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J. Am. Chem. Soc., **Just Accepted Manuscript** • Publication Date (Web): 08 Jun 2017

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Catalytic Dehydrogenative C-C Coupling by a Pincer-Ligated Iridium Complex

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Keywords: Dehydrogenative coupling, pincer-iridium complexes, C-C bond formation, diarylbutadienes, C-H activation.

Abstract

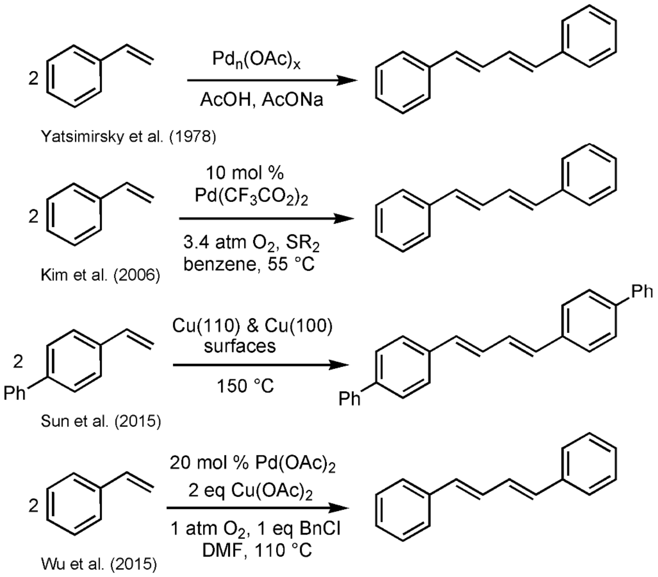
The pincer-iridium fragment (^{iPr}PCP)Ir (^{R}PCP = κ^3-2,6-$C_6H_3(CH_2PR_2)_2$) has been found to catalyze the dehydrogenative coupling of vinyl arenes to afford predominantly (*E*,*E*)-1,4-diaryl-1,3-butadienes. The eliminated hydrogen can undergo addition to another molecule of vinyl arene, resulting in an overall disproportionation reaction with one equivalent of ethyl arene formed for each equivalent of diarylbutadiene produced. Alternatively, sacrificial hydrogen acceptors (e.g. *t*-butylethylene) can be added to the solution for this purpose. Diarylbutadienes are isolated in moderate to good yields, up to ca. 90% based on the disproportionation reaction. The results of DFT calculations and experiments with substituted styrenes indicate that the coupling proceeds via double C-H addition of a styrene molecule, at β-vinyl and ortho-aryl positions, to give an iridium(III) metalloindene intermediate; this intermediate then adds a β-vinyl C-H bond of a second styrene molecule before reductively eliminating product. Several metalloindene complexes have been isolated and crystallographically characterized. In accord with the proposed mechanism, substitution at the ortho-aryl positions of the styrene precludes dehydrogenative homocoupling. In the case of 2,4,6-trimethylstyrene, dehydrogenative coupling of β-vinyl and ortho-methyl C-H bonds affords dimethylindene, demonstrating that the dehydrogenative coupling is not limited to C(sp^2)-H bonds.

1. INTRODUCTION

Carbon-carbon bond forming reactions are clearly among the most useful and important reactions in organic synthesis. Over the past several decades, transition metal complexes have revolutionized the ability to effect C-C bond formation. The majority of transition metal catalyzed systems for C-C bond formations require pre-activated substrates, including organometallic and/or organohalide species.[1-9] (Of course this applies even more so to non-transition-metal catalyzed C-C bond formations.) Significant progress has been made with respect to C-C bond formation between non-functionalized[10-14] alkanes, alkenes, and alkynes, with the dehydrogenative Heck (or Fujiwara-Moritani) reaction, an aryl-vinyl $C(sp^2)$-$C(sp^2)$ coupling, being perhaps the most well developed class of such reactions. However, these methodologies often require high to stoichiometric amounts of Pd species and/or oxidants, and the presence of directing groups, and often display poor selectivity and/or yields.[15-18] The few examples of C_{vinyl}-C_{vinyl} bond formation by double C_{vinyl}-H activation suffer from the same issues.[19]

Examples of the direct formation of C_{vinyl}-C_{vinyl} bonds by transition metal mediated dehydrogenative coupling of vinyl arenes to form specifically aryl substituted 1,3-butadienes are particularly quite limited. Scheme 1 depicts notable examples to date. In an early example, Yatsimirsky *et al.* studied the kinetics of stoichiometric dehydrogenative coupling of styrene by various palladium(II) acetate species in glacial acetic acid.[20] Much later, in 2006 the formation of 1,4-diphenyl-1,3-butadiene was identified by Kim *et al.* as a component (up to 53%) in the product mixture resulting from Fujiwara-Moritani coupling between benzene and styrene using $Pd(CF_3CO_2)_2$ as catalyst in the presence of thioether type ligands and 3.4 atm O_2.[21] Recently, 4-vinylbiphenyl was shown to undergo dehydrogenative coupling when deposited as a monolayer on copper surfaces;[22] however, the coupled product was only observed *in situ*. Also in 2015, the dehydrogenative coupling of various vinyl arenes was reported in up to 66% yield using $Pd(OAc)_2$ as catalyst (20 mol %) and $Cu(OAc)_2$ as oxidant under 1 atm O_2.[23] In addition, the reaction required one equivalent of benzyl chloride.

Scheme 1. Reported examples of dehydrogenative coupling of vinyl arenes



Although iridium has played a leading role in the development of stoichiometric C-H bond activation,[24] as well as catalytic C-H bond functionalization,[25,26] particularly alkane dehydrogenation,[27,28] there are surprisingly few examples of iridium-catalyzed dehydrogenative couplings of C-H bonds. Intramolecular ligand-based C(sp^3)-H couplings forming new C=C double bonds,[29,30] and several inter- and intramolecular couplings to form heterocycles[31,32] and fluorenols[33] have been reported. In the present work, we report the efficient dehydrogenative coupling of vinyl arenes to form (*E*,*E*)-1,4-diaryl-1,3-butadienes catalyzed by the reactive (^{iPr}PCP)Ir fragment. In addition we demonstrate efficient catalytic intramolecular C(sp^3)-C(sp^2) dehydrogenative coupling. These results indicate that the established ability of pincer-ligated iridium complexes to effect both C-H addition and C-C bond coupling[34] can be integrated into productive catalytic dehydrogenative coupling reactions that do not require the use of an oxidizing agent.

2. EXPERIMENTAL RESULTS

2.1. Catalytic intermolecular coupling by (^{iPr}PCP)Ir. Pincer-ligated iridium fragments (^{R}PCP)Ir have been reported to undergo facile and rapid addition of aryl and vinyl C-H bonds at room temperature,[35] (Scheme 2) as well as catalyzing alkane dehydrogenation. More recently, we have also reported the *double* C-H activation of biphenyl and phenanthrene to form iridacycles at (^{R}PCP)Ir with concomitant release of H_2.[36,37] In addition we have demonstrated that (^{R}PCP)IrRR' complexes can undergo relatively facile C-C bond reductive elimination[34] and, conversely, (^{R}PCP)Ir fragments can oxidatively add strained C-C bonds.[38] With this in mind, we have attempted to determine whether these stoichiometric reactions could be employed in catalytic dehydrogenative C-C bond coupling reactions as indicated in Scheme 2.

Scheme 2. **Simplified catalytic cycle for dehydrogenative coupling by (^{R}PCP)Ir proceeding via C-H addition to yield an Ir(III) hydrocarbyl hydride followed by a second C-H addition to the Ir(III) species**

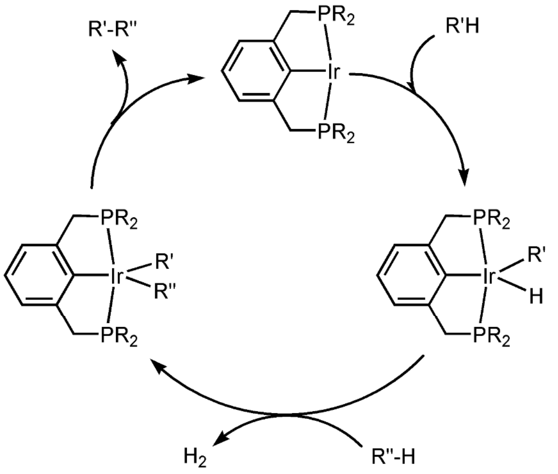
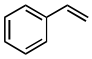
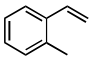
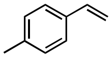
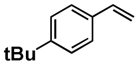
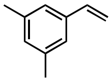
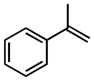
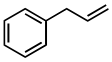
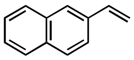
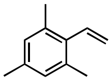
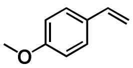
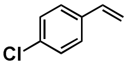
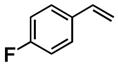
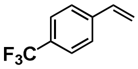
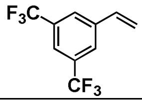
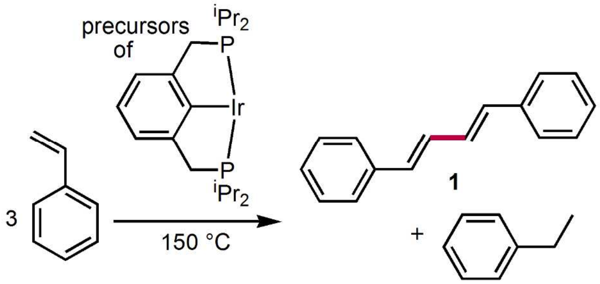


Table 1. Catalytic dehydrogenative coupling of vinyl arenes to form diarylbutadienes at 150 °C

