where, until now, the Pd(II)-catalyzed oxidation was not a viable alternative.

Experimental Section

All solvents were of spectroscopic quality. Olefins and palladium catalysts were commercially available (Aldrich) and were used as received. Benzoquinone was filtered through a silica gel column (chloroform as eluant) and recrystallized twice from hexane.

All reactions were carried out using a similar procedure which is described below.

Acid Dependence. Palladium(II) acetate (0.2 mmol), benzoquinone (9 mmol), and the inorganic acid (HCl, $HClO_4$, HBF_4, H_2SO_4, or HNO_3, 0.1 M) were dissolved in acetonitrile/water (7:1 v/v, 50 mL). The solution was deoxygenated by purging with argon for at least 30 min and stirred vigorously until the $Pd(OAl)_2$ had dissolved. The olefin (10 mmol) was then added to the flask (by syringe), and the reaction mixture was stirred for 10 min. The products were separated from the catalyst by extraction into hexane or diethyl ether, washed with 30% aqueous sodium hydroxide, and then analyzed by a capillary GC–internal standard method. *n*-Decane was the internal standard in cyclohexene and cycloheptene reactions, and both *n*-tridecane and *n*-hexadecane were used as internal standards in all other reactions.

Olefin Oxidation Reactions. Oxidations of various olefins listed in Table II were performed in the manner described above. In this case, perchloric acid (72% w/v, 1.0 mL) was used, and the reactions were carried out at either 23 °C or 60 °C as noted in Table II. The cyclohexene and 1-decene reactions listed in Table III were also performed in the method similar to that described above. For cyclohexene, the total volume was only 20 mL.

Perchloric Acid Concentration Dependence. In all reactions 0.1 mmol of the Pd(II) salt, 10 mmol of the olefin, 9 mmol of benzoquinone, and varying amounts of $HClO_4$ (72% w/v) in a total volume of 20 mL were used. The reaction time was 10 min. The reaction mixture was then extracted into diethyl ether, washed with 30% (w/v) aqueous NaOH, and finally dried over $MgSO_4$. Products were analyzed by a capillary GC–internal standard method, with both *n*-tridecane and *n*-hexadecane used as internal standard.

Registry No. $Pd(OAc)_2$, 3375-31-3; $PdCl_2$, 7647-10-1; 1-decene, 872-05-9; 2-decanone, 693-54-9; 3-decanone, 928-80-3; 4-decanone, 624-16-8; decanal, 112-31-2; 1-octene, 111-66-0; *trans*-2-octene, 13389-42-9; *cis*-2-heptene, 6443-92-1; cyclohexene, 110-83-8; cycloheptene, 628-92-2; styrene, 100-42-5; 2-octanone, 111-13-7; 3-octanone, 106-68-3; 4-octanone, 589-63-9; 2-heptanone, 110-43-0; 3-heptanone, 106-35-4; 4-heptanone, 123-19-3; cyclohexanone, 108-94-1; cycloheptanone, 502-42-1; acetophenone, 98-86-2; phenylacetaldehyde, 122-78-1.

Diiodosilane. 2.[1] A Multipurpose Reagent for Hydrolysis and Reductive Iodination of Ketals, Acetals, Ketones, and Aldehydes

E. Keinan,* D. Perez, M. Sahai, and R. Shvily

Department of Chemistry, Technion-Israel Institute of Technology, Technion City, Haifa 32000, Israel

Received July 3, 1989

The reaction patterns of diiodosilane (SiH_2I_2, DIS) with ketals, acetals, ketones, and aldehydes were explored. The reagent may be used for mild cleavage of ketals and acetals either hydrolytically to give the parent carbonyl functionality or reductively to produce the corresponding alkyl iodide. At low temperatures (−42 °C) and short reaction times (few minutes), catalytic amounts (5–10 mol %) of DIS provide clean deprotection of various ketals and acetals to yield ketones and aldehydes, with no apparent reduction of the latter. At temperatures above 0 °C, DIS effectively reduces ketals and acetals to iodoalkanes. This reduction is quite general both with respect to ketals and acetals and unprotected ketones and aldehydes. Reaction rates, however, are strikingly dependent on the substrate, with the following tendencies: (a) aromatic functionalities are generally reduced much faster than their aliphatic analogues; (b) ketals and acetals are rapidly reduced to the corresponding iodoalkanes, while free aldehydes, and particularly ketones, are essentially inert under the reaction conditions (but can be significantly activated by catalytic amounts of iodine); (c) dimethyl ketals form the parent ketones preferentially, while all other ketals, including diethyl ketals and dioxolanes, are reduced to iodoalkanes.

Introduction

The outstanding utility of iodotrimethylsilane (TMSI) as a versatile reagent in organic synthesis arises from two complementary characteristics. TMSI is both a strong "hard" Lewis acid with particular affinity to oxygen functionalities and an effective donor of strongly nucleophilic, "soft" iodide ions. This unique combination renders TMSI a highly advantageous reagent for cleavage of carbon–oxygen bonds into iodoalkanes.[2]

We have recently introduced a new, closely related synthetic reagent, diiodosilane (SiH_2I_2, DIS).[1] DIS, a stronger Lewis acid than TMSI and as good a donor of iodide ions, was found to be very useful for cleavage and deoxygenation of ethers and alcohols with high selectivity for secondary oxygen functions.[1] DIS also possesses a third mode of reactivity that significantly increases the scope of its synthetic applicability: it is also a donor of hydride ions. Thus, by a judicious choice of reaction conditions, DIS may serve as a versatile reagent, performing either iodination or reduction or both.

In this paper we explore the reaction patterns of DIS with ketals, acetals, ketones, and aldehydes. We show that the reagent may be used for mild cleavage of ketals and acetals either hydrolytically to give the parent carbonyl functionality or reductively to produce the corresponding alkyl iodide. Similar reduction/iodination reactions may be carried out with unprotected ketones and aldehydes as well.

Results and Discussion

1. Deprotection of Ketals and Acetals. Ketals and acetals, and particularly dioxolane derivatives, are the most

(1) For the first paper in this series, see: Keinan, E.; Perez, D. *J. Org. Chem.* **1987**, *52*, 4846.
(2) Olah, G. A.; Narang, S. C. *Tetrahedron* **1982**, *38*, 2225.

0022-3263/90/1955-2927$02.50/0

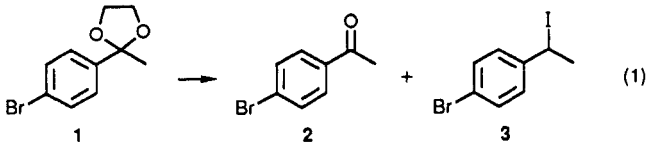
Table I. Reductive vs Nonreductive Cleavage of Ketal 1[a]

entry	silane	mol %	temp (°C)	time (min)	yield (%) 2	3
1	TMSI	180	22	1	100[b]	0
2	TMSI	180	0	1	58	0
3	TMSI	180	-42	10	61	0
4	TMSI	30	22	20	28	0
5	TMSI	60	22	20	65	0
6	DIS	10	-42	1	100	0
7	DIS	10	0	0.5	100	0
8	DIS	100	0	60	35	65
9	DIS	200	22	2	0	100

[a] The appropriate iodosilane was added to a solution of ketal 1 (0.1 mmol) in $CDCl_3$ (0.4 mL) at the given temperature and quenched at the given time with aqueous Na_2CO_3. Yields were determined by NMR. [b] The same result was observed after 1 h at the same temperature.

important protecting groups for ketones and aldehydes. Regeneration of the parent carbonyl from these functionalities has traditionally been accomplished by aqueous acid hydrolysis or by acid-catalyzed exchange with acetone.[3] Less acidic, milder techniques include use of acidified silica gel,[4] lithium tetrafluoroborate in wet acetonitrile,[5] and pyridinium tosylate in acetone.[6] More recent, milder approaches involve nonaqueous solvents and an appropriate combination of a Lewis acid with a strong nucleophile: for example, PI_3 or P_2I_4 in dichloromethane,[7] titanium tetrachloride with lithium iodide in diethyl ether,[8] and trimethylsilyl iodide (TMSI) in chloroform.[9] Treatment of cyclic and acyclic ketals and acetals with TMSI followed by aqueous workup is known to produce either the corresponding carbonyl compound or the relatively stable α-iodoalkoxy intermediate.[10]

To evaluate the potential usefulness of DIS in ketal cleavage reactions, we compared its reactivity with the known behavior of TMSI using the cyclic ketal 1 as a model substrate (eq 1 and Table I). The representative



1 2 3 (1)

reaction conditions listed and the resultant product distributions clearly illustrate major differences between these closely related reagents. Expectedly, the cyclic ketal 1 is rapidly cleaved by TMSI to the parent ketone 2 at room temperature and even below (entries 1–3). Ketone 2 is quite stable under the reaction conditions, as no further reaction is observed within 1 h (entry 1). It is also clear that the reagent is required in stoichiometric quantities (entries 4 and 5). With DIS, however, it appears that nonreductive cleavage of 1 proceeds much more rapidly than with TMSI, probably due to the higher Lewis acidity and lower steric demands of DIS relative to TMSI. The reactivity differences between TMSI and DIS are apparent at lower temperatures. For example, with DIS, quantitative cleavage of 1 is achieved at -42 °C within less than 1 min even with catalytic amounts of the reagent (entry 6). With TMSI, however, deprotection of 1 proceeds much more sluggishly at that temperature (entry 3).

More importantly, in contrast to TMSI, reactions with DIS may be driven to yield more than a single product, depending on reaction conditions. Indeed, at longer reaction times and/or higher temperatures DIS reveals its potential as a reducing agent (vide infra), providing reductive cleavage of 1 to the corresponding iodoalkane (entries 8 and 9).

