(%) for $Fe_{16}C_{180}H_{216}O_{84}N_4$: C 46.22, H 4.74, N 1.20; found: C 46.08, H 4.41, N 1.14; selected IR data (KBr pellet): $\tilde{\nu}$ = 1554(s), 1528(s) 1493(m), 1409(s), 1307(w), 1176(m), 1158(w), 1069(w), 1045(m), 1025(m), 877(w), 717 cm^{-1}(s).

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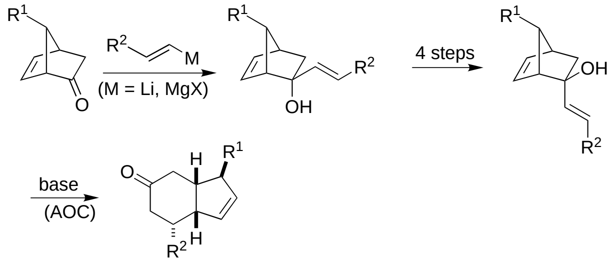
[19] The same molecular product may also be obtained using the mixed-valent triangular complex $[Fe_3O(PhCOO)_6(H_2O)_2(MeCN)]$. This has been confirmed by determination of the complete crystal and molecular structure: orthorhombic, space group Fddd, $a = 20.9903$, $b = 25.4990$, $c = 46.6602$ Å.

A Radical Alternative to the Anionic Oxy-Cope Rearrangement**

Rachel Chuard, Anne Giraud, and Philippe Renaud*

The anionic oxy-Cope rearrangement has emerged as a highly useful tool for organic synthesis.[1,2] Various 1,5-dien-3-ols readily undergo this electronic reorganization, and the usually easy preparation of the precursors contributes to the popularity of this reaction. However, a limitation of this sigmatropic rearrangement is the requirement of proximal double bonds. Indeed, the distance and the angular relationship between the two double bonds should be close to optimal values in order to achieve the rearrangement.[2,3] For example, with 1,5-dien-3-ols that result from the addition of alkenyl anions to 2-norbornenones, the double bonds are not proximal and therefore anionic sigmatropy is not possible. Two protocols that allow the inversion of the configuration of the quaternary center have been developed to remedy this problem. However, both are lengthy (four steps) and not high-yielding (Scheme 1).[4,5]



Scheme 1. Inversion of the stereogenic center of the alcohol is required prior to anionic oxy-Cope rearrangements (AOC) of norbornenone derivatives.[4,5]

We report herein a mechanistically different approach to solve this problem: a radical alternative to the oxy-Cope rearrangement. A cascade reaction that involves the fragmentation of an alkoxyl radical followed by a 6-*endo*-cyclization process leads to the oxy-Cope product (Scheme 2). According to this mechanism, the relative configuration of the alcohol has no influence on the efficacy of the rearrangement. Related anionic stepwise mechanisms have been observed for anionic amino-Cope rearrangements[6] as well as for oxy-Cope rearrangements of 4-phenylthio-1,5-dien-3-alkoxides.[7,8]

We investigated several methods to generate the desired alkoxyl radical **A**, starting from 2-norbornenone. Treatment

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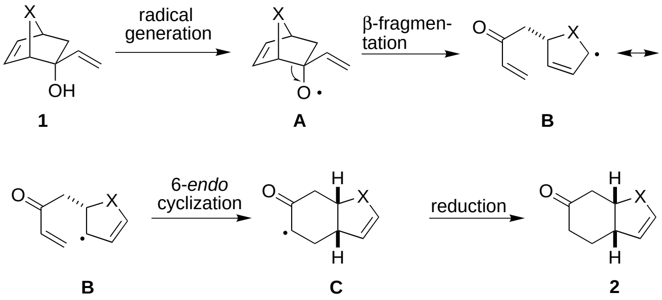
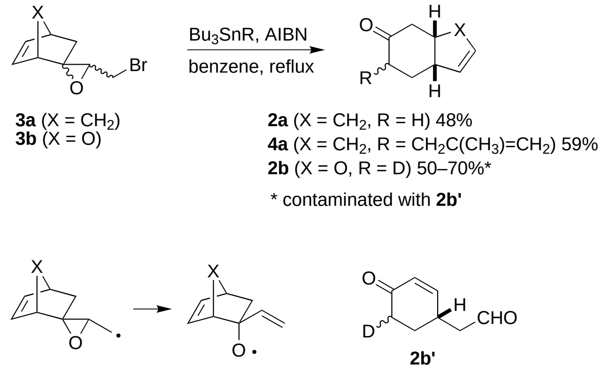


Scheme 2. Radical alternative to the oxy-Cope rearrangement.

