$C_{94}H_{180}Cl_4N_4O_{36}\cdot 5H_2O$: C, 51.76; H, 9.06; N, 2.57. Found: C 51.91; H, 9.05; N, 2.73.

Preparation of Tetrakis Quaternary Ligand 23a. A solution of **23b** (637 mg) in water (2 mL) containing concentrated HCl (0.1 mL) was stirred at 25 °C for 2 h and then evaporated to dryness. Water (0.5 mL) was added, and the mixture was evaporated to dryness again. The residue was dissolved in MeOH (0.5 mL) and purified by preparative TLC. The plate was developed with ether, it was dried, and then it was redeveloped with MeOH. The band at R_f 0.34 was removed and eluted with MeOH (2 × 0.5 mL). The MeOH was evaporated, and the residue was taken up in water (2 mL) and passed through an ion-exchange column (IRA-400, Cl^- form, 2.5 g). The eluent was evaporated to dryness, and the residue was further dried under vacuum (0.05 mm), giving **23a** (508 mg, 98%) as a yellow, viscous liquid. Anal. Calcd for $C_{64}H_{138}Cl_4N_4O_{30}\cdot 2H_2O$: C, 47.40; H, 8.83; N, 3.46. Found: C, 47.26; H, 8.91; N, 3.51.

Precipitation Experiments between Ligand 23a and Lysozyme, Concanavalin A, and Polylysine. Lysozyme. Three milliliters (23.3 × 3 × 18 = 1.3 μequiv of positive charge ignoring the single histidine residue) of a stirred 23.3 μM aqueous solution of lysozyme (0.350 mg/mL, pH adjusted to 7.1 by addition of 1 N NaOH) in a UV cell was titrated by the addition of 5-μL increments of a 1.80 mM aqueous solution of Dawson HPT **2b** (K^+ salt, pH 5.9). The turbidity of the mixture was monitored by observing changes in absorbance at 775 nm vs. microliters added (Figure 1a). The mixture became turbid after the first addition. After a total of 100 μL (1.80 × 100 × 7 = 1.3 μequiv of negative charge) was added, the resulting precipitate was collected by centrifugation and dried, giving 2.01 mg (100%).

A second titration was performed as described above using as the titrant 100 μL of a 1.80 μM solution of Dawson HTP **2b**, which was also 19 mM in ligand **23a** (i.e., 100 μL contained 5.0 mg of **23a**, 7.7 μequiv of positive charge). There was essentially no turbidity during this latter titration (see Figure 1a).

Concanavalin A. Three milliliters (13.0 × 3 × 19 = 0.74 μequiv of positive charge, ignoring the histidine residues) of a stirred 13.0 μM aqueous solution of concanavalin A (0.350 mg/mL, pH adjusted to 7.1 by addition of 1 N NaOH) in a UV cell was titrated by the addition of 5-μL increments of a 1.80 mM aqueous solution of Dawson HPT **2b** (K^+ salt, pH 5.9) as described above. After a total of 60 μL (1.80 × 60 × 7 = 0.76 μequiv of negative charge) was added, the resulting precipitate was collected and dried, giving 1.60 mg (100%).

A second titration was performed using as the titrant the Dawson solution which was also 32 mM in ligand **23a** (i.e., 60 μL contained 3.0 mg of **23a**, 7.6 μequiv of positive charge). There was essentially no turbidity during this latter titration (see Figure 1b).

Poly-L-Lysine. Poly-L-lysine hydrobromide (Sigma, MW ≃ 17,000, 1.08 mg, 5.2 μequiv of positive charge) was dissolved in 4.00 mL of water. The pH was adjusted to 7.1 by the addition of 1 N NaOH (0.1 mL), and then a 1.00-mL aliquot (1.3 μequiv of positive charge) was removed and diluted with 3.00 mL of water. This was placed in a UV cell and stirred while it was titrated by the addition of 5-μL increments of a 1.80 mM aqueous solution of Dawson HPT **2b** (K^+ salt, pH 5.9). After a total of 100 μL (1.3 μequiv of negative charge) was added, the resulting precipitate was collected and dried, giving 1.06 mg (100%).

A second titration was performed as described above using as the titrant 100 μL of a 1.80 mM solution of **2b**, which was also 66 mM in ligand **23a** (i.e., 100 μL contained 10.4 mg of **27a**, 26 μequiv of positive charge). A slight increase in turbidity was observed during this latter titration (Figure 1c).

Acknowledgment. This research was supported by PHS Research Grant GM-27137 from the National Institute of General Medical Sciences. G.L.W. thanks the Academia Sinica for a leave of absence. The 300-MHz NMR spectrometer was purchased with funds from PHS Grant RR02336 and NSF Grant CHE 8411177.

