Dehydrative Allylation of Alcohols and Deallylation of Allyl Ethers Catalyzed by [CpRu(CH_3CN)$_3$]PF_6 and 2-Pyridinecarboxylic Acid Derivatives. Effect of π-Accepting Ability and COOH Acidity of Ligand on Reactivity

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2-Quinolinecarboxylic acid efficiently promotes both the dehydrative allylation of alcohols and the deallylation of allyl ethers and esters in the presence of [CpRu(CH_3CN)$_3$]PF_6. Comparison of the relative reactivity of various 4-substituted 2-pyridinecarboxylic acids has revealed two linear relations with different ρ values in the Hammett plots. These phenomena can be rationalized by the balance between the π-accepting ability of the pyridine moiety and the acidity of the carboxylic acid of the 2-pyridinecarboxylic acid derivative.

In the presence of a 1:1 mixture of 2-quinolinecarboxylic acid and [CpRu(CH_3CN)$_3$]PF_6, alcohols react with one equiv of allyl alcohol in aprotic solvents such as dichloromethane, acetone, and THF to give allyl ethers in high yield (Figure 1).[1,2] The reverse reaction—that is, deallylation of allyl ethers—is also promoted by the same catalytic system in alcoholic solvents such as methanol, ethanol, and 2-propanol, giving quantitatively the corresponding alcohol.[3–5] The allylation and deallylation reactions are greatly affected by the structure of the 2-quinolinecarboxylic acid. When the quinoline ring is replaced with pyridine, for example, the reactivity is decreased 5–10-fold. Condensation of the benzene ring at C(5) and C(6) of 2-pyridinecarboxylic acid should be advantageous for rate acceleration. To gain a deeper understanding of this catalyst, we are investigating its structure–reactivity relationship in a systematic manner.

Figure 2 shows the standard allylation and deallylation reaction conditions. The parent ligand is 2-pyridinecarboxylic acid (**1a**) and derivatives **1b**–**1e**, which have the electronically different substituents CH_3O, Cl, CF_3, and NO_2 at the C(4) position of **1a**, were used to compare the reactivity in the allylation of 2-phenylethanol (**2**) to give allyl phenethyl ether (**3**) ([**2**] = 100 mM, [**1**] = [{CpRu(CH_3CN)$_3$}PF_6] = 1 mM, CH_2Cl_2, reflux) and in the deallylation of **3** to **2** ([**3**] = 500 mM, [**1**] = [{CpRu(CH_3CN)$_3$}PF_6] = 1 mM, CH_3OH, 30 °C).

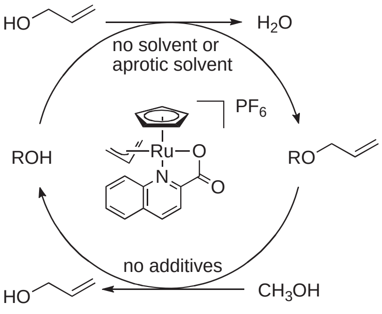

Figure 1. Dehydrative allylation of alcohols and deallylation of allyl ethers using [CpRu(CH_3CN)$_3$]PF_6/2-pyridinecarboxylic acid combined catalyst.

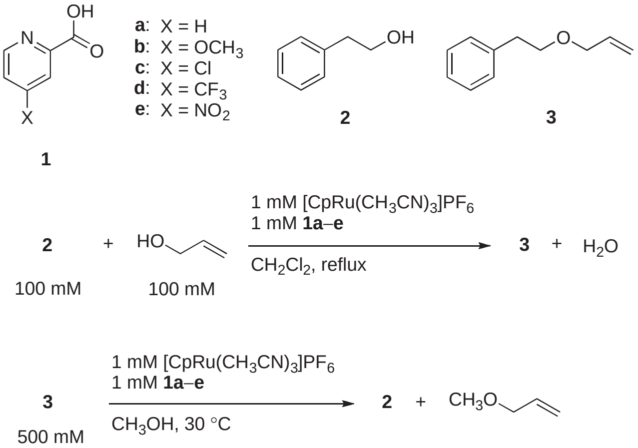

Figure 2. Standard reaction and conditions for the rate comparison.

