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Regioselective and Diastereoselective Alkyl–Alkene and Alkene–Alkene Coupling Promoted by Zirconocene and Hafnocene[1]

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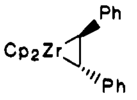
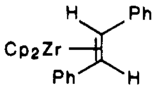
Summary: The reaction of $Cp_2Zr(CH_2CH_2R^1)_2$ with a monosubstituted terminal alkene ($H_2C{=}CHR^2$) can produce, in a highly regio- and diastereoselective manner, zirconacyclopentane derivatives; the *trans*-3,4-disubstituted derivatives may be formed to the extents of >98% in cases where both R^1 and R^2 are alkyl, while the *trans*-2-aryl-4-alkyl derivatives may be formed to the extents of >98% in the coupling between a monoalkyl-substituted olefin and styrene or its derivative.

Sir: Herein reported is a zirconium- or hafnium-promoted alkyl–alkene or alkene–alkene coupling reaction, which can proceed in a highly regio- and stereoselective manner to produce the corresponding zirconacyclopentanes. In the coupling between styrenes (or arylethyl) and monoalkyl-substituted alkenes (or alkyl), the reaction is even "pair"-selective, producing *trans*-2-aryl-4-alkyl-substituted zirconacyclopentanes. Some representative examples are shown in Schemes I–III.

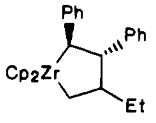
We have recently reported that treatment of $Cp_2Zr(Bu\text{-}n)_2$ (**1a**), generated in situ at −78 °C by the reaction of Cp_2ZrCl_2 with 2 equiv of *n*-BuLi, with 1 equiv of (*E*)- or (*Z*)-stilbene gives (*E*)-stilbene–zirconocene, which may be represented as a hybrid of **2a** and **2b**.[2] Although the reaction produces 1 equiv of 1-butene, no ring expansion reaction between **2** and 1-butene to produce zirconacyclopentane derivatives, such as **3a** and **3b**, takes place. In an attempt to induce ring expansion, an excess (4 equiv) of 1-butene was added to the reaction mixture containing **2**. Interestingly, the reaction gave an 88% yield of **4a** along with (*E*)-stilbene regenerated to the extent of 81%.



