distance between the two methyl carbon atoms in 1 (2.990 Å) is 0.03 Å longer than that in the former and 0.04 Å shorter than that in the latter. Thus the in-plane deformation of the molecular structure of 1 is alleviated by the out-of-plane distortion.

MMPI molecular mechanics calculations by Kao and Allinger[10] indicate that the most stable geometry for an isolated molecule of 1 is nonplanar; standard deviations of the bond lengths and angles between the experimental values and those recalculated by us are 0.019 Å and 1.2°, respectively. The calculated values for the three torisional angles in the bay region are 15.7°, 40.0°, and 15.7°, which are somewhat different from the experimental values.

Now we turn to the question of the nonequivalence of the two methyl groups in 1.[6] The absence of noncongruent molecules in the crystalline state indicates that the two nonequivalent methyl groups should be assigned to the 4- and 5-methyl groups in 1. The intramolecular placement of the two methyl groups in similar in the crystalline state: the difference between the C11–C4–C4a–C4b and the C12–C5–C4b–C4a torsional angles is only 2.1°, and the C11 methyl carbon atom lies 0.40 Å above the average plane for ring A, while the C12 methyl carbon atom lies 0.44 Å below the average plane for ring C (Figure 2). Therefore, the nonequivalence should be ascribed to their intermolecular environment. Since the C12 methyl carbon atom is very close to the C3 carbon atom of the other molecule whereas the C11 methyl carbon atom is separated by at least 3.82 Å from any carbon atom of other molecules, these differences may account for the difference in the rotation barriers of the 4- and 5-methyl groups in the solid state. It should be noted that the C12 methyl carbon atom is only 3.525 Å above ring A of the other molecule. The difference between the ^{13}C NMR chemical shifts of the two methyl carbon atoms in 1 is mainly due to the intermolecular effect of the local anisotropy[11] or the so-called ring current effect[12].

4-Methylphenanthrene. Crystals of 2 from chloroform–ethanol were subjected to X-ray analysis under the same conditions as those for 1. A total of 719 reflections were recorded with $2\theta < 50°$, and the data were analyzed by the same procedure. However, even after the anisotropic refinements for nonhydrogen atoms in 2, we could not arrive at R values low enough to reveal the hydrogen peaks on the D map with any trial-disordered features included in the methyl carbon atom. Therefore, the hydrogen atoms in 2 were calculated and included in the structure-factor calculations without refining their parameters. In the final isotropic refinement, instead of isotropic thermal parameters for the hydrogen atoms, we used those for the carbon atoms to which they are attached. The final discrepancy was $R = 0.1318$ or $R_w = 0.1273$ ($w = 1.0$).

The crystals are monoclinic, space group $P2_1/c$, $Z = 4$, $a = 8.661$ (3) Å, $b = 8.976$ (2) Å, $c = 13.716$ (4) Å, $\beta = 98.37$ (3)°, $V = 1055.0$ (6) Å^3, and $D_c = 1.210$ g cm^{-3} ($C_{15}H_{12}$, mol wt 192.26). Our solution implied planar molecules stacked very closely in pairs; the distance of the C11 methyl carbon atom from the best plane through the aromatic carbon atoms of 2 is only 0.07 Å, implying a planar structure. However, because of the large R values, the indicated planarity of the molecule in the solid state is questionable and should be examined more carefully.

Acknowledgment. We thank Dr. Kiyonori Takegoshi and Jun Furukawa of Kyoto University for preparations of the samples and helpful discussion. We are grateful to Professor Eiji Ōsawa of Hokkaido University for his kind offer of the MMPI program source. We also thank Dr. Yoshitaka Beppu for allowing us to use his program NAMOD in drawing Figures 1 and 2. The efficient services of the Data Processing Center at Kyoto University are gratefully acknowledged.

Registry No. 1, 3674-69-9; 2, 832-64-4.

Supplementary Material Available: Tables of the final least-squares fractional coordinates for 1 and 2, the thermal parameters for 1 and 2 with stereoscopic view of the thermal ellipsoids, and the bond lengths and the bond angles involving the carbon atoms for 2 (7 pages). Ordering information is given on any current masthead page.

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[10] Kao, J.; Allinger, N. L. *J. Am. Chem. Soc.* **1977**, *99*, 975.

[11] (a) Barfield, M.; Grant, D. M.; Ikenberry, D. *J. Am. Chem. Soc.* **1975**, *97*, 6956. (b) Lazzeretti, P.; Rossi, E.; Zanasi, R. *J. Chem. Phys.* **1982**, *77*, 3129.

[12] Memory, J. D. *J. Magn. Reson.* **1977**, *27*, 241 and references cited therein.

Conjugate Addition Reactions of α-Silylated α,β-Unsaturated Carboxylic Acid Salts

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Attempts to effect conjugate addition of organometallic reagents to α,β-unsaturated carboxylic acids are generally unsuccessful. Reactions of simple unsaturated acids with excess Grignard reagents give, in some cases, low yields of 1,4-adducts.[1a–c] Organolithium reagents generally give 1,2-addition products[1b,2] though exceptions have been noted.[3] Recently, successful additions to unsaturated carboxylic acids using modified organocopper reagents ($RCu{\cdot}BF_3$) have been reported,[4] but this method appears useful only for monosubstituted acrylic acids.