Supplementary Material Available: Preparation of $[H_3N(CH_2CH_2NH_2)_2CH_2CH_2NH_3]CpTiPW_{11}O_{39}$, $[H_3N(CH_2CH_2NH_2)_3CH_2CH_2NH_3]_4[CpTiPW_{11}O_{39}]_5$, $[H_3N(CH_2)_6NH_3]_2CpTiPW_{11}O_{39}$, $[Me_3N(CH_2CH_2NMe_2)_2CH_2CH_2NMe_3]CpTiPW_{11}O_{39}$, $[Me_3N(CH_2CH_2NMe_2)_3CH_2CH_2NMe_3]_4[CpTiPW_{11}O_{39}]_5$, $[Et_3N(CH_2CH_2O)_2CH_2CH_2NEt_3]CpTiPW_{11}O_{39}$, $[Et_3N(CH_2CH_2O)_2CH_2CH_2NEt_3]_7(CpTiP_2W_{17}O_{61})_2$, $[(CH_3CH(OH)CH_2)_2NHCH_2CH_2NH(CH_2CH(OH)CH_3)_2]_2CpTiPW_{11}O_{39}$, $[(HOCH_2CH_2)_3N(CH_2CH_2O)_2CH_2CH_2N(CH_2CH_2OH)_3]_2CpTiPW_{11}O_{39}$, and $[(HOCH_2CH_2)_3N(CH_2CH_2O)_2CH_2CH_2N(CH_2CH_2OH)_3]_7[CpTiP_2W_{17}O_{61}]_2$ (3 pages). Ordering information is given on any current masthead page.

Silicon Hydrides and Molybdenum(0) Catalyst: A Novel Approach for Conjugate Reduction of α,β-Unsaturated Carbonyl Compounds

Ehud Keinan*[†] and Daniel Perez

Department of Organic Chemistry, Weizmann Institute of Science, Rehovot 76100, Israel

Received April 25, 1986

A novel reducing system comprised of phenylsilane and catalytic amounts of $Mo(CO)_6$ in refluxing THF efficiently effects conjugate reduction of Michael acceptors, including α,β-unsaturated ketones, carboxylic acids, carboxylic esters, amides, and nitriles. The process involves molybdenum-catalyzed hydrosilation, followed by hydrolysis of the intermediate silyl enol ether. Hydride is regioselectively transferred from the hydridosilane to the β-carbon of the substrate, and a proton from water is incorporated into the α-carbon.

The design of composite reducing systems comprised of a relatively nonreactive source of hydride entities, such as group 14 metal hydrides and transition-metal catalysts of groups 8–10, represents a highly useful reduction strategy. This general approach, which is based on the specific delivery of hydride ions from a nonreactive donor to the target functionality, has provided new opportunities for reductive cleavage of allylic heterosubstituents[1] and conjugate reduction of Michael acceptors[2] with superior se-

---

[†] Incumbent of the Joseph and Madeleine Nash Career Development Chair established by Fondacion Madelon, Zurich, Switzerland.

(1) (a) Keinan, E.; Greenspoon, N. *Tetrahedron Lett.* **1982**, *23*, 241. (b) Keinan, E.; Greenspoon, N. *J. Org. Chem.* **1983**, *48*, 3545. (c) Keinan, E.; Greenspoon, N. *Isr. J. Chem.* **1984**, *24*, 82. (d) Greenspoon, N.; Keinan, E., submitted for publication.

0022-3263/87/1952-2576$01.50/0 © 1987 American Chemical Society

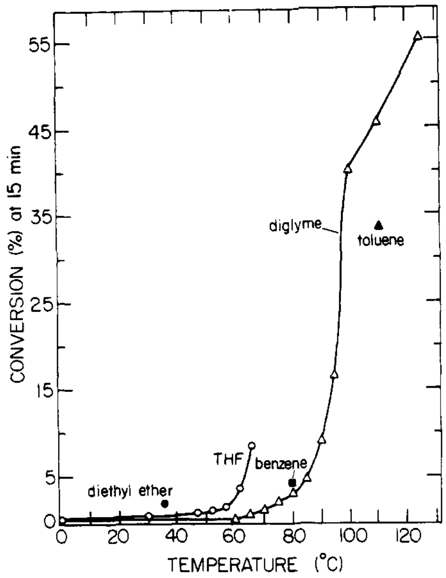


Figure 1. Temperature dependence of benzalacetone reduction in several solvents. Benzalacetone (0.3 mmol) was dissolved in the appropriate solvent (1 mL) along with $Mo(CO)_6$ (0.03 mmol) and $PhSiH_3$ (0.6 mmol). The mixture was placed in a thermoregulated bath under argon, and the reaction was monitored by GC. The given conversions, measured at 15 min, approximately reflect the initial rates of reduction.

lectivities, particularly chemoselectivity.

