

## Origins of the Selectivity for Borylation of Primary over Secondary C–H Bonds Catalyzed by Cp\*-Rhodium Complexes

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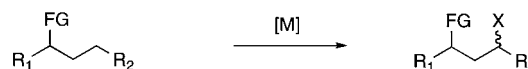
**Abstract:** Detailed experimental and computational studies of the high selectivity for functionalization of primary over secondary sp<sup>3</sup> C–H bonds in alkanes by borane reagents catalyzed by Cp\*Rh complexes are reported. Prior studies have shown that Cp\*Rh(X)(Bpin) (X = H or Bpin), generated from Cp\*Rh(H)<sub>2</sub>(Bpin)<sub>2</sub> and Cp\*Rh(H)<sub>2</sub>(Bpin)<sub>3</sub>, are likely intermediates in these catalytic reactions. To allow analysis of the system by H/D exchange, the current studies focused on reactions of Cp\*Rh(D)<sub>2</sub>(Bpin)<sub>2</sub> through the 16-electron species Cp\*Rh(D)(Bpin). Density functional theory (DFT) calculations of the reaction between Cp\*Rh(H)(BO<sub>2</sub>C<sub>2</sub>H<sub>4</sub>) and the primary and secondary C–H bonds of propane indicate that the lowest energy pathway for C–H bond cleavage occurs to form an isomer in which the alkyl and boryl groups are trans to each other, while the lowest energy pathway for functionalization of the primary C–H bond occurs by formation of the isomer in which these two groups are cis to each other. The barrier for formation of the rhodium complex by cleavage of secondary C–H bonds is higher than that by cleavage of primary C–H bond. The alkyl intermediates are formed reversibly, and steric effects cause the barrier for B–C bond formation from the secondary alkyl intermediate to be higher than that from the primary alkyl intermediate. Experimental studies are consistent with this computational analysis. H/D exchange occurs between (Cp\*d<sub>15</sub>)Rh(D)<sub>2</sub>(Bpin)<sub>2</sub> and *n*-octane, indicating that C–H bond cleavage occurs reversibly and occurs faster at primary over secondary C–H bonds. The observation of small amounts of H/D exchange into the secondary C–H bonds of linear alkanes and the clear observation of H/D exchange into the secondary positions of cyclic alkanes without formation of products from functionalization are consistent with the high barrier calculated for B–C bond formation from the secondary alkyl intermediate. A series of kinetic experiments are consistent with a mechanism for H/D exchange between (Cp\*d<sub>15</sub>)Rh(D)<sub>2</sub>(Bpin)<sub>2</sub> and *n*-octane occurring by dissociation of borane-d<sub>1</sub> to form (Cp\*d<sub>15</sub>)Rh(D)(Bpin). Thus, the origin of the selectivity for borylation of primary over secondary C–H bonds is due to the cumulative effects of selective C–H bond cleavage and selective C–B bond formation.

### Introduction

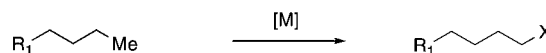
The selective installation of functional groups at the positions of typically unreactive C–H bonds has been a target of synthetic chemistry for many years.<sup>1–6</sup> A particular challenge has been the functionalization of terminal C–H bonds in alkanes and alkyl groups because primary C–H bonds are stronger than secondary C–H bonds, which are stronger than tertiary C–H bonds. To allow selective reactions among several types of aliphatic C–H bonds, such C–H bond functionalization reactions have been conducted with substrates containing a directing group, such as an amide, carbonyl, nitrile, or a heteroatom

### Scheme 1

Transformation of a C–H bond using a functional group (FG):



Transformation of a C–H bond without using a functional group (FG):



moiety.<sup>7,8</sup> These directing groups serve as docking sites for the metal catalyst and facilitate the cleavage of one C–H bond over the others. In most cases, these functionalization processes occur at aromatic or secondary C–H bonds (Scheme 1),<sup>1,9</sup> although this strategy has allowed for the selective functionalization of primary C–H bonds in certain cases.<sup>10–13</sup>

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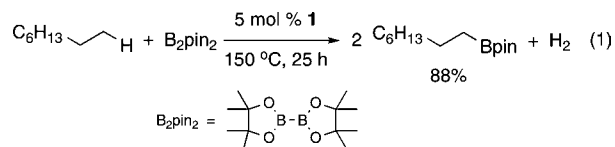
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The reactions of boranes with aliphatic C–H bonds catalyzed by complexes of rhodium<sup>14</sup> and ruthenium<sup>15</sup> are the most selective processes for the functionalization of primary over secondary C–H bonds in a variety of alkanes, as well as amines, ethers, acetals, and alkyl halides, in the absence of any directing groups.<sup>16</sup> For example, the reaction of *n*-octane with B<sub>2</sub>pin<sub>2</sub> (pin = pinacolate) in the presence of Cp\*Rh(η<sup>4</sup>-C<sub>6</sub>Me<sub>6</sub>) (**1**) as catalyst was reported to form two equivalents of *n*-octylboronate ester as the only product in 88% yield (eq 1).<sup>14</sup> More recently, Cp\* complexes of ruthenium were also shown to catalyze the borylation of alkanes at primary C–H bonds.<sup>15</sup>



Complexes that are likely intermediates in the rhodium-catalyzed borylation of alkanes have been identified.<sup>17</sup> Cp\*Rh(H)<sub>2</sub>(Bpin)<sub>2</sub> (**2**) and Cp\*Rh(H)(Bpin)<sub>3</sub> (**3**) were shown to form from the catalyst precursor Cp\*Rh(η<sup>4</sup>-C<sub>6</sub>Me<sub>6</sub>) (**1**) and HBpin. These two complexes are present in the catalytic system and are kinetically competent to be intermediates in the catalytic reaction. Studies of the reactions of **2** and **3** with phosphines led to the conclusion that the dissociation of borane from these two boryl complexes leads to the reactive 16-electron intermediates Cp\*Rh(H)(Bpin) (**4**) and Cp\*Rh(Bpin)<sub>2</sub> (**5**). Computational studies of the reactions of complexes **4** and **5** with C–H bonds suggested that C–H cleavage and C–B bond formation occur by pathways that involve the formation of σ-borane complexes after C–H bond cleavage. C–H bond cleavage by monoboryl intermediate **4** was calculated to occur by concomitant formation of a B–H bond and cleavage of the C–H bond of the coordinated alkane, while C–H bond cleavage by bisboryl intermediate **5** was calculated to occur by a process akin to σ-bond metathesis.

Although these studies led to an understanding of the elementary reactions of the catalytic process, they did not address the origin of the high selectivity for functionalization of primary C–H bonds. Several origins of this selectivity could be envisioned. First, the selectivity could arise from exclusive cleavage of the primary C–H bond to form a primary alkyl intermediate in a process involving either reversible or irreversible C–H bond cleavage. Second, the selectivity could result from reversible and unselective cleavage of primary and secondary C–H bonds to form both primary and secondary alkyl intermediates, followed by selective C–B bond formation from the primary alkyl species. Third, the selectivity could result from the multiplicative contributions of selective cleavage of primary C–H bonds and selective formation of the C–B bond from a primary alkyl intermediate over a secondary alkyl intermediate.

To distinguish among these possibilities, a combination of <sup>1</sup>H/<sup>2</sup>H isotope exchange and theoretical studies were conducted. These studies show that primary C–H bonds are cleaved selectively, but not exclusively, over secondary C–H bonds. Therefore, the exclusive selectivity for formation of products from functionalization of primary C–H bonds results from a combination of selective cleavage of the primary C–H bonds and selective functionalization of primary over secondary intermediates.

## Results

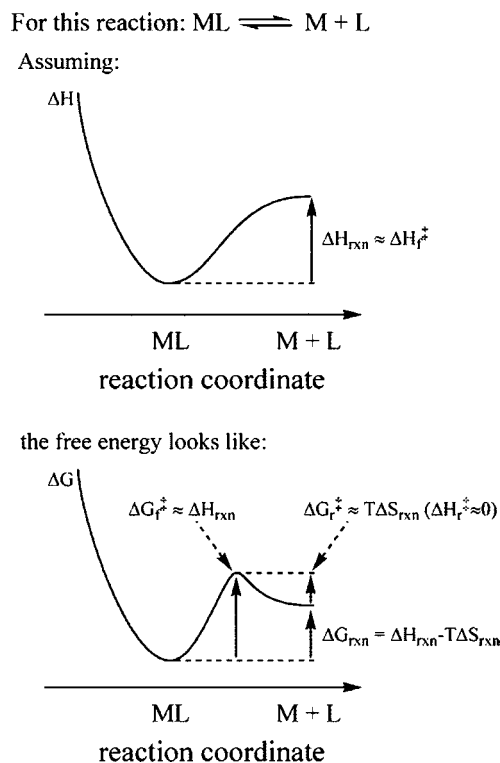
**Theoretical Studies on the Borylation of Propane by Cp\*Rh(H)(BO<sub>2</sub>C<sub>2</sub>H<sub>4</sub>) (**4**).** Previous calculations of the borylation of alkanes were conducted on the reactions of methane with the truncated model complex CpRh(H)(BO<sub>2</sub>C<sub>2</sub>H<sub>4</sub>).<sup>17</sup> To gain a theoretical understanding of the selectivity for borylation of primary aliphatic C–H bonds over secondary C–H bonds, the pathways for the borylation of the primary and secondary C–H bonds of propane by the model complex Cp\*Rh(H)(BO<sub>2</sub>C<sub>2</sub>H<sub>4</sub>) (**4**) were calculated.

**Computational Details.** All calculations were conducted using the Gaussian 03 suite of programs.<sup>18</sup> Density functional theory (DFT)<sup>19</sup> methods were used to perform full geometric optimizations and analytical frequency calculations of all structures studied. The number of imaginary modes in each frequency calculation was monitored to ensure that the optimized structure corresponded to a minimum or a transition state. In particular, the Becke three-parameter<sup>20</sup> exchange functional was used along with the Lee–Yang–Parr<sup>21</sup> correlation functional, a combination commonly referred to as B3LYP. The SDD<sup>22</sup> ECP and basis set was used on Rh including 2f and 1g polarization functions as recommended by Martin and Sundermann.<sup>23</sup> Dunning's cc-pVDZ<sup>24,25</sup> basis sets were used on all boron and oxygen atoms, as well as on metal-bound carbons and hydrogens, and all other atoms in the propane. All other carbons and hydrogens were described with the simpler D95<sup>26</sup> basis sets. Zero-point energies were computed, and thermodynamic functions were calculated at standard states (298.15 K and 1 atm). The activation energies for association and dissociation processes were calculated<sup>17</sup> as shown in Figure 1.

**Calculation of the Mechanism of Primary versus Secondary C–H Bond Functionalization.** Like previous calculations of the borylation of methane,<sup>17</sup> the DFT calculations of the borylation of propane suggest that the transition-metal boryl complexes cleave the C–H bonds of alkanes and form the C–B bond of alkylboronate products **6** by a metal-assisted σ-bond metathesis pathway.<sup>27,28</sup> However, propane is larger than methane, and this difference in steric properties leads to significant changes in the energetics of the reaction profile. The relative energies for

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**Figure 1.** Determination of activation free energies for association and dissociation processes.

the transition states and intermediates of the pathways for functionalization of both the primary and secondary C–H bonds of propane with **4'** are summarized in Table 1, and the free energy profile for functionalization of primary and secondary C–H bonds are illustrated in Figures 2 and 3. The lowest energy pathways are shown in Figure 2, and a comparison of the transition-state and intermediate energies for reaction of the primary C–H bond of propane through cis and trans isomers is shown in Figure 3.

The reaction coordinate begins with formation of a  $\sigma$ -complex between the 16-electron borylrhodium hydride species **4'** and propane.<sup>29–34</sup> The computational data suggest that, when a primary C–H bond of propane coordinates to **4'**, the alkyl chain in this complex can be oriented cis or trans to the boryl group. The cis and trans  $\sigma$ -complexes **7**<sub>prim/cis</sub> and **7**<sub>prim/trans</sub> are close in energy and interconvert through a low-energy transition state. The secondary C–H bonds of propane, on the other hand, coordinate with a large preference for the trans isomer **7**<sub>sec/trans</sub>, due to the greater steric encumbrance around the secondary C–H bond than around the primary C–H bond. Because the formation of these  $\sigma$ -complexes is fully reversible, it is their relative thermodynamic stability, rather than the mechanism by which they form, that contributes to the overall energy of the C–H bond cleavage step. Thus, potential mechanisms for interconversion of one  $\sigma$ -complex to another were not investigated.

