Mixed-ligand complexes of paddlewheel dinuclear molybdenum as hydrodehalogenation catalysts for polyhaloalkanes†

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We developed a hydrodehalogenation reaction of polyhaloalkanes catalyzed by paddlewheel dimolybdenum complexes in combination with 1-methyl-3,6-bis(trimethylsilyl)-1,4-cyclohexadiene (MBTCD) as a non-toxic H-atom source as well as a salt-free reductant. A mixed-ligated dimolybdenum complex Mo2(OAc)2(CH(NAr)2)2 (3a, Ar = 4-MeOC6H4) having two acetates and two amidinates exhibited high catalytic activity in the presence of 1Bu4NCl, in which [1Bu4N][Mo2(CH(NAr)2)2Cl4] (9a), derived by treating 3a with C3SiMe3 and 1Bu4NCl, was generated as a catalytically-active species in the hydrodehalogenation. All reaction processes, oxidation and reduction of the dimolybdenum complex, were clarified by control experiments, and the oxidized product, [1Bu4N][Mo2(CH(NAr)2)2Cl4] (10a), was characterized by EPR and X-ray diffraction studies. Kinetic analysis of the hydrodehalogenation reaction as well as a deuterium-labelling experiment using MBTCD-d2 suggested that the H-abstraction was the rate-determining step for the catalytic reaction.

Introduction

The M2L4-type paddlewheel dinuclear complexes having monomeric bridging ligands comprise the simplest metal cluster motif, and intensive investigation has been focused on their structures, redox behaviors, and spectroscopic properties, as well as their catalytic applications.1–3 Dinuclear paddlewheel complexes of the late transition metals such as rhodium and ruthenium act as useful and versatile catalysts for cyclopropanation of olefins and for functionalizing C-H, O-H, N-H, and Si-H bonds via the generation of metal-carbene, [M2L4(==CR1R2)], metal-alkoxide, and -nitride species, [M2L4(Z)] (Z = OR, N).3a–e,4 In all cases, because four supporting ligands tightly coordinate to the adjacent two metal centers while maintaining the dinuclear paddlewheel skeleton and the metal–metal bond, the architecture of the four supporting ligands was tunable to control redox behavior and catalytic performance of the paddlewheel complexes. In sharp contrast, few studies have examined the catalytic application of paddlewheel complexes of the early transition metals. As an example, Mo2(OAc)4 was used for an aza-Diels–Alder reaction of acyl hydrazones and dienes; however, the original paddlewheel structure was not maintained during the reaction. We and others have continued to investigate the stoichiometric and catalytic application of quadruply bonded M2 complexes of group 6 metals for organic radical generation by designing bridging ligands,4,12 and have achieved catalytic radical addition and polymerization reactions.3 During these transformations, the metal–metal bond responds to the one-electron redox processes without decomposition of the dinuclear structure. The structural stability of the dinuclear motif owes to both the surrounding four ligands and the metal–metal multiple bonds. In a further catalytic application of the M2 complexes, we used a cyclohexadiene derivative instead of α-olefins as a substrate for the organic radicals generated from polyhaloalkanes, leading to the formation of hydrodehalogenated products. Although hydrodehalogenation is one of the key reactions for decomposing environmentally unfriendly polyhaloalkanes, precious metal catalysts are often used.14 Herein, we report that paddlewheel Mo2 complexes, as shown in Fig. 1, act as catalysts for hydrodehalogenation reactions of polyhaloalkanes upon combination with 1-methyl-3,6-bis(trimethylsilyl)-1,4-cyclohexadiene (MBTCD)12 as an H-atom donor, and reveal the mechanism and actual active species in this catalytic process.

Results and discussion

We began by searching for the best paddlewheel Mo2 catalyst among the homoleptic and mixed-ligand complexes listed in Fig. 1 for the hydrodehalogenation reaction of 1,1,1,3-
trans-stereochemistry of the mixed-ligand complexes was a key factor: exhibited moderate catalytic activities (runs 2, 3, and 6). The dimolybdenum bearing both acetate and amidinate ligands exhibited low activities (runs 1 and 7), while mixed-ligand complexes of 1 were almost inactive, probably because the substrate approach was sterically prevented (run 5). Accordingly, we examined the hydrodehalogenation reaction of 1,1,1,3-tetrachloropropane (10 mol%) to the reaction mixture in acetonitrile led to the formation of 1,1,3-trichloropropane in 84% yield (run 10). In the blank reaction without MBTCD, no reaction proceeded since MBTCD acts as the H-donor and reductant for the catalytic reaction. When we used HSiE₅ as a commercially available H-donor instead of MBTCD, the yield decreased (11%), probably due to the inefficient reducing ability of the in situ generated intermediate [Mo₂]₅⁺ species (vide infra).

