Highly Efficient Deacetylation by Use of the Neutral Organotin Catalyst $[t\mathrm{Bu_2SnOH(Cl)}]_2$

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Abstract: Deprotection of acetyl esters is effected cleanly by the neutral organotin catalyst, $[t\mathrm{Bu_2SnOH(Cl)}]_2$. The mildness of the reaction gives rise to great synthetic versatility and in the process a variety of functional groups are tolerated. Differentiations between primary, secondary, and tertiary alcohols and between acetyl ester and other esters are feasible. No racemization occurs with chiral acetyl esters. Exclusive deprotection of primary acetyl esters in carbohydrates and nucleosides is observed. The crude product thus obtained can be used for further reactions without purification.

Keywords: acidity · catalysts · organometallic compounds · protecting groups · tin

Introduction

The acetyl ester plays an important role for protection of the hydroxyl group in organic synthesis.[1] Consequently, numerous methodologies have so far been put forth for the acetylation of alcohols. In striking contrast, the deprotection of the acetyl esters is much less studied despite its practical significance in synthetic processes. It should be carried out under mild conditions to suppress racemization as well as decomposition of coexisting functions. Alkaline hydrolysis is most commonly employed, yet a number of functional groups are not tolerated in this procedure. Transesterification serves considerably well to this end.[2] However, this protocol also requires the use of acidic or basic catalysts in most cases. Thus, if the transesterification is feasible under milder conditions, it would be of great synthetic promise.

Previously, we disclosed that 1,3-disubstituted tetraalkyldistannoxane catalysts effected smooth transesterification simply by heating the reaction mixture of the esters in alcohol.[3] The reaction proceeds under nearly neutral conditions thus allowing various acid- and base-sensitive functions to survive. The catalytic activity of the distannoxane originates from a template effect induced by unique dimeric formulation.[4] In this context, we expected the high efficiency for cationic organotin hydroxide dimers that we had encountered recently.[5] Surprisingly, however, we have found that a neutral counterpart is more active than the cationic species. We report herein the mild and efficient deacetylation of acetyl esters under the catalysis of the neutral organotin dimer.[6]

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Results and Discussion

A variety of organotin clusters shown below were screened in this study. Dinuclear clusters **1**–**4** have a hydroxy bridge in common but are different in the bonding mode of the anionic ligands. Both **1**[7] and **2**[5] are neutral due to the covalent bonding of the chlorine atom and nitrate group although the tin atoms in the former is five-coordinate while six-coordinate in the latter due to chelation by the nitrate group. The triflate **3**[5] is neutral with six-coordinate tin atoms in the solid state although it does undergo dissociation into a cationic species with five-coordinate tin in solution. The *tert*-butyl derivative **4**[5] has a cationic formulation both in the solid state and in solution. Tetranuclear distannoxane **5**[4, 8] is non-ionic whereas Sn_{12} cluster **6**[9] has a dicationic formulation.

The catalytic activity of various organotin compounds together with conventional Lewis acids was assessed for deprotection of 2-phenylethyl acetate (**7**) with methanol (see Table 1), the results of which are summarized in Table 1. Notably, **1** exhibited a greater activity than the others. A quantitative yield of the alcohol was obtained after 3.5 h with 5 mol% of **1** (entry 1) while distannoxane **5** afforded only a 6% yield under the same reaction conditions (entry 2). It was necessary to keep the reaction mixture under refluxing temperature for 9 h in order to achieve a quantitative yield with this catalyst (entry 3). The neutral mono-nuclear compounds Bu_2SnCl_2, $BuSnCl_3$, and $Bu_2Sn(OAc)_2$ were less active (29%, 21% and 22% yields, respectively, after 24 h: en-

