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Molecular Oxygen Oxidative Carbon-Carbon Bond Cleavage of α-Ketols Catalysed by Bi(III) Carboxylates

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Abstract *: Bi(III)-mandelate catalyses the oxidative carbon-carbon bond cleavage, by molecular oxygen, of a series of α–ketols into the corresponding carboxylic acids. The reaction is accelerated in the presence of DMSO.*

The development of bismuth chemistry has been largely devoted to its application in organic oxidation reactions.[1] However, homogeneous oxidations catalyzed by Bi(III) complexes are poorly documented. Triphenylbismuth associated to *N*-bromosuccinimide has been reported to catalyze the cleavage of α-glycols to carbonyl compounds.[2] We have recently reported that Bi(III) mandelate in dimethylsulfoxide (DMSO) was able to catalyze the oxidation of epoxides to carboxylic acids.[3] Under heterogeneous conditions, one example involving Bi(III) derivatives in oxidation reactions has been described by Rigby in 1951 for the Bi_2O_3/AcOH-mediated oxidation of acyloins to α-diketones.[4]

Otherwise, bismuth(V) derivatives have been reported to be selective oxidants in reactions involving alcohols or diols.[5-7] Thus, pentavalent organobismuth reagents such as triphenylbismuth carbonate or other arylbismuth(V) compounds have been described by Barton to mediate the oxidation of alcohols to carbonyl compounds,[6] and for the cleavage of gem-diols to carbonyl derivatives.[7] Sodium bismuthate has been used in heterogeneous media for the cleavage of 1,2-diols and α-ketols into carbonyl compounds.[8] However, all these transformations require the use of stoichiometric amounts of the Bi(V) reagent involving the Bi(V)/Bi(III) redox couple.

In connexion with our work on the reactivity of bismuth derivatives in organic synthesis,[3] we have found a novel Bi(III)-catalyzed oxidative transformation of α-ketols to carboxylic acids by molecular oxygen (eq. 1).

$$R^1COCHOHR^2 \xrightarrow[O_2]{\text{Bi(III) mandelate (5\% molar)}} R^1COOH + R^2COOH \qquad \text{(eq.1)}$$

The Bi(III)-catalyzed oxidative cleavage of α-ketols proceeds in DMSO or in DMF under mild conditions. The catalyst is a bismuth carboxylate, the dimeric complex $[Bi^{III}(mandelate)_2]_2(\mu\text{-}O)$, **1**, prepared from Bi_2O_3 and (L)-mandelic acid.[9]

With 1-hydroxy-2-decanone, **2**, as the model substrate, nonanoic carboxylic acid **3** was isolated in 63% yield in the presence of catalyst **1** (5% molar) in DMSO after 4 h at 80 °C, under atmospheric O_2 pressure (see Table 1, entry 1). The presence of Bi(III) was essential for the reaction. Thus, under the same conditions but in the absence of **1**, ketol **2** was quantitatively recovered (Table 1, entry 2).

An important result is that molecular oxygen is essential in our catalysis : **2**, under nitrogen atmosphere and in the presence of 5% catalyst (entry 3), afforded only very little amount (<5%) of the expected carboxylic acid **3**, while 56% of unreacted α-ketol were recovered together with heavy ketol adducts (37% polymerization). Further, the oxidation of **2** in DMF as the solvent under dioxygen did lead to the formation of carboxylic acid **3** in 40% yield. These results clearly indicate that molecular oxygen is an oxidant in this process and that DMSO acts mainly as a solvent which enhances the yield and the selectivity of **3**. In a 1:1 mixture of DMF and DMSO, **3** was isolated in 52% yield.

