Geminal acylation of α-heterosubstituted cyclohexanones and their ketals

Ian R. Pottie, Sheldon N. Crane, Anna Lee Gosse, David O. Miller, and D. Jean Burnell

Abstract: Geminal acylation of derivatives of cyclohexanone with Br, Cl, F, and OCH_3 in the α position, and of their corresponding dimethyl ketals, could not be accomplished to a significant extent following published procedures. The transformation was accomplished in two steps. The initial $BF_3{\cdot}Et_2O$-mediated reaction with 1,2-bis(trimethylsilyloxy)cyclobutene gave a cyclobutanone product as a mixture of diastereomers. Only with 2-chlorocyclohexanone did this occur with good diastereoselectivity. Then, pinacol rearrangement of the diastereomeric mixture mediated by Amberlyst-15 in benzene provided the heterosubstituted spirocyclic diketone.

Key words: diastereoselectivity, Mukaiyama aldol, geminal acylation, spirocyclic diketone.

Résumé : L'acylation géminale de dérivés de la cyclohexanone portant des substituants Br, Cl, F et OCH_3 en position α ainsi que celle des diméthylcétals correspondants ne peut pas être réalisée avec des rendements significatifs par les méthodes rapportées jusqu'à maintenant. On a réussi à effectuer cette transformation en deux étapes. La réaction initiale catalysée par le $BF_3{\cdot}Et_2O$ avec le 1,2-bis(triméthylsilyloxy)cyclobutène conduit à un produit à base de cyclobutanone, sous la forme de mélange de diastéréoisomères. Cette transformation ne s'est effectuée avec une bonne diastéréosélectivité qu'avec la 2-chlorocyclohexanone. La transposition pinacolique du mélange diastéréoisomère catalysée par l'Amberlyst-15 dans le benzène conduit alors à une dicétone spirocyclique hétérosubstituée.

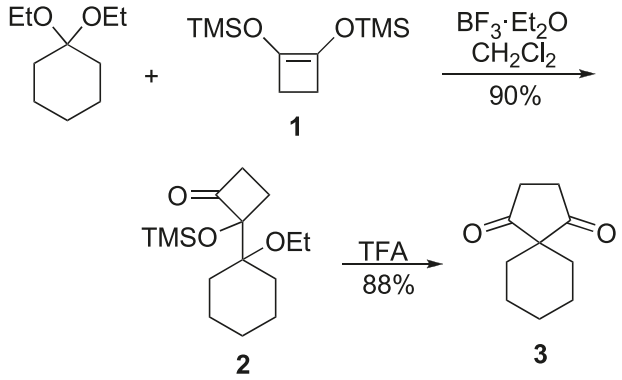
Mots-clés : diastéréosélectivité, aldol de Mukaiyama, acylation géminale, dicétone spirocyclique.

Introduction

The geminal acylation of ketones and their ketals with 1,2-bis(trimethylsilyloxy)cyclobutene (**1**) is a powerful method for generating 2,2-disubstituted 1,3-cyclopentanedione systems in high yield. Kuwajima and co-workers[1] introduced this transformation as a two-step procedure (Scheme 1). First, a $BF_3{\cdot}Et_2O$-mediated Mukaiyama aldol between a ketal and **1**[2,3] affords a cyclobutanone, e.g., **2**. Then, pinacol rearrangement of **2** is effected by treatment with trifluoroacetic acid (TFA), generating a 1,3-diketone such as **3**.

The process can be carried out, generally in excellent yield, in one pot by the use of a large excess of $BF_3{\cdot}Et_2O$.[4–7] Geminal acylation of ketones is facilitated by the addition of a small amount of water to the reaction medium after formation of the cyclobutanone intermediate.[8] Methyl-substituted versions of **1** can also be used for this reaction.[9,10] Geminal acylation has appeared as a key process in many synthetic and methodological endeavors.[11–13] Substitution by alkyl groups α to the ketone, or ketal, reduces the yield of the geminal acylation. For instance, the ethylene ketal of cyclohexanone was geminally acylated in 96% yield using the one-pot procedure,[13] but the ketal of 2-methylcyclohexanone gave only a 30% yield of the geminal acylation product.[7] In a similar way, yields with ketones were lower when the α position was more substituted. The geminal acylation of cyclohexanone gave the diketone product in 94% yield, but

