Selective transformations of alkynols catalyzed by ruthenium complexes

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(Received January 19, 1994)

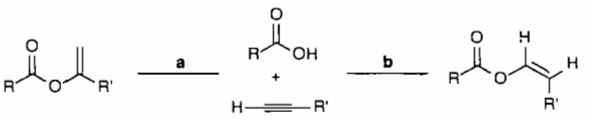
Abstract

Alkynols $HC{\equiv}CCR_2OH$, $HC{\equiv}CCH_2CH_2OH$ and (*E*)-$HC{\equiv}CC(Me){=}CHCH_2OH$ react with carboxylic acids in the presence of $[Ru(\mu\text{-}O_2CR)(CO)_2(PR_3)]_2$ to selectively afford keto esters or trisubstituted hydroxy dienyl esters, depending on the possibility to give intramolecular transesterification. The potential of β-oxopropyl esters as mild acylating reagents and precursors of hydroxy amides, dipeptides, pseudodipeptides, polycarbonyl compounds and acetylenic 1,2-diols has been shown.

Key words: Catalysis; Alkynols; Carboxylic acid; Esterification; Ruthenium complexes; Carboxylato complexes; Carbonyl complexes

Introduction

Selective transformations of alkynes attract interest for the straightforward access to a variety of polyfunctional reagents acting as building block in organic synthesis. In recent years a new trend has been brought into this area by the discovery of specific electrophilic activation of alkynes by ruthenium(II) complexes leading to novel ruthenium-catalyzed reactions. Initial works on the catalytic addition of carboxylic acids to alkynes involved $Ru_3(CO)_{12}$ as catalyst precursor [1]. Then bis(η^5-cyclooctadienyl)ruthenium [2, 3], (arene)$RuCl_2(PR_3)$ [4, 5] and $[Ru(\mu\text{-}O_2CR)(CO)_2(PR_3)]_2$ [6] were shown to be efficient catalyst precursors for the regioselective synthesis of enol esters via addition of carboxylic acids to the C2 carbon atom of terminal alkynes (eqn. (1), a). Whereas the addition of ammonium carbamates to terminal alkynes activated by (arene)$RuCl_2(PR_3)$ catalysts preferentially afforded 1-alkenyl carbamates [7], it is only recently that the regio and stereoselective anti-Markovnikov addition of carboxylic acids to afford *Z*-enol esters was performed using a diphosphine ruthenium complex $(Ph_2P(CH_2)_4PPh_2)$-$Ru(\eta^3\text{-}C_4H_7)_2$ [8] (eqn. (1), b).



(1)

These catalytic reactions have been successful with functional acids such as unsaturated acids [2, 4], diacids [9], hydroxy acids [3, 6] or protected amino acids [3, 10, 11]. They also tolerate the use of functional alkynes like enynes [12], ethoxyacetylene [13, 14], propargylic ethers, esters and carbonates [3, 15, 16].

It is noteworthy that the catalytic addition of carboxylic acids to prop-2-yn-1-ols in the presence of bis(η^5-cyclooctadienyl)ruthenium [3] or (arene)$RuCl_2(PR_3)$ [5, 17] apparently constituted an exception as it did not give the expected hydroxy enol esters but specifically afforded β-oxopropyl esters.

We now report that (i) β-oxopropyl esters can be easily obtained from hydroxy acids using $Ru(\mu\text{-}O_2CR)(CO)_2(PR_3)]_2$ complexes and are useful acylating reagents, (ii) γ-oxobutyl esters are obtained under similar conditions from homopropargylic alcohol and (iii) (*E*)-3-methylpent-2-en-4-yn-1-ol is a starting product of choice for the stereoselective access to trisubstituted functional dienes.

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SSDI 0020-1693(94)03905-4

Experimental

Preparation of catalysts

Complexes of type **A** ((arene)$RuCl_2(PR_3)$) are prepared according to ref. 18 by addition of a phosphine to the $[(arene)RuCl_2]_2$ dimer previously obtained from commercial $RuCl_3 \cdot xH_2O$. Complex **B** is prepared by treatment of $Ru_3(CO)_{12}$ with formic acid followed by addition of PPh_3 under an inert atmosphere of nitrogen according to ref. 19.

General procedure for the preparation of β-oxopropyl esters

One equivalent (10 or 20 mmol) of carboxylic acid, 1.1 equiv. (2 equiv. in the case of a diacid) of prop-2-yn-1-ol and 0.01 equiv. of catalyst precursor were stirred at 60–80 °C for 6–24 h in 10 ml of toluene or THF under an inert atmosphere of nitrogen. After treatment with $NaHCO_3$ and evaporation of the solvent, β-oxopropyl esters were isolated by distillation under reduced pressure, recrystallization or silica gel chromatography.

Preparation of β-oxopropyl pivalate (1)

From 2.04 g (20 mmol) of pivalic acid and 1.6 ml (24 mmol) of prop-2-yn-1-ol, 2.50 g (79%) of ester **1** were isolated as a colourless liquid (b.p. 63–65 °C (10 mm Hg)). *Anal.* Calc. for $C_8H_{14}O_3$: C, 60.75; H, 8.86. Found: C, 60.82; H, 8.97%. Mass spectrum (*m/z*): calc. for $C_8H_{14}O_3$ (M^+): 158.094; found: 158.093. ^1H NMR (80 MHz, CCl_4): δ 4.47 (s, 2H, CH_2); 2.05 (s, 3H, CH_3CO); 1.21 (s, 9H, $(CH_3)_3$). IR: 1770 and 1745 (C=O) cm^{-1}.

Preparation of β-oxopropyl isobutyrate (2)

From 1.76 g (20 mmol) of isobutyric acid and 1.32 ml (22 mmol) of prop-2-yn-1-ol, 2.42 g (84%) of ester **2** were isolated as a colourless liquid (b.p. 143–145 °C (760 mm Hg)). *Anal.* Calc. for $C_7H_{12}O_3$: C, 58.32; H, 8.39. Found: C, 58.30; H, 8.42%. Mass spectrum (*m/z*): calc. for $C_7H_{12}O_3$ (M^+): 144.079; found: 144.078. ^1H NMR (300.133 MHz, $CDCl_3$): δ 4.51 (s, 2H, OCH_2); 2.56 (m, 1H, $CH(Me)_3$); 2.12 (s, 3H, CH_3CO); 1.20 (d, 3H, $^3J(HH) = 7.0$ Hz, $CHMe$); 1.16 (d, 3H, $^3J(HH) = 7.0$ Hz, $MeCH$). IR: 1755 and 1725 (C=O) cm^{-1}.

Preparation of β-oxopropyl diphenylacetate (3)

From 4.24 g (20 mmol) of diphenylacetic acid and 1.32 ml (22 mmol) of prop-2-yn-1-ol, 4.82 g (90%) of ester **3** were isolated as pale yellow crystals (m.p. 115–117 °C). *Anal.* Calc. for $C_{17}H_{16}O_3$: C, 75.85; H, 6.38. Found: C, 76.15; H, 6.08%. Mass spectrum (*m/z*): calc. for $C_{17}H_{16}O_3$ (M^+): 268.110; found: 268.111. ^1H NMR (300.133 MHz, $CDCl_3$): δ 7.25–7.34 (m, 10H, 2 Ph); 5.16 (s, 1H, CH); 4.68 (s, 2H, OCH_2); 2.16 (s, 3H, CH_3). IR: 1755 and 1725 (C=O) cm^{-1}.