That molecular oxygen is the oxidant in our process was definitively evidenced when monitoring oxygen consumption during the oxidation, in DMF, of the internal ketol 6-hydroxy-5-decanone, **4**, $C_4H_9COCHOHC_4H_9$: the overall oxygen consumption was found to be 1.5 moles per mole of ketol and pentanoic acid was formed in a 50% yield. It is noteworthy that the yield in pentanoic acid was found to be increased to 66% when the reaction was performed in DMSO (vide infra) showing hereagain that this latter solvent does influence the selectivity.

$$\underset{2}{C_8H_{17}COCH_2OH} \xrightarrow[\text{DMSO, }O_2\text{, 80°C, 4h}]{1\ (5\%)} \underset{5}{[C_8H_{17}COCHO]} \longrightarrow \underset{3\quad 63\%}{C_8H_{17}COOH} \qquad \text{(eq.2)}$$

The ketoaldehyde **5** was shown to be an intermediate in the oxidation of **2** by Bi(III) mandelate (eq.2). Monitoring the reactant concentrations by GC showed **5** to be formed in the early stages of the reaction and to progressively disappear. The formation of an intermediate dicarbonyl compound was further confirmed during the oxidation of 6-hydroxy-5-decanone, **4** (eq.3). The internal α-ketol **4** was very easily oxidized into 5,6-decadione, **6**, in the presence of 5% of **1** in DMSO under O_2, as shown by the 50% formation of **6** after 0.5 h and 90% after 2 h. The subsequent oxidative cleavage of **6** slowly afforded n-pentanoic acid which was obtained in 66% yield after 53 h, when both **4** and **6** are totally consumed (Table 1, entry 10). Hereagain, the amount of carboxylic acid became very low when the oxidation of ketol **4** was run under dinitrogen ; only 30-40% of diketone **6** could be isolated after 24 h beside the unreacted ketol and traces of n-pentanoic acid.

$$\underset{4}{C_4H_9COCHOHC_4H_9} \xrightarrow[\text{DMSO, }O_2\text{, 95°C, 2h}]{1\ (5\%)} \underset{6\quad 90\%}{C_4H_9COCOC_4H_9} \xrightarrow[51h]{} \underset{66\%}{C_4H_9COOH} \qquad \text{(eq.3)}$$

It is noteworthy that the α-diketones are the only products that have been reported in the zinc bismuthate mediated α-ketol oxidation,[5] or in bismuth trioxide/AcOH-mediated system.[4] Our catalytic Bi(III) mandelate/dioxygen system constitutes a stronger oxidant as it enables the further C-C cleavage as shown in the examples of Table 1.

The scope of the Bi(III)-catalyzed O_2 oxidative cleavage was further investigated using a selection of differently substituted α-ketols in DMSO. The α-ketols were prepared according to literature procedures.[10]

Linear or cyclic terminal aliphatic α-ketols (with R^1 = primary or secondary alkyl groups, R^2 = H ; entries 1, 4-6) afforded the corresponding (n-1) carboxylic acids in moderate to good yields. The oxidation of ω-unsaturated 1-hydroxy-7-octen-2-one (entry 6) led to 6-heptenoic acid in 46% yield.

The reactivity of three terminal aromatic α-ketols, bearing electron-donating (Me) or electron-withdrawing (NO_2) substituents on the aryl ring (entries 7-9), was examined; the corresponding benzoïc acid derivatives being isolated in all cases. The more electron-rich sustrate was more rapidly converted in the presence of the Bi(III)/O_2 catalytic system. This is consistent with a better coordination of the electron-rich substrate to the Lewis-acid bismuth complex, in the rate-determining step.

Oxidative cleavage of disubstituted α-ketols (entries 10-12) occurred more slowly than for the terminal substrates. The corresponding carboxylic acids R^1COOH and R^2COOH are formed via the intermediate 1,2-diketones (compare entries 11 and 12).