Scheme 1. Geminal acylation in two steps with the diethyl ketal of cyclohexanone.[1]



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I.R. Pottie. Department of Chemistry and Physics, Mount Saint Vincent University, Halifax, NS B3M 2J6, Canada.
S.N. Crane, A.L. Gosse, and D.O. Miller. Department of Chemistry, Memorial University of Newfoundland, St. John's, NL A1B 3X7, Canada.
D.J. Burnell.[1] Department of Chemistry, Dalhousie University, Halifax, NS B3H 4J3, Canada.

[1]Corresponding author (e-mail: jean.burnell@dal.ca).

under very similar conditions 2-methylcyclohexanone provided the diketone in only 62% yield.[8] Differing degrees of α substitution has allowed selective geminal acylation to take place.[8,13] The reason for the attenuation of the yields has been presumed to be steric hindrance.

It was thought that α substitution by a heteroatom might be better tolerated than α substitution by an alkyl group because the former might have a smaller steric effect. The products of geminal acylations with α-substituted ketones or ketals would possess functionality that might be useful for further synthetic manipulation. The results of our experiments with α-substituted cyclohexanones and their corresponding dimethyl ketals are presented here.

Results and discussion

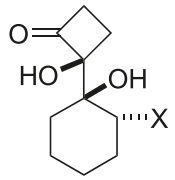
The dimethyl ketals of 2-bromo-, 2-chloro-, 2-fluoro-, and 2-methoxycyclohexanone were subjected to the conditions previously used by Kuwajima and co-workers[1] for the two-step geminal acylation of the ketal of cyclohexanone. Geminally acylated product was not detected from any of these ketals. The same ketals were treated with an excess of **1** and a large excess of $BF_3{\cdot}Et_2O$. These conditions would have geminally acylated the ketal of cyclohexanone in high yield,[4,7] but, once again, no geminally acylated product was obtained.

The procedure developed by Kuwajima and co-workers was used with the four α-substituted ketones, but only two gave geminally acylated products: **4** in 7% yield from the 2-bromocyclohexanone and **5** in 10% yield from the 2-methoxycyclohexanone. Conditions had been developed specifically for the geminal acylation of ketones in one pot.[8] When these conditions were applied to the four α-substituted ketones, only two yielded a detectable amount of a geminally acylated product: **4** in 24% yield from the 2-bromocyclohexanone and **6** in 4% yield from the 2-chlorocyclohexanone.

TLC analysis of the reactions of the ketals and of the ketones indicated that the starting compounds were consumed fairly rapidly. ^{13}C NMR spectra of the resulting material included clusters of resonances between δ 90 and 100 ppm. Chemical shifts in this region have been seen for the carbinolic carbon of a cyclobutane intermediate,[1,8,9] and it was surmised that as a result of these attempted geminal acylations, the Mukaiyama aldol reactions had taken place to give cyclobutanone derivatives (**7**–**14**), but the pinacol rearrangements had failed. The products from the ketals **7**–**10** were mixtures with silylated alcohol functions, but product ratios could not be determined owing to partial desilylation. The products from the ketones **11**–**14** were obtained with alcohol functions only. NMR signals were discerned for at least three of the four possible diastereomers of **11**–**14**, and the proportions of these diastereomers (Table 1) were estimated by integration of the NMR spectra of the crude mixtures of diastereomers.

Only 2-chlorocyclohexanone showed good stereoselectivity (80% of one diastereomer by NMR), and a tiny amount of the major diastereomer **12a** was isolated by repeated flash chromatography. 2-Bromocyclohexanone had reacted with modest stereoselectivity (the ratio of diastereomers was only 3:1:1:1), and a very small amount of the major diastereomer **11a** separated from the others during chromatography. (The diastereomeric mixtures **9**, **10**, **13**, and **14** could not be separated by flash chromatography.) It was fortuitous that both **11a** and **12a** provided crystals that allowed analysis by X-ray crystallography. This analysis revealed that these major diastereomers had the same basic structure (Figs. 1 and 2).

