

Insight into the Scope and Mechanism for Transmetalation of Hydrocarbyl Ligands on Complexes Relevant to C–H Activation

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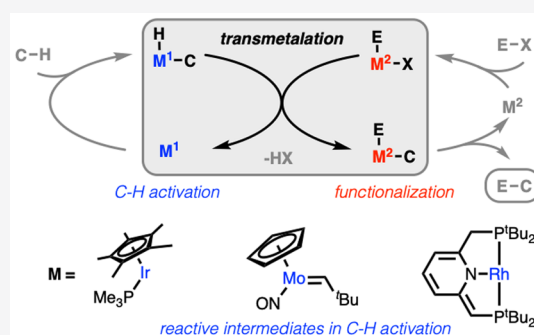


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ABSTRACT: We report the transmetalation of hydrocarbyl fragments (Me, Bn, Ph) from a variety of organometallic complexes relevant to C–H activation (Ir, Rh, W, Mo) to Pt(II) electrophiles. The scope of suitable hydrocarbyl donors is remarkable in that three different classes of organometallics with widely varying reactivity all undergo the same general reaction with Pt(II) electrophiles. A competitive substituent effect experiment reveals faster transmetalation of more electron-rich hydrocarbyl groups. This study suggests that transmetalation could provide a viable path for catalytic functionalization of stable complexes resulting from C–H bond activation and other processes.



The activation of C–H bonds to form organometallic compounds has been exploited to develop methods that allow for improved synthetic efficiency by conversion of C–H bonds to desired functionality.^{1–7} Studies of stoichiometric C–H activations that yield stable organometallic products form the basis for our current understanding of organometallic C–H activation.^{8–10} These efforts have led to the identification of reactive intermediates, including those in Figure 1A, that promote C–H cleavage under mild conditions. Functionalizing the resulting hydrocarbyl ligands under conditions compatible with catalytic C–H functionalization, on the other hand, remains challenging. We hypothesized that the C–H activation reactivity of intermediates like those in

Figure 1A might be harnessed by coupling C–H activation with one metal (M1) to functionalization on a second metal (M2) via transmetalation of the activated hydrocarbyl fragment, as shown in Figure 1B.^{11,12} Indeed, there have been several reports in recent years showing transmetalation of hydrocarbyl fragment between two transition metal complexes after C–H activation by (M1) in similar systems, where (M1) = Pd(II), Ag(I) and (M2) = Pd(II), Au(III).¹³ Although our efforts focus on transmetalation from organometallics related to C–H activation, a better understanding of transmetalation between transition metals may open new avenues for coupling a wide range of organometallic reactivities via transmetalation between transition metals.^{14–19}

The C–H activation and functionalization reactivities in Figure 1B are well established, but transmetalation between two transition metals is much less understood. We previously reported that hydrocarbyl ligands on Cp*(PMe₃)Ir complexes can undergo transmetalation with cationic d⁸ Pt and Pd complexes¹¹ and that this transmetalation process can be incorporated into Pd-catalyzed direct arylation reactions.¹² On the basis of this reactivity, we next sought to explore the scope and mechanism of transmetalation of hydrocarbyl ligands from complexes relevant to C–H activation to organometallic electrophiles.^{11,12,20} Herein, we show that a variety of

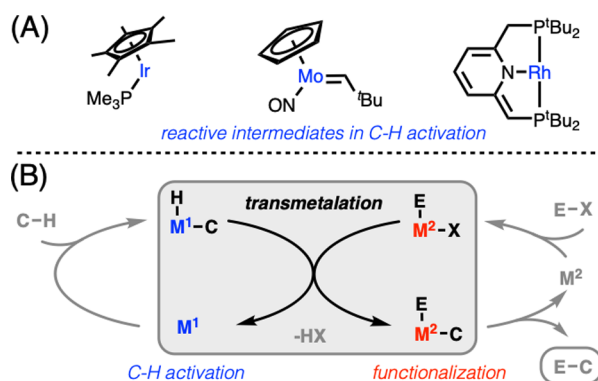
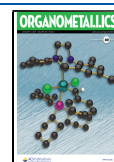


Figure 1. (A) Intermediates capable of mild, nondirected C–H activation. (B) Proposed dual catalytic cycle to enable turnover of activated fragments in (A).

