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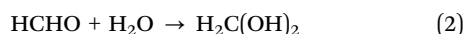
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## Catalytic hydrogen production from paraformaldehyde and water using an organoiridium complex†

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**Paraformaldehyde was decomposed using an organoiridium complex (1, [Ir<sup>III</sup>(Cp\*)(4-(1*H*-pyrazol-1-yl-κ*N*<sup>2</sup>)benzoic acid-κ*C*<sup>3</sup>)(H<sub>2</sub>O)]<sub>2</sub>SO<sub>4</sub>) as a catalyst in water to produce H<sub>2</sub> and CO<sub>2</sub> in a 2:1 molar ratio at room temperature. The catalytic cycle is composed of the reduction of 1 by paraformaldehyde under basic conditions to produce formic acid and the hydride complex, which reacts with protons to produce H<sub>2</sub>. Formic acid further decomposed to H<sub>2</sub> and CO<sub>2</sub> with 1.**

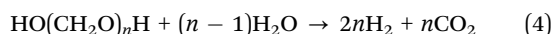
Paraformaldehyde is the polymerisation product of formaldehyde with a molecular formula of HO(CH<sub>2</sub>O)<sub>*n*</sub>H (*n* = 8–100).<sup>1</sup> Paraformaldehyde forms slowly in aqueous formaldehyde solutions as a white precipitate. Formalin actually contains very little monomeric formaldehyde, most of which forms short chains of polyformaldehyde.<sup>2</sup> Paraformaldehyde has been reported to be synthesised by electrocatalytic reduction of CO<sub>2</sub> and water.<sup>3–5</sup> Paraformaldehyde can be depolymerised to formaldehyde [eqn (1)], which is subsequently hydrated to form a geminal diol, *i.e.*, methanediol [eqn (2)] in water under basic conditions.<sup>6,7</sup>



Formic acid, which is the two-electron oxidation product of formaldehyde, has been regarded as a liquid H<sub>2</sub> carrier because of efficient generation of H<sub>2</sub> from HCOOH [eqn (3)] using an



appropriate catalyst under normal pressure at ambient temperature.<sup>8–14</sup> If H<sub>2</sub> can be generated from paraformaldehyde (eqn (4)), paraformaldehyde would be regarded as a convenient



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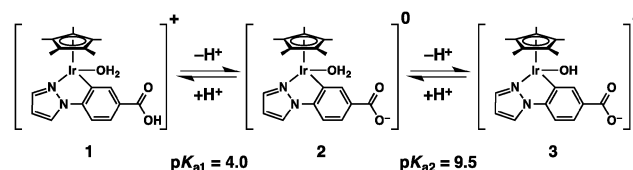
† Electronic supplementary information (ESI) available: Experimental and kinetic details. See DOI: 10.1039/c4cc06581f

solid H<sub>2</sub> carrier, which has a higher energy density (6.7%) than HCOOH (4.4%). Precht and coworkers recently reported selective hydrogen production from paraformaldehyde and formaldehyde using a Ru catalyst [(Ru(*p*-cymene))<sub>2</sub>(μ-Cl)<sub>2</sub>Cl<sub>2</sub>].<sup>15</sup> However, a relatively high temperature (95 °C) was required for the efficient hydrogen production from paraformaldehyde.<sup>15</sup> To the best of our knowledge, this is the only example of hydrogen production from paraformaldehyde.

We report herein the catalytic decomposition of paraformaldehyde to H<sub>2</sub> and CO<sub>2</sub> (eqn (4)) with a water-soluble iridium aqua complex [Ir<sup>III</sup>(Cp\*)(4-(1*H*-pyrazol-1-yl-κ*N*<sup>2</sup>)benzoic acid-κ*C*<sup>3</sup>)(H<sub>2</sub>O)]<sub>2</sub>SO<sub>4</sub> ([1]<sub>2</sub>·SO<sub>4</sub>, Cp\* = η<sup>5</sup>-pentamethylcyclopentadienyl) at room temperature.

