Acknowledgment. We thank the National Science Foundation for their generous support of our programs.

Registry No. 2, 80398-85-2; 3 (R = CH_3), 84851-70-7; 3 (R = n-C_4H_9), 84851-71-8; 3 (R = i-C_3H_7), 84851-72-9; 3 (R = $CH_2CH_2CH{=}CH_2$), 84851-73-0; 3 (R = CH_2CH_2Ph), 84851-74-1; 3 (R = $CH{=}CH_2$), 84851-75-2; 3 (R = Ph), 84851-76-3; 4 (R = CH_3) (isomer 1), 84851-77-4; 4 (R = CH_3) (isomer 2), 84894-10-0; 4 (R = n-C_4H_9) (isomer 1), 84851-78-5; 4 (R = n-C_4H_9) (isomer 2), 84894-11-1; 4 (R = i-C_3H_7) (isomer 1), 84851-79-6; 4 (R = i-C_3H_7) (isomer 2), 84894-12-2; 4 (R = $CH_2CH_2CH{=}CH_2$) (isomer 1), 84851-80-9; 4 (R = $CH_2CH_2CH{=}CH_2$) (isomer 2), 84894-13-3; 4 (R = CH_2CH_2Ph) (isomer 1), 84851-81-0; 4 (R = CH_2CH_2Ph) (isomer 2), 84894-14-4; 4 (R = $CH{=}CH_2$) (isomer 1), 84851-82-1; 4 (R = $CH{=}CH_2$) (isomer 2), 84894-15-5; 4 (R = Ph) (isomer 1), 84851-83-2; 4 (R = Ph) (isomer 2), 84894-16-6; 5 (R = CH_3), 84851-84-3; 5 (R = n-C_4H_9), 84851-85-4; 5 (R = i-C_3H_7), 84851-86-5; 5 (R = $CH_2CH_2CH{=}CH_2$), 84851-87-6; 5 (R = CH_2CH_2Ph), 84851-88-7; 5 (R = $CH = CH_2$), 84851-89-8; 5 (R = Ph), 84851-90-1; 8, 84851-91-2; CH_3Br, 74-83-9; n-C_4H_9Br, 109-65-9; i-C_3H_7Br, 75-26-3; $CH_2{=}CHCH_2CH_2Br$, 5162-44-7; $PhCH_2CH_2Br$, 103-63-9; $CH_2{=}CHBr$, 593-60-2; PhBr, 108-86-1; pivaloyl chloride, 3282-30-2.

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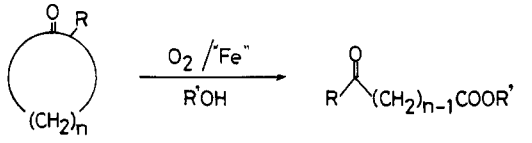
Ferric Salt Catalyzed Oxygenation of Cycloalkanones to Oxo Esters by Molecular Oxygen

Summary: Ferric salts catalyzed the regiospecific oxygenation of cycloalkanones by molecular oxygen to give oxo esters in the presence of aliphatic alcohol under mild conditions.

Sir: Transition-metal-catalyzed oxygenation by molecular oxygen has received much attention from a synthetic point of view as well as in connection with the oxygenation in biological systems.[1] However, there have been few examples of efficient iron-catalyzed oxygenations by molecular oxygen.[2]

We now report that regiospecific oxidative ring-opening of cycloalkanones[3] to oxo esters by molecular oxygen in the presence of aliphatic alcohol is catalyzed by simple ferric salts, which seems to activate substrate and molecular oxygen simultaneously (eq 1).



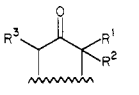
(1)

Table I. $FeCl_3$-Catalyzed Oxygenation of 1 with[a] Some Alcohols as Nucleophiles

ROH	yield, %
MeOH	93
EtOH	79
$PhCH_2OH$	80
t-$BuCH_2OH$	63
i-PrOH	73
t-BuOH	42
H_2O	86