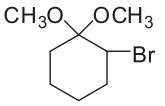
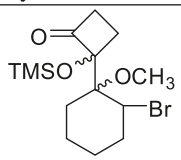
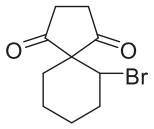
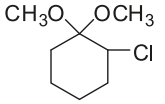
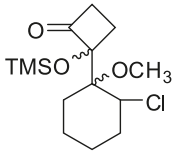
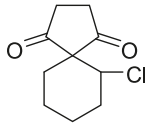
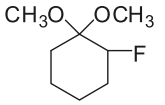
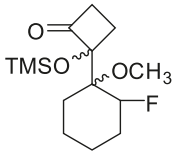
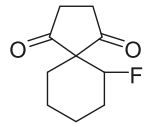
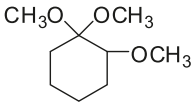
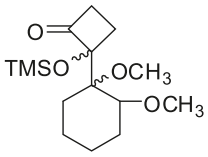
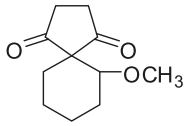
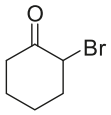
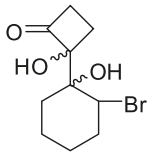
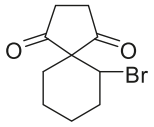
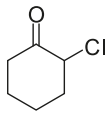
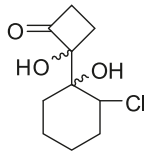
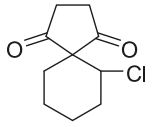
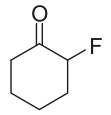
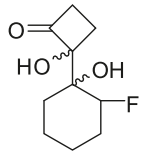
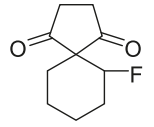
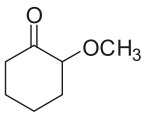
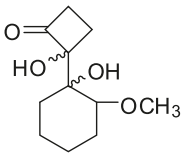
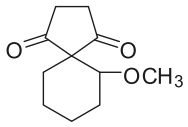
Diastereoselective additions of nucleophiles, such as hydride, organomagnesium reagents, and organolithium reagents, to α-heterosubstituted cyclohexanones have been noted a number of times.[14–16] The selectivity has been rationalized in terms of Felkin–Anh control[15] and electrostatic interactions.[14,17] Previous studies involved products that were predominantly the result of addition to the face of the carbonyl anti to the heteroatom. However, in both **11a** and **12a**, the position of the cyclobutanone moiety relative to the halogen was cis with respect to the cyclohexane ring, which implied that the Mukaiyama aldol reaction preferentially occurred on the face of the ketone syn to the halogen. Previous work with conformationally locked cyclohexanones indicated that addition of hydride was predominantly axial, and the rate of anti addition to the carbonyl was faster when the α-heteroatom was axial.[14] In other words, the diastereoselectivity of additions of smaller nucleophiles to α-substituted cyclohexanones arises from axial addition to the carbonyl when the α-substituent is axial and anti to the incoming nucleophile. NMR studies have shown that the cyclohexanone conformer with the α-halogen in an axial position is either the major conformer or at least similar in energy to the conformer with an equatorial halogen.[15,18]



11a X = Br
12a X = Cl

In contrast with the reactions of hydride and many organometallics, the initial step of the geminal acylation of cyclohexanone or its ketal gives mainly the product of equatorial addition.[1,8] If that mode of addition is still the case with the α-heterosubstituted cyclohexanones, what is intriguing is that the relative stereochemistry observed with **11a** and **12a** must have arisen by addition of **1** syn to the α-heteroatom, but with the conformation of the cyclohexanone having the heteroatom in an axial position. It has been accepted for a long time that equatorial additions to cyclohexanones by larger nucleophiles are due to larger steric interactions in the transition state for axial addition.[19] On the other hand, the axial disposition of the heteroatom is likely due to stabilization of the intermediate carbocation (e.g., **16**). Thus, a plausible reason for the generally low stereoselectivity of the addition reactions summarized in Table 1, relative to additions of smaller nucleophiles,[13–15] would be that the axial heteroatom would retard attack by **1**, since this larger nucleophile would be adding equatorially, which would be syn to the heteroatom, making other modes of reaction competitive in rate.