Entry	Substrate	Catalyst Precursor (% loading)	time	Conversion (%)[a]	Yield (%)[b]
1		(^{iPr}PCP)IrHCl (5%)[c]	24 h	92	70[e], 77[f]
		(^{iPr}PCP)Ir(C_2H_4) (1%)[d]	72 h	96	92[g], 83[e]
2		(^{iPr}PCP)IrHCl (5%)[c]	24 h	98	48[e]
		(^{iPr}PCP)Ir(C_2H_4) (1%)[d]	72 h	94	88[g], 81[e]
3		(^{iPr}PCP)Ir(C_2H_4) (1%)[d]	72 h	93	82[e]
4		(^{iPr}PCP)Ir(C_2H_4) (1%)[d]	96 h	92	88[g], 80[e]
5		(^{iPr}PCP)Ir(C_2H_4) (2%)[d]	120 h	43	31[g], 26[e]
6		(^{iPr}PCP)IrHCl (5%)[c]	24 h	9	trace[h]
7		(^{iPr}PCP)IrHCl (5%)[c]	24 h	82	0[i]
8		(^{iPr}PCP)IrHCl (5%)[c]	24 h	98	55[e]
9		(^{iPr}PCP)Ir(C_2H_4) (1%)[d]	48 h	95	0 (93)[j]
10		(^{iPr}PCP)IrHCl (5%)[c]	24 h	76	50[e]
		(^{iPr}PCP)Ir(C_2H_4) (1%)[d]	158 h	67	58[e]
11		(^{iPr}PCP)IrHCl (5%)[c]	24 h	20	~ 16[k]
12		(^{iPr}PCP)Ir(C_2H_4) (1%)[d]	145 h	88	75[g], 67[e]
13		(^{iPr}PCP)Ir(C_2H_4) (1%)[d]	145 h	90	70[g], 60[e]
14		(^{iPr}PCP)Ir(C_2H_4) (1%)[d]	120 h	36	13[g], 7[e]

(a) Percent disappearance of substrate. (b) Yields based on assumption of one equiv ethylbenzene produced for each equiv diarylbutadiene formed; all diarylbutadiene mixtures are > 90% *E,E* isomer and ca. 5 – 9% *E,Z* isomer. (c) (^{iPr}PCP)IrHCl, 2 equiv KO^{t}Bu, 654 mM substrate in toluene. (d) (^{iPr}PCP)Ir(C_2H_4), 500 mM substrate in *p*-xylene-d_{10}. (e) Isolated yield. Entries 1, 2, 8, and 10 are yields of purified *E,E* isomer only. (f) Yield determined by GC-MS, dodecane standard. (g) Yield determined by ^{1}H NMR spectroscopy. (h) Identified by GC-MS, dodecane standard. (i) Only isomerization to form 1-phenyl-1-propene was observed. (j) 93% yield of 4,6-dimethylindene. (k) Extensive hydrogen/halogen exchange, total yield mixed halogenated coupling products, yield estimated by GC-MS, dodecane standard.

A solution of styrene (0.654 M) in toluene containing 5 mol % (^{iPr}PCP)IrHCl and 2 equivalents KO^{t}Bu (based on Ir) was heated at 150 °C in a sealed ampoule, with stirring, for 24 h. It is presumed that the KO^{t}Bu reacts with (^{iPr}PCP)IrHCl to generate the reactive fragment (^{iPr}PCP)Ir.[39] In accord with the hypothesis indicated above, (*E*,*E*)-1,4-diphenyl-1,3-butadiene (**1**) was observed as one of two major organic products as indicated by GC-MS and ^{1}H NMR spectroscopy, in comparison with an authentic sample (Entry 1, Table 1). (*E*,*Z*)-1,4-diphenyl-1,3-butadiene was also observed, at a concentration less than ca. 10% of the *E*,*E* isomer, in this reaction as well as in the reactions of the various styrene derivatives that yield dehydrogenative coupling product (discussed below). The other major product was ethylbenzene, resulting from the hydrogenation of styrene (eq 1). Thus the reaction is a disproportionation wherein one equivalent of styrene is hydrogenated to form ethylbenzene for each equivalent of **1** produced. In the absence of (^{iPr}PCP)IrHCl, under otherwise identical conditions (including the presence of KO^{t}Bu), the formation of **1** was not observed.



(1)

(^{iPr}PCP)Ir(C_2H_4)[40] was also found to be an effective precatalyst for dehydrogenative coupling, presumably yielding the active (^{iPr}PCP)Ir fragment by dissociation of ethylene without the need for base or other activating agents. Our typical protocol with this precatalyst used 1 mole % (^{iPr}PCP)Ir(C_2H_4) with respect to substrate, in *p*-xylene-d_{10} heated at 150 °C (entry 1, Table 1). The (^{iPr}PCP)Ir catalyst was found to tolerate various substituents at the para-position of the aryl ring, including methyl, *t*-butyl, trifluoromethyl, methoxy, and fluorine, (Table 1, entries 3, 4, 10, 12, and 13) although conversions were lowered in some cases, perhaps due to C-H activation at the position ortho to the substituent.[41] 2-vinylnaphthalene (entry 8) was also converted to the corresponding dimer. Functional groups at the para position that are known to react with (PCP)Ir derivatives, such as C-Cl bonds (entry 11) or ester groups,[42,43] as well as a diphenylphosphino group, prevented catalytic coupling. Vinylferrocene and 2-vinylpyridine also proved incompatible, affording low conversions or complicated product mixtures.

Substitution with a methyl group at only one of the styrene ortho positions did not significantly inhibit the reaction (Table 1, entry 2). Substitution at the vinylic positions, however, severely limited coupling. α-Methylstyrene (entry 6) and 1-phenylpropene (β-methylstyrene) afforded no more than trace amounts of coupling product. Allylbenzene also did not produce observable coupling products (entry 7); instead, only isomerization to form 1-phenylpropene was observed.

The use of sacrificial hydrogen acceptors, *t*-butylethylene (TBE), norbornene (NBE), ethylene and propene was investigated as a means of achieving coupling without loss of an equivalent of styrene. The formation of ethylbenzene by-product (Table 2) was thereby indeed significantly decreased and the amount of 1,4-diphenylbutadiene produced was increased (entries 2, 3, 5-8). However, unidentified products, some possibly attributable to cross-coupling between styrene and the acceptor alkene, were also detected, particularly in the case of norbornene.

Table 2. Catalytic dehydrogenative coupling of styrene to form 1,4-diphenylbutadiene in the presence of added hydrogen acceptors at 150 °C

Entry	Catalyst Precursor (% loading)	Acceptor	time	Conversion (%)[a]	[ethylbenzene]	[diphenyl-butadiene]
1	(^{iPr}PCP)IrHCl (5%)[b]	none	24 h	92	241 mM[d]	168 mM[d]
2	(^{iPr}PCP)IrHCl (5%)[b]	TBE	24 h	80	126 mM[d]	190 mM[d]
3	(^{iPr}PCP)IrHCl (5%)[b]	NBE	24 h	78	54 mM[d]	183 mM[d]
4	(^{iPr}PCP)Ir(C_2H_4) (1%)[c]	none	72 h	96	151 mM[e]	153 mM[e]
5	(^{iPr}PCP)Ir(C_2H_4) (1%)[c]	TBE (500 mM)	72 h	87	57 mM[e]	184 mM[e]
6	(^{iPr}PCP)Ir(C_2H_4) (1%)[c]	NBE (500 mM)	72 h	82	37 mM[e]	181 mM[e]
7	(^{iPr}PCP)Ir(C_2H_4) (1%)[c]	ethylene (1.5 atm)	72 h	79	12 mM[e]	187 mM[e]
8	(^{iPr}PCP)Ir(C_2H_4) (1%)[c]	propene (1.5 atm)	72 h	85	40 mM[e]	187 mM[e]

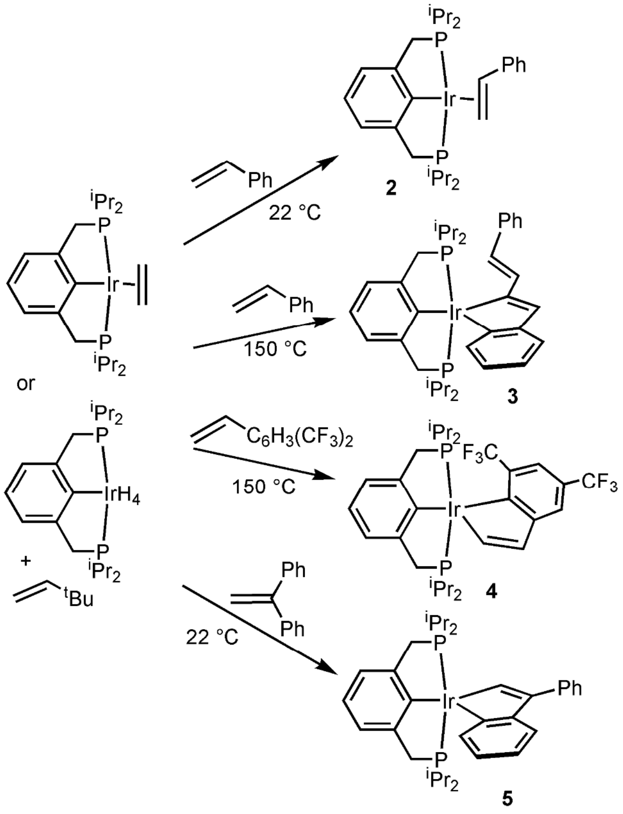
(a) Percent disappearance of substrate. (b) (^{iPr}PCP)IrHCl, 2 equiv KO^{t}Bu, 654 mM styrene in toluene. (c) (^{iPr}PCP)Ir(C_2H_4), 500 mM styrene in *p*-xylene-d_{10}. (d) Determined by GC-MS, dodecane standard. (e) Determined by ^{1}H NMR spectroscopy.

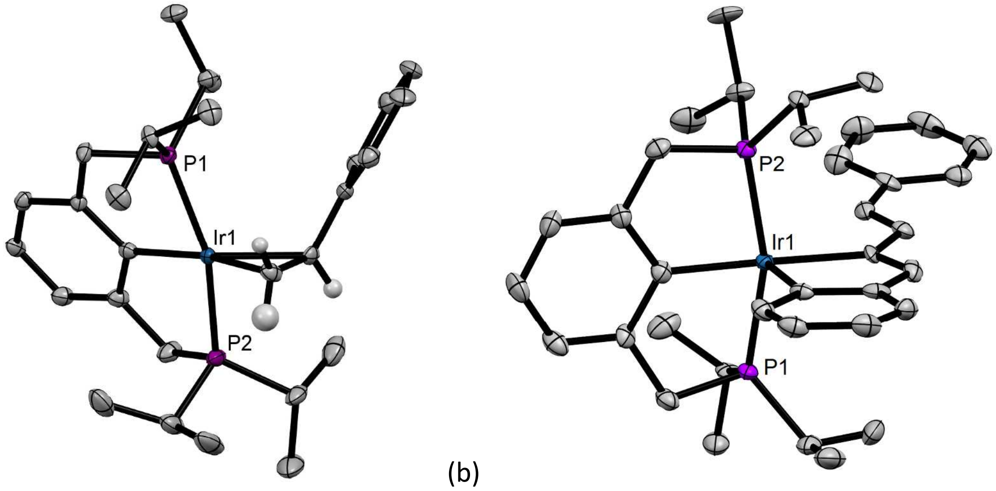
The formation of almost exclusively the (*E,E*)-stereoisomer of 1,4-diphenyl-1,3-butadiene is noteworthy. GC-MS revealed that an additional species with the same mass and very similar GC retention time as the major (*E,E*) product, presumably the (*E,Z*) isomer, was present in all reaction samples in low concentration (ca. 7% of the (*E,E*) isomer concentration).