Our interest in the conjugate addition reactions of α,β-unsaturated carbonyl systems in which 1,2-addition reactions are suppressed by the placement of a unit of negative charge adjacent to the carbonyl group (charge-directed conjugate addition reactions[5]) led us to examine conjugate addition reactions of strong nucleophiles with salts of acrylic acid. While low yields of 1,4-adducts with *n*-BuLi were observed, polymerization reactions dominated.[6] Boeckman[7] and Stork[8] previously demonstrated that the use of α-silylated α,β-unsaturated ketones in classical Michael addition reactions results in improved yields, presumably as a result of the α-silyl group's aid in reducing polymerization reactions as well as its positive electronic effect on the 1,4-addition process. While silylated ketone acceptors have received the most attention, an efficient

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[1] (a) Wotiz, J. H.; Matthews, J. S.; Greenfield, H. *J. Am. Chem. Soc.* **1953**, *75*, 6342. (b) Klein, J. *Tetrahedron Lett.* **1964**, 465. (c) Klein, J.; Zitrin, S. *J. Org. Chem.* **1970**, *35*, 666.

[2] Lutz, R. E.; Dickerson, C. L. *J. Org. Chem.* **1962**, *27*, 2040.

[3] Majewski, M.; Snieckus, V. *J. Org. Chem.* **1984**, *49*, 2682.

[4] Yamamoto, Y.; Maruyama, K. *J. Am. Chem. Soc.* **1978**, *100*, 3240.

[5] (a) Cooke, M. P., Jr.; Goswami, R. *J. Am. Chem. Soc.* **1977**, *99*, 642. (b) Cooke, M. P., Jr.; *Tetrahedron Lett.* **1979**, 2199. (c) Cooke, M. P., Jr.; Burman, D. L. *J. Org. Chem.* **1982**, *47*, 4955. (d) Cooke, M. P., Jr. *Ibid.* **1982**, *47*, 4963. (e) Cooke, M. P., Jr. *Ibid.* **1983**, *48*, 744. (f) Cooke, M. P., Jr.; Jaw, J. Y. *Ibid.* **1986**, *51*, 758.

[6] Unpublished work with R. Goswami.

[7] Boeckman, R. K. *J. Am. Chem. Soc.* **1974**, *96*, 6179.

[8] Stork, G.; Singh, J. *J. Am. Chem. Soc.* **1974**, *96*, 6181.

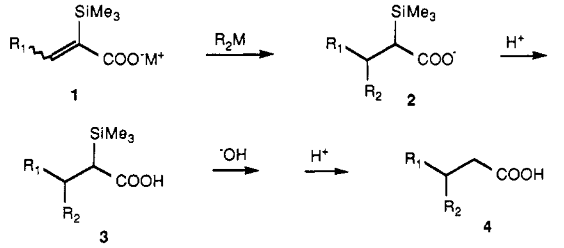
Table I. Carboxylic Acids from the Addition of Nucleophiles to 1 (Eq 1)

entry	acceptor	M^+	RM	method[a]	product[b]	yield,[c] %
1	$CH_2{=}C(SiMe_3)COO^-$ (**5**)	Na^+	*n*-BuLi	A	*n*-$BuCH_2CH_2COOH$ (**6**)	32
2		Na^+		B		75
3		Li^+		C		77
4		Li^+	*sec*-BuLi	C	*sec*-$BuCH_2CH_2COOH$ (**7**)	60
5		Na^+	*t*-BuLi	A	*t*-$BuCH_2CH_2COOH$ (**8**)	91
6		Li^+		C	$BuCH_2CH(SiMe_3)COOH$ (**13**)	95 (100)[d]
7		Na^+	PhLi	A	$PhCH_2CH_2COOH$ (**9**)	70
8		Li^+		C		89
9		Li^+	$CH_3CH_2CH_2CH_2CH{=}CHLi$	C	$CH_3CH_2CH_2CH_2CH{=}CHCH_2CH_2COOH$ (**10**)	33[e]
10		Li^+	$CH_2{=}CHLi$	C	$CH_2{=}CHCH_2CH_2COOH$ (**11**)	41
11		Mg^{2+}	$CH_2{=}CHMgBr$	C		57
12		Li^+	$\overline{SCH_2CH_2CH_2SC}HLi$	D	$\overline{SCH_2CH_2CH_2SC}HCH_2CH_2COOH$ (**12**)	85
13		Na^+		A		0
14		Mg^{2+}	*n*-BuMgCl	C	**6**	95
15		Mg^{2+}	*sec*-BuMgCl	C	**7**	96
16		Mg^{2+}	*t*-BuMgCl	C	**13**	95[d]
17		Mg^{2+}	C_5H_9MgBr	C	$C_5H_9CH_2CH_2COOH$ (**14**)	95
18		Mg^{2+}	$CH_2{=}CH(SiMe_3)MgBr$	C	$CH_2{=}C(SiMe_3)CH_2CH_2COOH$ (**15**)	95
19		Mg^{2+}	PhMgBr	C	**9**	94
20	*n*-$BuCH{=}C(SiMe_3)COO^-$ (**16**)	Li^+	*n*-BuLi	C	(*n*-$Bu)_2CHCH_2COOH$ (**17**)	87[f]
21		Mg^{2+}	*n*-BuMgCl	C		96[f]
22	$PhCH{=}C(SiMe_3)COO^-$ (**18**)	Li^+	PhLi	C	$(Ph)_2CHCH_2COOH$ (**19**)	81[f]

[a] A: RM added to the salt in THF at −78 °C. B: inverse addition of the salt to RM at −78 °C. C: inverse addition of the carboxylic acid to RM (2.2–2.5 equiv). D: addition of RM to the carboxylic acid in THF at −78 °C. [b] Initial silylated adducts were desilylated by heating with 3–6 equiv of NaOH for 1–2 h. [c] Isolated. [d] α-Trimethylsilylated acid isolated prior to desilylation. [e] Identified by spectral analysis and reduction to nonanoic acid (H_2, Pt/C). [f] Extended reaction time (40–45 h) required for complete desilylation.