Preparation of β-oxopropyl 2,6-difluorobenzoate (4)

From 3.16 g (20 mmol) of 2,6-difluorobenzoic acid and 1.6 ml (24 mmol) of prop-2-yn-1-ol, 3.12 g (73%) of ester **4** were isolated as a liquid (b.p. 144–146 °C (10 mm Hg)). *Anal.* Calc. for $C_{10}H_8O_3F_2$: C, 56.08; H, 3.76; F, 17.74. Found: C, 55.86; H, 3.86; F, 17.82%. Mass spectrum (*m/z*): calc. for $C_{10}H_8O_3F_2$ (M^+): 214.044; found: 214.043. ^1H NMR (80 MHz, CCl_4): δ 7.80–7.40 (m, 3H, Ph); 4.72 (s, 2H, CH_2); 2.05 (s, 3H, CH_3). IR: 1755 and 1730 (C=O) cm^{-1}.

Preparation of β-oxopropyl mandelate (5)

From 1.52 g (10 mmol) of (*R*)-mandelic acid and 0.6 ml (10 mmol) of prop-2-yn-1-ol, 1.32 g (63%) of ester **5** were isolated after recrystallization (m.p. 71–73 °C). *Anal.* Calc. for $C_{11}H_{12}O_4$: C, 63.45; H, 5.81. Found: C, 63.52; H, 5.85%. ^1H NMR (300.133 MHz, $CDCl_3$): δ 7.40 (m, 5H, Ph); 5.28 (s, 1H, *CH*OH); 4.66 (s, 2H, CH_2); 3.72 (m, 1H, OH); 2.00 (s, 3H, Me). ^{13}C NMR (75.469 MHz, $CDCl_3$): δ 26.2, 69.7, 73.4, 127.4, 129.03, 129.06, 138.6, 173.3, 201.4. IR: 3460 (OH), 1750 and 1730 (C=O) cm^{-1}. $[\alpha]_D = -101°$ ($c = 1.00$ g l^{-1}, EtOH, 20 °C).

Preparation of β-oxopropyl lactate (6)

From 0.75 ml (10 mmol) of (*S*)-lactic acid and 0.6 ml (10 mmol) of prop-2-yn-1-ol, 0.85 g (60%) of ester **6** was isolated as a colourless liquid. ^1H NMR (300.133 MHz, $CDCl_3$): δ 4.71 and 4.69 (2s, 2H, OCH_2); 4.35 (q, 1H, $^3J(HH) = 6.9$ Hz, $CHMe$); 3.2 (m, 1H, OH); 2.10 (s, 3H, Me); 1.40 (d, 3H, $^3J(HH) = 6.9$ Hz, $MeCH$). ^{13}C NMR (75.469 MHz, CD_2Cl_2): δ 20.5, 26.2, 67.3, 69.4, 175.2, 201.6. IR: 3460 (OH), 1750 and 1730 (C=O) cm^{-1}. $[\alpha]_D = -8°$ ($c = 1.10$ g l^{-1}, EtOH, 20 °C).

Preparation of bis(β-oxopropyl) tartrate (7)

From 0.750 g (5 mmol) of (2*R*,3*R*)-tartaric acid and 0.6 ml (10 mmol) of prop-2-yn-1-ol, 0.9 g (69%) of ester **7** was isolated as white crystals. *Anal.* Calc. for $C_{10}H_{14}O_8$: C, 45.81; H, 5.38. Found: C, 45.58; H, 5.40%. ^1H NMR (80 MHz, CD_2Cl_2): δ 4.79 (s, 6H, CH_2 and CH); 3.04 (m, 2H, OH); 2.14 (s, 6H, Me). IR: 3500 (OH), 1765, 1735 and 1720 (C=O) cm^{-1}.

General procedure for the preparation of amides and esters

Five mmol of β-oxopropyl ester and 5.5 mmol of primary amine were stirred at 20 °C for 10 h in 5 ml of ethyl acetate. After removal of the solvent, the amide was isolated by recrystallization. From secondary amines and primary alcohols, 10 mol% of KCN were added as acylation catalyst, and a longer reaction time (16–20

h) was necessary to achieve complete conversion of the reagents.

Preparation of N-((L)-(α)-phenylethyl)-BOC-(L)-alaninamide (8)

From 1.225 g (5 mmol) of β-oxopropyl BOC-(L)-alaninate and 0.61 g (5.5 mmol) of L-(−)-α-phenethylamine, 2.19 g (75%) of amide **8** were isolated as white crystals (m.p. 109–111 °C). *Anal.* Calc. for $C_{16}H_{24}N_2O_3$: C, 65.71; H, 6.60; N, 9.59. Found: C, 65.75; H, 6.56; N, 9.58%. Mass spectrum (*m/z*): calc. for $C_{16}H_{24}N_2O_3$ ($[M-CH(CH_3)CONCH(CH_3)Ph]^+$): 144.102; found: 144.102. ^{1}H NMR (300.133 MHz, CD_2Cl_2): δ 7.37 (m, 5H, Ph); 5.99 (broad signal, 2H, 2NH); 4.18 (q, 1H, ^3J(HH) = 6.8 Hz, CHCO); 3.70 (q, 1H, ^3J(HH) = 6.9 Hz, C*H*Ph); 1.52 (d, 3H, ^3J(HH) = 6.8 Hz, CH_3CHCO); 1.41 (s, 9H, $C(CH_3)_3$); 1.13 (d, 3H, ^3J(HH) = 6.9 Hz, CH_3CHPh). IR: 1695 and 1670 (C=O) cm^{-1}. $[\alpha]_D = -15.5°$ ($c = 1.00$ g l^{-1}, EtOH, 20 °C).

Preparation of N-allyl-Z-glycinamide (9)

From 1.325 g (5 mmol) of β-oxopropyl *Z*-glycinate and 0.4 ml (5.5 mmol) of allylamine, 1.05 g (85%) of amide **9** were isolated as white crystals after recrystallization (m.p. 105–107 °C). *Anal.* Calc. for $C_{13}H_{16}N_2O_3$: C, 62.87; H, 6.50; N, 11.29. Found: C, 62.89; H, 6.47; N, 11.28%. Mass spectrum (*m/z*): calc. for $C_{13}H_{16}N_2O_3$ (M^+): 248.116; found: 248.115. ^{1}H NMR (300.133 MHz, CD_3OD): δ 7.31 (m, 5H, Ph); 6.55 (t, 1H, ^3J(HH) = 5.6 Hz, NH); 5.81 (m, 1H, CH_2=C*H*); 5.30 (dd, 1H, $^3J(HH)_{trans}$ = 17.0 Hz, ^2J(HH) = 1.5 Hz, *H*CH=CH); 5.20 (dd, 1H, $^3J(HH)_{cis}$ = 10.3 Hz, ^2J(HH) = 1.5 Hz, HC*H*=CH); 5.12 (s, 2H, CH_2Ph); 3.88 (d, 2H, ^3J(HH) = 5.7 Hz, COCH_2); 3.82 (m, 2H, CH_2CH). ^{13}C NMR (75.469 MHz, CD_3OD): δ 41.8, 44.6, 67.2, 116.5, 129.4, 128.1, 133.8, 136.1, 156.8, 169.1. IR: 1695 and 1660 (C=O) cm^{-1}.