We considered the possibility that the (*E,Z*) isomer was actually a major kinetic product but underwent isomerization to the more thermodynamically stable (*E,E*) isomer. To assess this possibility, a mixture of (*E,E*) and (*E,Z*)-diphenylbutadiene (approximately 40:60) was independently generated[44] and was then used to prepare a toluene solution 0.2 M in total 1,4-diphenyl-1,3-butadienes. When samples of this solution were heated at 150 °C for 24 hours in the presence of KO^{t}Bu/(^{iPr}PCP)IrHCl, almost all (*E,Z*) isomer was converted to the (*E,E*) isomer, along with some formation of diphenylbutene and diphenylbutane (see SI). In the absence of (^{iPr}PCP)IrHCl, under otherwise identical conditions, no isomerization was observed. Thus the observation of predominantly (*E,E*) product in the coupling reaction does not indicate that this isomer is the major kinetic product.

Dehydrogenation of (^{iPr}PCP)IrH_4 with TBE in toluene solution at room temperature, followed by addition of styrene gives nearly quantitative conversion to a single product with a chemical shift of δ 45.7 ppm in the ^{31}P NMR spectrum (see SI); this is also the major signal observed at early times in the ^{31}P NMR spectrum during styrene coupling catalyzed by (^{iPr}PCP)Ir(C_2H_4). Removal of volatiles by vacuum and subsequent crystallization from pentane at -17 °C provided crystals suitable for X-ray diffraction, which allowed assignment as the styrene π-adduct (^{iPr}PCP)Ir(η^2-CH_2=CHC_6H_5) (**2**), shown in Figure 1a (Scheme 3).

Scheme 3. Reactions of (^{iPr}PCP)Ir with styrenes

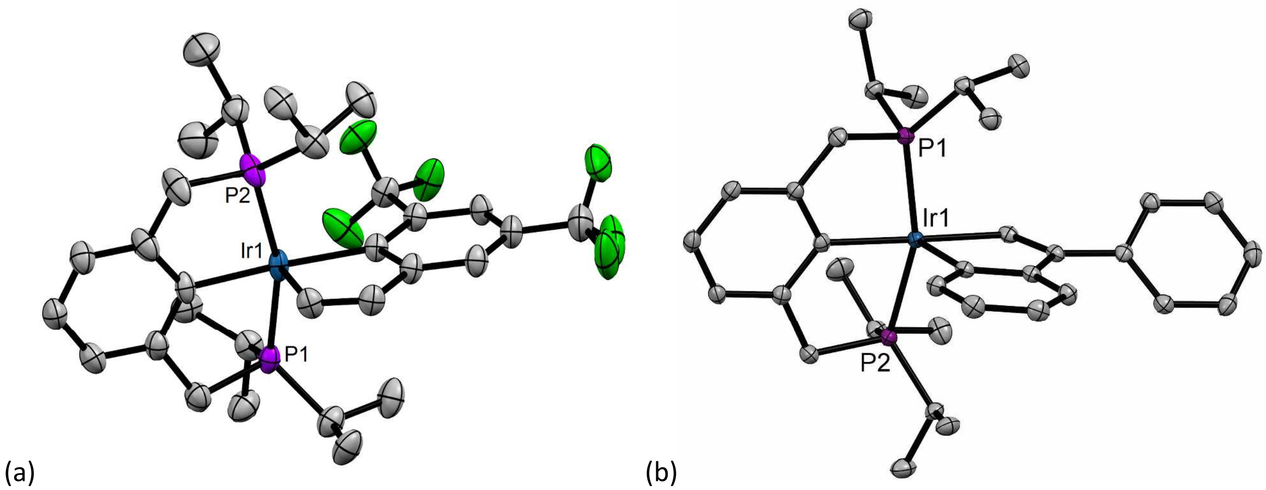




(a) (b)

Figure 1. ORTEP representations (50% probability ellipsoids) of (a) (^{iPr}PCP)Ir(η^2-styrene) (**2**) and (b) metalloindene complex **3**. (Hydrogen atoms omitted for clarity except vinylic H atoms of styrene in **2**.)

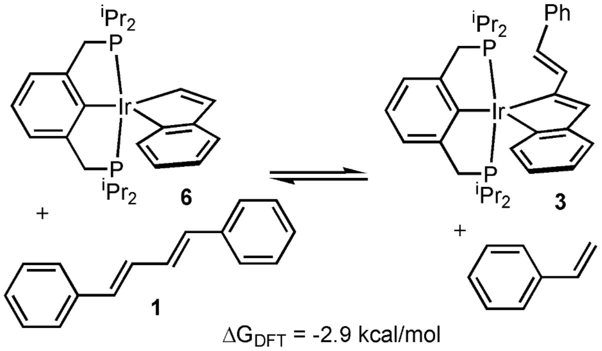
After 20 h at 150 °C, ^{1}H NMR and ^{31}P NMR spectroscopy of a toluene solution of (^{iPr}PCP)Ir(C_2H_4) and styrene revealed that the major iridium-containing species present was a complex with C_s symmetry (equivalent P nuclei and four sets of inequivalent *i*-Pr methyl groups). The ^{1}H NMR spectrum was consistent with that expected for the metalloindene complex **3** (Scheme 3, see SI) presumably formed by addition of β-vinyl and ortho aryl C-H bonds of **1** to an (^{iPr}PCP)Ir fragment. Crystals were obtained from a reaction solution, and X-ray diffraction confirmed this assignment (Figure 1b). Under the same conditions, a toluene solution of diphenylbutadiene **1**, (^{iPr}PCP)Ir(C_2H_4), and TBE gave the same product (**3**), as indicated by ^{1}H NMR and ^{31}P NMR. In addition to metalloindene **3**, two other (^{iPr}PCP)Ir metalloindenes, obtained from reactions of substituted styrenes with precursors of the (^{iPr}PCP)Ir fragment, have been characterized. The reaction of (^{iPr}PCP)Ir(C_2H_4) with 3,5-bis-trifluoromethylstyrene at 150 °C afforded the corresponding metalloindene, **4** (Scheme 3). Crystals were obtained by recrystallization in hexane at -40 °C, and the structure (of what appears to be the *n*-hexane solvate) was obtained by X-ray diffraction (Figure 2a). It has previously been reported that the presence of an ortho-trifluoromethyl group greatly stabilizes (PCP)Ir(aryl)H;[41,45] the apparently greater stability of **4** as compared with its unsubstituted analogue presumably derives from the same or closely related factors. In addition, dehydrogenation of (^{iPr}PCP)IrH_4 with TBE followed by addition of 1,1'-diphenylethylene in toluene (see SI) also affords a stable metalloindene (**5**) as determined by ^{1}H and ^{31}P NMR as well as single crystal X-ray diffraction (Figure 2b, Scheme 3). In contrast to **4**, formation of **5** does not require heating, perhaps because the very crowded styrene derivative 1,1'-diphenylethylene does not allow formation of a relatively stable π-adduct.



(a) (b)

Figure 2. ORTEP representations (50% probability ellipsoids) of metalloindene complex **4** (a) and **5** (b).

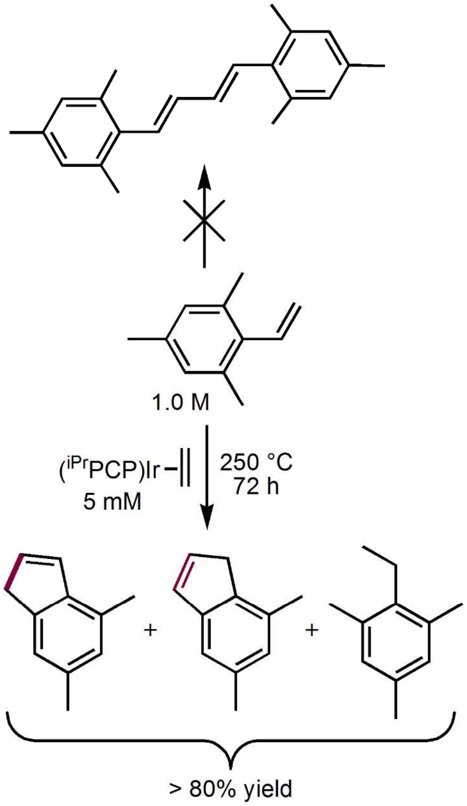
Complex **3** (along with complex **2**) is a major species present in solution even after only 1 h of thermolysis, at which time less than 50% of the styrene has undergone conversion to **1**. It may seem surprising that the parent (unsubstituted) (^{iPr}PCP)Ir metalloindene, **6**, is not observed under the same conditions. The results of DFT calculations (discussed in full in Section 3, below), however, explain the failure to observe **6** under the same conditions that allow observation of **3**. Formation of **3**, from **1** and (^{iPr}PCP)Ir, is calculated to be 2.9 kcal/mol more favorable than formation of **6** from styrene and (^{iPr}PCP)Ir. This corresponds to an equilibrium value greater than 30 for eq 2, suggesting that **6** would not be observable in the presence of a significant concentration of **1** (assuming that the formation of **3** from the reaction of **1** is kinetically facile, even if it is less rapid than formation of **6** from reaction of styrene). Moreover, since complexes **2** and **3** are present in comparable concentrations in the presence of **1**, this suggests, in accord with observation, that before significant concentrations of **1** (or **3**) are formed, the only major species present at very early reaction times would be the π-styrene complex **2**.



