

Double C–H Activation during Functionalization of Phenyl(methyl)ketene on Iridium(I) Using Alkynes. Synthesis of 1,4-Dien-3-ones

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Multiple C–H activation at a single carbon atom is rare, especially on one metal center.^{1,2} In some cases, strongly binding polydentate ligands are required to observe double or triple C–H activations on a single metal.^{11,j} Although such multiple-activation processes on mononuclear species lead to fascinating isomerizations or rearrangements, in particular the formation of carbene complexes from sp³-carbons in alkanes, there does not appear to be any use of such activation in coupling processes,¹ with concomitant C–C bond formation.³ Organic side products occasionally isolated from stoichiometric reactions of Fischer carbene complexes suggest that *single* C–H activation of carbene or ketene complexes and alkyne insertion is possible.^{4a} Here we report an efficient tandem process involving two C–H activations at the same carbon, unusual in itself and, as far as we are aware, unique for ketene ligands or intermediates.⁵

Phenyl(methyl)ketene complex **1** was prepared for this work in 83% yield by allowing P(*i*-Pr)₃ and [ClIr(cyclooctene)]₂ to react in benzene for 2 h, followed by careful addition of the ketene as a solution.^{6,7} The structure of the complex, in particular its C,O-coordination⁸ and the proximity of the ketene methyl substituent to the metal fragment, are indicated by diagnostic NMR and IR data.⁹ In a similar way, 2-butyne complex **2a**^{4c} was made, and its structure is reported here.^{7,10} Solutions of **1** or **2a** in dry and oxygen-free C₆D₆ were observed to be stable at ambient temperature, though **1** showed some thermal reactivity.¹¹ However, when phenyl(methyl)ketene (2.5 equiv) was added to a solution of **2a**, consumption of both **2a** and the ketene commenced immediately. The ketene reacted faster, perhaps because of competing polymerization. After 18 h, formation of a new Ir hydride complex **3a** was complete (94% yield by NMR, 78% after isolation). Similar results were obtained by heating ketene complex **1** and 2-butyne at 60 °C for 18 h. In the product **3a**, an Ir hydride was implicated by a triplet in the ¹H NMR spectrum at –22.42 ppm (1 H, *J* = 16.0 Hz, Ir–H coupled to two equivalent P nuclei), whereas the conversion of 2-butyne into a 2-butenyl moiety was suggested by resonances ascribed to a vinyl H (5.82 ppm, qq, *J* = 7.0, 1.4 Hz, 1 H) and two methyl groups (1.60 ppm, d, *J* = 7.0 Hz, 3 H; 1.84 ppm, narrow multiplet, 3 H). However, one resonance that was difficult to explain was a downfield singlet at 10.70 ppm (1 H).

An X-ray diffraction study¹² pointed the way to structure **3a** (Figure 1). Key features include (a) cis-coordination of hydride and vinyl ligands, (b) geometry of the 2-butenyl substituent consistent with insertion of 2-butyne into an Ir–H bond at some stage of the reaction (vide infra), and (c) an unusually short Ir–C bond length. The latter point shows that the core metallacycle of **3a** can be regarded as a metallafuran, with a significant contribution from resonance form **3'**.¹³ Contribution from **3'** helps explain the unusual downfield NMR shift of both the carbon bound to Ir (δ 197.7 ppm, assigned with aid of 2D NMR⁷) and its attached proton (vide supra).

Scheme 1

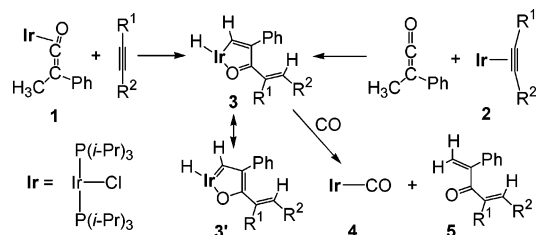


Table 1. Syntheses of Metallacycles **3** and Dienones **5**^a

	R ¹	R ²	yield of 3 from 2		yield of 5 from 3	
			NMR	isolated	NMR	isolated
a	CH ₃	CH ₃	94	78	92	78
b	Et	CH ₃	49	71 ^b	87 ^b	66 ^b
b'	CH ₃	Et	40			
c	Et	Et	96	81	93	82
d	Ph	CH ₃	— ^c	72 ^{b,c}	81 ^b	60 ^b
d' + d'' ^c	CH ₃	Ph	45 + 41			

^a See Supporting Information for details. ^b Combined yield of two stereoisomers. Full chromatographic separation not achieved. ^c **d''** = diastereomer of **d'** with opposite (*Z*) exocyclic alkene configuration. Only small amounts of **3d** were detected during the course of the reaction. See text.

