A new strategy for catalytic Baeyer–Villiger oxidation of KA-oil with molecular oxygen using *N*-hydroxyphthalimide

Osamu Fukuda, Satoshi Sakaguchi and Yasutaka Ishii*

Department of Applied Chemistry, Faculty of Engineering & High Technology Research Center, Kansai University, Suita, Osaka 564-8680, Japan

Received 14 March 2001; revised 16 March 2001; accepted 21 March 2001

Abstract—Catalytic Baeyer–Villiger oxidation of KA-oil (a mixture of cyclohexanone and cyclohexanol) with molecular oxygen has been developed. The oxidation of KA-oil under dioxygen atmosphere in the presence of a catalytic amount of *N*-hydroxyphthalimide followed by treatment with indium trichloride gave ε-caprolactone. © 2001 Elsevier Science Ltd. All rights reserved.

KA-oil, a mixture of cyclohexanone and cyclohexanol obtained by the aerobic oxidation of cyclohexane, is an important intermediate in the petroleum industrial chemistry for the production of adipic acid and ε-caprolactam which are key materials for manufacturing 6,6-nylon and 6-nylon, respectively.[1]

Baeyer–Villiger oxidation is a frequently used synthetic tool for conversion of cycloalkanones to lactones. Usually, this transformation is carried out by the use of peracids like peracetic acid and *m*CPBA,[2] hydrogen peroxide,[3] and bis(trimethylsilyl)peroxide.[4] However, the catalytic Baeyer–Villiger oxidation using dioxygen is limited to the in situ generation of peracids using excess aldehydes and O_2.[5] In industry, ε-caprolactone is manufactured by the reaction of cyclohexanone with peracetic acid generated by the aerobic oxidation of acetaldehyde.[1]

In previous work, we have shown that *N*-hydroxyphthalimide (NHPI) acts as an efficient catalyst for the aerobic oxidation of various organic substrates.[6] The NHPI-catalyzed oxidation of secondary alcohols gave ketones through the formation of α-hydroxyhydroperoxide as an intermediate.[7] From both synthetic and industrial points of view, it is very attractive that the KA-oil can be used as the starting material for the production of ε-caprolactone with molecular oxygen via a catalytic process. In this paper, we wish to report a new Baeyer–Villiger oxidation of KA-oil with molecular oxygen under the influence of the NHPI catalyst. To our best knowledge, there are no reports on the catalytic Baeyer–Villiger oxidation of KA-oil using dioxygen as the terminal oxidant.
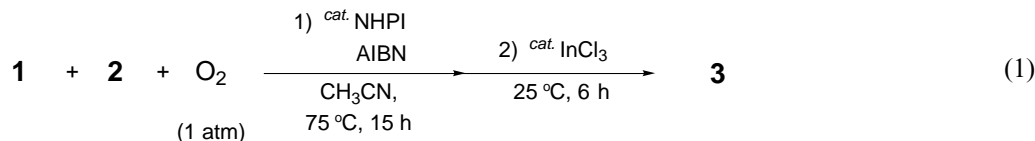
Our strategy is outlined in Scheme 1. The aerobic oxidation of cyclohexanol (**2**) catalyzed by NHPI gives
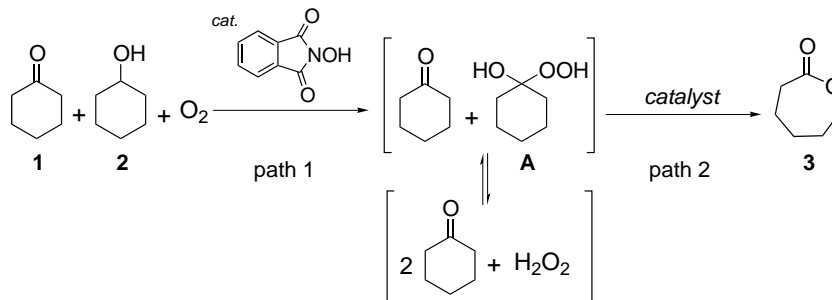
Scheme 1.

