Stereoselective Radical Addition to α-Methylenebutyrolactones by Indirect Electroreduction Catalyzed by a Nickel(II) Complex

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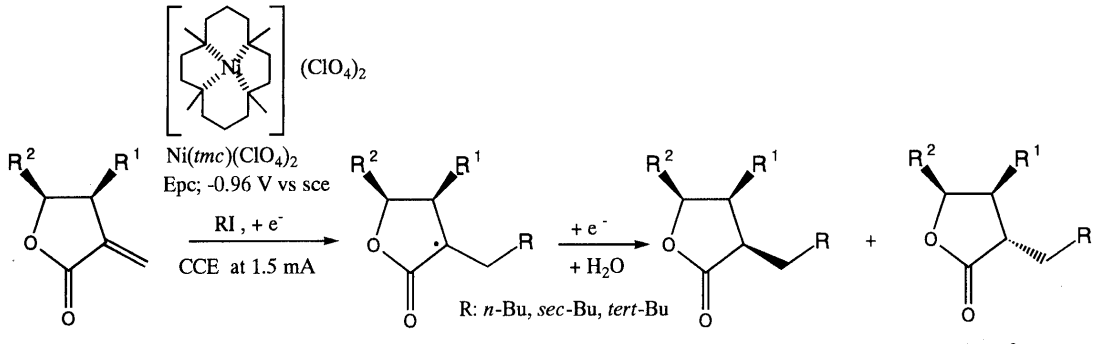
The addition of butyl radicals to β- and/or γ-disubstituted α-methylenebutyrolactones by a nickel(II) complex-catalyzed indirect electroreduction using equimolar amounts of butyl iodides and α-methylenebutyrolactones provides *cis*-(C-α) : (C-β)-trisubstituted lactones as the major product. The addition was successful because the present method to permits long lifetimes for the initial butyl radicals and decreases lifetimes of the final adduct radicals by selective reduction of these radicals.

Key words α-methylenebutyrolactone; radical addition; indirect electroreduction; nickel(II)(*tmc*)$(ClO_4)_2$; *cis*-trisubstituted lactone

Radical reactions, especially tin hydride mediated radical reactions are useful tools for constructing many types of molecules.[1] In the last decade, the chemo- and regioselectivity of radical processes, including intermolecular addition, has been shown to be highly predictable.[2] Recently, auxiliary[3] and substrate controls[4] for the stereoselectivity of acyclic radical reactions have been reported. Nevertheless, the intermolecular additions of alkyl radicals to activated alkenes are not widely used, unlike the intramolecular cyclizations. This may be partly because either reagent (in most reactions, alkene) must be used in significant excess to make the addition practical. For successful intermolecular radical reactions, it is crucial to make the lifetimes of the initial radicals long[5] and at the same time to shorten those of final adduct radicals with respect to hydrogen abstraction, in order to avoid undesirable side reactions of the final radicals.[6]

We have investigated the radical reactions by the nickel complex-catalyzed electroreduction,[7] and in the course of the studies we showed that 1,4-addition of the alkyl radicals to activated alkenes proceeds smoothly using almost equimolar amounts of reagents.[7b] The above reactions did not provide products formed by coupling or disproportionation of the adduct radicals unlike, the electroreductive cyclization of the halogenoether or vinyl bromides conducted under similar conditions.[7a,d] The observed smooth addition of the alkyl radicals[7b] was attributed to the long lifetimes permitted for the initial alkyl radicals in *N*,*N*′-dimethylformamide (DMF) in the absence of an overt hydrogen atom donor such as R_3Sn-H. However, we did not establish why the adduct radicals which could be expected to be more stable than the initial alkyl radicals have such short lifetimes with respect to hydrogen transfer, *i.e.*, why undesired side reactions of the final radical, such as addition to the activated alkenes or coupling reaction, do not occur. In this work, we examined the addition of butyl radicals to β and/or γ-disubstituted α-methylenebutyrolactones[8] to investigate why the lifetimes of the adduct radicals are selectively shortened with respect to hydrogen transfer and also to elucidate whether radical butylation by the present method follows the same stereochemical course as those conducted by other approaches.[4f] The α,β,(γ)-di(tri)substituted lactones and iodides used in this work are summarized in Chart 1.