To reveal the additive effects of ²⁷Bu₄NCl to 3a, we conducted control experiments. We observed the formation of trimethylsilyltoluene and ClSiMe₅ as the reaction byproducts derived from MBTCD, along with Me₃SiOAc, which was the reaction product of the acetate ligand and ClSiMe₅. Because the ligand replacement reaction of an acetate ligand by ClSiMe₅ was reported by Cotton et al.,¹⁴ we examined the reaction of 3a with excess ClSiMe₅ in CD₃CN (Scheme 1). In the ¹H NMR spectrum, new resonances assignable to the Mo₂ complex 6a appeared within 30 minutes at room temperature, and, after 41 h, all of 3a was converted to 7a, which was isolated as a purple powder.¹⁵⁰

Subsequent heating of a solution of 7a at 80 °C resulted in the formation of a dimeric molybdenum cluster, [Mo₂-[CH(NAr)₂]₂[μ-Cl]₁₂] (8a),¹⁶ which was previously isolated and structurally characterized. The dimeric complex 8a exhibited low catalytic activity even in the presence of ²⁷Bu₄NCl, probably due to the low solubility of 8a in the reaction media (run 13). In contrast, treatment of complex 3a with ClSiMe₅ in the presence of ²⁷Bu₄NCl in toluene at 80 °C afforded a dianionic Mo₂ species, [²⁷Bu₄N]₂[Mo₂{CH(NAr)₂}₂Cl₄] (9a), in which two amidinates and four chloride ligands coordinated to the Mo₂ core, based on single crystal X-ray diffraction analysis (Fig. 2[a]).¹⁵¹ Notably, no conversion of 9a to the Cl-bridged dimer 8a was observed, even upon prolonged heating of 9a in CH₃CN. The catalytic activity of 9a was equal to that of 3a/²⁷Bu₄NCl (runs 10 and 14). By monitoring the reaction progress using ¹H NMR spectroscopy, we found the induction period for the 3a/²⁷Bu₄NCl catalyst. Complexes 3a or 7a were slowly catalyzing the hydrodehalogenation reaction. Interestingly, complex 9a initiated the catalytic hydrodehalogenation reaction without any induction.

### Table 1
Hydrodehalogenation reaction of 1,1,1,3-tetrachloropropane catalyzed by Mo₂ paddlewheel complexes

<table>
<thead>
<tr>
<th>Run</th>
<th>Cat.</th>
<th>Solvent</th>
<th>Additive</th>
<th>Yield (%)</th>
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<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>CD₃CN</td>
<td>—</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
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<tr>
<td>4</td>
<td>3b</td>
<td>CD₃CN</td>
<td>—</td>
<td>9</td>
</tr>
<tr>
<td>5</td>
<td>3c</td>
<td>CD₃CN</td>
<td>—</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>4</td>
<td>CD₃CN</td>
<td>—</td>
<td>31</td>
</tr>
<tr>
<td>7</td>
<td>5</td>
<td>CD₃CN</td>
<td>—</td>
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</tr>
<tr>
<td>8</td>
<td>3a</td>
<td>THF-d₈</td>
<td>—</td>
<td>59</td>
</tr>
<tr>
<td>9</td>
<td>3a</td>
<td>C₆D₆</td>
<td>—</td>
<td>42</td>
</tr>
<tr>
<td>10</td>
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<td>CD₃CN</td>
<td>²⁷Bu₄NCl</td>
<td>84 (73)</td>
</tr>
<tr>
<td>11</td>
<td>7a</td>
<td>CD₃CN</td>
<td>—</td>
<td>71</td>
</tr>
<tr>
<td>12</td>
<td>7a</td>
<td>CD₃CN</td>
<td>²⁷Bu₄NCl</td>
<td>85</td>
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<tr>
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<td>CD₃CN</td>
<td>²⁷Bu₄NCl</td>
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</tr>
<tr>
<td>14</td>
<td>9a</td>
<td>CD₃CN</td>
<td>—</td>
<td>85</td>
</tr>
</tbody>
</table>

* Determined using ¹H NMR measurements. Yield in parentheses was the isolated yield. **²⁷Bu₄NCl (10 mol%) was added to the reaction mixture.

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Fig. 1 Paddlewheel dimolybdenum complexes 1–5.

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Scheme 1 Ligand substitution and dimerization reactions of 3a by the addition of Me₃SiCl.
period (Fig. 3), indicating that the dianionic complex 9a was the identity of the catalytically active species.