* Corresponding author.

a mixture of cyclohexanone (**1**) and hydrogen peroxide through the formation of 1-hydroxy-1-hydroperoxycyclohexane (**A**) (path 1). Treatment of the resulting reaction mixture with an appropriate catalyst would produce ε-caprolactone (**3**) (path 2). A KA-oil consisting of a 1:1 mixture of **1** and **2** was employed as a model starting material. If the aerobic oxidation of the KA-oil in the presence of NHPI is completed, 2 equiv. of **1** and 1 equiv. of H_2O_2 are expected to be formed.

without treatment with InCl$_3$ (run 3). Without treatment of the reaction mixture with PPh$_3$, the amount of KA-oil recovered was slightly lowered, because of the presence of unreacted hydroperoxides which are eventually converted into **1** and **2** upon treatment with PPh$_3$ (run 4). Indeed, the addition of a KI solution to the reaction mixture before treatment with PPh$_3$ led to color change from light yellow to red–brown, which indicates the presence of peroxy compounds.

$$\mathbf{1} \ + \ \mathbf{2} \ + \ O_2 \xrightarrow[\substack{CH_3CN, \\ 75\ ^\circ C,\ 15\ h}]{\substack{1)\ ^{cat.}\ NHPI \\ AIBN}} \xrightarrow[25\ ^\circ C,\ 6\ h]{2)\ ^{cat.}\ InCl_3} \mathbf{3} \tag{1}$$

(1 atm)

A standard experimental procedure is as follows: To a solution of NHPI (0.6 mmol) and 2,2′-azobisisobutyronitrile (AIBN) (0.3 mmol) in CH$_3$CN (3 mL) was added a 1:1 mixture of **1** (6 mmol) and **2** (6 mmol), and then the flask was flushed with dioxygen and equipped with a balloon filled with about 2 L of O$_2$. After stirring the reaction mixture at 75°C for 15 h, InCl$_3$ (0.45 mmol) was added and further stirred at 25°C for 6 h. To decompose the unreacted peroxides, the reaction mixture was treated with excess PPh$_3$ (10 mmol) at room temperature for several hours. The yields of products were estimated from the peak areas based on the internal standard technique using GC.

Table 1 summarizes the representative results for the Baeyer–Villiger oxidation of the KA-oil. The reaction under standard conditions gave ε-caprolactone (**3**) in 57% selectivity based on the KA-oil reacted,[8] and 77% of KA-oil was recovered (Eq. (1), run 1). This reaction is the first catalytic Baeyer–Villiger reaction of KA-oil with molecular oxygen. The KA-oil recovered includes cyclohexanone **1** as the main component. The same oxidation in the absence of AIBN gave **3** (0.9 mmol) (run 2). Compound **3** was formed in very low yield

Water-stable Lewis acids such as Sc(OTf)$_3$ and Gd(OTf)$_3$ were also effective to give **3** in somewhat lower yields (runs 5 and 6). When a protic acid like sulfuric acid was used instead of Lewis acids, peroxy compounds, **4a** and **4b**, derived from **2** and H_2O_2 were formed as major products. It is well-known that **1** reacts with aqueous hydrogen peroxide under neutral and acidic conditions to produce **4a** and **4b**, respectively.[3a,9]

The oxidation of **2** to **1** was enhanced by the use of the NHPI–Co(II) system,[10] but the formation of **3** was markedly inhibited by the Co ion (run 7). This is believed to be due to the rapid decomposition of the resulting hydroperoixde **A** as well as H_2O_2 by the Co ion, since hydroperoxides undergo the redox decomposition by transition metals.[11] The commercially available KA-oil consists of a 1:2.5–4 mixture of **1** and **2**,[1] therefore we examined the oxidation of a 1:2 mixture of **1** and **2**. The reaction under these reaction conditions
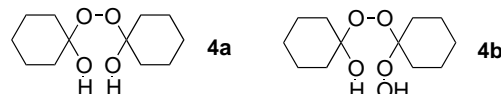
 4a   **4b**

