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Carbonylation of C_7–C_8 cycloalkanes leading to individual tertiary carbonyl-containing compounds

Irena Akhrem,* Lyudmila Afanas'eva, Pavel Petrovskii, Sergei Vitt and Alexander Orlinkov

A.N. Nesmeyanov Institute of Organoelement Compounds, Russian Academy of Sciences, 28 Vavilova St., 117813 Moscow, Russia

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Abstract

Carbonylation of cycloheptane, methylcyclohexane, cyclooctane and ethylcyclohexane by CO in the presence of $CBr_4{\cdot}2AlBr_3$ at −40°C and 1 atm was performed with good yields and selectivities. Individual esters of tertiary carboxylic acids of the cyclohexane series were the products of these cycloalkane carbonylations. © 2000 Elsevier Science Ltd. All rights reserved.

Selective functionalisation of alkanes and cycloalkanes is a topic of current interest.[1] One-pot reactions of saturated hydrocarbons with CO are of obvious potential. It has been reported that insertion of CO into unactivated C–H bonds may be achieved under the action of transition metals, Lewis and aprotic superacids and radical species.[1a,b,2] Selectivities of alkane (cycloalkane) transformations are known to decrease with the increase of hydrocarbon chain length. This effect is caused by the increase in the number of C–H bonds of close reactivities for the higher homologues. In addition, long chain carbocations produced in the course of electrophilic transformations of alkanes and cycloalkanes are more liable to fragment than their lower homologues.

Our approach to selective functionalisations of alkanes and cycloalkanes is based on the application of superelectrophiles capable of effective generation of carbocations from alkanes and cycloalkanes at low temperatures.[3] Under these conditions, side reactions such as cracking and subsequent transformations of functionalised products should be largely suppressed. Besides, low temperatures favour the formation of branched products rather than their linear isomers.[4] This paper reports the first examples of carbonylation of cycloheptane, cyclooctane and ethylcyclohexane. It is also noteworthy that the first selective electrophilic reaction of methylcyclohexane with CO was achieved under the action of $CBr_4{\cdot}2AlBr_3$ in the absence of any other additives.

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* Corresponding author. E-mail: cmoc@ineos.ac.ru

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Cycloheptane reacts with CO in the presence of $CBr_4 \cdot 2AlBr_3$ at −40°C and 1 atm for 2 h to give (after treatment with ${}^{i}PrOH$) ester **1** as the sole carbonyl-containing product in 82% yield (Table 1).[5] Under similar conditions, methylcyclohexane behaves analogously to afford ester **1** in a similar yield.

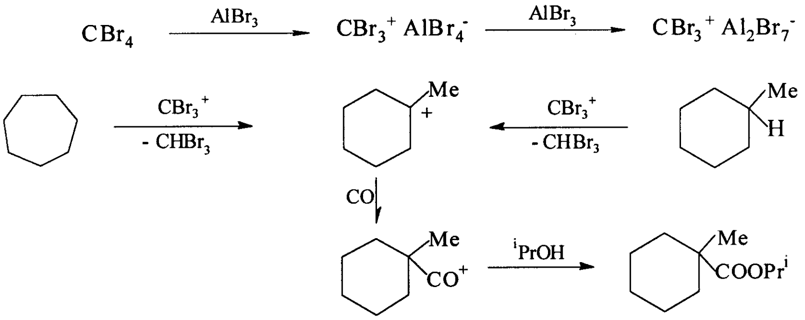

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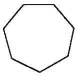
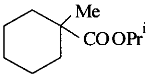
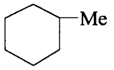
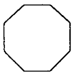
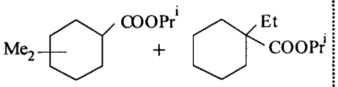
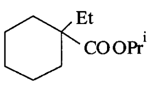
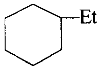
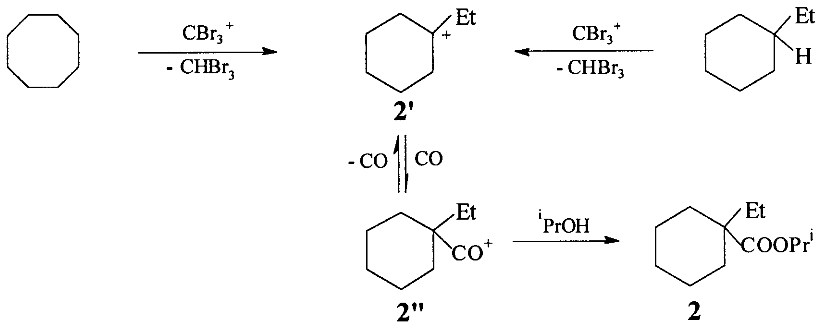
Table 1
Carbonylation of cycloalkanes C_7–C_8 with CO (1 atm) initiated by $CBr_4 \cdot 2AlBr_3$ (*E*) in CH_2Br_2