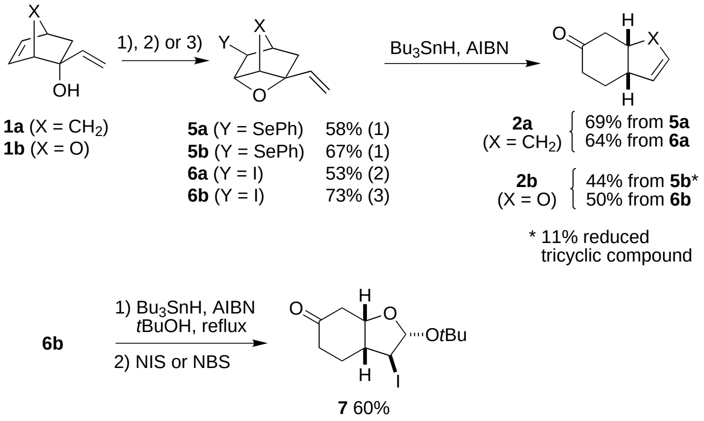
of the alcohol **1** with different oxidants and under various reaction conditions failed to give the desired rearranged compound. Instead, products of the oxidation of the allylic alcohol were observed. A milder route to the alkoxyl radical **A** from bromomethyloxiranes was then examined.[9–15] The desired radical precursors were prepared as a mixture of the four possible diastereomers from the corresponding ketones over four steps and in modest overall yields (not optimized). The radical reactions are shown in Scheme 3.



Scheme 3. Radical oxy-Cope rearrangement starting from bromomethyloxiranes.

Upon treatment of **3a** with tributyltin hydride and azobisisobutyronitrile (AIBN), the desired rearranged product **2a** was obtained in 48% yield. When the reaction was repeated with 2-methallyltributylstannane, the allylated product **4a** was isolated in 59% yield. Reaction of **3b** with Bu_3SnD afforded the rearranged product **2b** in variable yields. Apparently, this enol ether decomposes already during the radical reaction, presumably through a Lewis acid (Bu_3SnBr) catalyzed reaction, to afford **2b**′. Reactions of the bromomethyloxiranes give only moderate yields but proved the feasibility of the radical oxy-Cope rearrangement. No effort to optimize yields was attempted because the preparation of the radical precursors (four steps) from 2-norborneneone and 7-oxanorbornenone is clearly unsatisfactory.

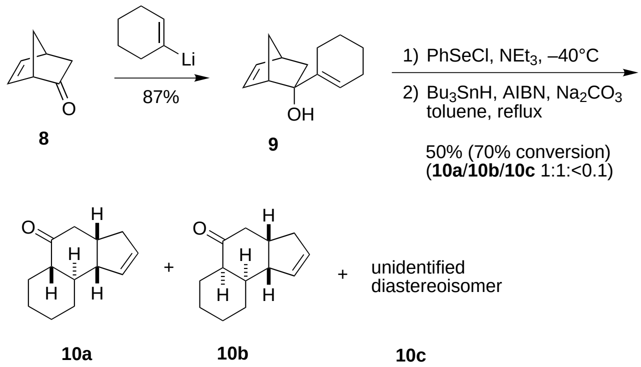
We next turned our attention towards a more efficient alkoxyl radical precursor that can be obtained directly from the *endo* alcohols **1a** and **1b**. Treatment of **1a** and **1b** with phenylselenyl chloride and triethylamine afforded the tricyclic oxetanes **5a** and **5b** in 60% and 67% yield, respectively (Scheme 4).[16] Similarly the iodides **6a** and **6b** were prepared