Early transition-metal complexes, especially those of group 6, are attractive hydride transfer agents in view of their low cost and usually high coordination number, enabling flexible design of the ligand sphere. Surprisingly, they have been rarely used to catalyze such reactions, although their implementation in transfer hydrogenation[3] and hydrogenation with hydrogen gas[4] has been reported. Even less is known about the application of these catalysts to hydrosilations.[5]

In this paper we report that under mild thermal conditions catalytic amounts of $Mo(CO)_6$ and phenylsilane engender a powerful reducing system suitable for conjugate reduction of Michael acceptors, including α,β-unsaturated ketones, carboxylic acids and esters, amides, nitriles, etc.

Results and Discussion

Catalytic properties of the coordinatively saturated group 6 metal hexacarbonyl complex $M(CO)_6$ (M = Cr, Mo, W) depend largely on the ease of removing one or more carbonyl ligands to yield a reactive, coordinatively unsaturated metal species. Although much is known about activating hexacarbonyls photochemically,[5] recent reports indicate that they may also catalyze hydrogen transfer by operating at temperatures between 50 and 100 °C.[4,6,7] We examined reduction of benzalacetone with phenylsilane using thermally activated $Mo(CO)_6$ and indeed obtained quantitative conversion to benzylacetone. A study of the temperature dependence of the rate of reduction was carried out in diglyme, yielding an interesting S-shaped curve (see Figure 1). This phenomenon is reminiscent of Marko's investigations of the catalytic hydrogenation of ketones with either $Mo(CO)_6$ or $Cr(CO)_6$.[4a]

Although the optimal temperature in diglyme, as concluded from the figure, is between 90 and 100 °C, reactions may be successfully carried out at lower temperatures in other solvents, e.g., in refluxing THF. It also appears that catalytic activity significantly depends on the physical removal of CO from the solution. If, for example, CO is purged from a diglyme reaction mixture by bubbling argon, reduction rates are markedly enhanced. Conversely, rates are decreased when reactions are performed in closed vessels. It is, therefore, advantageous to carry out these catalytic reductions in boiling solvents, assuring effective expulsion of carbon monoxide. Accordingly, the reaction is totally inhibited under 1 atm of CO or in the presence of triphenylphosphine (2 equiv/equiv of Mo). All of these observations suggest that the active catalytic entity is a thermally generated, coordinatively unsaturated complex, $Mo(CO)_n$ (n = 3–5), which is probably stabilized by a solvent coordination.[5] Accordingly, catalytic activity is suppressed by oxygen, and inert atmosphere is required. Reactions carried out in open flasks proceeded very slowly and halted at low conversions. Moreover, a latent period was observed in all reactions, representing the time required to generate the active catalyst. Yet, even in solutions containing active catalyst, reduction did not proceed below 40 °C.

Of the hexacarbonyl complexes of Cr, Mo, and W, $Mo(CO)_6$ is the most effective catalyst. Conjugate reduction of representative substrates **1**, **14c**, and **15** in refluxing THF occurs approximately 10 times faster with $Mo(CO)_6$ than with $Cr(CO)_6$, and essentially no reaction occurs with $W(CO)_6$. Water does not seem to inhibit catalytic activity. However, it does cause Mo-catalyzed decomposition of the silane with concomitant evolution of hydrogen gas.

Although the reaction also works with mono- and dihydridosilanes, phenylsilane was found to be the most effective hydride donor. For example, in the reduction of benzalacetone (**1**), pulegone (**2**), and mesityl oxide (**3**), significantly higher yields and faster reactions occur with phenylsilane than with diphenylsilane (see Table I). The general order of silane reactivity observed ($PhSiH_3$ > Ph_2SiH_2 > $Me(EtO)_2SiH$ > PMHS, $PhMe_2SiH$, Et_3SiH) correlates well with the order we found earlier with respect to Pd(0)-catalyzed allylic reductions with silicon hydrides.[1c]

Thus, conjugate reduction of a broad variety of α,β-unsaturated carbonyl compounds (Table I) was typically carried out in refluxing THF under argon atmosphere with a small excess (1.3–1.5 equiv) of phenylsilane and catalytic amounts (3–5 mol %) of $Mo(CO)_6$. Upon completion, water was added to hydrolyze totally the primary product (silyl enol ether) and to convert excess silane into high molecular weight siloxanes, easily separated from the product. This latter step is particularly advantageous for large-scale syntheses.

---

(2) For conjugate reductions with Pd(0) catalyst, see: (a) Keinan, E.; Gleize, P. A. *Tetrahedron Lett.* **1982**, *23*, 477. (b) Keinan, E.; Greenspoon, N. *Tetrahedron Lett.* **1985**, *26*, 1353. (c) Keinan, E.; Greenspoon, N. *J. Am. Chem. Soc.* **1986**, *108*, 7314. (d) Four, P.; Guibe, F. *Tetrahedron Lett.* **1982**, *23*, 1825. (e) Xian, Y. T.; Four, P.; Guibe, F.; Balavoine, G. *Nouv. J. Chim.* **1984**, *8*, 611. For conjugate reductions with Ru(II), see: (f) Keinan, E.; Godinger, N.; Greenspoon, N., submitted for publication. For conjugate reductions with Rh(I), see: (g) Ojima, I.; Kogure, T. *Organometallics* **1982**, *1*, 1390 and references cited therein.