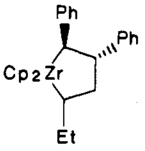
2a



2b



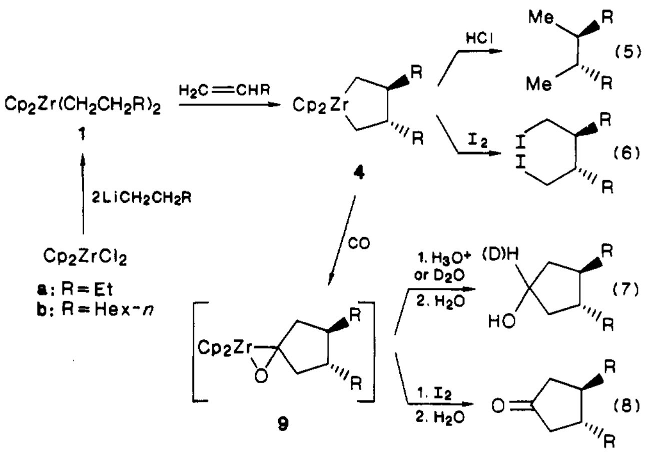
3a



3b

As expected, the formation of **4a** did not require **2**, and the reaction of **1a** with 1–2 equiv of 1-butene[3] provided **4a** in 60–70% yields. Protonolysis of **4a** with 3 N HCl afforded **5a** in 60% isolated yield based on Cp_2ZrCl_2, while its treatment with I_2 (3 equiv) gave **6a** in 52% isolated yield. The regio- and stereoisomeric purities of **5a** and **6a** are >98% as judged by their NMR spectra. Treatment of **4a** with 1.1 atm of CO at −78 °C followed by protonolysis with HCl in ether (−78 °C) produced **7a** in 45% yield along with only a trace of **8a**. Similarly, deuterolysis of the carbonylation product with D_2O gave monodeuterated **7a** in 46% isolated yield. The results indicate that the oxygen-bearing carbon atom in the carbonylation product is also bonded to a metal, i.e., Zr. Carbonylation of **4a** at 0 °C followed by treatment with 1.1 equiv of iodine at 0 °C provided **8a** as essentially the only cyclization product in 65% yield.[4] Although our attempts to spectroscopically characterize the carbonylation product before protonolysis or iodinolysis have not yielded definitive information, the results presented above strongly suggest **9a** as the structure of the initial product. The trans relationship of the two Et groups in **7a** has been clearly indicated by its ^{13}C NMR spectrum, which showed nine signals.[5]

Scheme I



In an analogous manner, treatment of Cp_2ZrCl_2 and 1.1 equiv of 1-octene with 2 equiv of *n*-OctLi, generated in situ by treating *n*-OctI with 2 equiv of *t*-BuLi in ether,[6] followed by protonolysis with 3 N HCl provided a 65% yield of 93% isomerically pure **5b**. To develop the corresponding alkene–alkene coupling procedure, a mixture of Cp_2ZrCl_2 and 3 equiv of 1-octene was treated with 2 equiv of *t*-BuLi at −78 °C, and the reaction mixture was slowly warmed to 0 °C. Protonolysis with 3 N HCl at 0 °C afforded **5b** in 51% yield. The use of *t*-BuMgCl in place of *t*-BuLi led to a lower product yield.

As anticipated, the reaction of $Cp_2Zr(Bu\text{-}n)_2$ with 1 equiv of 1-octene gave, after protonolysis, an essentially statistical 1:1:2 mixture of **5a**, **5b**, and **10** in 70% combined yield.

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[1] Metal-Promoted Cyclization. 28. Part 27. Zhang, Y.; Miller, J. A.; Negishi, E. *J. Org. Chem.* **1989**, *54*, 2043.

[2] (a) Negishi, E.; Cederbaum, F. E.; Takahashi, T. *Tetrahedron Lett.* **1986**, *27*, 1819. (b) Negishi, E.; Holmes, S. J.; Tour, J. M.; Miller, J. A.; Cederbaum, F. E.; Swanson, D. R.; Takahashi, T. *J. Am. Chem. Soc.* **1989**, *111*, 3336. (c) Takahashi, T.; Murakami, M.; Kunishige, M.; Saburi, M.; Uchida, Y.; Kozawa, K.; Uchida, T.; Swanson, D. R.; Negishi, E. *Chem. Lett.* **1989**, 761.

[3] During the course of our investigation a paper describing the reaction of $(\eta^5\text{-}C_5Me_5)_2Zr$ with 1 butene to produce $(\eta^5\text{-}C_5Me_5)_2Zr(CH_2CHEt)_2$ was published (Schock, L. E.; Marks, T. J. *J. Am. Chem. Soc.* **1988**, *110*, 7701).

[4] Yasuda, H.; Nagasuna, K.; Akita, M.; Lee, K.; Nakamura, A. *Organometallics* **1984**, *3*, 1470.

[5] ^{13}C NMR ($CDCl_3$, Me_4Si) δ 12.46, 12.53, 27.48, 27.89, 41.37, 41.62, 44.67, 45.83, and 71.82 ppm.

[6] Bailey, W. F.; Rossi, K. *J. Am. Chem. Soc.* **1989**, *111*, 765.