addition of an aryllithium reagent[9] and copper-catalyzed additions of Grignard and lithium reagents[10] to methyl (α-trimethylsilyl)acrylate have been reported. A single low-yield addition of a ketone enolate to *tert*-butyl α-(trimethylsilyl)acrylate has also been noted.[11]

Against this background, we have examined the conjugate addition reactions of salts of α-silylated α,β-unsaturated carboxylic acids, **1**, with lithium and Grignard reagents (eq 1) and find them to be excellent acceptors in



(1)

many cases. Alkaline desilylation of intermediate silylated acids, **3**, readily affords substituted saturated acids, **4**. Examples of the overall process shown in eq 1 are listed in Table I.

The efficiency of addition reactions is a function of the counterion used for the carboxylate ion and of the nucleophilicity of the organometallic reagent employed. Only alkyllithium reagents undergo additions with sodium salts while less reactive nucleophiles such as 2-lithiodithiane (entry 12) require the use of the more covalent lithium or magnesium salts. While not necessary, the use of lithium salts with alkyllithium reagents is seen to give slightly better yields.

For reasons not clear, the order of the addition is often important in reactions involving alkyllithium reagents and sodium salts. The addition of *n*-butyllithium to sodium salt **5**-Na (entry 1) results largely in the formation of unidentified high-boiling saturated acids, which are not desilylated under vigorous conditions.[12] The addition of the salt to the solution of *n*-butyllithium (entry 2) results in a clean addition reaction giving, after desilylation, heptanoic acid (**6**) in 75% yield.

Outstanding results were obtained in nearly every case with Grignard reagents and magnesium salts.[13] The addition of acceptor acids to Grignard reagents at −78 °C results in little or no 1,4-addition after 1 h, but after several hours at 20 °C excellent yields of addition products are obtained. The single exception is vinylmagnesium bromide (entry 11) where the desilylated acid (**11**) was obtained in only 57% yield. It should also be noted that vinyllithium reagents also gave poor yields in reactions with lithium salts (entries 9 and 10), but excellent results were obtained with [α-(trimethylsilyl)vinyl]magnesium bromide and **5**-Mg (entry 18). It should be pointed out that α-(trimethylsilyl)acrylic acid, **5**-H, is prepared by the carbonation of this Grignard reagent—a process that proceeds through the magnesium salt. Indeed, if care is not taken to add the Grignard reagent slowly to the solid CO_2 in order to maintain temperature control, substantial reductions in yield occur owing to the addition of the Grignard reagent to the carboxylate salt.

Monosubstituted α-silylated acrylate salts likewise undergo conjugate addition reactions efficiently (entries 20–22). Substituted acids **16**-H and **18**-H were prepared from iodides **20**[15] and **21** (by hydroalumination of the corresponding (trimethylsilyl)acetylene followed by iodination) by carbonation of metal–halogen exchange-generated lithium intermediates as shown in eq 2.

While intermediate silylated acids were usually directly desilylated, they could be isolated by acidifying addition reaction mixtures (entries 6 and 16). In NMR tube ex-

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[9] Narula, A. P. S.; Schuster, D. I. *Tetrahedron Lett.* **1981**, *22*, 3707.

[10] Tsuge, O.; Kanemasa, S.; Ninomiya, T. *Chem. Lett.* **1984**, 1993.

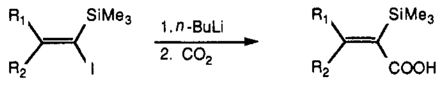
[11] Nartzell, S. L.; Rathke, M. W. *Tetrahedron Lett.* **1976**, 2737.

[12] Heating at 90 °C, pH >12, for 24 h left this material unchanged, suggesting that the silyl group is not on a saturated center adjacent to a carbonyl group.

[13] Magnesium salts were formed by treating acids with 1 additional equiv of the Grignard reagent.

[14] Mironov, V. F.; Petrov, A. D.; Maksimova, N. G. *Izv. Akad. Nauk SSSR, Ser. Khim.* **1958**, 954; *Chem. Abstr.* **1960**, *54*, 9731*a*).

[15] Zweifel, G.; Lewis, W. *J. Org. Chem.* **1978**, *43*, 2739.



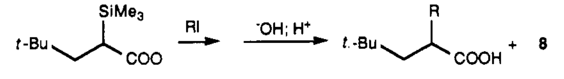
(2)

20 (R_1=Bu,R_2=H) 16-H

21 (R_1=H,R_2=Ph) 18-H

periments, we find that **3** (R_1 = t-Bu, R_2 = H) in aqueous Na_2CO_3 (pH 9) is not noticeably altered after 5 min at 90 °C, but significant desilylation is observed under the same conditions at pH >11, and complete desilylation is observed after 15 min. Adducts derived from substituted acrylates (**3**, R_1, R_2 ≠ H) are considerably more resistant to desilylation, however, and complete desilylation requires heating at 90 °C and pH >11 for up to 44 h (entries 20–22).