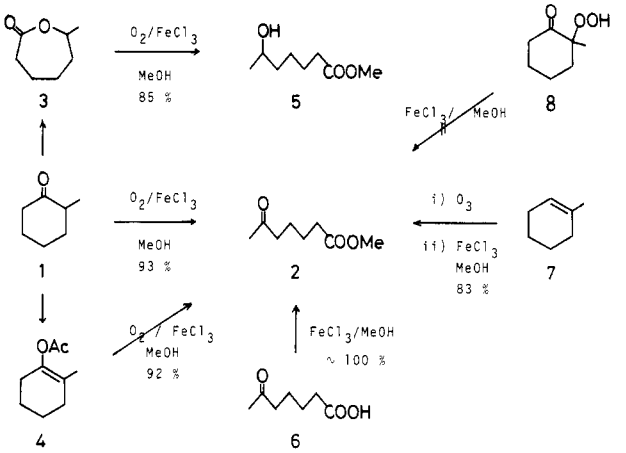
[a] Carried out using 10 equiv of ROH in benzene at 60 °C under oxygen atmosphere (1 atm).

Table II. Substituent Effect on the Oxygenation of Substituted Cyclohexanones[a]

run		conv, %	yield, %
1	$R^1 = R^2 = R^3 = H$	14	66[b]
2	R^1 = Me, $R^2 = R^3 = H$	100	93
3	R^1 = Et, $R^2 = R^3 = H$	100	81
4	R^1 = t-Bu, $R^2 = R^3 = H$	28	65
5	R^1 = OMe, $R^2 = R^3 = H$	5	0
6	$R^1 = CF_3$, $R^2 = R^3 = H$	5	0
7	R^1 = Br, $R^2 = R^3 = H$	46	complex
8	R^1 = Me, R^2 = H, R^3 = Me	60	63
9	R^1 = Me, R^2 = Cl, R^3 = Me	35	0[c]

[a] Carried out in methanol with $FeCl_3$. [b] A mixture of methyl 6-oxohexanoate and its dimethyl acetal (1:2). [c] Dehydrochlorination yielding 2,6-dimethylcyclohexenone was observed.

Chart I



Treatment of a benzene solution of 2-methylcyclohexanone (1) (0.2 M) including 10 equiv of methanol and a catalytic amount of $FeCl_3$ (2–5 mol %) at 60 °C under oxygen atmosphere (1 atm) for 20 h gave methyl 6-oxoheptanoate (2) in 93% yield. $FeCl_3$ can be replaced by other ferric salts such as $Fe(NO_3)_3$, $FeBr_3$, and $K_3Fe(CN_6H^+$ but not by ferric organometalic complexes such as $Fe(acac)_3$.[6] Ferrous salts also showed catalytic activity, though less than that of ferric salts ($FeCl_2$, 24% yield).[7] Methanol could be replaced by aliphatic alcohols as summarized in Table I. Not only primary and secondary but tertiary and sterically hindered alcohols could form an

(1) For reviews, see: (a) "Metal-Catalyzed Oxidation of Organic Compounds"; Sheldon, R. A., Kochi, J. K., Eds.; Academic Press: New York, 1981. (b) Ullrich, V.; Staudinger, H. J. "Biological and Chemical Aspects of Oxygenases"; Bloch, K., Hayaishi, O., Eds.; Maruzen: Tokyo, 1966.

(2) (a) Ito, S.; Inoue, K.; Matsumoto, M. *J. Am. Chem. Soc.* **1982**, *104*, 6450. (b) Paulson, D. R.; Ullman, R.; Sloane, R. B.; Closs, G. L. *J. Chem. Soc., Chem. Commun.* **1974**, 186.

(3) Autoxidation of cycloalkanones is known to be catalyzed by base[4] as well as certain transition metals such as Co and Mn.[5] However, in general, products were not oxo esters but dicarboxylic acids.

(4) For reviews, see: (a) Russell, G. A.; Bemis, A. G.; Geels, E. J.; Janzen, E. G.; Moye, A. J. *Adv. Chem. Ser.* **1968**, *No. 75*, 174. (b) Sosnovsky, G.; Zaret, E. H. "Organic Peroxides"; Swern, D., Ed.; Wiley: New York, 1970; Vol. 1, p 517.

(5) (a) Onopchenko, A.; Schulz, J. G. D. *J. Org. Chem.* **1973**, *38*, 3729. (b) Prengle, H. W.; Barona, N. *Hydrocarbon Process.* **1970**, *49*, 106.