The electroreductive alkylation of β,γ-disubstituted α-methylenebutyrolactones was conducted using 0.5 mmol of a butyl iodide, 0.6 or 0.42 mmol of a butyrolacton, 0.025 mmol of nickel(II)(*tmc*)$(ClO_4)_2$,[9] a graphite plate as a cathode, a zinc plate as an anode, a constant current of 1.5 mA, and 10 ml of DMF containing 1 mmol of



	1a	1b	1c	1d	1e	1f
R^1	Me	Me	Me	Me	Ph	Bn
R^2	Ph	C_5H_{11}	Bn	H	Ph	Ph

Chart 1

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tetraethylammonium perchlorate (TEAP) as a supporting electrolyte in an undivided cell under nitrogen gas at ambient temperature. Electricity consumption of 2F/mol based on the iodide was required for complete conversion of the iodide. The results are summarized in Table 1.

Considering that neither the butyl iodide or the α-methylene-γ-butyrolactone was used in large excess, the expected products were obtained in moderate to good yields, except for the addition of *tert*-butyl radical to **1e** (entry 7). The stereochemistry of the acceptors, the butyrolactone and the products was determined by nuclear Overhauser effect (NOE) difference spectroscopy (Fig. 1).

As can be seen from the results in Table 1, good diastereoisomeric excesses were observed for the lactones **1** whose substituents at the β- and γ-positions are methyl or phenyl groups. The decrease in stereoselectivity in the reaction using **1f** (entry 8) could be attributed to steric hindrance by the flexible benzyl group at the β-position to the approach of a hydrogen donor from both faces of the lactone. In the addition of *n*-butyl, *sec*-butyl or *tert*-butyl radical to **1e** (entries 5, 6, 7), the diastereoselectivity decreased in the order of primary > secondary > tertiary. These results could also be explained in terms of the structure of the intermediate adduct product (Fig. 2), *i.e.*, both faces of the adduct intermediate bearing *tert*-butyl or *sec*-butyl groups could be blocked to hydrogen approach.

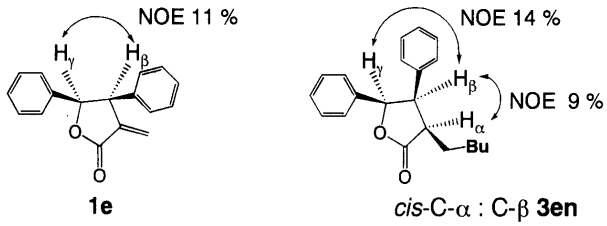
Table 1. Electroreductive Addition of Butyl Iodides to α-Methylene-butyrolactones **1**[a]

Entry	Lactone **1** (0.5 mmol)	Butyl iodide (0.6 or 0.42 mmol)	Product **3** yield (%)[b]	*cis*:*trans* ratio[c]
1	**1a**	*n*-Bu	**3a** (53)	90:10
2	**1b**	*n*-Bu	**3b** (73)	79:21
3	**1c**	*n*-Bu	**3c** (52)	76:24
4	**1d**	*n*-Bu	**3d** (17) (47)[d]	64:36
5	**1e**	*n*-Bu	**3en** (66)	>99: 1
6	**1e**	*sec*-Bu	**3es** (56)	95: 5
7	**1e**	*tert*-Bu	**3et** (27)	89:11
8	**1f**	*n*-Bu	**3f** (62)	67:33

a) Constant current (1.5 mA) electrolysis (2F/mol of RI) using RI (0.5 mmol), lactones **1** (0.42 or 0.6 mmol) and Ni(*tmc*)$(ClO_4)_2$ (0.025 mmol) in DMF. For detailes see the text. *b*) Isolated yield based on reagent used in smaller amount. *c*) (C-α):(C-β) *cis*-/*trans*-ratio. Determined based on NOE difference spectroscopy. *d*) Determined by GLC.