The alkylation of the intermediate dianion **2** generated by the addition reactions has been problematic, however. Treatment of dianion **22**, generated by the addition of t-BuLi to **5**–Li (entry 6), with MeI under a variety of conditions consistently gave, after desilylation, approximately 1:1 mixtures of α-methylated acid (**23**, R = CH_3) and unmethylated acid **8** (eq 3). Similar results were

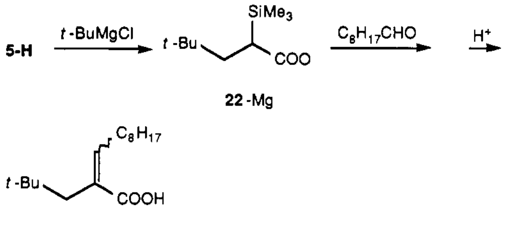


(3)

22 23

obtained with EtI as the alkylating agent. The reasons for the inability to completely alkylate such adduct dianions is unclear. Adventitious quenching of strongly basic **2** under our reaction conditions (2–12 h, 25 °C) or O-alkylation would seem to be plausable explanations, but the near absence of neutral materials (esters) prior to alkaline desilylation would appear to rule out the latter possibility. It should be noted that less highly substituted silylation dianion **2** (R_1 = R_2 = H) reportedly is C-alkylated in high yields.[16]

Initial attempts to use adduct dianions in Peterson olefination reactions were also disappointing. Treatment of lithium dianion **22**-Li with nonanal gave approximately equal amounts of olefins **24** and acid **8**. Similar results were obtained with benzaldehyde, which does not possess a potentially problematic acidic hydrogen. The interception of the magnesium enolate (**22**-Mg) (from Grignard reagent addition) was highly successful, however, and treatment with nonanal gave unsaturated acid **24**, as an 8:1 mixture of *Z* and *E* isomers, in 96% yield (eq 4).[17]



(4)

22-Mg

24

In summary, the salts of α-silylated α,β-unsaturated acids have been shown to undergo efficient conjugate addition reactions with reactive nucleophiles—reactions with Grignard reagents being especially attractive. While enolate dianions resulting from such additions have not been efficiently intercepted with alkylating agents, magnesium enolates from Grignard reagent additions are useful in the Peterson olefination reaction. Thus, α-silylated acrylic acid derivatives are useful conjugate addition acceptors for strong nucleophiles without the need of copper catalysts.

Experimental Section

THF was distilled from sodium benzophenone under an argon atmosphere. ^1H and ^{13}C NMR spectra were recorded with a JEOL FX-90q spectrometer with Me_4Si as an internal standard. All reactions involving air-sensitive materials were conducted under an argon atmosphere. Unless otherwise noted, organolithium and Grignard reagents were obtained from Aldrich Chemical Co. and used as received. Cyclopentylmagnesium bromide (~1 M) and [1-(trimethylsilyl)vinyl]magnesium bromide were prepared from the corresponding bromides and magnesium in THF, and *sec*-BuMgCl (1.5 M) was prepared from 2-chlorobutane and magnesium in Et_2O in the usual way. (E)-(1-Penten-1-yl)lithium was prepared by treating THF solutions of (E)-1-iodo-1-pentene[18] with 2 equiv of n-BuLi at −78 °C. 1-(Bromovinyl)trimethylsilane was obtained from Fluka Chemical Corp. Products in Table I were characterized by spectral analysis and comparison with authentic samples or reported data. Data characterizing new compounds is shown below. Analyses were performed by Galbraith Laboratories, Knoxville, TN. Temperatures cited for bulb-to-bulb distillations refer to the air oven temperatures employed.

2-(Trimethylsilyl)acrylic Acid (5-H). A modification of the literature procedure[14] was employed. Magnesium turnings (2.5 g, 0.1 mol), several crystals of I_2, and 50 mL of THF were briefly heated until the color of the iodine was discharged. To the warm solution was added 6.5 mL (42 mmol) of (1-bromovinyl)trimethylsilane at a rate sufficient to maintain reflux. After the addition was complete, the mixture was heated under reflux for 1 h and cooled, and the Grignard solution was transferred slowly by cannula onto crushed solid CO_2. Rapid addition results in reduced yields (see text). Upon evaporation of the CO_2, the mixture was concentrated under reduced pressure, and the residue was treated with water and then acidified with dilute H_2SO_4. The mixture was extracted with Et_2O, and the oil obtained upon concentration of the extracts was dissolved in alkaline water (NaOH) and twice extracted with Et_2O to remove neutral materials. The aqueous layer was acidified with 4 N H_2SO_4, saturated with NaCl, and extracted with 1:1 Et_2O–pentane. The dried extracts (Na_2SO_4) were concentrated and upon bulb-to-bulb distillation (180 °C, 15 mm) gave 4.5 g (74%) of **5**–H as an oil, which solidified: mp 48–52 °C (lit.[14] mp 50 °C); ^1H NMR ($CDCl_3$) δ 0.21 (s, 9 H), 6.14 (d, 1 H, J = 2.9 Hz), 6.91 (d, 1 H), 12.44 (s, 1 H); ^{13}C NMR ($CDCl_3$) δ −1.5, 141.2, 144.0, 175.3.

Typical Addition Procedures. Method A (Table I, Entry 5). 4,4-Dimethylpentanoic Acid (8). To a slurry of 130 mg (3.1 mmol) of 57% NaH (pentane washed) in 5 mL of THF at 0 °C was added dropwise 130 mg (0.9 mmol) of α-(trimethylsilyl)acrylic acid (**5**-H) with vigorous stirring. After 10 min, a small amount of hexane was added to break the foam, and the mixture was cooled to −78 °C and treated with 0.7 mL (1.26 mmol) of 1.8 M t-BuLi in pentane over 45 s. After the mixture had been stirred for 20 min, 200 μL of MeOH was added, and the mixture was warmed to 25 °C. Solvent was removed under reduced pressure, and the residue was treated with 10 mL of H_2O and 1 mL of 4 N NaOH. The mixture was heated on a steam bath for 1.5 h, cooled, and extracted with Et_2O to remove neutral materials. The aqueous layer was saturated with NaCl, acidified to pH <2 with aqueous HCl, and twice extracted with 2:1 pentane–ether. Concentration and bulb-to-bulb distillation (170 °C, 15 mm) gave 107 mg (91%) of **8**, $n^{20}{}_D$ 1.4190 (lit.[19] $n^{20}{}_D$ 1.4195).

