ (CO) ₉ Cp ₃ ^{37b}	
6	octahedron	6	8	1	86	86	Rh ₆ (CO) ₁₆ , ³⁸ [Fe ₆ C(CO) ₁₆] ²⁻ ³⁹	
				3	90	90	Ni ₆ (η ⁵ -C ₅ H ₅) ₆ , ⁴⁰ Fe ₆ S ₈ (PEt ₃) ₆ ²⁺ ⁴¹	
				0	84	84	[Mo ₆ Cl ₁₄] ²⁻ ⁴²	
7	trigonal antiprism	6	8	1	86	86	[Ni ₆ (CO) ₁₂] ²⁻ ⁴³	
8	capped square pyramid	6	7	0	86	86	Os ₆ H ₂ (CO) ₁₈ ^{44a}	
9	edge-sharing bitetrahedron	6	8	1	86	84	Os ₄ H ₂ (CO) ₁₂ (AuPPh ₃) ₂ ^{44b}	
10	pentagonal pyramid	6	6	0	88			
11	trigonal prism	6	5	0	90	90	[Rh ₆ C(CO) ₁₅] ²⁻ , ⁴⁵ [Co ₆ N(CO) ₁₅] ⁻ ⁴⁶	
					86 ^{b,c}		[Pt ₆ (CO) ₁₂] ²⁻ ¹⁶	
12a	tricapped tetrahedron	7	10	0	96	96	Au ₃ Ru ₄ (CO) ₁₂ (PPh ₃) ₃ H, ⁴⁷ Au ₃ CoRu ₃ (CO) ₁₂ (PPh ₃) ₃ ⁴⁸	
12b	bicapped trigonal bipyramid	7	10	2	100			
13	bicapped square pyramid	7	9	0	98			
14	capped octahedron	7	10	1	98	98	[Rh ₇ (CO) ₁₆] ³⁻ ⁴⁹	
15	pentagonal bipyramid (decadeltahedron)	7	10	2	100			
16a	capped (Δ) trigonal prism	7	7	0	102			
16b	capped (□) trigonal prism	7	8	1	102			
17	bicapped octahedron	8	12	1	110	110	[Os ₈ (CO) ₁₂] ²⁻ , ⁵⁰ [Re ₈ C(CO) ₂₄] ²⁻ ⁵¹	
18	fused octahedron and trigonal bipyramid	8	12	1	110	110	Cu ₂ Ru ₆ C(CO) ₁₆ (NCCH ₃) ₂ ⁵²	
19	triangular dodecahedron (dodecadeltahedron)	8	12	1	110			
				3	114			
20a	bicapped (Δ ²) trigonal prism	8	9	0	114	114	Cu ₂ Rh ₆ C(CO) ₁₅ (NCCH ₃) ₂ ⁵³	
20b	bicapped (Δ,□) trigonal prism	8	10	1	114			
20c	bicapped (□ ²) trigonal prism	8	11	1	112			
				2	114			
				3	116			
21	square antiprism	8	10	1	114	114	[Co ₈ C(CO) ₁₈] ²⁻ ⁵⁴	
				3	118	118	[Ni ₈ C(CO) ₁₆] ²⁻ , ⁵⁵ Bi ₈ ²⁺ ⁵⁶	
22	square-face-sharing bi(trigonal prism)	8	8	0	116	116	[Co ₆ Ni ₂ C ₂ (CO) ₁₆] ²⁻ ⁵⁷	
23	cube (hexahedron)	8	6	0	120	120	Ni ₈ (PPh) ₆ (CO) ₈ ⁵⁸	
24	cuneane	8	6	0	120	120	Co ₈ S ₂ (N- <i>t</i> -Bu) ₄ (NO) ₈ ⁵⁹	
25	tricapped octahedron	9	14	1	122			
26	face-sharing bioctahedron	9	14	2	124	122	[Rh ₉ (CO) ₁₉] ³⁻ ⁶⁰	
27a	tricapped (Δ ² ,□) trigonal prism	9	12	1	126			
27b	tricapped (Δ,□ ²) trigonal prism	9	13	2	126			
27c	tricapped (□ ³) trigonal prism	9	14	2	124			
				3	126			
				4	128	128	Ge ₉ ²⁻ ⁶³	
28a	capped (Δ) square antiprism	9	12	1	126			
				3	130			
28b	capped (□) square antiprism	9	13	2	126			
				4	130	130	[Rh ₉ P(CO) ₂₁] ²⁻ , ⁶⁵ [Ni ₉ C(CO) ₁₇] ²⁻ , ⁶⁶ Sn ₉ ⁴⁻ , ⁶⁷ Ge ₉ ⁴⁻ ⁶³	
29	face-sharing octahedron and trigonal prism	9	11	1	128	128	[Ni ₉ (CO) ₁₈] ²⁻ ⁶¹	
30	tricapped (□ ³) trigonal prism with elongated interlayer edges	9	11	2	130	130	Bi ₉ ⁵⁺ ⁶⁴	
				3	132			
				4	134			
31	(3 ⁸ 5 ²) decahedron	9	10	1	130			
32	triangular-face-sharing bi(trigonal prism)	9	8	0	132	128 ^{b,c}	[Pt ₉ (CO) ₁₈] ²⁻ ⁶²	
33	capped cube	9	9	1	132	132		
34	(3 ⁵ 5 ³) octahedron	9	8	1	134			
35	ν ₂ tetrahedron (tetracapped octahedron)	10	16	1	134	134	[Os ₁₀ C(CO) ₂₄] ²⁻ ⁶⁸	
36	bicapped (□ ²) square antiprism	10	16	3	138			
				5	142	142	[Rh ₁₀ S(CO) ₂₂] ²⁻ , ⁶⁹ [Rh ₁₀ P(CO) ₂₂] ³⁻ ⁷⁰	
37	edge-sharing bioctahedron	10	16	3	138	138	[Ru ₁₀ C ₂ (CO) ₂₄] ²⁻ ⁷¹	
38	bicapped cube	10	12	2	144			
39	pentagonal antiprism	10	12	3	146			
40	pentagonal prism	10	7	0	150			
41a	face-to-face fused trioctahedron	11	18	2 ^d	148	148	[Rh ₁₁ (CO) ₂₃] ³⁻ ⁷²	
41b	face-to-face fused trioctahedron without central bond	11	18	3 ^d	150			
42	tricapped (□ ³) cube with two face diagonals	11	17	3	152			
43	capped (□) square-face-sharing trigonal prism and square antiprism	11	16	2	152			
				3	154	154	[Co ₁₁ C ₂ (CO) ₂₂] ³⁻ ⁷³	
				4	156			
44a	octadecahedron	11	18	5	154			
44b	convex (expanded) octadecahedron	11	18	6	156			
45	tricapped cube	11	15	3	156			
46	capped pentagonal antiprism	11	16	5	158			
47	capped pentagonal prism	11	11	2	162			
48	hexacapped octahedron	12	20	1	158	160	[Fe ₆ Pd ₆ (CO) ₂₄ H] ³⁻ ⁷⁴	

