Ru-Catalyzed Oxidative Coupling of Arenes with Olefins Using O_2

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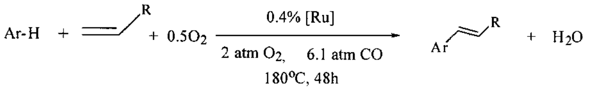
Catalytic carbon−carbon bond formation by C−H activation is a topic of much current interest. Significant progress has been made in recent years in the development of synthetically useful catalytic addition of arenes to alkenes to give the saturated alkyl arenes.[1,2] Catalytic oxidative coupling of arenes with alkenes to give aryl alkenes, in which the double bond is preserved, is a highly desirable goal. Such a reaction, which does not require the utilization of a reactive substituent and does not produce waste, may have an advantage over other methods for the preparation of aromatic alkenes, such as the well-known Heck reaction for the vinylation of aryl halides. Stoichiometric coupling of olefins with arenes promoted by Pd(II) is well-known.[3a] Tsuji et al.,[4] and lately Fujiwara et al.[5] and others,[6] have demonstrated catalysis by utilizing peroxides as oxidants in their systems. While good catalytic activity was achieved with some alkenes, acrylates resulted in low activity (∼10 turnovers). The use of peroxide oxidants and acetic acid solvent in these systems is problematic from the industrial point of view. Attempts to use O_2 or air resulted in low activity in intra-[7] and intermolecular[3b−d,8] coupling, and alkene oxidation took place in the intermolecular reaction. Another approach utilizing Rh carbonyl clusters under high (20−30 atm) CO pressure[9] resulted in modest catalytic activity with concomitant hydrocarbonylation of the alkene. Low catalytic activity was reported for the Rh-catalyzed photochemical coupling of arenes with alkenes, in which concomitant hydrogenation of the alkene took place and biaryls were formed as byproducts.[10] A low yield, Rh-catalyzed oxidative phenylation of ethylene was reported very recently.[11]

Herein we report on a novel oxidative coupling of arenes with olefins, in which O_2 can be directly used as the oxidant and good catalytic activity is obtained. The reaction is catalyzed by Ru complexes and requires a CO atmosphere (eqs 1, 2). Typical examples are listed in Table 1. The complexes $RuCl_3{\cdot}3H_2O$ (**1**), $[Ru(CO)_3Cl_2]_2$, $[(\eta^6\text{-}C_6H_6)RuCl_2]_2$, $Ru(NO)Cl_3{\cdot}5H_2O$, and $Ru(F_3CCOCHCOCF_3)_3$ show essentially the same catalytic activity, whereas $Ru_3(CO)_{12}$ is much less active (leading to 15 turnovers under the same conditions). Notably, the dehydrogenative coupling proceeds either under O_2 (eq 1) or in an inert atmosphere (eq 2). In absence of O_2 the olefin itself serves as an oxidant, and a 1:1 ratio of cinnamate:propionate is obtained. In comparison, under 2 atm of O_2 the cinnamate yield is doubled and a ratio of about 3:1 of cinnamate:propionate is obtained (see Table 1). Essentially no organic carbonylation products are observed. The product turnover number increases with CO pressure up to 6.1 atm, beyond which further pressure increase had no beneficial effect. Various arenes are reactive (see Table 2). Reactants containing acetyl groups (e.g., vinylmethyl ketone and acetophenone) undergo aldol condensation and are incompatible with our system. Alkyl acrylates are by far the most active of the olefins tested (Table 2).

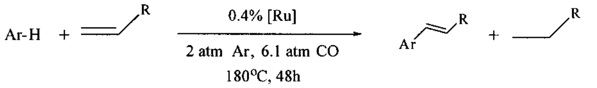
Table 1. Oxidative Coupling of Benzene with Acrylate Esters

entry	conditions[a]	residual acrylate %	yield propionate %	yield cinnamate % [TON]	mass balance %
1	MA[b], 2 atm O_2	22	10	35 [88]	67
2	MA, no O_2	41	20	20 [50]	81
3	MA, no O_2, no light, 0.2 mmol galvinoxyl	38	23	23 [57]	84
4	MA, 2 atm O_2, 0.1 mmol CuO	23	3	35 [88]	63
5	EA, 2 atm O_2	26	10	30 [75]	66
6	EA, 2 atm O_2, 0.2 mmol of HQ	21	19	40 [100]	80
7	EA, 2 atm O_2, 0.4 mmol of HQ	17	21	42 [105]	80

[a] Reaction conditions: a solution containing 8 mL of benzene, 0.02 mmol of **1** and 5 mmol of acrylate esters in a Fischer−Porter glass reactor is pressurized with 6.1 atm CO and 2 atm O_2 and heated to 180 °C with stirring for 48 h. [b] MA = methyl acrylate. [c] EA = ethyl acrylate. Yields are based on the acrylate ester.



