ORGANIC LETTERS

2000
Vol. 2, No. 13
1947−1949

Synthesis of [3]Ferrocenophanes via Samarium Diiodide Promoted Reductive Cyclizations of 1,1′-Dicinnamoylferrocenes

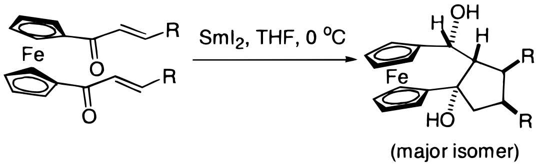
Shean-Jeng Jong and Jim-Min Fang*

Department of Chemistry, National Taiwan University,
Taipei, Taiwan 106, Republic of China

jmfang@mail.ch.ntu.edu.tw

Received May 5, 2000

ABSTRACT



A series of 1,1′-dicinnamoylferrocenes were converted to the corresponding [3]ferrocenophane diols (4a–e) in a stereoselective manner by using samarium diiodide to effect the intramolecular coupling reaction, aldol reaction, and reduction in one-pot operation. The major reaction pathway might be derived from a samarium chelated transition state (I_A) having the moieties of *s-cis* enone and (*Z*)-enolate. A solid-state structure of such [3]ferrocenophane diol product showed that the cyclopentadienyl groups were in an eclipsed orientation and slightly tilted.

Much attention has been paid to the study of carbon-bridged ferrocenophanes[1] due to their attractive features of chemical reactivities and potential use as building blocks for new materials. There are only a few reports on the conversion of 1,1′-dialkanoylferrocenes to [5]ferrocenophanes.[2] For example, 1,1′-dicinnamoylferrocene (**1a**) has been treated with NaOH to give 1,5-dioxo-3-phenyl-[5]ferrocenophanes,[2a] presumably via a three-step sequence: (i) base-catalyzed hydration of a cinnamoyl moiety to afford an intermediate of β-hydroxy ketone, (ii) retro-aldol reaction to give an enolate intermediate, and (iii) intramolecular Michael addition on the β-carbon of the other cinnamoyl moiety to furnish the cyclization product. 1,1′-Diacrylferrocene and 1,1′-dicrotonylferrocene also undergo the similar reactions in HCl or EtONa solution to give 1,5-dioxo-2-ethylidene-[5]ferrocenophanes.[2c,d]

We herein demonstrate that use of SmI_2 can convert a series of 1,1′-dicinnamoylferrocenes (**1a**−**f**) to the corresponding [3]ferrocenophanes (**3a**−**f** and **4a**−**f**) with annulation of cyclopentyl rings.[3] SmI_2 is a widely utilized one-electron-transfer reducing agent, which also shows good reactivity toward acylferrocenes.[4] Reduction, deoxygenation, and reductive coupling products have been obtained depending on the reaction conditions.

The following experimental procedure is typical. A deep blue SmI_2 solution (0.1 M, 1.8 mmol) was prepared by treatment of Sm (331 mg, 2.2 mmol) with 1,2-diiodoethane (507 mg, 1.8 mmol) in anhydrous THF (18 mL) for 1.5 h at room temperature. The SmI_2 solution was cooled in an ice

---

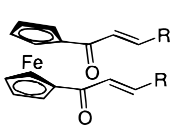
(1) For a recent review of ferrocenophanes with all carbon bridges, see: Heo, R. W.; Lee, T. R. *J. Organomet. Chem.* **1999**, *578*, 31.

(2) (a) Winstead, J. A. *J. Org. Chem.* **1972**, *37*, 1271. (b) Barr, T. H.; Watts, W. E. *Tetrahedron* **1968**, *24*, 3219. (c). Barr, T. H.; Watts, W. E. *Tetrahedron* **1969**, *25*, 861.

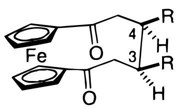
(3) The reductive cyclizations of 1,3-diphenyl-2-propen-1-one by using SmI_2 or $SmCl_3$/Zn give 1,3,4-triphenyl-2-benzoylcyclopentanol. See: (a) Cabrera, A.; Lagadec, R. L.; Sharma, P.; Arias, J. L.; Toscano, R. A.; Velasco, L.; Gavino, R.; Alvarez, C.; Salmon, M. *J. Chem. Soc., Perkin Trans. 1* **1998**, 3609. (b) Zhou, L.-h.; Shi, D.-q.; Gao, Y.; Shen, W.-b.; Dai, G.-y.; Chen, W.-x. *Tetrahedron Lett.* **1997**, *38*, 2729.

