# Alkane Dehydrogenation by Sequential, Double C-H Bond Activation by $Tp^{Br3}Ir(C_2H_4)_2$ ( $Tp^{Br3} =$ hydrotris(3,4,5-tribromo)pyrazolylborate)

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The new complex  $Tp^{Br_3}Ir(C_2H_4)_2$ , **1**, photochemically activates the C–H bonds of *n*-pentane in a two-step process, the first one being the formation of an isolable alkyl-hydride intermediate of composition  $Tp^{Br3}Ir(H)(C_2H_4)(C_5H_{11})$ , **3a**, that subsequently undergoes  $\beta$ -hydride elimination to generate a terminal olefin complex, Tp<sup>Br3</sup>Ir(H)<sub>2</sub>(C<sub>5</sub>H<sub>10</sub>), **4a**. The reaction can also be extended to diethyl ether. In this case, the reaction proceeds by the activation of one of the  $\beta$ -C-H bonds (with respect to the O-ether atom) with formation of the alkyl-hydride **3b** and the dehydrogenation product **4b**. These processes also compete with the intramolecular C-H activation of one of the coordinated ethylene ligand by the Ir(I) center in **1**, which affords the hydride-vinyl complex  $Tp^{Br3}Ir(H)(CH=CH_2)(C_2H_4)$ , **2**. Attempts to thermally induce the above transformations has led to the exclusive formation of a mixture of the hydride- $\alpha$ , $\omega$ -butenyl complex Tp<sup>Br3</sup>Ir(H)(CH<sub>2</sub>CH<sub>2</sub>CH=CH<sub>2</sub>), **5**, and the hydride-crotyl complex  $Tp^{Br3}Ir(H)(C_4H_7)$ , **6**.

## Introduction

The selective activation of carbon-hydrogen bonds in alkanes by transition metal complexes still finds an enormous interest in many researchers due to the potential application of such methodology in the development of new catalytic routes to valuable products.<sup>1</sup> Among the processes based on such activation, the dehydrogenation of *n*-alkanes to give the corresponding 1-alkenes ( $\alpha$ -olefins) is particularly interesting given the great versatility of alkenes as organic feedstock. It is generally accepted<sup>2</sup> that the addition, or elimination, of C–H bonds to, or from, the metal core is a requisite step for the catalytic alkane dehydrogenation reaction. However, in most of the reported systems<sup>3</sup> the direct observation or isolation of the alkyl-hydride intermediates has been precluded. Seminal work by Crabtree<sup>4</sup> and co-workers led to the first examples of stoichiometric alkane dehydrogenation. Catalytic cycles were later reported by Crabtree,<sup>5a</sup> Goldman,<sup>5b,c</sup> and Jensen.<sup>6a</sup> Kaska and Jensen have also reported a very efficient catalytic system based on iridium with pincer-type ligands,6b with a very high activity that only very recently has been improved by Brookhart et al.6c

Group 9 metal complexes appear in most of the reported systems regarding the activation of C-H bonds in the last two decades. In the early 1980s the first examples were achieved by Bergman,7 Graham,8 and Jones,<sup>9</sup> in all cases a  $Cp^*ML$  (M = Rh, Ir; L = CO, PMe<sub>3</sub>) fragment being responsible for the process. Later in that decade the activation of olefinic C-H bonds by oxidative addition to the metal was also accomplished, not only with the Cp\*ML core<sup>10</sup> but also with the isoelectronic Tp<sup>x</sup>ML unit (Tp<sup>x</sup> = trispyrazolylborate ligand,<sup>11</sup> L = olefin, CO). Graham, <sup>12a</sup> Crabtree, <sup>12b</sup> and Oro<sup>12c</sup> demonstrated the capabilities of this fragment to induce the

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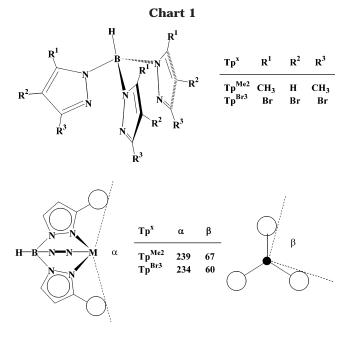
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activation of olefinic C-H bonds to produce hydridovinyl derivatives. Since then, a number of contributions involving the activation of carbon-hydrogen bonds by complexes containing the  $Tp^{x}M$  unit (M = Rh, Ir) have appeared in the literature.<sup>13</sup> An especially interesting system is based on Carmona's complex  $Tp^{Me2}Ir(C_2H_4)_2$ . This bis(ethylene) iridium(I) compound has been found to induce a considerable number of thermal activation processes.<sup>13,14</sup> In the case of ethers (cyclic and noncyclic) and aliphatic amines, a double  $\alpha$ -CH activation has been observed, leading to the formation of Fischer-type carbene complexes.<sup>15</sup>