(6) Although the reason is now ambiguous, $Fe(Acac)_3$ seems not to act as a competent Lewis acid for this oxidation.

(7) Hammond showed that LiCl accelarated the oxidaton of $FeCl_2$ by molecular oxygen in methanol.[8] Nevertheless, LiCl did not practically improve the $FeCl_2$-catalyzed oxidation of 1 in methanol.

(8) Hammond, G. S.; Wu, C. S. *Adv. Chem. Ser.* **1968**, *No. 77*, 186.

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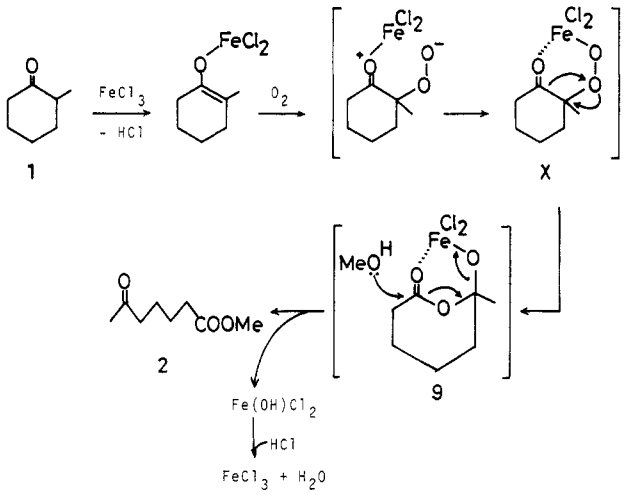
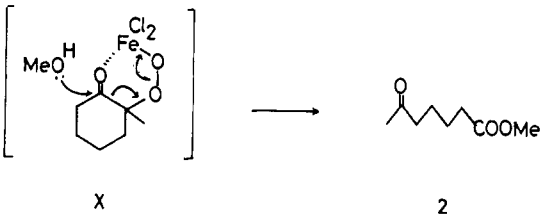
Scheme I



Scheme II



ester function of oxo esters. The reactivity of *t*-BuOH suggested the involvement of highly active intermediates in this oxygenation reaction.

α-Substituent effects of cyclohexanone derivatives for the present iron-catalyzed oxygenation were also noteworthy. As shown in Table II, alkyl groups, except for the bulky *tert*-butyl group, promoted this oxygenation, whereas trifluoromethyl and methoxy groups, inhibited it. Steric as well as electronic factors apparently affected oxygenation.

An attempt has been made to clarify the mechanistic aspects of this oxygenation. First, the $FeCl_3$-catalyzed reaction of **1** was attempted with iodosobenzene instead of molecular oxygen as an oxidant to result in no oxidation. This fact suggested that an iron–oxenoid type intermediate did not participate as an active species in the reaction of eq 1. Next, as shown in Chart I, several model reactions were studied. The enol acetate **4** could be easily oxidized into **2**. This result and the regiochemistry of the oxygenation shown in the table II suggested the intermediary of an enol and/or an enolate of cyclohexanone, which was probably coordinated by Fe(III).[9] Lactone **3** was merely converted to the solvolysis product **5** in high yield under the same conditions. This fact is markedly in contrast to the oxidation of **1** to **2** by $H_2O_2/Mo(O_2)$ where the lactone **3** was suggested as an intermediate.[11] Treatment of 2-(hydroperoxy)-2-methylcyclohexanone (**8**) (synthesized independently[12]) with $FeCl_3$ in methanol gave only a small amount of **2**. No inhibitory effect of 2,6-di-*tert*-butyl-*p*-cresol on the oxygenation suggested that this oxygenation did not proceed through a radical chain process, although it could not exclude short-lived-radical or caged-radical species as the intermediate. In the feric salt catalyzed reaction of **6** with alcohol, methanol gave the methyl ester **2** quantitatively, but *tert*-butyl alcohol afforded a slight amount of the *tert*-butyl ester (<7%). This result was inconsistent with that of the Table I and showed that the oxidative ring-opening of cyclohexanones did not proceed through a free oxocarboxylic acid (**6**). Considering these facts, we can draw a plausible mechanism as shown in Scheme I. In Scheme I, molecular oxygen attacks an iron enolate to yield a peroxide (X) coordinated by iron, which causes a Baeyer–Villiger type intramolecular redox reaction to yield a pseudoacid (**9**). The intermediate **9** is subjected by nucleophilic attack of alcohol to give **2**. This mechanism resembles that of metal-catalyzed decomposition of ozonides. In fact, ozonide of 1-methylcyclohexane (**7**) gave smoothly the ester **2** upon treatment with methanol in the presence of a catalytic amount of $FeCl_3$. Another mechanism is also possible as shown in Scheme II, where the intermediary peroxide (X) suffers directly nucleophilic attack of alcohol to yield the ester **2**.