The observed *cis* selectivity shows that the major products were formed by hydrogen transfer from the less hindered α face of these lactones; in other words, the formation of *cis*-**3** is kinetically controlled. Overall, the diastereoselectivities are close to those observed in the tin hydride mediated case,[4f] so that approach of water or Bu_3SnH to the adduct intermediate (Fig. 2) may follow the same stereochemical course.[4f]

The observed electricity consumption of around 2 F/mol seemed to suggest that further one-electron reduction of the adduct radicals **2** occurred; they are more reducible than simple alkyl radicals because of the electron-withdrawing ester group at the a position. The resultant carbanion would react rapidly with water, which is present as a contaminant in DMF, at a rate expected to be much greater than that of hydrogen atom abstraction from



1e *cis*-C-α : C-β **3en**

^{1}H NMR δ(ppm)

H_γ : 5.84 (d, *J* = 8.1)

H_β : 4.68 (ddd, *J*= 2.6, 3.4, 8.1)

H_γ : 5.81 (d, *J* = 5.1)

H_β : 3.95 (dd, *J* = 5.1, 7.7)

H_α : 3.13 (m)

Fig. 1

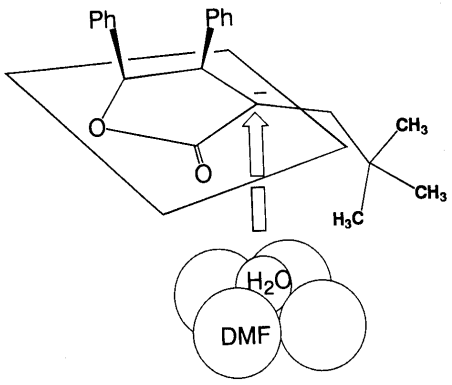
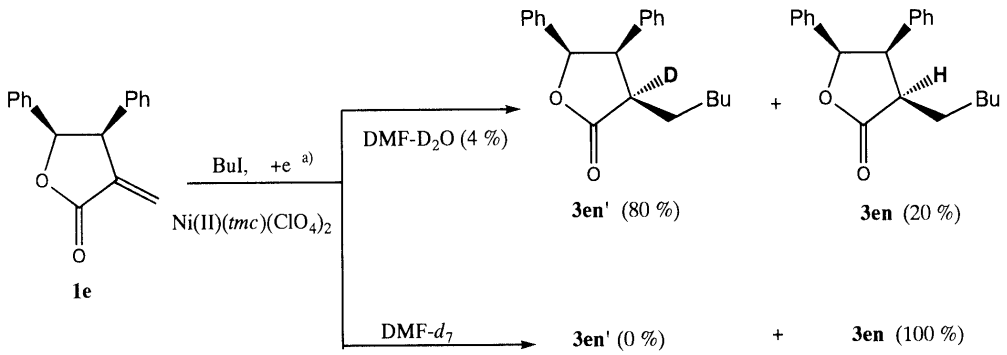


Fig. 2



a) For experimental conditions, see text.

Chart 2

DMF by the adduct radical.

Electroreductions to determine the source of the hydrogen in the products were performed by the use of **1e** and *n*-butyl iodide in deuterated DMF-d_7 and in DMF containing 4% D_2O.[10] The relative distributions of α-deuterated (**3en'**) and α-hydrogenated (**3en**) products from these electroreductions were tentatively analyzed by the integration of the β ring proton signal at 3.95 ppm (dd, $J=7.7$, 5.1 Hz) and the α ring proton signal at 3.13 ppm in the ^{1}H-NMR (500 MHz) spectrum of **3en**. The experiments summarized in Chart 2 show that deuterium incorporation into the α position was high in the product from the reaction in DMF containing D_2O, but the incorporation of deuterium did not occur in the reaction in DMF-d_7.

From these results, it is likely that a large part of the adduct radical is reduced to the corresponding carbanion before it abstracts a hydrogen atom from the solvent, DMF. The subsequent rapid protonation to the adduct carbanion by water shortens the lifetimes of the adduct radical with respect to hydrogen transfer.

Thus, we have established that the adduct radicals have shorter lifetimes than the initial alkyl radicals with respect to hydrogen transfer in the present method, which makes the smooth 1,4-addition of alkyl radicals possible using almost equimolar amounts of reagents. It has also been shown that the approach of the hydrogen atom from water to the adduct carbanion follows the same stereochemical course as that from tin hydrides to the adduct radical.