Table 1. Results of the two-step geminal acylation of α-heterosubstituted cyclohexanones and their ketals.

Substrate	Cyclobutanone	Yield (%)	1, 3-Diketone	Yield (%)
	 **7**	46	 **4**	62
	 **8**	48	 **6**	42
	 **9**	80	 **15**	80
	 **10**	90	 **5**	0
	 **11** (dr 3:1:1:1)	56	 **4**	80
	 **12** (dr 12:2:2:1)	77	 **6**	95
	 **13** (dr 2:1:1:0)	54	 **15**	92
	 **14** (dr 2:1:1:0)	83	 **5**	51

[a] The initial reaction involved **1** with $BF_3{\cdot}Et_2O$ in CH_2Cl_2 at –78°C, and the rearrangement step was with Amberlyst–15 in benzene under reflux.

Fig. 1. X-ray crystal structure of **11a**.

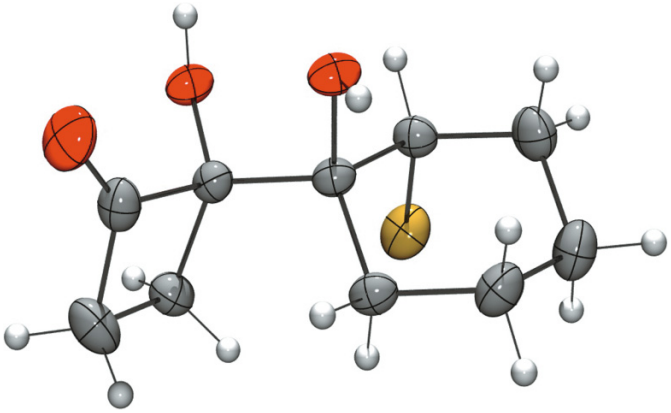
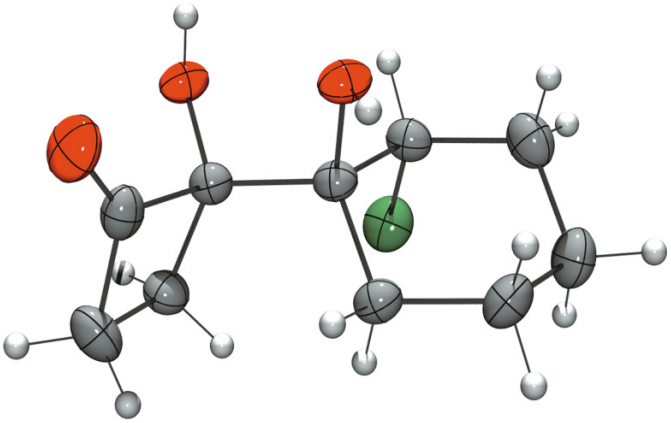
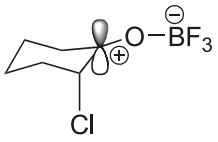


Fig. 2. X-ray crystal structure of **12a**.





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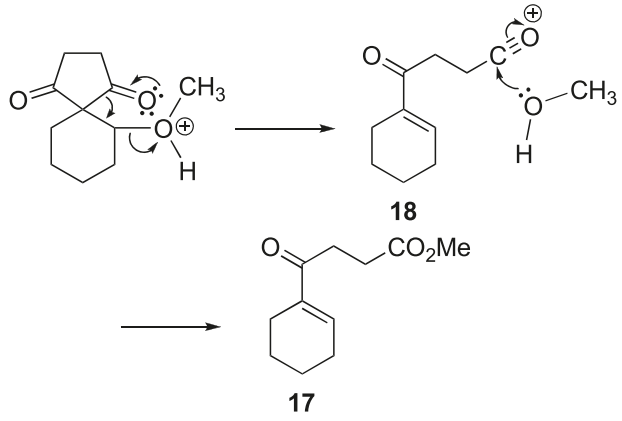
When some cyclobutanone compounds were maintained in warm TFA, very little, if any, rearrangement took place, but the starting compound was steadily consumed, and some material that was insoluble in common organic solvents was produced. The formation of a spirocyclic 1,3-diketone from the cyclobutanone might take place in a stepwise fashion, by initial generation of an intermediate tertiary carbocation followed by rearrangement, or by a concerted mechanism in which carbon–carbon bond reorganization accompanies the loss of the oxygen. TFA, being a polar medium, should stabilize a discreet carbocation. However, calculations by Nakamura and Osamura[20] suggested that as a carbocation is stabilized, the energy required for carbon–carbon bond reorganization increases. This would likely make other reaction pathways (leading to decomposition) more competitive. It was hypothesized that performing the rearrangement in a nonpolar medium would create a more favorable situation for a concerted process to occur instead of other more destructive reaction pathways.