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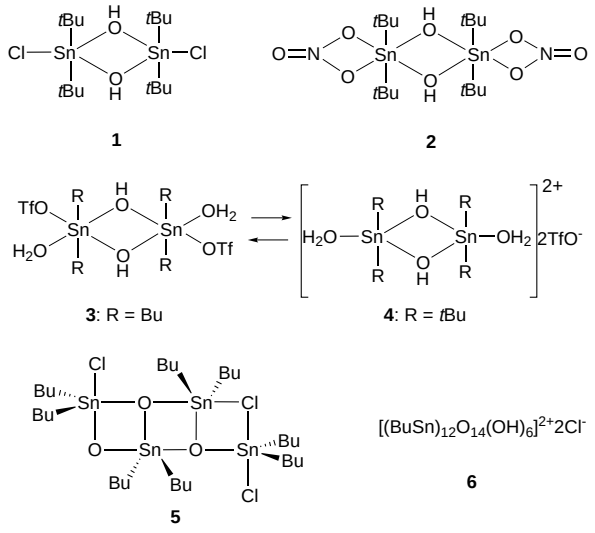
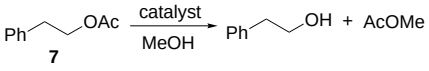


tries 4–6). The dimeric nitrate **2** was also found to be less active than **1** (entries 7 and 8), probably because the bidentate nitrate ligand retarded the interaction between the substrate and the tin center. Other neutral di- or polynuclear organotin oxides and hydroxide also failed to give satisfactory yields under the same conditions (entries 9–11).[10] We had supposed that the cationic triflates, **3** and **4**, are more active than **1** because of their increased acidity. To our surprise, however, these triflates were found to be much less active (entries 12–14), and, moreover, the Sn_{12} dication **6** exhibited virtually no activity as well (entry 15); this is indicative of a mechanism for which the Lewis acidity is not necessarily of primary importance. Consistent with these results, even stronger Lewis acids were not as effective; various metal triflates failed to afford quantitative yields after 3.5 h (entries 16, 17, 19, 21-23) and, thus, a prolonged reaction time or higher catalyst loading was required for satisfactory yields (entries 18, 20 and 24).[11] Both $BF_3 \cdot OEt_2$ and TfOH were virtually inactive (entries 25 and 26). Apparently, **1** is unique because no such high catalytic activity is attained with other organotin derivatives as well as other Lewis acid compounds with polynuclear structures or stronger acidity.

The deacetylation can be run in the presence of co-solvent (Table 2). A variety of solvents are employable (entries 2–6), yet polar ones such as CH_3CN, acetone, and water suppressed the reaction (entries 7–9). Ethanol can be used as well instead of methanol although the reactivity is somewhat lower (entry 10). The yield was decreased with allyl and isopropyl alcohols and no reaction was observed with 2,2,2-trihalo ethanols (entries 11–14).

Then, we investigated deacetylation of various acetyl groups under catalysis of **1** (Table 3). The acetyl groups from primary alcohols were deprotected smoothly (entries 1–3). The catalyst concentration could be reduced to a 1 mol% level though a prolonged reaction time was required (entry 1). As expected, acid-sensitive substrates were converted to the parent alcohols without decomposition (entries 4–10). Notably geranyl acetate **10** did not undergo smooth deacetylation under standard conditions (entry 4); however, the use of THF as a co-solvent at 40 °C successfully effected the deacetylation

Table 1. Screening of catalysts for deacetylation of 2-phenylethyl acetate.[a]



7

	Catalyst	Reaction time [h]	Yield [%][b]	Starting Material [%][b,c]
1	**1**	3.5	97	2
2	**5**	3.5	6	85
3	**5**	9[d]	96	3
4	Bu_2SnCl_2	24	29	62
5	$BuSnCl_3$	24	21	
6	$Bu_2Sn(OAc)_2$	24	22	72
7	**2**	24	82	
8	**2**	6.5[d]	91	
9	Bu_2SnO	24	10	85
10	$(Bu_3Sn)_2O$	24	0	97
11[e]	$(Me_3SnOH)_2$	3.5	0	89
12	**3**	3.5	29	52
13	**4**	3.5	29	63
14	**4**	7.5[d]	98	
15	**6**	24	3	92
16	$Sc(OTf)_3$	3.5	40	57
17[e]	$Sc(OTf)_3$	3.5	53	41
18	$Sc(OTf)_3$	24	95	2
19	$Bi(OTf)_3$	3.5	54	40
20	$Bi(OTf)_3$	24	91	1
21[e]	KOTf	3.5	0	92
22	TMSOTf	3.5	46	50
23[e]	TMSOTf	3.5	67	28
24[e]	TMSOTf	24	94	0
25[e]	$BF_3 \cdot OEt_2$	24	58	33
26[e]	TfOH	24	2	

[a] Reaction conditions: catalyst (5.0 mol%); 2-phenylethyl acetate (1.0 mmol); methanol (5.0 mL), 30 °C. [b] Determined by GC. [c] Starting material recovered. [d] Under reflux. [e] Catalyst concentration: 10.0 mol%.