The activation of the primary and secondary C–H bonds is calculated to occur by simultaneous formation of a B–H bond in a  $\sigma$ -borane complex and cleavage of the C–H bond of the  $\sigma$ -alkane complex to produce **8**<sub>prim/cis</sub>, **8**<sub>prim/trans</sub>, and **8**<sub>sec/trans</sub>. Cleavage of the C–H bond by the trans alkane complex **7**<sub>prim/trans</sub> occurs with a lower barrier than cleavage of the C–H bond by the cis complex **7**<sub>prim/cis</sub>. However, cleavage of the C–H bond by the trans isomer **7**<sub>prim/trans</sub> leads to the product **8**<sub>prim/trans</sub> in which the alkyl group and the boryl unit are located trans to each other. C–B bond formation through the trans isomer is then calculated to occur by initial rotation about the B–H bond to place the alkyl and boryl groups cis to each other in complex **8**<sub>prim/cis</sub>. This rotation is predicted to occur through a transition state that is 23.3 kcal·mol<sup>−1</sup> above the energies of the initial reactants. In contrast, reaction of **7**<sub>prim/cis</sub> to form **8**<sub>prim/cis</sub>, the isomer of the alkyl complex that contains a boryl group cis to the alkyl group, is predicted to occur through a transition state that lies only 20.9 kcal/mol in free energy above that of the initial reactants and to form the B–C bond through a transition state that lies at a similar free energy of 21.8 kcal·mol<sup>−1</sup>. Therefore, functionalization through the cis isomer **7**<sub>prim/cis</sub> could proceed faster than through the trans isomer **7**<sub>prim/trans</sub>, even though cleavage of the primary C–H bond in **7**<sub>prim/trans</sub> to form **8**<sub>prim/trans</sub> is predicted to occur with a lower barrier than cleavage of the primary C–H bond to form **8**<sub>prim/cis</sub>.

The secondary alkyl intermediate **8**<sub>sec/trans</sub> in Figure 2 containing trans alkyl and boryl units is calculated to be much more stable than the cis analogue **8**<sub>sec/cis</sub> and to be slightly more stable than the cis primary alkyl intermediate **8**<sub>prim/cis</sub>. However, the trans complex **8**<sub>sec/trans</sub> must undergo a rotation of the borane  $\sigma$ -complex about the B–H bond to form the cis alkyl complex **8**<sub>sec/cis</sub> to form the alkylboronate ester **6**. This rotation is predicted to occur through a transition state that has a free energy of 30.5 kcal·mol<sup>−1</sup> above that of the starting materials, and this energy is much higher than the free energy of any of the other calculated transition states.

A  $\sigma$ -bond metathesis process involving simultaneous B–H bond cleavage and C–B bond formation leads to the intermediates **9**<sub>prim</sub> and **9**<sub>sec</sub> in which the primary and secondary alkylboronate esters are coordinated to the metal through the C–B bond. This process is a version of metal-assisted  $\sigma$ -bond metathesis and  $\sigma$ -complex-assisted metathesis ( $\sigma$ -CAM) processes that are intermediate between oxidative addition and  $\sigma$ -bond metathesis mechanisms as discussed recently in reviews by Vastine and Hall<sup>27</sup> and by Perutz and Sabo-Etienne,<sup>28</sup> respectively. The intermediates **9**<sub>prim</sub> and **9**<sub>sec</sub> are then predicted to isomerize to the adducts **10**<sub>prim</sub> and **10**<sub>sec</sub> in which the primary and secondary alkylboronate esters are coordinated to the metal through the oxygen atom in the dioxaborolane ring. Intermediates **10**<sub>prim</sub> and **10**<sub>sec</sub> then dissociate the isomeric alkylboronate ester products.

The highest energy transition states for functionalization of primary C–H bonds by direct formation of the cis alkyl intermediate **8**<sub>prim/cis</sub> are those for C–H bond cleavage and C–B bond formation shown as TS (**7**<sub>prim/cis</sub>–**8**<sub>prim/cis</sub>) and TS (**8**<sub>prim/cis</sub>–**9**<sub>prim</sub>) in Figure 2, respectively. The transition-state energy for C–H bond cleavage to form the cis alkyl intermediate **8**<sub>prim/cis</sub> is calculated to lie 0.9 kcal·mol<sup>−1</sup> below that for C–B bond formation by the cis primary alkyl intermediate **8**<sub>prim/cis</sub> and 2.4 kcal/mol below the transition state for isomerization of the trans alkyl intermediate **8**<sub>prim/trans</sub> to the cis isomer **8**<sub>prim/cis</sub>. These differences in energy are likely within the error of these computational methods. Thus, the calculations of this portion of the mechanism involving the

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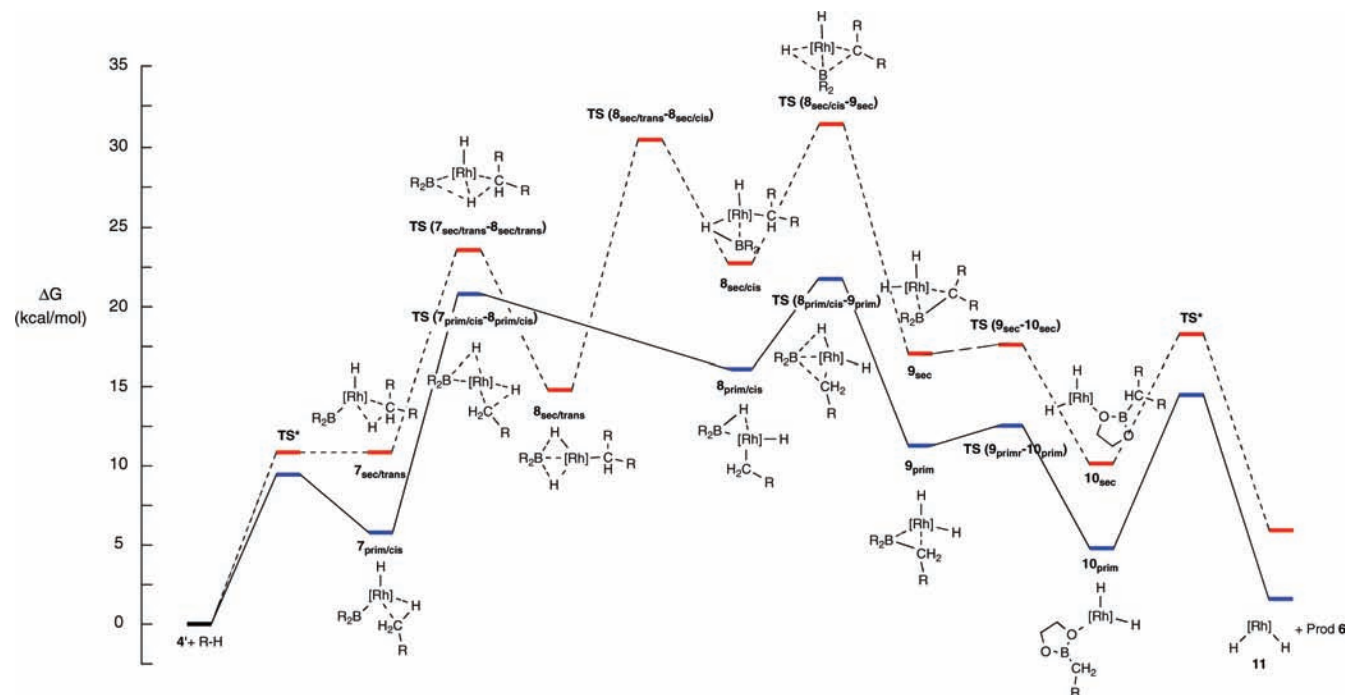
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**Table 1.** Relative Enthalpies and Free Energies<sup>a</sup> for the Reaction of Propane with 4'

	4 + Prod	TS*	7	TS <sub>7-8</sub>	8 <sub>trans</sub>	TS <sub>8<sub>trans</sub>-8<sub>cis</sub></sub>	8 <sub>cis</sub>	TS <sub>8<sub>cis</sub>-9</sub>	9	TS <sub>9-10</sub>	10 <sup>c</sup>	TS*	11 + Prod 6
Via the Cis Primary Alkyl Complex													
$\Delta H^{0,\ddagger}$	0.00	0.00	-2.84	8.51	---	---	3.18	8.36	0.10	2.80	-5.61	3.27	3.27
$\Delta G^{0,\ddagger}$	0.00	9.67	6.84	20.85	---	---	16.21	21.79	11.34	12.53	5.58	14.47	2.03
Via the Trans Primary Alkyl Complex													
$\Delta H^{0,\ddagger}$	0.00	0.00	-2.84	6.42	-1.61	10.05	<sup>b</sup>						
$\Delta G^{0,\ddagger}$	0.00	10.29	7.45	18.12	10.02	23.27	<sup>b</sup>						
Via Secondary Alkyl Complexes													
$\Delta H^{0,\ddagger}$	0.00	0.00	0.00	10.84	2.25	16.18	9.19	17.43	4.90	7.37	-0.86	6.88	6.88
$\Delta G^{0,\ddagger}$	0.00	10.42	10.42	23.41	14.23	30.46	22.71	31.27	17.27	17.66	10.23	17.97	6.07

<sup>a</sup> Energies are in units of kcal·mol<sup>-1</sup>. An asterisk following “TS” indicates that the energies are determined using the method described in the Computational Details and Figure 1. <sup>b</sup> The pathways for reaction of the cis and trans alkyl intermediates converge at intermediate 8<sub>cis</sub>. <sup>c</sup> Intermediate 10 was not evaluated during previous studies (see ref 17), but it is the most stable form found for a bound alkylboronate ester.



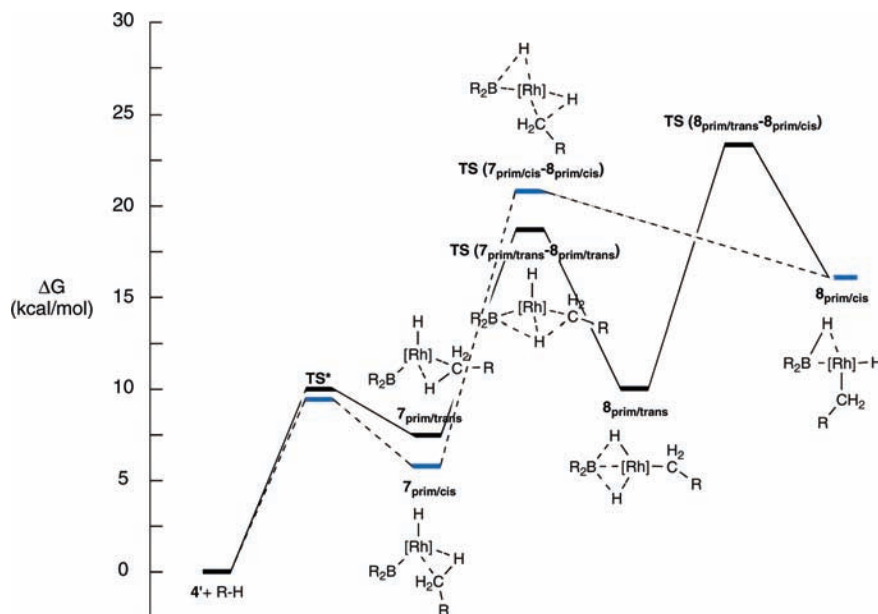
**Figure 2.** Free energy profiles of the reaction of propane with 4' through the lowest energy pathways for both primary and secondary C–H activation. For clarity purposes, the Cp\* ligand is not shown.

primary alkyl intermediates 8<sub>prim/cis</sub> and 8<sub>prim/trans</sub> underscore the issues of geometry, but the combination of these calculations and experimental data described later provides the clearest view into the reaction pathways through the different isomeric intermediates.