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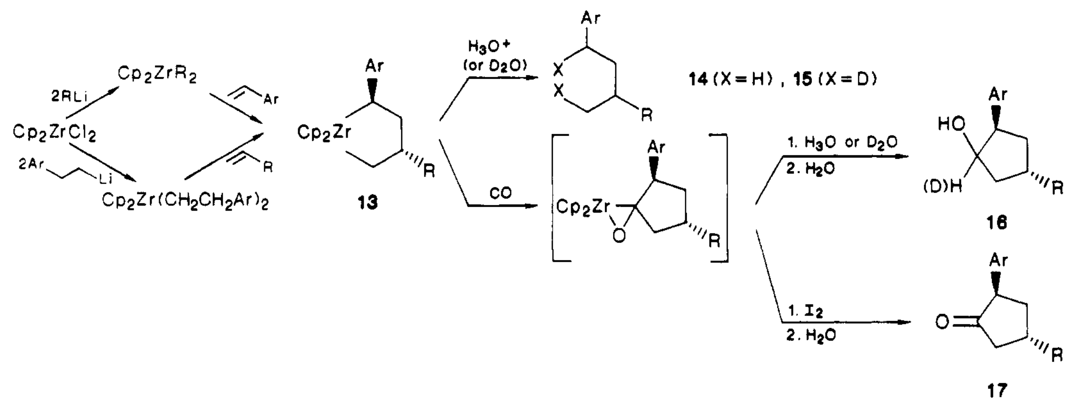
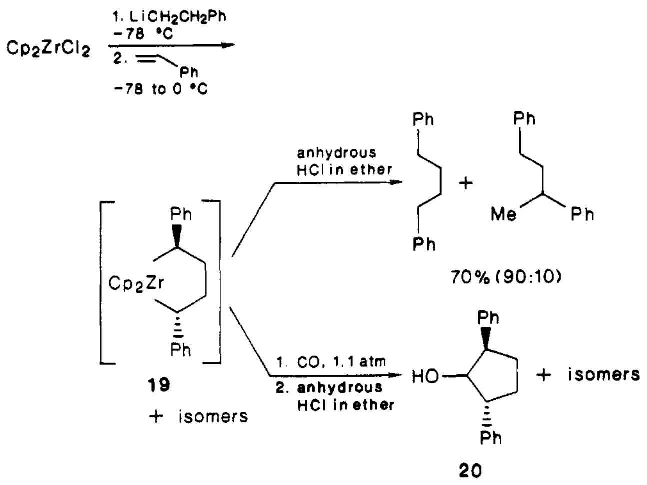
Scheme II

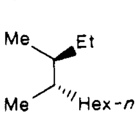


	a	b	c	d	e	f	g
Ar	Ph	Ph	p-Tol	p-FC6H4	Ph	Ph	Ph
R	Et	n-Hex	Et	Et	H	c-Hex	t-Bu

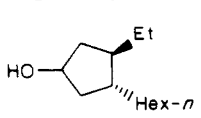
Scheme III



The corresponding mixtures of cyclopentanols and cyclopentanones were obtained by carbonylation–protonolysis and carbonylation–iodinolysis, respectively. Both cyclopentanol and cyclopentanone products were essentially 1:1:2 mixtures of the three expected products obtained in approximately 65% combined yields. The cross-coupled products 11 and 12 were readily obtained by distillation in 30–35% yields. While 11 was 1:1 diastereomeric mixture, 12 was >96% pure by ^{13}C NMR analysis.



10



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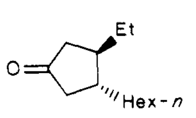
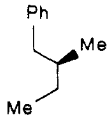


12



18

In sharp contrast with the above results, the reaction of $Cp_2Zr(Bu\text{-}n)_2$ with styrene (1.0–1.1 equiv) at −78 to 0 °C was "pair"-selective and produced **13a** in 70–80% yield. Its protonolysis with 3 N HCl gave >98% isomerically pure **14a** in 70% yield along with a 5% yield of **5a** and a 5–10% yield of 1,3- and 1,4-diphenylbutanes. Similarly, deuterolysis of **13a** with D_2O gave **15a** in 60% yield. The results indicate that the "pair"-selectivity of the reaction is 80–90%, and the regioselectivity for the formation of **13** is >98%.