Method B (Entry 2). Heptanoic Acid (6). In the manner described above, salt **5**–Na was prepared from 85 mg of NaH in 5 mL of THF and 135 mg (0.94 mmol) of **5**–H. This fine suspension was transferred by cannula to a stirred solution of 1.6 mL (2.4 mmol) of 1.5 N n-BuLi in 4 mL of THF at −78 °C. Stirring was continued for 0.5 h, whereupon 200 μL of MeOH was added. Workup with desilylation as described above gave, after bulb-to-bulb distillation (160 °C, 15 mm), 92 mg (75%) of hep-

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(16) Grieco, P. A.; Wang, C.-L. J.; Burke, S. D. *J. Chem. Soc., Chem. Commun.* **1975**, 537.

(17) The enolates from the copper-catalyzed addition of Grignard reagents to methyl [1-(trimethylsilyl)vinyl]acrylate have also been reported to undergo Peterson reactions.[10]

(18) Zweifel, G.; Whitney, C. C. *J. Am. Chem. Soc.* **1967**, *89*, 2753.

(19) Brown, H. C.; Imai, T. *J. Org. Chem.* **1984**, *49*, 892.

tanoic acid (**6**), identical by ^{1}H and ^{13}C NMR spectroscopy with an authentic sample.

Method C (Entry 6). 4,4-Dimethylpentanoic Acid (8). THF (5 mL) was cooled to −78 °C and treated with 1.2 mL (2.16 mmol) of 1.8 M *t*-BuLi solution. With stirring, a solution of 140 mg (0.97 mmol) of **5**–H in 2 mL of THF was added over 2 min. After 0.5 h at −78 °C, 200 μL of MeOH was added followed by alkaline desilylation as described above. Bulb-to-bulb distillation (160 °C, 15 mm) gave 120 mg (95%) of **8**.

Method D (Entry 12). 3-(2-Dithianyl)propanoic Acid (12). A solution of 360 mg (3.0 mmol) of dithiane in 8 mL of THF was treated with 1.7 mL (2.55 mmol) of 1.5 N *n*-BuLi at −30 °C and kept at −30 °C to −10 °C for 3 h. This solution of 2-dithianyllithium was added dropwise by cannula to a −25 °C solution containing 144 mg (1.0 mmol) of **5**–H in 4 mL of THF. The mixture was warmed to 25 °C and kept at this temperature for 2 h, whereupon MeOH (200 μL) was added. Solvent was removed under reduced pressure, and the residue was treated with 10 mL of water and 1 mL of 4 N NaOH. Neutral materials were removed by Et_2O extraction, and the aqueous phase was heated on a steam bath for 1 h and then allowed to stand at 25 °C overnight. The solution was acidified with hydrochloric acid to pH <2, saturated with NaCl, and extracted with 1:1 Et_2O–pentane. Concentration of the extracts gave, after recrystallization from Et_2O–hexane and chromatography of the mother liquors (PTLC, silica gel, Et_2O), 163 mg (85%) of **12**, mp 86.5–87.5 °C (lit.[20] mp 87–88 °C).

Typical Grignard Reagent Addition Reaction (Entry 14). Heptanoic Acid (6). A solution containing 2 mL (4.0 mmol) of 2 M *n*-BuMgCl in 4 mL of THF was cooled to −78 °C and with stirring was treated dropwise with a solution of 144 mg (1.0 mmol) of **5**–H in 1.5 mL of THF. The mixture was kept at 25 °C for 4 h and then treated with 250 μL of MeOH. Solvent was removed under reduced pressure, and 10 mL of H_2O was added. Following acidification with hydrochloric acid, the mixture was extracted with pentane. The residue obtained after concentration of the extracts was treated with 10 mL of H_2O and 1 mL of 4 N NaOH and heated on a steam bath for 2 h. The mixture was extracted with Et_2O to remove neutral materials, saturated with NaCl, acidified to pH <2, and extracted with pentane. Concentration of the extracts gave, after bulb-to-bulb distillation 160 °C, 15 mm), 123 mg (95%) of heptanoic acid (**6**).

4-(Trimethylsilyl)-4-pentenoic Acid (15). This acid was obtained as above in 95% yield (entry 18) after bulb-to-bulb distillation 170 °C, 4 mm): ^{1}H NMR ($CDCl_3$) δ 0.10 (s, 9 H), 2.48 (br s, 4 H), 5.37 (d, J = 2.3 Hz, 1 H), 5.58 (d, J = 2.3 Hz, 1 H); ^{13}C NMR ($CDCl_3$) δ −1.7, 30.0, 33.4, 124.1, 150.2, 180.1. Anal. Calcd for $C_8H_{16}O_2Si$: C, 55.76; H, 9.36. Found: C, 55.59; H, 9.78.