(2)

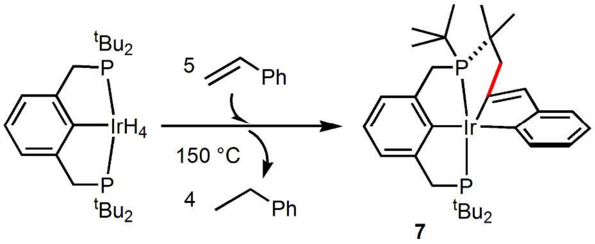
2.2. Catalytic intramolecular coupling by (^{iPr}PCP)Ir. Surprisingly, in contrast with the fairly efficient coupling observed with *p*-substituted or mono-ortho substituted substrates, no diarylbutadiene coupling product was observed from the reaction of 2,4,6-trimethylstyrene. Instead, however, intramolecular C(sp^3)-C(sp^2) coupling was achieved, with >80% yield (87% total conversion) giving two major dehydrogenative coupling products, 4,6-dimethylindene and 5,7-dimethylindene, as well as 2-ethylmesitylene (Scheme 4). The identity of the dimethylindenes was determined by ^{1}H and ^{13}C NMR spectroscopy and GC-MS. Further support for their assignment was obtained by Pd-catalyzed hydrogenation of the mixture which gave a single major product, 4, 6-dimethylindane, also assigned on the basis of ^{1}H and ^{13}C NMR and GC-MS (see SI).

Scheme 4. Intramolecular C(sp^3)-C(sp^2) dehydrogenative coupling catalyzed by (^{iPr}PCP)Ir



2.3. Stoichiometric reactions of (^{tBu}PCP)Ir with styrenes. In contrast to the ^{iPr}PCP analogs, no catalysis was obtained with the more crowded pincer-iridium species (^{tBu}PCP)Ir. The reaction of

(^{tBu}PCP)IrH_4 (20 mM) with styrene (120 mM) at 150 °C for 6 h instead resulted in the formation of a metalloindene species, **7**, in 80% yield (by ^{1}H NMR), which may be described as the product of dehydrogenative coupling of a phosphino-*t*-butyl methyl group and a molecule of styrene, plus C-H addition of the styrene β-vinyl and ortho-aryl C-H bonds (eq 3). Crystals were obtained by recrystallization in hexane at -40 °C, and X-ray diffraction revealed the structure shown in Figure 3.



(3)

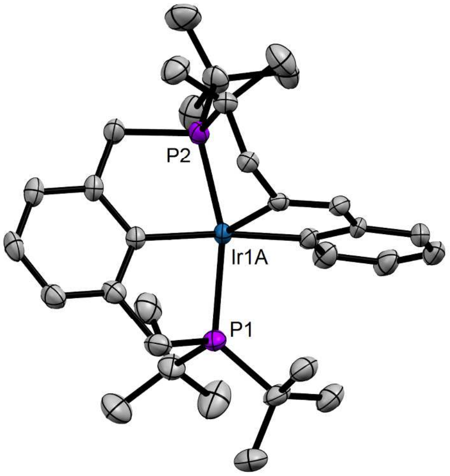
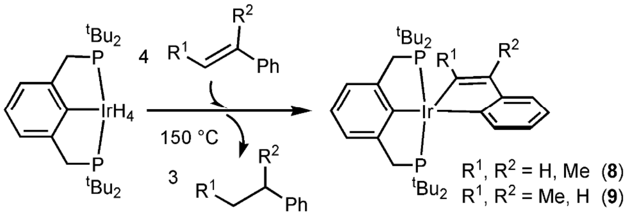


Figure 3. ORTEP representation of complex **7** (50% probability ellipsoids)

With either α-methylstyrene or β-methylstyrene, the reaction of (^{tBu}PCP)IrH_4 at 150 °C gave the simple metalloindene complexes (eq 4, complexes **8** and **9**, respectively) resulting from C-H addition of the β-vinyl and ortho-aryl C-H bonds of the respective uncoupled styrene (and presumably hydrogenation of another molecule of styrene). The iridium-containing products were identified by ^{1}H and ^{31}P NMR spectroscopy of the reaction solutions, as well as single-crystal X-ray diffraction (Figure 4).



(4)

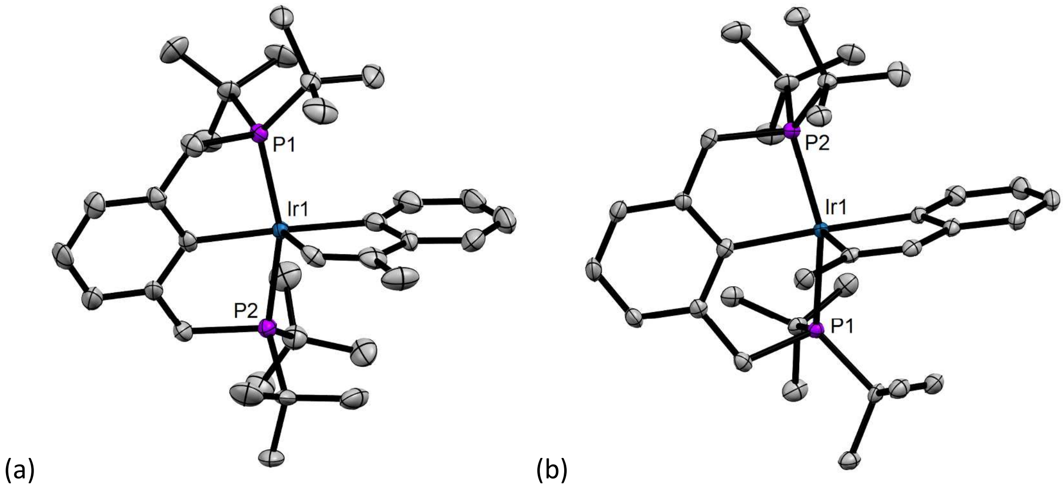


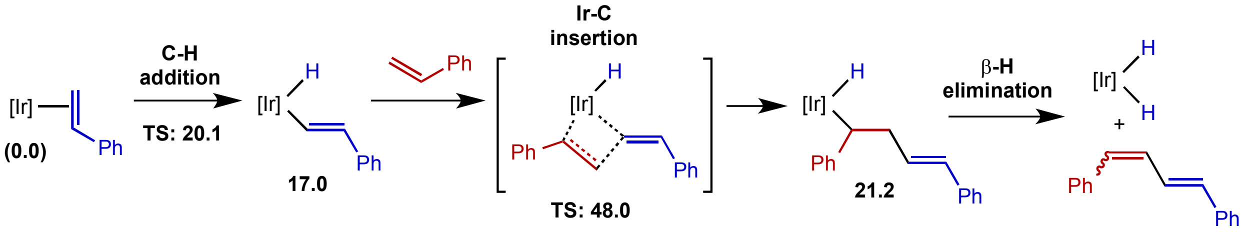
Figure 4. ORTEP representation of products of reaction of (^{iPr}PCP)Ir(C_2H_4) with (a) α-methylstyrene, **8**, and (b) β-methylstyrene, **9** (50% probability ellipsoids).

Thus it is seen that both (^{iPr}PCP)Ir and (^{tBu}PCP)Ir fragments have a strong tendency to react with vinyl arenes to form metalloindenes (complexes **3**, **4**, **5**, **7**, **8**, **9**). It appears likely that the greater steric bulk of the *t*-Bu groups mitigates the reactivity of the (^{tBu}PCP) complexes, facilitating their isolation.

3. DFT CALCULATIONS AND MECHANISTIC DISCUSSION

3.1. Double bond insertion mechanisms. A priori, several possible mechanisms for the tail-to-tail coupling reactions (Scheme 5) can be envisaged. In general, olefin dimerization probably proceeds most commonly via insertion of an olefin into a metal-carbon bond. The 14e fragments (^{R}PCP)Ir have been well established to oxidatively add C-H bonds, including the addition of a *trans*-β-C-H bond of a terminal olefin[35] to give observable 16e products. Addition of the styrene *trans*-β-C-H bond, followed by 2,1-insertion of a second styrene molecule into the resulting Ir-C bond, and then β-H elimination (which is known to be facile for (^{iPr}PCP)Ir(alkyl)H) would give the observed diphenylbutadiene (Scheme 5). Insertion of double bonds into Ir-C bonds, and metal-vinyl bonds more generally, however, is relatively rare.

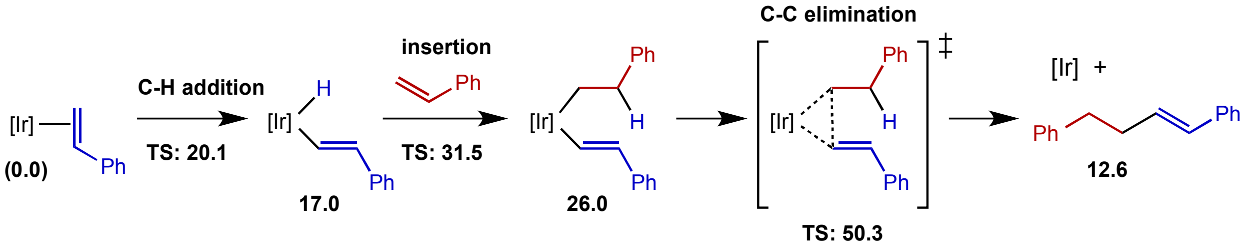
Scheme 5. Dehydrogenative styrene coupling via C-H addition and insertion into the resulting Ir-C bond; calculated pathway with free energies (150 °C; kcal/mol)



DFT calculations (see Computational Section for details) indicate that the kinetics of styrene β-vinylic C-H addition to (^{iPr}PCP)Ir are facile (in accord with experimental results with C-H addition of TBE to (^{tBu}PCP)Ir[35]), giving an oxidative addition product calculated to be 17.0 kcal/mol higher in free energy than the isomeric styrene π-adduct. Following C-H addition, however, coordination of a second molecule of styrene is endoergic by 0.8 kcal mol and insertion of its double bond into the Ir-vinyl bond is calculated to have a very high barrier, $\Delta G^{\ddagger}$ = 30.2 kcal/mol. The computed TS (transition state) for insertion is thus 48.0 kcal/mol above the resting state free energy, arguing against the likelihood of such a mechanism.