Table 2. Deacetylation of **7** catalyzed by **1** in various alcohols and co-solvents.[a]

	Alcohol	Co-solvent	Reaction time [h]	Yield [%][b]	Starting Material [%][b,c]
1	MeOH	none	19[d]	93	5
2	MeOH	THF	3.5	92	6
3	MeOH	Et_2O	3.5	95	2
4	MeOH	DME	3.5	97	2
5	MeOH	hexane	3.5	93	5
6	MeOH	toluene	3.5	93	6
7	MeOH	CH_3CN	3.5	69	29
8	MeOH	acetone	3.5	47	46
9	MeOH	H_2O	3.5[e]	62	33
10	EtOH	none	20	96	0
11	allyl alcohol	none	24	88	12
12	$(CH_3)_2CHOH$	none	24	73	0
13	CF_3CH_2OH	none	72	0	94
14	CCl_3CH_2OH	none	72	0	94

[a] Reaction conditions: **1** (5.0 mol%); acetyl ester (1.0 mmol); alcohol (5.0 mL); co-solvent (5.0 mL); 30 °C. [b] Determined by GC. [c] Starting material recovered. [d] Catalyst concentration: 1.0 mol%. [e] MeOH (10 mL) and H_2O (100 μL) were added.

(entry 5). A unique chemoselectivity was exemplified by selective deacetylation of a substrate with an ester group, as for example the methyl ester group stayed intact (entry 11). However, this outcome involved transesterification of the original methyl ester with solvent methanol as is evident from

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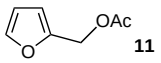
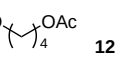
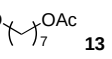
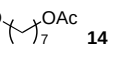
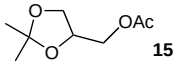
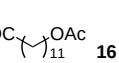
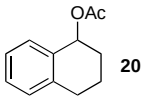
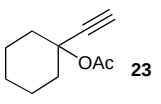
the result of Equation (1), where the ethyl ester was partially converted to the methyl ester under the same conditions.

$$EtOOC(CH_2)_{11}OAc \xrightarrow[\text{MeOH/THF, 0 °C, 20 h}]{\textbf{1}\ (5\ \text{mol \%})} \underset{21\ \%}{EtOOC(CH_2)_{11}OH} + \underset{60\ \%}{MeOOC(CH_2)_{11}OH} \quad (1)$$

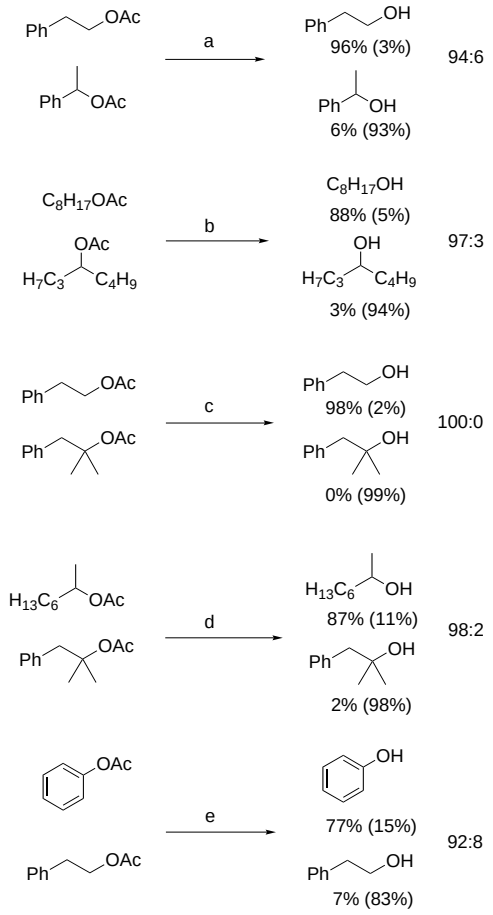
Acetyl groups from secondary alcohols were less reactive and higher reaction temperatures were needed for quantitative yields (entries 12–20). When the acetyl ester of 8-pentadecanol (**19**) was subjected to the reaction, only a 32% yield of the alcohol was recovered even at 50°C (entry 16). The refluxing conditions increased the yield to some degree but the concomitant elimination was also accelerated (entry 17). However, the yield was dramatically improved by adding a trace amount of water (entry 18). Acetyl groups from the tertiary alcohols **21** and **22** were resistant towards this reaction, and elimination occurred under more harsh conditions (entries 21–23). However, a tertiary propargylic acetate **23** was successfully deprotected (entry 24). Finally, phenol was smoothly recovered from phenyl acetate (**24**) (entry 25).