Table II demonstrates the generality of the low-temperature ketal cleavage with DIS, using various aliphatic and aromatic, cyclic and acyclic ketals and acetals. Although quantitative conversion could be attained with all the substrates, reactions were interrupted after partial conversion to compare substrate reactivities toward DIS and product distribution (by NMR). A number of control experiments were carried out by using either TMSI or HI in place of DIS (entries 2, 3, 9–11, and 16–19).

Some general features may be seen in Table II, as expected for ketal cleavage under acidic conditions. First, cleavage of aromatic ketals proceeds much faster than that of the corresponding aliphatic derivatives. Also, as has already been observed with TMSI[9,11] and with other acidic reagents,[5,8,12] DIS tends to cleave cyclic ketals, such as dioxolane derivatives, more slowly than it does with the corresponding acyclic analogues. For example, the acyclic ketal of acetone, 4, is cleaved at least twice as fast as the cyclic ketal 5 (entries 1, 4, and 5). Approximately the same situation is observed with the acyclic and cyclic ketals of cyclohexanone, 7 and 8 (entries 12 and 13).

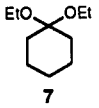
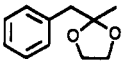
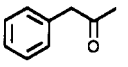
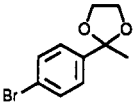
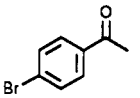
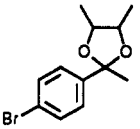
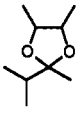
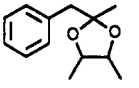
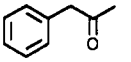
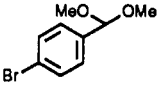
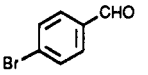
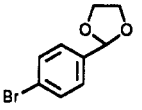
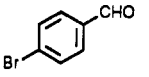
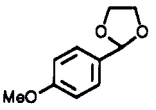
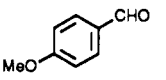
Perhaps the most useful advantage of DIS over TMSI in ketal cleavage is its ability to function as a catalyst (5–10 mol %). Because hydriodic acid can catalyze ketal cleavage, we initially suspected that the catalytic effect is due to HI formed by partial hydrolysis of the iodosilane by traces of water rather than DIS itself. However, TMSI, which may also produce traces of HI under the reaction conditions used, does not exhibit catalytic activity (entries 16–18). Control experiments with dry HI in chloroform indicated that although HI indeed acts as a catalyst in these reactions, it is less efficient than DIS (compare for example entries 3, 11, and 19 with entries 1, 6, and 14, respectively).

Another advantage of DIS over TMSI is its ability to operate on the more sterically congested ketals derived from butane-2,3-diol (entries 22–24). While these compounds react with TMSI quite sluggishly (see Tables III and IV), their reactions with DIS proceed almost as rapidly as observed that with nonhindered ketals. However, with such sterically hindered systems, DIS must be employed in stoichiometric quantities.

Catalytic cleavage of ketals converts 1 mol of ketal into 1 mol of ketone and 1 mol of dialkyl ether. Therefore, it is expected that any acidic reagent that promotes formation of ethers from other oxygen functionalities, and catalyzes transetherification in particular, would catalyze ketal cleavage. Strong acids, such as HI, may be used in catalytic amounts for this purpose. Although the majority of alkoxysilanes formed in our reactions are known etherification intermediate,[13,14] in cases where they are relatively more

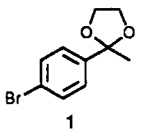
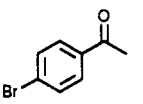
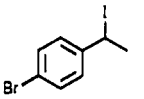
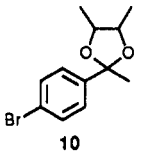
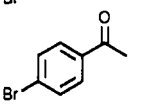
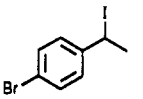
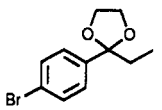
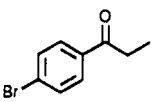
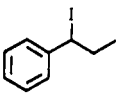
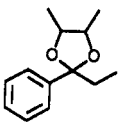
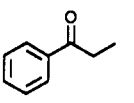
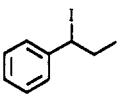
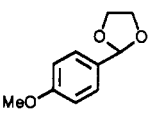
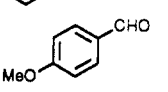
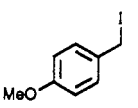
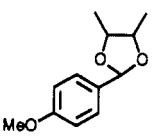
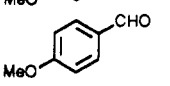
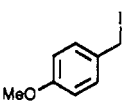
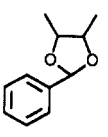
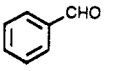
(3) Green, T. W. *Protective Groups in Organic Synthesis*; Wiley: New York, 1981; p 144.
(4) Huet, F.; Lechevalier, M.; Pellet, M.; Conia, J. M. *Synthesis* **1978**, 63.
(5) Lipshutz, B. H.; Harvey, D. F. *Synth. Commun.* **1982**, *12*, 267.
(6) Sterzycki, R. *Synthesis* **1979**, 724.
(7) Denis, J. N.; Krief, A. *Angew. Chem., Int. Ed. Engl.* **1980**, *19*, 1006.
(8) Balme, G.; Gore, J. *J. Org. Chem.* **1983**, *48*, 3336.
(9) Jung, M. E.; Andrus, W. A.; Orenstein, P. L. *Tetrahedron Lett.* **1977**, 4175.
(10) (a) Keyser, G. E.; Bryant, J. D.; Barrio, J. R. *Tetrahedron Lett.* **1979**, 3263. (b) Bryant, J. D.; Keyser, G. E.; Barrio, J. R. *J. Org. Chem.* **1979**, *44*, 3733. (c) Chan, T. H.; Lee, S. D. *Tetrahedron Lett.* **1983**, 1225. (d) Siraeva, I. N.; Chegodaeva, O. F.; Kiladze, T. K.; Musavirov, R. S.; Kantor, E. A.; Paushkin, Y. M. *Dokl. Akad. Nauk SSSR* **1984**, *280*, 896.
(11) Morita, T.; Okamoto, Y.; *Sakurai*, H. *Bull. Chem. Soc. Jpn.* **1981**, *54*, 267.
(12) Greene, T. W., ref 3, pp 116–129.

Table II. Deprotection of Ketals and Acetals[a]

entry	substrate	reagent	mol %	time (min)	products	(yield, %)[b]
1		DIS	10	1		100
2		TMS	120	1		100
3	4	HI	20	1		100
4		DIS	10	1		50 (50)
5	5	DIS	10	3		88 (12)
6		DIS	5	0.5		60 (40)
7		DIS	5	7		64 (36)
8		DIS	10	2		100
9		TMSI	120	1		87 (13)
10	6	TMSI	120	10		96 (4)
11		HI	20	10		34 (66)
12		DIS	10	1		99 (1)
13	7 	DIS	10	1		56 (44)
14	8 	DIS	5	0.5		50 (50)
15		DIS	10	1		86 (14)
16		TMSI	50	30		48 (52)
17	9	TMSI	120	1		79 (21)
18		TMSI	120	10		98 (2)
19		HI	20	10		40 (60)
20		DIS	5	1		53 (47)
21	1	DIS	10	1		100
22		DIS	10	10		20 (80)
23	10 	DIS	10	10		11 (89)
24	11 	DIS	10	10		15 (85)
25	12 	DIS	5	1		100
26	13 	DIS	5	1		100
27	14 	DIS	5	1		100
	15					

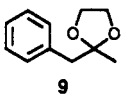
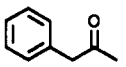
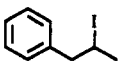
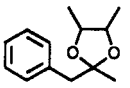
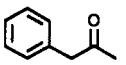
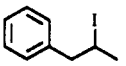
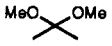
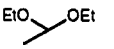
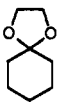
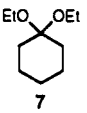
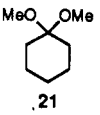
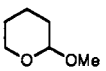
[a] All reactions were carried out at −42 °C (using an acetonitrile/dry ice bath) in NMR tubes. Solutions of DIS (25%) in $CDCl_3$ were added to cold solution of the substrate in $CDCl_3$, mixed well, and then quenched at the same temperature with a saturated solution of $NaHCO_3$ in D_2O. In reaction with TMSI, the reagent was added neat. In reactions with HI, a solution of dry HI in $CDCl_3$ was added. [b] Yields were determined by NMR; percentage of unreacted ketal is given in parentheses.

Table III. Reaction of Aromatic Ketals and Acetals with TMSI and DIS[a]

entry	substrate	SiI (equiv)	time (min)	products	(yield, %)[b]
1	 1	TMSI (3)	50		100
2		DIS (2)	<2		100
3	 10	TMSI (3)	300		60 (40)
4		DIS (2)	9		100
5	 16	TMSI (3)	30		20 (60)
6		DIS (2)	<2		100
7	 17	TMSI (3)	240		42 (58)
8		DIS (2)	<2		100
9	 15	TMSI (3)	4		100
10		DIS (2)	<2		100
11	 18	TMSI (3)	120		80 (15)
12		DIS (2)	<2		100
13	 19	TMSI (3)	30		40 (60)
14		DIS (2)	<2		100

[a] All reactions were carried out at 22 °C in NMR tubes in $CDCl_3$. [b] Percentage of unreacted ketal is given in parentheses.