Insertion of olefins into Ir-H bonds is much more facile than insertion into Ir-C bonds. Styrene insertion into the Ir-H bond of the C-H addition product (^{iPr}PCP)Ir(H)(CH=CHPh) yields (^{iPr}PCP)Ir(CH_2CH_2Ph)(CH=CHPh) (Scheme 6); the styrene insertion TS and product are calculated to be 31.5 kcal/mol and 26.0 kcal/mol above the π-styrene complex, respectively, presenting a substantial but not prohibitively high barrier. However, C-C elimination from this complex has a calculated barrier of $\Delta G^{\ddagger}$ = 24.3 kcal/mol and thus a prohibitively high-energy TS, 50.3 kcal/mol above the resting state. (Moreover, the monoene resulting from such a reaction would need to undergo subsequent dehydrogenation to give the observed diphenylbutadiene.) Our electronic structure calculations therefore argue strongly against this pathway.

Scheme 6. Dehydrogenative styrene coupling via C-H addition and insertion into Ir-H bond; calculated pathway with free energies (150 °C; kcal/mol)



3.2. A “direct” coupling mechanism. We have previously demonstrated that 16e Ir(III) complexes such as (^{R}PCP)IrH_2[46] and (^{R}PCP)Ir(CCPh)(H)[47] will undergo addition of C-H bonds. Further, we have shown that C-C bond reductive elimination from complexes (PCP)IrRR’ can be relatively favorable for C(sp^2)-bound R groups.[34,47] Thus, there is good precedent for a mechanism involving initial oxidative addition of a styrene *trans*-β vinylic C-H bond to (^{iPr}PCP)Ir, followed by addition of the same bond of a second styrene molecule to the resulting Ir(III) center; subsequent loss of H_2 and then C-C elimination would afford the coupled product (Figure 5). We will refer to this as the “direct” coupling pathway (to distinguish it from a more indirect pathway, proposed later, which also involves vinylic C-H additions to Ir(I) and Ir(III), and subsequent loss of H_2 followed by C-C elimination).

Following the same C-H addition to (^{iPr}PCP)Ir(I) that was considered in the pathways discussed above, C-H addition of a second molecule of styrene is calculated to proceed via a TS that is clearly Ir(V) in character (Figure 5); the Ir-H distances (1.62 Å and 1.66 Å) are typical of stable Ir hydrides, the C-H bond is essentially fully cleaved ($d_{C\text{-}H}$ = 1.59 Å), and the H-H distance (1.68 Å) is greater than that of even an elongated dihydrogen complex.[48] This second C-H addition step is calculated to have a free energy barrier of $\Delta G^{\ddagger}$ = 25.8 kcal/mol, arising from a very small activation enthalpy, $\Delta H^{\ddagger}$ = 5.1 kcal/mol, and a very unfavorable activation entropy, $\Delta S^{\ddagger}$ = -49 eu ($-T\Delta S^{\ddagger}$ = 20.7 kcal/mol). Although the crowded TS has largely Ir(V) character, it does not lead to an Ir(V) intermediate, but rather to an Ir(III) dihydrogen complex (**10•H₂**, $d_{H\text{-}H}$ = 0.85 Å). Periana has termed processes that proceed through such TSs without a net change in oxidation state as Oxidative Hydrogen Migrations.[49,50]

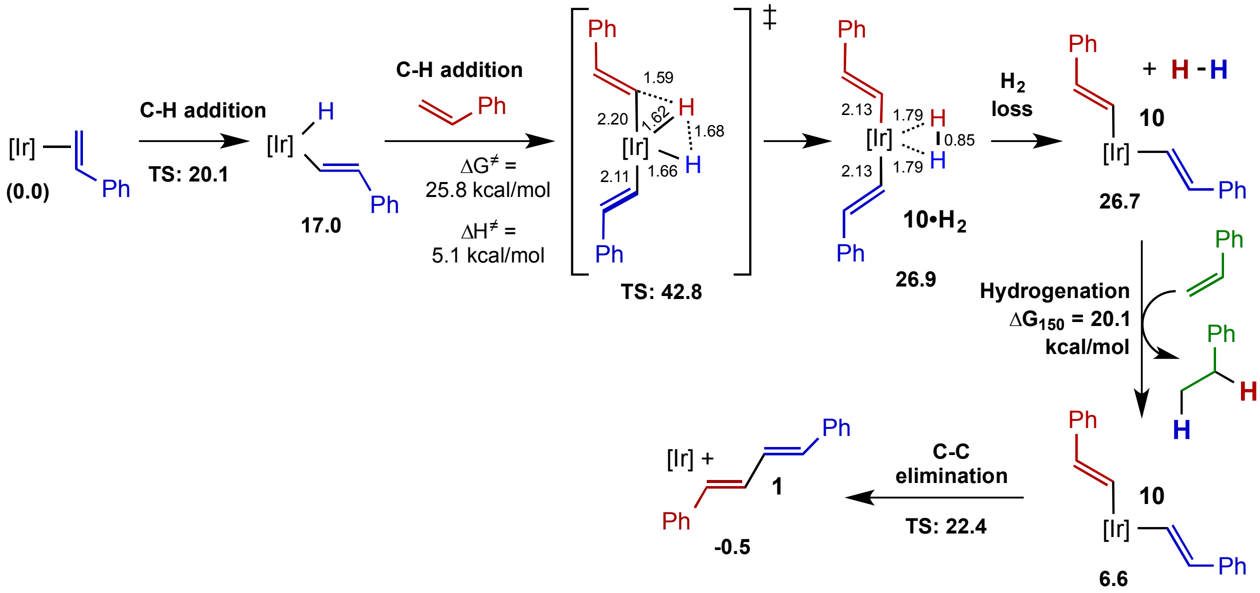


Figure 5. Dehydrogenative styrene coupling via consecutive vinylic C-H additions followed by loss of H_2, olefin hydrogenation and C-C elimination. Calculated pathway with free energies (150 °C; kcal/mol) and selected internuclear distances (Å) indicated.

The next step in this pathway would be loss of H_2 from **10•H₂** to afford products (^{iPr}PCP)Ir(CH=CHPh)$_2$ (**10**) and H_2, which have a free energy 26.7 kcal/mol above the π-styrene complex. Hydrogenation of another molecule of styrene (indicated in green in Figure 5) is likely to be very rapid on the overall time-scale of this reaction, and certainly more rapid than the back reaction with **10** which would be present in an extremely small concentration. The free energy of the resulting products, **10** plus PhEt, is 6.6 kcal/mol above that of complex **2** plus two molecules of free styrene. C-C reductive elimination from **10** would afford the observed coupling product, *E,E*-1,4-diphenylbutadiene.

Thus, the calculated overall barrier to the pathway of Figure 5 is 42.8 kcal/mol, assuming that C-H addition of the second styrene molecule is rate-determining. Although this is less than the barriers to the insertion mechanisms discussed above, it is significantly greater than the barrier that would be inferred from the very approximately determined rate of styrene coupling (ca. 3 x 10^{-4} s^{-1}), $\Delta G^{\ddagger} \sim 32$ kcal/mol.

Perhaps arguing against the mechanism of Figure 5 even more strongly than the calculated barrier is a combination of experimental results and DFT calculations with 2,4,6-trimethylstyrene as the substrate. As discussed in the experimental section above, the presence of *o*-methyl groups completely inhibited the tail-to-tail dimerization reaction. Based only on cursory consideration of the structures shown in Figure 5, such a result would probably not be expected. Indeed the DFT calculations predict that the overall barrier to tail-to-tail dimerization via the mechanism of Figure 5 is *lower* for 2,6-dimethylstyrene by 4.4 kcal/mol than for styrene (this is attributable to the lower binding energy of the π-olefin complex of the sterically hindered olefin in the π-olefin complex, not to any advantage conferred by the methyl groups to the TS (see SI for details)).

3.3. Metalloindene mechanism. Figure 6 shows our proposed pathway for the tail-to-tail coupling of styrene. Like the coupling mechanisms considered above (Schemes 5 and 6, and Figure 5), the proposed initial in-cycle step is addition of a styrene β-vinyl C-H bond but in this case it is addition of the β-C-H bond that is *cis* to the phenyl group. This is kinetically and thermodynamically less favorable than addition trans to phenyl ($\Delta\Delta G^{\ddagger}$ = 4.4 kcal/mol and $\Delta\Delta G$ = 0.5 kcal/mol, respectively) but the overall predicted barrier ($\Delta G^{\ddagger}$ = 24.5 kcal/mol) is certainly not prohibitive. Subsequent intramolecular addition of a styrenyl *o*-C-H bond is calculated to have a low barrier: $\Delta G^{\ddagger}$ = 8.9 kcal/mol and $\Delta H^{\ddagger}$ = 7.8 kcal/mol. As in the case of the vinylic C-H bond addition to (^{iPr}PCP)Ir(CH=CHPh)(H) (Figure 5), the C-H addition to this Ir(III) center proceeds via a TS that is essentially Ir(V) in character, to give an Ir(III) metalloindene dihydrogen complex, **6•H$_2$**.