Table 3. Deacetylation catalyzed by **1**.[a]

	Substrate	Reation conditions [°C/h]	Yield [%][b]
1	$PhCH_2CH_2OAc$ (**7**)	30/19[c]	93
2	$PhCH_2OAc$ (**8**)	30/4.5	93[d]
3	$C_8H_{17}OAc$ (**9**)	30/6	93
4	geranyl acetate (**10**)	30/24	86
5		40/24[e]	97
6	 **11**	30/24	82
7	 **12**	30/4	93
8	 **13**	30/5	92
9	 **14**	30/9[c]	91
10	 **15**	30/6	97
11	 **16**	30/16.5	100
12	PhCH(Me)OAc (**17**)	30/24	50
13	$C_6H_{13}CH(Me)OAc$ (**18**)	30/24	38
14		50/24	91
15	$(C_7H_{15})_2CHOAc$ (**19**)	30/24	12
16		50/24	32
17		reflux/24	72
18		reflux/48[f]	97
19	 **20**	30/24	25
20		reflux/12	95
21	$PhCH_2C(Me)_2OAc$ (**21**)	reflux/24	22
22	$C_9H_{19}C(Me)_2OAc$ (**22**)	50/24	3
23		reflux/24	21
24	 **23**	reflux/24[g]	86
25	phenyl acetate (**24**)	0/0.5	92

[a] Reaction conditions: **1** (5.0 mol%); acetyl ester (1.0 mmol); MeOH (5.0 mL). [b] Determined by GC. [c] Catalyst concentration: 1.0 mol%. [d] Isolated yield. [e] THF (5 mL) was added. [f] H_2O (5 μL) was added, and **1** (10 mol%) was used. [g] Catalyst concentration: 10 mol%.

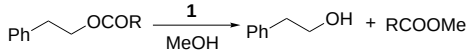
With these results at hand, we conducted competition reactions which led to a variety of synthetically useful differentiations (Scheme 1). Acetyl groups from primary alcohols were preferentially or exclusively deprotected in the presence of a secondary or tertiary alcohol derivative. The high selectivity for an acetyl group from a secondary alcohol was also attained in competition with a tertiary alcohol counterpart. In addition, phenyl acetate was predominantly deprotected over 2-phenylethyl acetate.



Scheme 1. Competitive deacetylation of acetyl esters (0.5 mmol each): The yield was determined by GC. The percentage of unreacted starting materials is given in parentheses; a) **1** (0.025 mmol), MeOH (5 mL), THF (5 mL), 0°C, 30 h; b) **1** (0.025 mmol), MeOH (5 mL), 30°C, 5 h; c) **1** (0.025 mmol), MeOH (5 mL), 30°C, 4.5 h; d) **1** (0.05 mmol), MeOH (2.5 mL), THF (2.5 mL), 50°C, 48 h; e) **1** (0.05 mmol), MeOH (2.5 mL), CH_3CN (2.5 mL), 0°C, 1 h.