In recent years, we have been working in the area of the functionalization of carbon-hydrogen bonds with the methodology based on the metal-catalyzed insertion of diazo compounds. We have obtained particularly good results with Tp<sup>Br3</sup>Cu(NCMe) as the catalyst,<sup>16</sup> a complex that contains the perbromo hydrotris(3,4,5-tribromo)pyrazolylborate ligand, TpBr3 (Chart 1). The ligands Tp<sup>Me2</sup> and Tp<sup>Br3</sup> display similar values for the cone ( $\alpha$ ) and wedge  $(\hat{\beta})$  angles,<sup>11</sup> and therefore the steric demand induced around the metal center should be similar (see Chart 1). However, the distinct nature of the groups attached to the ligand skeleton should infer any influence in terms of electron density. Actually, the complexes Tp<sup>x</sup>Cu(CO) (Tp<sup>x</sup> = Tp<sup>Me2</sup>, Tp<sup>Br3</sup>) showed different values for the  $\nu$ (CO) in the IR spectrum (Nujol mull).<sup>17</sup> The perbromo derivative displayed the absorption band centered at 2105 cm<sup>-1</sup>, whereas in the Tp<sup>Me2</sup> analogue this band appeared at 2056 cm<sup>-1</sup>. The differences in

electronics and the similarities in sterics motivated us to prepare the complex  $Tp^{Br3}Ir(C_2H_4)_2$ , 1, analogous to Carmona's complex, to study the effect, if any, of those differences in the activation of carbon-hydrogen bonds by the Tp<sup>x</sup>Ir core.

### **Results and Discussion**

Activation of Pentane by Tp<sup>Br3</sup>Ir(C<sub>2</sub>H<sub>4</sub>)<sub>2</sub> (1). The complex  $Tp^{Br3}Ir(C_2H_4)_2$  (1) was obtained, in high yield, following a procedure similar to that described for the Tp<sup>Me2</sup> derivative<sup>9a</sup> (eq 1) or, alternatively, by using [Ir- $(C_2H_4)_2Cl]_2$ <sup>18</sup> as the starting material (eq 2).

$$\frac{1/2[Ir(coe)_{2}(\mu-Cl)]_{2} \xrightarrow{(1) C_{2}H_{4}, -40 \ ^{\circ}C}}{Tp^{Br3}(10 \ ^{\circ}C)}}$$

$$Tp^{Br3}Ir(C_{2}H_{4})_{2} + TlCl \ (1)$$

$$1$$

$$1/2[Ir(C_{2}H_{4})_{2}(\mu-Cl)]_{2} + TlTp^{Br3} \xrightarrow{(10 \ ^{\circ}C)}$$

$$Tp^{Br3}Ir(C_{2}H_{4})_{2} + TlCl \ (2)$$

$$1$$

Like the Tp<sup>Me2</sup> analogue, compound **1** displayed fluxional behavior in solution. The ethylene groups gave rise to only one resonance, in both the <sup>1</sup>H and the <sup>13</sup>C- ${^{1}H}$  NMR spectra (C<sub>6</sub>D<sub>6</sub>, 20 °C), at  $\delta$  2.56 and 32.6 ppm, respectively, the latter being shifted to the downfield region as compared to the  $Tp^{Me2}$  complex.<sup>14a</sup> Only three resonances were observed in the <sup>13</sup>C{<sup>1</sup>H} NMR spectrum for the nine quaternary carbons of the pyrazolyl rings of the Tp<sup>Br3</sup> moiety centered at  $\delta$  133.6, 124.6, and 104.4. In addition, we observed a value of 2596  $cm^{-1}$ for  $\nu$ (B–H) in the IR spectrum of complex **1**, supporting the presence of a  $\kappa^3$ -Tp<sup>Br3</sup> ligand in the molecule.<sup>19</sup> These spectroscopic data are in good agreement with those reported for the structurally characterized TpMe2Ir- $(C_2H_4)_2$ , for which a trigonal bipyramidal structure in the solid state has been found.14a

Carmona's complex chemistry has been explained in terms of accessible Ir(III) species from the bis(ethylene) Ir(I) starting material. The irradiation of solutions of  $Tp^{Me2}Ir(C_2H_4)_2$  with an UV lamp provided high-yield conversions into the hydrido-vinyl complex Tp<sup>Me2</sup>Ir(CH=  $CH_2$ )(H)( $C_2H_4$ ). Under the same conditions, our perbromo analogue 1 decomposed massively, with no identified products being observed from the reaction mixture. However, irradiation of cyclohexane solutions under sunlight (visible) for 20 min led to the formation of the product derived from the C-H vinylic activation,  $Tp^{Br3}Ir(CH=CH_2)(H)(C_2H_4)$  (2), in 80% yield (with 20%) of the bis(ethylene) still unreacted). Complex 2 showed NMR patterns similar to those of the Tp<sup>Me2</sup> derivative (see Experimental Section). But when irradiation was carried out in *n*-pentane, with the temperature maintained at -10 °C, the results were quite different (Scheme 1). Photolysis for 40 min induced the total consumption of the bis(ethylene) complex and the formation of two new species, 3a (41%) and 4a (33%),

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**Scheme 1. Photochemical Activation of 1** 

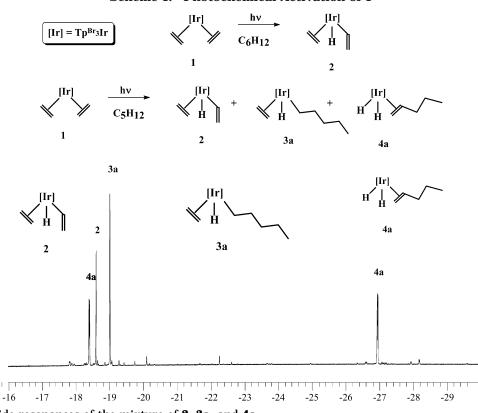


Figure 1. Hydride resonances of the mixture of 2, 3a, and 4a.