(4) (a) Neo, A. G.; Gref, A.; Riant, O. *Chem. Commun.* **1998**, 2353. (b) Christensen, T. B.; Riber, D.; Daasbjerg, K.; Skrydstrup, T. *Chem. Commun.* **1999**, 2051. (c) Jong, S.-J.; Chen, C.-T.; Fang, J.-M. *J. Organomet. Chem.* **1999**, *590*, 42. For the reaction of ferrocenyl ketone with Zn/Me_3-SiCl, see: (d) Denifl, P.; Hradsky, A.; Bildstein, B.; Wurst, K. *J. Organomet. Chem.* **1996**, *523*, 79.

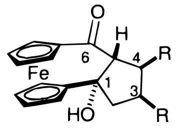
10.1021/ol0060228 CCC: $19.00



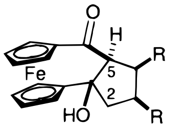
1a–f



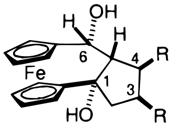
2a–f



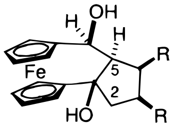
3a–f
(major isomer)



3a–f
(minor isomer)



4a–f
(major isomer)



4a–f
(minor isomer)

a series: R = C_6H_5
b series: R = p-$CH_3C_6H_4$
c series: R = m-$MeOC_6H_4$
d series: R = m-$CF_3C_6H_4$
e series: R = p-FC_6H_4
f series: R = p-ClC_6H_4

bath, and a THF (100 mL) solution of 1,1′-dicinnamolyferrocene (178 mg, 0.4 mmol) was added dropwise via a syringe pump over a period of 3 h. The mixture was stirred at 0 °C for an additional 3.5 h, and then filtered through a pad of silica gel by elution with EtOAc/hexane (1:1). The filtrate was concentrated and chromatographed on a silica gel column by elution with gradients of EtOAc/hexane (0−25%) to give two isomers of [3]ferrocenophane diols, **4a**-minor (58 mg, 32%, less retained on silica gel) and **4a**-major (88 mg, 49%).

Table 1 lists the results of the SmI_2 promoted reductive cyclizations of other 1,1′-cinnamoylferrocenes.[5] All reactions occurred readily at 0 °C in THF solutions without using dipolar additives such as hexamethylphosphoramide or *N*,*N*-dimethylacetamide.[6] It was found that the minor stereomers were less retained on silica gel column than the corresponding major isomers. When a THF solution of **1a** (0.5 mmol) was added dropwise to the freshly prepared SmI_2 solution (1.8 mmol) over a period of 1 h, followed by stirring at 0 °C for a brief period (10 min), dione **2a** and aldol **3a** were obtained in 23% and 44% yields (entry 2). The ^1H NMR analyses indicated that both products existed as single isomers. The starting material was entirely recovered when 0.8 mmol of **1a** was treated with 0.45 mmol of SmI_2 at 0 °C for 2 h (entry 3). The [3]ferrocenophane diols **4c** (R = m-$MeOC_6H_4$) were obtained in an excellent yield (97%) by treatment of **1c** (0.4 mmol) with an excess of SmI_2 (1.8 mmol). When a less amount of SmI_2 (0.9 mmol) was used, with respect to 0.4 mmol of ferrocene **1c**, the intermediate aldol products **3c** were isolated in 70% yield (entry 6). Because of the low solubility of **1f** (R = p-ClC_6H_4) in THF, it only reacted sluggishly with SmI_2 to give the aldol products **3f** in 15% yield along with a recovery of the starting material.

Table 1. SmI_2-Mediated Intramolecular Coupling Reactions of 1,1′-Dicinnamoylferrocenes **1a−f** (THF, 0 °C)[a]

entry	substrate	R	SmI_2	products (yields; ratio of isomers)
1	**1a**	C_6H_5	4.5[b]	**4a** (81%; 60:40)
2[c]	**1a**		3.6[b]	**2a** (23%; 100:0) **3a** (44%; 100:0)
3	**1a**		0.6[b]	no reaction
4	**1b**	p-$CH_3C_6H_4$	4.5[b]	**4b** (72%; 62:38)
5	**1c**	m-$MeOC_6H_4$	4.5[b]	**4c** (97%; 86:14)
6[d]	**1c**		2.3[b]	**3c** (70%; 69:31)
7	**1d**	m-$CF_3C_6H_4$	4.5[b]	**4d** (61%; 52:48)
8	**1e**	p-FC_6H_4	4.5[b]	**4e** (47%; 100:0)
9[e]	**1f**	p-ClC_6H_4	4.5[b]	**3f** (15%; 100:0)

[a] According to the typical experimental procedure (see text) by addition of a THF solution of substrate (0.4 mmol) to a SmI_2 solution (1.8 mmol) over a period of 3 h and stirring for 3.5 h at 0 °C. [b] The molar proportion of SmI_2 to substrate. [c] The substrate was added to a SmI_2 solution over 1 h and stirred for 10 min at 0 °C. [d] The substrate (0.4 mmol) was added to a SmI_2 solution (0.9 mmol) over 1.5 h and stirred for 1 h at 0 °C. [e] Because of low solubility of **1f** in THF, the SmI_2 solution was added to the THF solution of substrate at 0 °C.