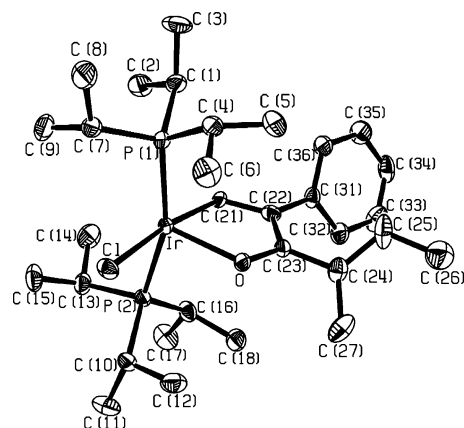


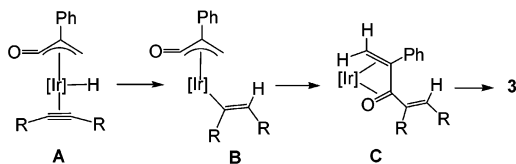
Figure 1. Molecular structure of **3a**. Key bond lengths (Å) and angles (°): Ir–O 2.193(5), C(23)–O 1.282(10), C(23)–C(22) 1.439(11), C(21)–C(22) 1.364(14), Ir–C(21) 1.955(8), P(1)–Ir–P(2) 161.6(1), Cl–Ir–O 92.6(1), O–Ir–C(21) 76.4(3). The hydride position is assumed to be trans to oxygen.

Table 1 shows that analogues of **3** are obtained in over 86% yield by heating **1** with a variety of internal alkynes.¹⁴ The unsymmetrical alkyne 2-pentyne is incorporated with modest regioselectivity, but 1-phenyl-1-propyne gave essentially one regiochemistry. The structures of **3** were assigned in analogy to that of **3a**, almost all proton and carbon resonances being assigned through extensive use of gCOSY, HMQC, and gHMBC data.⁷

Surprisingly, in the case of reactions of 1-phenyl-1-propyne or its complex **2d**, these data and careful use of NOE experiments revealed that only traces (7% at most) of metallacycle isomer **3d** were formed. Instead, the two major products (**3d'** and **3d''**, total 86% yield) shared the same regiochemistry but a different exocyclic alkene configuration.¹⁶

Demetalation of **3** could be effected by heating solutions under a CO atmosphere at 60–80 °C for 1–2 d. As monitored by ¹H NMR spectroscopy and careful integrations, the metal-containing product was **4**, whereas the organic species was dienone **5** (81–93% yield before isolation, Table 1). Intermediates were not detected in these reactions, but it would be reasonable to assume formation of **4** and **5** by ligand exchange of CO for carbonyl oxygen, followed by reductive elimination.

Several observations help explain the course of the double C–H activation. We previously characterized the first ketene–alkyne complexes, which could be generated either from the diphenylketene complex related to **1** and 2-butyne at 60 °C or from 2-butyne complex **2a** and diphenylketene at room temperature, both exchanges occurring with loss of one phosphine.^{4c} The formation of **3** from either **1** or **2** follows similar behavior (lower reaction temperature starting from the alkyne complex), except that we could not detect an intermediate. Thus, we propose that a ketene–alkyne complex (not shown) is formed, which unlike the diphenylketene case rapidly undergoes initial C–H activation at the ketene methyl carbon, forming **A**.¹⁵ Because we do not see intermediates in these



reactions, the metal center is identified simply as [Ir]. Subsequent alkyne insertion on **A** would give a vinyl ligand in **B**. Reductive elimination on **B**, perhaps favored by the availability of an extensive π -system, could produce dienone π -complex **C** or an isomer thereof. Finally, C–H activation on **C** would lead to **3**.¹⁷ According to this proposal, the double C–H activation may occur at two different stages in the alkyne incorporation process, but other variants are conceivable.