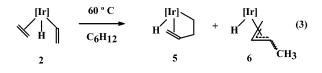
accounting for 74% of the species in solution, the remaining 26% being covered by 2. Figure 1 shows the high-field region (hydride resonances) of the <sup>1</sup>H NMR spectrum of the reaction mixture. On the basis of an extensive NMR study we have been able to obtain unambiguous information about their compositions. Thus, complex 3a has been identified as the hydridopentyl complex Tp<sup>Br3</sup>Ir(CH<sub>2</sub>CH<sub>2</sub>CH<sub>2</sub>CH<sub>2</sub>CH<sub>3</sub>)(H)(C<sub>2</sub>H<sub>4</sub>), derived from the activation of a C–H bond of the methyl group in pentane. The <sup>1</sup>H NMR (C<sub>6</sub>D<sub>6</sub>, 20 °C) exhibited a hydride resonance at  $\delta$  -19.01 ppm and two resonances at  $\delta$  2.79 (m) and 4.19 ppm (m) due to a static ethylene molecule. The *n*-pentyl unit displayed several multiplet resonances: the diastereotopic protons of the methylene group bonded to iridium appeared as two multiplets centered at 2.56 and 0.58 ppm, whereas other signals in the  $\delta$  0.65–1.29 ppm range corresponded to the remaining CH<sub>2</sub> groups, and a triplet at  $\delta$  0.82 ( $J_{\rm HH} = 7$  Hz) to the methyl group. The observation of resonances at  $\delta$  –7.0 (CH<sub>2</sub>–Ir), 14.6, 22.6, 31.6, and 43.4 ppm in the  $^{13}\text{C}\{^1\text{H}\}$  NMR spectrum of **3a** confirmed the presence of a five-carbon chain attached to the Ir(III) center, the resonance at 46.7 ppm being assigned to the ethylene ligand. It is also worth mentioning that the nine quaternary carbons supporting the nine bromine atoms have also been observed, as evidence of the octahedral, nonsymmetric geometry of the molecules of 3a.

The second compound formed in this reaction has been characterized as the dihydride  $Tp^{Br3}Ir$  (H)<sub>2</sub>-(CH<sub>2</sub>=CH-CH<sub>2</sub>CH<sub>2</sub>CH<sub>3</sub>) (**4a**). The <sup>1</sup>H NMR spectrum showed two doublets in the high-field region assigned to Ir-H groups (-18.39, d; -26.94, d;  $J_{HH}$  = 7.6 Hz). In addition, characteristic resonances for a terminal olefin

group were also observed at  $\delta$  2.55 (d,  $J_{\rm HH}$  = 8.2 Hz), 3.65 (d,  $J_{\text{HH}} = 11.6$  Hz), and 5.36 (ddt,  $J_{\text{HH}} = 7.3$  Hz). The formation of this compound could be explained as the consequence of a  $\beta$ -elimination reaction in the pentyl chain in 3a and ethylene loss. Prolonged irradiation (75 min overall time) effected a change in the 2:3a:4a ratio from 26:41:33 to 15:35:50, with no secondary C-H activation products nor isomerization of the terminal olefin in complex 4a being observed under these conditions. To our knowledge, the formation of C–H activation products from alkane substrates has not been observed with the Tp<sup>Me2</sup>-containing bis(ethylene) complex.<sup>20</sup> It has been mentioned above that group 9 transition metal unsaturated species of the type CpM-(L) (M = Rh, Ir) or RhTp(L) have been reported to promote the activation of C–H bonds of hydrocarbons under thermal or photochemical conditions. One interesting case is that of the cationic Ir(III) derivative, [Cp\*Ir(PMe<sub>3</sub>)(Me)]<sup>+</sup>, described by Bergman et al.<sup>21</sup> This complex was found to be very active and selective toward the activation of C-H bonds of saturated hydrocarbons at very mild conditions. However, the thermal activation of *n*-pentane in the presence of the above-mentioned Ir(III) complex produced the  $\alpha$ -alkene complex as the sole product, the alkyl-hydride complex being proposed as an intermediate, although it could not be detected. Thus, the system we report herein could constitute an example of a sequential double dehydrogenation of alkanes. But for this purpose, it seems necessary to verify that 4a forms directly from 3a.