Table I (Continued)

no.	polyhedron	predicted				obsd	
		V	F	X	N	N	example
49	truncated ν_2 trigonal bipyramid (hcp)	12	20	2	160		
50	face-sharing trioctahedron	12	20	3	166	166	$[\text{Ni}_{12}(\text{CO})_{21}\text{H}_{3-n}]^{n-75}$
51	face-sharing bi(square antiprism)	12	18	2	164	166	$[\text{Rh}_{12}(\text{CO})_{25}\text{H}_n]^{76}$
				6	172	167	$[\text{Rh}_{12}\text{C}_2(\text{CO})_{24}]^{2-78}$
						168	$[\text{Rh}_{12}\text{C}_2(\text{CO})_{24}]^{3-78}$
							$[\text{Rh}_{12}\text{C}_2(\text{CO})_{24}]^{4-78}$
52	capped (\square) fused trigonal prism-square antiprism-trigonal bipyramid	12	18	1	162		
				3	166	166	$\text{Rh}_{12}\text{C}_2(\text{CO})_{25}^{79}$
				5	170		
53	icosahedron	12	20	7	170	170	$[\text{Rh}_{12}\text{Sb}(\text{CO})_{27}]^{3-80}$
					162		$[\text{Au}_{13}\text{Cl}_2(\text{PMe}_2\text{Ph})_{10}]^{3+81}$
54	cuboctahedron (ccp)	12	14	1	170		
55	twinned cuboctahedron (hcp)	12	14	1	170	170	$[\text{Rh}_{13}(\text{CO})_{24}\text{H}_{5-n}]^{n-82}$
56	hexagonal antiprism	12	14	1	170		
				3	174		
57	bicapped pentagonal prism	12	15	4	174		
58	triangular-face-sharing tri(trigonal prism)	12	11	0	174	170 ^{b,c}	$[\text{Pt}_{12}(\text{CO})_{24}]^{2-77}$
59	hexagonal prism	12	8	0	180		
60	3-connected ν_3 truncated tetrahedron ((3^46^4) octahedron)	12	8	0	180		
61	(4^45^4) octahedron	12	8	0	180		
62	pentacapped cube	13	21	5	180	180	$[\text{Rh}_{14}(\text{CO})_{25}]^{4-83}$
63	octacapped octahedron (face-centered cube)	14	24	1	182		
64	ν_2 trigonal bipyramid	14	24	2	184		
				5	190		
65	hexacapped cube	14	24	6	192		
66	rhombic dodecahedron (body-centered cube)	14	"24"	>6	>192	198	$[\text{Rh}_{15}(\text{CO})_{30}]^{3-84}$
67	tetracapped (\square^2, \square^2) pentagonal prism	14	21	6	198	200 ^e	$[\text{Rh}_{15}\text{C}_2(\text{CO})_{28}]^{2-85}$
68	triangular-face-sharing tetra(trigonal prism)	15	14	0	216	212 ^{b,c}	$[\text{Pt}_{15}(\text{CO})_{30}]^{2-86}$
69	bicapped pentagonal-face-sharing bi(pentagonal prism)	17	20	4	244	238 ^c	$[\text{Pt}_{19}(\text{CO})_{22}]^{4-87}$
70	pentagonal dodecahedron	20	12	0	300		

^a With two triangular and two puckered square faces. ^b Platinum clusters with the general formula $[\text{Pt}_3(\text{CO})_6]_m^{2-}$ (formed by a stack of m nearly eclipsed platinum triangles) are $4e$ short ($42m + 2$) of the electron count predicted for triangular-face-sharing trigonal prisms ($42m + 6$). ^c Platinum carbonyl clusters are often 4–6e under the required electron count possibly due to its tendency to form a 16-electron configuration. ^d $X = 3 - 1 = 2$ for three octahedra fused face-to-face. If the hidden edge connecting atoms 1 and 2 in Chart XXII is lengthened, $X = 3$. ^e Two edges are lengthened to 3.332 (2) Å while others range from 2.734 (3) to 3.024 (3) Å.

(14) with 10 faces and 98-electron count as exemplified by the $[\text{Ru}_7(\text{CO})_{16}]^{3-}$ trianion,⁴⁹ both as predicted. The yet-unknown polyhedral geometries of pentagonal bipyramid (15) and capped (Δ or \square) trigonal prism (16) are predicted to have electron counts of 100 and 102e, respectively.