To this end, benzene was chosen as the solvent and

Scheme 2.



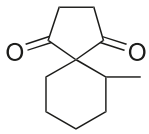
Amberlyst-15, which is a resin with sulfonic acid sites, was chosen as the acid. Amberlyst-15 had proven to be an excellent catalyst for the rearrangement of cyclobutanone intermediates generated from aldehydes.[21] It was gratifying that the desired spirocyclic 1,3-diketone (**6**) was obtained in 95% yield. The use of *p*-TsOH in the place of Amberlyst-15 gave no rearranged product, just intractable material. This dramatic difference in the result was evidence that the macroreticular structure of the resin, and not just its acidity, plays an important role in promoting the rearrangement of the cyclobutanone. This may be related to pinacol rearrangements mediated by acidic agents in other porous structures, e.g., iron(III)-substituted molecular sieves.[22]

The procedure using Amberlyst-15 was carried out with all of the cyclobutanone derivatives in Table 1. The cyclobutanones derived from ketones (**11**–**14**) rearranged within an hour in benzene under reflux. The halogenated compounds **11**–**13** provided the 1,3-diketones **4**, **6**, and **15** in excellent yield. The methoxy derivative **5** was obtained in modest yield from **14**. Diketone **5** was accompanied by a significant amount of by-product, which was difficult to separate. It appeared by ^{1}H NMR spectroscopic analysis to be **17**. (Its diagnostic NMR signals were a multiplet at δ 6.98 ppm, a singlet at δ 3.71 ppm, and triplets at δ 3.00 and 2.64 ppm.) It was likely that **17** was produced from **5** (Scheme 2). Acid-catalyzed elimination of methanol might be accompanied by ring-opening and generation of the acylium ion **18**, which would then capture the evolved methanol to provide **17**.

The reactions of the cyclobutanones derived from the ketals (**7**–**10**) were sluggish, requiring 48 h to consume the starting materials in benzene under reflux. The 1,3-diketones **4**, **6**, and **15** were isolated in poorer yield than from **11**–**13**, and the methoxycyclobutanone **10** gave none of the 1,3-diketone **5**. The reason for the slower reaction was the presence of the TMS group, because desilylation of **8** with TBAF followed immediately by treatment with Amberlyst-15 in benzene gave **6** in 88% yield.

The success of the two-step process from ketones prompted us to re-examine the reactions of two α-substituted substrates that had given only modest yields of 1,3-diketones previously. 2-Methylcyclohexanone and 3-methylbutanone had given **19** and **20** in yields of 62% and 52%, respectively, using the one-pot, two-step method using excess $BF_3{\cdot}Et_2O$ to effect the rearrangement.[8] In contrast, using the

same two-step procedure involving Amberlyst-15 that was used to produce the spirocyclic 1,3-diketones in Table 1, **19** and **20** were prepared in 84% and 80% yield, respectively, from the ketones.



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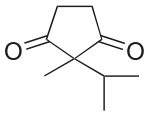

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In summary, a two-step procedure has been developed for the geminal acylation of an α-heterosubstituted cyclohexanone. The first step is the $BF_3{\cdot}Et_2O$-mediated addition of **1** to the ketone to give a cyclobutanone intermediate, and the second is the rearrangement of the cyclobutanone in benzene with Amberlyst-15. The process works less well with the corresponding ketal. Following the same procedure, yields of geminally acylated products from ketones substituted in the α position with alkyl groups are improved over the older one-pot, two-step procedure. It is expected that the procedure will be widely applicable for the geminal acylation of other cyclic and acyclic ketones with α substitution.