Experimental

Instrumentation NMR spectra were taken on a JEOL EX-270, JEOL GX-500 or Varian VXR-200 instrument. The *J*-values are given in hertz (Hz). IR spectra were taken on a JASCO Valor III instrument. Cyclic voltammetry was performed with a three-electrode system employing a linear scanning unit (Huso Electronical System HECS 321B) equipped with a potentiostat (Hokuto Denko PS-55B). Constant current electrolysis was carried out with a potentio-galvanostat (Hokuto Denko HA105S), and the quantity of electricity was recorded with a coulometer (Hokuto Denko HF-201). Analytical gas chromatography was performed on a JEOL JGC-20K equipped with a flame ionization detector (FID) using a glass column (2 m × 3 mm i.d.) packed with 5% polyethylene glycol (PEG) 20 M.

Materials β,γ-Disubstituted α-methylene-γ-butyrolactones were prepared according to the literature method.[11]

α-Methylene-β,γ-diphenyl-γ-butyrolactone (1e)[11] Methyl 2-(bromomethyl)-3-phenylacrylate,[12] benzaldehyde (0.238 ml, 2.34 mmol), and acetic acid (0.05 ml, 0.5 mmol) were added to a stirred suspension of metallic tin (232 mg, 1.95 mmol) and aluminum (52 mg, 1.93 mmol) in dimethoxyethane (DME, 5 ml), and the stirring was continued for 1 h under gentle refluxing. The mixture was taken up in Et_2O and washed with brine (50 ml × 1). The combined aqueous phase was washed with Et_2O, and the organic phase was dried over $MgSO_4$ and evaporated. The residue was treated with *p*-toluenesulfonic acid (30 mg) in benzene at room temperature, and subjected to silica gel column chromatography (hexane–AcOEt, 3 : 1), giving **1e** (215 mg, 44%) as a solid, mp 91 °C; IR (KBr): 1766 (lactone) cm^{-1}. ^{1}H-NMR (500 MHz, $CDCl_3$) δ: 4.68 (1H, ddd, $J=8.1$, 3.4, 2.6), 5.58 (1H, d, $J=2.6$), 5.84 (1H, d, $J=8.1$), 6.53 (1H, d, $J=3.4$), 6.73—7.48 (10H, m).

β-Methyl-α-methylene-γ-phenyl-γ-butyrolactone (1a) According to the preparation procedure for **1e**, **1a** was prepared by treatment of benzaldehyde (0.145 ml, 1.43 mmol) with methyl 2-(bromomethyl)-2-butenoate (250 mg, 1.30 mmol), metallic tin (116 mg, 0.977 mmol, and aluminum (26 mg, 0.962 mmol) in DME (2.5 ml). Purification of the crude product by silica gel column chromatography (hexane–AcOEt, 3 : 1) provided **1a** (138 mg, 56%) as a colorless oil. *Anal.* Calcd for $C_{12}H_{12}O_2$: C, 76.57; H, 6.43. Found: C, 76.43; H, 6.65. IR (KBr): 1764 (lactone) cm^{-1}. ^{1}H-NMR (500 MHz, $CDCl_3$) δ: 0.80 (3H, d, $J=7.7$), 3.41—3.46 (1H, m), 5.58 (1H, d, $J=2.6$), 5.62 (1H, d, $J=8.5$), 6.33 (1H, d, $J=2.6$), 7.16—7.40 (5H, m).

β-Methyl-α-methylene-γ-pentyl-γ-butyrolactone (1b) According to the preparation procedure for **1e**, **1b** was prepared by treatment of hexanal (0.172 ml, 1.43 mmol) with methyl 2-(bromomethyl)-2-butenoate (250 mg, 1.30 mmol), tin (116 mg, 0.977 mmol) and aluminum (26 mg, 0.962 mmol) in DME (2.5 ml). Purification of the crude product by silica gel column chromatography (hexane–AcOEt, 3 : 1) provided **1b** (108 mg, 46%) as a colorless oil. IR (KBr): 1765 (lactone) cm^{-1}. ^{1}H-NMR (500 MHz, $CDCl_3$) δ: 0.90 (3H, t, $J=6.8$), 1.15 (3H, d, $J=6.8$), 1.30—1.57 (8H, m), 3.13—3.17 (1H, m), 4.51 (1H, ddd, $J=4.3$, 7.7, 9.4), 5.52 (1H, d, $J=1.7$), 6.20 (1H, d, $J=2.6$).