To judge whether Scheme I or II is more plausible, we carried out labeling experiments using heavy molecular oxygen ($^{18}O_2$). However, it gave no clear cut results,[13] since the isotope exchange reaction of carbonyl oxygen occurred rapidly.[14]

From a synthetic point of view, this oxygenation of cycloalkanones has advantages over other methods for preparing the oxo esters such as electrochemical oxidation of enol ether of cyclohexanone,[15] ozonization of the enol ether,[16] and Mo-catalyzed oxidation of methoxycyclohexane by H_2O_2.[17] Annulated cycloalkanones also gave the oxo esters in moderate to high yields.[18] A study of the scope and limitation of iron-catalyzed oxygenation of cyclic ketones by molecular oxygen is now in progress.[19]

Typical Experiment. Preparation of Methyl 6-Oxoheptanoate (2). A solution of 2-methylcyclohexanone (**1**) (519 mg), $FeCl_3$ (50 mg), and MeOH (1 mL) in benzene (20 mL) was stirred under an oxygen atmosphere (1 atm) at 60 °C for 20 h. The reaction mixture was concentrated and chromatographed on silica gel. Elution with CH_2Cl_2 gave **2** (681 mg, 93% yield) as a colorless oil: bp 84–85 °C (3 mmHg); IR (neat) $\nu_{C=O}$ 1720, 1738 cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.46–1.76 (m, 4 H), 2.01 (s, 3 H), 2.18–2.56 (m, 4 H), 3.62 (s, 3 H). Calcd for $C_8H_{14}O_3$: C, 60.74; H, 8.92. Found: C, 60.60; H, 9.09.

Registry No. 1, 583-60-8; 2, 2046-21-1; 3, 2549-59-9; 4, 1196-73-2; 5, 2517-46-6; 6, 3128-07-2; 7, 591-49-1; 8, 21961-02-4; OHC-$(CH_2)_4$COOMe, 6654-36-0; $(MeO)_2CH(CH_2)_4$COOMe, 25176-55-0; EtCO$(CH_2)_4$COOMe, 2955-61-5; *t*-BuCO$(CH_2)_4$COOMe, 84928-33-6; MeCO$(CH_2)_3CH(CH_3)$COOMe, 2570-90-3; $FeCl_3$, 7705-08-0; $Fe(NO_3)_3$, 10421-48-4; $FeBr_3$, 10031-26-2; $K_3Fe(CN)_6H^+$, 72641-61-3; cyclohexanone, 108-94-1; 2-ethylcyclohexanone, 4423-94-3; 2-*tert*-butylcyclohexanone, 1728-46-7; 2-methoxycyclohexanone,

(9) Ferric salts are well-known to act as strong Lewis acid.[10] Catalytic activity of Lewis acids other than Fe(III) was also investigated; $CuCl_2$, $RuCl_3$, and $RhCl_3$ possessed weak catalytic activity for the oxygenation described here, while neither $AlCl_3$ nor $ZnCl_2$ acted as the catalyst.

(10) "Friedel Crafts and Related Reactions"; Olah, G. A., Ed.; Interscience: New York, 1963; Vol. 1.

(11) Jacobson, S. E.; Tang, R.; Mares, F. *J. Chem. Soc. Chem. Commun.* **1978**, 888.

(12) Cubbon, R. C. P.; Hewlett, C. *J. Chem. Soc.* **1968**, 2978.

(13) ^{18}O was initially incorporated in 70–80% yield. The incorporated heavy atom ($^{18}O_2$) was scrambled into the carbonyl and the ester carbonyl oxygen (3:2). However, the content of ^{18}O in the reaction mixture decreased significantly after the storage. Contact of the reaction mixture with silica gel for chromatography also promoted the isotope exchange.