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To gain information relevant to the  $3a \rightarrow 4a$  transformation, we have investigated the thermal stability of the mixture of 2, 3a, and 4a (26:41:33 molar ratio) obtained upon irradiation of pentane solutions of 1 for 40 min. Heating a cyclohexane or benzene solution of this mixture at 60 °C for several hours led to the quantitative conversion of **3a** into **4a**, along with the subsequent disappearance of the hydrido vinyl 2 and the formation of a new product, 5, with a hydride resonance centered at -20.08 ppm as well as minor hydrido-containing species (6) with  $\delta$  in the range -30to -32 ppm. Integration before and after the heating indicated that these new compounds 5 and 6 should proceed from 2. Because of this, we decided to investigate the thermal stability of 2. When a cyclohexane solution was heated at 60 °C for 4 h (eq 3), a smooth transformation took place, and the starting material cleanly converted into a mixture of 5 and 6, in a 80:20 ratio. However, when the heating was performed at 100 °C for 20 h (in the dark), only the group of resonances attributed to 6 were observed, with none of 5 remaining in the reaction mixture. This allowed us to characterize 6 as a hydrido-crotyl complex of formula Tp<sup>Br3</sup>Ir(H)-(C<sub>4</sub>H<sub>7</sub>), in a reaction nearly identical to that reported by Carmona and co-workers (see Experimental Section).<sup>14a</sup> Once the set of resonances for **6** was isolated, complex 5 could be characterized as the hydride- $\alpha, \omega$ butenyl Tp<sup>Br3</sup>Ir(H)(CH<sub>2</sub>CH<sub>2</sub>CH=CH<sub>2</sub>) complex. The olefinic protons originated three resonances centered at 5.12, 4.30, and 2.44, whereas the diastereotopic protons of the methylene group directly attached to iridium gave two separate signals at 1.95 and 1.09 ppm (see Experimental Section). A similar, cationic compound with a trispyrazolylmethane ligand has been reported, the NMR features being very similar to the butenyl fragment.<sup>22</sup> It is important to point out that these results have also been achieved using  $Tp^{Br3}Ir(C_2H_4)_2$  as the starting material.

With the above pieces of information we have rationalized the chemical behavior of the bis(ethylene) complex 1 under photochemical and thermal conditions (Scheme 2). Irradiation of solutions of 1 in an inert solvent like cyclohexane induced the oxidative addition of the ethylene C-H bond to give the hydrido-vinyl 2, a conversion that is also thermally accessible: this is again the case of a hydrido-vinyl compound that is thermodynamically stable compared to its olefin precursor.<sup>14</sup> But the latter pathway does not suppose a dead end, but the origin of two different transformations. According to Carmona's work,<sup>14</sup> the conversion of the hydrido-vinyl into the hydrido-crotyl complex occurs through the 16-electron intermediate Tp<sup>Me2</sup>Ir(CH= CH<sub>2</sub>)(CH<sub>2</sub>CH<sub>3</sub>) (Scheme 2, A) formed upon insertion of the ethylene into the Ir-H bond. The other alternative for a possible insertion would be that of ethylene into the Ir-C bond of the vinyl group, which would produce the hydrido-butenyl complex 5. It seems that in the  $Tp^{Br3}$  case both reactions are available at 60 °C, but heating at 100 °C resulted in the conversion of **5** into **6**, probably through the intermediacy of **2**.

When irradiation was performed in pentane, extrusion of one of the ethylene ligands in 1 took place, and the unsaturated species **B** underwent the oxidative addition of the C-H bond of *n*-pentane, leading to the formation of **3a**. The thermodynamically favored elimination of one of the  $\beta$ -hydrogen atoms of the alkyl chain explains the subsequent formation of 4a. The proposed reversibility of 2 into 1 is based in the observation that the increase in the irradiation time supposed the consumption of 2 and the exclusive formation of 3a and 4a, with neither 5 or 6 being detected. This could be explained if we assume that 2 is in equilibrium with small, undetectable amounts of 1 in solution.<sup>23</sup> Since the latter is consumed to give the activation products, the equilibrium is continuously displaced to the bis(ethylene) side, therefore explaining the disappearance of the hydrido-vinyl 2. Finally, the unsaturated species B is accessible only through irradiation: heating at 140 °C of pentane solutions (using a pressure vessel) of 1 or 2 led to mixtures of 5 and 6 and insoluble material, but neither **3a** or **4a** was detected. We believe that ethylene loss is the only photochemical reaction and that further reactions are thermal, in a transformation similar to that reported by Goldman et al.<sup>5b</sup>

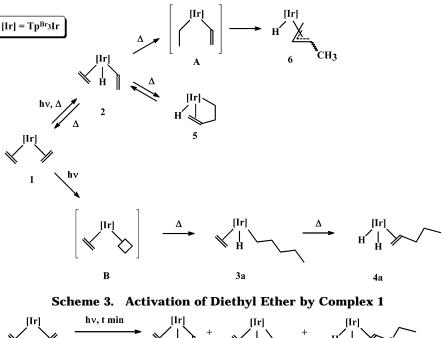
Activation of Diethyl Ether. One interesting feature displayed by Carmona's complex is the double activation of C-H bonds vicinal to the oxygen atoms in several ethers, leading to the formation of Fischer-type iridium carbene complexes,<sup>15</sup> with the only exception being diethyl ether. Our perbromo derivative 1 failed to react thermally under mild conditions (60 °C) with ethers (THF, Et<sub>2</sub>O). However, photolysis of a dilute solution of 1 in diethyl ether for 20 min afforded 3b (43% NMR yield) and the hydride-vinyl **2** (51% NMR yield) (Scheme 3). Complex 3b exhibited NMR spectroscopic features fairly similar to those already described for 3a, supporting its formulation as  $Tp^{Br3}Ir(H)(C_2H_4)(C_4H_9O)$ . The remaining yield (6%) corresponded to another species with a NMR pattern similar to those of 4a. Actually, irradiation for 2 h of the above solution gave this product in 50% yield (Scheme 3). This compound has been characterized as the ether dehydrogenation product 4b (10% of 2 and 40% of 4a completed the reaction mixture). The <sup>1</sup>H NMR spectrum of the crude reaction (C<sub>6</sub>D<sub>6</sub>) exhibited two hydride resonances at  $\delta$  $-26.79 (J_{\rm HH} = 7.3 \text{ Hz})$  and -18.63 that were coupled to one another, the latter also being coupled ( $J_{\rm HH} = 1.8$ Hz) with one of the protons of the vinyl ether functionality generated during the dehydrogenation process.