γ-Benzyl-β-methyl-α-methylene-γ-butyrolactone (1c) According to the preparation procedure for **1e**, **1c** was prepared by treatment of benzylaldehyde (40%, 430 mg, 1.43 mmol) with methyl 2-(bromomethyl)-2-butenoate (250 mg, 1.30 mmol), tin (116 mg, 0.977 mmol) and aluminum (26 mg, 0.962 mmol) in DME (2.6 ml). Purification of the crude product by silica gel column chromatography (hexane–AcOEt, 3 : 1) provided **1c** (84 mg, 32%) as a colorless oil. IR (KBr): 1754 (lactone) cm^{-1}. ^{1}H-NMR (200 MHz, $CDCl_3$) δ: 1.25 (3H, d, $J=7.1$), 2.82—2.87 (2H, m), 3.19—3.27 (1H, m), 4.78 (1H, ddd, $J=5.5$, 7.3, 8.4), 5.57 (1H, d, $J=2.4$), 6.24 (1H, d, $J=2.6$), 7.19—7.36 (5H, m).

β-Methyl-α-methylene-γ-butyrolactone (1d) According to the preparation procedure for **1e**, **1d** was prepared by treatment of formaldehyde (40% in water, 404 mg, 4.70 mmol) with methyl 2-(bromomethyl)-2-butenoate, tin (348 mg, 2.93 mmol) and aluminum (78 mg, 2.89 mmol) in Et_2O containing 20% water (30 ml). Purification of the crude product by silica gel column chromatography (hexane–AcOEt, 3 : 1) provided **1d** (108 mg, 49%) as a colorless oil. ^{1}H-NMR (200 MHz, $CDCl_3$) δ: 1.28 (3H, d, $J=7.0$), 3.10—3.221 (1H, m), 3.86 (1H, dd, $J=6.8$, 8.8), 4.52 (1H, dd, $J=8.8$, 8.8), 5.61 (1H, d, $J=2.7$), 6.27 (1H, d, $J=2.9$).

β-Benzyl-α-methylene-γ-phenyl-γ-butyrolactone (1f) According to the preparation procedure for **1e**, **1f** was prepared by treatment of benzaldehyde with methyl 2-(bromomethyl)-4-phenyl-2-butenoate (524 mg, 1.95 mmol), tin (232 mg, 1.95 mmol) and aluminum (52 mg, 1.93 mmol). Purification of the crude product provided **1f** (306 mg, 59%) as a colorless oil. ^{1}H-NMR (500 MHz, $CDCl_3$) δ: 2.30 (1H, dd, $J=14.5$, 9.4), 2.38 (1H, dd, $J=14.5$, 6.8), 3.57—3.66 (1H, m), 5.03 (1H, d, $J=2.6$), 5.65 (1H, d, $J=6.8$), 6.22 (1H, d, $J=1.7$), 7.17—7.40 (10H, m).

Methyl 2-bromomethyl-3-phenylacrylate, methyl 2-(bromomethyl)-2-butenoate and 2-bromomethyl-4-phenyl-2-butenoate were prepared according to the literature method.[12]

Ni(II)(*tmc*)$(ClO_4)_2$: 1,4,8,11-Tetramethyl-1,4,8,11-tetraazacyclotetradecane nickel(II) Perchlorate was prepared by the method in the literature.[13]