Preparation of N-(2-hydroxyethyl)-Z-glycinamide (10)

From 1.325 g (5 mmol) of β-oxopropyl *Z*-glycinate and 0.33 ml (5.5 mmol) of 2-aminoethanol, 1.13 g (91%) of amide **10** were isolated as white crystals (m.p. 118–120 °C). *Anal.* Calc. for $C_{12}H_{16}N_2O_4$: C, 57.14; H, 6.34; N, 11.11. Found: C, 56.85; H, 6.33; N, 11.37%. Mass spectrum (*m/z*): calc. for $C_{12}H_{16}N_2O_4$ (M^+): 252.110; found: 252.110. ^{1}H NMR (300.133 MHz, CD_3OD): δ 7.33 (m, 5H, Ph); 5.10 (s, 2H, CH_2Ph); 4.86 (s, 1H, OH); 3.78 (s, 2H, CH_2CO); 3.59 (t, 2H, ^3J(HH) = 5.7 Hz, CH_2OH); 3.32 (t, 2H, ^3J(HH) = 5.6 Hz, CH_2NH). IR: 3550 (OH), 1710 and 1655 (C=O) cm^{-1}.

Preparation of N-piperidine benzamide (11)

From 0.89 g (5 mmol) of β-oxopropyl benzoate and 0.55 ml (5.5 mmol) of piperidine, 0.70 g (80%) of amide **11** was isolated as white crystals (m.p. 49–51 °C). *Anal.* Calc. for $C_{12}H_{15}NO$: C, 76.16; H, 7.99; N, 7.38. Found: C, 76.21; H, 7.97; N, 7.40%. Mass spectrum (*m/z*): calc. for $C_{12}H_{15}NO$ (M^+): 189.115; found: 189.114. ^{1}H NMR (300.133 MHz, $CDCl_3$): δ 7.34 (m, 3H, Ph); 7.25 (m, 2H, Ph); 3.61 (m, 2H, CH_2N); 3.34 (m, 2H, CH_2N); 1.57 (m, 6H, 3CH_2). IR: 1630 (C=O) cm^{-1}.

Preparation of the dipeptide Z-Gly-Gly-OEt (12)

From 0.7 g (5 mmol) of ethyl glycinate hydrochloride, 0.8 g (5.5 mmol) of triethylamine and 1.325 g (5 mmol) of β-oxopropyl *Z*-glycinate, 1.38 g (94%) of dipeptide **12** were isolated as white crystals (m.p. 76–78 °C). *Anal.* Calc. for $C_{14}H_{18}N_2O_5$: C, 57.14; H, 6.12; N, 9.52. Found: C, 57.04; H, 6.19; N, 9.40%. Mass spectrum (*m/z*): calc. for $C_{14}H_{18}N_2O_5$ (M^+): 294.121; found: 294.120. ^{1}H NMR (300.133 MHz, $CDCl_3$): δ 7.32 (s, 5H, Ph); 7.00 (broad signal, NH); 5.10 (s, 2H, CH_2Ph); 4.16 (q, 2H, ^3J(HH) = 7.1 Hz, CH_2CH$_3$); 3.98 (d, 2H, ^3J(HH) = 5.3 Hz, CH_2NH); 3.90 (d, 2H, ^3J(HH) = 5.25 Hz, CH_2NH); 1.25 (t, 3H, ^3J(HH) = 7.1 Hz, CH_3). ^{13}C NMR (75.469 MHz, $CDCl_3$): δ 14.1, 41.2, 44.3, 61.6, 67.1, 128.9, 128.1, 136.1, 156.8, 169.7, 169.9. IR: 1745, 1690 and 1650 (C=O) cm^{-1}.

Preparation of the dipeptide Z-Pro-Gly-OEt (13)

From 1.525 g (5 mmol) of β-oxopropyl *Z*-(L)-prolinate, 0.7 g (5 mmol) of ethyl glycinate hydrochloride and 0.8 g (5.5 mmol) of triethylamine, 1.3 g (80%) of dipeptide **13** were isolated. *Anal.* Calc. for $C_{17}H_{22}N_2O_5$: C, 61.07; H, 6.63; N, 8.38. Found: C, 60.85; H, 6.54; N, 8.29%. Mass spectrum (*m/z*): calc. for $C_{17}H_{22}N_2O_5$ ($[M-C_2H_5]^+$): 305.113; found: 305.113. ^{1}H NMR (300.133 MHz, $CDCl_3$): δ 7.32 (s, 5H, Ph); 5.12 (s, 2H, CH_2Ph); 4.32–4.55 (m, 1H, CH); 4.18 (q, 2H, ^3J(HH) = 7.2 Hz, CH_2CH$_3$); 3.90 (d, 2H, ^3J(HH) = 5.2 Hz, CH_2NH); 3.45–3.77 (m, 2H, CH_2N); 1.90–2.30 (m, 4H, CH_2CH_2); 1.23 (t, 3H, ^3J(HH) = 7.2 Hz, CH_3). IR: 1750, 1710 and 1650 (C=O) cm^{-1}. $[\alpha]_D = -47.5°$ ($c = 2.00$ g l^{-1}, EtOH, 20 °C).

Preparation of prop-2-yn-1-yl benzoate (14)

From 0.89 g (5 mmol) of β-oxopropyl benzoate and 0.32 ml (5.5 mmol) of prop-2-yn-1-ol, 0.71 g (94%) of ester **14** was isolated as a colourless liquid (b.p. 85 °C (2 mm Hg)). *Anal.* Calc for $C_{10}H_8O_2$: C, 74.99; H, 5.03. Found: C, 74.81; H, 5.22%. Mass spectrum (*m/z*): calc. for $C_{10}H_8O_2$ (M^+): 160.052; found: 160.051. ^{1}H NMR (300.133 MHz, $CDCl_3$): δ 8.05 (m, 2H, Ph); 7.53 (m, 1H, Ph); 7.40 (m, 2H, Ph); 4.89 (d, 2H, ^4J(HH) = 2.5 Hz, CH_2); 2.52 (t, 1H, ^4J(HH) = 2.4 Hz, CH). IR: 3300 (≡CH), 2140 (C≡C), 1725 (C=O) cm^{-1}.

Preparation of prop-2-en-1-yl benzoate (15)

From 0.89 g (5 mmol) of β-oxopropyl benzoate and 0.37 ml (5.5 mmol) of prop-2-en-1-ol, 0.56 g (70%) of

ester **15** was isolated as a colourless liquid (b.p. 90 °C (2 mm Hg)). *Anal.* Calc. for $C_{10}H_{10}O_2$: C, 74.20; H, 6.25. Found: C, 74.16; H, 6.21%. Mass spectrum (*m/z*): calc. for $C_{10}H_{10}O_2$ (M^+): 162.068; found: 162.068. ^{1}H NMR (300.133 MHz, $CDCl_3$): δ 8.05 (m, 2H, Ph); 7.54 (m, 1H, Ph); 7.40 (m, 2H, Ph); 6.04 (ddt, 1H, $^3J(HH)_{trans}$ = 18.0 Hz, $^3J(HH)_{cis}$ = 10.5 Hz, $^3J(HH)$ = 5.6 Hz, CH=); 5.40 (dq, 1H, $^3J(HH)_{trans}$ = 18.0 Hz, $^2J(HH)$ = $^4J(HH)$ = 1.5 Hz, =C*H*H); 5.27 (dq, 1H, $^3J(HH)_{cis}$ = 10.5 Hz, $^2J(HH)$ = $^4J(HH)$ = 1.5 Hz, =CH*H*); 4.81 (dt, 2H, $^4J(HH)$ = 1.5 Hz, $^3J(HH)$ = 5.6 Hz, OCH_2). IR: 1725 (C=O), 1650 (C=C) cm^{-1}.