In contrast, these calculations show clearly that the highest energy transition state for functionalization of secondary C–H bonds is that for formation of the C–B bond (TS(8<sub>sec/cis</sub>-9<sub>sec</sub>) in Figure 2). The calculated transition-state energy for C–B bond formation from a secondary alkyl intermediate lies 7.9 kcal·mol<sup>-1</sup> above the calculated transition state for cleavage of the secondary C–H bond to form 8<sub>sec/trans</sub>. The large difference between the barriers for C–H bond cleavage and C–B bond formation involving primary and secondary alkyl intermediates appears to result largely from the more unfavorable steric interactions created by placing the boryl ligand cis to the secondary alkyl group than by placing the boryl ligand cis to the primary alkyl group. The sterically congested cis isomer of the secondary alkyl complex 8<sub>sec/cis</sub> is calculated to lie 8.5 kcal·mol<sup>-1</sup> above the less congested trans isomer 8<sub>sec/trans</sub>.

The relative stability of the products from activation of the primary and secondary C–H bonds contributes significantly to

the selectivity of the overall functionalization process because the functionalization of secondary C–H bonds is predicted to involve reversible cleavage of secondary C–H bonds. The trans isomer of the primary alkyl intermediate 8<sub>prim/trans</sub> is calculated to be 4.2 kcal·mol<sup>-1</sup> more stable than the trans isomer of the secondary alkyl intermediate 8<sub>sec/trans</sub>, and the cis isomer of the primary alkyl intermediate 8<sub>prim/cis</sub> is calculated to be 6.5 kcal·mol<sup>-1</sup> more stable than the cis isomer of the secondary alkyl intermediate 8<sub>sec/cis</sub>. These differences in energy are significant, but they are less than the calculated difference in energy between the highest barriers on the pathways to functionalization of primary and secondary C–H bonds. The barrier for B–C bond formation from the secondary alkyl intermediate lies about 10 kcal·mol<sup>-1</sup> above the highest (and similar) barriers for cleavage and functionalization of the primary C–H bonds. Thus, the differences in barriers for B–C bond formation by the primary and secondary alkyl intermediates reinforce the differences in energies of the primary and secondary alkyl intermediates. In other words, the selectivity for formation of the product from functionalization of the primary C–H bond is predicted to result from a more stable intermediate formed from cleavage of the primary C–H bond



**Figure 3.** Free energy profiles for the cleavage of primary C–H bonds in propane by **4'** through cis and trans isomers.

and more favorable C–B bond formation from this same alkyl intermediate.

**Experimental Studies on the Reactions of  $[\text{Cp}^*\text{Rh}(\text{H})_2(\text{Bpin})_2]$  (**2**) and  $[(\text{Cp}^*d_{15})\text{Rh}(\text{D})_2(\text{Bpin})_2]$  (**2-d<sub>17</sub>**) with Alkanes. Stoichiometric Reactions of  $[\text{Cp}^*\text{Rh}(\text{H})_2(\text{Bpin})_2]$  (**2**) with Octane and Octane-*d*<sub>18</sub>.** The reactions of octane with  $[\text{Cp}^*\text{Rh}(\text{H})_2(\text{Bpin})_2]$  (**2**) were reported previously.<sup>17</sup> These reactions occur around 125 °C, and like the reaction of  $\text{B}_2\text{pin}_2$  with octane catalyzed by  $[\text{Cp}^*\text{Rh}(\eta^4\text{-C}_6\text{Me}_6)]$ , they exclusively form the linear alkylboronate ester. The kinetic isotope effect for the catalytic reaction was reported previously,<sup>14</sup> but the kinetic isotope effect for the stoichiometric reaction was not. Because this value distinguishes between mechanisms in which either C–H bond cleavage or C–B bond formation is rate-limiting, we measured this effect for the stoichiometric reaction. The kinetic isotope effect determined by conducting the reaction of **2** with a 1:1 mixture of octane and octane-*d*<sub>18</sub> at 100 °C was  $2.6 \pm 0.1$ , which is consistent with the  $2.0 \pm 0.1$  value measured for the catalytic reaction at 150 °C.

**H/D Exchange Studies between  $[(\text{Cp}^*d_{15})\text{Rh}(\text{D})_2(\text{Bpin})_2]$  (**2-d<sub>17</sub>**) and Alkanes.** To assess the validity of the predictions obtained from the computational studies and to gain information on the reversibility of the C–H bond cleavage and C–B formation steps with higher alkanes and cyclic alkanes, we conducted experimental studies that would identify the reversible and irreversible steps of the catalytic process. Previous experimental studies indicated that the reductive elimination to form C–B bonds is fast in some cases,<sup>35–37</sup> but predictions from experimental studies of the relative rates for C–B bond formation and reversion to form C–H bonds were difficult to make. Moreover, few data are available on the relative rates for reductive elimination from primary and secondary alkyl complexes. The data that have been published<sup>38–40</sup> indicate that

reductive elimination is faster from secondary than from primary alkyl complexes.

To assess experimentally whether the rate-limiting step for the generation of alkylboronate esters involves B–C bond formation, a series of isotope exchange experiments was conducted. We conducted these H/D exchange studies with the bisboryl complex **2-d<sub>17</sub>** because dissociation of borane from **2-d<sub>17</sub>** gives the 16-electron deuterido boryl complex **4-d<sub>16</sub>** and the presence of a deuteride ligand on the 16-electron species that reacts with the alkane is necessary to observe any isotope scrambling between the deuterium-labeled metal complex and the C–H bonds of the alkane. Exchange of deuterium from the hydride position of **2** into the primary or secondary positions of the alkane solvent would imply that the C–H bond cleavage preceding B–C bond formation is reversible. In addition, the degree of deuterium incorporation into the primary and secondary positions would assess the relative rates for cleavage of the two types of C–H bonds by the boryl complexes.

**Preparation of Deuterium-Labeled  $\text{Cp}^*\text{Rh}$  Complexes.** The dideuterated complex  $\text{Cp}^*\text{Rh}(\text{D})_2(\text{Bpin})_2$  (**2-d<sub>2</sub>**) was prepared from  $\text{Cp}^*\text{Rh}(\eta^4\text{-C}_6\text{Me}_6)$  (**1-d<sub>15</sub>**) and excess DBpin following a previously established procedure for the unlabeled complex.<sup>17</sup> As described later in this paper, rapid H/D exchange between the methyl groups of the  $\text{Cp}^*$  ligand and the deuteride ligand complicated the isotope exchange studies. To prevent washing of deuterium from the hydride position into the  $\text{Cp}^*$  ligand, the perdeuterated bisboryl complex **2-d<sub>17</sub>** was prepared. Initial attempts to prepare the deuterated precursor  $[\text{d}_{15}\text{-Cp}^*\text{RhCl}_2]_2$  (**13-d<sub>30</sub>**) from deuterated pentamethylcyclopentadiene (*d*<sub>15</sub>- $\text{Cp}^*\text{H}$ ) and rhodium trichloride hydrate were unsuccessful due to the rapid loss of deuterium on the *d*<sub>15</sub>- $\text{Cp}^*\text{H}$  from H/D exchange with the protic methanol solvent. Both <sup>1</sup>H and <sup>2</sup>H NMR spectroscopy indicated a 65–70% loss of the deuterium in the  $\text{Cp}^*$  ligand. Moreover, the scandium-catalyzed preparation

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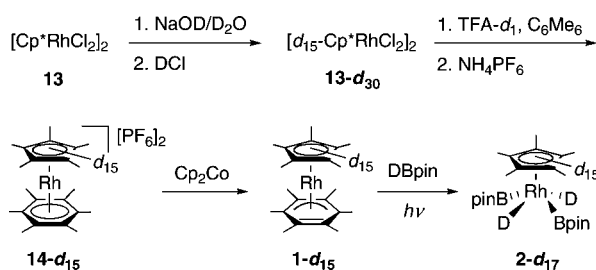
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## Scheme 2



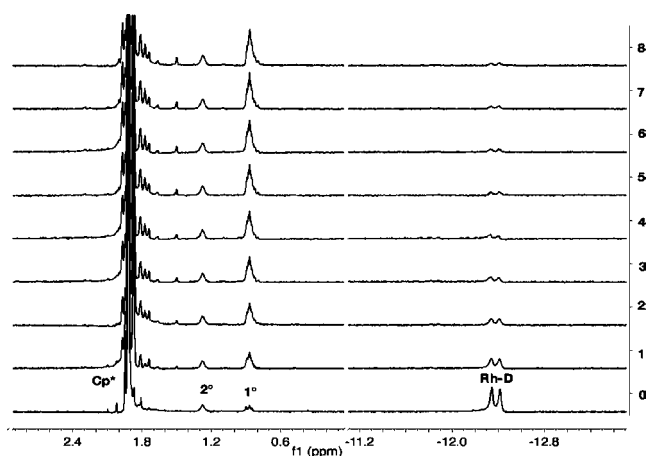
of  $d_{15}$ -Cp\*H from H/D exchange between pentamethylcyclopentadiene and  $C_6D_6$  required 4–5 weeks.<sup>41</sup>

Instead, perdeuterated complex  $2-d_{17}$  was prepared by the procedure outlined in Scheme 2. This sequence was initiated by heating  $[Cp^*RhCl_2]_2$  (**13**) in  $D_2O$  with 2 M NaOD for 3 days to form  $[d_{15}-Cp^*Rh(OD)_2]_2$ .<sup>42</sup>  $[d_{15}-Cp^*Rh(OD)_2]_2$  was then converted to **13-d<sub>30</sub>** by addition of an excess of deuterium chloride until the yellow solution turned dark red. A quantitative yield of **13-d<sub>30</sub>** was obtained, and  $^1H$  and  $^2H$  NMR spectroscopy indicated that the deuterium content of the Cp\* ligand was 95%. The reaction of **13-d<sub>30</sub>** with trifluoroacetic acid- $d_1$  and hexamethylbenzene with subsequent addition of aqueous  $NH_4PF_6$  resulted in the formation of  $d_{15}$ -Cp\* $Rh(C_6Me_6)[PF_6]_2$  (**14-d<sub>15</sub>**), and reduction of **14-d<sub>15</sub>** with  $Cp_2Co$  formed  $d_{15}$ -Cp\* $Rh(\eta^4-C_6Me_6)$  (**1-d<sub>15</sub>**). The photochemical reaction of **1-d<sub>15</sub>** with 10 equiv of DBpin in cyclohexane generated the deuterated bisboryl complex **2-d<sub>17</sub>**.

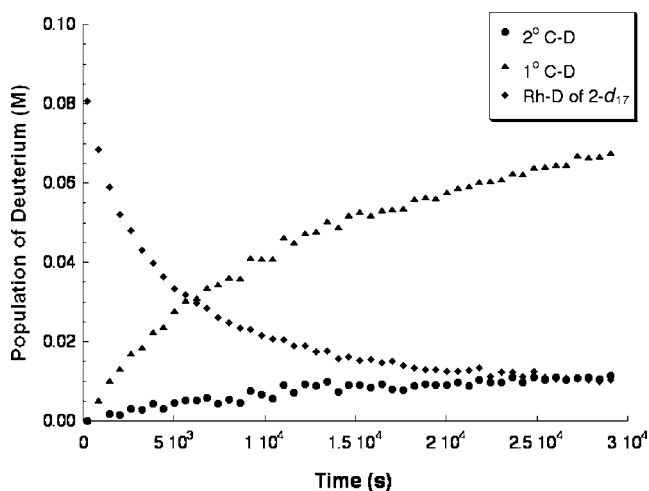
**Reaction of Complex 2-d<sub>17</sub> with *n*-Octane.** A simple isotope exchange experiment between proteo-bisboryl complex **2** and deuterated *n*-octane was initially conducted to determine whether cleavage of the C–H bonds of alkanes by the bisboryl complex **2** occurs reversibly. Heating a solution of **2** in octane- $d_{18}$  for 8 h at 70 °C resulted in the gradual increase of the  $^1H$  NMR signal corresponding to the terminal methyl group of octane. However, the large abundance of residual hydrogen in commercial octane- $d_{18}$  (99% D)<sup>43</sup> and low concentrations of **2** prevented an accurate assessment of whether H/D exchange had occurred at the primary positions and would not allow us to detect small amounts of deuterium incorporation into the secondary positions. Thus, it was necessary to prepare a deuterated alkane of higher isotope content or to conduct the study with a deuterium-labeled rhodium complex. We elected to pursue the latter strategy.