2-(Trimethylsilyl)-(*Z*)-2-heptenoic Acid (16–H). A solution containing 1.41 g (5.0 mmol) of (*E*)-1-iodo-1-(trimethylsilyl)-1-hexene (**20**)[15] in 20 mL of Et_2O was treated at −78 °C with 3.2 mL (4.96 mmol) of *n*-BuLi. The mixture was stirred at −78 °C for 1 h and then transferred by cannula onto freshly powdered dry ice. After evaporation of the excess CO_2, water was added, and the mixture was twice extracted with Et_2O to remove neutral materials. Acidification of the aqueous layer and extraction with 1:1 Et_2O–pentane gave, after concentration of the extracts and bulb-to-bulb distillation (180 °C, 1 mm), 550 mg (56%) of **16**–H as an oil: ^{1}H NMR ($CDCl_3$) δ 0.10 (s, 9 H), 0.77 (t, 3 H), 1.22 (m, 4 H), 2.13 (m, 2 H), 7.19 (t, J = 8.4 Hz, 1 H); ^{13}C NMR ($CDCl_3$) δ 0.7, 13.9, 22.5, 31.2, 31.4, 133.4, 160.0, 177.3. Anal. Calcd for $C_{10}H_{20}O_2Si$: C, 59.95; H, 10.06. Found: C, 59.80; H, 10.55.

3-Butylheptanoic Acid (17). By the procedure cited above for a typical Grignard reagent addition reaction, **16**–H and *n*-BuMgCl gave, after 15 h addition reaction time and 24 h desilylation reaction time, **17** in 96% yield as an oil (bulb-to-bulb distillation, 170 °C, 0.1 mm): ^{1}H NMR ($CDCl_3$) δ 0.89 (t, 3 H), 1.27 (br, 12 H), 1.88 (br, 1 H), 2.28 (d, J = 6.5 Hz, 2 H), 11.95 (s, 1 H); ^{13}C NMR ($CDCl_3$) δ 14.1, 22.9, 28.8, 33.6, 34.9, 39.2, 180.6. Anal. Calcd for $C_{11}H_{22}O_2$: C, 70.92; H, 11.91. Found: C, 71.00; H, 11.86.

(*Z*)-1-Iodo-2-phenyl-1-(trimethylsilyl)ethene (21). As previously described,[21] (phenylethynyl)trimethylsilane (5.08 g, 29.0 mmol) in 40 mL of pentane was treated at 20 °C with 30 mL (30 mmol) of 1 M diisobutylaluminum hydride in hexane. After 16 h, the solution was cooled to −78 °C and a solution containing 7.9 g (31 mmol) of I_2 in 50 mL of Et_2O was added by cannula with stirring over several minutes. Stirring was continued for 15 min, whereupon the mixture was poured onto an ice–water–hydrochloric acid mixture and was then extracted with pentane. The extracts were washed successively with aqueous NaOH, aqueous $NaHSO_3$, and water and then concentrated. The residue was passed through a short plug of silica gel (pentane). Concentration and distillation gave 7.7 g (87%) of **21**: bp 80–84 °C (0.1 mm); ^{1}H NMR ($CDCl_3$) δ 0.27 (s, 9 H), 7.20–7.65 (m, 6 H); ^{13}C NMR ($CDCl_3$) δ −1.3, 111.7, 127.9, 128.1, 128.4, 139.0, 144.2. Anal. Calcd for $C_{11}H_{15}ISi$: C, 43.71; H, 5.00. Found: C, 43.99; H, 4.97.

(*Z*)-3-Phenyl-2-(trimethylsilyl)propenoic Acid (18–H). A solution containing 1.20 g (4.0 mmol) of **21** in 20 mL of Et_2O was cooled to −78 °C and treated with 2.5 mL (3.88 mmol) of 1.55 N *n*-BuLi solution over 1–2 min. After 15 min at −78 °C, the mixture was transferred by cannula onto solid CO_2. After excess solid CO_2 had evaporated, 25 mL of water and 1 mL of 4 N NaOH were added, and the mixture was twice extracted with pentane. Acidification of the aqueous phase gave a solid, which was extracted into pentane. Concentration of the extracts and crystallization from cold pentane gave in two crops 650 mg (76%) of **18**–H: mp 80–81 °C; ^{1}H NMR ($CDCl_3$) δ 0.28 (s, 9 H), 6.86 (s, 1 H), 7.2–7.5 (m, 5 H); ^{13}C NMR ($CDCl_3$) δ −1.7, 128.2, 128.4, 128.7, 136.3, 137.5, 142.3, 178.5. Anal. Calcd for $C_{12}H_{16}O_2Si$: C, 65.41; H, 7.32. Found: C, 65.48; H, 7.30.

3,3-Diphenylpropanoic Acid (19). THF (5 mL) was treated with 1.4 mL (2.8 mmol) of 2 M PhLi and cooled to −78 °C. A solution containing 220 mg (1.0 mmol) of **18**–H in 1.5 mL of THF was added dropwise with vigorous stirring over 3.5 min. The mixture was stirred at −78 °C for 40 min and at 0 °C for 20 min, whereupon 200 μL of MeOH was added. Solvent was removed under reduced pressure, and the residue was treated with 10 mL of H_2O and 2 mL of 4 N NaOH and heated on a steam bath for 44 h. The solution was twice extracted with Et_2O to remove neutral materials. The aqueous phase was saturated with NaCl, acidified (pH <2), and extracted with Et_2O. Concentration of the dried extracts (Na_2SO_4) gave a residue, which upon recrystallization and chromatography of the mother liquors (PTLC, silica gel, 3:1 CH_2Cl_2–Et_2O) gave 184 mg (81%) of **19**, mp 154.5–155.5 °C (lit.[22] mp 154.5–155.5 °C).

