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

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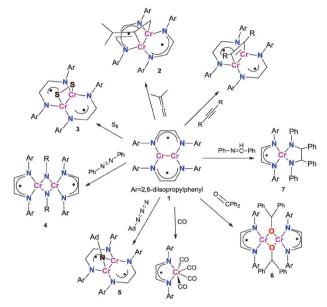
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The quintuply bonded  $[{}^{H}L^{iPr}Cr]_2$  reacts with various small molecules, revealing a pattern of two kinds of transformations. Unsaturated molecules that are neither polar nor oxidizing form binuclear [2+*n*] cyclo-addition products retaining 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.<sup>1–16</sup> Herein we describe the products of reactions between quintuply bonded [ $^{H}L^{iPr}Cr$ ]<sub>2</sub> (1, where  $^{H}L^{iPr} = Ar - N = C(H) - (H)C = N - Ar$ , with Ar = 2,6-diisopropylphenyl)<sup>17</sup> 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.<sup>18</sup> 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 [<sup>H</sup>L<sup>iPr</sup>Cr]<sub>2</sub>( $\mu$ - $\eta^1$ : $\eta^1$ -H<sub>2</sub>CCCMe<sub>2</sub>) (**2**, see Fig. 1). The terminal C=C bond of the allene ligand has added across the two metal centers, forming a fourmembered dimetallacycle. The C53–C54 distance of **1**.466(5) Å and the Cr–Cr distance of **1**.9462(8) Å are consistent with a twoelectron 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).



Scheme 1 Reactions of 1 with alkyne, allene, sulfur, PhN=NPh, AdN<sub>3</sub>, CO, benzophenone and benzylideneaniline.

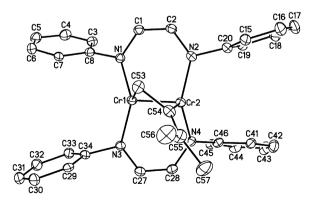


Fig. 1 The molecular structure of  ${\bf 2}$  (30% probability level). Ligand i-Pr groups and H-atoms have been omitted for clarity.

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

	Cr–Cr	$C-C^{c}$	$C-N^{c}$	$\theta^a$	$\delta^b$
1	1.8028(9)	1.350(5)	1.368(3)	N/A	N/A
2	1.9462(8)	1.337(5)	1.380(4)	$24.3^{\circ}$	$151^{\circ}$
3	1.9305(8)	1.367(3)	1.360(3)	$15.6^{\circ}$	$143^{\circ}$
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	$142^{\circ d}$
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
<b>1</b> -Butyne <sup>18</sup>	1.9248(7)	1.352(4)	1.370(4)	$23.7^{\circ}$	$146^{\circ}$

<sup>*a*</sup> Twist angle (X–X)–(Cr–Cr) (X = C or S). <sup>*b*</sup> Dihedral angle between two ligand planes (see the ESI for details). <sup>*c*</sup> Average bond lengths in the α-diimine backbones. <sup>*d*</sup> 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.<sup>18</sup> The <sup>1</sup>H 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 Et<sub>2</sub>O-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,  $[{}^{H}L^{iPr}Cr]_{2}(S_{2})$  (3) in modest yield (20%). The molecular structure of 3 is depicted in Fig. S1 (ESI<sup>+</sup>); it features a four-membered  $Cr_2S_2$  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(1) to Cr(11) 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  $(2.058(4) \text{ Å})^2$ , which, however, features perpendicular coordination of the  $S_2^{2-}$  unit and that of  $Cp_2Cr_2(\mu-S)_2(\mu-\eta^1-\eta^1-S_2)$  (2.028(2) Å).<sup>19</sup> As is typical of the [2+2] cycloaddition products of 1, the  $Cr_2S_2$  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  $\mu$ - $\eta^1$ : $\eta^1$  bonding mode for the X<sub>2</sub> ligands (X = C, S); this differs from the perpendicular (*i.e.*  $\mu_2$ - $\eta^2$ : $\eta^2$ ) bonding motif more typically observed for complexes with metal-metal bonds, e.g. in Kempe's aminopyridinato dichromium complexes.<sup>2-4,20</sup> At the same time, the dihedral angles ( $\delta$ ) between the  $\alpha$ -diimine ligand planes are significantly larger than those of the aminopyridinato complexes (e.g.  $107^{\circ}$  for both the disulfide and the tolylacetylene adduct). In other words, the [L<sub>2</sub>Cr<sub>2</sub>] fragments of the  $\alpha$ -diimine complexes are considerably flatter than those with aminopyridinato ligands. The near preservation of the planar geometry of 1 and the formation of unsaturated fourmembered Cr<sub>2</sub>X<sub>2</sub> 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  $\alpha$ -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