The H/D exchange process was, therefore, conducted between  $Cp^*Rh(D)_2(Bpin)_2$  (**2-d<sub>2</sub>**) and *n*-octane containing a natural abundance isotope composition. However, approximately 47% of the deuterium was transferred to the Cp\* ligand and only 19% was transferred to octane after 4 h at 70 °C. To prevent the loss of deuteride in the hydride position by exchange with the methyl hydrogens of the Cp\* ligand, further experiments were conducted with the bisboryl complex **2-d<sub>17</sub>** containing deuterium in both the hydride and Cp\* positions, the synthesis of which was described in the previous section.

Solutions of **2-d<sub>17</sub>** in octane (0.046 M) were heated at 70 °C and monitored by  $^2H$  NMR spectroscopy. During the course of 8 h, the deuterium signal corresponding to the primary C–H bonds of octane gradually increased, while the deuterium signal



**Figure 4.** 600 MHz  $^2H$  NMR spectra of the isotope exchange between **2-d<sub>17</sub>** and *n*-octane during the course of 8 h at 70 °C; y-axis is in 1 h increments.



**Figure 5.** Decay of the  $^2H$  NMR signal due to deuterium in the hydride position of **2-d<sub>17</sub>** and growth of the  $^2H$  NMR signal due to deuterium in the primary and secondary positions of *n*-octane at 70 °C.

corresponding to the hydride position of **2-d<sub>17</sub>** decreased (Figure 4). Curves of the appearance of deuterium at the primary and secondary positions of octane and of the decay of bisboryl complex **2-d<sub>17</sub>** are provided in Figure 5. Indistinguishable curves were obtained from multiple runs with separate batches of **2-d<sub>17</sub>**. For each experiment, the amount of deuterium at the primary C–H bonds of octane increased as a first-order exponential, while the amount of deuterium in the rhodium-hydride position decreased as a first-order exponential. We have not extracted rate constants for the intermolecular H/D exchange from the curves because of complications from competing isotope exchange between the hydride position and the Cp\* ligand and competitive decomposition of the bisboryl complex **2-d<sub>17</sub>** to form DBpin. However, qualitative comparisons of the relative rates for different processes can be drawn from data like those in Figure 5.

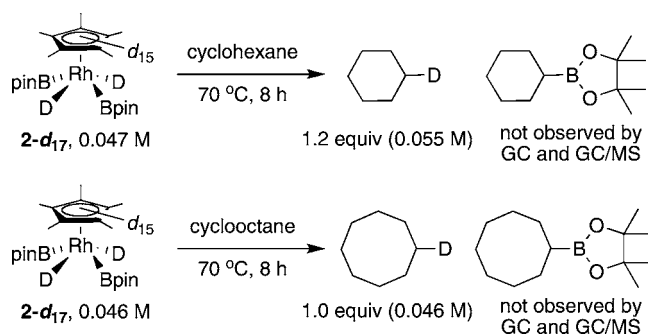
After heating bisboryl **2-d<sub>17</sub>** in octane at 70 °C for 8 h, the rhodium deuteride signal of **2-d<sub>17</sub>** was reduced by 79%, and approximately 1.4 equiv (0.068 M) of deuterium was transferred from **2-d<sub>17</sub>** to the terminal methyl group of octane (eq 2). A small amount of deuterium incorporation into the methylene position of octane was detected, but exchange into this position clearly occurred more slowly than exchange into the methyl

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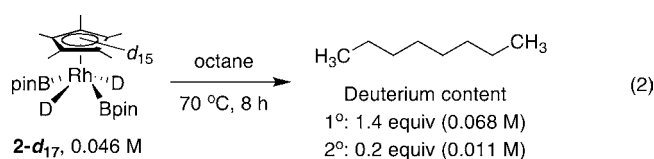
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## Scheme 3



position. After heating at 70 °C for 8 h, the reaction mixture was diluted with diethyl ether, a GC standard was added, and the solution was analyzed by GC for the amount of *n*-octylboronate ester **6** formed. After this time, only 15% of **6** was formed; thus, H/D exchange into the primary position is faster than the formation of functionalized product.



Approximately 0.5 equiv (0.022 M) of DBpin was also detected by  $^2\text{H}$  NMR spectroscopy. An assessment of whether the H/D exchange occurs by a pathway involving dissociation of borane and decomposition of rhodium to a second species will be presented later. In brief, the isotope exchange process is inhibited rather than promoted by free DBpin, and the exchange process appears to occur with the 16-electron rhodium intermediate generated by reversible dissociation of borane rather than with a product from the decomposition of the rhodium-boryl complex.

**Reaction of Complex  $2\text{-}d_{17}$  with Cycloalkanes.** Numerous studies on the oxidative addition of C–H bonds have shown that the addition of secondary C–H bonds occurs when primary C–H bonds are absent. For example, Bergman and co-workers reported the oxidative addition of secondary C–H bonds of unstrained cycloalkanes by  $\text{Cp}^*\text{Rh}(L)$  ( $L = \text{PMe}_3, \text{CO}$ ) fragments,<sup>44–46</sup> but Jones and co-workers observed that  $\text{Cp}^*\text{Rh}(L)$  reacts with linear alkanes exclusively at primary C–H bonds.<sup>47</sup> Since the H/D exchange between  $2\text{-}d_{17}$  and octane led to little deuterium incorporation at the secondary C–H bonds of octane, isotope exchange studies were conducted between  $2\text{-}d_{17}$  and cyclohexane and cyclooctane to determine whether cleavage of the secondary C–H bonds of cyclic alkanes occurs, even though functionalization of these alkanes does not occur (Scheme 3).

The reaction between  $2\text{-}d_{17}$  and cyclohexane resulted in appreciable amounts of deuterium incorporation into the C–H bonds of the cycloalkane (Figure 6). After heating at 70 °C for 8 h, the rhodium deuteride signal of  $2\text{-}d_{17}$  decreased by 73%, and 1.2 equiv (0.055 M) of deuterium was transferred from  $2\text{-}d_{17}$

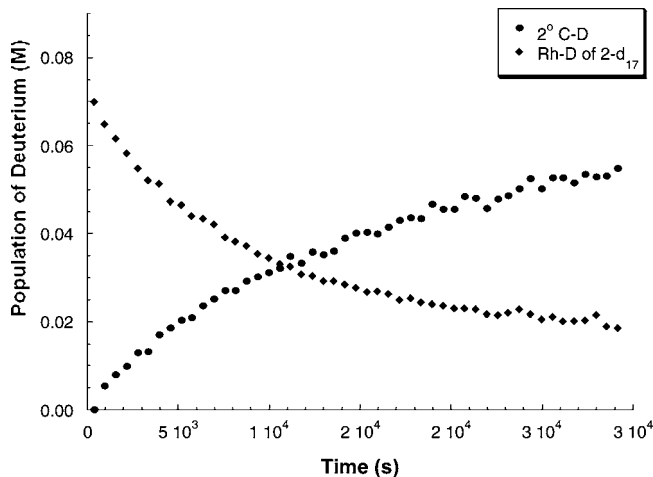


Figure 6. H/D exchange of  $2\text{-}d_{17}$  with cyclohexane, monitored at 70 °C.

to cyclohexane. Similar to the reaction with octane, free DBpin was generated during the reaction. No formation of cyclohexylboronate ester from C–H bond functionalization was detected by either gas chromatography (GC) or gas chromatography/mass spectrometry (GC/MS) analysis. Similar results were observed from the reaction of  $2\text{-}d_{17}$  with cyclooctane. Heating  $2\text{-}d_{17}$  in cyclooctane at 70 °C for 8 h led to the transfer of approximately 1.0 equiv (0.046 M) of deuterium from  $2\text{-}d_{17}$  to the cyclic alkane without detectable formation of the cycloalkylboronate ester that would result from functionalization of the alkane. The absence of this alkylboronate ester product is consistent with the computational data. The calculated transition state for formation of the B–C bond by the secondary alkylboryl complex is 7.9 kcal·mol<sup>−1</sup> higher than that for C–H bond cleavage; therefore, formation of a branched alkylboronate ester product does not occur readily.

**Determination of the Relative Rates for Exchange at Primary C–H Bonds of Linear Alkanes and Secondary C–H Bonds of Cyclic Alkanes.** An intermolecular competition for isotope exchange between  $2\text{-}d_{17}$  and cyclohexane and octane provided a qualitative comparison of the relative reactivity of primary C–H bonds, secondary C–H bonds of linear alkanes, and secondary C–H bonds of cyclic alkanes. A 0.045 M solution of the bisboryl complex  $2\text{-}d_{17}$  in an equimolar mixture of the two solvents resulted in the gradual transfer of deuterium from  $2\text{-}d_{17}$  into the terminal methyl groups of octane and the C–H bonds of cyclohexane. In contrast, deuterium transfer into the secondary C–H bonds of octane was negligible (Figure 7). Thus, the primary C–H bonds of the linear alkanes react faster than secondary C–H bonds in linear alkanes, and secondary C–H bonds of cyclic alkanes react faster than secondary C–H bonds of linear alkanes. The amount of deuterium transferred to different C–H bonds at several time points are shown in Table 2. These data show that the relative reactivity of primary C–H bonds of octane to secondary C–H bonds of cyclohexane, after correcting for the number of hydrogens, is between 4:1 and 5:1.

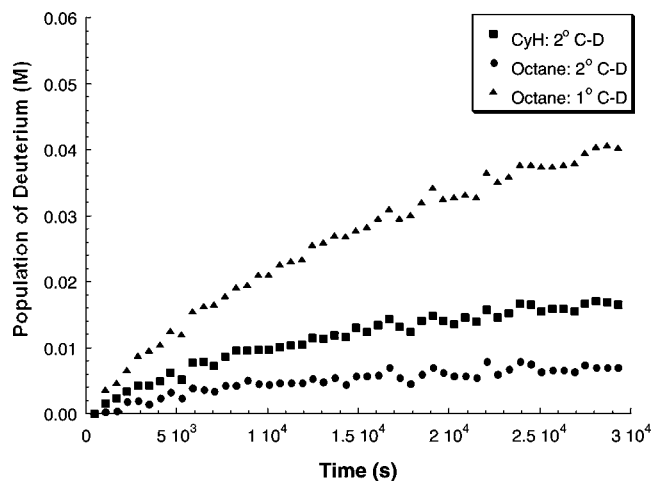
To examine whether the same relative rates occur during intramolecular competition experiments, we studied H/D exchange between  $2\text{-}d_{17}$  and the alkyl-substituted cyclohexanes ethylcyclohexane and *n*-butylcyclohexane. These results are summarized in Scheme 4. Because of the overlap of the  $^2\text{H}$  NMR resonance for the Cp\* ligand in  $2\text{-}d_{17}$  with one of the resonances for the methylene hydrogens of the alkane solvent, the amount of H/D exchange was measured after vacuum

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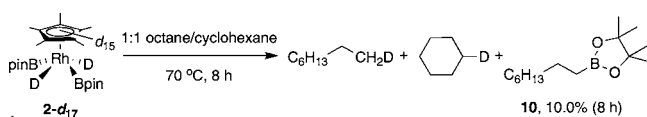
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**Figure 7.** H/D exchange between **2-d<sub>17</sub>** and a 1:1 mixture of *n*-octane and cyclohexane, monitored at 70 °C.

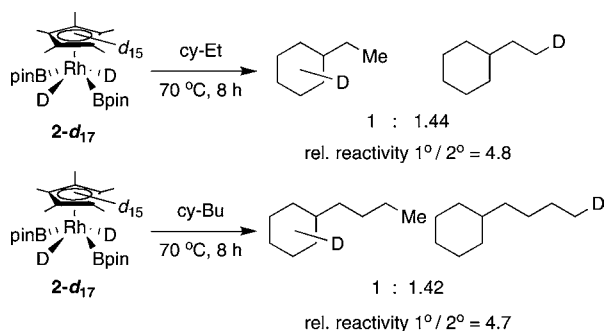
**Table 2.** Deuterium Transfer from **2-d<sub>17</sub>** to Primary and Secondary C–H Bonds



time (h)	equivalents of deuterium			relative reactivity <sup>a</sup>
	1° C–H bonds of C <sub>8</sub> H <sub>18</sub>	2° C–H bonds of C <sub>8</sub> H <sub>18</sub>	2° C–H bonds of C <sub>6</sub> H <sub>12</sub>	
2	0.38	0.09	0.19	4.0:1
4	0.60	0.12	0.28	4.3:1
6	0.75	0.13	0.31	4.8:1
8	0.87	0.15	0.36	4.8:1

<sup>a</sup> Relative reactivity was calculated by dividing the ratio of deuteriums transferred to the primary C–H bonds of octane and secondary C–H bonds of cyclohexane by the ratio of primary C–H bonds in octane (6) and secondary C–H bonds in cyclohexane (12).