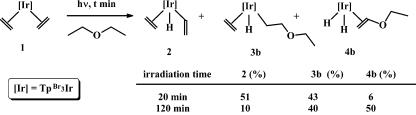
The formation of **3b** can be explained as the result of the activation of one of the  $\beta$ -C–H bonds (to the ether functionality) of the diethyl ether molecule. This is in contrast with Carmona's work, where Tp<sup>Me2</sup>Ir(C<sub>2</sub>H<sub>4</sub>)<sub>2</sub> induced C–H activation only at the  $\alpha$ -positions. It has been recently reported that the complex Tp<sup>Ph</sup>Ir( $\eta^4$ -

<sup>(22)</sup> Padilla-Martínez, I. I.; Poveda, M. L.; Monge, M. A.; Ruiz-Valero C.; Carmona, E. Organometallics **2002**, *21*, 93

<sup>(23)</sup> A similar equilibrium lying in the bis(ethylene) complex has been proposed for the related rhodium system  $Tp^{Me2}Rh(C_2H_4)_2$ . See: (a) Pérez, P. J.; Poveda, M. L.; Carmona, E. *Angew. Chem., Int. Ed. Engl.* **1995**, *34*, 231. (b) Paneque, M.; Pérez, P. J.; Pizzano, A.; Poveda, M. L.; Taboada, S.; Trujillo, M.; Carmona, E. *Organometallics* **1999**, *18*, 4310.

Scheme 2. Activation of Olefinic and Aliphatic C-H Bonds by Complex 1





isoprene)<sup>24a</sup> indeed activates the  $\alpha$ -C–H bonds of Et<sub>2</sub>O to generate a hydride ethoxy carbene derivative, and a similar transformation has been observed for platinum.<sup>24b</sup> Bergman's complex [Cp\*Ir(PMe<sub>3</sub>)(Me)]<sup>+</sup> promoted the dehydrogenation<sup>21</sup> of diethyl ether to produce a vinyl ether complex similar to 4b. This reaction was postulated to proceed by the initial addition of a  $\beta$ -C–H bond of the diethyl ether molecule to the Ir(III) center to form an unobserved cationic methyl-activated intermediate similar to **3b**, which then rearranges by rapid  $\beta$ -H elimination to the isolated hydride (ethyl vinyl ether) complex. In our case, we believe that the overall reaction mechanism depicted in Scheme 2 finds application in the diethyl ether system. Similar experiments were carried out to demonstrate this proposal: (i) heating of the solution enriched in 2 and 3b induced the independent conversions of 2 into 5 and 6 as well as that of 3b into 4b; (ii) a diethyl ether solution heated at 140 °C did not provide detectable amounts of **3b** and/or **4b**, again evidencing the need of photolysis to induce the ethylene extrusion necessary to initiate the activation reaction.

#### Conclusions

The results described in this contribution demonstrate the distinct chemical behavior toward C–H bond activation processes of the complexes  $Tp^{Br3}Ir(C_2H_4)_2$  and  $Tp^{Me2}Ir(C_2H_4)_2$ . These differences must be related to the electronic effect induced by the  $Tp^x$  ligand in the iridium

center, since their steric properties are quite similar. The perbromo ligand generates a more electron-poor complex, compared to the  $Tp^{Me2}$  analogue, that must be responsible for the differences in the observed chemical behavior. Complex 1 induced the dehydrogenation of pentane and diethyl ether, similarly to the cationic complex [ $Cp*Ir(PMe_3)(Me)$ ]<sup>+</sup>. We interpret this similarity in terms that a decrease in the electron density at iridium seems to be a requirement for this reaction to occur. Finally, our system has allowed the stepwise observation of the dehydrogenation process, for both *n*-pentane and diethyl ether, demonstrating that the alkyl-hydrido complexes **3** are intermediates in the formation of **4**.

### **Experimental Section**

All manipulations were performed under nitrogen atmosphere using standard Schlenk techniques. Solvents were distilled under nitrogen with the appropriate drying agents and degassed before use. [Ir(coe)<sub>2</sub>Cl]<sub>2</sub><sup>25</sup> and Tl[Tp<sup>Br3</sup>]<sup>11</sup> were prepared as reported in the literature. NMR spectra were recorded in a Varian Mercury 400 MHz spectrometer. Infrared spectra were recorded as Nujol mulls in KBr using a ATI Mattson Genesis Series FTIR spectrometer. Photolysis experiments were carried out using a conventional tungsten 300 W lamp and a water cooling system.