Table IV. Reaction of Aliphatic Ketals and Acetals with TMSI and DIS[a]

entry	substrate	SiI (equiv)	time	products	(yield, %)[b]
1	 **9**	TMSI (3)	20 min		100
2		DIS (3)	2 h		90
3	 **12**	TMSI (3)	14 h		25 (65)
4		DIS (2)	2 h		95
5	 **4**	TMSI (3)	1 min		100
6		DIS (2)	3 min		100
7		DIS (2)[c]	30 min		100
8	 **5**	DIS (3)	4 h		99
9	 **20**	DIS (2)[c]	30 min	3EtI	100
10	 **8**	DIS (3)	24 h		50
11	 **7**	DIS (3)	3 h		95
12	 **21**	DIS (3)[c]	40 min		90
13		DIS (3)	2 h		100
14	 **22**	DIS (1)	24 h		100
15		DIS (3)	12 h		100

[a] All reactions were carried out at 22 °C in NMR tubes in $CDCl_3$. [b] Percentage of unreacted ketal is given in parentheses. [c] Iodine (25 mol %) was added to the mixture after 10 min.

stable (as with alkoxytrimethylsilane) and/or less nucleophilic (as with secondary alkoxysilanes), they do not form ethers easily. Consequently, stoichiometric amounts of iodosilane reagent would be needed in such cases.

In summary, catalytic amounts (5–10 mol %) of DIS provide clean deprotection of various ketals and acetals to yield the parent carbonyl compounds at low temperatures (−42 °C) and short reaction times (few minutes) with no apparent reduction of the latter.

2. Reduction of Aromatic Ketals and Acetals. Silicon hydrides are capable of transferring hydride to highly electrophilic centers, usually generated in the presence of strong acids. This approach, known as ionic hydrogenation,[15] can be used to reduce carbonyl compounds, or their corresponding ketals, to alcohols, ethers, or carboxylic esters by using combinations of trialkylsilanes with strong protic acids,[16] including trifluoroacetic acid,[17]

(13) Sassaman, M. B.; Prakash, G. K. S.; Olah, G. A. *Tetrahedron* **1988**, *44*, 3771.
(14) Keinan, E.; Sahai, M.; Roth, Z.; Nudelman, A.; Herzig, J. *J. Org. Chem.* **1985**, *50*, 3558.
(15) (a) Kursanov, D. N.; Parnes, Z. N.; Loim, N. M. *Synthesis* **1974**, 633. (b) Colvin, E. W. *Silicon in Organic Synthesis*; R. E. Krieger Publishing Co.: Malabar, FL, 1985; pp 329–331. (c) Weber, W. P. *Silicon Reagents in Organic Synthesis*; Springer-Verlag: New York, 1983; pp 273–287.
(16) Doyle, M. P.; DeBruyn, D. J.; Donnelly, S. J.; Kooistra, D. A.; Odubela, A. A.; West, C. T.; Zonnebelt, S. M. *J. Org. Chem.* **1974**, *39*, 2740.
(17) Loim, N. M.; Parnes, Z. N.; Vassilyeva, S. P.; Kursanov, D. N. *Zhur. Org. Khim.* **1972**, *8*, 896; *Chem. Abstr.* **1972**, *77*, 125841.

Nafion-H,[18] and various Lewis acids.[19]

Of particular interest are the recently described carbonyl reductions using unique mixtures of hydride donors and the Lewis acids, which are both organosilicon compounds. For example, combinations of trialkylsilane with either trimethylsilyl triflate[9,20] or trialkylsilyl iodide[13,21] were used for carbonyl reductions. Similarly, 1-iodo-1,1,3,3-tetramethyldisiloxane, in which the iodosilane functionality is covalently attached to the hydridosilane moiety via a siloxane bridge, was employed for the same purpose.[22]

As was shown in eq 1, DIS effectively reduces ketal 1 to iodoalkane at temperatures above 0 °C, in sharp contrast to the behavior of TMSI. Even at 0 °C, reduction of 1 proceeds at a reasonable rate and reaches completion within 2 h. Although the final reduction product is the corresponding benzylic iodide, steady-state quantities of the symmetrical dibenzyl ether (<10%) are formed but disappear toward the end of the reaction.

This reduction was found to be quite general both with respect to ketals and acetals and unprotected ketones and aldehydes. Reaction rates, however, were strikingly dependent on the substrate, with the following tendencies: (a) aromatic functionalities, which may develop benzylic carbonium intermediates, are generally reduced much faster than their aliphatic analogues; (b) ketals and acetals are rapidly reduced to the corresponding iodoalkanes, while free aldehydes, and particularly ketones, are essentially inert under the reaction conditions (but can be significantly activated by catalytic amouts of iodine); (c) dimethyl ketals form the parent ketones preferentially, while all other ketals, including diethyl ketals and dioxolanes are reduced to iodoalkanes. These features are discussed below.

Aromatic Ketals and Acetals. As was exemplified by 1 (Table I, entries 8 and 9), ketals and acetals derived from aryl ketones and aryl aldehydes are readily reduced by DIS to the corresponding benzylic iodides. Reaction of these substrates with TMSI, however, leads to the parent carbonyl compounds. A general comparison of these complementary reactivities is given in Table III.

DIS reactions are characterized by their remarkably high rates of reduction. Most reactions are complete within less than 2 min at room temperature. Cleavage reactions with TMSI at this temperature are 1 or 2 orders of magnitude slower. Again, as was observed with respect to nonreductive cleavage, DIS appears to be a more reactive and much less sterically demanding reagent than TMSI. This is clearly illustrated by reactions with the more sterically congested ketals derived from butane-2,3-diol (entries 3, 4, 7, 8, and 11–14). These react sluggishly with TMSI, while reductions with DIS proceed almost as rapidly as those with normal ketals.

Aliphatic Ketals and Acetals. The reactions listed in Table IV provide a general view of the reactivity of aliphatic ketals and acetals toward TMSI and DIS. As was observed with the aromatic compounds, the aliphatic substrates are normally deprotected by TMSI and reduced to iodoalkanes by DIS. However, reaction rates here are significantly lower. Moreover, since the initial reduction products, dialkyl ethers,[23] are relatively more stable under the reaction conditions than benzyl ethers,[1] they may be isolated if the reaction is interrupted at partial conversion. Nevertheless, sufficiently long reaction times drive the reaction to completion, providing iodoalkanes as the final products.

As was observed with the aromatic ketals, here also DIS is much less sensitive to steric effects than is TMSI, as may be concluded from the comparison of entries 1 and 3 of Table IV with entries 2 and 4. Again, as observed earlier, cyclic ketals are cleaved somewhat slower than are the acyclic derivatives. For example, the dioxolane derivative of cyclohexanone 8 is cleaved more slowly and in lower yields than is 1,1-diethoxycyclohexane (7) (entries 10 and 11).

An interesting feature of the reaction of DIS with ketals is the reactivity of dimethyl ketals as compared to that of all other ketals, including diethyl and cyclic ketals. For example, 1,1-dimethoxycyclohexane (**21**) is cleaved to cyclohexanone (entry 13), which is stable for several hours under the reaction conditions (unless iodine is added to promote its reduction, entry 12). Conversely, 1,1-diethoxycyclohexane (**7**) is reduced in high yields to iodocyclohexane under the same conditions within 3 h (entry 11). Similarly, 1,1-dimethoxypropane (**4**) is rapidly cleaved to acetone with either DIS or TMSI (entries 5 and 6), which is relatively stable under the reaction conditions unless iodine is added (entry 7). In contrast, the corresponding cyclic ketal **5** is directly reduced to 2-iodopropane (entry 8). These remarkable reactivity differences may be rationalized on the basis of several competing mechanistic pathways (vide infra, Schemes I and II).

Another interesting point is the synthetically useful two-step cleavage of tetrahydropyranyl (THP) derivatives (entries 14 and 15). One equivalent of DIS cleaves 2-methoxy-THP (**22**) to give 2-iodo-THP exclusively, while excess reagent drives the reaction to completion to produce 1,5-diiodopentane.

3. Reduction of Ketones and Aldehydes. Ketones and aldehydes rapidly add TMSI to form the corresponding α-iodo silyl ether, which is easily observed by ^{1}H NMR. This adduct is usually hydrolyzed back to the free carbonyl functionality upon aqueous workup. With a limited number of cases, such as benzaldehyde, the adduct may react further and produce the corresponding *gem*-diiodide.[24] Alternatively, it may react as a strong electrophile in polar reactions, such as Friedel–Crafts alkylation.

With DIS the situation is remarkably different. Aromatic aldehydes are rapidly reduced with DIS to the corresponding benzyl iodides (Table V, entries 1–3), much like their acetal derivatives. Aromatic ketones seem to be much less reactive toward DIS, as acetophenone is incompletely reduced to yield a mixture of 1-iodo-1-phenylethane and 3-methyl-1,3-diphenylpropan-1-one, even after 20 h (entry 4). The latter product probably results from alkylation of acetophenone with 1-iodo-1-phenylethane.

In contrast to the aromatic aldehydes and ketones, the aliphatic compounds are reduced very sluggishly to iodoalkanes. They are essentially inert under conditions that completely reduce their corresponding acetals and ketals. For example, the reduction yield of butanal with DIS to given iodobutane does not exceed 15% within 48 h at room temperature (entry 5). Similarly, reduction of acetone and phenylacetone with DIS under the same conditions gives

(18) Olah, G. A. Yamato, T.; Iyer, P. S.; Prakash, G. K. S. *J. Org. Chem.* **1986**, *51*, 2826.

(19) (a) Doyle, M. P.; West, C. T.; Donnelly, S. J.; McOsker, C. C. *J. Organomet. Chem.* **1976**, *117*, 129. (b) Kato, J.; Iwasawa, N.; Mukaiyama, T. *Chem. Lett.* **1985**, 743.

(20) Tsunoda, T.; Suzuki, M.; Noyori, R. *Tetrahedron Lett.* **1979**, 4679.