#### Scheme 4



transferring the volatile materials from the rhodium complexes after heating.

The reaction of **2-d<sub>17</sub>** and ethylcyclohexane indicated that H/D exchange occurred and that it occurred faster at the primary C–H bonds of this substrate than at the secondary C–H bonds. After heating at 70 °C for 8 h, the ratio of the amount of deuterium at the methyl versus methylene positions was 1.4 to 1. It was not possible to distinguish the C–H bonds of the cyclohexane ring from the secondary C–H bonds of the alkyl chain by <sup>2</sup>H NMR spectroscopy. Thus, we made the assumption, based on the lack of significant H/D exchange with the secondary C–H bonds of linear alkanes, that the deuterium

incorporation at secondary C–H bonds occurs primarily into the cyclohexane ring. After correcting for the ratio of hydrogens (10 methylene C–H bonds in the cyclohexyl group and 3 methyl C–H bonds in the alkyl group), deuterium exchange between **2-d<sub>17</sub>** and ethylcyclohexane was calculated to be nearly five times faster at the individual primary C–H bonds than at the individual secondary C–H bonds of the cycloalkane ring. The same relative rates were observed for H/D exchange at methyl and methylene positions of *n*-butylcyclohexane. This ratio of deuterium incorporation into primary versus secondary C–H bonds within ethylcyclohexane and *n*-butylcyclohexane was indistinguishable from the ratio of isotope exchange into the primary position of octane and the secondary positions of cyclohexane.

**Assessment of the Complex Leading to H/D Exchange.** Because catalytic H/D exchange<sup>48,49</sup> of alkanes has been reported to occur with homogeneous metal complexes of Pt,<sup>50–54</sup> Ir,<sup>55–57</sup> and Rh<sup>58</sup> and recently with heterogeneous mixtures of Pd/C<sup>59</sup> and Rh/C,<sup>60</sup> it was important to address whether the isotope exchange involved a species generated by decomposition of **2-d<sub>17</sub>**. Thus, several experiments were conducted to evaluate the potential that H/D exchange occurred between the alkane and a species generated from decomposition of **2-d<sub>17</sub>**.

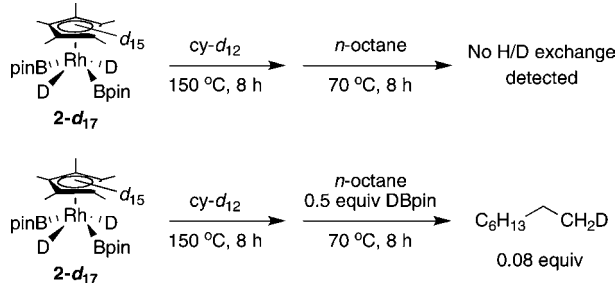
If irreversible generation of a second complex leads to isotope exchange, and the exchange is observed over a time scale similar to that of the decomposition, then one would expect to observe an induction period for the isotope exchange. In our case, **2-d<sub>17</sub>** is observed during the H/D exchange process by <sup>2</sup>H NMR spectroscopy, and based on the observation of some free DBpin, it appears to decompose with a rate that is slower than but within an order of magnitude of that of H/D exchange. Yet, the data in Figure 5 do not reveal an observable induction period for the isotope exchange reaction. This absence of an induction period for the isotope exchange strongly argues against exchange between the alkane and a product from decomposition of **2-d<sub>17</sub>**.

If the isotope exchange occurs with a complex formed from decomposition of **2-d<sub>17</sub>** or by the generation of DBpin or both, then one might expect to observe a faster rate of H/D exchange following the decomposition of **2-d<sub>17</sub>**. Thus, we heated **2-d<sub>17</sub>** at 150 °C for 8 h in cyclohexane-*d*<sub>12</sub> and tested the ability of the resulting material to undergo H/D exchange with octane in the absence and presence of DBpin. The results are summarized in Scheme 5. Heating **2-d<sub>17</sub>** in cyclohexane-*d*<sub>12</sub> led to several unknown Cp\*Rh complexes. Evaporating the solvent, dissolu-

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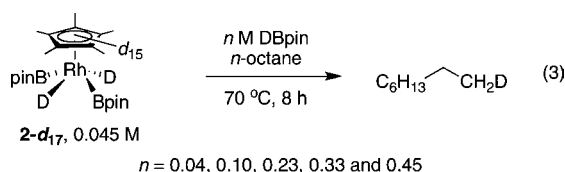
## Scheme 5



tion of the resulting black oil in octane, and heating at 70 °C for 8 h led to no deuterium incorporation into octane, as detected by  $^2\text{H}$  NMR spectroscopy. The same experiment, except heating the decomposed material in octane with 0.5 equiv of added DBpin, led to transfer of less than 0.1 equiv of deuterium to the terminal position of octane. Because the amount of H/D exchange from the reaction of  $2-d_{17}$  with octane was nearly 20 times greater than that from the reaction of decomposed  $2-d_{17}$  and octane in the presence or absence of DBpin, we conclude that the H/D exchange observed between octane and  $2-d_{17}$  does not result from a material formed by decomposition of  $2-d_{17}$ . Our data imply that the isotope exchange process occurs between octane and  $2-d_{17}$  or a species generated reversibly from it.

Finally, we conducted experiments to assess whether the 16-electron intermediate generated reversibly by dissociation of DBpin from  $2-d_{17}$ , as has been proposed to lead to C–H bond functionalization, also leads to the isotope exchange. Earlier work by Hartwig and co-workers showed that added HBpin inhibited the rate of formation of octylBpin from the reaction of octane with  $\text{B}_2\text{pin}_2$  catalyzed by bisboryl complex **2**.<sup>17</sup> Because C–H bond cleavage precedes C–B bond formation and the subsequent release of the alkylboronate ester, added borane should inhibit the rate of C–H bond cleavage and the isotope exchange between  $2-d_{17}$  and octane.

Thus, to obtain data on the potential intermediacy of a 16-electron boryl complex on the pathway to isotope exchange, we monitored the isotope exchange between  $2-d_{17}$  and octane in the presence and absence of varying concentrations of added borane. To prevent the loss of deuterium from the bisboryl complex  $2-d_{17}$  by isotope exchange between the metal complex and the added borane ligand, these experiments were conducted with added DBpin instead of HBpin. Reactions of  $2-d_{17}$  with octane at 70 °C in the presence of varying concentrations of added DBpin were monitored by  $^2\text{H}$  NMR spectroscopy over 8 h (eq 3). As shown by the plot of deuterium incorporation versus time in Figure 8, increasing amounts of DBpin increasingly retarded the rate of isotope exchange between  $2-d_{17}$  with octane.



These experiments on the isotope exchange in the presence of DBpin are potentially complicated by two factors. First, reactions conducted in the presence of added DBpin contain all the reagents for a catalytic borylation of alkanes. This complication was minimized by conducting the studies of

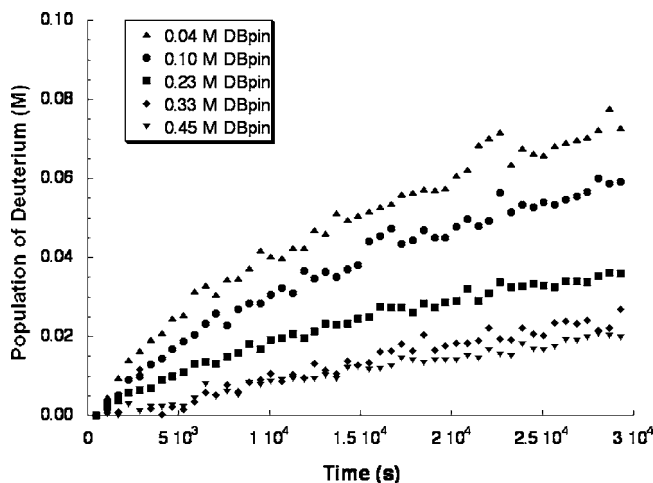


Figure 8. H/D exchange between  $2-d_{17}$  and octane at different concentrations of DBpin, monitored at 70 °C.

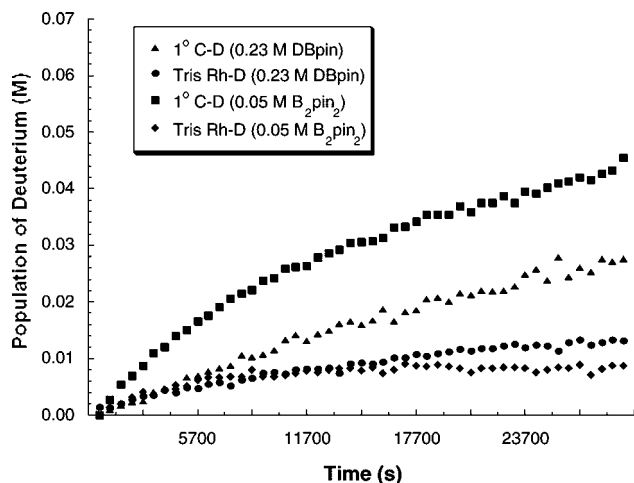
isotope exchange at temperatures low enough that little formation of the functionalized product occurs.

Second, a gradual generation of trisboryl complex  $3-d_{16}$  was observed by  $^2\text{H}$  NMR spectroscopy, and one might propose that the inhibition of isotope exchange between  $2-d_{17}$  and octane in the presence of DBpin results from this conversion of  $2-d_{17}$  into  $3-d_{16}$ . We conducted several experiments to test this hypothesis. If the rate inhibition results from the conversion of  $2-d_{17}$  into  $3-d_{16}$ , then a majority of  $2-d_{17}$  must be converted into  $3-d_{16}$  to account for the 5–10 fold decrease in the rate of H/D exchange observed. Moreover, if the rate inhibition results from the accumulation of trisboryl complex  $3-d_{16}$ , then a similar decrease in rate would be observed for reactions conducted with added  $\text{B}_2\text{pin}_2$ , since  $2-d_{17}$  is known to react with  $\text{B}_2\text{pin}_2$  to form  $3-d_{16}$ .<sup>17</sup> Inconsistent with these predictions, the effect of DBpin on the rate of H/D exchange was much greater than the conversion of  $2-d_{17}$  into  $3-d_{16}$ , and the reaction of  $2-d_{17}$  with octane was unaffected by the presence of added  $\text{B}_2\text{pin}_2$  (Scheme 6, Figure 9).

Therefore, we conclude that the slower rate of H/D exchange in the presence of added DBpin is due to an effect of the added DBpin on the pre-equilibrium involving dissociation of DBpin from  $2-d_{17}$  and not on competitive generation of the trisboryl complex  $3-d_{16}$  or complications from catalysis. This inhibition of the rate of H/D exchange by added borane, along with the lack of an induction period and the lack of H/D exchange after heating of the complex to decomposition implies that the observed isotope exchange results from reaction with the 16-electron species generated from the starting complex  $2-d_{17}$ .