Octavertex Metal Clusters. To the best of our knowledge, there are seven known polyhedral geometries for octametal clusters. The most compact cluster is the bicapped octahedra (17a–c) shown in Chart III. Since capping triangular faces does not increase the X value (rule 2), the X value remains the same as that of an octahedron ($X = 1$, rule 4); with 12 faces, N is predicted to be 110e as observed in, for example, the $[\text{Os}_8(\text{CO})_{22}]^{2-}$ dianion⁵⁰ and the $[\text{Re}_8\text{C}(\text{CO})_{24}]^{2-}$ dianion,⁵¹ both with structure 17a.

A recently reported cluster, $\text{Cu}_2\text{Ru}_6\text{C}(\text{CO})_{16}(\text{NCCH}_3)_2$,⁵² has an interesting polyhedral structure of a fused octahedron and trigonal bipyramid (18; cf. Chart XIII in the preceding paper), which has an electron count of 110e, as predicted (cf. Table I). Adding (formally) four electrons to $\text{Cu}_2\text{Ru}_6\text{C}(\text{CO})_{16}(\text{NCCH}_3)_2$ gives rise to $\text{Cu}_2\text{Rh}_6\text{C}(\text{CO})_{15}(\text{NCCH}_3)_2$,⁵³ which has a bicapped (Δ^2) trigonal prismatic structure (20a) with, as predicted, 114 electrons.

For square antiprisms (21, cf. Chart IV), rule 5 predicts $X = 1$ or 3, which corresponds to $N = 114$ or 118 for square antiprisms. Examples include $[\text{Co}_8\text{C}(\text{CO})_{18}]^{2-}$,⁵⁴ which is a 114e system, and $[\text{Ni}_8\text{C}(\text{CO})_{16}]^{2-}$,⁵⁵ and Bi_8^{2+} ,⁵⁶ which are 118e systems.

The eight-vertex triangular dodecahedron or dodeca-deltahedron (19) is rather interesting. As demonstrated in Chart XIII of the preceding paper, it can be derived from either a bicapped octahedron (17b) or a fused octahedron and trigonal bipyramid (18), giving rise to $X = 1$. It can also be formed by removing two electron pairs ($Y = -2$) from a square antiprism (21), one from each of the two square faces, thereby forming two new metal-metal bonding interactions (Chart IV), giving rise to $X = 1$ or 3. With 8 vertices and 12 faces, a triangular-dodecahedral metal cluster is predicted to have 110 or 114 electrons. No such structures are known in metal cluster chemistry. It is, however, interesting to note that the $[\text{Ni}_8\text{C}(\text{CO})_{16}]^{2-}$ dianion⁵⁵ is a square-antiprismatic metal cluster with 118e. Removal of four electrons from the 118e system results in the 114e tetragonally distorted square antiprism as observed in the $[\text{Co}_8\text{C}(\text{CO})_{18}]^{2-}$ dianion.⁵⁴ It can, in principle, also lead to a 114e triangular dodecahedron. The fact that the triangular dodecahedron is yet unknown in metal cluster geometry (in contrast to boranes) may be due to the size and shape of

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Chart V

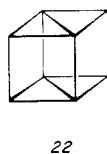
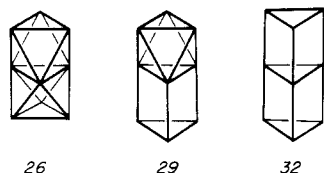


Chart VI



the cavity. Thus a possible candidate, e.g. $\text{Cu}_2\text{Ru}_6\text{C}(\text{CO})_{16}(\text{NCCH}_3)_2$,⁵² instead adopts a different geometry based on a face-sharing octahedron and trigonal bipyramid.

From Table I we see that bicapped trigonal prisms are predicted (rule 2) to be 114 e systems as is indeed observed in $\text{Cu}_2\text{Rh}_6\text{C}(\text{CO})_{15}(\text{NCCH}_3)_2$,⁵³ with two triangular caps (20a). The bicapped trigonal prisms with two square caps (20c), however, can also be formed by removing two electrons from one of the square diagonals of a square antiprism 21 as illustrated in Chart XIII of the preceding paper. Hence 20c should take on X values of 1, 2, and 3 (cf. eq 6 of the preceding paper), leading to electron counts of 112, 114, and 116e.

The square-face-sharing bi(trigonal prism) (22; cf. Chart V) can also be viewed as a distorted cube (23) with two face diagonals. In both cases, $X = 0$ (rules 1 and 6 in the former case; rule 7 in the latter) and with 8 faces, $N = 116e$ as is indeed observed for the $[\text{Co}_6\text{Ni}_2\text{C}_2(\text{CO})_{16}]^{2-}$ dianion.⁵⁷

The cube (23) and the cuneane (24) polyhedra are rather interesting. Despite their drastically different symmetries, both cube and cuneane share the common geometrical characteristic that each vertex has a degree of three (3-connected), giving rise to $X = 0$ (rule 1). Since each has six faces, we expect an electron count of 120e for both the cube and the cuneane. This is indeed observed in $\text{Ni}_6(\text{PPh})_6(\text{CO})_8$ ⁵⁸ and $\text{Co}_8\text{S}_2(\text{N}-t\text{-Bu})_4(\text{NO})_8$,⁵⁹ respectively. Note that cuneane can be formed by rotating one edge of a cube by 90° , thereby transforming four of the square faces into two trigonal and two pentagonal faces.

It should be noted that the electron counts for the known octametal polyhedral clusters span the range of 110–120e with the bicapped octahedron having the smallest cage and the cube having the largest cage size.