(14) Meijer, E. W.; Wynberg, H. *J. Am. Chem. Soc.* **1982**, *104*, 1145.

(15) Shono, T.; Matsumura, Y. Hamaguchi, H.; Imanishi, T.; Yoshida, K. *Bull. Chem. Soc. Jpn.* **1978**, *51*, 2179.

(16) Schmidt, U.; Grafen, P. *Justus Liebigs Ann. Chem.* **1962**, *656*, 97.

(17) Waldmann, H.; Schwerdtel, W.; Swodenk, G. Ger. Offen. 2 252 780, 1974.

(18) For example, β-tetralone gave methyl 3-(*o*-formylphenyl)-propionate (61%).

(19) Cyclopentanone and cycloheptanone derivatives also provided the corresponding oxoesters in moderate yields. However, this iron salt catalyzed oxygenation was specific for cyclic ketones.

7429-44-9; 2-(trifluoromethyl)cyclohexanone, 56734-74-8; 2-bromocyclohexanone, 822-85-5; 2,6-dimethylcyclohexanone, 2816-57-1; 2-chloro-2,6-dimethylcyclohexanone, 84928-32-5; oxygen, 7782-44-7.

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Synthesis and Diels–Alder Reactions of Allylidenecyclopropane

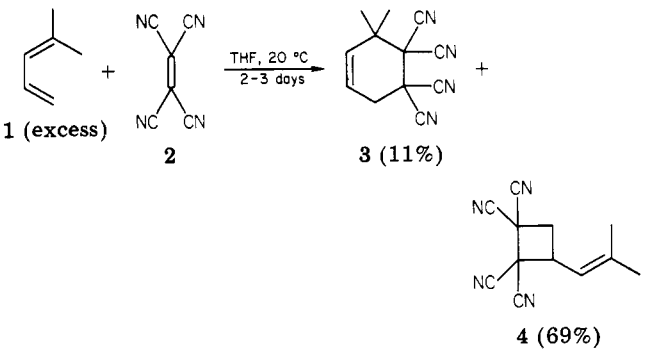
Summary: Allylidenecyclopropane, readily available from 1-lithio-1-(phenylthio)cyclopropane, reacts with a large variety of electrophilic olefins and produces functionalized spirooctenes. The reactions are, in most cases, highly regioselective but lead mainly to the unexpected regioisomers.

Sir: Despite the wide applicability of the Diels–Alder[1] reaction, there remain cases for which the cycloaddition cannot be achieved due to the lack of reactivity of one of the two partners. This is the case, among others, of 1,1-disubstituted butadienes.[1-5] For example, 4-methyl-1,3-pentadiene (1) is known to react very sluggishly with reactive dienophiles such as tetracyanoethylene[3] and maleic anhydride,[4,5] leading to various cycloadducts **4** and **7** besides the expected ones, **3** and **6** (Scheme I).

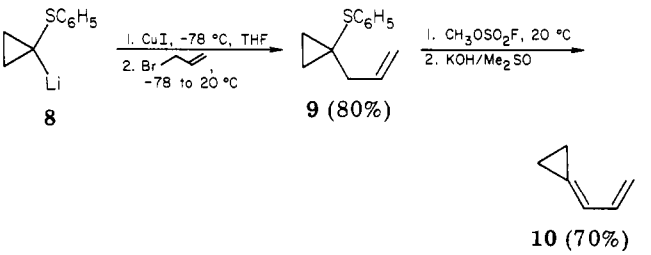
We report our results concerning the reactivity of allylidenecyclopropane (**10**) toward some electrophilic olefins. Although it is a member of the 1,1-dialkyl-substituted family, it is expected to be far more reactive than **1** due to the strain present in the alkylidenecyclopropane moiety. This should provide a very direct access to the spiro[2.5]octene system, present as a substructure in some natural products (i.e., illudins[7]) and that could also serve as a precursor of 1,1-dimethylcyclohexanes.[8]