Preparation of O-(Z-Ala)-N-(Z-Gly)ethanolamine (16)

From 1.26 g (5 mmol) of *N*-(2-hydroxyethyl)-*Z*-glycinamide and 1.53 g (5 mmol) of butyl-1-vinyl *Z*-(L)-alaninate, 1.71 g (75%) of **16** were isolated as a liquid. *Anal.* Calc. for $C_{23}H_{27}N_3O_7$: C, 60.37; H, 5.95; N, 9.19. Found: C, 60.01; H, 6.20; N, 8.93%. ^{1}H NMR (300.133 MHz, DMSO): δ 7.86 (m, 1H, Ph); 7.44 (m, 1H, Ph); 7.33 (m, 8H, Ph); 5.10 (s, 2H, C*H*$_2$Ph); 5.08 (s, 2H, C*H*$_2$Ph); 4.80 (broad signal, 1H, NH); 4.12 (q, 1H, $^3J(HH)$ = 7.1 Hz, C*H*CH$_3$); 3.88 (d, 2H, $^3J(HH)$ = 5.8 Hz, CH_2CO); 3.39–3.50 (m, 4H, 2 CH_2); 1.49 (2, 3H, $^3J(HH)$ = 7.1 Hz, CH_3). IR: 1770, 1730 and 1690 (C=O) cm^{-1}.

Preparation of methyl (Z-alanyl)acetoacetate (17)

From 1.395 g (5 mmol) of β-oxopropyl *Z*-(L)-alaninate, 0.54 ml (5 mmol) of methyl acetoacetate and 0.12 g (5 mmol) of sodium hydride, 0.98 g (61%) of ester **17** was isolated as a yellow liquid. *Anal.* Calc. for $C_{16}H_{19}NO_6$: C, 59.90; H, 6.06; N, 4.38. Found: C, 59.81; H, 5.96; N, 4.36%. ^{1}H NMR (300.133 MHz, $CDCl_3$): δ 7.33 (m, 5H, Ph); 5.41 (broad signal, 1H, NH); 5.12 (s, 2H, C*H*$_2$Ph); 4.40 (q, 1H, $^3J(HH)$ = 7.2 Hz, C*H*NH); 3.83 (s, 3H, OCH_3); 3.51 (s, 1H, CH); 2.32 (s, 3H, CH_3CO); 1.44 (d, 3H, $^3J(HH)$ = 7.2 Hz, CHC*H*$_3$). IR: 3340 (NH), 1765, 1730 and 1710 (C=O) cm^{-1}. $[\alpha]_D = -56°$ (c = 2.00 g l^{-1}, EtOH, 20 °C).

Preparation of 2-hydroxy-2-methylbut-3-yn-1-ol (18)

From 0.89 g (5 mmol) of β-oxopropyl benzoate and 12 mmol of lithium acetylide, 0.26 g (52%) of **18** was isolated as a colourless liquid (b.p. 55–58 °C (2 mm Hg)). *Anal.* Calc. for $C_5H_8O_2$: C, 59.97; H, 8.06. Found: C, 59.19; H, 8.23%. Mass spectrum (*m/z*): calc. for $C_5H_8O_2$ (M^+): 100.052; found: 100.051. ^{1}H NMR (80 MHz, $CDCl_3$): δ 4.94 (s, 1H, CH); 4.32 (s, 2H, C*H*$_2$OH); 2.92 (s, 1H, OH); 2.23 (s, 1H, OH); 1.56 (s, 3H, CH_3). IR: 3400 (OH), 2230 (C≡C) cm^{-1}.

Preparation of 2-hydroxy-2-methyl-4phenylbut-3-yn-1-ol (19)

From 0.89 g (5 mmol) of β-oxopropyl benzoate and 12 mmol of lithium phenylacetylide, 0.49 g (51%) of **19** was isolated as a colourless liquid. *Anal.* Calc. for $C_{11}H_{12}O_2$: C, 74.98; H, 6.86. Found: C, 74.81; H, 6.98%. Mass spectrum (*m/z*): calc. for $C_{11}H_{12}O_2$ (M^+): 176.083; found: 176.083. ^{1}H NMR (80 MHz, $CDCl_3$): δ 7.40 (m, 2H, Ph); 7.33 (m, 1H, Ph); 7.26 (m, 2H, Ph); 4.60 (s, 2H, C*H*$_2$OH); 2.83 (broad signal, 1H, OH); 2.28 (broad signal, 1H, OH); 1.54 (s, 3H, CH_3). IR: 3395 (OH), 2230 (C≡C) cm^{-1}.

General procedure for the preparation of γ-oxobutyl esters

Ten mmol of acid, 10 mmol of but-3-yn-1-ol and 0.05 mmol of $[Ru(O_2CH)(CO)_2(PPh_3)]_2$ were stirred at 60 °C for 8 h in 10 ml of toluene under a nitrogen atmosphere. After usual workup, the esters were isolated by distillation or silica gel chromatography.

Preparation of γ-oxobutyl benzoate (21)

From 1.22 g (10 mmol) of benzoic acid and 0.756 ml (10 mmol) of but-3-yn-1-ol, 1.40 g (73%) of ester **21** were isolated by distillation under reduced pressure (b.p. 105 °C (2.5 mm Hg)). *Anal.* Calc. for $C_{11}H_{12}O_3$: C, 68.74; H, 6.29. Found: C, 68.44; H, 6.31%. Mass spectrum (*m/z*): calc. for $C_{11}H_{12}O_3$ (M^+): 192.079; found: 192.078. ^{1}H NMR (300.133 MHz, $CDCl_3$): δ 7.51 (m, 2H, Ph); 7.37 (m, 1H, Ph); 7.26 (m, 2H, Ph); 4.56 (t, 2H, $^3J(HH)$ = 6.3 Hz, CH_2O); 2.89 (t, 2H, $^3J(HH)$ = 6.3 Hz, CH_2CO); 2.20 (s, 3H, CH_3). IR: 1750 and 1710 (C=O) cm^{-1}.

Preparation of γ-oxobutyl Z-glycinate (22)

From 2.09 g (10 mmol) of *Z*-glycine and 0.756 ml (10 mmol) of but-3-yn-1-ol, 2.09 g (75%) of ester **22** were isolated by column chromatography on silica gel with hexane–ether as eluent (m.p. 87–89 °C). *Anal.* Calc. for $C_{14}H_{17}O_5N$: C, 63.85; H, 6.51; N, 5.32. Found: C, 63.79; H, 6.49; N, 5.30%. Mass spectrum (*m/z*): calc. for $C_{14}H_{17}O_5N$ (M^+): 279.111; found: 279.111. ^{1}H NMR (300.133 MHz, $CDCl_3$): δ 7.28 (m, 5H, Ph); 5.28 (broad signal, 1H, NH); 5.10 (s, 2H, C*H*$_2$Ph); 4.39 (t, 2H, $^3J(HH)$ = 6.2 Hz, CH_2O); 3.93 (d, 2H, $^3J(HH)$ = 5.7 Hz, C*H*$_2$NH); 2.76 (t, 2H, $^3J(HH)$ = 6.2 Hz, C*H*$_2$CO); 2.16 (s, 3H, CH_3). IR: 1755, 1730 and 1715 (C=O) cm^{-1}.