(3) (a) Tatsumi, T.; Shibagaki, M.; Tominaga, H. *J. Mol. Catal.* **1981**, *13*, 331. (b) Tatsumi, T.; Hashimoto, K.; Tominaga, H.; Mizuta, Y.; Hata, K.; Hidai, M.; Uchida, Y. *J. Organomet. Chem.* **1983**, *252*, 105. (c) Lin, Y.; Lu, X. *J. Organomet. Chem.* **1983**, *251*, 321.

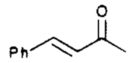
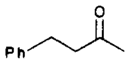
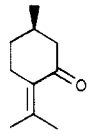
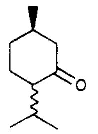
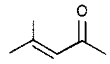
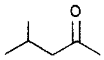
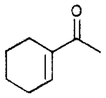
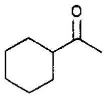
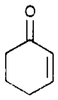
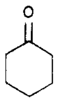
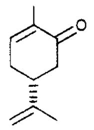
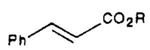
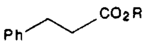
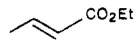
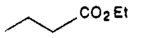
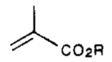
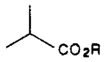
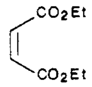
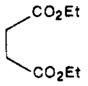
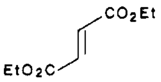
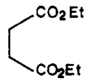
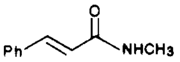
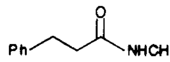
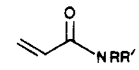
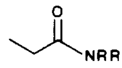
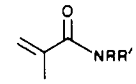
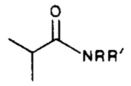
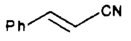
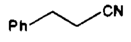
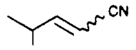
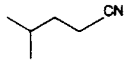
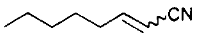
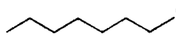
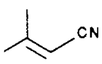
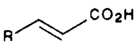
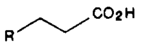
(4) (a) Marko, L.; Nagy-Magos, Z. *J. Organomet. Chem.* **1985**, *285*, 193. (b) Frankel, E. N. *J. Org. Chem.* **1972**, *37*, 1549. (c) Sodeoka, M.; Shibasaki, M. *J. Org. Chem.* **1985**, *50*, 1147.

(5) (a) Wrighton, M. S.; Graff, J. L.; Kazlauskas, R. J.; Mitchener, J. C.; Reichel, C. L. *Pure Appl. Chem.* **1982**, *54*, 161. (b) Wrighton, M. *Chem. Rev.* **1974**, *74*, 401. (c) Wrighton, M. S.; Schroeder, M. A. *J. Am. Chem. Soc.* **1974**, *96*, 6235. (d) Schroeder, M. A.; Wrighton, M. S. *J. Organomet. Chem.* **1974**, *74*, C29. (e) Calhoun, A. D.; Lung, K. R.; Nile, T. A.; Stokes, L. L.; Smith, S. C. *Transition Met. Chem.* (*Weinheim, Ger*) **1983**, *8*, 365. (f) Yates, R. L. *J. Catal.* **1982**, *78*, 111.

(6) Kao, S. C.; Spillett, C. T.; Ash, C.; Lusk, R.; Park, Y. K.; Darensbourg, M. Y. *Organometallics* **1985**, *4*, 83 and references cited therein.

(7) Lewis, K. E.; Golden, D. M.; Smith, G. P. *J. Am. Chem. Soc.* **1984**, *106*, 3905.

Table I. Mo(0)-Catalyzed Conjugate Reduction of Michael Acceptors[a]

no.	substrate	time, h	product	yield, %
1		7^d 1.5		$95^{b,c}$ $100^{b,c}$
2		15^d 3		$100^{b,c}$ $100^{b,c}$
3		24^d 23		5^b 95^b
4		4.5		$100^{b,c}$
5		4		25^b
6		11.5	no reactn	$0^{b,c}$
7				
	a, R = Cy	30		75^b
	b, R = *i*-Pr	24		$90^{b,c}$
8		11.5		75^b
9				
	a, R = Me	20		90^b
	b, R = Cy	35		100^b
10		10		$100^{b,c}$
11		4.5		$100^{b,c}$
12		4		$80^{b,c}$
13				
	a, R = R' = H	1		80^c
	b, R = H, R' = *n*-Pr	0.3		$100^{b,c}$
	c, R = R' = *n*-Pr	0.2		$100^{b,c}$
	d, R = R' = *i*-Pr	0.2		$95^{b,c}$
14				
	a, R = R' = H	1.7		$100^{b,c}$
	b, R = H, R' = *n*-Pr	1.3		$100^{b,c}$
	c, R = R' = *n*-Pr	4		$70^{b,c}$
	d, R = R' = *i*-Pr	15		80^b
15		12		$90^{b,c}$
16	 (*E*:*Z* = 1:1)	9		$100^{b,c}$
17	 (*E*:*Z* = 1:1)	4.5		$100^{b,c}$
18		12	no reactn	$0^{b,c}$
19				
	a, R = H	1.5		100^c
	b, R = Me	6.5		100^c
	c, R = Ph	6.5		100^c