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complexes related to the intermediates in Figure 1A were competent hydrocarbyl donors in transmetalation to (cod)Pt(Me)(TFA) (cod = cyclooctadiene, TFA = trifluoroacetate) (Figure 2). The scope of hydrocarbyl donors is striking for the

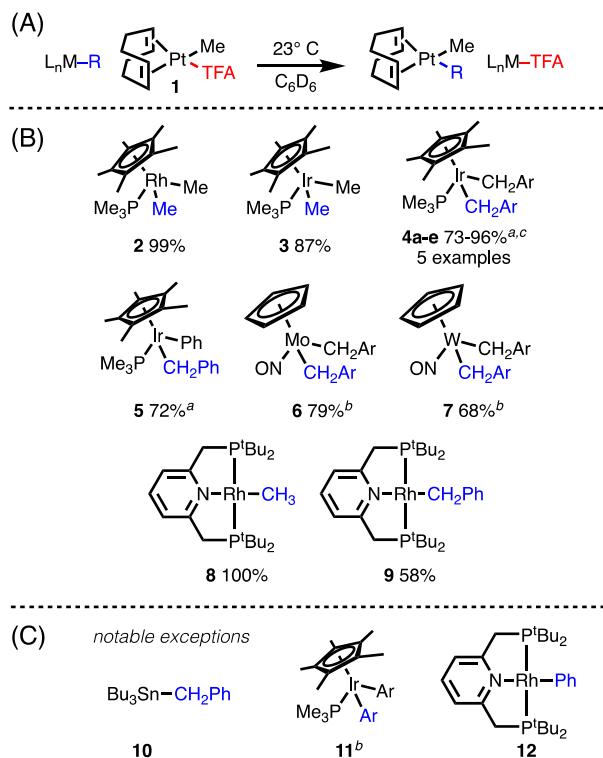


Figure 2. (A) Transmetalation reaction outline. (B) Scope of transition metal nucleophiles in transmetalation to (cod)Pt(Me)(TFA) and yield of hydrocarbyl group transfer. (C) Transition metal nucleophiles that did not transmetalate to (cod)Pt(Me)(TFA). ^aReactions conducted at 70 °C. ^bAr = *p*-tolyl. ^c4a: *p*-F (73%); 4b: *m*-F (96%); 4c: H (77%); 4d: *p*-Me (83%); 4e: *m*-Me (80%).

diversity of suitable metals (Ir, Rh, W, Mo) and the widely varying geometries, electronic structures, and divergent reactivities of the organometallic complexes. This finding opens the door for subsequent studies focused on exploiting this reactivity for catalysis and potentially enabling new approaches to functionalize unactivated C–H bonds.

The general transformation in Figure 2A summarizes the transmetalation reactivity examined in this work, namely, transfer of a hydrocarbyl ligand (R) to (cod)Pt(Me)(TFA) (1) from a variety of organometallic complexes. Rhodium and iridium complexes supported by Cp*(PMe₃) are capable of cleaving the C–H bonds of numerous alkanes, including methane, via the corresponding intermediate in Figure 1A. Related rhodium (2) and iridium (3) complexes are suitable methyl group donors to (cod)Pt(Me)(TFA) (Figure 2B). Related iridium dibenzyl complexes (4a–e) transfer benzyl groups at elevated temperature (70 °C), and the mixed phenylbenzyl complex (5) undergoes selective transmetalation for the benzyl ligand over the phenyl ligand. Benzyl ligand transfer from molybdenum (6) and tungsten (7) complexes supported by (Cp)(NO), on the other hand, highlights the diversity of compatible organometallic hydrocarbyl donors. Like Cp*(PMe₃)Rh/Ir complexes, (Cp)(NO)Mo/W complexes are also capable of activating various hydrocarbons, but do so via alkylidene intermediates like that shown in Figure 1A.

Transmetalation of methyl and benzyl ligands was also achieved from the square-planar rhodium pincer complexes 8 and 9, respectively, which harness metal–ligand cooperativity to cleave C–H bonds via the dearomatized intermediate in Figure 1A.^{9,21–24} The three distinct reactive intermediates in Figure 1A underscore the diverse geometries and reactivities of organometallic complexes related to C–H activation that are suitable alkyl group donors in transmetalation to 1.