Synthesis of Tp<sup>Br3</sup>Ir( $C_2H_4$ )<sub>2</sub>, 1. Procedure A. [Ir(coe)<sub>2</sub>Cl<sub>2</sub>]<sub>2</sub> (0.45 g, 0.5 mmol) was disolved in THF (40 mL) and the solution cooled to -40 °C. Ethylene was bubbled through the solution for 15 min, and TlTp<sup>Br3</sup> (1.13 g, 1.01 mmol) was added. The reaction mixture was maintained at 10 °C to give a golden

<sup>(24) (</sup>a) Slugovc, C.; Mereiter, K.; Trofimenko S.; Carmona, E. *Angew. Chem., Int. Ed.* **2000**, *39*, 2158. (b) Holtcam, M. W.; Labinger J. A.; Bercaw, J. E. *J. Am. Chem. Soc.* **1997**, *119*, 848.

<sup>(25)</sup> Herde, J. L.; Lambert, J. C.; Senoff, C. V. Inorg. Synth. 1974, 15, 19.

yellow suspension, which was stirred at that temperature for 3 h. After filtration, the volatiles were removed under vacuum. Complex **1** was obtained in quantitative yield and needed no further purification.

**Procedure B.**  $[Ir(C_2H_4)_2Cl]_2$  (0.30 g, 0.47 mmol) was dissolved in THF (30 mL) and the resulting red solution cooled at 0 °C. TlTp<sup>Br3</sup> (1.06 g, 0.94 mmol) was then added. The resulting brown suspension was stirred for 3 h at 10 °C. The solvent was pumped off and the residue extracted with CH<sub>2</sub>-Cl<sub>2</sub> (20 mL) and filtered off. The yellow solution was taken to dryness, yielding complex **1** in quantitative yield. IR (Nujol):  $\nu$ (B–H) 2596 cm<sup>-1</sup>. <sup>1</sup>H NMR (400 MHz, C<sub>6</sub>D<sub>6</sub>):  $\delta$  2.56 (s, 8 H, C<sub>2</sub>H<sub>4</sub>). <sup>13</sup>C{<sup>1</sup>H}</sup> NMR (100 MHz, C<sub>6</sub>D<sub>6</sub>):  $\delta$  104.4, 124.6, 133.6 (*C*Br), 32.6 (*C*<sub>2</sub>H<sub>4</sub>).

**Synthesis of Tp**<sup>Br3</sup>**Ir(H)(C**<sub>2</sub>**H**<sub>4</sub>)(**CH=CH**<sub>2</sub>), **2.** A solution of **1** (0.08 g, 0.07 mmol) in cyclohexane (20 mL) was irradiated at 10 °C for 20 min. The resulting dark yellow solution was evaporated under vacuum, and the solid residue was analyzed by <sup>1</sup>H NMR spectroscopy, which confirmed the presence of the hydride-vinyl **2** in 80% yield (the starting material accounted for the remaining 20% yield). IR (Nujol): v(Ir–H) 2220 cm<sup>-1</sup>. <sup>1</sup>H NMR (400 MHz, C<sub>6</sub>D<sub>6</sub>):  $\delta$  6.59 (1 H, Ir–C*H*=CH<sub>2</sub>), dd, *J*<sub>HH</sub> = 17.4 and 9.9 Hz), 5.29 (1 H, d, Ir–CH=CH<sub>2</sub>), 4.44 (m, 2 H, AA' part of a AA'XX' spin system, C<sub>2</sub>H<sub>4</sub>), 4.33 (1 H, d, Ir–CH=CH<sub>2</sub>), 3.05 (m, 2 H, XX' part of a AA'XX' spin system, C<sub>2</sub>H<sub>4</sub>), -18.57 (s, 1 H, Ir–H). <sup>13</sup>C{<sup>1</sup>H} NMR (100 MHz, C<sub>6</sub>D<sub>6</sub>):  $\delta$  135.1, 133.3, 132.3, 124.6, 124.0, 123.3 (*C*Br), 121.1 (Ir-*C*H=CH<sub>2</sub>), 119.3 (IrCH=*C*H<sub>2</sub>), 104.8, 104.0, 103.1 (*C*Br), 49.4 (*C*<sub>2</sub>H<sub>4</sub>).

**Synthesis of the Complexes 3a and 4a.** A solution of **1** (0.2 g, 0.17 mmol) in *n*-pentane (60 mL) was irradiated for 40 min at 10 °C. The solvent was removed in vacuo, and the residue analyzed by <sup>1</sup>H NMR, which confirmed the presence of **2**, **3a**, and **4a** in 26:41:33 ratio. Similar results were obtained using **2** as the starting material. We have failed in separating these two compounds, either by fractional crystallization or by column chromatography, the characterization being accomplished by 1D and 2D NMR studies of the reaction mixture.