(1)



(2)

Addition of Cu(II) salts as potential cocatalysts does not have a beneficial effect on the reaction. In the presence of CuO the amount of propionate is diminished, but the amount of the cinnamate does not increase, due to side reactions. Addition of $CuCl_2$ slows down the reaction. This fact and the observed inhibition of the reaction by CsCl indicate that excess of chloride anions has a detrimental effect on the catalytic performance. Addition of a catalytic amount of hydroquinone (HQ) improves the yield, the turnover number, and the mass balance of the reaction, perhaps by inhibiting competing radical reactions. Ten or twenty equiv of HQ (relative to Ru) had a similar effect. Addition of Galvinoxyl does not retard the reaction, and it proceeds as well in the dark (entry 3 in Table 1). These observations tend to exclude a radical chain mechanism for the reaction. The reaction rate exhibits first-order dependence on the acrylate concentration under pseudo-first-order conditions, the derived second-order rate constant being $k_{obs} = 2.328(\pm 0.005) \times 10^{-3}\ M^{-1}\ h^{-1}$.

Using C_6D_6 instead of C_6H_6, a kinetic isotope effect of $k_H/k_D = 2$ was measured in the reaction with methyl acrylate. Similar kinetic isotope effects of 2.8[12a] and ∼3[12b] were observed in other systems involving activation of benzene with electrophilic complexes. Addition of a catalytic amount of the weak non-

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Table 2. Oxidative Coupling of Various Arenes with Olefins under O_2[16]

entry	arene	olefin	product *p*:*m*:*o* ratio	yield % [TON]
(1)	chlorobenzene	MA	(*E*)-methyl 3-(chlorophenyl)propenoate 1:2:0	34 [86]
(2)	benzene	MA	(*E*)-methyl cinnamate	41 [88]
(3)	toluene	MA	(*E*)-methyl 3-(tolyl)propenoate 1:1.6:0	44 [110]
(4)	anisole	MA	(*E*)-methyl 3-(methoxyphenyl)propenoate 1:1.3:1.05	47 [118]
(5)	benzene	ethylene	styrene	3.0 [19]
(6)	toluene	ethylene	methyl styrene 1:1.6:0	4.4 [28]
(7)	benzene	$H_2C{=}CH(CF_2)_3CF_3$	(3,3,4,4,5,5,6,6,6-nonafluoro-hex-1-enyl)benzene	4.1 [5.4]
(8)	*p*-xylene	MA	(*E*)-methyl 3-(2,5-dimethylphenyl)propenoate	2.3 [5.7]
(9)	*p*-dichlorobenzene	MA	no coupling product	0
(10)	naphthalene	MA	(*E*)-methyl 3-(2-naphtyl)propenoate	28 [70]

coordinating base lutidine inhibits the reaction, supporting a proton release step in the catalytic cycle. The reaction is unaffected by the addition of 1 g of Hg, indicating that catalysis by metallic ruthenium is unlikely.[13] IR of the reaction mixture indicates the presence of Ru carbonyl species (bands at 2054 and 1983 cm^{-1}).

The reaction is mildly accelerated by electron-donating substituents on the arene. A competitive experiment using methyl acrylate (5 mmol) with a mixture of anisole, toluene, benzene, and chlorobenzene (25 mmol each) and 0.02 mmol catalyst in the presence of 90 psi CO and 2atm O_2 yielded a linear Hammett plot ($\rho = -1.16$ for σ_p and -0.82 for $\sigma^\dagger$)[14] (Figure 1). Similar ρ values were reported for stoichiometric metal-promoted electrophilic systems ($\rho^+ = -1.4^{3d}$ and -1.5^{12b}). Notably, substituent directive effects are not observed in the reaction, and an almost statistical distribution of the *para* and *meta* products are obtained. Formation of *ortho* products is significantly retarded due to steric effects (Table 2 Entries 1−4) as observed in similar systems.[3,12] The lack of directive effects and the low ρ value suggest that the C−H activation does not proceed via a simple electrophilic aromatic substitution pathway involving the arene π system (i.e., a Wheland-type complex). Arene metalation without involvement of the π system has been reported.[12a,15] One possibility is a mechanism involving deprotonation of an agostic arene C−H bond, as demonstrated by us.[15]