Preparation of γ-oxobutyl Z-alaninate (23)

From 2.23 g (10 mmol) of *Z*-(L)-alanine and 0.756 ml (10 mmol) of but-3-yn-1-ol, 2.20 g (75%) of ester **23** were isolated by column chromatography on silica gel with hexane–ether as eluent (m.p. 93–95 °C). *Anal.* Calc. for $C_{15}H_{19}O_5N$: C, 61.49; H, 6.53; N, 4.77. Found: C, 61.45; H, 6.60; N, 4.53%. Mass spectrum (*m/z*): calc.

for $C_{15}H_{19}O_5N$ (M^+): 293.126; found: 293.126. ^1H NMR (300.133 MHz, $CDCl_3$): δ 7.35 (m, 5H, Ph); 5.12 (s, 2H, CH_2Ph); 4.35 (t, 2H, $^3J(HH) = 6.8$ Hz, CH_2O); 4.01 (q, 1H, $^3J(HH) = 7.1$ Hz, $CHCH_3$); 2.64 (t, 2H, $^3J(HH) = 6.8$ Hz, CH_2CO); 2.15 (s, 3H, CH_3CO); 1.44 (d, 3H, $^3J(HH) = 7.1$ Hz, $CHCH_3$). IR: 1750, 1720 and 1710 (C=O) cm^{-1}.

General procedure for the preparation of (E)-1-hydroxy-3-methylpenta-2,4-dien-4-yl esters

Ten mmol of acid, 10 mmol (30 mmol for adipic acid) of (*E*)-3-methylpent-2-en-4-yn-1-ol and 0.05 mmol of $[Ru(O_2CH)(CO)_2(PPh_3)]_2$ were stirred at 80 °C for 15 h in 10 ml of toluene. The isolation of the esters was similar to that of β-oxopropyl esters.

Preparation of (E)-1-hydroxy-3-methylpenta-2,4-dien-4-yl acetate (27)

From 0.59 ml (5.5 mmol) of (*E*)-3-methylpent-2-en-4-yn-1-ol and 0.29 ml (5 mmol) of acetic acid, 0.7 g (90%) of ester **27** was isolated by distillation under reduced pressure (b.p. 130 °C (10 mm Hg)). *Anal.* Calc. for $C_8H_{12}O_3$: C, 61.52; H, 7.74. Found: C, 61.19; H, 7.75%. Mass spectrum (*m/z*): calc. for $C_8H_{12}O_3$ (M^+): 156.078; found: 156.078. ^1H NMR (300.133 MHz, $CDCl_3$): δ 5.71 (t, 1H, $^3J(HH) = 6.2$ Hz, HC=C); 5.03 (d, 1H, $^2J(HH) = 2.0$ Hz, *H*HC=C); 4.76 (d, 1H, $^2J(HH) = 2.0$ Hz, H*H*C=C); 4.17 (d, 2H, $^3J(HH) = 6.2$ Hz, CH_2O); 2.85 (s, 1H, OH); 2.14 (s, 3H, CH_3COO); 1.74 (s, 3H, CH_3–C=). IR: 3460 (OH), 1765 (C=O), 1650 and 1620 (C=C) cm^{-1}.

Preparation of (E)-1-hydroxy-3-methylpenta-2,4-dien-4-yl benzoate (28)

From 2.14 ml (20 mmol) of (*E*)-3-methylpent-2-en-4-yn-1-ol and 2.44 g (20 mmol) of benzoic acid, 4.1 g (95%) of ester **28** were isolated by column chromatography on silica gel with hexane–ether (80:20) as eluent. *Anal.* Calc. for $C_{13}H_{14}O_3$: C, 71.54; H, 6.46. Found: C, 71.06; H, 6.58%. ^1H NMR (300.133 MHz, $CDCl_3$): δ 8.04–7.97 (m, 2H, Ph); 7.53–7.34 (m, 3H, Ph); 5.77 (t, 1H, $^3J(HH) = 6.5$ Hz, HC=C); 5.11 (d, 1H, $^2J(HH) = 1.8$ Hz, *H*HC=C); 4.87 (d, 1H, $^2J(HH) = 1.8$ Hz, H*H*C=C); 4.13 (d, 2H, $^3J(HH) = 6.5$ Hz, CH_2O); 2.38 (s, 1H, OH); 1.77 (s, 3H, CH_3). IR: 3460 (OH), 1740 (C=O), 1650 and 1620 (C=C) cm^{-1}.

Preparation of (E)-1-hydroxy-3-methylpenta-2,4-dien-4-yl 2,6-difluorobenzoate (29)

From 1.07 ml (10 mmol) of (*E*)-3-methylpent-2-en-4-yn-1-ol and 1.58 g (10 mmol) of 2,6-difluorobenzoic acid, 1.7 g (68%) of ester **29** were isolated by column chromatography on silica gel with hexane–ether (80:20) as eluent. ^1H NMR (300.133 MHz, $CDCl_3$): δ 7.38 (m, 1H, Ph); 6.91 (t, 2H, $^3J(HH) = 8.3$ Hz, Ph); 5.94 (t, 1H, $^3J(HH) = 6.4$ Hz, HC=C); 5.13 (d, 1H, $^2J(HH) = 2.2$ Hz, *H*HC=C); 4.96 (d, 1H, $^2J(HH) = 2.2$ Hz, H*H*C=C); 4.21 (d, 2H, $^3J(HH) = 6.4$ Hz, CH_2O); 2.14 (s, 1H, OH); 1.79 (s, 3H, CH_3). IR: 3500 (OH), 1750 (C=O), 1625 and 1590 (C=C) cm^{-1}.

Preparation of (E)-1-hydroxy-3-methylpenta-2,4-dien-4-yl BOC-(L)-alaninate (30)

From 1.07 ml (10 mmol) of (*E*)-3-methylpent-2-en-4-yn-1-ol and 1.89 g (10 mmol) of BOC-(L)-alanine, 1.8 g (63%) of ester **30** were isolated by column chromatography on silica gel with ether as eluent. ^1H NMR (300.133 MHz, $CDCl_3$): δ 5.80 (m, 1H, HC=C); 5.22 (m, 1H, NH); 5.05 (d, 1H, $^2J(HH) = 2.0$ Hz, *H*HC=C); 4.80 (d, 1H, $^2J(HH) = 2.0$ Hz, H*H*C=C); 4.38 (m, 1H, CH); 4.20 (d, 2H, $^3J(HH) = 6.4$ Hz, CH_2O); 2.66 (s, 1H, OH); 1.77 (s, 3H, CH_3–C=); 1.45 (d, 3H, $^3J(HH) = 7.3$ Hz, CH_3CH); 1.39 (s, 9H, tBu). IR: 3500 (OH), 1760 and 1695 (C=O), 1615 (C=C) cm^{-1}. $[\alpha]_D = -41°$ ($c = 1.00$ g l^{-1}, EtOH, 20 °C).