Experimental

General

All reactions were performed under N_2. $BF_3{\cdot}Et_2O$ was distilled before use. CH_2Cl_2 and benzene were distilled from calcium hydride before use. Flash chromatography used 230–400 mesh silica gel, starting with 20% ethyl acetate – hexane mixtures with an increasing portion of ethyl acetate as the eluting solvent. ^{1}H NMR spectra were recorded in $CDCl_3$. Chemical shifts are relative to internal TMS. ^{13}C NMR chemical shifts are relative to the $CDCl_3$ solvent (δ 77.0 ppm). Each ^{13}C NMR chemical shift is followed by a number in parentheses that represents the number of attached protons as determined by DEPT experiments. Compound **1** was prepared by the method of Bloomfield and Nelke.[3] 2-Chloro-, 2-methoxy-, and 2-methyl-cyclohexanone and 3-methylbutanone were purchased (Sigma-Aldrich). 2-Bromo- and 2-fluorocyclohexanone were prepared by oxidation of the corresponding alcohols[23] with pyridinium chlorochromate. Ketals[24] were formed by treatment of the ketones with methanol–trimethylorthoformate (1:1) with some *p*-TsOH.

General procedure for geminal acylation

To a solution of the ketone or ketal (1.0 mmol) in CH_2Cl_2 (8 mL) at –78 °C was added $BF_3{\cdot}Et_2O$ (1.5 mmol) and then **1** (3.0 mmol) dropwise. The mixture was warmed slowly to room temperature (rt) and then stirred until TLC indicated that the starting ketone or ketal was consumed. The mixture was concentrated under reduced pressure. Flash chromatography was used to remove unreacted and decomposed **1** from the mixture of cyclobutanone products. The cyclobutanone mixture was dissolved in benzene (25 mL). Amberlyst-15 (0.25 g) was added to this solution, and the resulting mixture was heated under reflux. When TLC indicated that the cyclobutanones had been consumed, the mixture was cooled to rt, and the Amberlyst-15 was removed by gravity filtration. The filtrate was concentrated under reduced pressure, and flash chromatography afforded the 1,3-diketone. Characterization data for the 1,3-diketones **4**, **5**, **6**, and **15** and the cyclobutanone intermediates **11a** and **12a** are given in the following. Data for **19** and **20** were consistent with published data.[7]

6-Bromospiro[4.5]decane-1,4-dione (4)

Solid, mp 56–58 °C. IR (Nujol, cm^{-1}): 1728, 1460, 1377, 1311, 1178, 986, 696. ^{1}H NMR (500 MHz) δ: 4.12 (dd, *J* = 12.7, 4.7 Hz, 1H), 2.81–2.73 (m, 4H), 2.54 (dq, *J* = 13.1, 4.1 Hz, 1H), 2.13 (m, 1H), 1.86 (m, 1H), 1.80–1.73 (m, 2H), 1.59 (m, 1H), 1.51 (m, 1H), 1.40 (m, 1H). ^{13}C NMR (125 MHz) δ: 214.2 (0), 213.1 (0), 59.3 (0), 49.4 (1), 35.5 (2), 34.8 (2), 32.9 (2), 31.7 (2), 26.7 (2), 18.9 (2). GC–MS: 246 (M^{+2}, 2), 244 (M^+, 2), 166 (11), 165 (100), 164 (8), 147 (4), 123 (15), 109 (14), 95 (7). HRMS (EI) calcd. for $C_{10}H_{13}BrO_2$: 244.0099; found: 244.0098.