**Tp**<sup>Br3</sup>**Ir**(**H**)(**C**<sub>2</sub>**H**<sub>4</sub>)(**C**<sub>5</sub>**H**<sub>11</sub>), **3a.** <sup>1</sup>H NMR (400 MHz, C<sub>6</sub>D<sub>6</sub>): δ 4.19 (m, 2 H, AA' part of a AA'XX' spin system, C<sub>2</sub>H<sub>4</sub>), 2.79 (m, 2 H, XX' part of a AA'XX' spin system, C<sub>2</sub>H<sub>4</sub>), 2.35, 0.58 (m, 1 H each, Ir–CH<sub>2</sub>Bu), 1.29 (m, 2 H, Ir(CH<sub>2</sub>)<sub>2</sub>CH<sub>2</sub>Et), 1.20 (m, 2 H, Ir(CH<sub>2</sub>)<sub>3</sub>CH<sub>2</sub>CH<sub>3</sub>), 0.82 (t, 3 H, Ir(CH<sub>2</sub>)<sub>4</sub>CH<sub>3</sub>), J<sub>HH</sub> = 7 Hz), 0.78 and 0.65 (m, 1 H each, IrCH<sub>2</sub>CH<sub>2</sub>Pr), -19.01 (s, 1 H, Ir–H). <sup>13</sup>C {<sup>1</sup>H} NMR (100 MHz, C<sub>6</sub>D<sub>6</sub>): δ 135.3, 133.9, 131.8, 124.3, 124.1, 123.4, 104.4, 102.9, 102.6 (*C*Br), 46.7 (*C*<sub>2</sub>H<sub>4</sub>), 43.4 (Ir(CH<sub>2</sub>)<sub>2</sub>CH<sub>2</sub>Et), 31.6 (IrCH<sub>2</sub>CH<sub>2</sub>Pr), 22.6 (Ir-(CH<sub>2</sub>)<sub>3</sub>CH<sub>2</sub>CH<sub>3</sub>), 14.6 (Ir(CH<sub>2</sub>)<sub>4</sub>CH<sub>3</sub>), -7.0 (Ir–CH<sub>2</sub>Bu).

**Tp<sup>Br3</sup>Ir(H)<sub>2</sub>(C<sub>5</sub>H<sub>10</sub>), 4a.** <sup>1</sup>H NMR (400 MHz, C<sub>6</sub>D<sub>6</sub>): δ 5.36 (ddt, 1 H, CH<sub>2</sub>=C*H*Pr, *J*<sub>HH</sub> = 11.6 and 8.2 Hz, *J*<sub>H-CH2</sub> = 7.2 Hz), 3.65 (d, 1 H, C*H*H=CHPr) 2.55 (d, 1 H, CH*H*=CHPr), 2.30–2.40 (m, 2 H, CH<sub>2</sub>=CHC*HH*Et), 1.89 (m, 1 H, CH<sub>2</sub>= CHCH<sub>2</sub>C*H*HMe), 1.76 (m, 1 H, CH<sub>2</sub>=CHCH<sub>2</sub>CH*H*Me), 1.07 (t, 3 H, CH<sub>2</sub>=CH(CH<sub>2</sub>)<sub>2</sub>C*H*<sub>3</sub>, *J*<sub>HH</sub> = 7 Hz), -18.39 (d, 1 H, Ir–*H*, *J*<sub>HH</sub> = 7.6 Hz), -26.94 (d, 1 H, Ir–*H*). <sup>13</sup>C{<sup>1</sup>H} NMR (100 MHz, C<sub>6</sub>D<sub>6</sub>): δ 136.0, 134.8, 132.4, 123.7, 123.2, 122.4, 103.3, 102.7, 102.2 (*C*Br), 68.8 (CH<sub>2</sub>=*C*HPr), 43.4 (*C*H<sub>2</sub>=CHPr), 42.7 (CH<sub>2</sub>=CH*C*H<sub>2</sub>Et), 27.2 (CH<sub>2</sub>=CHCH<sub>2</sub>*C*H<sub>2</sub>Me), 14.2 (CH<sub>2</sub>=CH-(CH<sub>2</sub>)<sub>2</sub>*C*H<sub>3</sub>).

Synthesis of the Complexes 3b and 4b. A solution of 1 (0.15 g, 0.13 mmol) in  $Et_2O$  (60 mL) was irradiated at 10 °C for 20 min. The solvent was pumped off and the residue studied by <sup>1</sup>H NMR, which showed the formation of 2, 3b, and 4b in a 51:43:6 ratio. We have characterized 3b and 4b by 1D and 2D NMR studies of the reaction mixture.

**Tp**<sup>Br3</sup>**Ir (H)(C<sub>2</sub>H<sub>4</sub>)(C<sub>4</sub>H<sub>9</sub><b>O)**, **3b.** <sup>1</sup>H NMR (400 MHz, C<sub>6</sub>D<sub>6</sub>): δ 4.24 (m, 2 H, AA' part of a AA'XX' spin system, C<sub>2</sub>H<sub>4</sub>), 3.25 and 3.23 (dq, 1 H each, Ir(CH<sub>2</sub>)<sub>2</sub>OCH<sub>2</sub>Me, J<sub>HH</sub> = 10 and 7 Hz), 2.94–2–91 (m, 2 H, IrCH<sub>2</sub>CH<sub>2</sub>OEt), 2.87 (m, 2 H, XX' part of a AA'XX' spin system, C<sub>2</sub>H<sub>4</sub>), 2.71 (td, 1 H, IrCHHCH<sub>2</sub>OEt, J<sub>HH</sub> = 10.4 and 5.6 Hz), 1.11 (m, 1 H, IrCHHCH<sub>2</sub>OEt), 1.07 (t, 3 H, Ir(CH<sub>2</sub>)<sub>2</sub>OCH<sub>2</sub>CH<sub>3</sub>, J<sub>HH</sub> = 7 Hz), -19.17 (s, 1 H, Ir-H). <sup>13</sup>C{<sup>1</sup>H} NMR (100 MHz, C<sub>6</sub>D<sub>6</sub>): δ 135.8, 134.3, 132.0, 124.4, 123.8, 123.6, 104.5, 103.5, 103.1 (*C*Br), 73.1 (IrCH<sub>2</sub>CH<sub>2</sub>OEt), 65.3 (Ir(CH<sub>2</sub>)<sub>2</sub>OCH<sub>2</sub>Me), 49.2 (*C*<sub>2</sub>H<sub>4</sub>), 15.9 (Ir(CH<sub>2</sub>)<sub>2</sub>OCH<sub>2</sub>CH<sub>3</sub>), -9.3 (Ir-*C*H<sub>2</sub>CH<sub>2</sub>OEt).