In summary, we show that a single metal center in **1** is able to activate a ketene substituent twice under mild conditions, and in a way which allows efficient C–C bond formation with alkynes. The resulting metallacycles **3** afford dienones **5** in good yields. There are few examples of dienones related to **5**, yet similar dienones undergo useful Lewis acid-promoted cyclizations.¹⁸ The role of multiple activation processes in tandem with insertion and C–C coupling processes in forming new organometallic and organic products is a subject of continuing investigation.

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Supporting Information Available: Details of the synthesis and characterization of products and crystal structures of **2a** and **3a** (PDF,

CIF). This material is available free of charge via the Internet at <http://pubs.acs.org>.

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- (5) Geoffroy, G. L.; Bassler, S. L. *Adv. Organomet. Chem.* **1988**, *28*, 1–83. Tidwell, T. T. *Ketenes*; Wiley: New York, 1995.
- (6) If the ketene was added neat, or if there was excess phosphine or metal precursor, lower yields of ketene complex were obtained; observation of insoluble white opaque material suggested that the ketene had polymerized.
- (7) See Supporting Information for full details.
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- (10) Crystal data for **2a**: triclinic, $P\bar{1}$ (No. 2), orange block, $0.35 \times 0.35 \times 0.60$ mm, $a = 9.415(3)$ Å, $b = 9.858(3)$ Å, $c = 14.708(4)$ Å, $\alpha = 79.67(3)^\circ$, $\beta = 83.31(3)^\circ$, $\gamma = 77.89(8)^\circ$, $V = 1308.7(8)$ Å³, $Z = 2$, $T = 173$ K, $D_{\text{calc}} = 1.528$ mg/m³, $wR = 9.36\%$ for 5687 observed reflections, $wR = 9.60\%$ for 6037 independent reflections, $GOF = 1.079$.
- (11) Heating **1** in the absence of alkyne at 85 °C for 6 d in dry and oxygen-free C₆D₆ produced CO complex **4** and styrene (each $\geq 98\%$ yield).
- (12) Crystal data for **3a**: monoclinic, $P2_1/n$, orange prism, $0.4 \times 0.5 \times 0.6$ mm, $a = 10.028(1)$ Å, $b = 15.732(2)$ Å, $c = 21.362(2)$ Å, $\beta = 98.543(9)^\circ$, $V = 3332.7(6)$ Å³, $Z = 4$, $T = 298$ K, $D_{\text{calc}} = 1.49$ g/cm³, $wR = 9.85\%$ for 5853 observed reflections, $wR = 22.25\%$ for 5887 independent reflections, $GOF = 1.039$.
- (13) Similar unusual bond lengths have been noted in other, related species. See, for example: Bleeke, J. R.; New, P. R.; Blanchard, J. M. B.; Haile, T.; Beatty, A. M. *Organometallics* **1995**, *14*, 5127–5137 and ref 6 therein.
- (14) Not surprisingly, the small amount of **1** which did not react with the alkyne was converted to **4**.¹¹ Terminal alkynes led to formation of vinylidene complexes, without incorporation of the ketene. 1-Trimethylsilyl-1-propyne produced small amounts (ca. 5%) of **3** of undetermined regiochemistry, but most alkyne was converted to the vinylidene complex *trans*-[Me₃Si-(Me)CC]Ir(C)[P(*i*-Pr)₃]₂.^{4c}
- (15) We previously reported the photochemical activation of the methyl group in **1**, which leads to a hydride related to **A** but lacking the alkyne. See footnote 26 of ref 4b.
- (16) The ratio of these products changed somewhat over time,⁷ in a reaction which was slightly accelerated by addition of 2-phenylpropionic acid, a likely product of hydrolysis of some phenyl(methyl)ketene. Thus, the most likely isomerization mechanism involves proton catalysis, though see also: Huggins, J. M.; Bergman, R. G. *J. Am. Chem. Soc.* **1979**, *101*, 4410–4412. Alexander, J. J. In *The Chemistry of the Metal–Carbon Bond*, Vol. 2; Hartley, F.; Patai, S., Eds.; Wiley: New York, 1985; pp 339–400.
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