

Binding and activation of small molecules by a quintuply bonded chromium dimer[†]

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The quintuply bonded $[^H\text{L}^{\text{iPr}}\text{Cr}]_2$ reacts with various small molecules, revealing a pattern of two kinds of transformations. Unsaturated molecules that are neither polar nor oxidizing form binuclear [2+*n*] cycloaddition products retaining Cr–Cr quadruple bonds. In contrast, polar or oxidizing molecules effect the complete cleavage of the Cr–Cr bond.

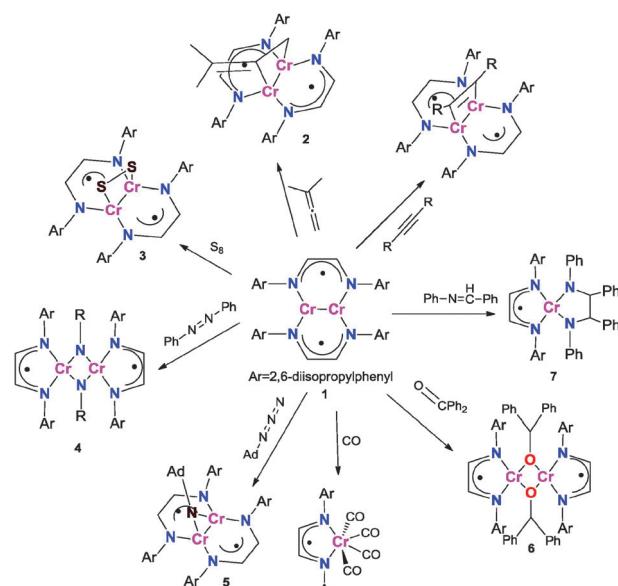
Occasioned by the discovery of a dinuclear chromium complex featuring a sterically accessible quintuple metal–metal bond, we have begun to explore the reactivity of this novel functional group unique to transition metal chemistry. Recent studies indicate that M–M quintuple bonds have a remarkable reaction chemistry.^{1–16} Herein we describe the products of reactions between quintuply bonded $[^H\text{L}^{\text{iPr}}\text{Cr}]_2$ (**1**, where $^H\text{L}^{\text{iPr}} = \text{Ar}-\text{N}=\text{C}(\text{H})-(\text{H})\text{C}=\text{N}-\text{Ar}$, with Ar = 2,6-diisopropylphenyl)¹⁷ and various small molecules (Scheme 1). These reactions are of interest in their own right and make for fascinating comparisons with the reactivities of other binuclear metal complexes.

1 reacts rapidly with molecules containing multiple bonds. For example, we have previously described [2+2] cycloaddition reactions between **1** and alkynes.¹⁸ While the analogous reaction with ethylene is apparently reversible, **1** adds to the destabilized C=C double bond of 1,1-dimethylallene, yielding another isolable [2+2] cycloaddition product, namely $[^H\text{L}^{\text{iPr}}\text{Cr}]_2(\mu-\eta^1:\eta^1-\text{H}_2\text{CCCMe}_2)$ (**2**, see Fig. 1). The terminal C=C bond of the allene ligand has added across the two metal centers, forming a four-membered dimetallacycle. The C53–C54 distance of 1.466(5) Å and the Cr–Cr distance of 1.9462(8) Å are consistent with a two-electron reduction of allene and concomitant oxidation of the Cr–Cr center, which, however, retains the short Cr–Cr distance characteristic of a quadruple bond (see Table 1). The other C=C bond of the allene remains essentially unperturbed (1.346(5) Å).

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Scheme 1 Reactions of **1** with alkyne, allene, sulfur, PhN=NPh, AdN₃, CO, benzophenone and benzylideneaniline.

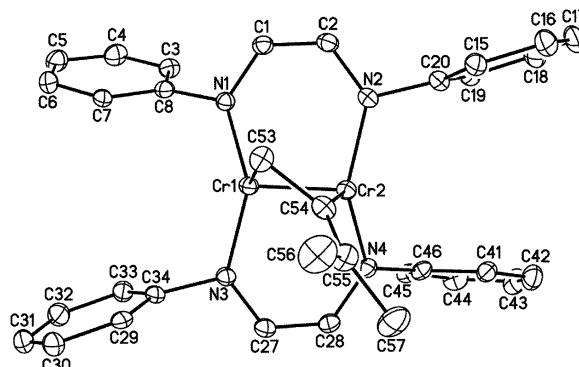


Fig. 1 The molecular structure of **2** (30% probability level). Ligand i-Pr groups and H-atoms have been omitted for clarity.