Preparation of bis[(E)-1-hydroxy-3-methylpenta-2,4-dien-4-yl] adipate (31)

From 1.6 ml (15 mmol) of (*E*)-3-methylpent-2-en-4-yn-1-ol and 0.73 g (5 mmol) of adipic acid, 1 g (60%) of ester **31** was isolated by column chromatography on silica gel with ether as eluent (m.p. 99–101 °C). ^1H NMR (300.133 MHz, $CDCl_3$): δ 5.75 (t, 2H, $^3J(HH) = 6.3$ Hz, 2 HC=C); 5.07 (d, 2H, $^2J(HH) = 2.0$ Hz, 2 *H*HC=C); 4.82 (d, 2H, $^2J(HH) = 2.0$ Hz, 2 H*H*C=C); 4.22 (d, 4H, $^3J(HH) = 5.7$ Hz, 2 CH_2O); 2.50–2.56 (m, 6H, 2 OH + 2 CH_2–C=O); 1.76–1.79 (m, 10H, 2 $CH_3 + CH_2$–CH_2). IR: 3500 (OH), 1760 (C=O), 1620 (C=C) cm^{-1}.

Preparation of (E)-1-hydroxy-3-methylpenta-2,4-dien-4-yl (R)-mandelate (32)

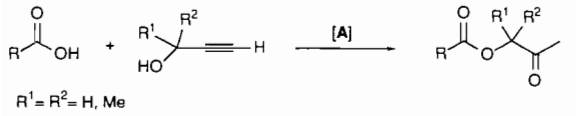
From 2.14 ml (20 mmol) of (*E*)-3-methylpent-2-en-4-yn-1-ol and 1.52 g (10 mmol) of (*R*)-mandelic acid, 1.7 g (68%) of ester **32** were isolated by column chromatography on silica gel with hexane–ether (70:30) as eluent (m.p. 64–67 °C). ^1H NMR (300.133 MHz, $CDCl_3$): δ 7.50–7.32 (m, 5H, Ph); 5.34 (s, 1H, C*H*OH); 5.15 (t, 1H, $^3J(HH) = 6.2$ Hz, HC=C); 5.08 (d, 1H, $^2J(HH) = 2.4$ Hz, *H*HC=C); 4.80 (d, 1H, $^2J(HH) = 2.4$ Hz, H*H*C=C); 4.07 (d, 2H, $^3J(HH) = 6.2$ Hz, CH_2O); 2.15 (s, 2H, OH); 1.73 (s, 3H, CH_3). IR: 3450 (OH), 1760 (C=O), 1650 and 1620 (C=C) cm^{-1}. $[\alpha]_D = -88°$ ($c = 1.00$ g l^{-1}, EtOH, 20 °C).

Results and discussion

1. Synthesis of β-oxopropyl esters

Our initial report [17] described the efficient synthesis of β-oxopropyl esters via the catalytic addition of car-

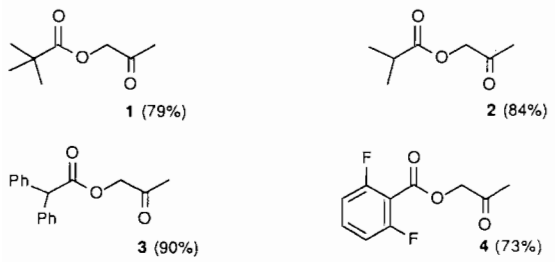
boxylic acids, including amino acids derivatives to propargyl alcohol and its 1,1-dimethyl derivative (eqn. (2)). This reaction took place without racemization of N-protected amino acids.



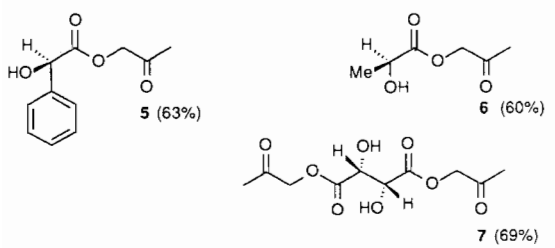
(2)

This initial reaction actually appears quite general since β-oxopropyl esters can be prepared from bulky or functional carboxylic acids using the readily accessible catalyst (*p*-cymene)$RuCl_2(PPh_3)$ (**A**) [18]. Thus, the reaction of propargyl alcohol itself with pivalic, isobutyric, diphenylacetic and 2,6-difluorobenzoic acid in toluene at 60 °C for 6 h with 1 mol% of (*p*-cymene)-$RuCl_2(PPh_3)$ (**A**) led to the formation of the corresponding β-oxopropyl esters **1**, **2**, **3** and **4** in 79, 84, 90 and 73% yields, respectively (Scheme 1).

α-Hydroxy acids failed to add to propargyl alcohol in the presence of (arene)$RuCl_2(PR_3)$ complexes. However, we had previously found that binuclear ruthenium complexes of type $[Ru(\mu\text{-}O_2CR)(CO)_2(PR_3)]_2$ were able to activate terminal alkynes towards the addition of α-hydroxy acids [6]. The complex $[Ru(\mu\text{-}O_2CH)(CO)_2(PPh_3)]_2$ (**B**) appeared to be also an efficient catalyst for the addition of α-hydroxy acids to propargylic alcohol (eqn. (3)). β-Oxopropyl-(*R*)-mandelate (**5**) and -(*S*)-lactate (**6**) were obtained in 63 and 60% yield, respectively, by treatment of 10 mmol of the corresponding α-hydroxy acid with 10 mmol of prop-2-yn-1-ol in the presence of 0.05 mmol of **B** in 10 ml of toluene at 80 °C for 10 h (Scheme 2). Both keto esters **5** and **6** showed optical activity, their optical

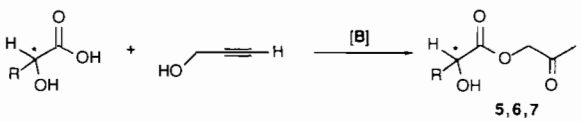


Scheme 1. Synthesis of β-oxopropyl esters.



Scheme 2. Synthesis of β-oxopropyl esters from α-hydroxy acids.

rotation measured in EtOH at 20 °C was −101° for **5** and −8° for **6**. Similarly, starting from 1 equiv. of the optically pure (*R*,*R*)-tartaric acid and 2 equiv. of prop-2-yn-1-ol, the optically active bis(β-oxopropyl)tartrate (**7**) was isolated in 69% yield after reaction at 80 °C for 24 h in THF in the presence of 0.05 equiv. of **B** (Scheme 2), whereas diacids such as fumaric or aspartic acid gave only low yields of diesters with catalyst **A** [17].



(3)

2. β-Oxopropyl esters as acylating reagents: C−O, C−N and C−C bond formation

The good reactivity of enol esters towards nucleophiles under mild conditions [5, 9, 11, 14, 20, 21] prompted us to study the behaviour of β-oxopropyl esters as acylating reagents for the formation of C−N, C−O and C−C bonds according to eqn. (4).