4,4-Dimethyl-2-(trimethylsilyl)pentanoic Acid (13). With use of the typical Grignard reaction addition procedure cited earlier, 1 mmol of **5**–H was allowed to react with 3.2 mmol of *t*-BuMgCl at 25 °C for 15 h. The mixture was then cooled to −78 °C and treated with 200 μL of MeOH, whereupon the solvent was removed under reduced pressure, and the residue was treated with H_2O (10 mL) and quickly acidified to pH 2. The mixture was extracted (4×) with pentane, giving, upon concentration of the extracts, 201 mg (100%) of crude **13**, mp 95–99 °C. Recrystallization from MeOH–H_2O gave, in three crops, 192 mg (95%) of pure **20**: mp 101–102.5 °C; ^{1}H NMR ($CDCl_3$) δ 0.06 (s, 9 H), 0.6–0.9 (br 2 H), 0.84 (s, 9 H), 1.75–2.10 (m, 1 H); ^{13}C NMR ($CDCl_3$) δ −3.0, 28.8, 32.1, 34.0, 40.2, 183.3. Anal. Calcd for $C_{10}H_{22}O_2Si$: C, 59.35; H, 10.96. Found: C, 59.72; H, 10.90.

2-(2,2-Dimethylpropyl)-2-undecenoic Acid (24). To 6 mL of THF were added 154 mg (1.07 mmol) of **5**–H and 1.6 mL (3.5 mmol) of 2.25 M *t*-BuMgCl in Et_2O. After 2.5 h at 25 °C, the mixture was cooled to 0 °C and treated with 600 μL (3.5 mmol) of freshly distilled nonanal. The mixture was heated at 30–40 °C for 2.5 h and then at 50–55 °C for 15 min, whereupon the solvent was removed under reduced pressure. The residue was treated with H_2O (10 mL), made acidic, and extracted with pentane. The oil obtained after concentration of the extracts was treated with 10 mL of H_2O and 4 mL of 4 N NaOH and was then heated on a steambath under an argon atmosphere for 20 min. The mixture was cooled to 25 °C, and neutral materials were removed by extraction with pentane. The aqueous phase (containing poorly soluble carboxylate salts which partially separate) was reheated on a steam bath for 13 h, cooled, extracted again with pentane to remove any neutral materials, acidified, and extracted with pentane. Concentration of the latter extracts and

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(20) Ghiringhelli, D. *Tetrahedron Lett.* **1983**, *24*, 287.

(21) Eisch, J. J.; Foxton, M. W. *J. Org. Chem.* **1971**, *36*, 3520.

(22) Higa, T.; Krubsack, A. J. *J. Org. Chem.* **1976**, *41*, 3399.

J. Org. Chem. **1987**, *52*, 5733–5740

bulb-to-bulb distillation (180 °C, 0.5 mm) gave 260 mg (96%) of **24** as an 8:1 mixture of Z/E isomers, which could be separated by PTLC (silica gel, 8:1 CH_2Cl_2–Et_2O). Major Z isomer: ^1H NMR ($CDCl_3$) δ 0.83 (t, 3 H), 0.88 (s, 9 H), 1.27 (br 12 H), 2.23 (s, 2 H), 2.25–2.65 (m, 2 H), 5.91 (t, J = 7.3 Hz, 1 H). The olefinic proton in the minor (lower R_f) E isomers appears as a triplet at δ 6.95. Anal. Calcd for $C_{16}H_{30}O_2$: C, 75.53; H, 11.89. Found: C, 75.65; H, 11.73.

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Synthesis of α-Keto Esters via Palladium-Catalyzed Double Carbonylation

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In recent years, increasing importance has been placed on the utilization of carbon monoxide for organic synthesis.[1] Of particular industrial value are those reactions in which more than one unit of carbon monoxide are incorporated in the products. One reaction of considerable interest in this field is the direct reductive carbonylation of carbon monoxide with the chief aim being the synthesis of C_2 oxygenates such as ethylene glycol, ethanol, and/or acetic acid.[2] The alternative copolymerization of carbon monoxide with olefins also seems to be of great promise.[3] Another of industrial potential is the cobalt[4] or palladium[5-7] catalyzed double carbonylation of organic halides leading to the formation of α-keto acid derivatives, which are useful starting materials for α-amino acids and others.

Table I. Steric Effect of Alcohols on the Reaction Rate[a]

ROH	total yield,[b] %	
	$PR_3 = PPh_3$	$PPh_2(o\text{-}MeC_6H_4)$
MeOH	67	
EtOH	51	70
i-PrOH	17	33
t-BuMeCHOH	4	9
t-BuOH	0	

[a] $PdCl_2(PR_3)_2$ (0.02 mmol), PhI (2.2 mmol), ROH (2.5 mmol), NEt_3(2.5 mmol), benzene (2.5 mL), p(CO) = 150 atm at room temperature, 80 °C, 14 h. [b] $PhCOCO_2R + PhCO_2R$.

Table II. Effect of Alcohols on Keto Ester Synthesis[a]

ROH	selectivity,[b] %	total yield,[c,d] %
MeOH	0	83
EtOH	13	92
n-BuOH	32	90
i-BuOH	40	77
t-$BuCH_2OH$	51	98
i-PrOH	37	99
$C_6H_{11}OH$[e]	41	97
sec-BuOH	26	99
t-BuOH	0	24
$PhCH_2OH$	0	95
PhMeCHOH	12	100
PhOH	0	94

[a] $PdCl_2(PPh_3)_2$ (0.038 mmol), PhI (4 mmol), ROH (1 mL), NEt_3 (5 mL), p(CO) = 150 atm at room temperature, 120 °C, 10 h. [b] 100 × $PhCOCO_2R/(PhCOCO_2R + PhCO_2R)$. [c] $PhCOCO_2R + PhCO_2R$. [d] Conversions were 100% except the case of *t*-BuOH (54%). [e] Cyclohexanol.