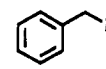
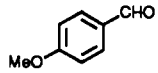
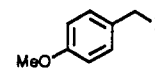
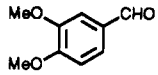
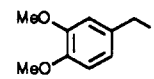
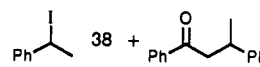
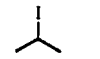
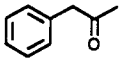
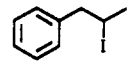
(21) (a) Sassaman, M. B.; Kotian, K. D.; Prakash, G. K. S.; Olah, G. A. *J. Org. Chem.* **1987**, *52*, 4314.

(22) Lecea, B.; Aizpurua, J. M.; Palomo, C. *Tetrahedron* **1985**, *41*, 4657.

(23) More details on this reduction product as well as on the reduction of iodoalkanes into alkanes using DIS will be reported shortly.

(24) Jung, M. E.; Mossman, A. B.; Lyster, M. A. *J. Org. Chem.* **1978**, *43*, 3698.

Table V. Reduction of Aldehydes and Ketones with DIS[a]

entry	substrate	solvent	time	product	(yield, %)
1		CH_2Cl_2	5 min		96
2		CH_2Cl_2	5 min		98
3		$CDCl_3$	30 min		97[b]
4		CCl_4	20 h		50
5		$CDCl_3$	2 h		15
6		$CDCl_3$	2 h		88[b,c]
7		$CDCl_3$	2 h		88[b,c]
8		$CDCl_3$	2 h		87[b-d]
9		$CDCl_3$	48 h		40[e]
10		$CDCl_3$	3 h		100[c]
11		$CDCl_3$	48 h		15[e]
12		$CDCl_3$	4 h		68[c,e]

[a] All reactions were carried out at 22 °C with 150 mol % of DIS. [b] Yield was determined by NMR. [c] Iodine (50 mol %) was added to the mixture before addition of DIS. [d] The same reaction carried out in CH_2Cl_2 afforded the same product in 81% isolated yield. [e] Small amounts of unidentified side products were observed.

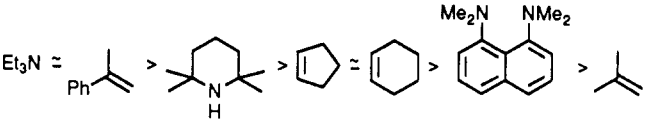
2-iodopropane and 2-iodo-1-phenylpropane in 40% and 15% yields, respectively (entries 9 and 11). In sharp contrast to reduction of the free ketones, the cyclic ketals of acetone and phenylacetone are quantitatively reduced within a few hours under the same conditions (Table IV, entries 2, 4, and 8).

However, the addition of iodine, in even less than stoichiometric amounts, greatly promotes reduction of saturated carbonyl compounds. For example, in the presence of 50 mol % iodine, butanal, hexanal, decanal, acetone, and phenylacetone are reduced within 2–4 h in 88%, 88%, 87%, 100%, and 68% yields, respectively (entries 6–8, 10, and 12).

4. α,β-Unsaturated Carbonyl Compounds. While the above-described saturated substrates are not significantly affected by the presence of hydrogen iodide, with unsaturated compounds this contaminant may lead to undesired side products. Cinnamyl alcohol, for example, reacts rapidly with an excess of either TMSI or DIS in $CDCl_3$ to produce cinnamyl iodide (**23**) and at least 1 equiv of HI (this is in addition to unavoidable traces of HI that are normally present in iodosilane solutions). Thus, the initially formed cinnamyl iodide rapidly adds HI to give the Markovnikov adduct 1-phenyl-1,3-diiodopropane (**24**). To eliminate this problem, we sought to explore the utility of proton scavengers.

A number of proton scavengers, such as amines and olefins, were checked for their effectiveness in removing hydrogen iodide from the reaction mixture. The reaction of cinnamyl alcohol with TMSI in chloroform was used as a probe for this purpose. The following additives were used: triethylamine, α-methylstyrene, 2,2,6,6-tetramethylpiperidine, cyclopentene, cyclohexene, 1,8-bis(dimethylamino)naphthalene (Proton sponge), and isobutylene. Scavenger efficiency was evaluated by the ratio between the two products, **23** and **24**, determined by integration of the appropriate NMR signals.

The same set of experiments was repeated with DIS replacing TMSI, leading to similar ratios between **23** and **24**. However, in contrast to the former reactions, a third product was formed, 1-iodo-1-phenylpropane,[23] whose relative concentration slowly increased at the expense of **23** and **24**. The results of these experiments suggest the following qualitative order of HI removal efficiency:



Although the rather basic amines 2,2,6,6-tetramethylpiperidine and triethylamine are very effective HI scavengers, they both react rapidly with iodosilanes, altering the nature and concentration of this reagent. Thus, employment of the "Proton sponge" produced complex mixtures. Conversely, the various olefins, α-methylstyrene in particular, are much more useful, as they do not react directly with iodosilane. Nevertheless, in the case of α-methylstyrene, the HI addition product 2-phenyl-2-iodopropane is slowly reduced by DIS to yield isopropylbenzene.[25] Cyclohexene and cyclopentene are sufficiently reactive and appear to be the additives of choice. Isobutylene is much less effective, probably due to its high volatility and low solubility at room temperature.

The reactions of three representative substrates, cinnamaldehyde, benzylideneacetone, and cyclopropylmethyl ketone, with either TMSI and DIS are described below.

Cinnamaldehyde. The reactions of cinnamaldehyde with either TMSI or DIS demonstrate nicely the reactivity difference between these two reagents. Aldehydes are known to react reversibly with TMSI to produce the highly electrophylic α-iodosilyl ether, which may participate in a number of processes, including Friedel–Crafts-type reactions.[24] Accordingly, when the reaction of cinnamaldehyde and TMSI in $CDCl_3$ is quenched within a few minutes of its onset, unreacted starting material can be recovered. At longer times, however, complex mixtures of unidentified products are produced. With DIS, the initially formed electrophylic intermediate is rapidly reduced to give cinnamyl iodide (**23**) quantitatively. The

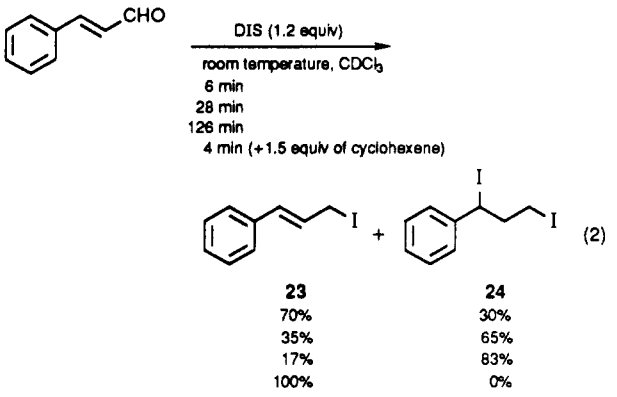
(25) Miller, R. D.; McKean, D. R. *Tetrahedron Lett.* **1979**, 2305.

Table VI. Reaction of Benzylideneacetone with TMSI and DIS[a]

entry	SiI (mol %)	cyclohexene (mol %)	time (min)	products (yield, %)[b] 25	26	27
1	TMSI (50)		8	48[c]	0	0
2	TMSI (50)	50	220	39[c]	0	0
3	TMSI (400)		3	100[d]	0	0
4	TMSI (400)		220	100[d]	0	0
5	TMSI (400)	400	8	67[c]	0	0
6	DIS (50)		4	74	26	0
7	DIS (50)		50	64	36	0
8	DIS (50)	50	76	60	40	0
9	DIS (200)		45	47	33	20
10	DIS (200)		5[e]	84	12	4
11	DIS (200)		5[f]	100	0	0

[a] All reactions were carried out in $CDCl_3$ at 22 °C unless otherwise indicated. [b] Yields were determined by NMR. [c] The rest of the mixture is unreacted benzylideneacetone. [d] Small quantities of unidentified side products, not II or III, were observed. [e] The reaction mixture was kept at 50 °C for 3 min and then at 22 °C for 2 min. [f] The reaction mixture was kept at −20 °C for 3 min and then at 22 °C for 2 min.

latter may add HI to give **24**, as is the case with cinnamyl alcohol. However, in the presence of cyclohexene, formation of **24** is totally inhibited, as shown in eq 2.



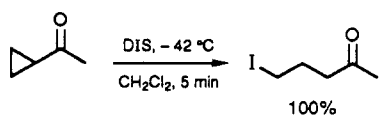
(2)

Benzylideneacetone. TMSI is known to react with α,β-unsaturated ketones to give the corresponding β-iodo ketone.[25] Table VI compares the relative reactivity of TMSI and DIS in this reaction.

1,4-Addition to produce the β-iodo ketone **25** is the only observed reaction of benzylideneacetone with TMSI, and this adduct is stable for long periods under the reaction conditions (entries 1–5). At short reaction times and temperatures below 0 °C DIS also produces **25** cleanly (entry 11). It appears that with both reagents **25** does not arise from HI addition to the enone system, as the reaction is independent of the presence or absence of a good proton scavenger, such as cyclohexene (entries 1, 2, 4, 5, 7, and 8).