Nonavertex Metal Clusters. The face-sharing bioctahedral nonametal cluster (26; Chart VI) has a face count of 14 and an X value of 2 (two octahedra, rules 4 and 6), giving rise to the predicted electron count of 124e. The observed value in the $[\text{Rh}_9(\text{CO})_{19}]^{3-}$ trianion⁶⁰ is 122e (two electrons less than expected). The closely related face-sharing octahedron and trigonal prism (29; Chart VI), with 11 faces and $X = 1$, is predicted to have $N = 128e$ as is indeed observed in the $[\text{Ni}_9(\text{CO})_{18}]^{2-}$ dianion.⁶¹ Yet another related polyhedron is the triangular-face-sharing bi(trigonal prism) (32; Chart VI), which has $F = 8$ and $X = 0$ and is therefore predicted to have 132 electrons. The observed value in the $[\text{Pt}_9(\text{CO})_{18}]^{2-}$ dianion⁶² is 128 (four electrons less than expected). Once again,

Chart VII

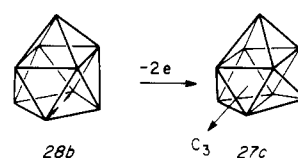


Chart VIII

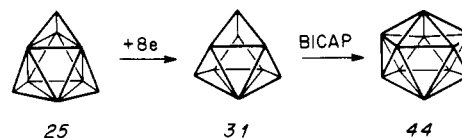


Chart IX

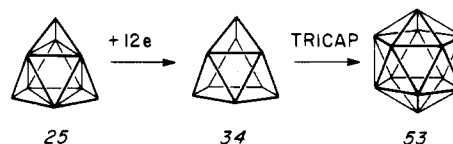
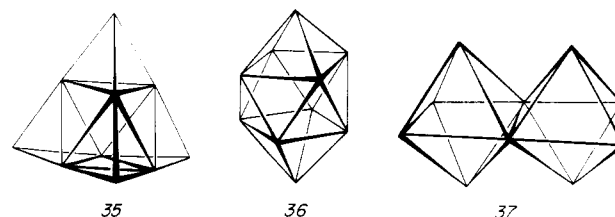


Chart X



the platinum carbonyl clusters exhibit a tendency to have 4 or 6 electrons less than expected.

There are three types of tricapped trigonal prisms, depending upon the location of the capping atoms (27a–c in Table I). For the nine-vertex tricapped (\square^3) trigonal prism, 27c, which is the only one known to date, rule 2 predicts $X = 3$ for capping the three square faces of the trigonal prism 11. A second route (cf. Chart VII) to a tricapped trigonal prism (a deltahedron) is to remove one electron pair ($Y = -1$) from the square face of a monocapped (\square) square antiprism (28b), thereby forming a new metal–metal bond and buckling the square face to form two triangle faces ($F_2 - F_1 = 1$). Again $X_2 = X_1 = 2$ or 4 remains unchanged (cf. eq 6 of the preceding paper). Thus the expected X value for the tricapped trigonal prism is 2, 3, and 4; eq 5b of the preceding paper gives electron counts of 124, 126, and 128e, respectively. The Ge_9^{2-} dianion⁶³ is an example of the 128e system. Elongation along the C_3 axis gives rise to polyhedron 30, reducing the number of faces to 11 (8 triangular and 3 rhombic square faces) and leads to $N = 130$, 132, or 134e. The Bi_9^{5+} pentacation⁶⁴ is an example of a 130e system.

Similarly, there are two types of capped square antiprisms (28a,b in Table I); only 28b shown in Chart VII has been observed in, for example, $[\text{Rh}_9\text{P}(\text{CO})_{21}]^{2-}$ ⁶⁵ and $[\text{Ni}_9\text{C}(\text{CO})_{17}]^{2-}$,⁶⁶ as well as in the post-transition-metal clusters Sn_9^{4-} ⁶⁷ and Ge_9^{4-} .⁶³ With 13 faces and $X = 2$ or 4 (a square antiprism gives rise to $X = 1$ or 3, capping the square face gives rise to $X = 1$), 28b is predicted to have $N = 126$ or 130e. The observed value in the above-mentioned examples is 130e.

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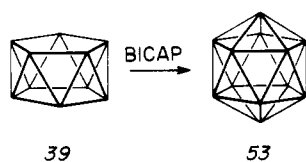
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Chart XI



Cleavage of only four metal-metal bonds in the tricapped octahedron 25 (Chart VIII) with $X = 1$ via addition of four electron pairs ($Y = 4$) gives rise to the ($3^8 5^2$) decahedron 31 ($F_2 - F_1 = 10 - 14 = -4$) with $X = 1$ and $N = 130e$. No examples are known.

Similarly, the nonavertex ($3^5 5^3$) octahedron (34) shown in Chart IX can be visualized as being formed by adding six electron pairs ($Y = 6$) to a tricapped octahedron (25), which has an X value of 1, resulting in cleavage of six metal-metal bonds. Once again, the $X = 1$ (eq 6 of the preceding paper) value remains unchanged since $F_2 - F_1 = 8 - 14 = -6$. With eight faces (five triangles and three pentagons), eq 5 of the preceding paper predicts $N = 134e$ for the yet-unknown polyhedron 34.

Finally, the monocapped cube (33) is predicted to have an electron count of 132e since $X = 1$ (rule 2, capping a square face) and $F = 9$. No examples are yet available.