[a] All reactions were carried out with 0.2–0.5 mmol of substrate, 3–5 mol % of $Mo(CO)_6$, and 1.3–1.5 equiv of $PhSiH_3$ in 1 mL of refluxing THF. [b] Yields were determined by GC, using an internal standard. [c] Yields were determined by ^1H NMR. [d] Diphenylsilane was employed instead of phenylsilane.

All reductions described in Table I were carried out on a small scale, and yields were determined by either GC or NMR with internal standards. Nevertheless, in order to illustrate the synthetic usefulness of this method we carried out preparative-scale (6–9-mmol) reductions of four representative substrates, pulegone, isopropyl cinnamate, *N*-propylmethacrylamide, and cinnamonitrile, providing the corresponding α,β-saturated compounds in isolated yields of 90%, 81%, 83%, and 78%, respectively.

A qualitative order of reactivity of the various unsaturated functionalities (ketone > amide > carboxylic acid ⩾ nitrile ⩾ carboxylic ester) is apparent from the reaction times required to complete reduction under similar conditions (see Table I) and, particularly, from a comparison of the structurally related substrates **1**, **7**, **12**, **15**, and **19c**.

α,β-Unsaturated aldehydes are rapidly reduced by phenylsilane and $Mo(CO)_6$. However, a mixture of products, arising from 1,2- and 1,4-reduction modes in approximately 2:1 ratio, is formed. For example, reduction of cinnamaldehyde afforded cinnamyl alcohol and dihydrocinnamaldehyde in a ratio of 2:1, respectively (by NMR), as well as a number of other minor products, including 3-phenylpropanol. An even more complex mixture was obtained in the reduction of citral by this method. Although conditions for better selectivity of aldehyde reduction may be found (e.g., employment of other silanes), we did not investigate this issue any further.

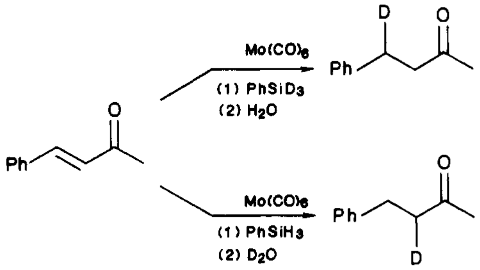
Of special interest are the relative rates of reduction of the three cyclohexenyl enones: acetylcyclohexene (**4**), cyclohexenone (**5**), and carvone (**6**). While the enone systems in **5** and **6** are frozen in transoid form, in **4** it is flexible and may adopt either transoid or cisoid conformation. Enone **4** is reduced significantly faster than **5**, while essentially no reaction is observed with **6**, demonstrating the clear preference of the cisoid form and indicating that the molybdenum atom interacts simultaneously with both the olefinic bond and the carbonyl of the enone system. Accordingly, pulegone (**2**), although sterically more hindered than **4**–**6**, is reduced much faster than these other compounds, most probably due to its frozen cisoid form. The difference in reactivities of maleate and fumarate esters (**10**, **11**), favoring the latter (Table I), may be explained on the same basis, the cisoid conformation of fumarate being less sterically biased than that of maleate.[8]

In comparison with our previously described diphenylsilane/Pd(0)/$ZnCl_2$ reducing system, the present one operates on a much wider range of substrates. On the

---

(8) In conjugate reduction of enones catalyzed by arenechromium tricarbonyl, the cisoid conformation is also markedly preferred.[4c] With Pd(0) catalyst, however, enones behave as monodentate ligands and reductions of **2**, **4**, **5**, and **6** proceed at comparable rates.[2b,c] A similar monodentate behavior is also observed with ruthenium(II) catalysts,[2f] where the normally higher reactivity of the maleate ester over the fumarate is observed.

Scheme I



other hand, in agreement with the recognized bulkiness of π-olefin and π-allyl molybdenum complexes,[9] these catalysts are much more sensitive to steric effects.

The above-mentioned reactivity characteristics may be utilized for chemoselective differentiation between similar enones. For example, reduction of a 1:1 mixture of benzalacetone (1) and carvone (**6**) according to the general procedure resulted in quantitative formation of benzylacetone and quantitative recovery of unreacted **6**.