When a mixture of 1 equiv each of styrene and 1-octene was added to $Cp_2Zr(Bu\text{-}n)_2$, the product obtained after protonolysis contained **14a** and **14b** in 33 and 32% GLC yields, respectively. Significantly, the amounts of 3,4-dimethyldecane and other possible cross- and homo-coupling products, if any, were <5% each. Addition of 1 equiv of styrene to **4a** at 0 °C gave within 1 h at 70% yield of **13a**. On the other hand, addition of even 4 equiv of 1-butene to **13a** did not cause a decrease in its amount by more than 10%. All these results indicate that **13a** is the thermodynamically favored product. Although we are still in search of spectroscopic evidence, it is likely that the Ph group α to Zr may exert benzylic and/or agostic stabilization. This would explain not only the observed regiochemistry but also the "pair"-selectivity.

To probe the stereochemistry of **13a**, it was carbonylated with 1.1 atm of CO at −78 °C for 1 h followed by treatment with 3 N HCl at −78 °C gave the alcohol **16a** in 60% yield without producing **17a** in a detectable amount. The crude carbonylation product was ≃95% isomerically pure. Detailed ^{1}H and ^{13}C NMR analysis including decoupling and ^{1}H 2D NOESY experiments has established the stereochemistry of **16a** to be 1*R**,2*S**,4*R**. Carbonylation of **13a** as above followed by deuterolysis with D_2O produced 1-deuterio-2-phenyl-4-ethylcyclopentanol (>96% D incorporation) in 60% yield. Making a reasonable assumption that the carbonylation reaction proceeds with retention of configuration, the trans stereochemistry may be assigned to **13a**. Treatment of the carbonylation product with 1.1 equiv of I_2 followed by $Na_2S_2O_3$ and $NaHCO_3$ provided a 60% yield of **17a**, which was ca. 85% trans. The procedure developed above has been applied to the preparation of **14c**, **14d**, **14e**, and **18** in 77, 57, 67, and 77% yields, respectively, with >98% regioselectivity. The preparation of **14** has also been achieved by successively treating Cp_2ZrCl_2 with $LiCH_2CH_2Ar^6$ (−78 °C), an alkene (−78 to 0 °C), and 3 N HCl. The yields of **14** were in the 60–80% range in cases where *n*-alkyl-substituted ethylenes were used. On the other hand, the use of vinylcyclohexane and 3,3-dimethyl-1-butene led to lower yields of 50 and 35%, respectively. To overcome this problem Cp_2HfCl_2 was used in place of Cp_2ZrCl_2. Thus treatment of Cp_2HfCl_2 in toluene with 2 equiv of $LiCH_2CH_2Ph$ produced a hafnocene derivative showing a ^{1}H NMR singlet at δ 6.25 ppm, which has been tentatively identified as $Cp_2Hf(CH_2CH_2Ph)_2$. Addition of 3,3-dimethyl-1-butene at 25 °C did not induce any change, but heating the mixture at 80–90 °C for 6 h gave, after protonolysis, a 68% yield of **14g**.

Finally, the reaction of $Cp_2Zr(CH_2CH_2Ph)_2$ generated in situ with styrene (1.1 equiv) in THF at −78 to 0 °C displayed yet another, albeit predictable, regioselectivity pattern. The ^1H NMR spectrum of the zirconacyclic product (**19**) showed a dominant singlet at δ 5.85 ppm. Protonolysis with anhydrous HCl in ether at −78 °C provided a 90:10 mixture of 1,4- and 1,3-diphenylbutanes in 70% isolated yield (80% by GLC), while its carbonylation followed by protonolysis with anhydrous HCl in ether at −78 °C afforded *trans*-2,5-diphenylcyclopentanol (**20**) in 45% yield along with minor amounts of unidentified but apparently isomeric products.