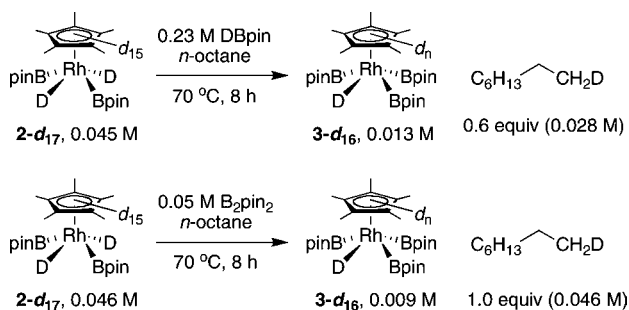
## Discussion

**Experimental Design.** A combination of computational and experimental studies was conducted to assess several potential origins of the selectivity for the borylation of primary over secondary C–H bonds in alkanes. The DFT calculations we conducted were based on prior mechanistic studies<sup>17</sup> that identified likely intermediates in the borylation of alkanes catalyzed by  $\text{Cp}^*\text{-rhodium}$  boryl complexes. These computational studies provided energies of transition states and intermediates for C–H bond cleavage of both primary and secondary C–H bonds in propane and for C–B bond formation to generate alkylboronate esters from both primary and secondary alkyl intermediates. To assess the validity of the conclusions drawn



**Figure 9.** H/D exchange between 2-*d*<sub>17</sub> and octane in the presence of 0.05 M B<sub>2</sub>pin<sub>2</sub> and in the presence of 0.23 M DBpin, monitored at 70 °C. Tris-Rh-D refers to the appearance of Cp\*Rh(Bpin)<sub>3</sub>(D) during the exchange reactions.

#### Scheme 6



from these studies, we designed a series of H/D exchange reactions. These H/D exchange reactions were conducted with discrete rhodium complexes because H/D exchange between a deuterium source and an alkane can be catalyzed by many species that would not be related to the alkane borylation. Moreover, control experiments to determine if the exchange occurred with any decomposition product and qualitative kinetic studies on the effect of added borane were conducted to assess whether the proposed intermediate leading to C–H bond functionalization was the same as that leading to H/D exchange. As described in the results section, all of these experiments were consistent with H/D exchange between 2-*d*<sub>17</sub> and octane after reversible dissociation of borane from 2-*d*<sub>17</sub> to generate the 16-electron, monoboryl monodeuteride intermediate (Cp\**-d*<sub>15</sub>)-Rh(D)(Bpin) (4-*d*<sub>16</sub>).

**Potential Origins of Regioselectivity and Evidence for Two Reinforcing Effects.** The high selectivity for terminal functionalization could result from (1) a high kinetic selectivity for cleavage of primary over secondary C–H bonds; (2) a high thermodynamic selectivity for cleavage of primary over secondary C–H bonds, coupled with similar rates for functionalization of the resulting primary and secondary alkyl intermediates; (3) unselective, reversible cleavage of primary and secondary C–H bonds, followed by selective functionalization of the resulting primary alkyl intermediate over the second alkyl intermediate; or (4) a reinforcing combination of selective, reversible cleavage of primary over secondary C–H bonds, coupled with selective functionalization of the primary alkyl intermediate over the secondary alkyl intermediate. The combination of theoretical

and experimental work reported here allows us to distinguish between these possible scenarios for control of selectivity.

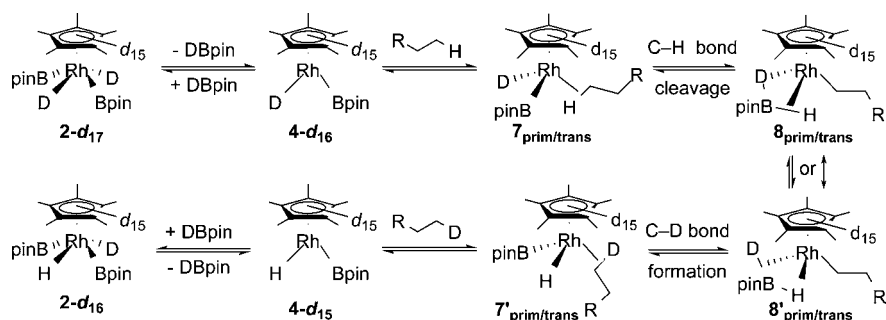
The computational and experimental data are best explained by the presence of three reaction channels. One channel leads to the observed H/D exchange with the primary C–H bonds of the alkane. A second channel leads to functionalization of the primary C–H bonds. A third channel leads to functionalization of secondary C–H bonds. The stereochemistry of the intermediates differentiates the two channels involving reactions of primary C–H bonds, and this stereochemistry is an important factor that controls the ability of the C–H bond cleavage events to lead to functionalized product.

The computed pathway for H/D exchange with primary C–H bonds involves formation of the trans alkyl intermediate **8**<sub>prim/trans</sub>, and this pathway is illustrated in Scheme 7. C–H bond cleavage by this pathway was calculated to occur with the lowest barrier (18.1 kcal·mol<sup>-1</sup>) of the three reaction channels. Although the computed barrier for functionalization by this pathway after isomerization of the alkyl isomer containing trans boryl and alkyl groups **8**<sub>prim/trans</sub> to the isomer containing cis boryl and alkyl groups **8**<sub>prim/cis</sub> is accessible, the transition state for isomerization of **8**<sub>prim/trans</sub> to **8**<sub>prim/cis</sub> is calculated to have a barrier of 23.3 kcal·mol<sup>-1</sup>. This barrier is higher than that for functionalization by the second reaction channel involving direct formation of the cis isomer **8**<sub>prim/cis</sub>. The conclusion from the computational work that C–H bond cleavage occurs with a lower barrier than C–H bond functionalization, due in part to the geometric preference for formation of trans isomers by C–H bond cleavage, is consistent with the experimental observation that H/D exchange between the rhodium complex and C–H bonds is faster than functionalization of the C–H bonds.

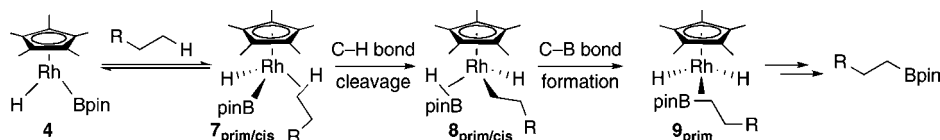
The functionalization of primary C–H bonds is calculated to occur by the second reaction channel involving initial cleavage of the C–H bond to form an alkyl complex containing cis alkyl and boryl units. This mechanism is shown in Scheme 8 and indicates that the alkyl complex containing cis alkyl and boryl units can undergo C–B bond formation without a need for isomerization. The barrier for formation of the C–B bond (21.8 kcal·mol<sup>-1</sup>) is calculated to be sufficiently similar to that for cleavage of the C–H bond (20.9 kcal·mol<sup>-1</sup>) that either step could be rate limiting in the experimental system. The observation of a primary isotope effect for the functionalization of octane and octane-*d*<sub>18</sub> by complex **2** indicates that the C–H bond is cleaved in the transition state that has the highest energy after formation of the reactive intermediate. Thus, these data indicate that the energy of the transition state for cleavage of the primary C–H bond shown as TS(**7**<sub>prim/cis</sub>–**8**<sub>prim/cis</sub>) in Figure 2 is higher than that for formation of the C–B bond shown as TS(**8**<sub>prim/cis</sub>–**9**<sub>prim</sub>) in Figure 2.

Finally, the reaction channel for functionalization of secondary C–H bonds (Scheme 9) is calculated to have the highest barrier. The computed energy for cleavage of the secondary C–H bond to form the isomer containing trans alkyl and boryl groups (23.4 kcal·mol<sup>-1</sup>) is higher than that for cleavage of primary C–H bonds (18.1 kcal·mol<sup>-1</sup>), but it remains at an accessible energy. However, the energies for generating the isomer containing secondary alkyl and boryl groups oriented cis to each other (30.5 kcal·mol<sup>-1</sup>) and for forming the C–B bond from this isomer (31.3 kcal·mol<sup>-1</sup>) are calculated to be too high to allow this cis isomer to form and to generate product from functionalization of the secondary C–H bond with any significant rate under the experimental conditions. Thus, C–H bond cleavage of the secondary C–H bonds leads to the

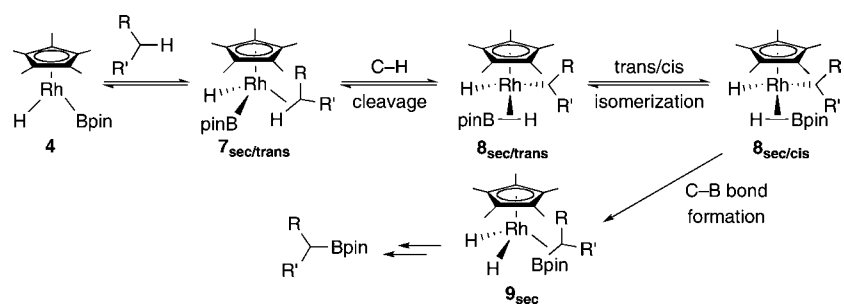
Scheme 7



Scheme 8



Scheme 9



formation of a secondary alkyl intermediate but does not lead to functionalized product. These computed relative energies for cleavage and functionalization of secondary C–H bonds are consistent with the observation of a small amount of H/D exchange into the secondary position of linear alkanes and a significant amount of H/D exchange into cyclic alkanes without the formation of products from the functionalization of secondary C–H bonds.

This analysis leads us to conclude that the selectivity results from a combination of scenarios (1) and (4) described in the introduction to the discussion section. A reaction manifold that is consistent with the kinetic isotope effect for functionalization of the primary C–H bond, the isotope exchange into the primary position of the alkane, and the computational data involves cleavage of the C–H bond to form an alkyl complex containing cis alkyl and boryl units and H/D exchange by a reaction mechanism that is related to the functionalization pathway but proceeds through the trans alkyl isomer. The pathway leading to a trans isomer of the alkyl intermediates is calculated to have a higher barrier for functionalization than that leading to functionalized product by direct formation of the cis isomer of the alkyl intermediate. The reactions involving secondary C–H bonds appear to include reversible cleavage of the secondary C–H bond, albeit slower cleavage than of the primary C–H bonds, but to confront a high barrier for B–C bond formation due to the steric congestion in a structure containing the larger secondary alkyl ligand cis to the boryl unit. Thus, the high selectivity for the borylation of primary C–H bonds results from a reinforcing combination of selective formation of primary alkyl intermediates and selective functionalization of the primary alkyl intermediate.

**Comparison of the Selectivity of the Borylation of Alkanes to That of Prior C–H Bond Functionalization through Organometallic Intermediates.** Although several catalysts have been developed for the functionalization of linear and cyclic alkanes, few of these catalysts selectively functionalize primary C–H bonds. Many organometallic complexes undergo selective cleavage of primary C–H bonds to form primary alkyl intermediates. However, most complexes that catalyze the functionalization of primary C–H bonds, even those occurring through metal-alkyl intermediates, do not provide products from functionalization of primary C–H bonds in high yield.

For example, the well-known Shilov-type Pt(II)-catalyzed oxidation of alkanes to alcohols or alkyl chlorides displays little selectivity for reaction with primary versus secondary C–H bonds.<sup>51</sup> An early study probed the selectivity for cleavage of the C–H bond by H/D exchange between *n*-pentane and deuterated acetic acid catalyzed by K<sub>2</sub>PtCl<sub>4</sub>, and this study indicated that the rate of activation of primary C–H bonds was comparable to the rate of activation of secondary C–H bonds.<sup>52</sup> The relative rates for deuterium exchange at primary versus secondary C–H bonds was 1.6:1.0.<sup>52</sup>

More recently developed reactions, such as the dehydrogenation<sup>61</sup> of *n*-alkanes catalyzed by pincer complexes of Ir and the photochemical carbonylation<sup>62,63</sup> of terminal C–H bonds catalyzed by RhCl(CO)(PMe<sub>3</sub>)<sub>2</sub> selectively form products from

(61) Liu, F.; Pak, E. B.; Singh, B.; Jensen, C. M.; Goldman, A. S. *J. Am. Chem. Soc.* **1999**, *121*, 4086.

(62) Sakakura, T.; Sodeyama, T.; Sasaki, K.; Wada, K.; Tanaka, M. *J. Am. Chem. Soc.* **1990**, *112*, 7221.