6-Methoxyspiro[4.5]decane-1,4-dione (5)

Yellow oil. ^{1}H NMR (500 MHz) δ: 3.44 (dd, *J* = 11.7, 4.5 Hz, 1H), 3.20 (s, 3H), 2.73–2.63 (m, 4H), 1.97 (m, 1H), 1.88 (m, 1H), 1.83–1.75 (m, 2H), 1.59 (m, 1H), 1.50–1.44 (m, 2H), 1.30–1.24 (m, 2H). ^{13}C NMR (125 MHz) δ: 217.8 (0), 215.9 (0), 83.8 (1), 59.4 (0), 56.9 (3), 36.5 (2), 35.9 (2), 30.1 (2), 24.9 (2), 23.8 (2), 19.9 (2). GC–MS: 196 (M^+, 64), 182 (25), 181 (100), 165 (53), 164 (80), 163 (54), 141 (51), 138 (58), 136 (58), 125 (68), 112 (96). HRMS (EI) calcd. for $C_{11}H_{16}O_3$: 196.1099; found: 196.1092.

6-Chlorospiro[4.5]decane-1,4-dione (6)

Solid, mp 42–46 °C. ^{1}H NMR (500 MHz) δ: 4.08 (dd, *J* = 12.5, 4.7 Hz, 1H), 2.82–2.72 (m, 4H), 2.38 (m, 1H), 2.01 (m, 1H), 1.91 (m, 1H), 1.78–1.71 (m, 2H), 1.56–1.46 (m, 2H), 1.38 (m, 1H). ^{13}C NMR (125 MHz) δ: 214.4 (0), 213.1 (0), 59.4 (0), 59.1 (1), 35.9 (2), 35.2 (2), 32.2 (2), 31.0 (2), 25.6 (2), 18.9 (2). GC–MS: 202 (M^{+2}, 2), 200 (M^+, 5), 166 (11), 165 (100), 164 (28), 147 (9), 137 (6), 123 (24), 109 (34). HRMS (EI) calcd. for $C_{10}H_{13}ClO_2$: 200.0604; found: 200.0598.

6-Fluorospiro[4.5]decane-1,4-dione (15)

Solid, mp 62–63 °C. IR (Nujol, cm^{-1}): 1721, 1456, 1377, 1307, 1182, 1020, 963. ^{1}H NMR (500 MHz) δ: 4.70 (ddd, *J* = 4.8, 11.8, 47.4 Hz, 1H), 2.80–2.70 (m, 4H), 2.15 (m, 1H), 1.97–1.89 (m, 2H), 1.78–1.65 (m, 2H), 1.51–1.45 (m, 2H), 1.32 (m, 1H). ^{13}C NMR (125 MHz) δ: 215.0 (0), 213.4 (0), 94.2 (1, d, *J* = 175.4 Hz), 58.9 (0, d, *J* = 20.0 Hz), 35.8 (2, d, *J* = 70.7 Hz), 30.2 (2, d, *J* = 5.7 Hz), 26.8 (2, d, *J* = 18.0 Hz), 23.1 (2, d, *J* = 11.5 Hz), 19.2 (2). GC–MS: 184 (M^+, 80), 164 (49), 155 (18), 129 (18), 109 (96), 103 (23), 81 (100). HRMS (EI) calcd. for $C_{10}H_{13}FO_2$: 184.0900; found: 184.0904.

(1′*R**,2*R**,2′*S**)-2-(2-Bromo-1-hydroxycyclohexyl)-2-hydroxycyclobutanone (11a)

Solid. IR (Nujol, cm^{-1}): 3389 (sharp), 1776, 1737, 1462, 1377. ^{1}H NMR (300 MHz) δ: 4.40 (narrow m, 1H), 3.25 (ddd, *J* = 8.6, 12.4, 17.4 Hz, 1H), 3.23 (s, OH), 2.93 (ddd, *J* = 6.9, 10.8, 17.4 Hz, 1H), 2.70 (m, 1H), 2.45 (s, OH),

Table 2. X-ray crystallographic data for **11a** and **12a**.