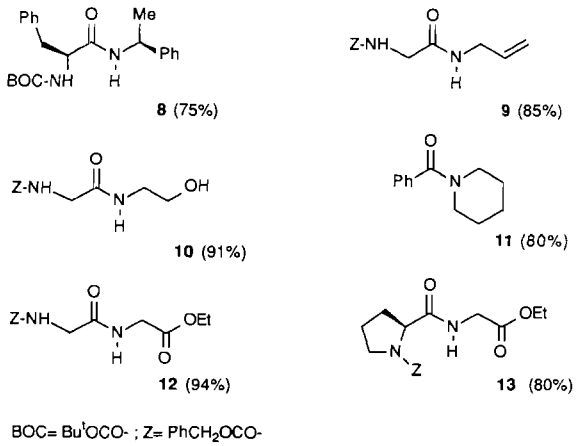
(4)

Indeed, functional amides **8**, **9** and **10** were easily obtained in 75, 85 and 91% yields, respectively, by reaction at room temperature in ethylacetate of β-oxopropyl esters with L-(−)-α-phenylethylamine, allylamine and 2-aminoethanol (eqn. (5)). These amides were isolated as white solids and only one diastereoisomer of **8** was obtained, as shown by ^1H NMR analysis, which exhibited an optical rotation of −15.5° ($c = 1$, EtOH). The reaction is fast and takes place without the addition of an acylation catalyst; moreover the only byproduct is the neutral hydroxypropanone.

The acylation of secondary amines and α-amino esters under the above conditions did not take place. However, the use of KCN as acylation catalyst [22] made possible the obtention of amides from secondary amines and functional primary amines. Thus *N*-piperidine benzamide (**11**) and the dipeptide ZGlyGlyOEt (**12**) were isolated as white solids in 80 and 94% yields, respectively, whereas the enantiopure dipeptide *Z*-ProGlyOEt (**13**) was collected as an oil in 80% yield ($[\alpha]_D = -47.5°$, $c = 2$, EtOH) after reaction at room temperature in the presence of 10 mol% of KCN (Scheme 3).

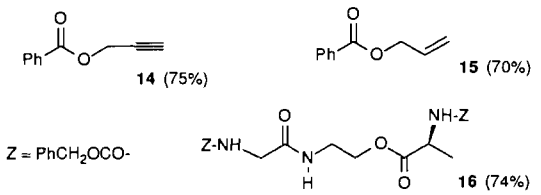
(5)

A similar catalytic system based on the use of potassium cyanide allowed acylation of oxygenated nu-



BOC= Bu^{t}OCO- ; Z= $PhCH_2OCO$-

Scheme 3. Synthesis of amides and dipeptides from β-oxopropyl esters.



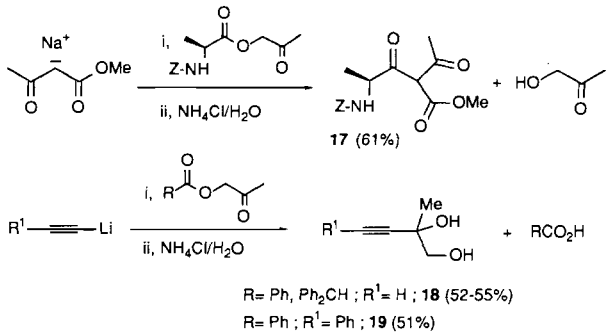
Z = $PhCH_2OCO$-

Scheme 4. Synthesis of functional esters from β-oxopropyl esters.

cleophiles like alcohols (eqn. (6)). Prop-2-yn-1-yl (**14**) and prop-2-en-1-yl (**15**) benzoates were obtained in 94 and 70% yields, respectively, by reacting β-oxopropyl benzoate with prop-2-yn-1-ol and prop-2-en-1-ol at 25 °C for 16 h in the presence of 20 mol% of KCN in alcohol as solvent. Under these experimental conditions, the acylation of the alcohol functionality of compound **10** by β-oxopropyl *Z*-alaninate led to the pseudodipeptide (*Z*-Gly)$NHCH_2CH_2O$(*Z-Ala*) (**16**) in 74% isolated yield (Scheme 4).

(6)

The possibility of C–C bond formation was investigated via the reaction of carbonucleophiles. The carbanion, generated by abstraction of proton from acetoacetate with NaH, reacted with β-oxopropyl-*Z*-alaninate at 80 °C for 4 h in THF to give the polycarbonyl compound **17** in 61% yield after hydrolysis. Thus, sodium methyl acetylacetate reacts like amines or alcohols by nucleophilic attack on the ester carbonyl group of β-oxopropyl esters, but requires more drastic conditions. On the other hand, lithium acetylides react differently by nucleophilic attack on the ketonic carbonyl to afford acetylenic 1,2-diols. Thus, when β-oxopropyl benzoate or diphenyl acetate was added to lithium acetylide at −78 °C and slowly warmed at room temperature, 2-



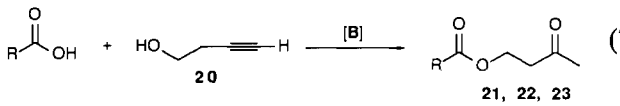
R= Ph, Ph_2CH ; R¹= H ; **18** (52-55%)
R= Ph ; R¹= Ph ; **19** (51%)

Scheme 5. Reaction of carbonucleophiles with β-oxopropyl esters.

hydroxy-2-methylbut-3-yn-1-ol (**18**) was isolated in 52 and 55% yields, respectively. Under similar conditions, lithium phenylacetylide and β-oxopropyl benzoate led to 2-hydroxy-2-methyl-4-phenylbut-3-yn-1-ol (**19**) in 51% yield (Scheme 5). Compounds **18** and **19** are suitable substrates for the access to acetylenic cyclic carbonates.

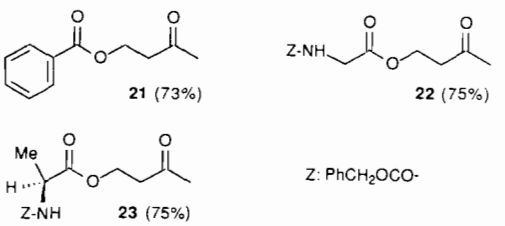
3. Synthesis of γ-oxobutyl esters

The catalytic formation of β-oxopropyl esters via addition to prop-2-yn-1-ols is likely to result from initial addition of carboxylic acid to carbon C2 of the alkyne followed by internal transesterification (see 'Mechanism', Section 5). It was thus of interest to study if the transesterification could take place when the free hydroxy group was at carbon β of the C≡CH bond. The catalytic addition of carboxylic acids to but-3-yn-1-ol (**20**) was thus studied in the presence of the catalyst precursor **B**.



(7)

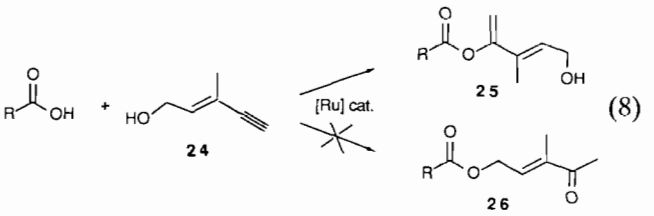
The reaction of 10 mmol of benzoic acid and 10 mmol of but-3-yn-1-ol in toluene at 60 °C for 8 h in the presence of 0.5 mol% of complex **B** gave γ-oxobutyl benzoate (**21**) in 73% yield (eqn. (7)). In the presence of (*p*-cymene)$RuCl_2(PPh_3)$ (**A**) as catalyst precursor, the reaction did not take place at 60 °C but only at 100 °C leading to a dark reaction mixture from which it was possible to isolate 40% of ester **21**. This is another example illustrating the high efficiency of the binuclear ruthenium complex **B** in catalytic addition to alkynes. N-protected amino acids *Z*-glycine and *Z*-alanine also added to alcohol **20** in the presence of catalyst **B** to afford γ-keto esters **22** (75%) and **23** (75%), showing the generality of the transformation. During the transformation of *Z*-alanine into **23**, it was shown that no racemization of the amino acid moiety took place (Scheme 6).