Although full mechanistic details of this conjugate reduction are yet unavailable, the process clearly involves molybdenum-catalyzed hydrosilation, followed by hydrolysis of the resulting silyl enol ether. When reduction of benzalacetone (1) was carried out in dry C_6D_6, formation of the corresponding silyl enol ether (mixture of Z and E isomers at a 3:1 ratio, respectively) was observed by proton NMR. These silyl enol ethers were immediately hydrolyzed by water to benzylacetone. The preferential formation of Z over E isomer is consistent with the favored coordination of molybdenum to the cisoid conformation of the enone substrate (vide supra). As expected, employment of trideuteriophenylsilane for the reduction of 1 led to highly regioselective incorporation of a single deuterium atom at the β-carbon, yielding β-deuteriobenzylacetone (Scheme I). Conversely, using trihydridophenylsilane and quenching the reaction mixture with D_2O resulted in the isomeric product, monodeuteriated at the α-position.

Conclusion

The results presented here clearly indicate that composite reducing systems can also be built around group 6 metal catalysts. Efficient conjugate reduction of Michael acceptors by our system is particularly significant in light of the poor results reported for an attempted Mo(0)-catalyzed conjugate reduction under transfer-hydrogenation conditions.[3a] We are currently investigating selective reduction of other functional groups with silicon hydrides and group 6 catalysts, including allylic heterosubstituents, acetylenes, and α-halo carbonyl compounds.[10]

Experimental Section

General Methods. Melting points (uncorrected) were determined on a Buchi apparatus. Infrared spectra were measured on the neat compounds with an FT infrared CYGNUS 25 Mattson instrument and are given in reciprocal centimeters. Patterns are designated as follows: br, broad; sh, shoulder; s, strong; w, weak; m, medium. ^1H NMR spectra were measured in deuteriochloroform (unless otherwise cited) on Varian FT-80A or Bruker WH-270 NMR spectrometers. All chemical shifts are reported in δ units downfield from Me_4Si, and the J values are given in hertz. Splitting patterns are designated as follows: s, singlet; d, doublet; t, triplet; q, quartet; m, multiplet; br, broad. High-resolution mass spectra were recorded on a Varian MAT-731 spectrometer. GC-MS analyses were carried out on a Finnigan 4500 instrument. Thin-layer chromatography (TLC) was performed on aluminum sheets precoated with silica gel (Merck, Kieselgel 60, F254, Art. 5549). GC analyses were performed on a Spectra Physics 7100 (FI detector) gas chromatograph equipped with either a 0.125 in. × 2 ft column packed with 10% SE-30 on Chromosorb W or a 0.125 in. × 4 ft column packed with 5% OV-17 on Chromosorb W. Distillations were usually performed with a Buchi Kugelrohr apparatus, and the temperatures given are pot temperatures.

Materials. Tetrahydrofuran and diethyl ether were distilled over sodium benzophenone ketyl. Phenylsilane and trideuteriophenylsilane were prepared by reduction of trichlorophenylsilane with $LiAlH_4$ and $LiAlD_4$, respectively, in dry ether.[11] Diphenylsilane was prepared in a similar way.[2c] Compounds **1**–**6**, **8**, **9a**, **10**, **11**, **13a**, **14a**, **15**, and **19** were purchased from Aldrich. Compounds **7**, **9b**, **13b**–**d**, and **14b**–**d** were prepared from the corresponding acyl chloride derivative and the appropriate alcohol or amine, with reactions being carried out in hexane at room temperature in the presence of excess triethylamine. The esters and amides were isolated by ether/water extraction and subsequent distillation and found to be pure by GC and NMR. Compounds **16**–**18** were prepared from the appropriate carbonyl compound and diethyl (cyanomethyl)phosphonate.[12]

Reductions of Benzalacetone with Various Silanes. Reduction of benzalacetone (1; 0.20 mmol) was carried out in refluxing THF by the general procedure described below involving $Mo(CO)_6$ (0.012 mmol, 6 mol %) and the appropriate silane; reaction progress was followed by GC. Six representative silanes were checked, and the following was observed: (a) with phenylsilane (0.22 mmol), the reaction was completed within 1.5 h; (b) with diphenylsilane (0.22 mmol), 95% conversion was attained within 7 h; (c) with diethoxymethylsilane (0.42 mmol), about 30% conversion was observed within 6 h; (d–f) with poly(methylhydrosiloxane) (0.42 mmol), dimethylphenylsilane (0.42 mmol), or triethylsilane (0.42 mmol), less than 5% conversion was attained within 6 h.

Reductions of Benzalacetone with Various Catalysts. A. With Diphenylsilane. Reduction of 1 (0.20 mmol) was carried out in refluxing THF by the general procedure described below employing diphenylsilane (0.5 mmol) and the appropriate catalyst; reaction progress was followed by GC. The following results were obtained: (a) without catalyst, no reaction was observed within 6 h; (b) with $Mo(CO)_6$ (0.013 mmol), reduction was completed within 5 h; (c) with both $Mo(CO)_6$ (0.013 mmol) and PPh_3 (0.027 mmol), no reaction was observed within 4 h; (d) with $Cr(CO)_6$ (0.013 mmol), 6% conversion was attained within 5 h; (e) with $W(CO)_6$ (0.016 mmol), no reaction was observed within 4 h.