Despite this broad scope, the incompatible donors (10–12) highlight notable gaps in our understanding of this transformation (Figure 2C). In contrast to the transition metal complexes in Figure 2B, tributyl(benzyl)stannane (10)—a prototypical reagent for benzyl group transfer—afforded no transmetalation under the same reaction conditions (Figure 2C).^{25,26} This unexpected difference in reactivity suggests that transition metal donors may exhibit complementary reactivity patterns relative to main group organometal(oid) reagents. For example, whereas tin-based reagents favor sp² transmetalation (e.g., selective phenyl group transfer from Bu₃SnPh), 5 afforded selective sp³ group transfer.^{25,26} Importantly, organometallic complexes in Figure 2 bearing only sp² hydrocarbyl fragments (11 and 12) were not reactive toward phenyl group transfer to (cod)Pt(Me)(TFA).

The lack of phenyl group transfer posed a challenge to further development of the dual catalytic cycle proposed in Figure 1 because the relevant intermediates are more reactive toward sp² C–H bond activation.^{8–10} A central objective of this work, therefore, was to better understand sp³ hydrocarbyl group transfer between transition metals and to leverage those insights to enable transmetalation of aryl ligands generated via C–H activation (Figure 1).

Pioneering studies by Stille revealed that transmetalation to Pd(II) is faster for benzylstannanes bearing electron-withdrawing substituents.^{25,26} In contrast to transmetalation from tin, we hypothesized, on the basis of prior kinetic studies demonstrating the role of a cationic intermediate ((cod)Pt(Me)⁺),¹¹ that electron-withdrawing substituents would suppress transmetalation from [Ir](CH₂Ar)₂ by destabilizing positive charge buildup in the transmetalation transition state. Consistent with this hypothesis, the five substrates tested followed the general trend expected for a transition state with positive charge buildup (*k*_{rel} *m*-F ≅ *p*-F < H < *m*-Me ≅ *p*-Me) (Figure 3A). Notably, however, the relative rates did not obey a linear free energy relationship—perhaps a consequence of the fact two inequivalent benzyl fragments are varied in each experiment. The same trend was observed in transmetalation of the same five iridium substrates to a catalytic palladium electrophile in the presence of an ionizing additive KB(Ar^F)₄ (Figure 3B). Overall, these results support the hypothesis that transmetalation from iridium hydrocarbyl donors to platinum(II) and palladium(II) proceeds with a developing positive charge in the group transfer transition state.¹¹

Given the chemical diversity of the hydrocarbyl donors in Figure 2, it is perhaps not surprising that group transfers from these complexes proceed with widely varying rates. Across the complexes surveyed, benzyl group transfer was slower than even the slowest methyl group transfer (from [Ir](Me)₂, Figure 4). The substituent effects presented in Figure 3, which are consistent with positive charge buildup in the transmetalation transition state, suggest that benzyl ligands should undergo faster transmetalation than methyl ligands due the greater ability of benzyl groups to stabilize positive charge buildup.¹² On the contrary, transmetalation of methyl group

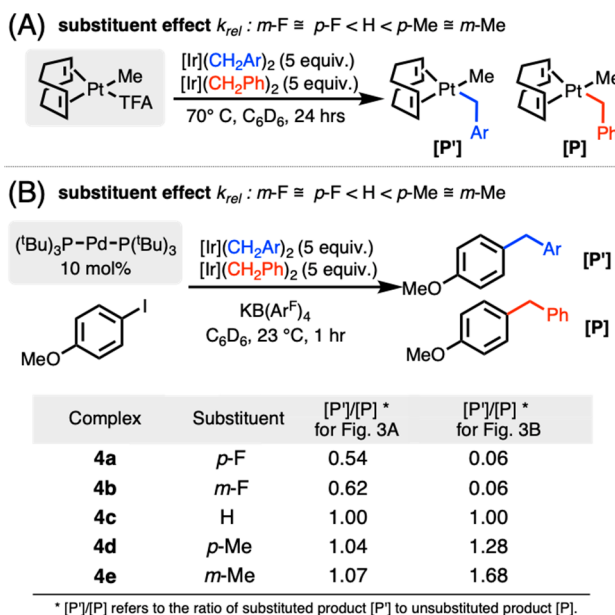


Figure 3. Substituent effect competition experiment reveals faster transmetalation from more electron-rich substituents.