Run	Cycloalkane (RH)	[RH] : [E]	t, °C	Time, h	Product, (after ${}^{i}PrOH$ work-up)	Yield, mol.% on E
1		1 : 1	-20	0.5		36
2		1 : 1	-40	2.0		82
3		1 : 1	-40	0.5		67
4		1 : 1	-40	1.0		73
5		2 : 1	-20	0.66		46**
6*		1.2 : 1	-40	1.0		75**
7		1.2 : 1	-40	0.5		67
8		1.2 : 1	-40	1.0		69

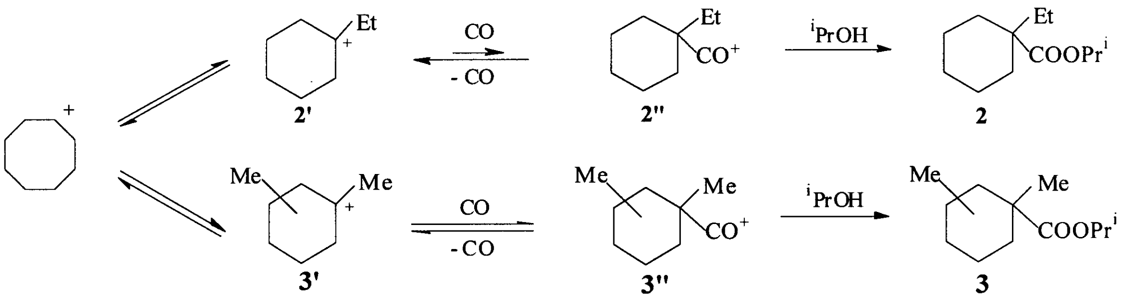
*) The run was carried out under 30 atm CO; **)A mixture of four isomers is formed in the ratio ~ 4:2:4:1 (run 5) and 2.2:1.2:0.2:1 (run 6) (the order of isomers is given according to their increasing GC retention times, capillary column -DB-5.625).

Both cyclooctane and ethylcyclohexane also react with CO in the presence of $CBr_4{\cdot}2AlBr_3$ in CH_2Br_2 at −40°C and 1 atm affording ester **2** as a sole carbonyl-containing product in 67–70% yield after 0.5–1 h.



The structures of **1** and **2** were proved by ^1H and ^{13}C NMR and mass spectra.[5] Isomeric bromides *cyclo*-$C_7H_{13}Br$ were formed as by-products in the reactions of cycloheptane or methylcyclohexane, while *cyclo*-$C_8H_{15}Br$ and small amounts of C_8H_{14} were found in the reactions of cyclooctane or ethylcyclohexane. Yields of these bromides are 10–30% based on $CBr_4{\cdot}2AlBr_3$, depending on the experimental conditions. During the course of these reactions, CBr_4 is converted completely into its reduced product $CHBr_3$.

At −20°C ester **1** is also formed selectively as a sole carbonyl-containing product from cycloheptane or methylcyclohexane carbonylation. However, under the same conditions (at −20°C) the reaction of cyclooctane or ethylcyclohexane with CO occurred non-selectively affording the mixture of the four isomeric esters, *cyclo*-$C_8H_{15}COOPr^i$ (**2**+**3a**), in the ratio of ≈4:2:4:1 with the isomer **2** being the minor component.



Semiempirical quantum-chemical calculations by the PM3 method revealed that *cyclo*-$EtC_6H_{10}^+$ (**2′**) is the most stable cation among the isomeric tertiary cations *cyclo*-$C_8H_{15}^+$. Cation **2′** (152.6 kcal/mol) is 2.1 kcal/mol more stable than any of the isomeric tertiary *cyclo*-$Me_2C_6H_9^+$ (**3′**) cations of equal stability (150.5 kcal/mol). As a result, the accumulation of the most stable **2′** cation (and hence the formation of acyl cation **2″** and finally ester **2**) should occur. At the same time, the stabilities of acyl cations RCO^+ are known to fall down with the increase of the stabilities of the corresponding R^+ cation.[6] Therefore, decarbonylation of **2″** proceeds more easily than the similar process for **3″** and the ester **2**, which is formed exclusively upon the carbonylation at −40°C, becomes a minor component of the carbonylation products at −20°C.