(63) Rosini, G. P.; Zhu, K.; Goldman, A. S. *J. Organomet. Chem.* **1995**, *504*, 115.

functionalization of primary C–H bonds over secondary C–H bonds, but the yields of these isomers are limited by secondary reactions. The  $\alpha$ -olefins formed by dehydrogenation undergo isomerization to the internal olefins, and the aldehydes formed by carbonylation undergo aldol reactions and Norrish type II cleavages. Most recently, Che and co-workers reported the most selective reaction, other than the C–H borylation chemistry, for functionalization of primary C–H bonds.<sup>64</sup> In this process, the insertion of the carbene generated from an aryl diazoacetate catalyzed by a rhodium-porphyrin complex formed a 3.5:1 ratio of products from functionalization of the primary over secondary C–H bond of hexane.<sup>64</sup>

## Conclusions

A detailed mechanistic understanding of the origins of selectivity from rhodium-catalyzed alkane borylation was obtained by the combination of computational studies, isotope exchange studies, and qualitative kinetic data. The results for these experiments revealed important mechanistic details and provided us with an explanation for the exclusive functionalization of terminal C–H bonds.

**1. DFT Calculations and Isotope Exchange Studies Imply That C–H Bond Cleavage by Cp\*Rh-Boryl Complexes Is Reversible.** The computational results reported in this work on the borylation of propane indicate that the transition-state energies for formation of C–B bonds at primary and secondary positions are higher than the lowest transition-state energies for cleavage of primary and secondary C–H bonds that form alkyl complexes in which the alkyl and boryl moieties in the rhodium coordination sphere are trans to each other. The clear observation of H/D exchange into the primary C–H bonds of *n*-octane and secondary C–H bonds of cyclohexane and the negligible formation of alkylboronate ester during the isotope exchange studies with the rhodium complex **2-d<sub>17</sub>** are consistent with reversible C–H bond cleavage followed by irreversible C–B bond formation. Additionally, the inhibition of isotope exchange by added borane supports reversible dissociation of borane to generate a 16-electron intermediate prior to C–H bond cleavage.

**2.  $\Delta\Delta G^\ddagger$  Favor Cleavage of Primary versus Secondary C–H Bonds by Cp\*Rh-Boryl Complexes.** Isotope exchange between **2-d<sub>17</sub>** and octane indicated that the rhodium complex reacted about an order of magnitude faster with the terminal methyl C–H bonds than with the internal methylene C–H bonds. This H/D exchange provides a measure of the kinetic selectivity for cleavage of primary versus secondary C–H bonds by Cp\*Rh-boryl complexes. In addition, competition experiments with alkyl-substituted cyclohexanes and the intermolecular competition experiment between cyclohexane and octane indicated that secondary C–H bonds in cycloalkanes underwent H/D exchange faster than secondary C–H bonds in linear alkanes. The selectivity for H/D exchange of primary versus secondary C–H bonds is consistent with the calculated  $\Delta\Delta G^\ddagger$  for cleavage of the two types of bonds and the significantly higher transition-state energy for the functionalization of secondary C–H bonds than for the cleavage of secondary C–H bonds. The calculations also imply that the difference in free energies  $\Delta\Delta G$  of the primary and secondary alkyl intermediates is significantly larger than the difference in free energies of activation  $\Delta\Delta G^\ddagger$  for formation of the two alkyl

complexes. The faster rates for cleavage of the secondary C–H bonds in cycloalkanes than for cleavage of the secondary C–H bonds in linear alkanes can be attributed to the reduced steric effects surrounding the C–H bonds of cyclic alkanes.

**3. Effect of Geometry on the Barriers to C–H Bond Cleavage and C–B Bond Formation.** The lowest energy pathways for cleavage of both primary and secondary C–H bonds form complexes containing an alkyl group and a coordinated borane in which the alkyl ligand and boryl moiety of the borane ligand are located trans to each other. These complexes are proposed to lead to H/D exchange; however, they cannot form the C–B bond directly. Instead, a pathway leading to the direct formation of the isomer in which the alkyl and boryl ligands are located cis to each other is calculated to have the lowest overall barrier, with similar transition-state energies for C–H bond cleavage and C–B bond formation. A primary isotope effect for reaction of octane and octane-*d*<sub>18</sub> implies that C–H bond cleavage to form the cis isomer of the primary alkyl complex has a higher barrier than C–B bond formation from this cis isomer. The high energy required to adopt a structure in which the secondary alkyl group is located cis to the boryl group is proposed to lead to the high barrier for functionalization of secondary C–H bonds. These proposals are consistent with the observation of H/D exchange involving the primary C–H bonds, a primary isotope effect for the overall C–H bond functionalization process, and the computed energies for the primary and secondary alkyl complexes in which the boryl moiety is located cis and trans to the alkyl ligand.

**4. High Selectivity for Functionalization of Primary versus Secondary C–H Bonds Results from Reinforcing Effects of the High Equilibrium Selectivity for Formation of Primary versus Secondary Alkyl Intermediates and High Selectivity for Functionalization of the Primary Alkyl Intermediate.** The computational studies lead to the proposal that the equilibrium ratio of primary versus secondary alkyl intermediates favoring the primary alkyl species and the lower transition-state energy for C–B bond formation from the primary alkyl intermediate than from the secondary alkyl intermediate both lead to the high selectivity of the catalytic process. Our experimental studies on H/D exchange with linear alkanes are consistent with preferential cleavage of primary C–H bonds over secondary C–H bonds in linear alkanes and our observation of H/D exchange with cycloalkanes that do not undergo functionalization support the assertion that C–B bond formation from the appropriate primary alkyl intermediate is faster than C–B bond formation from the analogous secondary alkyl intermediates. This conclusion implies that a higher selectivity for functionalization of one type of C–H bond over another can be observed, at least in some systems, even when the C–H bond cleavage process occurs reversibly and with modest selectivity.

## Experimental Section

**General Remarks.** All reactions were conducted under a nitrogen atmosphere using standard Schlenk and glovebox techniques, unless otherwise noted. All glassware was dried by a flame or in an oven. Glassware and NMR tubes used in the isotope exchange reactions were deuterated by heating to 100 °C with deuterium oxide or by washing three times with deuterium oxide. Cyclohexane-*d*<sub>12</sub> and *n*-octane-*d*<sub>18</sub> were dried over a sodium/benzophenone ketyl, and dichloromethane-*d*<sub>2</sub> was dried over calcium hydride. Alkenes were removed from *n*-octane and cyclooctane by repeatedly stirring over concentrated H<sub>2</sub>SO<sub>4</sub> until no further coloration developed, decanted from the acid layer, then

(64) Thu, H.-Y.; Tong, G. S.-M.; Huang, J.-S.; Chan, S. L.-F.; Deng, Q.-H.; Che, C.-M. *Angew. Chem., Int. Ed.* **2008**, *47*, 9747.

washed with H<sub>2</sub>O and four times with saturated NaHCO<sub>3</sub>.<sup>65</sup> Cyclohexane, ethylcyclohexane, and butylcyclohexane were stirred over nitric acid then separated and washed several times with 25% NaOH and once with H<sub>2</sub>O to remove traces of arene. The resulting alkanes were then dried over anhydrous MgSO<sub>4</sub> and passed through a column of neutral Al<sub>2</sub>O<sub>3</sub>. Each alkane was then dried over sodium/benzophenone and degassed prior to use. HBpin and DBpin were distilled by vacuum transfer. [d<sub>15</sub>-Cp\*RhCl<sub>2</sub>]<sub>2</sub> was prepared according to a literature procedure.<sup>42</sup> [d<sub>15</sub>-Cp\*Rh(C<sub>6</sub>Me<sub>6</sub>)]<sub>2</sub>[PF<sub>6</sub>]<sub>2</sub> was prepared from [d<sub>15</sub>-Cp\*RhCl<sub>2</sub>]<sub>2</sub> by methods that were similar to those for the published preparation of [Cp\*Rh(C<sub>6</sub>Me<sub>6</sub>)]<sub>2</sub>[PF<sub>6</sub>]<sub>2</sub>,<sup>66</sup> except that trifluoroacetic acid-d<sub>1</sub> was used as the solvent. d<sub>15</sub>-Cp\*Rh(η<sup>4</sup>-C<sub>6</sub>Me<sub>6</sub>) was prepared from [d<sub>15</sub>-Cp\*Rh(C<sub>6</sub>Me<sub>6</sub>)]<sub>2</sub>[PF<sub>6</sub>]<sub>2</sub> by procedures analogous to those published for the preparation of Cp\*Rh(η<sup>4</sup>-C<sub>6</sub>Me<sub>6</sub>).<sup>67</sup> Cp\*Rh(H)<sub>2</sub>(Bpin)<sub>2</sub><sup>17</sup> was prepared from Cp\*Rh(η<sup>4</sup>-C<sub>6</sub>Me<sub>6</sub>)<sup>67</sup> and HBpin, then filtered through a plug of Darco G-60 activated carbon powder. Reaction solvents including pentane, diethyl ether, and benzene were dried by percolation through a column packed with neutral alumina and a column packed with Q5 reactant, a supported copper catalyst for scavenging oxygen, under a positive pressure of N<sub>2</sub>. All other chemicals were used as received from commercial suppliers.

<sup>1</sup>H and <sup>13</sup>C NMR spectra were recorded on 500 MHz spectrometers. <sup>2</sup>H NMR spectra were obtained at 77 MHz. <sup>11</sup>B NMR spectra were recorded at 96 MHz. All <sup>1</sup>H, <sup>2</sup>H, and <sup>13</sup>C chemical shifts are reported in ppm (δ) relative to tetramethylsilane and referenced using chemical shifts of residual solvent resonances. Integrations of the <sup>2</sup>H NMR signals obtained on samples in ethylcyclohexane and *n*-butylcyclohexane were referenced to an internal capillary standard of C<sub>6</sub>Me<sub>6</sub>-d<sub>18</sub> (2.22 ppm, <sup>2</sup>H). <sup>11</sup>B NMR spectra were referenced to an external standard of BF<sub>3</sub>·OEt<sub>2</sub> (0 ppm, <sup>11</sup>B). All temperatures for kinetic experiments were calibrated relative to the chemical shift differences in the NMR spectra of neat ethylene glycol.

The glassware used for the deuterium labeling and H/D exchange studies was washed with D<sub>2</sub>O and dried prior to addition of the reagents. To remove residual protons from reaction vessels that are fused to vacuum valves, the vessel was washed with D<sub>2</sub>O and placed on a vacuum line. The vessel was then evacuated and heated to remove residual D<sub>2</sub>O. NMR sample tubes equipped with screw caps were washed with D<sub>2</sub>O and dried in an oven prior to addition of the samples.

**Preparation of d<sub>15</sub>-Cp\*Rh(D)<sub>2</sub>(Bpin)<sub>2</sub> (2-d<sub>17</sub>).** A solution of d<sub>15</sub>-Cp\*Rh(η<sup>4</sup>-C<sub>6</sub>Me<sub>6</sub>) (1-d<sub>15</sub>, 323 mg, 0.783 mmol) in dry cyclohexane (5 mL) was prepared in a 20 mL scintillation vial under an atmosphere of nitrogen. A separate solution of DBpin (1.30 g, 10.1 mmol) in cyclohexane (5 mL) was also prepared. The two solutions were combined and then transferred to a 10 mL reaction vessel fused to a vacuum adaptor. The red solution was sealed under 1 atm of nitrogen and irradiated at 10 °C for 24 h with a 450 W medium-pressure mercury arc lamp. The resulting clear brown solution was filtered through a plug of Darco G-60 activated carbon powder into a 100 mL round-bottom flask and then washed with dry pentane (2 × 10 mL). The clear light yellow solution was transferred to a sublimation apparatus, and the volatile materials were evaporated under reduced pressure to leave a yellow powder. Sublimation under dynamic vacuum at 40 °C removed C<sub>6</sub>Me<sub>6</sub> and left a tan powder. The crude material was purified by dissolving in pentane (10 mL) and passing the clear brown solution through a fresh plug of activated carbon powder. Removal of the pentane solvent under reduced pressure left 243 mg (0.478 mmol, 61%) of a light yellow powder. Compound 2-d<sub>17</sub> is stable under a nitrogen atmosphere at -35 °C for weeks but decomposes within an hour at room temperature. Microanalysis was not obtained due to the instability of the complex. <sup>1</sup>H NMR (C<sub>6</sub>D<sub>12</sub>) δ 1.11 (s, 24 H,

BO<sub>2</sub>(CH<sub>3</sub>)<sub>4</sub>). <sup>2</sup>H NMR (C<sub>6</sub>H<sub>12</sub>) δ 1.88 (s, 15 D, C<sub>5</sub>(CD<sub>3</sub>)<sub>5</sub>), -12.40 (br d, 2 D, <sup>1</sup>J<sub>Rh-D</sub> = 40.0 Hz, RhD). <sup>13</sup>C NMR (C<sub>6</sub>H<sub>12</sub>) δ 101.2 (C<sub>5</sub>(CD<sub>3</sub>)<sub>5</sub>), 82.2 (BO<sub>2</sub>C<sub>2</sub>(CH<sub>3</sub>)<sub>4</sub>), 25.2 (BO<sub>2</sub>C<sub>2</sub>(CH<sub>3</sub>)<sub>4</sub>), 10.0 (m, C<sub>5</sub>(CD<sub>3</sub>)<sub>5</sub>). <sup>11</sup>B NMR (C<sub>6</sub>H<sub>12</sub>) δ 40.2 (br s).