Decavertex Metal Clusters. Three recently synthesized and structurally characterized *decametal* clusters with different electron counts and drastically different geometries (Chart X) also conform to the rules set forth in the preceding paper. The $[\text{Os}_{10}\text{C}(\text{CO})_{24}]^{2-}$ dianion,⁶⁸ which has a carbide, has the two-frequency (ν_2) tetrahedral structure 35 (i.e., a tetrahedron with edges formed by three atoms linked by two metal-metal bonds). This structure can also be viewed as a tetracapped octahedron (or, equivalently, that it has an octahedral hole), and hence we expect $X = 1$. With 16 (small) triangular faces on the surface, eq 5b of the preceding paper predicts $N = 134e$, as is indeed observed. $[\text{Rh}_{10}\text{S}(\text{CO})_{22}]^{2-}$ ⁶⁹ or $[\text{Rh}_{10}\text{P}(\text{CO})_{22}]^{3-}$,⁷⁰ with a central sulfide or phosphide atom, has been shown to adopt the bicapped-square-antiprismatic structure 36. A square antiprism is expected to have $X = 1$ or 3, and capping the two square faces ($X = 1$ for each capping) increases the X value to either 3 or 5. With 16 exposed triangular faces, eq 5b of the preceding paper predicts an electron count of 138 or 142. The latter was actually observed for both clusters. Finally, the $[\text{Ru}_{10}\text{C}_2(\text{CO})_{24}]^{2-}$ anion,⁷¹ with two carbides, adopts the edge-sharing bioctahedral geometry 37. Since each octahedron contributes $X = 1$ and edge-sharing further increases the X value by 1, the total X value equals 3. With 16 exposed triangular faces, $N = 138$, as is indeed observed.

Three other yet-unknown polyhedral structures are also tabulated in Table I: the bicapped cube (38), with $F = 12$ and $X = 2$, is expected to be a 144e cluster; the pentagonal antiprism (39, in Chart XI), with $F = 12$ and $X = 3$, is predicted to have 146 electrons; finally the pentagonal prism (40 in Chart I of the preceding paper), with $F = 7$ and $X = 0$, is likely to have 150 electrons.

Undecavertex Metal Clusters. One of the most interesting undecametal polyhedral clusters is the $[\text{Rh}_{11}(\text{CO})_{23}]^{3-}$ trianion⁷² shown in Chart XII. It can be described as a face-to-face

Chart XII

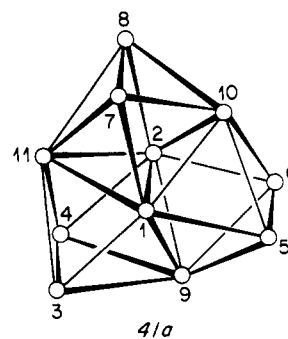


Chart XIII

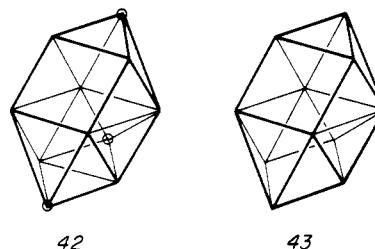
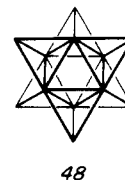


Chart XIV



fused trioctahedron (41a) with 18 "exposed" faces. The net X value is 2 since three octahedra give rise to a total X value of 3 (rule 4) and one "hidden" edge within the polyhedron contributes an X value of -1 (rule 7). We therefore predict an electron count of 148e for 41a, which is gratifyingly observed. If the "hidden" edge is lengthened by adding two electrons to 41a, the yet-unknown polyhedron of face-to-face trioctahedron without the central edge (41b) with a 150-electron count is expected.

Tricapping (\square^3 , indicated by open circles) a cube with two face diagonals (22 in Chart V) produces the polyhedron 42 shown in Chart XIII with 17 faces and X of 3 (tricapping, rule 2). This yet-unknown polyhedron is predicted to have 152 electrons (cf. Table I). The related structure 43 is also shown in Chart XIII; it has one less edge as well as one less face than 42 and hence $X = 3$ (rule 7) and $N = 154e$. The polyhedron 43 can also be considered as a monocapped (\square) trigonal prism (top half) sharing a square face with a square antiprism (bottom half); the shared square face, of course, is just the plane that divides the cube in the first description into two equal halves. The X value for this latter description is 2 or 4 (capping a square face of the trigonal prism contributes $X = 1$ and the square antiprism has $X = 1$ or 3); the predicted N value is therefore 152 or 156e. The observed N value of 154e in the $[\text{Co}_{11}\text{C}_2(\text{CO})_{21}]^{3-}$ trianion⁷³ better fits the first description.

The 11-vertex octadecahedron (44), a deltahedron with 18 faces, can be formed by capping the two pentagonal faces of the 9-vertex ($3^8 5^2$) decahedron (31) as illustrated in Chart VIII. The X value for 44 is 5 (X for 31 is 1, and capping each pentagonal face increases X by 2). The predicted electron count is 154e. This polyhedral skeleton, however, is yet un-

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Chart XV

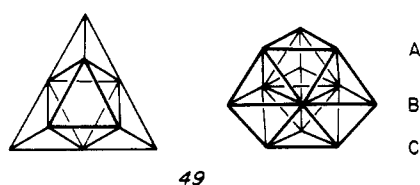
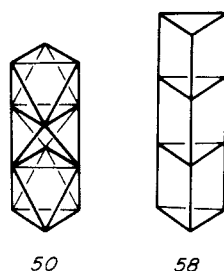


Chart XVI



known in metal cluster chemistry.

The yet to be discovered undecametal polyhedral clusters are, for example, the tricapped cube and the capped pentagonal antiprism and prism; the predicted electron counts are 156, 158, and 162e, respectively (cf. Table I).