Synthesis and characterisation of 1 were performed as reported previously (see ESI†).<sup>14,16</sup> The carboxylic acid form 1 is deprotonated to give the carboxylate form 2 with p*K*<sub>a</sub> = 4.0 and the aqua ligand of 2 is further deprotonated to the hydroxo complex (3) as shown in Scheme 1.<sup>14,16</sup> Under an N<sub>2</sub> atmosphere at pH 11 in the presence of a catalytic amount of 2, paraformaldehyde decomposed to produce H<sub>2</sub> and CO<sub>2</sub> with a 2:1 molar ratio as shown in Fig. 1 as expected from eqn (4). The turnover number (TON) based on the Ir catalyst (5.0 μM) at 14 h was 21 at 298 K. When the catalyst concentration was decreased to be one-fifth, *i.e.*, 1.0 μM, the TON remains almost unchanged (24) at 298 K as shown in Fig. S1a in ESI†. The TON increased to 51 at 333 K as shown in Fig. S1b (ESI†). The detailed experimental procedure is described in the Experimental section in ESI†.

It should be noted that 1 is converted to 3 at pH 11 (Scheme 1). The rate of production of H<sub>2</sub> decreases with decreasing pH as shown in Fig. 2. No production of H<sub>2</sub> from paraformaldehyde



Scheme 1 Deprotonation equilibrium of 1 to 2 and 3.



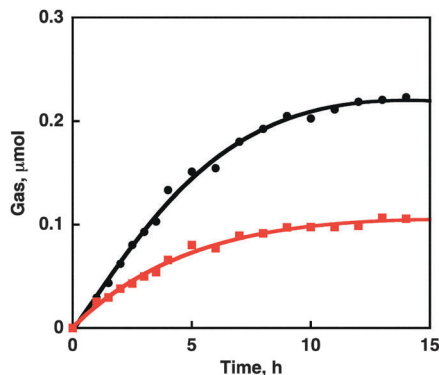


Fig. 1 Time course of catalytic production of H<sub>2</sub> (black line) and CO<sub>2</sub> (red line) from paraformaldehyde (2.0 mg, 66.7 μmol) with **3** (5.0 μM) in an aqueous solution (1.0 mL at pH 11) at 298 K.

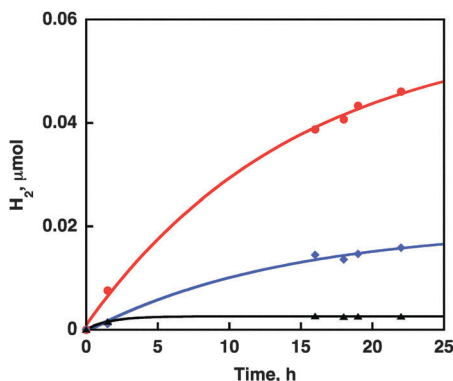


Fig. 2 pH dependence of catalytic production of H<sub>2</sub> from paraformaldehyde (2.0 mg, 66.7 μmol) with **2** or **3** (5.0 μM) in an aqueous solution (1.0 mL) at pH 6.0 (black line), 8.0 (blue line) and 10 (red line) at 298 K.

with **3** was observed at pH 3. Thus, the hydroxo form **3** rather than **1** or **2** is the actual catalyst for the production of H<sub>2</sub> and CO<sub>2</sub>. This is confirmed by no spectral change of **2** with paraformaldehyde at pH 7 (Fig. 3a).<sup>17</sup>

At pH 11, however, **3** reacted with paraformaldehyde to produce the hydride complex ( $\lambda_{\text{max}} = 340 \text{ nm}$ )<sup>16</sup> as shown in Fig. 3b.

It was confirmed that no hydrogen evolution was observed from methanol with **1** at pH 3–11 in water.<sup>16b</sup> Thus, hydrogen evolution occurs from either paraformaldehyde or its monomerised as well as hydrated equivalent, methanediol rather than *via* disproportionation of formaldehyde to methanol and formic acid.