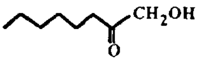
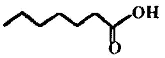
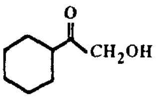
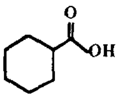
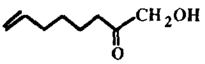
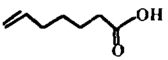
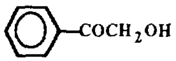
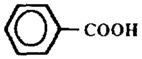
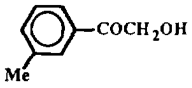
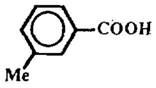
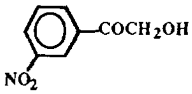
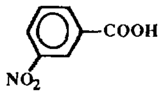
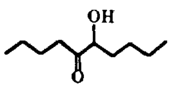
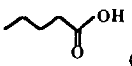
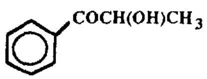
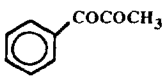
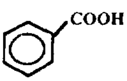
The oxidation of benzoïn (at 95 °C, 72 h) led to benzil (72%) and benzoïc acid (13%). The C-C bond cleavage is in this case more difficult, probably due to the steric hindrance of the phenyl groups.

Among the various reagents for the oxidative cleavage of α-diols or α-ketols to carbonyl compounds or to carboxylic acids, the more classical and versatile are sodium periodate,[18] lead tetraacetate,[19] sodium bismuthate,[8] manganese dioxide,[20] chromium (VI) reagents,[21] alkaline hydrogen peroxide,[22] ceric ammonium nitrate,[23] and calcium hypochlorite.[24] The herein reported bismuth(III) mandelate catalytic system differs markedly from these reagents. It affords carboxylic acids from α-ketols in yields that are comparable to those obtained with stoichiometric amounts of *e.g.* sodium periodate, but it is catalytic in metal and operates under milder conditions. While sodium bismuthate brings carbonyl compounds from α-ketol oxidation,[8] carboxylic acids are directly formed with our **1**/O_2 system. Finally, in contrast to sodium bismuthate, the use of **1** in DMSO under dioxygen does not cleave α-hydroxycarboxylic acids,[8] and does not oxidize olefins.[25] Thus, under the standard reaction conditions, mandelic acid could be quantitatively recovered after 24 h at 95 °C and norbornene was unreactive.

The originality and the advantages of our Bi^{III}/O_2 system can thus be highlighted with the following characteristics : first, the reactions are catalytic in bismuth(III), **1** being a stable complex, easily prepared. Second, the use of molecular oxygen as the oxidant in selective catalytic oxidations is of particular interest, as a simple, cheap and clean oxidant; furthermore, atmospheric pressure of dioxygen is simply required for the oxidations. Third, the system presents a very interesting functional group selectivity : thus, alcohols, gem-diols or olefins are not reactive, in contrast to their ease of transformation by most of the strong oxidants cited above.

In conclusion, the Bi(III) mandelate/O_2 system has a different, new and most promising activity as compared with all previously described bismuth(V) or bismuth(III) reagents.

Table 1 : **Oxidative cleavage of α-ketols in DMSO catalyzed by 1.**

Entry	α ketol	Reference for the ketol	Reaction conditions	Products (% yield)
1	n-$C_8H_{17}COCH_2OH$	11	O_2 (1 atm) 80 °C, 4 h	n-$C_8H_{17}COOH$ (63%)
2	"		id., no catalyst	n-$C_8H_{17}COCH_2OH$ (99%)
3	"		N_2 (1 atm) 80 °C, 4 h	n-$C_8H_{17}COCH_2OH$ (56%) heavy ketol adducts (37%)
4		12	O_2 (1 atm) 80 °C, 4.5 h	 (64%)
5		13	O_2 (1 atm) 80° C, 4 h	 (64%)
6		this work	O_2 (1 atm) 80 °C, 6 h	 (46%)
7		14	O_2 (1 atm) 80 °C, 3 h	 (63%)
8		15	O_2 (1 atm) 80 °C, 2.2 h	 (78%)
9		this work	O_2 (1 atm) 80 °C, 5.5 h	 (70%)
10		16	O_2(1 atm) 95 °C, 53 h	 (66%)
11		17	O_2 (1 atm) 80 °C, 25 h	 +  (30%) (39%)
12	"		O_2 (1 atm) 95°C, 72 h	(3%) (79%)

Experimental details

Products and Instrumentation

DMSO was distilled under vacuum in the presence of CaH_2. The Bi(III)-mandelate was prepared from Bi_2O_3 and (L)-mandelic acid.[9] Most of the α-ketols in this study are known compounds (see Table 1 for references) and were prepared according to the literature.[10] Ketols for entry 6 and 9 in Table 1 which, to the best of our knowledge, have not been reported previously, are described below. The acids and diketones in Table 1 could all be obtained from Aldrich, for comparison.