Scheme 6. Synthesis of γ-oxobutyl esters.

4. Synthesis of functional dienes

The catalytic addition of carboxylic acids to *E*-3-methylpent-2-en-4-yn-1-ol (**24**), containing a hydroxy group at the γ carbon of the C≡CH bond was investigated for its potentiality to generate α,β-unsaturated ketones **26** containing a leaving group at the allylic position. But, when 1 equiv. of carboxylic acid was heated with 1 equiv. of **24** at 80 °C for 20 h in toluene in the presence of $[Ru(O_2CH)(CO)_2(PPh_3)]_2$ as catalyst precursor, the conversion of the starting compounds was complete and the only isolated product, instead of **26**, corresponded to functional dienes of type **25** containing both hydroxy and ester functions (eqn. (8)).

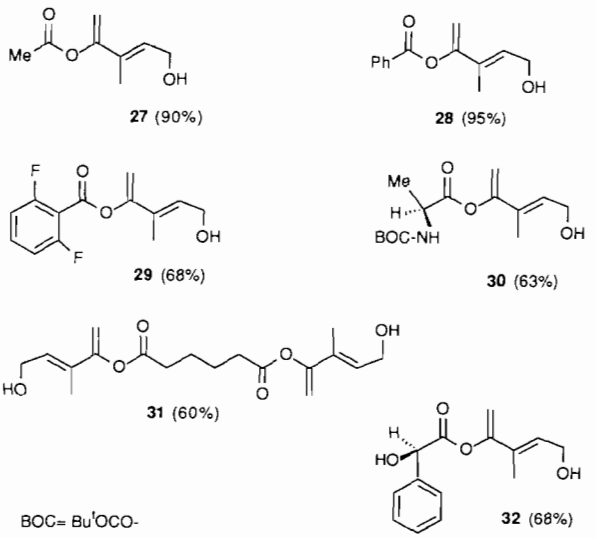


(8)

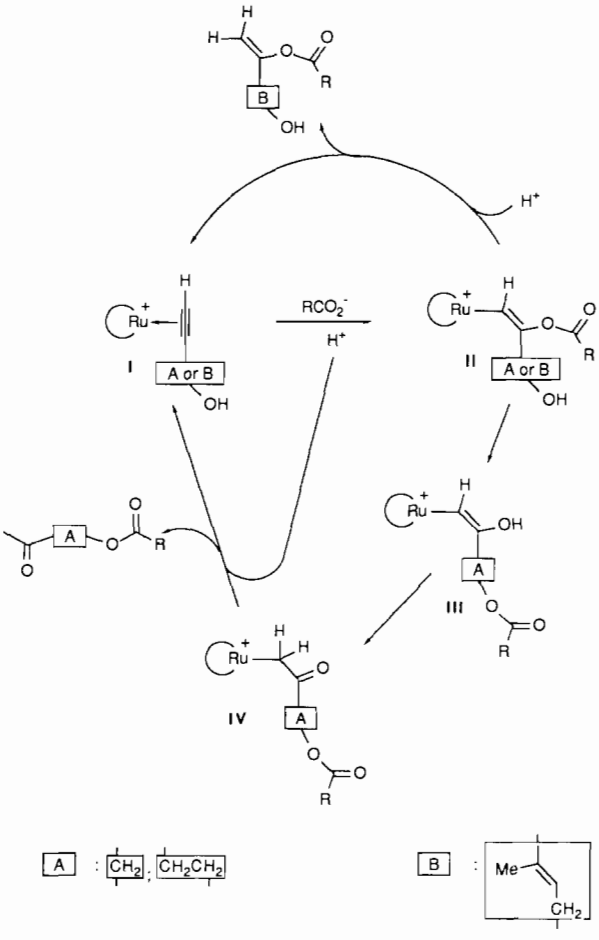
The reaction of acetic and benzoic acid gave the esters **27** and **28** in comparable yields (90, 95% isolated yields, respectively). The functional 2,6-difluorobenzoic acid, which is usually less reactive in additions to alkynes, led to ester **29** in 68% yield. The addition of an N-protected amino acid such as BOC-alanine gave BOC-alaninate **30** (63%) after 22 h at 70 °C. Adipic acid led to adipate **31** in 60% yield after 15 h at 80 °C with 3 equiv. of the alkynol **24**, and an α-hydroxy carboxylic acid such as (*R*)-mandelic acid afforded mandelate **32** in 68% yield after 22 h at 70 °C (Scheme 7).

This catalytic reaction provides a straightforward route to trisubstituted dienes **27–32**. They present a potential for Diels Alder reactions and the alcohol functionality modification. The use of catalyst **B** makes this reaction possible under mild conditions and enantiopure esters of type **30,32** can be prepared.

The above examples show that only regioselective addition of the carboxylate to the C2 carbon of the triple bond took place without the transesterification that would have given ester of type **26** (eqn. (8)), and only the presence of the *E* stereoisomer was observed.



Scheme 7. Synthesis of hydroxy dienyl esters.



Scheme 8. Proposed mechanism for the formation of keto esters and hydroxy dienyl esters.

This is likely due to both the configuration of the double bond and the distance of the hydroxy group from the C≡CH group. Indeed, the *Z*-isomer of **24** under similar

conditions reacts quite differently giving rise to cyclization into 2,3-dimethylfuran [23].

5. Mechanism discussion

The formation of keto esters is formally equivalent to esterification of the alcohol function and hydration of the triple bond of the starting acetylenic alcohol. However, we have shown that under our catalytic conditions, (i) acetylenic esters resulting from such a process were not hydrated by water and (ii) addition of carboxylic acid to the C2 carbon of triple bonds took place in the presence of catalyst **B** (eqn. (1)) when the OH group was protected or as in the transformation of the *E* derivative **24**. These observations have led us to propose as the first step of this catalytic reaction the coordination of the triple bond to give an Ru(η^2-alkyne) intermediate **I** (Scheme 8). The addition of the carboxylate to the alkyne electrophilically activated by ruthenium, then takes place at C2 to give **II**. When an intramolecular transesterification is possible, this crucial intermediate **II** leads to **III**, which after tautomerization into **IV** releases a keto ester on protonation. When the hydroxy group cannot be intramolecularly transesterified, as from **24**, hydroxy enol esters are formed on protonation.

Conclusions

We have shown that it is possible to obtain a variety of functional esters in one step by catalytic addition of carboxylic acids to acetylenic alcohols. The location of the hydroxy group with respect to the triple bond of the acetylenic has an important role for inducing intramolecular transesterification. With propargyl and homopropargyl alcohols, the hydroxy group orientates the reaction towards the formation of keto esters via intramolecular transesterification. When the internal transesterification cannot take place, functional hydroxy dienyl esters are formed.

We have found that binuclear ruthenium complexes containing bridging carboxylate ligands make possible the addition from functional acids under mild conditions and provide a one-step synthesis of optically pure esters from chiral acids.

β-Oxopropyl esters are efficient reagents for the acylation of O- and N-nucleophiles under neutral conditions and give access to amides, peptide derivatives and functional esters. The reaction with carbonucleophiles allows the C–C bond formation and the synthesis of functional polycarbonyl or dihydroxy derivatives.

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