Scheme 4. The tricyclic oxetane approach. 1) PhSeCl, NEt_3; 2) NIS, NaH; 3) NIS, DBU.

by treatment with *N*-iodosuccinimide (NIS) in the presence of a base. Treatment of **5a** and **6a** with Bu_3SnH in refluxing toluene afforded the rearranged product **2a** in 69% and 64% yields (Scheme 4). The same treatment of oxygenated analogues **5b** and **6b** in refluxing *tert*-butanol gave lower yields. A better result was obtained when the reaction was immediately followed by iodoacetalization upon treatment with NIS or NBS (*N*-bromosuccinimide). In this case, the stable iodide **7** was isolated in 60% yield.[17]

Finally, the radical oxy-Cope rearrangement was tested for the preparation of a tricyclic framework (Scheme 5). Reaction of 2-norbornenone **8** with cyclohexenyllithium afforded the



Scheme 5. Preparation of a tricyclic system.

endo alcohol **9** in good yield. Reaction of **9** with PhSeCl/Et_3N gave an unstable tricylic selenide that was used without purification for the next step. Treatment of this crude selenide with Bu_3SnH/AIBN in refluxing toluene in the presence of sodium carbonate (to minimize acid catalyzed degradation) afforded the rearranged compound **10** in 50% yield (70% conversion) as a mixture of three isomers **10a/b/c** (1:1:$<$0.1). After separation by HPLC, the relative configuration of **10a** and **10b** was established by ^{1}H NMR and NOE differential experiments.

In conclusion, we have developed a radical alternative to the anionic oxy-Cope rearrangement that is independent of the stereochemistry of the starting material. A nonconcerted fragmentation–cyclization mechanism is involved. Further extension of this chemistry to more complex substrates is currently under investigation, along with the development of alternative methods to generate the starting tertiary alkoxyl radicals.[18]

Experimental Section

6b: 1,8-Diazabicyclo[5.4.0]undec-7-ene (DBU; 1.08 mL, 7.24 mmol) was added to a solution of allylic alcohol **1b** (1.00 g, 7.24 mmol) in dry CH_2Cl_2 (123 mL) at room temperature. NIS (5.32 g, 21.7 mmol) was added in portions over 3 h at −40 °C. The reaction was stirred overnight at room temperature and then water was added. After extraction with CH_2Cl_2, the organic phases were washed with aqueous $Na_2S_2O_3$ and brine, dried over $MgSO_4$, and concentrated. Flash column chromatography (Et_2O/hexane 1:12) of the crude product afforded **6b** (1.4 g, 73 %) as a white solid. M.p.: 74–76 °C; IR (KBr): $\tilde{\nu} = 3009, 2930, 2361, 1633, 1408, 1147, 1049, 964, 927\,cm^{-1}$; ^1H NMR (360 MHz, $CDCl_3$): $\delta = 5.87$ (dd, $J = 17.7, 10.9$ Hz, 1 H; $C\mathit{H}{=}CH_2$), 5.31 (dd, $J = 17.2, 0.9$ Hz, 1 H; $CH{=}C\mathit{H}H$), 5.23 (m, $CH{=}CH\mathit{H}$, 2 H; 1-H), 5.06 (d, $J = 5.0$ Hz, 1 H; 6-H), 4.90 (dd, $J = 3.2, 1.4$ Hz, 1 H; 3-H), 4.29 (s, 1 H; I-CH), 2.26 (d, $J = 12.7$ Hz, 1 H; *endo* 8-H), 1.93 ppm (dd, $J = 12.9, 4.5$ Hz, 1 H; *exo* 8-H); ^{13}C NMR (90.5 MHz, $CDCl_3$): $\delta = 135.1$ (d), 116.4 (t), 92.7 (s), 85.9 (d), 83.8 (d), 82.1 (d), 43.4 (d), 28.2 ppm (t). MS (CI): m/z (%): 265 (26) $[M^+ + 1]$, 137 (72) $[M\text{-}I]^+$, 109 (100), 95 (95), 83 (50), 55 (51); elemental analysis: calcd for $C_8H_9IO_2$ (264.06): C 36.39, H 3.44; found: C 36.44, H 3.39.