Elemental analyses were performed by the Service Central de Microanalyses of the CNRS. Infra-red spectra were recorded on a Bruker FT-IFS 45 spectrometer. The ^1H and ^{13}C NMR spectra were recorded on a Bruker AC-200 spectrometer. Mass Spectra were obtained with a FINNIGAN MAT INCOS 500E spectrometer (GC/MS). The GC analyses were obtained on a DELSI-300 chromatograph (column SE 30, 10%, 3m x 3/8") and on a VARIAN-3400 chromatograph (capillary column DB-1, 25 m).

2-hydroxy-1-(3-nitrophenyl)ethanone was obtained in 5 % yield following procedure [10b].
^1H-NMR ($CDCl_3$, ppm) : 8.48(ddd, 1H, J = 8.0, 2.0, 2.0 Hz) ; 8.26(ddd, 1H, J = 8.0, 2.0, 2.0 Hz) ; 7.75 (dd, 1H, J = 8.0, 8.0 Hz) ; 3.45 (s, 1H) ; 4.96 (s, 2H). ^{13}C-NMR ($CDCl_3$, ppm) : 196.8 ; 148.6 ; 134.7 ; 133.2 ; 130.4 ; 128.4 ; 122.6 ; 65.9. IR (KBr, cm^{-1}) : 3410 ; 1708 ; 1612 ; 1519 (NO_2) ; 1354 (NO_2) ; 1229 ; 1090 ; 735 ; 710 ; 690. Anal. Calcd. for $C_8H_7NO_4$: C, 53.04 ; H, 3.89 ; N, 7.73, Found : C, 53.14; H, 3.92 ; N, 7.81.

1-hydroxy oct-7-en-2-one: was obtained in 34 % yield following procedure [10a]. ^1H-NMR ($CDCl_3$, ppm) : 5.80 (1H, tdd, J = 7.0, 16.9, 10.0 Hz) ; 4.98(1H, dd, J = 16.9, 1.6 Hz) ; 4.95 (1H, dd, J = 10.0, 1.6 Hz) ; 4.20 (2H, d, J = 3.4 Hz) ; 3.20 (1H, t, J = 3.4 Hz) ; 2.40 (2H, t, J = 7.2 Hz) ; 2.05 (2H, td, J = 7.0, 7.0 Hz) ; 1.64-1.50 (2H, m) : 1.49-1.30 (2H, M). ^{13}C-NMR ($CDCl_3$, ppm) : 209.7 ; 138.1 ; 114.9 ; 68.1 ; 38.2 ; 33.3 ; 28.4 ; 23.1. IR (film, cm^{-1}) : 3450 ; 3077 ; 2977 ; 2959 ; 2933 ; 1720 ; 1641 ; 1439 ; 1409 ; 1372 ; 1281 ; 1078 ; 994 ; 911 ; 720 . Anal. Calcd for $C_8H_{14}O_2$: C, 67.57 ; H, 9.92, Found : C, 66.04; H, 9.75.

General procedure for the oxidation of α-ketols

Anhydrous DMSO (5 ml) was stirred in the presence of Bi(III)-mandelate, **1**, (156 mg, 0.15 mmol) at 80° C for 30 min under oxygen (1 atm), followed by the addition of the α-ketol (3 mmol). The reaction was followed by GC until complete consumption of the substrate. Acidic hydrolysis by aqueous 0.1N HCl solution, ether rextraction, treatment of the organic layer by aqueous 0.1N NaOH solution until pH =12-14 and ether reextraction gave the neutral products of the reaction, e.g. the 1,2-diketones. Acidification of the basic aqueous phase with 1N HCl solution to pH 1-2 followed by a final ether extraction afforded the carboxylic acids. The products were analyzed by GC, ^1H and ^{13}C NMR, mass spectra and their spectral data compared to those of authentic samples.