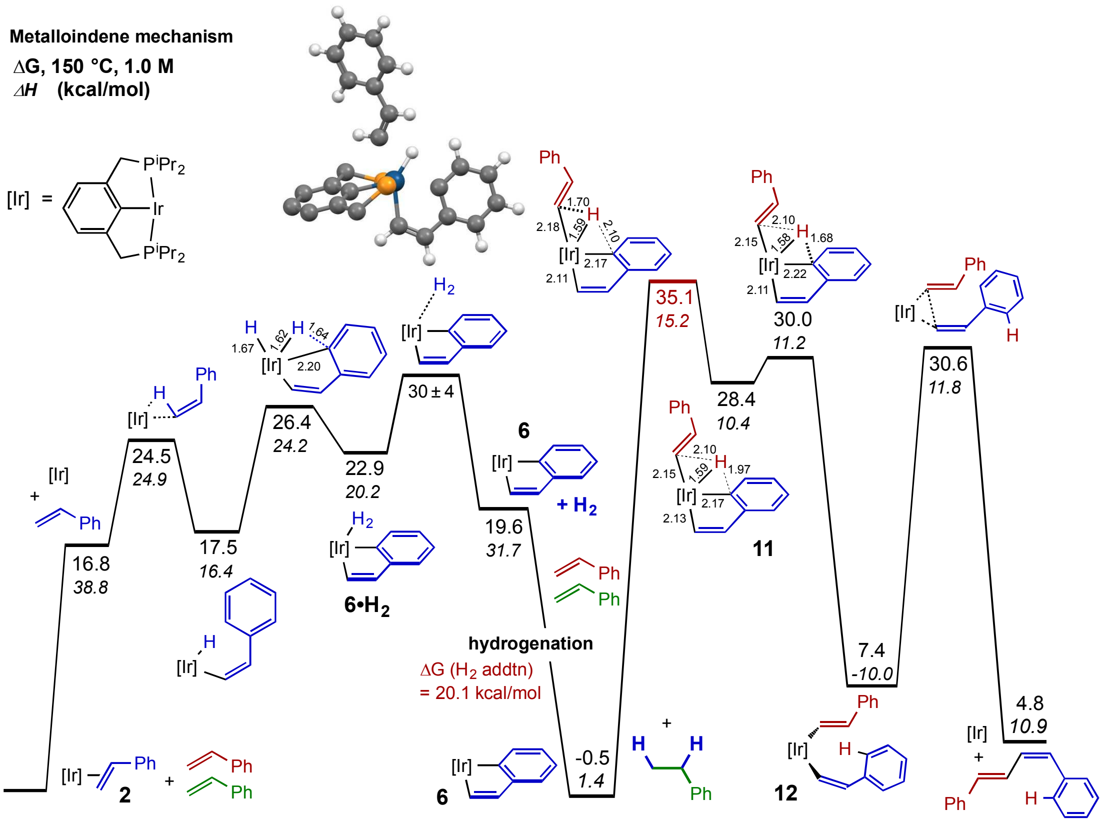


Figure 6. Calculated free energies and enthalpies (below, italic) for the tail-to-tail coupling of styrene via a cyclometalation (metalloindene) mechanism. Ball-and-stick model of calculated highest-energy TS shown (^{i}Pr groups and pincer-backbone H atoms omitted for clarity). Energy values (kcal/mol) are referenced to T = 423 K (150 °C) and concentrations of 1 M for each species participating in the reaction. Selected internuclear distances (Å) are indicated.

The facile cyclometalation to give metalloindene dihydrogen complex **6•H$_2$** is followed by loss of H_2. This reaction appears to have no barrier on the potential energy surface in the reverse direction, and we were unable to locate a true TS (first-order saddle point on the potential energy surface). If we assume that the enthalpic barrier to H_2 loss is at least equal to the (thermodynamic) enthalpy of H_2 loss, which is 11.5 kcal/mol in the present case, while the entropy of activation is ≥ 0 but no more than ca. 20 eu, then the highest point on the free energy surface for H_2 loss from the metalloindene dihydride is ca. 26 - 34 kcal/mol above the π-styrene complex.

The H_2 lost from **6•H$_2$** is presumably consumed relatively quickly in the hydrogenation of styrene (or other olefin if added). The resulting products, metalloindene **6** plus ethylbenzene, are calculated to have a free energy that is 0.5 kcal below that of the π-styrene complex (**2**) plus an additional styrene molecule (indicated in green in Figure 6). **6** then undergoes addition of the *trans*-β C-H bond of another molecule of styrene. This reaction is calculated to proceed via a TS with a free energy that is 35.1 kcal/mol above the π-styrene complex, and 35.6 kcal/mol above **6**, leading to the Ir(V) metalloindene complex, **11**. Aryl-H reductive elimination from this species has an extremely low kinetic barrier ($\Delta G^{\ddagger}$ = 1.6 kcal/mol and $\Delta H^{\ddagger}$ = 0.8 kcal/mol), leading to [Ir](*cis*-CH=CHPh)(*trans*-CH=CHPh), **12**.

The bis(vinyl) complex (^{iPr}PCP)Ir(*cis*-CH=CHPh)(*trans*-CH=CHPh) (**12**, Figure 6) is only slightly higher in free energy than the *trans,trans* isomer (**10**, Figure 5). More significantly, the calculated barrier to C-C elimination from **12** is $\Delta G^{\ddagger}$ = 23.2 kcal/mol, as compared with $\Delta G^{\ddagger}$ = 15.8 kcal/mol for **10**. Nevertheless, this TS is calculated to be 4.5 kcal/mol lower in free energy than the TS for C-H addition to the metalloindene to give **11**, which necessarily gives rise to a cis-vinyl unit and ultimately the E,Z isomeric product. As noted above, control experiments show that cis-trans isomerization of this species to give the observed E,E isomer is rapid relative to the overall reaction.

The overall barrier calculated for the metalloindene mechanism of Figure 6 (35.6 kcal/mol) is thus significantly lower than that for the “direct” addition mechanism of Figure 5 (42.8 kcal/mol) and in good agreement with the approximate experimentally determined barrier, $\Delta G^{\ddagger} \sim 32$ kcal/mol.

Additional calculations in which the effects of bulk solvation were included (CPCM continuum dielectric model, toluene model solvent) anticipate very small changes relative to the idealized gas-phase energy profile presented in Figure 6 (cf. Table S7 in SI). Computed changes in TS free energies from solvation in toluene are all less than 2 kcal/mol and, in particular, the barrier for the rate determining step of the metalloindene mechanism, namely addition of the *trans*-β C-H bond of a styrene molecule to **6**, is predicted to increase modestly, by just 0.9 kcal/mol.

The energy profile of the proposed mechanism of Figure 6 suggests that addition of the phenyl *ortho*-C-H bond leads reversibly to the metalloindene dihydrogen complex **6•H$_2$**. Assuming that the dihydrogen ligand can undergo rotation, this process would lead to H/D exchange. When the reaction is conducted with $C_6H_5C_2D_3$ we see extensive H/D scrambling at all sites on styrene, including the styrene *o*-C-H bond. Exchange at the meta and para positions is presumably the result of intermolecular H-D scrambling. However, we have previously found that any substituent on an arene ring, even a methyl group, strongly inhibits C-H addition;[35,42,51] the failure of the vinyl group to block H/D exchange at the *o*-C-H position is consistent with the reversible cyclometalation implied by Figure 6.

3.4. Intramolecular coupling. Consistent with the proposed mechanism of Figure 6, tail-to-tail coupling is not observed for 2,4,6-trimethylstyrene, which cannot form a metalloindene intermediate as it lacks an ortho-C-H bond. Instead, the conversion of 2,4,6-trimethylstyrene to dimethylindenes occurs, representing an unusual example of dehydrogenative C(sp^3)-C(sp^2) coupling with an unfunctionalized hydrocarbon. For this reaction, a “direct” C-C coupling pathway is calculated (Figure 7). As in the case of the metalloindene mechanism (Figure 6), the coupling pathway begins with C-H addition to give the cis-2-arylvinyl iridium hydride (Figure 7). The bulkiness of the trimethylphenyl group slightly raises the barrier to vinylic C-H addition to the 14e (^{iPr}PCP)Ir fragment, but it raises the relative energy of the π-olefin complex even more. Cis-β-vinyl C-H addition of 2,4,6-trimethylstyrene is thus kinetically, as well as thermodynamically, slightly more favorable, relative to the respective π-complex, than is the case for the parent styrene (cf. Figure 6; $\Delta\Delta G^{\ddagger}$ = -2.1 kcal/mol and $\Delta\Delta G$ = -1.5 kcal/mol).

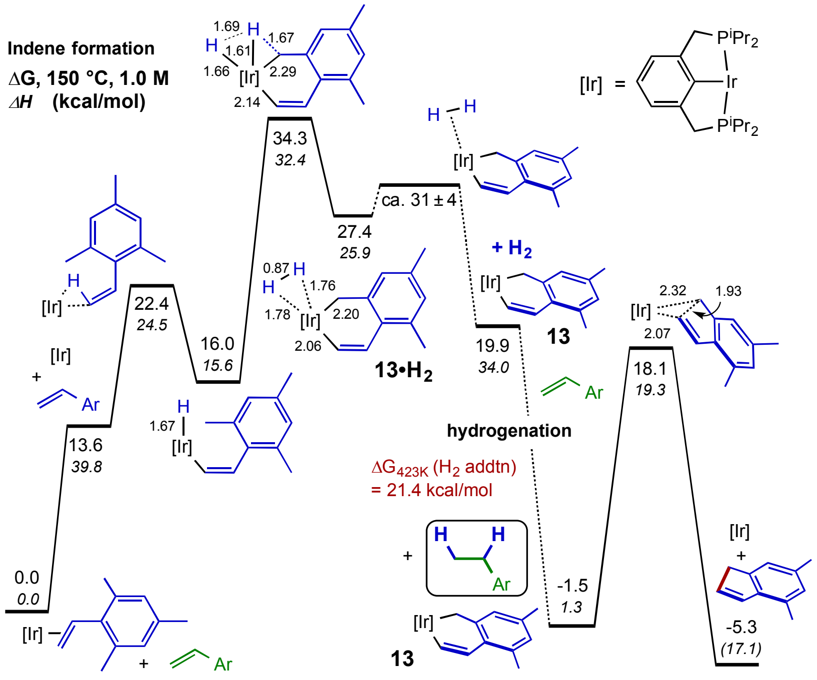


Figure 7. Calculated free energies and enthalpies (below, italic) for the (^{iPr}PCP)Ir-catalyzed conversion of 2,4,6-trimethylstyrene to 4,6-dimethylindene at 150 °C. Energy values (kcal/mol) are referenced to T = 423 K (150 °C) and concentrations of 1 M for each species participating in the reaction. Selected internuclear distances (Å) are indicated.

Intramolecular addition of an ortho-methyl C-H bond then proceeds through a TS with significant Ir(V) character (Figure 7). The length of the newly formed Ir-H bond in the TS (1.61 Å) is actually slightly less than that of the Ir-H bond in the preceding intermediate or that same bond in the TS (1.67 Å and 1.66 Å, respectively). The incipient Ir-C bond is nearly, but not quite fully, formed ($d_{C\text{-}Ir}$ = 2.29 Å) and the C-H bond is fully or nearly fully cleaved ($d_{C\text{-}H}$ = 1.67 Å). This addition of the methyl C-H bond (Figure 7) has a barrier $\Delta G^{\ddagger}$ = 18.3 kcal/mol resulting in a TS with free energy 34.3 kcal/mol above the π-complex resting state. The product of this benzylic C-H activation is an Ir(III) dihydrogen complex ($d_{H\text{-}H}$ = 0.87 Å), **13•H$_2$**.