The results presented above expand the synthetic utility of the rapidly growing methodology involving 3- and 5-membered zirconocene and hafnocene derivatives.[2,4,7-11]

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(7) For papers describing alkyne-zirconocene and related reactions, see: (a) Atwood, J. L.; Hunter, W. E.; Alt, H.; Rausch, M. D. *J. Am. Chem. Soc.* **1976**, *98*, 2454. (b) Gell, K. I.; Schwartz, J. *J. Chem. Soc., Chem. Commun.* **1979**, 224. (c) Thanedar, S.; Farona, M. F. *J. Organomet. Chem.* **1982**, *235*, 65. (d) McDade, C.; Bercaw, J. E. *J. Organomet. Chem.* **1985**, *279*, 281. (e) Buchwald, S. L.; Lum, R. T.; Dewan, J. C. *J. Am. Chem. Soc.* **1986**, *108*, 7441. (f) Takahashi, T.; Swanson, D. R.; Negishi, E. *Chem. Lett.* **1987**, 623. (g) Buchwald, S. L.; Watson, B. T.; Huffman, J. C. *J. Am. Chem. Soc.* **1987**, *109*, 2544.

(8) For aryne–zirconocene reactions, see: (a) Erker, G.; Kropp, K. *J. Am. Chem. Soc.* **1979**, *101*, 3659. (b) Erker, G. *Acc. Chem. Soc.* **1984**, *17*, 103. (c) Buchwald, S. L.; Watson, B. T.; Huffman, J. C. *J. Am. Chem. Soc.* **1986**, *108*, 7411.

(9) For enyne–zirconocene and diyne–zirconocene reactions, see: (a) Negishi, E.; Holmes, S. J.; Tour, J. M.; Miller, J. A. *J. Am. Chem. Soc.* **1985**, *107*, 2568. (b) Negishi, E.; Swanson, D. R.; Cederbaum, F. E.; Takahashi, T. *Tetrahedron Lett.* **1987**, *28*, 917. (c) Nugent, W. A.; Thorn, D. L.; Harlow, R. L. *J. Am. Chem. Soc.* **1987**, *109*, 2788. (d) RajanBabu, T. V.; Nugent, W. A.; Taber, D. F.; Fagan, P. J. *J. Am. Chem. Soc.* **1988**, *110*, 7128.

(10) For conjugated diene–zirconocene reactions, see: Yasuda, H.; Tatsumi, K.; Nakamura, A. *Acc. Chem. Res.* **1985**, *18*, 120, and references therein.

(11) For hafnacyclopentane reactions, see: Erker, G.; Dorf, U.; Rheingold, A. L. *Organometallics* **1988**, *7*, 138. For titanacyclopentane reactions, see: (a) McDermott, J. X.; Wilson, M. E.; Whitesides, G. M. *J. Am. Chem. Soc.* **1976**, *98*, 6529. (b) Cohen, S. A.; Auburn, P. R.; Bercaw, J. E. *J. Am. Chem. Soc.* **1983**, *105*, 1136.

An Estimate of the Lifetime of 1,4-Dioxybutane Biradicals

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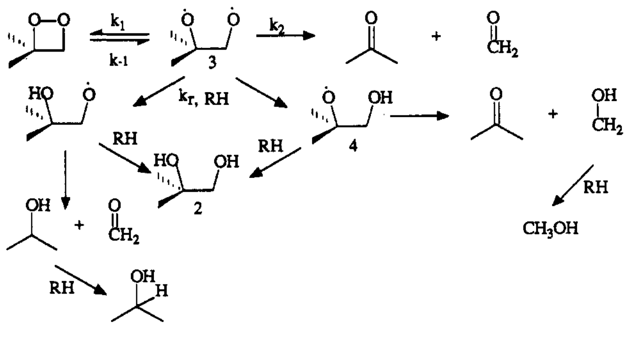
Summary: Previous kinetic data for the thermolysis of 1,2-dioxetanes has suggested a biradical or biradicaloid decomposition route, but direct evidence for a biradical intermediate has been lacking. We now report the trapping of a 1,4-dioxybutane biradical in the thermolysis of 3,3-dimethyl-1,2-dioxetane, where the lifetime is estimated to be in the range of 30–75 ps. Attempts to trap biradicals from the thermolysis of trimethyl- and tetramethyl-1,2-dioxetane were unsuccessful, and it was estimated that the maximum lifetimes of these biradicals were 7 ps.