The reaction of cyclooctane at −40°C and 30 atm CO also occurs non-selectively to result in the isomeric mixture of esters qualitatively similar to that formed in the reaction at −20°C. However, at −40°C the percentage of **2** increases by 2–2.5 times. The decrease in carbonylation selectivity with the increase of CO pressure has been previously reported.[7] Obviously, in the presence of excess CO all carbocations generated in the system are trapped as acylium ions, while the most stable carbocations are carbonylated if CO is deficient.

Isomerisations of cycloalkanes accompanied by the ring contraction is well documented.[8] In particular, it was observed[9] that under comparable conditions cycloheptane is quantitatively converted into methylcyclohexane, while cyclooctane furnished a mixture of 90% of ethylcyclohexane and 10% of isomeric dimethylcyclohexanes, and the relative rates for these reactions were evaluated as 3:2. To the best of our knowledge, the carbonylations of cycloheptane, cyclooctane and ethylcyclohexane have not been described previously. The reaction of methylcyclohexane with CO in the HF–SbF_5 medium was reported[2g] to result in a mixture of 90% of isomeric *cyclo*-$Me_2C_6H_9COOH$ and 10% of tertiary 1-methylcyclohexyl carboxylic acid. The carbonylation of methylcyclohexane by CO in 98% H_2SO_4 (or BF_3–H_2O) in the presence of Cu or Ag salts as the metallocarbonyl sources and olefins or alcohols as carbocation precursors, was reported to give tertiary $MeC_6H_{10}COOH$ in 20–70% yield.[10] The drawback of this method is the necessity to employ both the Cu (or Ag) salts and olefins or alcohols. As a result, besides the desired product $MeC_6H_{10}COOH$, the carbonylation products derived from the olefin (or alcohol) are formed in comparable amounts.

In conclusion, the use of the polyhalomethane based superelectrophilic systems allows selective functionalisation by CO for the cycloalkanes C_7–C_8. Thus, the set of saturated hydrocarbons susceptible to the selective carbonylation is broadened to a substantial extent.

Acknowledgements

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5. A solution of tetrabromomethane and anhydrous aluminium bromide in molar ratio 1:2 in methylene bromide (2 ml per 1 g of $AlBr_3$) was cooled to −40°C (or to −20°C), and the reaction flask was filled with gaseous CO. Then a hydrocarbon was added under CO atmosphere. The mixture was stirred under slightly excessive pressure of CO at −40°C (or at −20°C) for 0.5–2 h. Then an excess of ^{i}PrOH was carefully added, the reaction mixture was left to warm up to room temperature and stirred for an additional 30 min. After water work-up, extraction with ether and drying with $MgSO_4$ the reaction products were analysed by GC and GC-MS. For NMR studies, ether and other light products were distilled from ether extracts. Spectral data: **1**, ^{1}H NMR (δ, ppm from TMS): 1.10 (s, 3H, CH_3), 1.29 (d, 6H, CH_3, $^{3}J=6.4$ Hz), 1.10–2.10 (m, 10H, CH_2 of *cyclo*-C_6H_{10}), 5.00 (sept., 1H, CH, $J=6.4$ Hz); ^{13}C NMR (δ, ppm from TMS): 21.71 (2 CH_3), 23.19 (2 CH_2), 25.71 (1CH_2), 26.50 (1CH_3), 35.49 (2 CH_2,), 42.85 (1C), 66.84 (1CH); 176.74 (1CO); MS, m/z ($I_{\text{rel.}}$, %): 184 (M^+, 3), 142 (11), 97 (95), 96 (15), 87 (25), 81 (20), 69 (12), 67 (13). **2**, ^{1}H NMR (δ, ppm from TMS): 0.93 (t, 3H, CH_3, $^{3}J=8.0$ Hz), 1.22 (d., 6H, CH_3, $^{3}J=6.0$ Hz), 1.00–2.10 (m, 12H, CH_2), 5.00 (sept., 1H, CH, $^{3}J=6.0$ Hz); ^{13}C NMR (δ, ppm from TMS): 8.41 (1CH_3), 21.75 (2 CH_3), 23.30 (2 CH_2), 26.09 (1CH_2), 33.40 (1CH_2), 33.82 (2 CH_2), 46.93 (1C), 66.66 (1CH), 175.59 (1CO); MS, m/z ($I_{\text{rel.}}$, %): 198 (M^+, 5), 170 (10), 156 (15), 127 (15), 111 (90), 110 (51), 109 (13), 101 (51), 81 (50), 57 (17), 53 (16).

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