The TS for loss of H_2 from **13•H$_2$** could not be located but, again, in the reverse direction, addition of H_2 to **13** appears to be barrierless on the potential energy surface. This implies a TS enthalpy equal to that of the product and, again assuming that $\Delta S^{\ddagger}$ = 0 to 20 eu, a free energy of the TS approximately 27-35 kcal/mol above the resting state. Following hydrogenation of an additional molecule of styrene (ΔG = -21.4 kcal/mol), C-C reductive elimination from **13** is relatively facile ($\Delta G^{\ddagger}$ = 19.6 kcal/mol), releasing indene and regenerating the 14e (^{iPr}PCP)Ir intermediate.

Hence, the overall barrier to the intramolecular dehydrogenative C(sp^3)-C(sp^2) coupling is calculated to be 34.3 kcal/mol with C-H addition to give **13•H$_2$** as the rate-determining step (Figure 7). Loss of dihydrogen from **13•H$_2$** appears to have a lower calculated barrier, although we cannot rule out that step as rate-determining, particularly in view of the error limits of the calculations. In either case, the calculations seem to be in very good agreement with the experimental rate of the cyclization which implies a barrier of ca. 32 kcal/mol.

3.5. Hetero-coupling with pentafluorophenylethylene. Like 2,4,6-trimethylstyrene, pentafluorophenylethylene (F_5-styrene) cannot undergo dehydrogenative coupling via the proposed metalloindene mechanism; accordingly, F_5-styrene is found to undergo no detectable homocoupling. However, addition of the F_5-styrene β-vinyl C-H bond to the (unsubstituted) metalloindene complex **6** is calculated to be *more* favorable (by 1.4 kcal/mol) than addition of the corresponding styrene bond which is the rate-determining step proposed for the mechanism of Figure 6. Accordingly, a *p*-xylene-d_{10} solution with (^{iPr}PCP)Ir(C_2H_4) catalyst (5 mM) and roughly equal concentrations of F_5-styrene (270 mM) and styrene (230 mM) reveals high selectivity for dehydrogenative heterocoupled product, $C_6F_5CH{=}CHCH{=}CHPh$, **1-F$_5$**. Over the course of the first five hours at 150 °C, with 46% of total styrenes consumed, the ratio of **1-F$_5$** : **1** remains constant at ca. 11:1 (Figure 8), implying that $\Delta G^\ddagger$ is 1.9 kcal/mol lower for C-H addition of F_5-styrene than for styrene, in excellent agreement with the calculated value of 1.4 kcal/mol. It should also be noted that F_5-styrene is preferentially hydrogenated vs. styrene (ca. 4.5:1). Hence, the ratio of F_5-styrene:styrene decreases during the course of the reaction and styrene is present in greater concentration after 4 hours, although the rate of formation of heterocoupled product continues to greatly exceed that of homocoupled product. After 40 hours, quantitative conversion to dimer and hydrogenated products is observed; the observed (^{1}H NMR) concentrations of heterodimer and styrene homodimer are 161 mM and 19 mM respectively, while concentrations of $C_6F_5CH_2CH_3$ and ethylbenzene are 124 mM and 28 mM respectively.

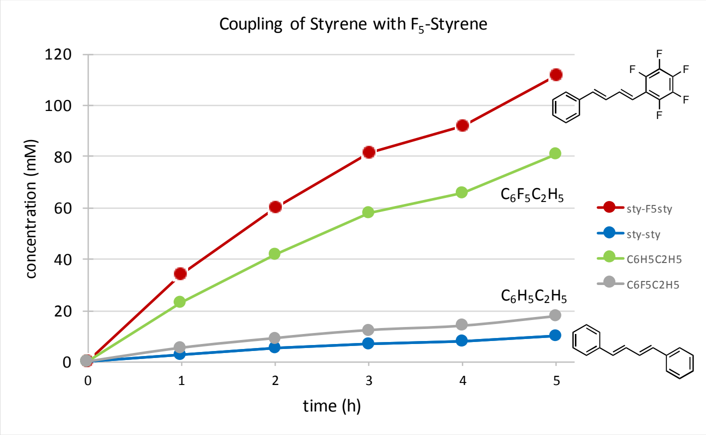


Figure 8. Products of (^{iPr}PCP)Ir-catalyzed dehydrogenative coupling of styrene and F_5-styrene (150 °C).

The failure of F_5-styrene to undergo homodimerization, even under conditions where styrene homodimerization and cross-coupling occurs, argues strongly against the "direct" addition mechanism (Figure 5). With a common resting state (as is necessarily the case in a single-solution competition experiment of the type described above) the rate-determining step for homocoupling of F_5-styrene via the “direct addition” mechanism is calculated to be 2.8 kcal/mol lower in free energy than that for styrene (Figure 9). (Thus it is 40.0 kcal/mol above the styrene π-complex plus two molecules of free F_5-styrene, but the nature of the actual resting state affects only this absolute value and not the relevant differences). This would imply that the rate of F_5-styrene homocoupling would be ca. 30-fold greater than that of styrene homocoupling, in direct contradiction with the failure to observe *any* F_5-styrene homocoupling product. The TS for F_5-styrene homocoupling in the "direct" mechanism is also calculated to be slightly lower in free energy than those for heterocoupling (40.6 kcal/mol above the styrene π-

complex for styrene C-H addition to the C-H adduct of F_5-styrene, and 41.4 kcal/mol for the converse heterocoupling TS) again in contradiction with experimental results. Since the expected errors in computed free energies for such isodesmic comparisons are quite small, the implication that the “direct addition” mechanism would strongly favor formation of the F_5-styrene homocoupling product (which is experimentally not observed) argues strongly against this being the operative mechanism.

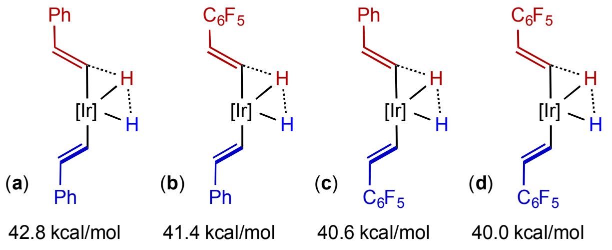


Figure 9. Schematic diagrams of the TSs for the calculated rate-determining step for dehydrogenative coupling, via the “direct mechanism”, for homocoupling of styrene (**a**); heterocoupling of F_5-styrene with styrene (**b**) and (**c**); homocoupling of F_5-styrene (**d**). (Absolute energies are given relative to the non-fluorinated (^{iPr}PCP)Ir(π-styrene) complex plus the corresponding two molecules of styrene. Note that relative energies, which are relevant to the results of a competition experiment, are not affected by the choice of reference state.)

Additionally, the greater rate of hydrogenation of F_5-styrene relative to that of styrene, noted above, suggests that F_5-styrene inserts more favorably into an Ir-H bond. This observation offers an additional argument against the insertion-based mechanisms of Scheme 5 (proceeding through insertion into an Ir-C bond) and particularly Scheme 6 (insertion into an Ir-H bond). In agreement with this inference, DFT calculations indicate that the TS for the rate-determining step (C-C elimination) for the mechanism of Scheme 6 is 7.8 kcal/mol lower in free energy for the homocoupling of F_5-styrene than for styrene, and 2.8 kcal/mol lower than for heterocoupling of F_5-styrene and styrene (Figure 10, structures a - c). Likewise, for the mechanism of Scheme 5, the TS of the rate-determining step (insertion into the Ir-C bond) is 5.7 kcal/mol lower in free energy for homocoupling of F_5-styrene than for styrene, and 1.9 kcal/mol lower than for heterocoupling (Figure 10, structures d - f).

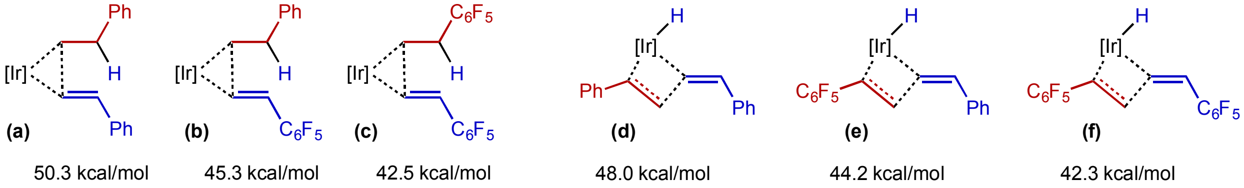


Figure 10. Schematic diagrams of the TSs for the calculated rate-determining step for homocoupling of styrene, heterocoupling of F_5-styrene with styrene, and homocoupling of F_5-styrene, via mechanism of Scheme 6 (insertion into Ir-H bond of arylvinyl hydride followed by rate-determining C-C elimination; **a**, **b**, and **c**) and mechanism of Scheme 5 (rate-determining insertion into Ir-C bond of arylvinyl hydride; **d**, **e**, and **f**). (Absolute energies are given relative to the non-fluorinated (^{iPr}PCP)Ir(π-styrene) complex plus the corresponding two molecules of styrene; relative energies, which are relevant to the results of a competition experiment, are not affected by the choice of reference state.)

Finally, we have also calculated a pathway that is perhaps a less obvious possibility than the direct and insertion-based mechanisms discussed above. Styrene β-vinyl C-H addition, followed by α-H-abstraction of the phenylvinyl group and loss of H_2 to give vinylidene complex (^{iPr}PCP)Ir=C=CHPh is calculated to be relatively facile ($\Delta G^{\ddagger}$ = 26.8 kcal/mol; ΔG = 23.2 kcal/mol). Addition of the β-vinyl C-H bond of a second molecule of styrene to (^{iPr}PCP)Ir=C=CHPh is calculated to have a rate-determining barrier ($\Delta G^{\ddagger}$ = 39.8 kcal/mol) that is only ca. 5 kcal/mol greater than the highest barrier for the metalloindene mechanism. Subsequent migration of hydride to the vinylidene moiety and C_{vinyl}-C_{vinyl} elimination is calculated to be relatively fast. However, as was calculated for the direct and insertion-based mechanisms, homo-coupling of F_5-styrene by the vinylidene mechanism is calculated to be much more favorable ($\Delta G^{\ddagger}$ = 34.0 kcal/mol) than either homo-coupling of styrene or F_5-styrene/styrene heterocoupling, in strong disagreement with the experimental results.