7: A solution of Bu_3SnH (0.3 mL, 1.14 mmol) and AIBN (6 mg, 0.04 mmol) in benzene (3 mL) was added over 15 h (syringe pump) to the iodide **6b** (200 mg, 0.76 mmol) in refluxing *t*BuOH (74 mL). Heating was stopped at the end of the addition process and CH_2Cl_2 (30 mL) was added. The mixture was cooled at −20 °C and NBS[17] (137 mg, 0.77 mmol) was added in portions over 15 min. After 2 h at −20 °C, the organic layer was washed with water, dried over Na_2SO_4, and concentrated. Flash column chromatography of the residue (EtOAc/hexane 1:9) gave the stable iodoacetal **7** (143 mg, 60 %) as a colorless oil. IR (film): $\tilde{\nu} = 2974, 2936, 1722, 1368, 1003\,cm^{-1}$; ^1H NMR (360 MHz, $CDCl_3$): $\delta = 5.51$ (d, $J = 3.2$ Hz, 1 H; OCHO), 4.57 (td, $J = 6.4, 6.4$ Hz, 1 H; 7a-H), 3.88 (dd, $J = 3.9, 4.1$ Hz, 1 H; ICH), 2.6–2.82 (m, 3 H, 2 × 7-H, 3a-H), 2.43–2.54 (m, 1 H; 5-H), 1.95–2.26 (m, 3 H; 2 × 4-H, 5-H), 1.23 ppm (s, 9 H; *t*Bu); ^{13}C NMR (125.8 MHz, $CDCl_3$): $\delta = 209.6$ (s), 106.5 (d), 75.7 (d), 75.6 (s), 47.2 (d), 44.3 (t), 36.8 (t), 31.0 (d), 28.6 (q), 24.5 ppm (t); MS (CI): m/z (%):339 (1) $[M^+]$, 265 (100) $[M^+ - O\mathit{t}Bu]$, 137 (29); HRMS (CI, isobutane) for $C_{12}H_{19}O_3I$ ($[M^+\text{-}O\mathit{t}Bu]$): calcd 264.97199; found 264.97194.

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Allyl Sulfoxides as Precursors for Radical Two-Carbon Ring Expansion of Cyclobutanones**

Rachel Chuard, Anne Giraud, and Philippe Renaud*

Ring-expansion reactions are extremely useful processes that take advantage of existing ring structures for the construction of larger cyclic systems. Various ion-based methods have been developed for selective ring-expansion reactions.[1] More recently, following the tremendous development of preparative radical chemistry, ring expansion of ketones by using alkoxyl radicals (Dowd–Beckwith reaction) has been reported.[2–5] This approach proved to be quite efficient for one-, three-, and four-carbon ring expansions. However, enlargement by two carbon atoms is not possible.[3] For this purpose, Galatsis et al. developed a three-step method based on the rearrangement of 1-vinylcycloalkoxyl radicals.[6–8] The low yields and lack of regioselectivity make this procedure unsatisfactory for preparative purposes.[6] Therefore, an efficient two-step procedure for the ring expansion of cycloalkanones would be useful.[9,10] The strategy that we developed is based on an unusual cascade reaction, which consists of a [2,3]-sigmatropic rearrangement (Mislow–Braverman–Evans rearrangement)[11–13] of an allylic sulfoxide followed by a radical fragmentation–cyclization process (Scheme 1). The experimental reaction sequence involves the one-pot preparation of an allylic sulfoxide from the ketone according to the procedure of Evans et al.,[14] followed by treatment of the sulfoxide with tributyltin hydride in refluxing benzene. The challenge of this approach is to develop a chain process with a radical precursor that is available from an equilibrium reaction. The efficacy of the reaction will depend on the ability of the intermediate sulfenate, present only in small amounts, to sustain a chain reaction.

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