B. With Phenylsilane. Experiments similar to those described in A were carried out with phenylsilane instead of diphenylsilane: (a) without catalyst, no reaction was observed within 6 h; (b) with $Mo(CO)_6$ (0.028 mmol), reduction was completed within 1.5 h; (c) with both $Mo(CO)_6$ (0.013 mmol) and PPh_3 (0.027 mmol), no reaction was observed within 4 h; (d) with $Cr(CO)_6$ (0.034 mmol), 30% conversion was attained within 2 h; (e) with $W(CO)_6$ (0.016 mmol), no reaction was observed within 4 h; (f) reduction of dipropylmethacrylamide (**14c**; 0.4 mmol) with $Mo(CO)_6$ (0.04 mmol) reached 70% conversion within 4 h; (g) reduction of **14c** (0.4 mmol) with $Cr(CO)_6$ (0.04 mmol) reached 10% conversion within 6.5 h.

Reductions of Benzalacetone with Various Concentrations of Mo(0). Reduction of 1 (0.4 mmol) was carried out as described in General Procedure with $Mo(CO)_6$ (1.7–105 mol %) and diphenylsilane (0.5 mmol) in refluxing THF; progress of the reactions was followed by GC. Four representative concentrations of the catalyst were examined, and the time required to achieve 50% conversion was measured: (a) with 105 mol %, 2.5 h; (b) with 28 mol %, 3 h; (c) with 10 mol %, 4 h; (d) with 1.7 mol %, 6 h.

---

[9] (a) Trost, B. M.; Lautens, M. *J. Am. Chem. Soc.* **1982**, *104*, 5543. (b) *Ibid.* **1983**, *105*, 3343. (c) Trost, B. M.; Hung, M. H. *J. Am. Chem. Soc.* **1984**, *106*, 6837. (d) Faller, J. W.; Chao, K. H. *J. Am. Chem. Soc.* **1983**, *105*, 3893. (e) Pearson, A. J.; Khan, M. N. I. *J. Am. Chem. Soc.* **1984**, *106*, 1872.

[10] Perez, D.; Greenspoon, N.; Keinan, E., submitted for publication.

[11] Harvey, M. C.; Nebergall, W. H.; Peake, J. S. *J. Am. Chem. Soc.* **1957**, *79*, 1437.

[12] Pettit, G. R.; Dias, J. R. *J. Org. Chem.* **1971**, *36*, 3209.

General Procedure for Conjugate Reduction of α,β-Unsaturated Carbonyl Compounds. A THF (1 mL) solution of the α,β-unsaturated carbonyl compound (0.2–0.5 mmol), $Mo(CO)_6$ (3–5 mol %), and $PhSiH_3$ (1.3–1.5 equiv) was refluxed under argon atmosphere, and progress of the reaction was followed by either GC or NMR. Upon completion (evident by either GC or TLC), water was added (3–4 equiv) and the product was purified and analyzed by both GC and NMR. Results are given in Table I. Preparative-scale procedures are described below.

Reduction of Pulegone. Pulegone (**2**; 1.30 g, 8.56 mmol) was dissolved in dry THF (10 mL) together with phenylsilane (1.2 mL, 9.6 mmol) and $Mo(CO)_6$ (84 mg, 0.32 mmol). The mixture was refluxed for 3 h and then carefully quenched with 1 mL of water. The solvent was removed under reduced pressure, water (10 mL) was added, and the mixture was extracted with ether (5 × 50 mL). The organic solution was dried over $MgSO_4$, the solvent was evaporated, and the residue was Kugelrohr distilled [150 °C (0.5 mm)], affording 1.182 g (7.7 mmol, 90%) of a 4.5:1 mixture of menthone and isomenthone (pure by GC and NMR).[13]

Reduction of Isopropyl Cinnamate. Reduction of isopropyl cinnamate (1.27 g, 6.7 mmol) was carried out as described above with phenylsilane (1.1 mL, 8.8 mmol) and $Mo(CO)_6$ (145 mg, 0.57 mmol) in 10 mL of refluxing THF for 24 h. Kugelrohr distillation [170 °C (0.5 mm)] afforded 1.029 mg (5.39 mmol, 81%) of isopropyl dihydrocinnamate.[14]

Reduction of *N*-Propylmethacrylamide. Reduction of *N*-propylmethacrylamide (**14b**; 0.99 g, 7.8 mmol) was carried out as described above with phenylsilane (1.1 mL, 8.8 mmol) and $Mo(CO)_6$ (82 mg, 0.31 mmol) in 10 mL of refluxing THF for 2 h. Kugelrohr distillation [140 °C (0.5 mm)] afforded 0.838 mg (6.5 mmol, 83%) of *N*-propyl-2-methylpropionamide.