4. SUMMARY AND CONCLUSIONS

Dehydrogenative coupling of unactivated C-H bonds (intermolecular vinyl-vinyl, intramolecular vinyl-benzyl) is found to be catalyzed by precursors of the (^{iPr}PCP)Ir fragment. The reactions proceed via C-H activation to (^{iPr}PCP)Ir(I) followed by a second C-H activation by the resulting (^{iPr}PCP)Ir(III) product. The C-H additions to Ir(III) occur via TSs that are strongly Ir(V) in character although the reactions generally do not lead to an Ir(V) product, but rather to the formation of a new Ir(III) dihydrogen complex.

For intermolecular dehydrogenative vinyl-vinyl coupling, addition of a vinylic C-H bond to Ir(I), followed by addition of a second vinylic C-H bond to the resulting Ir(III) vinyl hydride, loss of H_2, and then C-C elimination would comprise what we refer to as a “direct” pathway (Figure 5). Instead, however, the Ir(III) vinyl hydride complex undergoes addition of an aryl ring ortho C-H bond to give an Ir(III) metalloindene, **6**, plus H_2 (Figure 6). The activation enthalpy of this reaction (7.8 kcal mol) is slightly greater than the intermolecular addition (5.1 kcal/mol), but the entropic penalty is much less. Subsequent intermolecular vinyl C-H addition to the Ir(III) metalloindene **6** has a much *greater* calculated barrier ($\Delta G^{\ddagger}$ = 35.6 kcal/mol) than vinyl C-H addition to the Ir(III) vinyl hydride (25.8 kcal/mol) in the “direct” mechanism. However, the metalloindene pathway is driven by addition of the released dihydrogen to another mol of olefin, prior to the second vinylic C-H addition; this significantly lowers the free energy of the system (by ca. 20 kcal/mol), which would lead to a commensurately much greater concentration of Ir(III) metalloindene **6**, thus favoring occurrence of the subsequent intermolecular reaction. In contrast, in the case of the “direct” mechanism, loss of H_2 and hydrogenation of styrene does not occur until after the entropically unfavorable second addition of a vinyl C-H bond (which is calculated to be rate-determining), and thus cannot provide any driving force.

As we have shown previously, C-C elimination from (pincer)IrRR' complexes can be relatively facile when R and R' are sp^2-C-bound fragments.[34] Accordingly in all mechanisms investigated, C-C elimination is not calculated to be rate-determining.

Although in most of this work the H_2 by-product of the reaction is consumed by an additional molecule of styrene, it is found that other olefins can play the same role as hydrogen-acceptor; this allows, in principle, complete conversion of the styrene to dehydrogenatively coupled dimer. Either with or without added olefin, no conventional oxidizing agent (including acids) is required.

In accord with the proposed metalloindene mechanism, styrenes that lack a C-H bond ortho to the vinyl group are found not to undergo tail-to-tail homocoupling. In contrast, the DFT calculations predict that the ortho-substituents would not adversely affect coupling via the “direct” mechanism. In the case of 2,4,6-trimethylstyrene, the product of vinylic C-H addition to (^{iPr}PCP)Ir(I) undergoes cyclometalation by subsequent C-H addition of an ortho-methyl C-H bond. This reaction is enthalpically much less favorable than any of the C(sp^2)-H bond additions considered above but, due to the low entropic penalty, the calculated barrier, although high, is not prohibitive. Subsequent loss of H_2 and then C-C elimination to give indene are calculated to proceed relatively rapidly. The calculated overall barrier, corresponding to the cyclometalation TS, is 34.3 kcal/mol above the π-complex resting state, in good agreement with the observed rates.

The absence of an ortho-C-H bond precludes homocoupling of $C_6F_5CH{=}CH_2$ (F_5-styrene) via the metalloindene mechanism; this is fully confirmed experimentally. However, although F_5-styrene cannot undergo double C-H activation to form a metalloindene complex, the fluorination of the aryl ring is calculated to favor β-vinylic C-H bond addition to a metalloindene complex. Accordingly, although it undergoes no homocoupling, the dehydrogenative hetero-coupling of F_5-styrene with styrene is much more favorable than styrene homocoupling. This is well explained by the metalloindene mechanism and the calculations even capture fairly well the ratio of hetero- to homocoupling. Conversely, the calculations predict that if any of the other mechanisms investigated were operative, the homocoupling of F_5-styrene would be *more* favorable than either heterocoupling or styrene homocoupling.

We believe that the principles elucidated in this work will be applicable to the development of more general dehydrogenative coupling reactions. Most obviously, the metalloindene mechanism should be viable for the coupling of styrenes and their derivatives with other C-H bonds (including both alkenes and non-alkenes). While a “direct” mechanism was found to not be operative in the intermolecular case studied in this work, it was found to operate for intramolecular coupling involving sp^3 C-H bonds. Even for the intermolecular case, the barrier to the direct mechanism was not calculated to be extremely high. Thus, such a mechanism, or more generally sequential C-H activations and C-C coupling, may well be viable with closely related catalysts. In that context, efforts in our lab are underway to determine the factors that favor such pathways.

5. EXPERIMENTAL SECTION

General Remarks. All manipulations were carried out under argon atmosphere either in a glove box, or by modified Schlenk techniques. All NMR spectra were collected on a 500-MHz Varian VNMRS or a Bruker AMX 400-MHz spectrometer. ^{1}H and ^{13}C NMR spectra were referenced to residual deuterated solvent signal. All aromatic solvents were dried over sodium/benzophenone, distilled from the resultant purple solution prior to use, and stored over 3-Å molecular sieves. X-ray structure collection was conducted on a Bruker SMART APEX II CCD platform diffractometer. GC-MS analysis was conducted using a Shimadzu GCMS-QP5000 with an Equity-1701 column, helium as carrier gas, and dodecane used as internal standard. Melting points (uncorrected) were determined on a Laboratory Devices Mel-Temp instrument. The ^{iPr}PCPH ligand precursor[52] and (^{iPr}PCP)IrHCl complex[53] were synthesized by literature methods.

General Procedure for Coupling of Vinyl Arenes with (^{iPr}PCP)IrHCl as Precatalyst. To a 4-mL glass ampoule with Teflon closure, 10 mg (0.0177 mmol) (^{iPr}PCP)IrHCl, 4 mg (0.0356 mmol) potassium *tert*-butoxide, a stir bar, and 0.5 mL toluene were added. This was followed by addition of 0.354 mmol vinyl arene. The sealed vessel was then heated, with stirring, at 150 °C for 24 h in an aluminum heating block. Soluble products were isolated as a crude mixture by removal of volatiles in vacuo, redissolution in petroleum ether, and passage of this concentrated solution through a short plug of silica to remove catalyst. Several washes with petroleum ether were conducted to collect organics and concentration of the combined solutions to dryness provided the crude product. The desired (*E*,*E*)-1,4-diaryl-1,3-butadienes could be further purified by vacuum sublimation or recrystallization from aliphatic alcohols.

General Procedure for Coupling of Vinyl Arenes with (^{iPr}PCP)Ir(ethylene) as Precatalyst. To an NMR tube attached to a short extension of glass tubing, 1.4 mg (0.0025 mmol) (^{iPr}PCP)Ir(ethylene) complex and 0.25 mmol vinyl arene in 0.5 mL *p*-xylene-d_{10} were added (for cross-couplings a total of 0.25 mmol vinyl arene was used, in a 1:1 ratio). A sealed capillary tube with triethyl phosphite in *p*-xylene-d_{10} inside the NMR tube provided an external standard. The NMR tube was connected to a closed Kontes valve by a piece of Tygon tubing. The contents of the tube were then frozen with liquid nitrogen, and the tube was flame-sealed under vacuum. The sealed NMR tube was then heated at 150 °C inside an oven and the reaction was then monitored by NMR spectroscopy. Products were isolated by column chromatography using hexane as the eluent, which gives a mixture of both (*E*,*E*) and (*E*,*Z*) isomers. Further purification was carried out by recrystallization in hexane to give pure (*E*,*E*) isomer.

6. COMPUTATIONAL SECTION

All electronic structure calculations employed the DFT method.[54] Data presented in the text result from calculations which employed the M06-L exchange-correlation functional.[55] We also examined two additional functionals, M06[56] and PBE [57], in selected calculations; the results obtained with these functionals fully support the mechanisms we propose based on calculations with the M06-L functional. For Ir, we applied the Hay-Wadt relativistic effective (small) core potential[58] and the LANL2TZ basis set[59] augmented by a set of diffuse d-type functions (exponent=0.07645)[60]; all other atoms (P, F, C, and H) were assigned 6-311G(d,p) basis sets.[61]

Geometries were calculated for stationary points along the reaction paths by standard optimization procedures.[62] Normal mode analysis was performed to further verify the nature of a particular stationary point (minimum or transition state). The resulting set of vibrational frequencies was employed (without scaling) to determine zero-point energy corrections. Enthalpies (ΔH, $\Delta H^{\ddagger}$; T = 298.15) and Gibbs free energies (ΔG, $\Delta G^{\ddagger}$; T = 298.15 K, P = 1 atm) were subsequently obtained from the potential energies using standard statistical mechanical expressions applicable to an ideal gas.[63] To facilitate comparisons with measured energetics, computed Gibbs free energies quoted in the text have been adjusted to a standard state of 1 M for each species participating in the reaction, and T = 423 K (150 °C , the temperature applied in the experiments reported here).[63] We note in passing that, based on the ideal gas law, a concentration of 1 M is equivalent to a pressure P = 34.7 atm at T = 423 K. The polarizable conductor self-consistent reaction field model (CPCM) was applied in a few calculations to probe general bulk solvation effects using Gaussian 09 default parameters for toluene as the model solvent.[64] In order to enhance computational stability and accuracy[65] in geometry optimizations and normal mode calculations, we used increased atomic grid sizes (grid=ultrafine option).[66] All calculations made use of the Gaussian 09 electronic structure program.[67] Geometries of principal species and energetic quantities are available in Supporting Information.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/jacs.xxxx and includes full experimental details, NMR, and GC characterization data for compounds and reactions; listing of crystallographic information including data collection parameters, bond lengths, fractional atomic coordinates, and anisotropic thermal parameters for complexes (PDF); optimized structures (Cartesian coordinates, .mol2 formatted files); tables of energetic quantities. Crystallographic data (CCDC deposition nos. 1540144-6 and 1539909-13) (CIF).

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Notes

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■ ACKNOWLEDGMENTS

We thank the NSF for support through the CCI Center for Enabling New Technologies through Catalysis (CENTC) Phase II Renewal, CHE-1205189.

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