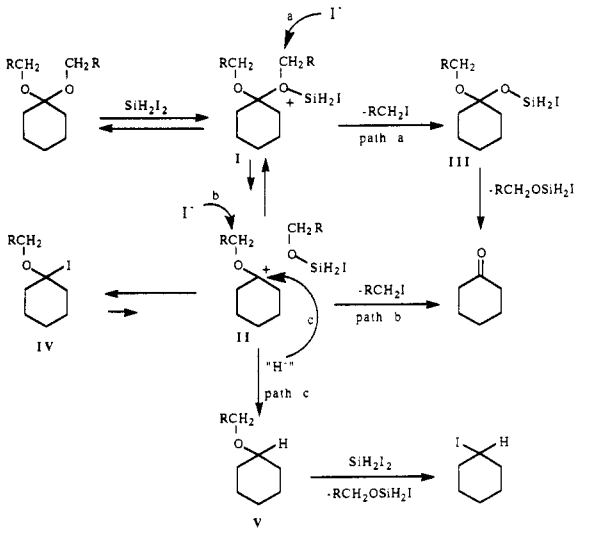
With DIS, however, the initial addition product may be reduced to the saturated ketone, benzylacetone (**26**).[23] Moreover, the latter may be further reduced to give 3-iodo-1-phenylbutane (**27**). These two reduction processes are dependent on the relative concentration of DIS, reaction time, and temperature. Since carbonyl reduction is slower than conjugate reduction, the reaction may be stopped with a relatively high proportion of saturated ketone. Obviously, with excess reagent, sufficient time, and added iodine, reduction proceeds to give **27** as the main product.

Cyclopropyl Methyl Ketone. The reactivity of cyclopropyl ketones toward TMSI is reminiscent of that of α,β-unsaturated ketone, yielding γ-iodo ketones by cleavage of the cyclopropyl rings.[25,26] This synthetically useful transformation is typically carried out at temperatures between −20 and +25 °C for approximately 2 h, followed by hydrolytic workup. We found that the same reaction, when carried out with DIS, is completed within less than 5 min at −42 °C, yielding 5-iodopentan-2-one (eq 3).

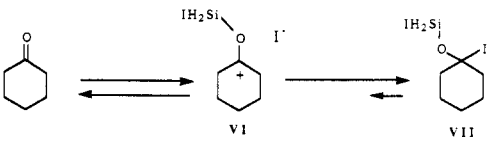


(3)

Scheme I



Scheme II



5. Mechanistic Considerations. A most remarkable phenomenon observed in the above-described experiments is the reactivity difference between the group of ketals and acetals on the one hand and their corresponding ketones and aldehydes on the other. The former are reduced to iodoalkanes much faster than the latter. Similar phenomena of such unusual chemoselectivity, with ketals serving as activating groups rather than protecting func-

(26) Miller, R. D.; McKean, D. R. *J. Org. Chem.* **1981**, *46*, 2412.

tions, have been observed in the condensation of enol silyl ethers with ketals and ketones using either trimethylsilyl triflate (TMSOTf)[33] or dibutyltin bis(triflate) as catalysts.[34] An attempted rationalization of this unusual situation is outlined in Schemes I and II. An effective complexation of the strong Lewis acid DIS to one of the ketal's oxygen atoms may engender a highly electrophilic intermediate. It may be envisioned as either a stabilized oxonium ion (structure I) or a stabilized carbonium ion (II) or, most probably, an equilibrium mixture of the two. These intermediates may undergo various nucleophilic attacks (paths a–c). An S_N2-type attack by an iodide ion at carbon would lead to the parent ketone. This may occur directly with II (path b) or indirectly, from I by path a to silyl ether III, which may decompose to the free ketone. Alternatively, reversible nucleophilic attack of iodide at the carbonyl carbon of II would form the well-documented α-iodo ether[10a-c,27] IV, which seems to be quite stable under the reaction conditions. In principle, IV may react further with iodosilane to give the *gem*-diiodo derivative, as was reported for benzaldehyde and TMSI.[24] The reaction, however, does not seem to operate with other carbonyl compounds, particularly with ketones. Nucleophilic transfer of hydride to either I or carbonium ion II (path c) would result in irreversible formation of the ether V, an obvious precursor of the observed iodoalkane product.

In order to explain the poor tendency of ketones to be reduced under these conditions, one should consider the coordination of DIS to the ketone oxygen. This should produce an electrophilic intermediate VI in analogy to the formation of I and II from the corresponding ketals (Scheme II). Carbonium ion VI is expected to be less stable than the oxonium ion I or the mixture of I and II. It is therefore expected that formation of the α-iodo ether VII would be much less reversible than formation of IV; carbonyl reduction would thus be inhibited. This situation is very common with TMSI, which produces stable adducts with ketones and aldehydes. The intermediacy of carbonium ions II and VI in reduction is supported by the fact that all aromatic substrates, including aldehydes, ketones, acetals and ketals, are readily reduced to the corresponding iodoalkanes, as all of them produce relatively stable benzylic carbonium ions.

The S_N2 nature of paths a and b may explain the major reactivity difference between dimethyl and diethyl ketals (R = H and CH_3, respectively, in Scheme I). With dimethyl ketals, direct substitution (paths a and b) dominates. With diethyl and with cyclic ketals, direct substitution is less important, and the actual products arise from the reduction pathway c. Paths a and b lead to the parent ketone, which is reduced very sluggishly under the reaction conditions. Path c leads directly to iodoalkane from the ketal.

In principle, hydrogen may be transferred to the electrophilic carbon in the form of either a hydride anion or a hydrogen radical. While the former involves a polar mechanism, the latter occurs via a radical chain process. In order to verify this point and clarify the role of iodine in ketone reduction, we carried out a number of NMR experiments.

Reduction of phenylacetone with DIS in $CDCl_3$ was followed by ^1H NMR. Only sluggish formation of 2-iodo-1-phenylpropane (14% yield) was observed, even after 48 h at room temperature. Interestingly, the two absorptions of phenylacetone at 2.16 (3 H) and 3.70 (2 H) were essentially unaffected by the presence of either DIS or iodine, although iodine is known to complex with ketones to produce minor downfield shifts in the ^1H NMR spectrum.[28] Nevertheless, in the presence of 0.5 equiv of iodine, a significant rate increase was observed, with the yield of 2-iodo-1-phenylpropane reaching 60% within 6 h. This iodine-promoted reduction was unaffected by addition of a potent radical scavenger such as *m*-dinitrobenzene (DNB),[29] as reduction of phenylacetone with DIS in the presence of iodine and DNB reached 55% yield within 6 h. Apparently, iodine promotes polar addition of hydride to the carbonyl carbon rather than radical chain reduction.

Similar effects were observed with solutions of acetone and DIS (100 mol %) in $CDCl_3$. Four compounds were observed 10 min after mixing: acetone, 2-iodo-2-siloxypropane, 2-iodopropane, and diisopropyl ether in a 63:27:5:5 ratio, respectively. This composition, which was confirmed by a ^{13}C NMR spectrum, was changed slowly within 80 min into a ratio of 38:38:12:12, respectively.

Reactions carried out with both DIS and iodine (10 mol %) proceeded much faster, leading, within 10 min, to a mixture of the above-mentioned four compounds in a ratio of 7:82:10:1, respectively. This composition, which was confirmed by a ^{13}C NMR spectrum, changed to 15:23:62:<1 after 90 min. Interestingly, a significant line broadening of the ^1H signal at 2.31 ppm, assigned to 2-iodo-2-siloxypropane ($W_{1/2}$ = 6.5 Hz) was observed. This phenomenon could be related to a possible equilibrium dissociation of the adduct into an ion pair.

One possible explanation for the effect of iodine is that it facilitates formation of a highly polarized complex, such as VI in Scheme II. The iodide counteranion of VI may react with iodine to form an I_3^- anion, which is more stable than I^-. This may increase the ionic character as well as the electrophilicity of VI.

Conclusion

In this paper we have demonstrated the applicability of DIS with respect to ketal, acetal, ketone, and aldehyde chemistry and shown that the reagent may be used for mild cleavage of ketals and acetals either hydrolytically to give the parent carbonyl functionality or reductively to produce the corresponding alkyl iodide. Reactions with DIS are simple and conveniently performed, as all silicon compounds, including excess reagent, form insoluble polymers upon aqueous workup and are easily removed by filtration.

DIS cleaves ketals to the parent ketone faster than does TMSI or HI. At low temperatures (−42 °C) and short reaction times (few minutes), catalytic amounts (5–10 mol %) of DIS provide clean deprotection of various ketals and acetals to yield ketones and aldehydes, with no apparent reduction of the latter. At temperatures above 0 °C, DIS effectively reduces ketals and acetals to iodoalkanes in sharp contrast to the behavior of TMSI. This reduction is quite general both with respect to ketals and acetals and unprotected ketones and aldehydes. Reaction rates, however, are strikingly dependent on the substrate, with the following tendencies: (a) aromatic functionalities are generally reduced much faster than their aliphatic analogues; (b) ketals and acetals are rapidly reduced to the corresponding iodoalkanes, while free aldehydes, and particularly ketones, are essentially inert under the reac-

(27) (a) Jung, M. E.; Mazurek, M. A.; Lim, R. M. *Synthesis* **1978**, 588. (b) Muchmore, D. C.; Dahlquist, F. W. *Biochem. Biophys. Res. Commun.* **1979**, *86*, 599.

(28) (a) Fratiel A. *J. Chem. Phys.* **1964**, *41*, 2204. (b) Wobschall, D.; Norton, D. A. *J. Am. Chem. Soc.* **1965**, *87*, 3559. (c) Singh, R. A. *Can. J. Chem.* **1986**, *64*, 2371.

(29) Tanner, D. D.; Gilberto, E. E.; Potter, A. *J. Org. Chem.* **1985**, *50*, 2149.

tion conditions (but can be significantly activated by catalytic amounts of iodine); (c) dimethyl ketals form the parent ketones preferentially, while all other ketals, including diethyl ketals and dioxolanes, are reduced to iodoalkanes.

An attempted rationalization of these findings is based on an effective complexation of the strong Lewis acid DIS to the substrate, producing a highly electrophilic intermediate that may undergo various nucleophilic attacks. Further applications of DIS as a useful synthetic reagent are currently being investigated in our laboratories and will be published shortly.