Table 1 Selected interatomic distances (Å) and angles (°)

	Cr–Cr	C–C ^c	C–N ^c	θ^a	δ^b
1	1.8028(9)	1.350(5)	1.368(3)	N/A	N/A
2	1.9462(8)	1.337(5)	1.380(4)	24.3°	151°
3	1.9305(8)	1.367(3)	1.360(3)	15.6°	143°
4	2.498(4)	1.395(11)	1.380(9)	N/A	N/A
5	1.9575(11) ^d	1.346(6)	1.385(6)	N/A	142°
6	3.1667(15)	1.360(6)	1.336(6)	N/A	N/A
7	N/A	1.383(6)	1.355(5)	N/A	N/A
1-Butyne ¹⁸	1.9248(7)	1.352(4)	1.370(4)	23.7°	146°

^a Twist angle (X-X)-(Cr-Cr) (X = C or S). ^b Dihedral angle between two ligand planes (see the ESI for details). ^c Average bond lengths in the α -diimine backbones. ^d Average.

The core of **2** adopts an almost planar geometry with a (C–C)–(Cr–Cr) twist angle of 24.3°, similar to the aforementioned alkyne adducts.¹⁸ The ¹H NMR spectrum of **2** exhibited sharp resonances consistent with a diamagnetic ground state of the molecule.

Oxygen atom sources, such as O₂, N₂O, and NO led to decomposition of **1** accompanied by loss of the diimine ligand. This motivated us to extend the exploration to less oxidizing chalcogens. Thus, treatment of an Et₂O-toluene solution of **1** with elemental sulphur, at room temperature, caused the initially green solution to turn deep blue. A standard work-up of the reaction and recrystallization from diethyl ether yielded the simple binuclear adduct, [^HL^{iPr}Cr]₂(S₂) (**3**) in modest yield (20%). The molecular structure of **3** is depicted in Fig. S1 (ESI[†]); it features a four-membered Cr₂S₂ ring. The “supershort” (Cr–Cr < 2.0 Å) Cr–Cr bond of **3** (1.9305(8) Å) is appreciably longer than that in **1** (1.8028(9) Å), indicating an oxidation from Cr(i) to Cr(ii) and hence a bond order reduced to 4. The S–S bond length of 2.0513(10) Å approximates that of Kempe’s disulfide analog (2.058(4) Å),² which, however, features perpendicular coordination of the S₂²⁻ unit and that of Cp₂Cr₂(μ-S)₂(μ-η¹-η¹-S₂) (2.028(2) Å).¹⁹ As is typical of the [2+2] cycloaddition products of **1**, the Cr₂S₂ core is not perfectly planar. The (S–S)–(Cr–Cr) twist angle for the core is 15.6°, somewhat smaller than the analogous angles in the alkyne adducts and **2**.

Table 1 contains selected bond lengths and angles for compounds 2–7. All the ‘cycloaddition’ products of **1** that maintain Cr–Cr bonds, *i.e.* 2, 3, and 1-2-butyne, exhibit the twisted $\mu\text{-}\eta^1\text{:}\eta^1$ bonding mode for the X_2 ligands ($\text{X} = \text{C, S}$); this differs from the perpendicular (*i.e.* $\mu_2\text{-}\eta^2\text{:}\eta^2$) bonding motif more typically observed for complexes with metal–metal bonds, *e.g.* in Kempe’s aminopyridinato dichromium complexes.^{2–4,20} At the same time, the dihedral angles (δ) between the α -diimine ligand planes are significantly larger than those of the aminopyridinato complexes (*e.g.* 107° for both the disulfide and the tolylacetylene adduct). In other words, the $[\text{L}_2\text{Cr}_2]$ fragments of the α -diimine complexes are considerably flatter than those with aminopyridinato ligands. The near preservation of the planar geometry of **1** and the formation of unsaturated four-membered Cr_2X_2 rings as opposed to tetrahedrane-like structures is unlikely to be steric in origin. An electronic explanation may be rooted in the electronic flexibility afforded by the redox-active α -diimine ligands; this remains to be explored.