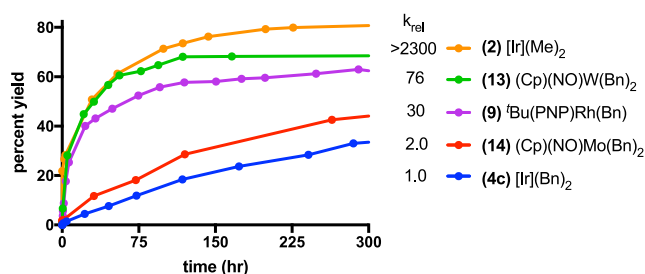


Figure 4. Product formation versus time in transmetalation of benzyl fragments to (cod)Pt(Me)(TFA) with the slowest methyl transmetalation included for comparison. Reactions were run in C_6D_6 . The k_{rel} values are initial rates determined by $[Pt]$ -alkyl product formation at <10% conversion. In the fastest cases, the reactions achieved >10% conversion by the first time point (ca. 2 min after mixing). For these fast reactions, the k_{rel} represents a lower bound on the initial rate and was defined as the slope between the origin and the concentration of product at the first time point.

was much faster than that of benzyl groups, consistent with steric effects dominating the relative rates of methyl versus benzyl group transfer.

Striking differences were also observed in the relative conversion versus time profiles of methyl group transfer as illustrated in Figure 5. Notably, the coordinatively unsaturated rhodium pincer complex $tBu(PNP)Rh(Me)$ (**8**) gave dramatic rate acceleration relative to coordinatively saturated $[Ir/Rh](Me)_2$ (**2**)/(**3**). We previously observed a 100-fold increase in initial rates of C–H activation upon modifying the $tBu(PNP)$ ligand to $iPr(PNP)$ and hypothesized that such a modification could afford rate acceleration for transmetalation.²⁰ Much faster methyl group transfer was observed with $iPr(PNP)Rh(Me)$ (**15**) relative to $tBu(PNP)Rh(Me)$ (**8**). Reactions in Figures 4 and 5 were conducted under conditions shown to examine scope and relative initial rates rather than obtain detailed mechanistic information; some were not monitored until full conversion of starting materials, and thus the possibility of reaching equilibrium cannot be excluded.

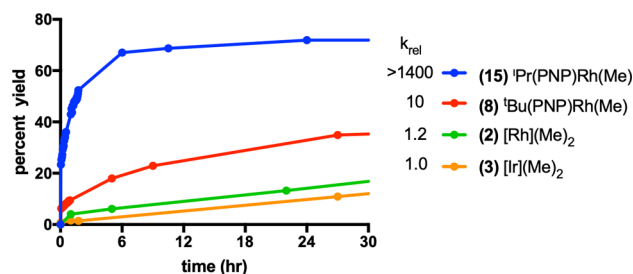


Figure 5. Product formation versus time in transmetalation of methyl fragments to (cod)Pt(Me)(Cl). Reactions were run in C_6D_6 . The k_{rel} values are initial rates determined by Pt-alkyl product formation at <10% conversion. In the fastest cases, the reactions achieved >10% conversion by the first time point (ca. 2 min after mixing). For these fast reactions, the k_{rel} represents a lower bound on the initial rate and was defined as the slope between the origin and the concentration of product at the first time point.