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References and Notes

1. Kitchin, J. P. in *Bismuth Salt Oxidations*, "Organic Synthesis by Oxidation with Metal Compounds", ed. W. J. Mijs, C. R. H. I. de Jonge, Plenum Press, New York, **1986**, Chap. 15.
2. Barton, D.H.R.; Finet, J.P.; Motherwell, W.B.; Pichon, C. *Tetrahedron* **1986**, *42*, 5627-5636.
3. Zevaco, T.; Duñach, E.; Postel, M.; *Tetrahedron Lett.* **1993**, *34*, 2601-2604.
4. a) Rigby, W.; *J. Chem. Soc.* **1951**, 793-795. b) Djerassi, C.; Ringold, H.J.; Rosenkranz, G. *J. Am. Chem. Soc.* **1954**, *76*, 5533-5535.
5. Firouzabadi, H.; Mohammadpour-Baltork, I. *Bull. Chem. Soc. Jpn.* **1992**, *65*, 1131-1134.
6. Barton, D.H.R.; Kitchin, J. P.; Motherwell, W.B. *J. Chem. Soc., Chem. Commun.* **1978**, 1099-1100.
7. Barton, D.H.R.; Kitchin, J.P.; Lester, D.J.; Motherwell, W.B.; Papoula, M.T.B. *Tetrahedron* **1981**, *37*, Suppl. 1, 73-79.
8. Rigby, W. *J. Chem. Soc.* **1950**, 1907-1913.
9. Zevaco, T.; Postel, M. *Synth. React. Inorg. Met.-Org. Chem.* **1992**, *22*, 289-297.
10. a) Cohen, T.; Tsuji, T. *J. Org. Chem.* **1961**, *26*, 1681 ; b) Moriarty, R. M.; Hu H.; Gupta C. *Tetrahedron Lett.* **1981**, *22*, 1283-1286.
11. Yorozu, K.; Takai, T.; Yamada, T.; Mukaiyama, T. *Bull. Chem. Soc. Jpn* **1994**, *67*, 2195-2202.
12. Tsuji, T. *Tetrahedron Lett.* **1966**, 2413-2414.
13. Matsumoto, T.; Ohishi, M.; Inoue, S. *J. Org. Chem.* **1985**, *50*, 603-606.
14. "*Organic Synthesis*", Coll. Vol. 7, J.P. Freeman ed., J. Wiley and Sons, New York, **1990**, pp 263-266.
15. Morozov, A. A. *Zh. Obskh. Khim.* **1989**, *59*, 215-222
16. Avetisyan, A. A.; Mellkyan, G. S.; Dangyan, M. T.; Matsayan, S.G. *Zh. Org. Khim.* **1972**, *8*, 274-277.
17. Moriarty, R. M.; Berglund, B.A.; Penmasta, R. *Tetrahedron Lett.* **1992**, *33*, 6065-6068.
18. Dryhurst, G. in *Periodate Oxidation of Diols and other Functional Groups*; Pergamon Press; New York, **1970**.
19. Rubottom, G. in *Oxidation in Organic Chemistry*, Trahanovsky, W.,Ed, Academic Press; New York, **1982**, part D.
20. Ohloff, G.; Giersch,W. *Angew. Chem. Int. Ed. Engl.* **1973**, *12*, 401-402.
21. Epifanio, R. A.; Camargo, W.; Pinto, A. C. *Tetrahedron Lett.* **1988**, *29*, 6403-6406.
22. Ogata, Y.; Sawaki, Y.; Shiroyama, M. *J. Org. Chem.* **1977**, *42*, 4061-4065.
23. Ho, T. L. *Synthesis* **1972**, 560-561.
24. Nwaukwa, S. O.; Keehn, P. M. *Tetrahedron Lett.* **1982**, *23*, 3135-3138.
25. Truesdale, L. K.; Reuman, M.E. *J. Org. Chem.* **1980**, *45*, 726-727.

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