Dodecavertex Metal Clusters. Dodecametal clusters exhibit intriguing polyhedral skeletal variation. The hexacapped octahedral (48) cluster⁷⁴ $[\text{Fe}_6\text{Pd}_6(\text{CO})_{24}\text{H}]^{3-}$, shown in Chart XIV, has 160 electrons, in reasonable agreement with the predicted value of 158e based on $F = 20$ and $X = 1$ (cf. Table I).

The truncated v_2 (frequency two, meaning that each edge corresponds to two metal-metal bonds) trigonal bipyramid (49), shown in Chart XV, has two octahedral holes and three trigonal-bipyramidal holes. If each octahedral hole contributes $X = 1$ (rule 4) and each trigonal-bipyramidal hole contributes $X = 2$ (rule 4), with three "hidden edges" (inner triangle of the center layer), $X = -3$ (rule 7), and a net X value of 5 can be calculated. The predicted electron count is thus 166e as is indeed observed in the $[\text{Ni}_{12}(\text{CO})_{21}\text{H}_{4-n}]^{n-}$ anions.⁷⁵ We note that the interlayer metal-metal distances are longer than the intralayer metal-metal bonds, in accord with the use of the X value of 2 for each of the three trigonal-bipyramidal holes. We predict that an electron count of 160e is more appropriate for a similar structure with more or less equal inter- and intralayer metal-metal distances. It is interesting to note that the layer stacking arrangement in 49 corresponds to the hexagonal close-packed (hcp) structure. Polyhedron 49 therefore represents the most compact 12-vertex polyhedron.

The face-sharing trioctahedral structure (50), which can also be described as a stack of four staggered triangles of metal atoms, is shown in Chart XVI and observed in $[\text{Rh}_{12}(\text{CO})_{25}\text{H}_n]^{n-}$,⁷⁶ where n is still undetermined. With 20 faces and $X = 3$ (three octahedra of $X = 1$ each), we predict $N = 162$. The observed value is $158 + n$, where $n > 0$. We predict that $n = 4$ and that face-sharing trioctahedral clusters of general formula $[\text{Rh}_{12}(\text{CO})_{25}\text{H}_{4-n}]^{n-}$ should exist. The related triangular-face-sharing tri(trigonal prismatic) structure (58 in Chart XVI) is observed in $[\text{Pt}_{12}(\text{CO})_{24}]^{2-77}$ (which can also be described as a stack of four eclipsed (though somewhat twisted) metal triangles); with 11 faces and $X = 0$, $N = 174e$

Chart XVII

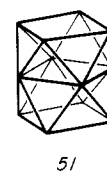


Chart XVIII

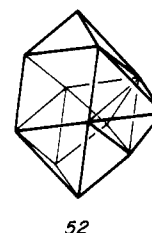
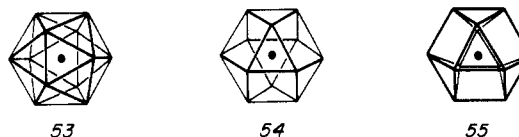


Chart XIX



is predicted. The observed value in $[\text{Pt}_{12}(\text{CO})_{24}]^{2-}$ is 170e, again 4e below the expected value.

The square-face-sharing bi(square antiprism) 51, shown in Chart XVII, has 18 faces and $X = 2$ or 6 (each square antiprism contributes $X = 1$ or 3); the predicted electron count is 164 or 172e. The observed values in the $[\text{Rh}_{12}\text{C}_2(\text{CO})_{24}]^{n-}$ anions,⁷⁸ where $n = 2, 3$, and 4, are 166, 167, and 168e, respectively, well within the predicted range.

The structure of the $\text{Rh}_{12}\text{C}_2(\text{CO})_{25}$ cluster⁷⁹ (52, Chart XVIII) can be described as a square-face-capped fused trigonal prism-square antiprism-trigonal bipyramid. The X value is 1 (square cap) + $\frac{1}{3}$ (square antiprism) + $\frac{0}{2}$ (trigonal bipyramid) - 1 (one hidden edge) or a net of 1, 3, or 5. Another way of describing 52 is to "fuse" polyhedron 43 with a trigonal bipyramid; in this case, $X = 3$ (for 43) + $\frac{0}{2}$ (for trigonal bipyramid) = $\frac{3}{2}$. The predicted N value is 162, 166, or 170e. The observed electron count in $\text{Rh}_{12}\text{C}_2(\text{CO})_{25}$ is 166e.

The *icosahedron* 53 (Chart XIX) can be considered as a bicapped pentagonal antiprism (39, Chart XI). Rule 5 predicts $X = 3$ for the pentagonal antiprism 39. Capping the two pentagonal faces further increases the X value to 7 (rule 2; $X = 2$ for each capping). Hence, for a dodecametal cluster of icosahedral geometry (20 triangular faces), one expects an electron count of 170 as is indeed observed in the $[\text{Rh}_{12}\text{Sb}(\text{CO})_{27}]^{3-}$ trianion⁸⁰ (though with three very long (3.3 Å) Rh-Rh bonds). An 162e icosahedral cluster, which is 8 electrons below the expected value, was reported for the $[\text{Au}_{13}\text{Cl}_2(\text{PMe}_2\text{Ph})_{10}]^{3+}$ trication.⁸¹ As with the platinum carbonyl clusters, gold phosphine clusters also have the tendency to have electron counts 4 or 6 electrons under the expected values.