We recently reported the first example of a palladium complex catalyzed double carbonylation of halides in the presence of primary or secondary amines that affords α-keto amides in good yields (eq 1).[5a,b] Our continuous

$$ArX + CO + HNu \rightarrow ArCOCONu\ (+ ArCONu) \qquad (1)$$

$$(HNu:\ R_2NH,\ RNH_2,\ ROH,\ H_2O)$$

and comprehensive research on the double carbonylation has revealed that α-keto esters can also be synthesized from organic halides and alcohols in the presence of tertiary amines.[6a,b] However, the selectivities for the double carbonylation were usually lower than those observed in the α-keto amide synthesis, so that the reaction recipe should be more strictly specified for the α-keto ester synthesis. We now report the full details of the influence of the various reaction parameters that affect the selec-

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(1) (a) Sheldon, R. A. *Chemicals from Synthesis Gas*; D. Reidel: Dordrecht, 1983. (b) *New Synthesis with Carbon Monoxide*; Falbe, J., Ed.; Springer-Verlag: Berlin, 1980.

(2) (a) Dombek, B. D. *Adv. Catal.* **1983**, *32*, 325. (b) Dombek, B. D. *Organometallics* **1985**, *4*, 1707. (c) Knifton, J. F.; Grigsby, R. A., Jr.; Lin, J. J. *Organometallics* **1984**, *3*, 62.

(3) Sen, A.; Brumbauch, J. S. *J. Organomet. Chem.* **1985**, *279*, C5 and the references cited therein.

(4) (a) Alper, H.; Des Abbayes, H. *J. Organomet. Chem.* **1977**, *134*, C11. (b) Des Abbayes, H.; Bulop, A. *J. Chem. Soc., Chem. Commun.* **1978**, 1090. (c) Perron, R. C. (Rhone Poulenc), U.S. Patent 4 152 352, 1979. (d) Gambarotta, S.; Alper, H. *J. Organomet. Chem.* **1981**, *212*, C23. (e) Francalanci, F.; Foa, M. *J.* Organomet. *Chem.* **1982**, *232*, 59. (f) Francalanci, F.; Gardano, A.; Abis, L.; Fiorani, T.; Foa, M. *J. Organomet. Chem.* **1983**, *243*, 87. (g) Fell, B.; Chrobaczek, H. *Chem.-Ztg.* **1984**, *108*, 291. (h) Alper, H.; Arzoumanian, H.; Patrignani, J.-F.; Saldana-Maldonado, M. *J. Chem. Soc., Chem. Commun.* **1985**, 340. (i) Lee, J. Y.; Walter, T. J. (Ethyl Corp.), U.S. Patent 4 473 706, 1985. (j) Lee, J. Y.; Wolfram, J. W. Jpn. Kohyo Tokkyo Koho, JP 85-500,445, 1984; *Chem. Abstr.* **1985**, *102*, 78371*r*. (k) Kashimura, T.; Kudo, K.; Mori, S.; Sugita, N. *Chem. Lett.* **1986**, 483. (l) Francalanci, F.; Bencini, E.; Gardano, A; Vincenti, M.; Foa, M. *J. Organomet. Chem.* **1986**, *301*, C27.

(5) Keto amide synthesis: (a) Kobayashi, T.; Tanaka, M. *J. Organomet. Chem.* **1982**, *233*, C64. (b) Kobayashi, T.; Tanaka, M. (Agency of Industrial Science and Technology, Japan), Jpn. Kokai Tokkyo Koho 83-185,548; U.S. Patent 4 503 232, 1985; Jpn. Kokai Tokkyo Koho 83-213,724. See also: (c) Ozawa, F.; Soyama, H.; Yamamoto, T.; Yamamoto, A. *Tetrahedron Lett.* **1982**, *23*, 3383. (d) Ozawa, F.; Soyama, H.; Yanagihara, H.; Aoyama, I.; Takino, H.; Izawa, K.; Yamamoto, T.; Yamamoto, A. *J. Am. Chem. Soc.* **1985**, *107*, 3235. (e) Ozawa, F.; Yanagihara, H.; Yamamoto, A. *J. Org. Chem.* **1986**, *51*, 415.

(6) Keto ester synthesis: Preliminary results have been reported. (a) Tanaka, M.; Kobayashi, T.; Sakakura, T.; Itatani, H.; Danno, S.; Zushi, K. *J. Mol. Catal.* **1985**, *32*, 115; (b) Yamashita, H.; Kobayashi, T.; Sakakura, T.; Tanaka, M. *Shokubai* **1986**, *28*, 150. See also: (c) Itatani, H.; Danno, S.; Zushi, K. Jpn. Kokai Tokkyo Koho 85-19,750. (d) Ozawa, F.; Kawasaki, N.; Yamamoto, T.; Yamamoto, A. *Chem. Lett.* **1985**, 567. (e) Morin, B.; Hirshauer, A.; Hugues, F.; Commereuc, D.; Chauvin, Y. *J. Mol. Catal.* **1986**, *34*, 317.

(7) Keto acid synthesis: (a) Tanaka, M.; Kobayashi, T.; Sakakura, T. *J. Chem. Soc., Chem. Commun.* **1985**, 837. (b) Kobayashi, T.; Yamashita, H.; Sakakura, T.; Tanaka, M. *J. Mol. Catal.* **1987**, *41*, 379. See also: (c) Kobayashi, T.; Sakakura, T.; Tanaka, M. *Tetrahedron Lett.* **1987**, *28*, 2721.

0022-3263/87/1952-5733$01.50/0