Table 1. Baeyer–Villiger oxidation of KA-oil with molecular oxygen under various conditions[a]

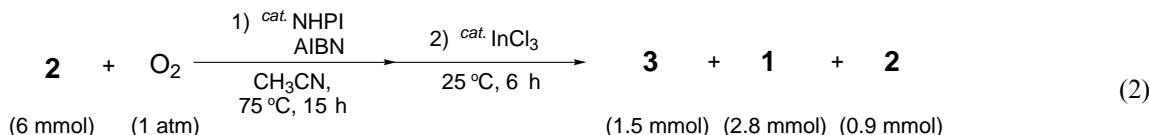| Run	Catalyst	Yield of **3** (mmol)	Selectivity of **3** (%)[b]	Recovery of KA-oil (%)	**1**/**2** (mmol/mmol)
1	InCl$_3$	1.6	57	77	(8.0/1.2)
2[c]	InCl$_3$	0.9	60	88	(6.9/3.6)
3	–	0.4	19	83	(8.9/1.0)
4[d]	InCl$_3$	1.6	36	63	(6.8/0.8)
5	Sc(OTf)$_3$	0.7	18	67	(7.1/0.9)
6	Gd(OTf)$_3$	1.4	40	70	(7.4/1.0)
7[e]	InCl$_3$	<1	<1	91	(10.9/0.1)
8[f]	InCl$_3$	1.6	57	69	(4.9/1.3)
9[g]	InCl$_3$	1.5	60	79	(8.0/1.5)

[a] Reaction conditions are shown in text.
[b] See Ref. 8.
[c] Without AIBN.
[d] Without treatment of the reaction mixture with PPh$_3$.
[e] Co(OAc)$_2$ (0.03 mmol) was added in the step of the aerobic oxidation of KA-oil.
[f] A 1:2 mixture of **1** (3 mmol) and **2** (6 mmol) was used.
[g] 0.9 mmol of InCl$_3$ was used.

$$\mathbf{2} + O_2 \xrightarrow[\substack{CH_3CN, \\ 75\,^\circ C,\ 15\ h}]{\substack{1)\ ^{cat.}\ NHPI \\ AIBN}} \xrightarrow[\substack{25\,^\circ C,\ 6\ h}]{2)\ ^{cat.}\ InCl_3} \mathbf{3} + \mathbf{1} + \mathbf{2} \tag{2}$$

(6 mmol) (1 atm)   (1.5 mmol) (2.8 mmol) (0.9 mmol)

was found to afford **3** in almost the same yield and selectivity as run 1 (run 8). As expected, similar treatment of cyclohexanol **2** alone with that of the KA-oil led to ε-caprolactone **3** and cyclohexanone **1**. The aerobic oxidation of **2** under the influence of the NHPI catalyst followed by treatment with InCl$_3$ and then PPh$_3$ afforded **3** (1.5 mmol) and **1** (2.8 mmol) (Eq. (2)).

In conclusion, a catalytic Baeyer–Villiger oxidation of KA-oil with molecular oxygen has first been developed by the use of NHPI as a catalyst. Although the efficiency of the reaction must be improved and more efficient and cheaper catalyst than InCl$_3$ should be developed, this method may provide an ideal strategy for the production of ε-caprolactone **3** from a KA-oil which is a raw material manufactured largely by the aerobic oxidation of cyclohexane.