Experimental Section

Infrared spectra were measured on the neat compounds with an FT infrared Nicolet MX-1 spectrometer. ^1H NMR spectra were measured in deuteriochloroform on a Bruker AM-400 or Bruker AC-E200 NMR spectrometer. GC-MS analyses were carried out on a Finnigan 4500 spectrometer. Thin layer chromatography (TLC) was performed on aluminum sheets precoated with silica gel (Merck, kieselgel 60, F-254, Art. 5549). Column chromatography separations were performed on silica gel (Merck, kieselgel 60, 230–400 mesh, Art. 9385) under pressure of 0.4 atm (flash chromatography). GC analyses were performed on either a Varian 3300 or a Spectra Physics 7100 (FI detector) gas chromatograph equipped with a 0.125 in. × 4 ft column packed with 5% OV-101 on Chromosorb W. Preparative GC separations were carried out with a Varian Aerograph 90P (TC detector) equipped with either a $^1/_2$ in. × 20 ft column packed with 10% Carbowax 20M on Chromosorb W or a $^3/_8$ in. × 20 ft column packed with 10% SE-30 on Chromosorb W. Distilations were usually performed with a Büchi Kugelrohr apparatus and the temperatures given are pot temperatures. Tetrahydrofuran, benzene, and toluene were distilled over sodium benzophenone ketyl. Phenylsilane was prepared by reduction of trichlorophenylsilane with $LiAlH_4$ in dry ether.[30] DIS was prepared from phenylsilane and iodine, as described earlier.[1] TMSI was prepared according to the literature.[31]

Substrates. All cyclic acetals and ketals were prepared from the corresponding aldehydes and ketones and the appropriate glycol with catalytic amounts of *p*-toluenesulfonic acid by azeotropic distillation of benzene. 2,2-Dimethoxypropane and 1,1-diethoxyethane were purchased from Fluka. 1,1-Diethoxycyclohexane was prepared from cyclohexanone and triethylorthoformate. 1,1-Dimethoxycyclohexane was prepared from cyclohexanone and methanol with catalytic amounts of *p*-toluenesulfonic acid. 2-Methoxytetrahydropyran was similarly prepared from dihydropyran and methanol under acidic conditions. All substrates were purified by distillation before use.

Hydrolysis of Ketal 1 with DIS. Ketal 1 (625 mg, 2.58 mmol) was dissolved in $CHCl_3$ (25 mL) and cooled under a nitrogen atmosphere to −42 °C (acetonitrile–dry ice bath). DIS (73 mg, 0.26 mmol) was added and the mixture was stirred at the same temperature for 1 min. A saturated aqueous solution of $NaHCO_3$ (1 mL) was added with vigorous stirring and the mixture was allowed to warm up to room temperature. The organic layer was separated and washed with a saturated solution of sodium thiosulfate (5 mL) and dried over $MgSO_4$ and the solvent was removed under reduced pressure. The residue was further purified by being passed through a short silica gel column (15 cm) with CH_2Cl_2. The solvent was removed under reduced pressure, affording *p*-bromoacetophenone (510 mg, 99%).

Reactions of Acetal 15 with DIS and TMSI. A. Hydrolysis with DIS. Acetal 15 (750 mg, 4.17 mmol) was reacted with DIS (59 mg, 0.21 mmol) according to the above-described procedure, affording *p*-methoxybenzaldehyde (557 mg, 98%).

B. Reduction with DIS. Acetal 15 (850 mg, 4.72 mmol) was dissolved in CH_2Cl_2 (50 mL) under a nitrogen atmosphere at room temperature. DIS (2.69 g, 9.47 mmol) was added slowly over 5 min and the mixture was stirred for an additional 2 min. A saturated aqueous solution of $NaHCO_3$ (10 mL) was added and the mixture was vigorously stirred for 5 min. The organic layer was separated and washed with a saturated solution of sodium thiosulfate (20 mL) and dried over $MgSO_4$ and the solvent was removed under reduced pressure. The residue was further purified by being passed through a short silica gel column (15 cm) with CH_2Cl_2. The solvent was removed under reduced pressure, affording *p*-methoxybenzyl iodide (1.136 g, 97%).

C. Hydrolysis with TMSI. An experiment similar to the one described above was carried out with acetal 15 (362 mg, 2.01 mmol) and TMSI (6 mmol) instead of DIS. The reaction mixture was worked up as described above, affording *p*-methoxybenzaldehyde (268 mg, 99%).

Reduction of Ketal 9 with DIS. Ketal 9 (36 mg, 0.2 mmol) was dissolved in $CDCl_3$ (0.5 mL) and cooled to −42 °C. DIS (140 mg, 0.6 mmol) was added, and the mixture was warmed to room temperature and placed in the NMR probe. After 2 h at room temperature the mixture was comprised of phenylacetone (10%) and 2-iodo-1-phenylpropane (90%). ^1H NMR: 1.95 (d, J = 6.8 Hz, 3 H), 3.06 (dd, J = 6.7, 14.6 Hz, 1 H), 3.29 (dd, J = 6.7, 14.6 Hz, 1 H), 4.35 (sextet, J = 6.8 Hz, 1 H), 7.23 (m, 5 H).

Reaction of 2,2-Dimethoxypropane (4) with DIS and TMSI. A. With DIS. DIS (93.6 mg, 0.4 mmol) was added to a cooled NMR tube containing a solution of 2,2-dimethoxypropane (20.9 mg, 0.2 mmol) in $CDCl_3$ (0.5 mL). An NMR spectrum, taken after 3 min at room temperature, showed complete and clean conversion into acetone and methyl iodide. No reduction of the ketone to 2-iodopropane was noticed even after 4 h at room temperature. Iodine (12 mg, 0.05 mmol) was then added to this reaction mixture. Approximately 30 min later, complete conversion of the acetone into 2-iodopropane was observed.

B. With TMSI. A similar experiment was carried out as described above with TMSI being employed instead of DIS. Quantitative formation of acetone was observed.

Reaction of 5 with DIS. DIS (85.3 mg, 0.6 mmol) was added to a cooled solution of 5 (20 mg, 0.2 mmol) in $CDCl_3$ (0.5 mL). The first NMR spectrum, taken after 2 min at room temperature, showed total disappearance of the starting ketal and slow formation of 2-iodopropane. The reduction was complete after 4 h.

Reaction of 1,1-Diethoxyethane (20) with DIS. A. DIS (57 mg, 0.2 mmol) was added to a cooled NMR tube containing a solution of 1,1-diethoxyethane (12 mg, 0.1 mmol) in $CDCl_3$ (0.5 mL). An NMR spectrum, taken after 3 min at room temperature showed quantitative formation of 1-iodo-1-ethoxyethane. (The original absorptions of 1,1-diethoxyethane [1.35 d, J = 6.8 Hz, 3 H), 1.21 (t, J = 6.6 Hz, 6 H), 3.51 (q, J = 6.6 Hz, 2 H), 3.68 (q, J = 6.6 Hz, 2 H), 4.70 (q, J = 6.8 Hz, 1 H)] were replaced by the following: 2.30 (d, J = 7 Hz, 3 H), 6.28 (q, J = 7 Hz, 1 H). No further change in the spectrum was noticed even after 4 h at room temperature.

B. An experiment similar to the one described above was carried out with the exception that iodine (13 mg, 0.05 mmol) was added to the mixture 10 min after the addition of DIS. ^1H NMR spectrum recorded after 30 min at room temperature showed complete conversion to ethyl iodide.

Reaction of 1,1-Dimethoxycyclohexane (21) with DIS. A. DIS (170 mg, 0.6 mmol) was added to a cooled NMR tube containing a solution of 1,1-dimethoxycyclohexane (28.9 mg, 0.2 mmol) in $CDCl_3$ (0.5 mL). An NMR spectrum, taken after 3 min at room temperature, showed complete and clean conversion into cyclohexanone and methyl iodide. No reduction of the ketone to iodocyclohexane was noticed even after 2 h at room temperature. Iodine (12.8 mg, 0.05 mmol) was then added to this reaction mixture. Approximately 15 min later, complete conversion of the cyclohexanone into iodocyclohexane was observed.

B. An experiment similar to the one described above was carried out with the exception that iodine (25.5 mg, 0.1 mmol) was added to the mixture before the addition of DIS (57 mg, 0.2 mmol). An ^1H NMR spectrum recorded after 15 min at room temperature showed complete conversion of the cyclohexanone into iodocyclohexane.

Reaction of 2-Methoxytetrahydropyran (22) with DIS. A. DIS (56.5 mg, 0.2 mmol) was added to a cooled NMR tube containing a solution of 2-methoxytetrahydropyran (23 mg, 0.2 mmol)

(30) Harvey, M. C.; Nebergall, W. H.; Peake, J. S. *J. Am. Chem. Soc.* **1957**, *79*, 1437.

(31) (a) Seitz, D. E.; Frreira, L. *Synth. Commun.* **1979**, *9*, 931. (b) Sakurai, H.; Shirahata, A.; Sasaki, K.; Hosomi, A. *Synthesis* **1979**, 740.

in $CDCl_3$ (0.5 mL). An NMR spectrum, taken after 24 h at room temperature, showed quantitative conversion into methyl iodide and 2-iodotetrahydropyran. ^1H NMR of the latter: 4.75 (br, s, 1 H), 3.88 (br, d, J = 6.6 Hz, 1 H), 3.65 (br, t, J = 10 Hz, 1 H), 2.0 (m, 6 H).

B. An experiment similar to the one described above was carried out with the exception that 3 equiv of DIS (0.6 mmol) were employed. An ^1H NMR spectrum recorded after 12 h at room temperature showed complete conversion into 1,5-diiodopentane. NMR: 3.16 (t, J = 6.5 Hz, 4 H), 1.8 (quintet, J = 6.5 Hz, 4 H); 1.5 (quintet, J = 6.5 Hz, 2 H).