While the mechanism of the reaction is unclear at this stage, the following steps are plausible: (a) electrophilic attack of the metal on a C−H bond to give an Ar−[Ru] species and a proton; (b) olefin insertion into the metal−aryl bond; (c) β-H elimination to yield the aromatic alkene and a ruthenium hydride; (d) regeneration of the electrophilic species by olefin insertion into Ru−H followed by protonation of the metal−alkyl complex and alkane elimination (when an inert atmosphere is used), or by oxidation when oxygen is present. The CO pressure may be required for the formation and stabilization of the electrophilic species.

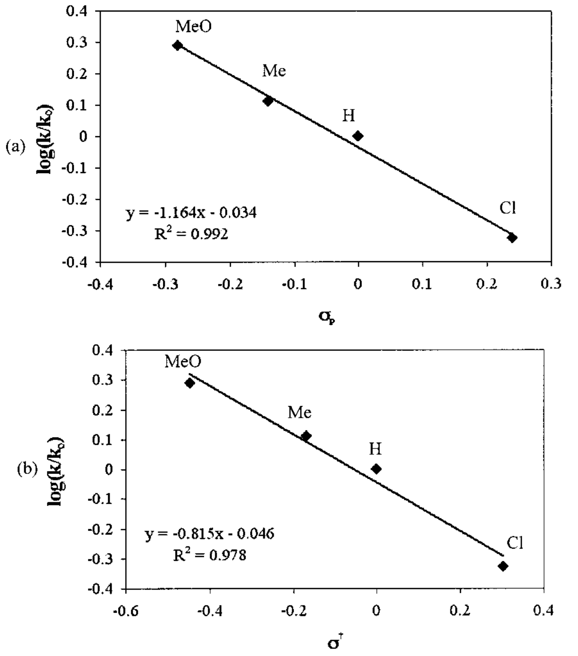

Figure 1. Hammett plot for the reaction of Ar−X (X = MeO, Me, H, Cl) with methyl acrylate using σ_p and $\sigma^\dagger$ values.[14]

In summary, a novel Ru-catalyzed oxidative coupling of arenes with olefins to produce aryl alkenes, which can either directly utilize dioxygen or can utilize the alkene as oxidant, and results in reasonable turnover numbers, has been discovered. The coupling is catalyzed by a homogeneous electrophilic Ru carbonyl species. Work is underway toward better understanding of the scope and mechanism of this reaction.

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(14) (a) The σ values used for the plots were taken from March, J. *Advanced Organic Chemistry*, 3rd ed.; John Wiley & Sons: New York, 1985; p 244. (b) We define a value $\sigma^\dagger$ which is calculated by weighting the σ_p^+ and σ_m^+ values for the aromatic hydrogen atom that reacted in the competitive reaction. In the case of anisole the contribution for $\sigma^\dagger$ of the *ortho* hydrogen atoms was calculated as for the *para* atom. We admit that this is a rough estimation; however, if one considers the similar electronic character of the *ortho* and *para* positions, it gives some compensation for the competitive coordination−directed route for the *ortho* substituted anisole. (c) The relative rates for the plots were calculated per reactive hydrogen atom of each aromatic compound.

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(16) In a typical reaction protocol, an 80 mL glass pressure tube is charged with 90 mmol arene, 0.02 mmol **1**, and 5 mmol acrylate. The reactor is then evacuated until the benzene starts to boil. Then the reactor is pressurized with 6.1 atm CO and 2 atm O_2 and heated to 180 °C with stirring for 48 h. The liquid phase is sampled and analyzed by GC (FID), GC−MS and HNMR at the end of the reaction. Entries 5 and 6 were carried out under 3.6 atm of CO and 3.6 atm of ethylene. 40 mmol of naphthalene were used in Entry 10. 2.63 mmol olefin were used in Entry 7.