**Preparation of DBpin.** A solution of bis(η<sup>4</sup>-1,5-cyclooctadiene)-di-μ-methoxy-diiridium(I) ([Ir(cod)(OMe)]<sub>2</sub>) (78 mg, 0.12 mmol) and 4,4'-di-*tert*-butyl-2,2'-bipyridine (dtbpy) (79 mg, 0.30 mmol) in dry pentane (10 mL) was prepared in a 20 mL scintillation vial under an atmosphere of nitrogen. The clear green-brown solution was transferred to an oven-dried, 500 mL thick-walled reaction vessel equipped with a vacuum valve and containing a Teflon-coated magnetic stir bar. Bis(pinacolato)diboron (B<sub>2</sub>pin<sub>2</sub>) (11.21 g, 44.12 mmol) was subsequently added to the reaction vessel, followed by pentane (40 mL). The dark red solution containing solid B<sub>2</sub>pin<sub>2</sub> was degassed, then cooled with liquid nitrogen. Deuterium (22.9 mmol) was added to the reaction vessel from a calibrated gas bulb. The vessel was sealed and allowed to warm to room temperature. After stirring for 12 h at room temperature, the solid B<sub>2</sub>pin<sub>2</sub> was partially consumed. A second portion of deuterium (22.9 mmol) was added to the vessel, and the reaction mixture was stirred for another 12 h at room temperature to afford a clear, dark red solution. The solution was degassed, and the volatile contents were vacuum transferred to a 100 mL Schlenk flask equipped with a magnetic stir bar. The pentane solvent was removed via distillation under 1 atm of argon to afford a clear, colorless liquid (107–110 °C). Remaining impurities, such as (Bpin)<sub>2</sub>(μ-O), were removed by vacuum transfer of the deuterated pinacolborane (9.22 g, 71.47 mmol, 81%) into an oven-dried, 25 mL Schlenk bomb. Anal. Calcd for C<sub>6</sub>H<sub>12</sub>DBO<sub>2</sub>: C, 55.9; H, 10.9. Found: C, 56.3; H, 10.7. <sup>1</sup>H NMR (CD<sub>2</sub>Cl<sub>2</sub>) δ 1.24 (s, 12 H, DBO<sub>2</sub>(CH<sub>3</sub>)<sub>4</sub>). <sup>2</sup>H NMR (CH<sub>2</sub>Cl<sub>2</sub>) δ 3.8 (br q, 1D, <sup>1</sup>J<sub>B-D</sub> = 24 Hz, DBO<sub>2</sub>(CH<sub>3</sub>)<sub>4</sub>). <sup>13</sup>C NMR (CD<sub>2</sub>Cl<sub>2</sub>) δ 83.6 (DBO<sub>2</sub>C<sub>2</sub>(CH<sub>3</sub>)<sub>4</sub>), 25.0 (DBO<sub>2</sub>C<sub>2</sub>(CH<sub>3</sub>)<sub>4</sub>). <sup>11</sup>B NMR (CH<sub>2</sub>Cl<sub>2</sub>) δ 27.8 (t, <sup>1</sup>J<sub>B-D</sub> = 21 Hz).

**Determination of the Kinetic Isotope Effect.** Cp\*Rh(H)<sub>2</sub>(Bpin)<sub>2</sub> (2, 20.1 mg, 0.0407 mmol) and dodecahydrotriphenylene (5.0 mg, 0.0208 mmol) were weighed into an oven-dried 4 mL vial then dissolved with a equimolar mixture of *n*-octane (400 μL) and *n*-octane-d<sub>18</sub> (400 μL). The pale yellow solution was transferred to a 2 mL Schlenk bomb and sealed under nitrogen. The bomb was submerged in a 100 °C oil bath. At intervals of 2 h, the bomb was removed from the oil bath and quickly cooled by submersion in a ice-water bath. Under a nitrogen atmosphere, a 10 μL aliquot of the solution was removed, and the bomb was then resealed and placed back into the oil bath. Each aliquot was diluted with diethyl ether and then analyzed by GC and GC/MS analysis. The formation of *n*-octylBpin-d<sub>0</sub> and *n*-octylBpin-d<sub>17</sub> was determined by integration of the area of the material versus dodecahydrotriphenylene internal standard. The rate constant ratio *k*<sub>H</sub>/*k*<sub>D</sub> (100 °C) was determined to be 2.6 ± 0.1.

**Typical Procedure for the H/D Exchange of 2-d<sub>17</sub> and Alkanes.** In a glovebox containing a nitrogen atmosphere, complex 2-d<sub>17</sub> (15.6 mg, 0.0305 mmol) was placed into an oven-dried 4 mL vial and dissolved in 0.65 mL of neat alkane. The clear, pale yellow solution was transferred to a screw-capped NMR tube and sealed under 1 atm of nitrogen. The reaction was heated at 70 °C in the spectrometer probe and monitored by <sup>2</sup>H NMR spectroscopy every 10 min for 8 h. The increase of the <sup>2</sup>H NMR signal from deuterium in the alkane and the decrease of the <sup>2</sup>H NMR signal of 2-d<sub>17</sub> were determined by integration of the corresponding peaks in the <sup>2</sup>H NMR spectra. After heating for 8 h, the clear, dark brown solution was diluted with diethyl ether, and dodecane was added as a GC standard by syringe. The reaction mixture was analyzed by GC and GC/MS, and the yield of alkylboronate ester was determined.

**H/D Exchange of Decomposed 2-d<sub>17</sub> and *n*-Octane.** Complex 2-d<sub>17</sub> (15.4 mg, 0.0301 mmol) was pretreated by dissolving in 0.6 mL of dry cyclohexane-d<sub>12</sub> and heating the solution to 150 °C for 8 h in a 2 mL reaction vessel equipped with a vacuum valve. Prolonged heating resulted in the thermal decomposition of 2-d<sub>17</sub> into several, unknown Cp\*Rh complexes. The solvent was removed

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in vacuo, and the dark brown oil was redissolved in 0.6 mL of neat *n*-octane. The dark brown solution was transferred to a screw-capped NMR tube and sealed under 1 atm of nitrogen. The reaction was heated at 70 °C in the spectrometer probe and monitored by <sup>2</sup>H NMR spectroscopy every 10 min for 8 h. After heating for 8 h, the clear, dark brown solution was diluted with diethyl ether, and dodecane was added as a GC standard by syringe. No formation of *n*-octylboronate ester was detected by GC and GC/MS.

#### Competition Experiments between *n*-Octane and Cyclohexane.

In a glovebox with a nitrogen atmosphere, complex **2-d<sub>17</sub>** (15.5 mg, 0.0301 mmol) was placed into an oven-dried 4 mL vial and dissolved in an equimolar solution of cyclohexane (0.3 mL) and *n*-octane (0.4 mL). The clear, pale yellow solution was transferred to a screw-capped NMR tube and sealed under 1 atm of nitrogen. The reaction was heated at 70 °C in the spectrometer probe and monitored by <sup>2</sup>H NMR spectroscopy every 10 min for 8 h. The increase of the <sup>2</sup>H NMR signal from deuterium in the alkane and the decrease of the <sup>2</sup>H NMR signal of **2-d<sub>17</sub>** were determined by integration of the corresponding peaks in the <sup>2</sup>H NMR spectra. After heating for 8 h, the clear, dark brown solution was diluted with diethyl ether, and dodecane was added as a GC standard by syringe. The reaction mixture was then analyzed by GC, and the yield of *n*-octylboronate ester (0.0030 mmol) was calculated to be 10%.

**Typical Procedure for the Competition Experiments Using Alkyl-Substituted Cyclohexanes.** Complex **2-d<sub>17</sub>** (15.5 mg, 0.0301 mmol) was placed into an oven-dried 4 mL vial and dissolved in ethylcyclohexane (0.65 mL). The clear, pale yellow solution was transferred to a 2 mL reaction vessel equipped with a vacuum valve, then sealed under 1 atm of nitrogen. After heating at 70 °C for 8 h, the reacted solvent was vacuum transferred from the dark brown rhodium residue into a second reaction vessel. To determine the relative deuterium incorporation into the different C–H bonds of the ethylcyclohexane, a <sup>2</sup>H NMR spectrum of the reacted solvent was compared to the <sup>2</sup>H NMR spectrum of unreacted solvent by integrating relative to a capillary standard.

**Typical Procedure for the H/D Exchange of **2-d<sub>17</sub>** and *n*-Octane in the Presence of DBpin.** In a glovebox containing a nitrogen atmosphere, complex **2-d<sub>17</sub>** (15.5 mg, 0.0301 mmol) was placed into an oven-dried 4 mL vial. A 0.10 M solution of DBpin was prepared by diluting DBpin (10.0 μL, 0.068 mmol) with 0.66 mL of dry *n*-octane. The sample of **2-d<sub>17</sub>** was then

dissolved in 0.65 mL of the 0.10 M solution of DBpin in *n*-octane. The clear, pale yellow solution of **2-d<sub>17</sub>** was transferred to a screw-capped NMR tube and sealed under 1 atm of nitrogen. The reaction was heated at 70 °C in the spectrometer probe and monitored by <sup>2</sup>H NMR spectroscopy every 10 min for 8 h. The increase of the <sup>2</sup>H NMR signal from deuterium in *n*-octane, the decrease of the <sup>2</sup>H NMR signal of **2-d<sub>17</sub>**, and the increase of the <sup>2</sup>H NMR signal of trisboryl complex **3-d<sub>16</sub>** were determined by integration of the corresponding peaks in the <sup>2</sup>H NMR spectra. The reaction was repeated with 0.04, 0.23, 0.33, and 0.45 M solutions of DBpin in *n*-octane.

#### H/D Exchange of **2-d<sub>17</sub>** and *n*-Octane in the Presence of **B<sub>2</sub>pin<sub>2</sub>**.

In a glovebox containing a nitrogen atmosphere, complex **2-d<sub>17</sub>** (15.5 mg, 0.0301 mmol) was placed into an oven-dried 4 mL vial. A 0.05 M solution of **B<sub>2</sub>pin<sub>2</sub>** was prepared by dissolving **B<sub>2</sub>pin<sub>2</sub>** (7.6 mg, 0.030 mmol) with 0.66 mL of dry *n*-octane. The sample of **2-d<sub>17</sub>** was then dissolved in 0.65 mL of the 0.05 M solution of **B<sub>2</sub>pin<sub>2</sub>** in *n*-octane. The clear, pale yellow solution of **2-d<sub>17</sub>** was transferred to a screw-capped NMR tube and sealed under 1 atm of nitrogen. The reaction was heated at 70 °C in the spectrometer probe and monitored by <sup>2</sup>H NMR spectroscopy every 10 min for 8 h. The increase of the <sup>2</sup>H NMR signal from deuterium in *n*-octane, the decrease of the <sup>2</sup>H NMR signal of **2-d<sub>17</sub>**, and the increase of the <sup>2</sup>H NMR signal of trisboryl complex **3-d<sub>16</sub>** were determined by integration of the corresponding peaks in the <sup>2</sup>H NMR spectra.

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**Note Added after ASAP Publication.** The version published ASAP on February 1, 2010, had errors in Figures 2 and 3. The corrected version was published February 4, 2010.

**Supporting Information Available:** Optimized structures for the species discussed in the paper, tables and figures for H/D exchanges involving **2-d<sub>17</sub>**, and full ref 18. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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