**Tp**<sup>Br3</sup>**Ir(H)**<sub>2</sub>(**C**<sub>4</sub>**H**<sub>8</sub>**O**), **4b.** <sup>1</sup>H NMR (400 MHz, C<sub>6</sub>D<sub>6</sub>): δ 7.50 (ddd, 1 H, IrCH<sub>2</sub>=C*H*OEt,  $J_{HH} = 9.5$  and 5 Hz,  $J_{HH} = 1.8$  Hz), 4.17 (dq, 1 H, CH<sub>2</sub>=CHOC*H*HMe,  $J_{HH} = 9.5$  and 7 Hz), 4.04 (dd, 1 H C*H*H=CHOEt), 3.74 (dq, 1 H, CH<sub>2</sub>=CHOCH*H*Me,  $J_{HH} = 7$  Hz), 2.28 (dd, 1 H CH*H*=CHOEt), 1.21 (t, 3 H, CH<sub>2</sub>=CHOCH<sub>2</sub>CH<sub>3</sub>,  $J_{HH} = 7$  Hz), -18.63 (dd, 1 H, Ir-H,  $J_{HH} = 7.3$  Hz), -26.79 (d, 1 H, Ir-*H*). <sup>13</sup>C{<sup>1</sup>H} NMR (100 MHz, C<sub>6</sub>D<sub>6</sub>): δ 136.4, 135.5, 134.0, 124.2, 123.4, 122.3, (*C*Br), 106.9 (CH<sub>2</sub>=*C*HOEt), 103.4, 102.7, 102.1 (*C*Br), 69.2 (CH<sub>2</sub>=CHO*C*H<sub>2</sub>Me), 28.2 (*C*H<sub>2</sub>=CHOEt), 14.7 (CH<sub>2</sub>=CHOCH<sub>2</sub>*C*H<sub>3</sub>).

Synthesis of the Complexes 5 and 6. A solution of 1 (0.1 g, 0.085 mmol) in cyclohexane was heated at 60 °C for 4 h. The solvent was removed under vacuum, and the solid residue was investigated by <sup>1</sup>H NMR, confirming the formation of 5 and 6 in 4:1 ratio.

**Tp**<sup>Br3</sup>**İr(H)(CH<sub>2</sub>CH<sub>2</sub>CH**<sup> $\doteq$ </sup>**CH**<sub>2</sub>, **5**. IR (Nujol):  $\nu$ (Ir–H) 2210 cm<sup>-1</sup>. <sup>1</sup>H NMR (400 MHz, C<sub>6</sub>D<sub>6</sub>):  $\delta$  5.12 (m, 1 H, CH=CH<sub>2</sub>), 4.30 (d, 1 H, CH=CHH, J = 11.3 Hz), 3.99 (m, 1 H, Ir– CH<sub>2</sub>CHH), 3.00 (m, 1 H, Ir–CH<sub>2</sub>CHH), 2.44 (d, 1 H, CH=CHH, J = 7.6 Hz), 1.95 (m, 1 H, IrCHHCH<sub>2</sub>), 1.09 (dt, 1 H, IrCHHCH<sub>2</sub>, J = 14.6 and 8 Hz), -20.08 (d, 1 H, Ir–H, J = 2.1Hz). <sup>13</sup>C{<sup>1</sup>H} NMR (100 MHz, C<sub>6</sub>D<sub>6</sub>):  $\delta$  134.2, 132.9, 132.3, 123.9, 123.0, 122.7, 104.3, 103.6, 101.9 (CBr), 49.2 (CH<sub>2</sub>=CH), 31.4 (Ir–CH<sub>2</sub>CH<sub>2</sub>), 18.5 (CH<sub>2</sub>=CH), -46.8 (Ir–CH<sub>2</sub>CH<sub>2</sub>).

**Tp**<sup>Br3</sup>**Ir**(**H**)( $\eta^3$ -**CH**<sub>2</sub>**CHCHMe**), **6.** Only the major isomer (>85%) was detected<sup>14a</sup> by <sup>1</sup>H NMR (400 MHz, C<sub>6</sub>D<sub>6</sub>): δ 5.58 (dt, 1 H, CH<sub>2</sub>C*H*CHMe, *J* = 11 and 7.1 Hz), 4.58 (dq, 1 H, CH<sub>2</sub>CH*C*HMe, *J*<sub>H-CH<sub>3</sub></sub> = 6.5 Hz), 3.44 and 2.85 (dd, 2 H each, CH<sub>2</sub>CHCHMe, *J* = 1.6 Hz), -31.76 (s, 1 H, Ir–*H*).

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