Sir: There has been a growing interest in biradicals and their detection as intermediates in chemical and photochemical reactions.[1] Considerable evidence has been presented for 1,4-butane biradicals that are produced in the Norrish Type II photolysis of ketones.[2] The 1,4-butane biradical has also been postulated as intermediate in the thermal decomposition of cyclobutanes, based on kinetics[3] and the cis/trans isomerization of substituted cyclobutanes.[4] In the thermolysis of 1,2-dioxetanes, a stepwise mechanism has been proposed where 1,4-dioxybutane biradicals are postulated intermediates.[5] However, it has also been suggested that dioxetanes undergo ther-

Scheme I



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(1) (a) Salem, L.; Rowland, C. *Angew. Chem., Int. Ed. Engl.* **1972**, *11*, 92. (b) *Diradicals*; Borden, W. T., Ed.; Wiley: New York, 1982. (c) Michl, J.; Bonacic-Koutecky, V. *Tetrahedron* **1988**, *44*, 7559.

(2) (a) Saltiel, J.; Atwater, B. W. *Adv. Photochem.* **1988**, *14*, 1. (b) Scaiano, J. C.; Wagner, P. J. *J. Am. Chem. Soc.* **1984**, *106*, 4626. (c) Scaiano, J. C. *Acc. Chem. Res.* **1982**, *15*, 252. (d) Caldwell, R. A.; Majima, T.; Pac, C. *J. Am. Chem. Soc.* **1982**, *104*, 629.

(3) Benson, S. W. *Thermochemical Kinetics*, 2nd ed.; Wiley: New York, 1976.

(4) Gerberich, R.; Walters, W. D. *J. Am. Chem. Soc.* **1961**, *83*, 3935; **1962**, *84*, 4884.

(5) (a) Richardson, W. H.; Anderegg, J. H.; Price, M. E.; Crawford, R. *J. Org. Chem.* **1978**, *43*, 4045. (b) Richardson, W. H.; Anderegg, J. H.; Price, M. E.; Tappen, W. A.; O'Neal, H. E. *Ibid.* **1978**, *43*, 2236. (c) Richardson, W. H.; Montgomery, F. C.; Slusser, P.; Yelvington, M. B. *J. Am. Chem. Soc.* **1975**, *97*, 2819. (d) Richardson, W. H.; Montgomery, F. C.; Yelvington, M. B.; O'Neal, H. E. *Ibid.* **1974**, *96*, 7525. (e) Richardson, W. H.; Yelvington, M. B.; O'Neal, H. E. *Ibid.* **1972**, *94*, 1619. (f) Koo, J.-Y.; Schuster, G. B. *J. Am. Chem. Soc.* **1977**, *99*, 5403. (g) Horn, K. A.; Koo, J.-Y.; Schmidt, S. P.; Schuster, G. B. *Mol. Photochem.* **1978–79**, *9*, 1. (h) Wilson, T.; Golan, D. E.; Harris, M. S.; Baumstark, A. L. *J. Am. Chem. Soc.* **1976**, *98*, 1086. (i) Harding, L. B.; Goddard, W. A., III *Ibid.* **1977**, *99*, 4520. (j) Schaap, A. P.; Gagnon, S. D.; Zaklika, K. A. *Tetrahedron Lett.* **1982**, *23*, 2943. (k) Baumstark, A. L.; Dunams, T. *J. Org. Chem.* **1982**, *47*, 3754. (l) Kopecky, K. R.; Lockwood, P. A.; Gomez, R. R.; Ding, J.-Y. *Can. J. Chem.* **1981**, *59*, 851.

0022-3263/89/1954-3523$01.50/0