Table 1. Relative reactivity in the [CpRu(CH_3CN)$_3$]PF_6/4-X-2-pyridinecarboxylic acid-catalyzed allylation of **2** with allyl alcohol and deallylation of **3**

				Reactivity	
Entry	Ligand (X)	σ_p	pK_a	Allylation[a]	Deallylation[b]
1	**1b** (CH_3O)	−0.28	6.71	0.11	0.7
2	**1a** (H)	0.00	5.40	1	1
3	**1c** (Cl)	0.22	4.07	3.5	1.4
4	**1d** (CF_3)	0.53	3.43	6.1	1.6
5	**1e** (NO_2)	0.81	2.90	6.5	1.9

[a]Condition: [**2**] = 100 mM; [allyl alcohol] = 100 mM; [{CpRu(CH_3CN)$_3$}PF_6] = 1 mM; [**1**] = 1 mM; solvent, CH_2Cl_2; reflux. [b]Condition: [**3**] = 500 mM; [{CpRu(CH_3CN)$_3$}PF_6] = 1 mM; [**1**] = 1 mM; solvent, CH_3OH; temp., 30 °C.

First, we examined the relative reactivity of 2-pyridinecarboxylic acid (**1a**) and its derivatives **1b**–**1e** in the allylation of **2** to **3** by using one equiv of allyl alcohol. The reaction was interrupted at <20% conversion, and aliquots were analyzed by GC (column: DB-WAX (0.25 mm × 15 m), initial temp.: 50 °C, rate: 10 °C/min, t_R of **2**: 6.0 min, t_R of **3**: 4.2 min). As illustrated in Table 1, the presence of an electron-donating CH_3O group at the C(4) position of the pyridine ring decreased the reactivity by a factor of 10. The ligand possessing the electron-withdrawing (EW) group Cl shows a reactivity ca. 3 times higher than that of the parent ligand **1a** (X = H). The degree of the enhancement became more significant with stronger EW

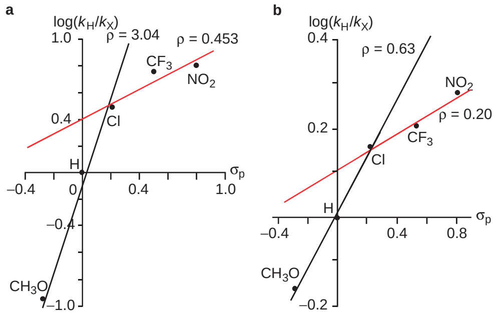

Figure 3. Hammet plots for the allylation and deallylation promoted by [CpRu(CH$_3$CN)$_3$]PF$_6$/4-X-2-pyridinecarboxylic acid combined catalytic system. **a**: the initial rate ratio/σ_p relation in allylation of **2** to **3**. **b**: the initial rate ratio/σ_p relation in deallylation of **3** to **2**. ρ = reaction constant.

substituents. As the σ_p value rose from 0.22 (Cl) to 0.53 (CF$_3$), for example, the reactivity doubled. With a σ_p value of 0.81 (NO$_2$), however, the reaction was not accelerated as much as expected. A Hammett plot using standard σ_p constants for the substituents exhibited two linear free-energy relationships with ρ values of +3.04 for **1a**, **1b**, and **1c**, and +0.453 for **1c**, **1d**, and **1e**, respectively (Figure 3a).

A similar tendency was also observed in the deallylation reaction, as shown in Figure 3b, although the rate dependence on the substituents was less significant than in the allylation reaction. The two linear lines had high correlation coefficients ($R = 0.996$ and 0.967); however, the correlation was less when all of the measurements were used in a least-squares approximation.