The catalytic cycle is shown in Scheme 2. At pH 11, **1** is converted to the hydroxo complex **3**, which reacts with paraformaldehyde HO(CH<sub>2</sub>O)<sub>n</sub>H to produce the methanediol adduct ([Ir-OCH<sub>2</sub>OH]<sup>-</sup>) and HO(CH<sub>2</sub>O)<sub>n-1</sub>H. The  $\beta$ -hydrogen elimination from [Ir-OCH<sub>2</sub>OH]<sup>-</sup> occurs to produce the hydride complex (**4**) and formic acid. The hydride complex (**4**) reacts with H<sub>2</sub>O to produce H<sub>2</sub>, accompanied by regeneration of **3** (upper-side catalytic cycle in Scheme 2). The hydroxo complex **3** also reacts with formate to produce the hydride complex (**4**) and CO<sub>2</sub> by  $\beta$ -hydrogen elimination. The characteristic visible absorption bands at  $\lambda_{\text{max}} = 420 \text{ nm}$  appeared due to formation of a formate

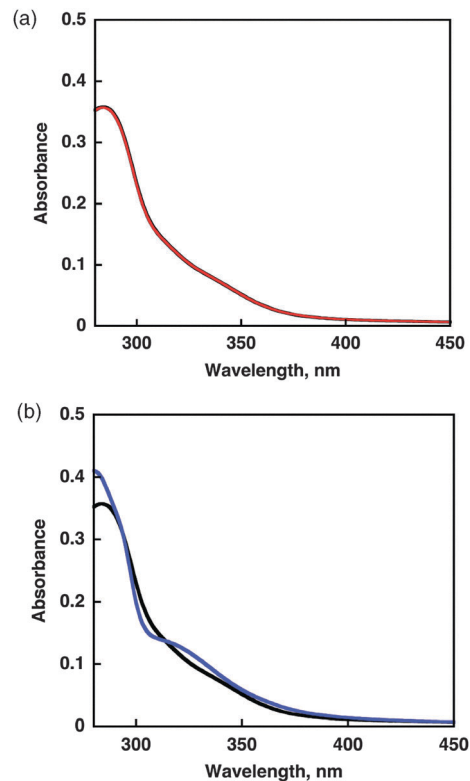
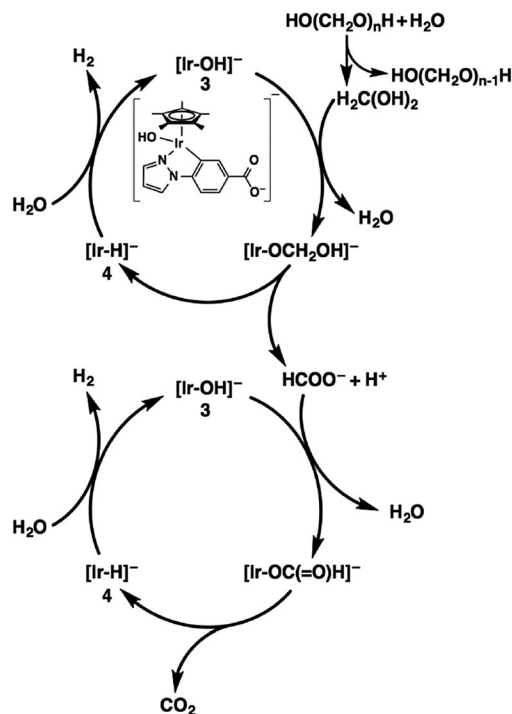


Fig. 3 UV-visible absorption spectra of (a) an aqueous solution of **2** (25 μM, 2.0 mL, pH 7) before (black line) and after (red line) addition of paraformaldehyde (31 μM) and (b) the resulting solution before (black line) and after (blue line) addition of an aliquot of conc. NaOH solution (1 M) for the adjustment of pH at 11.