An isoelectronic – but less oxidizing – analog of O_2 is azobenzene ($PhN=NPh$). When one equivalent of the latter

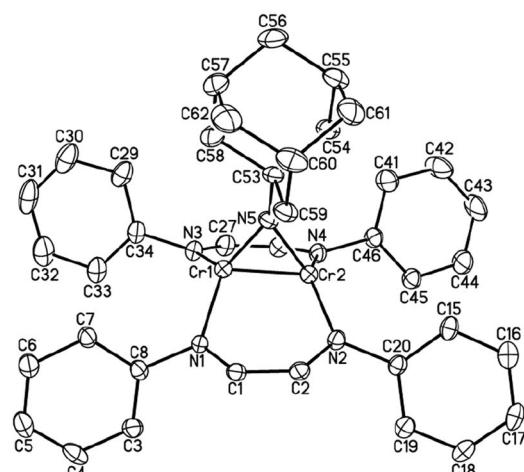
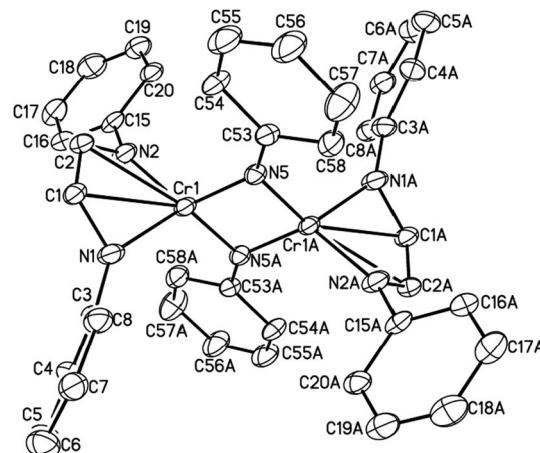


Fig. 2 The molecular structure of **4** and **5** (both at 30% probability level).

was added to a solution of $(\mu\text{-}\eta^1\text{:}\eta^1\text{-}^{\text{H}}\text{L}^{\text{iPr}})_2\text{Cr}_2$ (**1**) in diethyl ether, subsequent work-up and recrystallization produced red-brown crystals of dinuclear complex $[\text{H}^{\text{iPr}}\text{Cr}(\mu\text{-NPH})]_2$ (**4**) in 40% isolated yield. **4** is a dinuclear complex with bridging imido ligands (Fig. 2, top). This reaction may well go through an unstable [2+2] cycloaddition intermediate, which suffers oxidative addition, due to the high electronegativity of nitrogen. The molecular structure of **4** features four-coordinate chromium (ignoring the rather long Cr-C interactions) adopting pseudo-tetrahedral geometry, which is the preferred geometry of 4-coordinate Cr(III). The N=N double bond has been severed completely ($N\cdots N_{\text{avg}} = 2.695 \text{ \AA}$). Similarly, the distance between the two chromium atoms in **4** is 2.498(4) \AA , indicating the absence of any significant bonding interactions.

The average bond lengths of C–C, C–N bonds in the backbone of the α -diimine ligand are 1.395(11) and 1.380(9) Å, characteristic of a diimine radical anion; accordingly, chromium is in the formal oxidation state +III ($S = 3/2$). The effective magnetic moment of 4 at room temperature was 2.4(1) μ_B , consistent with antiferromagnetic coupling, both between the metal and its radical ligand as well as between the chromium atoms.

The reaction between $(\mu\text{-}\eta^1\text{:}\eta^1\text{-H}_1\text{L}^{\text{IPr}})_2\text{Cr}_2$ (**1**) and sterically demanding Ad-N_3 afforded another imido complex, namely

$[\text{H}^{\text{L}}\text{Cr}]_2(\text{NAd})$ (5), as shown in Fig. 2 (bottom). Only one imido group has been added across the Cr–Cr bond. Once again, we suggest that a five-membered [2+3] cycloaddition product may be formed first, which rapidly extrudes N_2 . The bond distances and angles of 5 are comparable to those of other known bridging imido complexes of chromium.^{22–26} Similar to the geometries of the [2+2] cycloaddition products, the elongated Cr–Cr distance of 1.9575(11) Å is consistent with the two-electron oxidation of the Cr_2 unit (to $\text{Cr}(\text{II})$). 5 is also diamagnetic, presumably due to metal–metal quadruple bonding.