This two-line behavior observed in both allylation and deallylation can be rationalized by considering two factors: one is the π-accepting ability of the pyridine part, and the other is the acidity of the COOH part. Although the detailed mechanism is not clear at present, we believe that the π-allyl intermediate is in the resting state and that the nucleophilic attack of the alcohol on the π-allyl ligand determines the overall reaction rate. As the rate-determining step proceeds via reduction of the central Ru atom from Ru^{IV} to Ru^{II}, a ligand with higher π-accepting ability should stabilize the transition state. Consistent with this view, π-expanded 2-quinolinecarboxylic acid, in which the lowest unoccupied molecular orbital (LUMO) level is 0.6 eV lower than that of **1a** (2.12 vs. 1.52),[6] is 5–10-fold more reactive.[1,2] Introduction of an EW group at C(4) of **1a** also lowers the LUMO level, and the reactivity increases. At the same time, however, a strong EW group with a high σ_p value raises the acidity of COOH. As shown in Figure 4, the dibasic mono salt, [CpRu^{II}(4-X-2-pyridinecarboxylic acid)]PF$_6$, is essentially in equilibrium with a neutral [CpRu^{II}(4-X-2-pyridinecarboxylato)] species and a strong acid (HPF$_6$). The carboxylic proton in the cationic Ru complex can activate the hydroxy or alkoxy group via hydrogen bonding, thereby increasing the electrophilicity of the γ-carbon of the allyl alcohol or allyl ether through charge alternation. Combined with the highly nucleophilic Ru^{II} atom, oxidative addition of the allyl C–O bond to Ru^{II} smoothly proceeds to give an π-allyl Ru^{IV} intermediate. This redox-mediated donor–acceptor bifunctional catalyst ability[7,8] is lost in a neutral Ru carboxylato complex. If COOH in **1a** is replaced with SO$_3$H, then deallylation is several times slowed. The highly acidic SO$_3$H group should more easily generate the monobasic salt by liberating HPF$_6$. The balance between the π-accepting ability and the acidity of the ligand is thus important for gaining high catalytic reactivity in these allylation and deallylation reactions.[9]

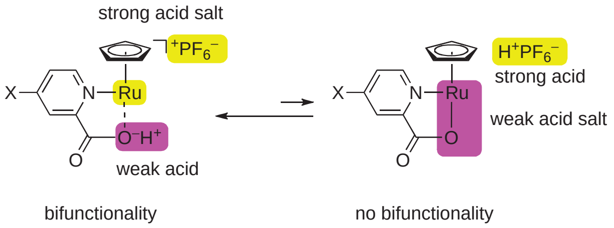

Figure 4. Equilibrium between dibasic monosalt and monobasic salt/acid.

In summary, the relationship between reactivity and ligand structure has been systematically investigated in the allylation of alcohols by allylic alcohol and the deallylation of allyl ethers catalyzed by a combined system of [CpRu(CH$_3$CN)$_3$]PF$_6$ and 4-X-2-pyridinecarboxylic acid. Both reactions proceed more rapidly with ligands possessing an EW group at C(4), but the pattern of the increase in rate is not simple. Linear relationships are observed for two ranges of σ_p values: namely, −0.30–0.2 and 0.2–0.8. This phenomenon can be rationalized by the balance between the π-accepting ability and the acidity of the ligand. A ligand with an EW group lowers the LUMO level to enhance the reactivity, whereas one with increased acidity lowers the reactivity. Therefore, the ideal ligand should have high π-accepting ability but maintain appropriate acidity. This observation would explain the high efficiency of 2-quinolinecarboxylic acid.[10]

This work was supported by Grant-in-Aid for Scientific Research on Priority Areas (No. 19028024, "Chemistry of Concerto Catalysis") from Ministry of Education, Culture, Sports, Science and Technology, Japan.

Dedicated to Professor Ryoji Noyori on the occasion of his 70th birthday.

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9 Less basicity of the oxygen atom in highly acidic groups may weaken the hydrogen bond to the alcoholic hydrogen atom, leading to less reactivity. A theoretical calculation of the transition state is now under investigation.

10 For the steric effect of anionic ligand on the reactivity in allylation using Cp*Ru(π-allyl) complexes, see: A. B. Zaitsev, S. Gruber, P. A. Plüss, P. S. Pregosin, L. F. Veiros, M. Wörle, *J. Am. Chem. Soc.* **2008**, *130*, 11604.