General Procedure for Constant Current Electrolysis of Butyl Iodides in the Presence of the α-Methylene Butyrolactones Electroreductions were carried out using 10 ml of DMF containing TEAP (1 mmol) in an undivided cell with an iodide (0.5 mmol), a butyrolactone (0.6 or 0.42 mmol) and nickel(*tmc*)$(ClO_4)_2$ (0.025 mmol) at a constant current of 1.5 mA between a graphite cathode (*ca.* 6.3 cm^2) and a zinc anode (*ca.* 3 cm^2) under nitrogen gas at an ambient temperature until consumption of electricity reached 2F/mol based on the iodide. The electrolysis in DMF-d_7 (5 ml) was performed at one-half scale of the electrolysis in DMF (10 ml). The products were extracted with Et_2O from the electrolyte, after dilution with saturated aqueous NH_4Cl or brine, then separated by silica gel column chromatography. Spectral data and analytical results of the products are as follows. The assignments of protons in ^{1}H-NMR were performed with the aid of ^{1}H–^{1}H correlation spectroscopy (COSY) spectra. ^{1}H-NMR signals due to α, β, γ, ring protons of the *cis*-(C-α) : (C-β) isomer are denoted by *. The stereochemistry of the major product **3a** was assigned as *cis*-(C-α) : (C-β) on the bases of NOE difference spectroscopy.

β-Methyl-α-pentyl-γ-phenyl-γ-butyrolactone (3a) **3a** was obtained as a mixture of two diastereoisomers in a ratio of 9 : 1 with the *cis*-(C-α) : (C-β) isomer predominating, as estimated from the integrated peak intensities of the methyl protons on the ring. ^{1}H-NMR signals due to the major isomer are denoted by *. A colorless oil. IR (KBr): 1778 (lactone) cm^{-1}. ^{1}H-NMR (500 MHz, $CDCl_3$) δ: 0.53 (3H, d, $J=6.8$, $CHC\underline{H}_3^*$), δ: 0.78 (3H, d, $J=6.8$, $CHC\underline{H}_3$), 0.91 (3H, t, $J=7.7$, $CH_2C\underline{H}_3$), 1.33—1.49 (7H, m, $C\underline{H}HC\underline{H}_2C\underline{H}_2C\underline{H}_2$), 1.84—1.90 (1H, m, $CHCH\underline{H}CH_2$), 2.46 (1H, q, $J=7.7$, $C\underline{H}CH_2$), 2.66 (1H, sext., $J=7.7$, $C\underline{H}CH_3$), 2.78—2.85 (2H, m, $C\underline{H}^*CH_3$ and $C\underline{H}^*CH_2$), 5.50 (1H, d, $J=4.3$, $C\underline{H}^*Ph$), 5.55 (1H, d, $J=7.7$, $C\underline{H}Ph$), 7.18—7.40 (5H, m, ArH).

β-Methyl-α,γ-dipentyl-γ-butyrolactone (3b) **3b** was obtained as a mixture of two diastereoisomers in a ratio of 79:21 with the *cis*-(C-α):(C-β) isomer predominating, as estimated from the integrated peak intensity of one of the γ-protons. A colorless oil. IR (KBr): 1770 (lactone) cm^{-1}. ^{1}H-NMR (500 MHz, $CDCl_3$) δ: 0.82 (3H, d, J=7.7, C$\underline{H}_3$*CH), 0.91 (6H, J=7.7, C$\underline{H}_3CH_2\times2$), 0.99 (3H, d, J=6.8, C$\underline{H}_3$CH), 1.22—1.59 (14H, m, $CH_2\times7$), 1.69—1.79 (2H, m, COCHC$\underline{H}_2$), 2.17 (1H, m, COC$\underline{H}$CH$_2$), 2.32 (1H, m, COCH), 2.48 (1H, ddd, J=6.8, 6.8, 4.8, COCH*), 2.59—2.62 (1H, m, C$\underline{H}$*CH$_3$), 4.28 (1H, dt, J=8.6, 4.3, OCH*), 4.42 (1H, m, OCH).