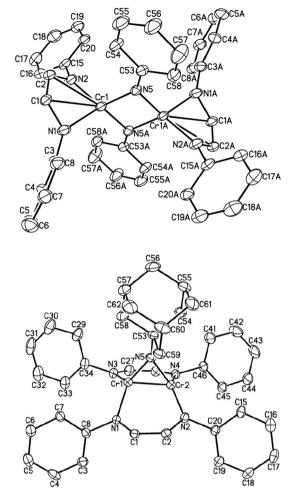


Fig. 2 The molecular structure of 4 and 5 (both at 30% probability level).

was added to a solution of  $(\mu-\eta^{1}:\eta^{1}-^{H}L^{iPr})_{2}Cr_{2}$  (1) in diethyl ether, subsequent work-up and recrystallization produced redbrown crystals of dinuclear complex  $[^{H}L^{iPr}Cr(\mu-NPh)]_{2}$  (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 pseudotetrahedral geometry, which is the preferred geometry of 4-coordinate Cr(m). The N=N double bond has been severed completely ( $N \cdots N_{avg} = 2.695$  Å). Similarly, the distance between the two chromium atoms in 4 is 2.498(4) Å, indicating the absence of any significant bonding interactions.

The average bond lengths of C–C, C–N bonds in the backbone of the  $\alpha$ -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)  $\mu_{\rm B}$ , consistent with antiferromagnetic coupling, both between the metal and its radical ligand as well as between the chromium atoms.

The reaction between  $(\mu - \eta^1 - \mu^1 - \mu^1 - \mu^1)_2 Cr_2$  (1) and sterically demanding Ad-N<sub>3</sub> afforded another imido complex, namely

 $[^{H}L^{iPr}Cr]_{2}$ (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<sub>2</sub>. The bond distances and angles of 5 are comparable to those of other known bridging imido complexes of chromium.<sup>22–26</sup> Similar to the geometries of the [2+2] cycloaddition products, the elongated Cr–Cr distance of 1.9575(11) Å is consistent with the twoelectron oxidation of the Cr<sub>2</sub> unit (to Cr( $\pi$ )). 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 <sup>H</sup>L<sup>iPr</sup>Cr(CO)<sub>4</sub>, as confirmed by <sup>1</sup>H NMR spectroscopy.<sup>21</sup> The reaction of 1 with benzophenone resulted in dinuclear  $[{}^{H}L^{iPr}Cr(\mu-OPh_2)]_2$  (6). The structure of 6 (shown in Fig. S2, ESI<sup>+</sup>) 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,<sup>27</sup> 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  $\alpha$ -diimine ligand are 1.360(6) and 1.336(6) Å, consistent with those of a monoanionic diimine ligand.<sup>21</sup> These structural features suggest that 6 is a  $Cr(\pi)$  complex. Like  $[{}^{H}L^{iPr}Cr(\mu-Cl)]_{2}$ , 6 exhibited a simple isotropically shifted and broadened <sup>1</sup>H NMR spectrum in C<sub>6</sub>D<sub>6</sub>, 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)  $\mu_{\rm B}$  (3.6(1)  $\mu_{\rm B}$  per chromium), which is consistent with two antiferromagnetically coupled  $Cr(\pi)$  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 transbenzylideneaniline. The reaction was found to form the coupling product,  ${}^{\rm H}L^{\rm iPr}Cr(\kappa^2-N_2C_{26}H_{22})$  (7). The crystal structure is shown in Fig. 3. 7 adopts tetrahedral coordination about chromium

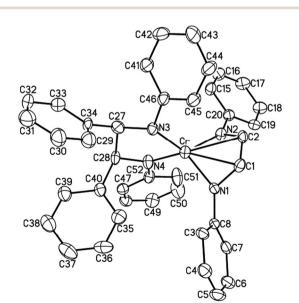


Fig. 3 The molecular structure of 7 (30% probability level).

with the  $\alpha$ -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)  $\mu_{\rm B}$ , consistent with a Cr(m) 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  $\alpha$ -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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