Acknowledgements

References

1. (a) Michael, T.; Musser, E. I. *Ullman's Encyclopedia Industrial Organic Chemicals*; Wiley-VCH: Weinheim, 1999; Vol. 3, pp. 1807–1823; (b) Fisher, W. B.; Van Peppen, J. F. In *Kirk–Othmer Encyclopedia of Chemical Technology*; Kroshwite, J. L.; Home-Grant, M., Eds., 4th ed.; John Wiley and Sons: New York, 1995; Vol. 7, pp. 851–859.
2. (a) Krow, G. R. In *Comprehensive Organic Synthesis*; Trost, B. M., Ed.; Pergamon Press: New York, 1991; Vol. 7, pp. 671–688; (b) *Organic Peroxides*; Swern, D. Ed.; Wiley-Interscience: New York, 1971.
3. (a) Fischer, J.; Hölderich, W. F. *Appl. Catal. A: Gen.* **1999**, *180*, 435–443; (b) Strukul, G.; Varagnolo, A.; Pinna, F. *J. Mol. Catal. A: Chem.* **1997**, *117*, 413–423; (c) Wang, Z. B.; Mizusaki, T.; Sano, T.; Kawakami, Y. *Bull. Chem. Soc. Jpn.* **1997**, *70*, 25967–25970; (d) Frisone, M.; Del, T.; Pinna, F.; Strukul, G. *Organometallics* **1993**, *12*, 148–156.
4. Göttlich, R.; Yamakoshi, K.; Sasai, H.; Shibasaki, M. *Synlett* **1997**, 971–973.
5. (a) Bolm, A.; Schlingloff, G.; Weickhardt, K. *Tetrahedron Lett.* **1993**, *34*, 3405–3408; (b) Hamamoto, M.; Nakayama, K.; Nishiyama, Y.; Ishii, Y. *J. Org. Chem.* **1993**, *58*, 6421–6425; (c) Murahashi, S.; Oda, Y.; Naota, T. *Tetrahedron Lett.* **1992**, *33*, 7557–7560; (d) Yamada, T.; Takahashi, K.; Kato, K.; Takai, T.; Inoki, S.; Mukaiyama, T. *Chem. Lett.* **1991**, 641–644.
6. (a) Sakaguchi, S.; Takase, T.; Iwahama, T.; Ishii, Y. *Chem. Commun.* **1998**, 2037–2038; (b) Sakaguchi, S.; Kato, S.; Iwahama, T.; Ishii, Y. *Bull. Chem. Soc. Jpn.* **1998**, *71*, 1237–1240; (c) Yoshino, Y.; Hayashi, Y.; Iwahama, T.; Sakaguchi, S.; Ishii, Y. *J. Org. Chem.* **1997**, *62*, 6810–6813; (d) Ishii, Y.; Kato, S.; Iwahama, T.; Sakaguchi, S. *Tetrahedron Lett.* **1996**, *37*, 4993–4996.
7. (a) Iwahama, T.; Sakaguchi, S.; Ishii, Y. *Chem. Commun.* **1999**, 727–728; (b) Iwahama, T.; Sakaguchi, S.; Ishii, Y. *Org. Pro. Res. Dev.* **2000**, *4*, 94–97.
8. The selectivity (%) of **3** was calculated by the following equation.

$$\frac{[\text{the amount (mmol) of } \mathbf{3} \text{ produced}]}{\left[\substack{\text{the amount (mmol)} \\ \text{of starting KA-oil}}\right] - \left[\substack{\text{the amount (mmol)} \\ \text{of KA-oil recovered}}\right]} \times 100$$

9. Kharash, M. S.; Sosnovsky, G. *J. Org. Chem.* **1958**, *23*, 1322–1326.
10. Iwahama, T.; Yoshino, Y.; Keitoku, T.; Sakaguchi, S.; Ishii, Y. *J. Org. Chem.* **2000**, *65*, 6502–6507.
11. Shilov, A. E.; Shul'pin, G. B. *Activation and Catalytic Reactions of Saturated Hydrocarbons in the Presence of Metal Complexes*; Kluwer Academic: Dordrecht, 2000; pp. 371–429.