γ-Benzyl-β-methyl-α-pentyl-γ-butyrolactone (3c) **3c** was obtained as a mixture of two diastereoisomers in a ratio of 76:24 with the *cis*-(C-α):(C-β) isomer predominating, as estimated from the integrated peak intensity of the γ-protons. A solid, mp 40 °C. IR (KBr): 1774 (lactone) cm^{-1}. ^{1}H-NMR (500 MHz, $CDCl_3$) δ: 0.90 (3H, t, J=7.7, C$\underline{H}_3CH_2$), 0.94 (3H, d, J=6.8, C$\underline{H}_3$*CH), 1.15 (3H, d, J=6.8, C$\underline{H}_3$CH), 1.25—1.61 [7H, m, C$\underline{H}$H(C$\underline{H}_2$)$_3$], 1.78—1.84 (1H, m, CH$\underline{H}$CH$_2$), 2.21—2.23 (1H, m, COCH), 2.39 (1H, m, C$\underline{H}$CH$_3$), 2.51—2.54 (1H, m, C$\underline{H}$*CH$_3$), 2.81—2.92 (3H, m, C$\underline{H}$*HPh, CH$_2$Ph), 3.09 (1H, dd, J=14.1, 8.6, CH$\underline{H}$*Ph), 4.56 (1H, ddd, J=8.6, 5.9, 4.3, OCH*), 4.68—4.72 (1H, m, OCH), 7.23—7.35 (5H, m, ArH).

β-Methyl-α-pentyl-γ-butyrolactone (3d) **3d** was obtained as a mixture of two diastereoisomers in a ratio of 64:36 with the *cis*-(C-α):(C-β) isomer predominating, as estimated from the integrated intensity of peak height of one of the γ-protons. A colorless oil. ^{1}H-NMR (500 MHz, $CDCl_3$) δ: 0.90 (3H, t, J=6.8, C$\underline{H}_3CH_2$), 1.02 (3H, d, J=6.8, C$\underline{H}_3$CH), 1.16 (3H, d, J=6.8, C$\underline{H}_3$*CH), 1.31—1.62 [6H, m, (C$\underline{H}_2$)$_3$CH$_3$], 1.71—1.79 (2H, m, CHC$\underline{H}_2$CH$_2$), 2.21 (1H, ddd, J=10.3, 6.0, 6.0, COCH*), 2.30—2.35 (1H, m, C$\underline{H}$*CH$_3$), 2.51 (1H, m, COCH), 2.61 (1H, m, C$\underline{H}$CH$_3$), 3.71 (1H, dd, J=8.6, 8.6, C$\underline{H}$*HCHCH$_3$), 3.95 (1H, dd, J=8.6, 2.1, C$\underline{H}$HCHCH$_3$), 4.26 (1H, dd, J=8.6, 5.6, CH$\underline{H}$CHCH$_3$), 4.36 (1H, dd, J=8.6, 8.6, CH$\underline{H}$*CHCH$_3$).

α-Pentyl-β,γ-diphenyl-γ-butyrolactone (3en) **3en** was obtained as a mixture of two diastereoisomers in a ratio of 99:1 with the *cis*-(C-α):(C-β) isomer predominating, as estimated from the integrated intensity of peak height of one of the γ-protons. A solid, mp 91 °C. *Anal.* Calcd for $C_{21}H_{24}O_2$: C, 81.78; H, 7.84. Found: C, 81.66; H, 7.89. IR (KBr): 1773 (lactone) cm^{-1}. ^{1}H-NMR (500 MHz, $CDCl_3$) δ: 0.79 (3H, t, J=6.8, CH_3), 1.11—1.28 (6H, m, $CH_2\times3$), 1.36 (1H, m, C$\underline{H}$*HCH), 1.78 (1H, m, CH$\underline{H}$*CH), 3.13 (1H, m, COCH*), 3.95 (1H, dd, J=7.7, 5.1, C$\underline{H}$*(Ph)CHCH$_2$), 5.81 (1H, d, J=5.1, OCH*), 5.78 (1H, d, J=5.1, OCH), 6.87—7.14 (10H, m, ArH×2).