Reaction of 1,1-Diethoxycyclohexane (7) with DIS. DIS (170 mg, 0.6 mmol) was added to a cooled NMR tube containing a solution of 1,1-dimethoxycyclohexane (29 mg, 0.2 mmol) in $CDCl_3$ (0.5 mL). An NMR spectrum, taken after 10 min at room temperature, showed partial conversion into iodocyclohexane. Although no iodine was added, complete conversion into iodocyclohexane was observed within 3 h.

Reduction of Aldehydes to Iodoalkanes. A. Benzaldehyde. DIS (420 mg, 1.5 mmol) was added to a solution of benzaldehyde (106.2 mg, 1 mmol) in CH_2Cl_2 (5 mL). The mixture was stirred for 5 min at room temperature and then quenched with a 10% aqueous solution of $NaHCO_3$ (0.5 mL) and 10% aqueous $Na_2S_2O_3$ (0.5 mL), diluted with CH_2Cl_2 (20 mL), and washed with water. The organic phase was separated, the solvent was removed under reduced pressure, and the residue was filtered through a short silica gel column with CH_2Cl_2. Removal of the solvent afforded benzyl iodide (210 mg, 96%).

B. Anisaldehyde. An experiment similar to the one described above was carried out with DIS (840 mg, 3 mmol) and *p*-methoxybenzaldehyde (273 mg, 2 mmol), affording *p*-methoxybenzyl iodide (488 mg, 98%). NMR: 7.15 (d, J = 8.5 Hz, 2 H), 6.82 (d, J = 8.5 Hz, 2 H), 4.44 (s, 2 H), 3.81 (s, 3 H).

C. Hexanal. DIS (700 mg, 2.5 mmol) was added to a stirred solution of hexanal (200 mg, 2 mmol) and iodine (254 mg, 1 mmol) in CH_2Cl_2 (10 mL) and the mixture was stirred for 2 h at room temperature. The usual workup with aqueous bicarbonate and thiosulfate afforded 1-iodohexane (340.4 mg, 80.3%).

An attempt to reduce hexanal without iodine was carried out with DIS (700 mg, 2.5 mmol) and hexanal (200 mg, 2 mmol) in CH_2Cl_2 (10 mL). The mixture was stirred at room temperature for 20 h with no observable product. Aqueous workup followed by distillation afforded pure, unreacted hexanal (184 mg, 92%).

Another experiments was carried out in an NMR tube with DIS (0.15 mmol), hexanal (0.1 mmol), and $CDCl_3$ (0.4 mL). The first NMR spectrum taken within 3 min indicated quantitative addition of DIS to the aldehyde to give α-iodo silyl ether [6.15 (t, J = 7.0 Hz, 1 H)]. No further change in the spectrum was observed even after 20 h at room temperature. Addition of iodine (0.05 mmol) to the mixture resulted in immediate conversion into 1-iodohexane (87% yield).

Reaction of DIS with Acetophenone. DIS (840 mg, 3 mmol) was added to a stirred solution of acetophenone (250 mg, 2.08 mmol) in CCl_4 (20 mL) and stirred at room temperature until TLC indicated total disappearance of starting material (20 h). The mixture was worked up in the usual way, affording two products. Chromatographic separation afforded 1-iodo-1-phenylethane (179.6 mg, 38%) and 1,3-diphenylbutan-1-one (222 mg, 50%). NMR: 7.3 (m, 10 H), 6.52 (m, 1 H), 3.32 (dd, J = 14.6, 6.5 Hz, 1 H), 3.21 (dd, J = 14.6, 6.5 Hz, 1 H). MS (m/e, rel intensity): 224 (M^+, 6), 209 ($M - CH_3$, 9), 120 (11), 119 (2), 105 (100), 91 (14), 78 (13), 77 (81).

Evaluation of Proton Scavenger Efficiency. Cinnamyl alcohol (13.5 mg, 0.1 mmol) was dissolved in 0.5 mL of $CDCl_3$ (freshly dried over basic alumina) in a 5-mm NMR tube together with the appropriate proton scavenger at 22 °C. Either DIS (34 mg, 0.12 mmol) or TMSI (60 mg, 0.3 mmol) was added and the reaction was monitored by ^1H NMR. The starting alcohol disappeared within less than 4 min and two major products were observed: cinnamyl iodide (**23**) (NMR: 7.31 (m, 5 H), 6.61 (d, J = 16.6 Hz, 1 H), 6.42 (quintet, J = 8.3 Hz, 1 H), 4.11 (d, J = 8 Hz, 2 H) and 1,3-diiodo-1-phenylpropane (**24**) (NMR: 7.33 (m, 5 H), 5.23 (t, J = 7.5 Hz, 1 H), 2.78 (sextet, J = 7.2 Hz, 1 H), 2.46 (sextet, J = 7.2 Hz, 1 H), 3.16 (t, J = 6.8 Hz, 2 H). Product ratios were calculated from the integral ratio of the signals at 4.11 and 5.23 ppm. The proton scavenging efficiency was evaluated on the basis of the ratio between **23** and **24**.

The following were observed with TMSI (scavenger, ratio of **23**:**24**): triethylamine, 99:1; α-methylstyrene, 100:0; 2,2,6,6-tetramethyl-piperidine, 99:1; cyclohexene, 91:9; cyclopentene, 92:8; 1,8-bis(dimethylamino)naphthalene, 72:28; isobutylene, 45:55; none, 38:62. These ratios were found to be independent of time within 3 h.

The same set of experiments was repeated with DIS instead of TMSI, leading to similar ratios between **23** and **24**. However, in contrast to the reactions with TMSI, a third product was formed here, 1-iodo-1-phenylpropane (NMR: 7.5 (m, 5 H), 5.05 (t, J = 7.6 Hz, 1 H), 2.36 (sepstet, J = 7.4 Hz, 1 H), 2.06 (sepstet, J = 7.4 Hz, 1 H), 0.95 (t, J = 7.2 Hz, 3 H), whose relative concentration was slowly increased at the expense of **23** and **24**.

Reaction of Cinnamaldehyde with DIS and with TMSI. A. DIS (34 mg, 0.12 mmol) was added to an NMR tube containing cinnamaldehyde (13 mg, 0.1 mmol) and $CDCl_3$ (0.5 mL). The first NMR spectrum taken after 6 min at room temperature indicated quantitative conversion of the substrate into cinnamyl iodide (**23**) (70%) and 1,3-diiodo-1-phenylpropane (**24**) (30%). The relative concentration of these two products was calculated from the integral ratio of the signals at 4.11 and 5.23 ppm, respectively.

B. An experiment similar to the one described above was carried out with the exception that cyclohexene (12 mg, 0.15 mmol) was added to the mixture before the addition of DIS. ^1H NMR spectrum recorded after 4 min at room temperature showed quantitative formation of cinnamyl iodide.

C. An experiment similar to the one described in **A** was carried out with the exception that TMSI (60 mg, 0.3 mmol) was employed instead of DIS. The NMR spectrum recorded after 10 min at room temperature indicated complete disappearance of the substrate with concomitant formation of a complex mixture of unidentified products.

Reaction of Benzylideneacetone with DIS and TMSI (Table VI). In a typical experiment, DIS (14 mg, 0.05 mmol) was added to an NMR tube containing benzylideneacetone (15 mg, 0.1 mmol) and $CDCl_3$ (0.5 mL). The reaction was monitored by NMR at 22 °C. Two products were observed: 1-iodo-1-phenylbutan-3-one (**25**) [7.30 (m, 5 H), 5.55 (dd, J = 6.3, 8.5 Hz, 1 H), 3.62 (dd, J = 8.5, 17.6 Hz, 1 H), 3.36 (dd, J = 6.3, 17.6 Hz, 1 H), 2.12 (s, 3 H)] and 1-phenylbutan-3-one (**26**) [7.25 (m, 5 H), 2.89 (m, 2 H), 2.80 (m, 2 H), 2.19 (s, 3 H)] (Table VI, entries 6–8). The relative concentrations of these two products were calculated from the integral ratio of the signals at 2.12 and 2.19 ppm, respectively. In experiments where cyclohexene was employed, it was added to the mixture before the addition of DIS. In two experiments where DIS was added in larger proportions (57 mg, 0.2 mmol), the NMR spectrum showed the appearance of a third product, 3-iodo-1-phenylbutane (**27**) [7.25 (m, 5 H), 4.38 (m, 1 H), 2.85 (quintet, J = 6.8 Hz, 2 H), 2.70 (quintet, J = 6.8 Hz, 2 H), 1.95 (d, J = 6.8 Hz, 3 H)]. For example, the ratio of the three products **26**:**27**:**28** (47:33:20) in entry 10 was determined on the basis of the NMR absorptions at 2.12, 2.19, and 1.95 ppm, respectively.

Reaction of Cyclopropyl Methyl Ketone with DIS. DIS (633 mg, 2.3 mmol) was added to a cold (−42 °C) solution of cyclopropyl methyl ketone (193 mg, 2.3 mmol) in CH_2Cl_2 (10 mL). The mixture was stirred at the same temperature for 5 min and then quenched with 5 mL of 10% aqueous sodium thiosulfate. The mixture was worked up with CH_2Cl_2 and water and dried over $MgSO_4$, the solvent was removed under reduced pressure, and the residue was passed through a short silica gel column (10 cm) with CH_2Cl_2. Removal of the solvent yielded 5-iodopenta-2-one (485 mg 99.5%). NMR ($CDCl_3$): 2.05 (quintet, J = 6.8 Hz, 2 H), 2.12 (s, 3 H), 2.55 (t, J = 7.0 Hz, 2 H), 3.19 (t, J = 6.5 Hz, 2 H).[26]

NMR Study of the Reaction between Phenylacetone and DIS. A. Without Additives. DIS (28 mg, 0.1 mmol) was added to a solution of phenylacetone (13.4 mg, 0.1 mmol) in $CDCl_3$ (0.4 mL). An ^1H NMR spectrum recorded after 48 h at room temperature showed partial reduction (14% yield) to 2-iodo-1-phenylpropane.[32] ^1H NMR: 1.90 (d, J = 6.8 Hz, 3 H), 3.05 (dd,

(32) Laurent, A.; Laurent, E.; Tardivel, R. *Tetrahedron* **1974**, *30*, 3429.
(33) Murata, S.; Suzuki, M.; Noyori, R. *Tetrahedron* **1988**, *44*, 4259.
(34) Sato, T.; Otera, J.; Nozaki, H. *J. Am. Chem. Soc.* **1990**, *112*, 901.