Allylidenecyclopropane (**10**) was efficiently synthesized[9] (Scheme II) in two steps from 1-lithio-1-(phenylthio)-cyclopropane (**8**).[10] The first step requires the allylation of **8**. This was achieved successfully, and for the first time, in 80% yield by using allyl bromide (2 molar equiv, −78 to 20 °C) provided that cuprous iodide (0.5 molar equiv) was present in the reaction medium. The second step was accomplished in one pot and 70% overall yield, by methylation of **9** (CH_3OSO_2F (1.5 molar equiv), neat, 20 °C, 0.5 h, then trituration with pentane to remove the excess of magic methyl) and further treatment of the resulting sulfonium salt with base (powdered KOH (4 equiv) in Me_2SO, 20 °C, 15 h). The diene **10** was isolated by flash distillation from the reaction medium (20–40 °C (200–15 mmHg) receiver cooled in liquid nitrogen). It is oxygen sensitive and must be stored under inert gas (argon) at −20 °C.

Scheme I



Scheme II



As expected, allylidenecyclopropane (**10**) exhibits a much higher reactivity than **1** toward dienophiles. It reacts at room temperature with dienophiles possessing two or more activating groups such as tetracyanoethylene, maleic anhydride, and *p*-benzoquinone (Table I). Its reaction with dimethyl acetylene dicarboxylate, dimethyl fumarate, and dimethyl maleate require more drastic conditions (80, 110, 150 °C, respectively). These reactions and others reported in this paper have been performed under argon in sealed glass tubes, and only 1 equiv of the diene **10** was normally used. Monoactivated dienophiles also react with **10** (Table II), but the presence of an alkyl substituent on the dienophile dramatically lowers the yield if it is branched at the α-position or almost completely inhibits the reaction if it is located in the β-position of the activating group (see Table II, entry 7). In these specific cases, the temperature at which these reactions were performed was found to be critical. 100 °C was found to be the best compromise since

(1) March, J. "Advanced Organic Chemistry: Reactions, Mechanisms and Structure"; McGraw-Hill Kogakusha: Tokyo, 1977; p 761.
(2) Wollweber, H. *Methoden Org. Chem. (Houben-Weyl), 4th ed.* **1970**, *5*, 1019.
(3) (a) Stewart, C. A. *J. Org. Chem.* **1963**, *28*, 3320. (b) Stewart, C. A. *J. Am. Chem. Soc.* **1962**, *84*, 1117.
(4) (a) Slobodin, Y. M.; Grigoreva, V. I.; Schmulyakovskii, Y. E. *Zh. Obshch. Khim.* **1958**, *23*, 1873. (b) Goldman, N. L. *Chem. Ind. (London)* **1963**, 1036. (c) Ichikizaki, I.; Avai, A. *Bull. Chem. Soc. Jpn.* **1964**, *37*, 432 and references cited.
(5) Erratic results have been reported for that specific reaction which produces under similar conditions but depending on the authors: (a) polymers,[4a] (b) the normal Diels–Alder adduct **6**,[4b] or a mixture of adducts **6** and **7**.[4c] We have repeated this reaction using an excess of the diene **1** and a small amount of hydroquinone, performing the reaction under argon in a sealed glass tube at 100 °C for 72 h. We obtained a 20:80 mixture of **6**/**7** if the maleic anhydride contains some diacid. However, if carefully purified[6] maleic anhydride is used, the **6**/**7** ratio increased to 50:50. Omission of hydroquinone results in polymer formation.
(6) Vogel, A. I. "Practical Organic Chemistry"; Longman: London, 1970; p 376.
(7) Matsumoto, T.; Shirahama, H.; Ichihara, A.; Shin, H.; Kagama, S.; Saken, F.; Miyano, K. *Tetrahedron Lett.* **1971**, 2049.
(8) See, for example: Wender, P. A.; Eck, S. L. *Tetrahedron Lett.* **1982**, 1871.
(9) (a) For a previous synthesis of **10**: Binger, P.; Germer, A. *Chem. Ber.* **1981**, *114*, 3325. (b) Three other routes to **10** have been devised in our laboratory. They imply 1-lithio-1-(methylseleno)cyclopropane or its phenylseleno analogue as the starting material. The last route uses a strategy we previously described. They will be reported later. (c) Halazy, S.; Krief, A. *Tetrahedron Lett.* **1981**, 1836, 2135.
(10) Trost, B. M.; Keeley, D.; Bogdanowicz, M. J. *J. Am. Chem. Soc.* **1973**, *95*, 3068.

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