	Crystal	
Data	**11a**	**12a**
Empirical formula	$C_{10}H_{15}BrO_3$	$C_{10}H_{15}ClO_3$
Formula mass	263.13	218.68
Color, habit	Colorless, irregular	Colorless, irregular
Dimensions (mm)	0.40×0.25×0.25	0.40×0.30×0.10
Crystal system	Orthorhombic	Orthorhombic
Space group	*Pbca* (No. 61)	*Pbca* (No. 61)
Z	8	8
a (Å)	11.490(2)	11.440(5)
b (Å)	22.733(5)	22.389(6)
c (Å)	8.156(2)	8.122(7)
Collection ranges	$-12\le h\le 12$; $-25\le k\le 25$; $-9\le l\le 9$	$0\le h\le 12$; $0\le k\le 25$; $0\le l\le 9$
Temperature (K)	299(2)	299(2)
V (Å^3)	2130.1(8)	2080.4(20)
Calcd. density (g cm^{-3})	1.641	1.396
Absorption coefficient μ (Cu Kα) (cm^{-1})	51.15	31.02
F(000)	1072	928
θ range for data collection (°)	3.89–59.97	3.95–59.99
No. of reflections	3278	1612
No. of unique reflections	1583 (R_{int} = 0.0177)	1545 (R_{int} = 0.0215)
Reflection parameter	12.37	11.98
Maximum shift –error	0.001	0.001
Goodness-of-fit on F^2	1.037	1.099
R_1, [$I > \sigma(I)$]	0.0399	0.0365
R indices (all reflections)	R = 0.0529, wR_2 = 0.1153	R = 0.0572, wR_2 = 0.1126
Largest diff. peak and hole (e Å^{-3})	0.32 and –0.83	0.22 and –0.34

2.37–2.14 (m, 4H), 1.91 (d of narrow m, J = 15.0 Hz, 1H), 1.81–1.55 (m, 4H), 1.41 (br d, J = 13.8 Hz, 1H). ^{13}C NMR (75 MHz) δ: 212.7 (0), 95.5 (0), 74.6 (0), 51.4 (1), 44.4 (2), 30.5 (2), 27.6 (2), 26.0 (2), 20.1 (2), 20.0 (2). GC–MS: no M$^+$, 182 (2), 164 (46), 139 (53), 125 (43), 112 (59), 111 (60), 81 (68), 79 (57), 55 (100).

(1′*R,2*R**,2′*S**)-2-(2-Chloro-1-hydroxycyclohexyl)-2-hydroxycyclobutanone (12a)**

Solid, mp 126–128 °C. ^{1}H NMR (300 MHz) δ: 4.29 (br s, 1H), 3.42 (s, OH), 3.24 (m, 1H), 2.90 (m, 1H), 2.67 (m, 1H), 2.44 (s, OH), 2.35–1.94 (m, 4H), 1.82 (d of narrow m, J = 17 Hz, 1H), 1.81–1.55 (m, 4H), 1.41 (br d, J = 12 Hz, 1H). ^{13}C NMR (75 MHz) δ: 211.8 (0), 94.2 (0), 74.6 (0), 60.2 (1), 46.1 (2), 31.7 (2), 29.1 (2), 27.2 (2), 21.9 (2), 21.0 (2). GC–MS: no M$^+$, 183 (3), 165 (56), 133 (45), 109 (77), 81 (100), 79 (64), 55 (80), 43 (99).

X-ray crystallography

Table 2 summarizes the crystallographic data for **11a** and **12a**. Diffraction data were acquired using a Rigaku AFC6S diffractometer with graphite-monochromated Cu Kα radiation (λ = 1.541 78 Å). An empirical absorption correction was applied. The data were corrected for Lorentz and polarization effects. The structures were solved by direct methods and expanded using Fourier techniques. The non-hydrogen atoms were refined anisotropically. Hydrogen atoms were refined using the riding model. Final cycles of full-matrix least-squares refinement were applied. All calculations were performed using the CrystalStructure[25] crystallographic software package except for refinement, which was performed using SHELXL-97.[26]

Supplementary data

Supplementary data for this article are available on the journal Web site (canjchem.nrc.ca). CCDC 760849 and 760850 contain the X-ray data in CIF format for this manuscript. These data can be obtained, free of charge, via www.ccdc.cam.ac.uk/conts/retrieving.html (or from the Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB2 1EZ, UK; fax +44 1223 336033; or deposit@ccdc.cam.ac.uk).

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