The faster transmetalation observed with the $iPr(PNP)$ ligand scaffold, relative to $tBu(PNP)$, enabled transfer of phenyl groups from $iPr(PNP)Rh(Ph)$ to (cod)Pt(Me)(TFA) and a variety of other metal(loid) complexes as illustrated in Figure 6. The reaction proceeds with trifluoroacetate, methanesulfonate, and chloride leaving groups and tolerates aromatic ancillary ligands (Figure 6A–D). Notably, transmetalation is not limited to platinum complexes chelated by cod; for

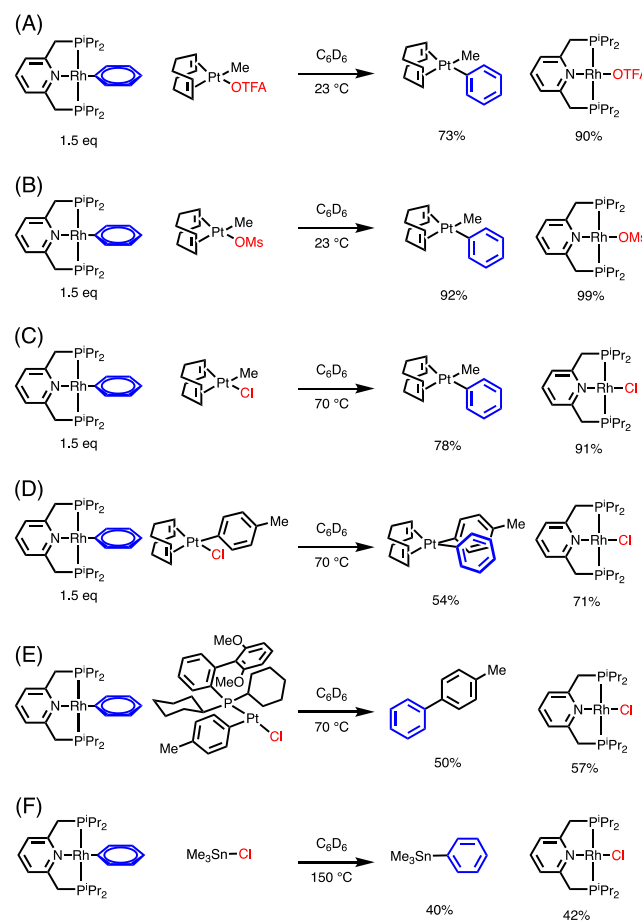


Figure 6. Scope of phenyl group transfer from $iPr(PNP)Rh(Ph)$ to metal(loid) electrophiles. Lower yielding reactions reflect competing decomposition pathways.

example, $^i\text{Pr}(\text{PNP})\text{Rh}(\text{Ph})$ generated an organometalloid nucleophile by phenyl group transfer to trimethylstannane chloride (Figure 6F). The novel SPhos complex in Figure 6E reacted to give phenyl group transfer and subsequent reductive elimination,^{27,28} which also appears to be the first time a Buchwald ligand has been reported to coordinate to Pt(II), though analogous Pd(II) complexes are known²⁹ (Figure 7).

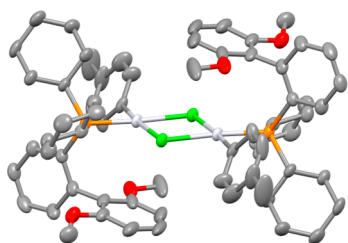


Figure 7. Crystal structure of $(\text{SPhos})\text{Pt}(\text{p-Tol})(\text{Cl})$. The complex was recrystallized as dimers.

Overall, our study of the scope of hydrocarbyl group transfer between transition metals reveals that a variety of organometallic species relevant to C–H activation are capable of transferring hydrocarbyl fragments to Pt(II) electrophiles.³⁰ A substituent effect study indicates that electron-rich hydrocarbyl fragments are transferred more rapidly than electron-poor fragments. As a whole, these studies shed light on the scope and molecular details of hydrocarbyl group transfer between transition metals. These findings will be useful in the development of dual catalytic systems that leverage stoichiometric organometallic reactions for new catalytic transformations via transmetalation of activated fragments between transition metals with complementary reactivity.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acs.organomet.0c00628>.

General and synthetic procedures (PDF)

Accession Codes

CCDC 2016679 and 2016680 contain the supplementary crystallographic data for this paper. These data can be obtained free of charge via www.ccdc.cam.ac.uk/data_request/cif, or by emailing data_request@ccdc.cam.ac.uk, or by contacting The Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB2 1EZ, UK; fax: + 44 1223 336033.

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Notes

The authors declare no competing financial interest.

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