Because of the inactivity of MBTCD toward [Mo₂]⁵⁺ complexes, the catalytic reaction of 9a (3a/⁴Bu₄NCl) was assumed to be initiated by the first reductive cleavage of a carbon–halogen bond, which produced a carbon radical and an [Mo₂]⁵⁺ species. Thus, we next performed an oxidation reaction of 9a with CCl₄ at room temperature, and the oxidized [Mo₂]⁵⁺ species, [⁴Bu₄N][Mo₂(CH(NAr)₂)_2Cl₄] (10a), was isolated in 88% yield (Scheme 2, path a). During the reaction, ⁴Bu₄NCl was eliminated, and the ligand system of the Mo₂ core remained intact. A single crystal X-ray diffraction study of 10a confirmed the elongation of the Mo–Mo bond by ~0.04 Å from 9a, and the distance of the Mo–Mo bond is typical for [Mo₂]⁵⁺ species (Fig. 2(b)).¹⁷ The formation of [Mo₂]⁵⁺ was further confirmed using EPR spectroscopic analysis, in which resonances typical of [Mo₂]⁵⁺ species were detected (g = 1.955). The high catalytic activity of 9a was ascribed to the relatively negative E⁰([Mo₂]⁴⁺/⁵⁺) value: the E⁰([Mo₂]⁴⁺/⁵⁺) value of 9a was −0.29 V, which shifted to a more negative value compared to that of 7a (−0.14 V) and 8a (−0.08 V). The other aspect of the high catalytic activity of 9a is the stability of the Mo₂(L)₂Cl₄ structure and solubility during the redox processes. In fact, complex 7a reacted with CCl₄ to form a [Mo₂]⁶⁺ species, [Mo₂(CH(NAr)₂)_2Cl₄(CH₃CN)] (11a), as poorly soluble dark-red microcrystals that precipitated from the reaction mixture (eqn (1)).³⁵

When the oxidized species 10a was treated with MBTCD in the absence of ⁴Bu₄NCl or without MBTCD in the presence of ⁴Bu₄NCl to reduce 10a, no reaction was observed, even after heating. On the other hand, in the presence of MBTCD, ⁴Bu₄NCl, and AIBN as a carbon radical source, we observed the formation of 9a together with ClSiMe₃, trimethylsilyltoluene, and isobutyronitrile, after heating at 80 °C for 1.5 h (Scheme 2, path b). This indicated that the AIBN-derived carbon radical abstracted one hydrogen atom from MBTCD to generate isobutyronitrile and a radical derivative of MBTCD, which subsequently reduced 10a to give 9a, along with ClSiMe₃ and trimethylsilyltoluene.

By using the complex 9a as a catalyst for the hydrodehalogenation of 1,1,1,3-tetrachloropropane, we checked the initial reaction rate dependence for the catalyst, 1,1,1,3-tetrachloropropane, and MBTCD. A first-order rate dependence on the catalyst and MBTCD concentration was observed, whereas the reaction was not dependent on the concentration of 1,1,1,3-tetrachloropropane (Fig. 4(a)–(c)). During the catalytic reaction as described in Table 1, we did not find any byproducts such as radical homo-coupling and disproportionated products, suggesting that the reaction of 9a and 1,1,1,3-tetrachloropropane is in fast equilibrium with 10a before reacting with MBTCD. Zero-order in 1,1,1,3-tetrachloropropane might indicate the saturation of the reactive intermediate composed of 10a and the carbon radical in the coordination sphere, which is consistent with the large negative entropy value (vide infra). In addition, MBTCD-d₄ was applied to the catalytic reaction: the KIE value was 1.71, suggesting that the H-abstraction from MBTCD by the organic radical was involved in the rate-determining step. Furthermore, the rate of the catalytic reaction over a temperature ranging from 50 to 65 °C was monitored by ²H NMR
spectroscopy. Eyring kinetic analyses of the reaction profile afforded the activation parameters of $\Delta H^\ddagger = 25.7 \pm 0.9$ kJ mol$^{-1}$, $\Delta S^\ddagger = -56.5 \pm 0.7$ e.u., and $\Delta G^\ddagger(298 \text{ K}) = 96.2 \pm 1.8$ kJ mol$^{-1}$ (Fig. 4(d)). A large negative $\Delta S^\ddagger$ value indicated an ordered transition state for the H-abstraction step: we presume that the organic radical derived from 1,1,1,3-tetrachloropropane stays in the coordination sphere of 10a during C–Cl reductive cleavage, while the radical abstracts the H-atom from MBTCD.

Based on the above observations for the kinetic study and redox reactions of the Mo$_2$ complexes, we propose a plausible catalytic cycle as shown in Scheme 3. In the initial stage, the dinuclear metal cluster 9a is in equilibrium with [Mo$_2$]$^{5+}$ species 10a in the presence of alkyl halides, which is often observed for the carbon radical generation by low-valent metal species with alkyl halides.
catalytic reaction in the presence of $^{8}$Bu$_3$NCl. Control experiments revealed that the ligand exchange of two acetate ligands of 3a by C(SiMe$_3$)$_2$ and $^{8}$Bu$_3$NCl to form an ionic [($^{8}$Bu$_3$N)$_2$Mo$_2$(CH(NA)$_3$)$_2$Cl$_4$] (9a) were key reaction events to generate the catalytically active species. In addition, kinetic analysis of the catalytic reaction profile, a deuterium-labeling experiment using MBTCD-d$_8$, and isolation of the oxidized species 10a clarified the catalytic cycle and the rate-determining step in the catalytic reaction. Further studies of the applications of one electron redox processes by paddlewheel Mo$_2$ complexes toward various organic transformations are ongoing in our laboratory.

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Notes and references


15 See ESL†.