α-Deuteriodihydrocinnamonitrile. Reduction of cinnamonitrile (0.75 g, 5.8 mmol) was carried out as described above with phenylsilane (1.0 g, 9.2 mmol) and $Mo(CO)_6$ (75 mg, 0.28 mmol) in 4 mL of THF. The mixture was refluxed for 12 h, and the resulting dark red solution was quenched with D_2O (0.2 mL). Removal of solvent under reduced pressure and inspection of the crude product before distillation with an internal standard indicated a 90% yield. Kugelrohr distillation [150 °C (0.5 mm)] afforded α-deuteriodihydrocinnamonitrile (0.60 g, 4.55 mmol, 78%). The clean incorporation of a single deuterium atom at the α-position was evident by both NMR and GC–MS: ^1H NMR δ 2.63 (1 H, m), 2.94 (2 H, d), 7.27 (5 H, m); MS, m/z 132 $(M(D)^+$, 18.4), 131 $(M(H)^+$, 1.8), 92 (8.1), 91 (100).

Deuterium Incorporation Experiments with Benzalacetone. A. Reduction of Benzalacetone with $PhSiD_3$. Reduction of **1** (28 mg, 0.19 mmol) was carried out in THF (1 mL) according to the general procedure with $Mo(CO)_6$ (4.4 mg, 0.017 mmol) and trideuteriophenylsilane (0.30 mmol). The solution was refluxed for 2 h, after which complete conversion of **1** into 4-deuterio-4-phenylbutan-2-one[2c] was observed by NMR and MS.

B. Partial Reduction. The same reaction was repeated with the same quantities and conditions. However, it was interrupted at 40% conversion. Only one product was observed (4-deuterio-4-phenylbutan-2-one). Examination of the recovered starting material **1** by both NMR and GC–MS indicated no incorporation of any deuterium atoms.

C. Reduction in THF-d_8. The same experiment as described in A was repeated, except that perdeuteriated THF was employed as the solvent instead of THF and $PhSiH_3$ was used in place of $PhSiD_3$. Inspection of the product, benzylacetone, indicated no incorporation of deuterium into the molecule.

D. Reduction with $PhSiH_3/D_2O$. An experiment similar to A was carried out, except that $PhSiH_3$ was employed and the THF used was dried over active alumina, then mixed with D_2O, and dried again. The reaction mixture was refluxed for 1.2 h, quenched with two drops of D_2O, and analyzed by both NMR and GC–MS, indicating complete conversion to 3-deuterio-4-phenylbutan-2-one.[2c]

Silyl Enol Ethers. Benzalacetone (30.3 mg, 0.21 mmol) was dissolved in dry C_6D_6 (0.5 mL) together with $PhSiH_3$ (0.25 mmol) and $Mo(CO)_6$ (3.2 mg, 0.012 mmol), and the resultant mixture was placed in a dry NMR tube. The solution was kept at 75 °C for 2 h, then cooled to room temperature, and analyzed by NMR (270 MHz). The mixture was found to contain 2-(phenylsiloxy)-4-phenylbut-2-ene (*Z* and *E* isomers in a 3:1 ratio) as the major constituent, less than 30% of unreacted benzalacetone, unreacted phenylsilane, and less than 5% of benzylacetone. NMR spectra of the two silyl enol ethers were assigned on the basis of similar, known derivatives.[2g,15]

^1H NMR of the *Z* isomer (major): δ 1.77 (br s, 3 H), 3.47 (d, J = 7.1 Hz, 2 H), 4.63 (br t, J = 7.1 Hz, 1 H), 5.26 (s, 2 H, $OSiH_2Ph$), 7.1 (m, 10 H).

^1H NMR of the *E* isomer (minor): δ 1.77 (br s, 3 H), 3.12 (d, J = 7.7 Hz, 2 H), 5.09 (br t, J = 7.7 Hz, 1 H), 5.26 (s, 2 H, $OSiH_2Ph$), 7.1 (m, 10 H).

Acknowledgment. We thank the fellowship program of the Consejo Nacional de Investigaciones Cientificas y Tecnicas de la Republica Argentina for their generous financial support.

---

[13] Compounds were compared with authentic samples (Aldrich). See also: Willham, B.; Thomas, A. F. *J. Chem. Soc.* **1965**, 6478.

[14] (a) Schiori, T.; Yokoyama, Y.; Kasai, Y.; Yamada, S. *Tetrahedron* **1976**, *32*, 2211. (b) Kadentsev, V. I.; Zolotarev, B. M.; Chizhov, O. S.; Shachidatayov, Ch.; Yanovskaya, C. A.; Kuchesov, V. F. *Org. Mass Spectrom.* **1968**, *1*, 899.

[15] Heathcock, C. H.; Buse, C. T.; Kleschick, W. A.; Pirrung, M. C.; Sohn, J. E.; Lampe, J. *J. Org. Chem.* **1980**, *45*, 1066.