α-(2-Methylbutyl)-β,γ-diphenyl-γ-butyrolactone (3es) **3es** was obtained as a mixture of three of four possible diastereoisomers. The ratio of 95:5 with the *cis*-(C-α):(C-β) isomer predominating was estimated from the integrated peak intensity of one of the γ-protons. The *cis* isomer is composed of about a 1:1 mixture of two diastereoisomers. A solid, mp 123 °C. *Anal.* Calcd for $C_{21}H_{24}O_2$: C, 81.78; H, 7.84. Found: C, 81.81; H, 7.92. IR (KBr): 1756 (lactone) cm^{-1}. ^{1}H-NMR (500 MHz, $CDCl_3$) δ: 0.53 (3H, t, J= 7.7, C$\underline{H}_3$*CH$_2$), 0.74 (3H, d, J=6.8, C$\underline{H}_3$*CH), 0.86 (3H, t, J= 7.7, C$\underline{H}_3$*CH$_2$), 0.92 (3H, d, J=6.8, C$\underline{H}_3$*CH), 1.04—1.80 (5H, m, CH$_2$CHCH$_2$), 2.99—3.04 (1H, m, COCH), 3.28—3.38 (1H, m, COCH*), 3.74 [1H, m, C$\underline{H}$(Ph)CHCO], 3.91 [1H, t, J=5.13, C$\underline{H}$*(Ph)CHCO], 3.92 [1H, t, J=5.13, CH*(Ph)C$\underline{H}$CO], 5.82 (1H, d, J=5.13, OC$\underline{H}$*Ph), 5.83 (1H, d, J=5.13, OC$\underline{H}$*Ph), 6.84—7.13 (10H, m, ArH×2).

α-(2,2-Dimethylpropyl)-β,γ-diphenyl-γ-butyrolactone (3et) **3et** was obtained as a mixture of two diastereoisomers in a ratio of 89:11 with the *cis*-(C-α):(C-β) isomer predominating, as estimated from the integrated peak intensity of one of the γ-protons. A solid, mp 175 °C. *Anal.* Calcd for $C_{21}H_{24}O_2$: C, 81.78; H, 7.84. Found: C, 81.70; H, 7.83. IR (KBr): 1760 (lactone) cm^{-1}. ^{1}H-NMR (500 MHz, $CDCl_3$) δ: 0.89 (9H, s, $CH_3\times3$), 1.26 (1H, dd, J=14.5, 3.4, CHC$\underline{H}$*H), 1.77 (1H, d, J=3.7, CHC$\underline{H}$H), 1.91 (1H, dd, J=7.7, 3.4, CHCH$\underline{H}$*), 2.91 (1H, m, COCH), 3.13 (1H, ddd, J=7.7, 7.7, 3.4, COCH*). 3.70 [1H, m, OC$\underline{H}$(Ph)CH(Ph)], 3.92 [1H, dd, J=7.7, 5.1, OCH(Ph)C$\underline{H}$*(Ph)], 5.76 (1H, d, J=7.0, OC$\underline{H}$Ph), 5.80 (1H, d, J=5.1, OC$\underline{H}$*Ph), 6.76—7.14 (10H, m, ArH×2).

α-Pentyl-β-benzyl-γ-phenyl-γ-butyrolactone (3f) **3f** was obtained as a mixture of two diastereoisomers in a ratio of 67:33 with the *cis*-(C-α):(C-β) isomer predominating, as estimated from the integrated peak intensity of one of the γ-protons. A solid, mp 66 °C. IR (KBr): 1777 (lactone) cm^{-1}. *Anal.* Calcd for $C_{22}H_{26}O_2$: C, 81.95; H, 8.13. Found: C, 81.68; H, 8.07. ^{1}H-NMR (500 MHz, $CDCl_3$) δ: 0.80 (3H, t, J=6.4, CH_3), 0.82—1.60 [7H, m, CH$\underline{H}$(C$\underline{H}_2$)$_3$], 1.82—1.88 (1H, m, CHCH$\underline{H}$*CH$_2$), 2.38 (2H, dd, J=6.3, 2.6, C$\underline{H}_2$*Ph), 2.79—2.85 (1H, m, COCH), 2.33 (1H, dd, J=12.8, 5.5, C$\underline{H}$HPh), 2.55 (1H, d, J=12.8, 6.4, CH$\underline{H}$Ph), 2.87—2.91 (1H, m, COCH*), 3.20—3.26 (1H, m, C$\underline{H}$*CH$_2$Ph), 5.59 (1H, d, J=4.6, C$\underline{H}$*Ph), 5.67 (1H, d, J=6.4, C$\underline{H}$Ph), 6.77—7.46 (10H, ArH).

References and Notes

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