J = 16.2, 8.0 Hz, 1 H), 3.28 (dd, J = 16.2, 8.0 Hz, 1 H), 4.31 (m, 1 H), 7.26 (m, 5 H.

B. With Iodine. An experiment similar to the one described above was carried out with the exception that iodine (12.5 mg, 0.05 mmol) was added to the mixture before the addition of DIS. An ^{1}H NMR spectrum recorded after 6 h at room temperature showed phenylacetone (2.16 and 3.70 ppm), 2-iodo-2-siloxy-1-phenylpropane (2.37 and 4.05 ppm), and 2-iodo-1-phenylpropane in a ratio of 18:22:60, respectively. It should be noted that the absorptions assigned to phenylacetone were unaffected by the presence of iodine.

C. With Iodine and *m*-Dintrobenzene. An experiment similar to the one described in **B** was carried out with the exception that *m*-dinitrobenzene (1.7 mg, 0.01 mmol) was added to the mixture after addition of iodine and before addition of DIS. An ^{1}H NMR spectrum recorded after 6 h at room temperature showed a mixture of the above-mentioned three compounds in a ratio of 24:21:55, respectively.

NMR Study of the Reaction between Acetone and DIS. A. DIS (300 mg, 1.03 mmol) was added to a solution of acetone (60 mg, 1.03 mmol) in $CDCl_3$ (0.4 mL). An ^{1}H NMR spectrum recorded after 10 min at room temperature showed acetone (s, 2.18 ppm), 2-iodo-2-siloxypropane (s, 2.31 ppm), 2-iodopropane (1.88, 4.35 ppm), and diisopropyl ether (1.19, 3.75 ppm) in a 63:27:5:5 ratio, respectively, as well as traces of 2-siloxypropane. Another ^{1}H NMR spectrum recorded 80 min later indicated the presence of the same four compounds in a ratio of 38:38:12:12, respectively. This composition was confirmed by a ^{13}C NMR spectrum (30.5 and 206.5; 37.8 and 60.7; 31.1 and 21.6; 22.7 and 66.2 ppm, respectively) that was recorded within 80 min (between the two ^{1}H NMR measurements).

Iodine (26 mg, 10 mol %) was then added to the NMR tube and the first ^{1}H NMR spectrum was recorded 5 min later. The above-mentioned components, acetone, 2-iodo-2-siloxypropane, 2-iodopropane, and diisopropyl ether, were observed in a ratio of 1:70:19:10, respectively. This situation was confirmed by a ^{13}C NMR spectrum that was recorded over 100 min (between 5 and 105 min after the addition of iodine). A second ^{1}H NMR spectrum recorded at 105 min from addition of iodine showed the above-mentioned four compounds in a 6:25:68:1 ratio, respectively. Another change observed in the second ^{1}H NMR spectrum was a significant line broadening of the signal at 2.31 ppm, assigned to 2-iodo-2-siloxypropane ($W_{1/2}$ = 6.5 Hz relative to 1 Hz of other signals).

B. An experiment similar to the one described above was carried out with the exception that iodine (10 mol %) was added to the mixture before DIS. An ^{1}H NMR spectrum recorded after 10 min at room temperature showed acetone, 2-iodo-2-siloxypropane, 2-iodopropane, and diisopropyl ether in a ratio of 7:82:10:1, respectively. This situation was confirmed by ^{13}C NMR, recorded over 80 min (between 10 and 90 min after the addition). Another ^{1}H NMR spectrum recorded at 90 min from addition indicated the presence of the above-mentioned four compounds in a ratio of 15:23:62:<1, respectively. Again, a significant line broadening of the signal at 2.31 ppm, ($W_{1/2}$ = 5 Hz) was observed in the second ^{1}H NMR spectrum.

Acknowledgment. D.P. thanks the postdoctoral fellowship program of the Consent Nacional de Investigaciones Cientificas y Tecnicas de la Rupublica Argentina for their generous financial support. M.S. is grateful to the Banaras Hindu University for his study leave.

Registry No. 1, 4360-68-3; 2, 99-90-1; 3, 125763-63-5; 4, 77-76-9; 5, 2916-31-6; 6, 4405-16-7; 7, 1670-47-9; 8, 177-10-6; 9, 4362-18-9; 10, 125763-64-6; 11, 79449-69-7; 12, 5406-60-0; 13, 24856-58-4; 14, 10602-01-4; 15, 2403-50-1; 16, 4359-49-3; 17, 100847-13-0; 18, 5420-89-3; 19, 4359-31-3; 20, 105-57-7; 21, 933-40-4; 22, 6581-66-4; 23, 62606-31-9; 24, 125763-65-7; 25, 125763-66-8; 26, 13760-02-6; 27, 16029-98-4; MeCOMe, 67-64-1; i-PrCOCH$_3$, 563-80-4; PhCH$_2$COCH$_3$, 103-79-7; p-BrC$_6$H$_4$CHO, 1122-91-4; p-MeOC$_6$H$_4$CHO, 123-11-5; HI, 10034-85-2; PhCOCH$_2$CH$_3$, 93-55-0; PhCHICH$_2$CH$_3$, 4119-41-9; p-MeOC$_6$H$_4$CH$_2$I, 70887-29-5; PhCHO, 100-52-7; PhCH$_2$I, 620-05-3; PhCH$_2$CHICH$_3$, 29527-87-5; CH$_3$CHICH$_3$, 75-30-9; EtI, 75-03-6; I(CH$_2$)$_5$I, 628-77-3; PhCOCH$_3$, 1334-78-7; H$_3$C(CH$_2$)$_2$CHO, 123-72-8; H$_3$C(CH$_2$)$_4$CHO, 66-25-1; H$_3$C(CH$_2$)$_8$CHO, 112-31-2; PhCHICH$_3$, 10604-60-1; PhCOCH$_2$CH(CH$_3$)Ph, 1533-20-6; H$_3$C(CH$_2$)$_3$I, 542-69-8; H$_3$C(CH$_2$)$_5$I, 638-45-9; H$_3$C(CH$_2$)$_9$I, 2050-77-3; H$_3$CCOCH=CHPh, 122-57-6; PhCH=CHCH$_2$OH, 104-54-1; PhCH=CHCHO, 104-55-2; ICH$_2$CH$_2$CH$_2$COCH$_3$, 3695-29-2; cyclohexanone, 108-94-1; iodocyclohexane, 626-62-0; 2-iodotetrahydrofuran, 7429-25-6; 3,4-dimethoxybenzaldehyde, 120-14-9; 3,4-dimethoxybenzyl iodide, 76950-76-0; cyclopropyl methyl ketone, 765-43-5.

Electrochemical Oxidation of Polycyclic Cyclopropanes and Camphene.[1] Novel Synthesis of *exo*-5,5-Dimethyl-6-methylenebicyclo[2.2.1]heptan-2-ol (Nojigiku Alcohol)

Toshikazu Uchida,[†] Yoshiharu Matsubara,[†] Ikuzo Nishiguchi,*[,2] Tsuneaki Hirashima, Takashi Ohnishi,[‡] and Koichi Kanehira[‡]

Osaka Municipal Technical Research Institute, 1-6-50, Morinomiya, Jyoto-ku, Osaka 536, Japan, Department of Applied Chemistry, Faculty Science and Engineering, Kinki University, Kowakae, Higashi-Osaka, Osaka 537, Japan, and Central Research Laboratory, Kuraray Co. Ltd., Sakazu, Kurashiki, Okayama 710, Japan

Received April 10, 1989

Anodic oxidation of tricyclene (**1a**) in acetic acid containing triethylamine, followed by hydrolysis, provides a facile and efficient synthesis of *exo*-5,5-dimethyl-6-methylenebicyclo[2.2.1]heptan-2-ol (**2a**), named "nojigiku alcohol", which was isolated from the essential oil of *chrysanthemum japonese*. Furthermore, a method for large-scale production of **2a** starting from the readily available impure starting tricyclene (**1a**) has been developed by appropriate selection of reaction conditions. Similar electrooxidation of the related naturally occurring polycyclic methylcyclopropanes, cyclofenchene (**1b**) and longicyclene (**1c**), followed by hydrolysis also brought about stereo- and regioselective cleavage of carbon–carbon bonds of the cyclopropane rings to give the corresponding homoallylic alcohols **2b,c** in good yields.

exo-5,5-Dimethyl-6-methylenebicyclo[2.2.1]heptan-2-ol (**2a**) was isolated by Matsubara and co-workers[3] from the essential oil of *chrysanthemum japonese* in 1974 and was called "nojigiku alcohol". This alcohol was shown to be

[†] Kinki University.
[‡] Kuraray Co. Ltd.

(1) A part of this work was reported in a preliminary communication, see: Matsubara, Y.; Uchida, T.; Ohnishi, T.; Kanehira, K.; Fujita, Y.; Hirashima, T.; Nishiguchi, I. *Tetrahedron Lett.* **1985**, 4513.

0022-3263/90/1955-2938$02.50/0