Finally, we were interested in studying the reactivity of 1 toward unsaturated molecules featuring X–Y bonds (X, Y = C, N, O). Exposure of a benzene solution of 1 to CO (1 atm) produced the dark blue carbonyl $[\text{H}^{\text{L}}\text{Cr}(\text{CO})_4]$, as confirmed by ^1H NMR spectroscopy.²¹ The reaction of 1 with benzophenone resulted in dinuclear $[\text{H}^{\text{L}}\text{Cr}(\mu\text{-OPh}_2)]_2$ (6). The structure of 6 (shown in Fig. S2, ESI[†]) reveals a benzophenone-bridged dimer with square planar Cr centers. The average carbon–oxygen bond length of the benzophenone is 1.355(5) Å, which is much longer than the 1.230(3) Å in benzophenone,²⁷ suggesting some degree of reduction of the C=O bonds. The average bond lengths of C–C, C–N bonds of the backbone of the α -diimine ligand are 1.360(6) and 1.336(6) Å, consistent with those of a monoanionic diimine ligand.²¹ These structural features suggest that 6 is a $\text{Cr}(\text{II})$ complex. Like $[\text{H}^{\text{L}}\text{Cr}(\mu\text{-Cl})_2]$,¹⁷ 6 exhibited a simple isotropically shifted and broadened ^1H NMR spectrum in C_6D_6 , with chemical shifts at 96, 14.6, 3.2, 1.56, and –13.0 ppm. $\mu_{\text{eff}}(\text{RT})$ of this complex was found to be 5.1(2) μ_{B} (3.6(1) μ_{B} per chromium), which is consistent with two antiferromagnetically coupled $\text{Cr}(\text{II})$ metal centers ($S = 2$) coordinated by ligand radicals ($S = 1/2$).

In contrast to 6, reductive coupling of C=N double bonds was observed upon exposure of 1 to four equivalents of trans-benzylideneaniline. The reaction was found to form the coupling product, $[\text{H}^{\text{L}}\text{Cr}(\kappa^2\text{-N}_2\text{C}_{26}\text{H}_{22})]$ (7). The crystal structure is shown in Fig. 3. 7 adopts tetrahedral coordination about chromium

with the α -diimine apparently being in the singly reduced state (see Table 1). The room temperature effective magnetic moment of 7 was found to be 2.9(1) μ_{B} , consistent with a $\text{Cr}(\text{III})$ metal center ($S = 3/2$) strongly coupled to a ligand radical ($S = 1/2$).

In summary, reactivity studies on a quintuply bonded dichromium complex supported by α -diimine ligands have been extended to a variety of molecules. The products are varied and their structures differ from those established for quintuply bonded complexes supported by other ligands. A pervasive feature of 1 seems to be the formation of [2+n] cycloaddition products with nonpolar substrates. Polar, heteroatomic multiple bonds on the other hand effect complete cleavage of the metal–metal bond.

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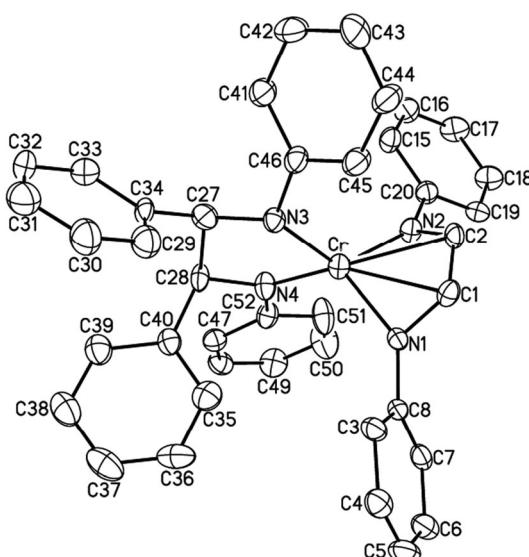


Fig. 3 The molecular structure of 7 (30% probability level).