A sample of **4a**-major diol was obtained by recrystallization from $CHCl_3$/hexane, and the (1*S**,3*S**,4*S**,5*S**,6*R**) configuration was rigorously determined by an X-ray diffraction analysis (Figure 1).[7] The solid-state **4a**-major contained two cyclopentadienyl groups in an eclipsed orientation (ring twist angle = 2.7° ± 0.2). The Cp rings were just slightly displaced (ring tilt angle = 9.63° ± 0.12) despite **4a**-major having an additional annulation of five-membered ring.[8]

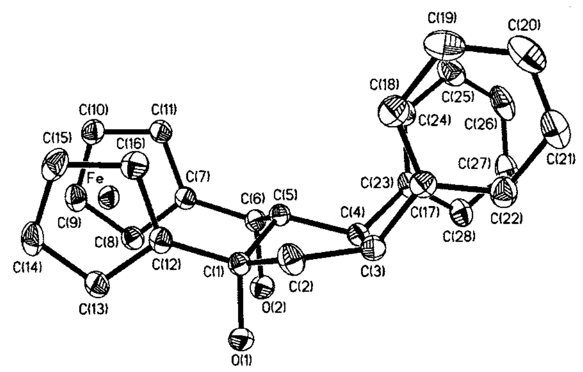


Figure 1. ORTEP drawing of compound **4a**-major.

A reaction pathway (Scheme 1) is proposed to explain the stereochemical outcome. The samarium-chelated transition state $\mathbf{I_A}$, having the moieties of *s-cis* enone and (*Z*)-enolate, could undergo a coupling reaction to link the β,β'-carbons to give the *meso*-type intermediate $\mathbf{II_A}$. The subsequent aldol

---

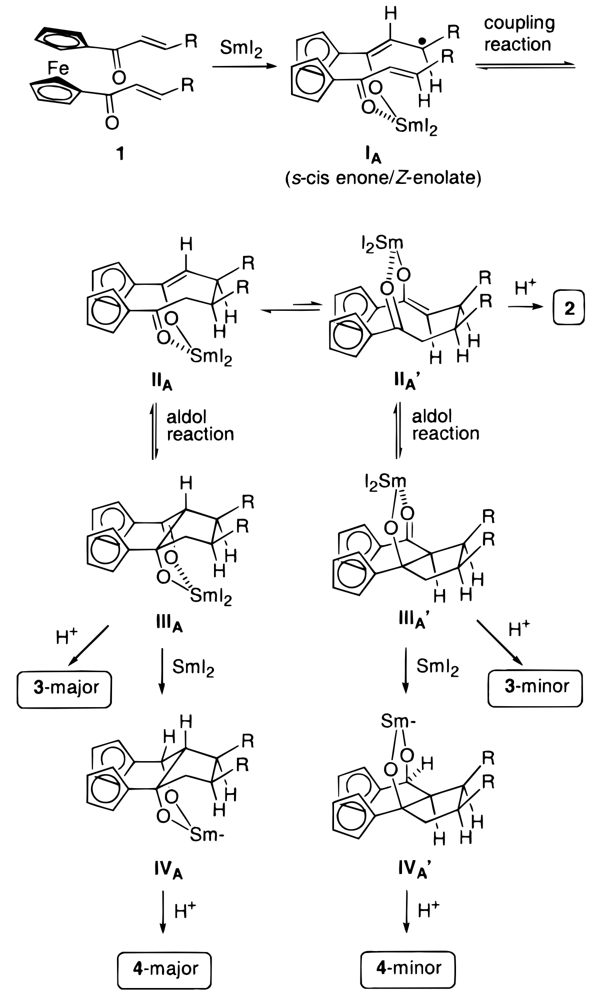
(5) All new compounds are characterized by spectral methods (IR, MS, HRMS, ^1H and ^{13}C NMR).

(6) Additives HMPA and DMA can promote the reduction of enones to the corresponding ketones. See: Fujita, Y.; Fukuzumi, S.; Otera, J. *Tetrahedron Lett.* **1997**, *38*, 2121.

(7) Crystal data for **4a**-major: monoclinic, $a = 11.9621$ (2), $b = 7.6080$ (2), $c = 23.7632$ (5) Å, $V = 2129.94$ (8) Å^3, crystal size 0.25 × 0.2 × 0.15 mm, $T = 296$ (2) K, space group $P2_1/c$, $Z = 4$, absorption coefficient = 0.731 mm^{-1}, reflections collected 12124, independent reflections 3741 ($R_{\mathrm{int}} = 0.0239$). Final R indices [$I > 2\sigma(I)$] $R1 = 0.0300$, w$R2 = 0.0777$, R indices (all data) $R1 = 0.0388$, w$R2 = 0.0816$. Refinement method: full-matrix least-squares on F^2.