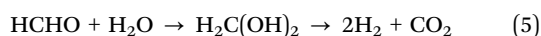


Scheme 2 Catalytic cycles for decomposition of paraformaldehyde to H<sub>2</sub> and formate that is further decomposed to H<sub>2</sub> and CO<sub>2</sub> with **3**.



complex<sup>16b</sup> in the reaction between **3** and paraformaldehyde at pH 7 as shown in Fig. S3 in ESI†. The hydride complex also reacts with H<sub>2</sub>O to produce H<sub>2</sub>, accompanied by regeneration of **3** (lower-side catalytic cycle in Scheme 2).<sup>14</sup> The formation of the methanediol adduct, the formate complex as well as hydride species in Scheme 2 has been supported by <sup>1</sup>H-NMR and ESI-MS analyses as shown in Fig. S4 and S5 (ESI†), respectively. The IR bands as well as NMR peaks of the hydride species in the steady state of the catalytic reaction would be too weak to be assigned well. Thus, the overall stoichiometry is given by eqn (4), where H<sub>2</sub> and CO<sub>2</sub> are produced with a 2:1 molar ratio as observed in Fig. 1.<sup>18</sup>

When formalin without a stabilizer, *i.e.*, methanol was used instead of paraformaldehyde, HCHO that exists in the form of methanediol [eqn (2)] in water under basic conditions also decomposed to produce H<sub>2</sub> and CO<sub>2</sub> with a 2:1 molar ratio [eqn (5)]



as shown in Fig. 4. However, the rate of formation of H<sub>2</sub> and CO<sub>2</sub> from formalin (Fig. 4) is much slower as compared with that from paraformaldehyde (Fig. 1). The formation of the methanediol adduct from paraformaldehyde may be faster than that from formalin because of partial polymerization of HCHO in formalin without a stabilizer. When formaldehyde was replaced by propanal, butanal or 2-methylpropanal (4.2 M) at pH 11.8, no reaction occurred with **3**. Because only formaldehyde can be converted in water to the hydrated form as methanediol,<sup>7</sup> methanediol may act as a hydride source as well as a proton source for the hydrogen production as suggested by Prechtl and coworkers.<sup>15</sup> On the other hand, the catalytic transformation of primary alcohols to the corresponding carboxylic acid salts and H<sub>2</sub> has recently been reported by using a ruthenium complex at high temperature under reflux conditions.<sup>19</sup> In the same manner, methanol can directly be converted to carbon dioxide with evolution of H<sub>2</sub> in the presence of a transition metal complex as a catalyst in aqueous solution at temperatures higher than 65 °C.<sup>20,21</sup>

In conclusion, a water-soluble iridium(III)-hydroxo complex **3** catalyses production of H<sub>2</sub> from paraformaldehyde in water under basic conditions at 298 K. Although the catalytic activity

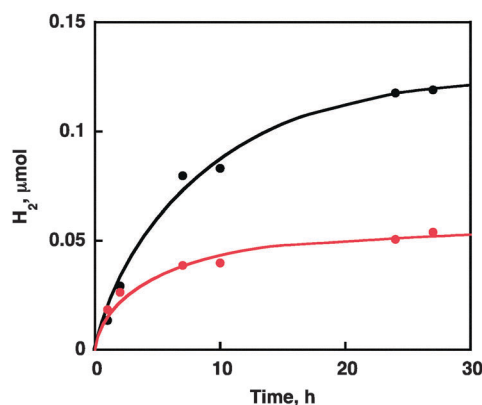


Fig. 4 Time courses of catalytic production of H<sub>2</sub> (black line) and CO<sub>2</sub> (red line) from formalin (66.7 μmol) with **3** (5.0 μM) in an aqueous solution (1.0 mL at pH 11) at 298 K.

and stability of **3** should be further improved, this study provides a convenient way to produce hydrogen from paraformaldehyde as a solid hydrogen carrier at ambient temperature.

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- The IR spectrum of **2** changed in the presence of paraformaldehyde (or methanediol) as shown in Fig. S2 in ESI†.
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