As discussed in the preceding paper, both the cuboctahedron (ccp) 54 and the twinned cuboctahedron (hcp) 55 (Chart XIX) can be formed by structural perturbation of the icosahedron 53. With $V = 12$, $F = 14$, and $X = 1$, both are predicted to have 170 electrons. A twinned cuboctahedron was observed for the 170e systems $[\text{Rh}_{13}(\text{CO})_{24}\text{H}_{5-n}]^{n-}$.⁸² The reason that

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Chart XX

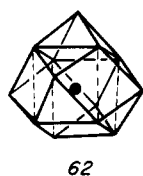


Chart XXI

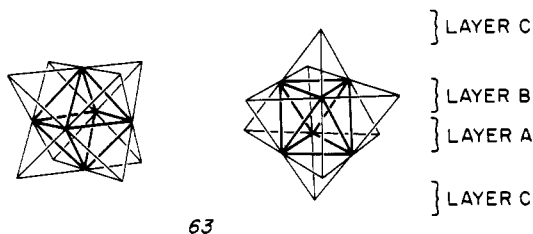
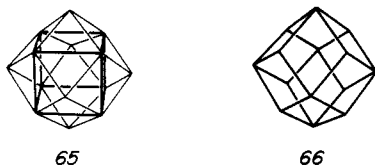


Chart XXII



the icosahedron, the cuboctahedron, and the twinned cuboctahedron all require 170 electrons is that their bonding requirements are quite similar despite their distinctive symmetries.

Note that the cuboctahedron (54) has an A, B, C pattern, corresponding to the cubic close-packed (ccp) structure, whereas the twinned cuboctahedron (55) has an A, B, A pattern, corresponding to the hexagonal close-packed (hcp) structure as shown in Chart XIX. Of all the polyhedra described so far, the icosahedron, cuboctahedron, and twinned cuboctahedron have a cavity large enough to completely encapsulate a metal atom. Note that the encapsulated metal atom is *not* considered part of the polyhedral network. It is considered merely as an electron contributor in the total electron count. Note also that a cuboctahedron is formed by truncating either a cube or an octahedron of frequency two (ν_2).

Also included in Table I are the yet unknown hexagonal antiprism (56), bicapped pentagonal prism (57), hexagonal prism (59), 3-connected ν_3 truncated tetrahedron (or (3^46^4) octahedron) (60), and (4^45^4) octahedron (61; cf. Chart I in the preceding paper), predicted to have electron counts of 170 (or 174), 174, 180, 180, and 180e, respectively.

Tridecavertex Metal Clusters. There is only one known 13-vertex tridecametal polyhedral cluster: the pentacapped cube (62) shown in Chart XX. With 21 faces and $X = 5$ (capping 5 square faces), the predicted electron count is 180e as is indeed observed in the $[\text{Rh}_{14}(\text{CO})_{25}]^{4-}$ tetraanion.⁸³ Other tridecametal polyhedral clusters are, of course, possible by either capping or fusing lower polyhedra.

Tetradecavertex Metal Clusters. The 14-vertex polyhedra octacapped octahedron (or face-centered cube) 63 (Chart XXI), hexacapped cube 65 (Chart XXII), and rhombic dodecahedron (or body-centered cube; central atom not shown) 66 (Chart XXII) are interrelated in that the expansion of the inner octahedron in 63 and the concomitant shrinkage of the outer cube result in 65. Similarly, slight expansion of the inner

Chart XXIII

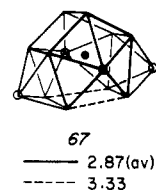
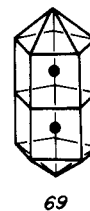


Chart XXIV



cube in 65 will produce 66. Our rules readily apply to 63 and 65, predicting $X = 1$ for 63 which has an octahedral cavity, and $X = 6$ for 65, which has the six square faces of the inner cube ($X = 0$) capped. Adding Y electron pairs (where Y is a small number) to 65 produces 66. Assuming that the 12 rhombic faces in 66 can be approximated by 24 triangular faces, the X value for 66 is then $6 + Y$. As tabulated in Table I, the predicted electron counts for 63, 65, and 66 are 182, 192, and $(192 + 2Y)e$, respectively. The observed value for the structurally known rhombic dodecahedral cluster⁸⁴ $[\text{Rh}_{15}(\text{CO})_{30}]^{3-}$ is 198e, from which a Y value of 3 can be deduced.

The tetracapped (\square^2, \triangle^2) pentagonal prism (67, Chart XXIII), with 21 faces and $X = 6$ (cappings, rule 2), is predicted to have an electron count of 198e. The observed value in the $[\text{Rh}_{15}\text{C}_2(\text{CO})_{28}]^-$ monoanion⁸⁵ is 200e. The latter, though, has two long metal-metal bonds, making one of the square faces of the pentagonal prism into a rectangular face. This may account for the two extra electrons.

Also included in Table I is the yet-unknown 14-vertex trigonal bipyramid (64), which can be formed by bicapping (Δ^2) polyhedron 49. The X value of 2 or 5 remains unchanged; with 24 faces, the electron count of 184 or 190e is expected.

Pentadecavertex Metal Clusters. Only one polyhedron is known for 15-vertex polyhedral metal clusters; the triangular-face-sharing tetra(trigonal prism) (68) formed by a stack of five eclipsed (though slightly twisted) metal triangles. With 14 faces and $X = 0$, 68 is predicted to have an electron count of 216e. The observed value in the $[\text{Pt}_{15}(\text{CO})_{30}]^{2-}$ dianion⁸⁶ is 212e, again four electrons below the predicted value.