(8) The Cp rings in the crystal structure of [3]ferrocenophane-1-one are slightly staggered with a ring twist angle of 11.8° and a ring tilt angle of 8.8°. See: Jones, N. D.; Marsh, R. E.; Richards, J. H. *Acta Crystallogr.* **1965**, *19*, 330.

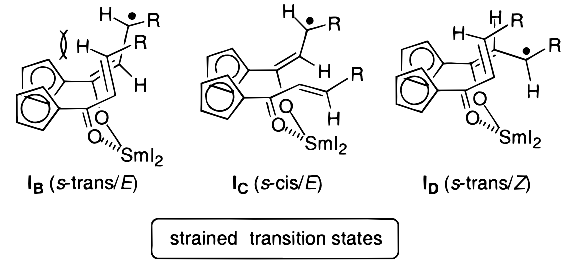
Scheme 1



reaction of $\mathbf{II_A}$ could be mediated by samarium ion to give $\mathbf{III_A}$ with the carbonyl and hydroxyl groups on the same face. Further reduction of the carbonyl group with SmI_2, followed by abstraction of hydrogen atom from the less hindered *exo* face, would afford **4a**-major in a stereoselective fashion. All the transition states $\mathbf{I_A}-\mathbf{IV_A}$ showed their dispositions similar to the single-crystal structure of **4a**-major.

Attempts to crystallize **2a**, **3a**, **3c**, **3f**, or the minor isomers of **4a**−**e** failed. The stereochemistry of minor products **3c** and **4a** were inferred from their NOESY spectra (500 MHz). The NOE correlations of H-3 (at δ 3.55, m), H-4 (at δ 3.89, dd, $J = 12.4$, 9.7 Hz), and H-5 (at δ 4.63, d, $J = 12.4$ Hz) in **3c**-minor aldol indicated that these protons were on the same face. A D_2O-exchangeable signal at δ 2.86 (s) was attributed to the hydroxyl group, which likely formed intramolecular hydrogen bonding with the carbonyl group. In addition to the NOE correlations of H-3 (at δ 3.64, m), H-4 (at δ 4.00, br d, $J = 12.6$ Hz), and H-5 (at δ 2.69, br d, $J = 12.6$ Hz), the **4a**-minor diol also showed the NOE correlation of H-6 (at δ 4.31, br d, $J = 5.0$ Hz) with H-4.

On the basis of mechanistic consideration (Scheme 1), the **3**-major and **4**-major products were thus assigned to have the (1*S**,3*S**,4*S**,5*S**) and (1*S**,3*S**,4*S**,5*S**,6*R**) configurations, whereas the corresponding **3**-minor and **4**-minor isomers were assigned to have the (1*R**,3*S**,4*S**,5*R**) and (1*R**,3*S**,4*S**,5*R**,6*S**) configurations. After a prolonged reaction time, the transition state $\mathbf{II_A}$ might undergo conformational interchange to the transition state $\mathbf{II_A}'$. Both $\mathbf{II_A}$ and $\mathbf{II_A}'$ would afford dione **2** upon protonation. The aldol reaction of $\mathbf{II_A}'$ would give **3**-minor products via a chelated transition state $\mathbf{III_A}'$. Further reduction of $\mathbf{III_A}'$ would also occur in a stereoselective manner to give **4**-minor diols.



Other reaction pathways via the transition states $\mathbf{I_B}$, $\mathbf{I_C}$, and $\mathbf{I_D}$ were disfavored due to the steric effects. Transition state $\mathbf{I_B}$ with the moieties of *s-trans* enone and (*E*)-enolate might exert certain repulsion between Cp rings and the β-hydrogen atoms. The transition states $\mathbf{I_C}$ and $\mathbf{I_D}$ with *s-cis*/*E* enone or *s-trans*/*Z* enone arrangements would cause severe strains in the intramolecular coupling reactions. Formation of the *dl*-type isomer $\mathbf{I_C}$ or $\mathbf{I_D}$ would be less likely, in accordance with no finding of the **2a** isomer in our present study.

In summary, our present SmI_2 promoted method is the first report on the efficient reductive cyclization of 1,1′-dicinnamoylferrocenes in a stereoselective manner. Application of this method to synthesize strained [*m*]ferrocenophanes is currently under investigation.

Acknowledgment. We thank the National Science Council for financial support.

Supporting Information Available: Additional experimental procedures and spectral data of new compounds. This material is available free of charge via the Internet at http://pubs.acs.org.

OL0060228