Higher Clusters. Metal clusters of higher nuclearities are less common than metal clusters of lower nuclearities. Nevertheless, tremendous progress has been made in recent years. A few examples of structurally characterized large clusters are $[\text{Pt}_{19}(\text{CO})_{22}]^{4-87}$ and $[\text{Pt}_{38}(\text{CO})_{44}\text{H}_2]^{2-88}$ as well as $[\text{Rh}_{17}(\text{CO})_{30}]^{3-89}$ and $[\text{Rh}_{22}(\text{CO})_{37}]^{4-90}$. For these high-nuclearity clusters, electron counting becomes an increasingly difficult problem. Many simple rules are no longer applicable

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for metal clusters containing, e.g., more than 13 metal atoms. Our rules are no exception. Nevertheless, we include in Table I a 17- and a 20-vertex polyhedra of high symmetry. The 17-vertex bicapped (\square^2) face-sharing bi(pentagonal prism) (69, Chart XXIV), with 20 faces and $X = 4$, is expected to have 244 electrons. The observed value in the $[\text{Pt}_{19}(\text{CO})_{22}]^{4-}$ tetraanion,⁸⁷ with two encapsulated platinum atoms in the pentagonal-prismatic holes, is 238e, six electrons below the predicted value, again a characteristic of platinum carbonyl clusters.

The 20-vertex pentagonal dodecahedron (70), with 12 pentagonal faces and $X = 0$ (3-connected, rule 1; cf. Chart I in the preceding paper), is predicted to have an electron count of 300e. This polyhedral structure is yet unknown in metal cluster chemistry though the corresponding polyhedron in organic chemistry—the dodecahedrane⁹¹ $\text{C}_{20}\text{H}_{20}$ —has been synthesized recently.

A new approach to electron counting for high nuclearity metal clusters has been developed by Teo.⁹²

Conclusion

It is shown in this paper that the topological electron-counting theory, developed in the preceding paper, can be applied to a wide variety of transition-metal or post-transition-metal clusters. This theory encompasses polyhedra that follow, as well as those that violate, the effective atomic number and/or the skeletal electron pair rule. As is evident from Table I, the agreement between the predicted and the

observed electron counts (N) is generally very good. The only major exceptions are the platinum carbonyl or gold phosphine clusters of high nuclearity, which often have electron counts of four or six electrons under the predicted value. For example, the series of $[\text{Pt}_3(\text{CO})_6]_m^{2-}$ clusters, which have structures formed by stacking m nearly eclipsed platinum triangles (polyhedra 11, 32, 58, 68), all have electron counts of $42m + 2$, four electrons below the expected value of $42m + 6$.⁹³ Another example is the $[\text{Pt}_{19}(\text{CO})_{22}]^{4-}$ tetraanion, which has 238 electrons (six electrons short) rather than the expected value of 244e. A similar situation is also found for gold phosphine clusters. For example, the $[\text{Au}_{13}\text{Cl}_2(\text{PMe}_2\text{Ph})_{10}]^{3+}$ trication⁸¹ is 8e below the expected electron count of 170e for an icosahedral cluster. This phenomenon may be related to the fact that platinum or gold has a tendency to form 16e rather than 18e complexes.

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Steric and Electronic Control of the Arbuzov Reaction in Transition-Metal Halides: A ^1H and ^{31}P NMR Study of the Reaction of $[\text{CpCo}(\text{L}\text{L})\text{X}]^+$ Complexes ($\text{L}\text{L} = \text{N}, \text{P}, \text{As}$ Chelate Ligands; $\text{X}^- = \text{Cl}^-, \text{Br}^-, \text{I}^-, \text{CN}^-$) with $\text{P}(\text{OCH}_3)_3$

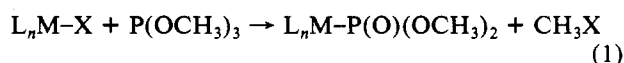
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Synthesis of a series of complexes, $[\text{CpCo}(\text{L}\text{L})\text{X}]^+$ ($\text{L}\text{L} = \text{N}, \text{P}, \text{As}$ chelate ligands; $\text{X}^- = \text{Cl}^-, \text{Br}^-, \text{I}^-, \text{CN}^-$), was undertaken with the goal of characterizing the Michaelis-Arbuzov reaction between these complexes and $\text{P}(\text{OCH}_3)_3$. ^1H and ^{31}P NMR results provide support for the previously postulated two-step mechanism involving an initial equilibrium reaction $[\text{CpCo}(\text{L}\text{L})\text{X}]^+ + \text{P}(\text{OCH}_3)_3 \rightleftharpoons \{\text{CpCo}(\text{L}\text{L})[\text{P}(\text{OCH}_3)_3]\}^{2+} + \text{X}^-$ followed by alkylation of X^- to produce an organo-metal-phosphonate complex, $\{\text{CpCo}(\text{L}\text{L})[\text{P}(\text{OCH}_3)_3]\}^{2+} + \text{X}^- \rightarrow \{\text{CpCo}(\text{L}\text{L})[\text{P}(\text{O})(\text{OCH}_3)_2]\}^+ + \text{CH}_3\text{X}$. Several of the intermediate phosphite dications were synthesized and characterized. They enable the above reactions to be qualitatively separated. The initial reaction was quenched by sterically bulky chelate ligands. The rate of the overall reaction parallels the electron donor power of the attacking nucleophile ($\text{CN}^- > \text{I}^- > \text{Br}^- > \text{Cl}^-$) and also depends on the donor atoms of LL ($\text{N} > \text{P}$). Chelate dissociation occurs when $\text{L}\text{L} = \text{As}$. The results for $[\text{CpCo}(\text{L}\text{L})\text{X}]^+$ and other transition metal-halide complexes are discussed in terms of why the Arbuzov reaction takes place in some of these complexes but not with others.

Introduction

Some transition-metal complexes possessing a substitutionally labile nucleophilic ligand are known to react with alkyl phosphites and yield a final product containing a coordinated phosphonate ligand rather than coordinated phosphite.¹⁻⁸



Equation 1 is formally analogous to the Michaelis-Arbuzov reaction (hereinafter referred to as the Arbuzov reaction)

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