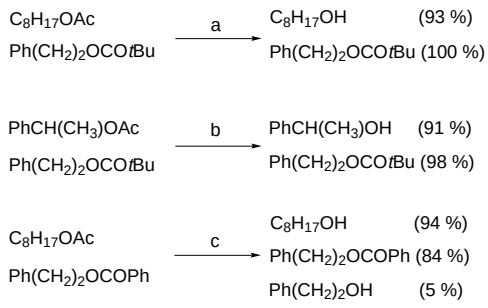
The applicability of the present protocol to other esters was also investigated (Table 4). The propionate **25** and acrylate **26** underwent deprotection to some extent while the isobutyrate **27**, pivalate **28**, and benzoate **29** were virtually inert. Accordingly, the acetyl group could be discriminated from these esters (Scheme 2). The acetyl groups from the primary alcohol were deprotected in the presence of 2-phenylethyl pivalate which survived completely. The corresponding benzoate

Table 4. Deprotection of various 2-phenylethyl esters.[a]



	R	Time [h]	Yield [%][b]
1	C_2H_5 (**25**)	3.5	65
2	CH_2=CH (**26**)	16	78
3	$(CH_3)_2CH$ (**27**)	24	16
4	$(CH_3)_3C$ (**28**)	24	0
5	C_6H_5 (**29**)	24	15

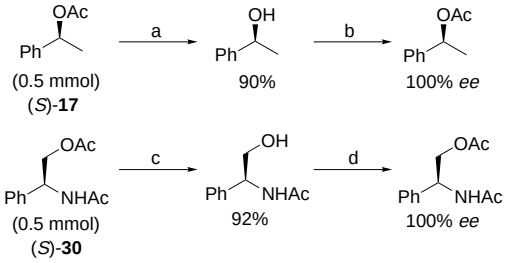
[a] Reaction conditions: **1** (5.0 mol%); 2-phenylethyl ester (1.0 mmol); methanol (5.0 mL); 30°C. [b] Determined by GC.



Scheme 2. Discriminative deacetylation of primary acetyl ester: The yield was determined by GC; a) **1** (0.05 mmol), MeOH, 30°C, 6 h; b) **1** (0.05 mmol), MeOH, reflux, 24 h; c) **1** (0.05 mmol), MeOH, 30°C, 24 h.

slightly suffered deprotection in competition with octyl acetate.[12]

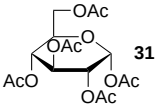
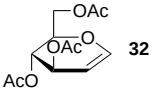
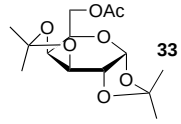
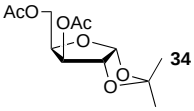
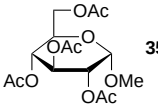
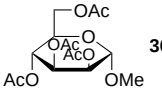
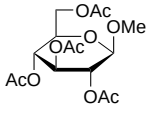
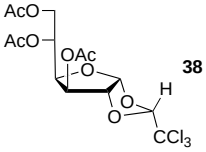
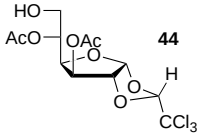
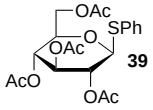
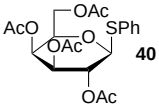
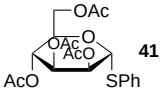
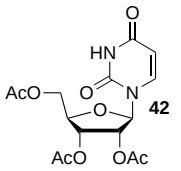
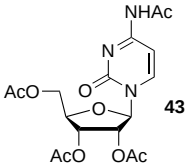
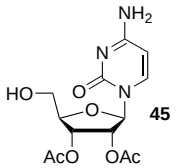
The mildness of the present protocol was also exemplified by the deacetylation of chiral acetyl esters (*S*)-**17** and (*S*)-**30** of secondary alcohols and amino alcohols. No racemization was observed in the product alcohols (Scheme 3).



Scheme 3. Deacetylation of chiral acetyl esters: a) **1** (0.025 mmol), MeOH (2.5 mL), reflux, 24 h; b) 1) Ac_2O/pyridine; 2) HPLC analysis (Daicel chiral OD column, *i*PrOH/hexanes 10%, flow rate 1.0 mL min^{-1}); c) **1** (0.025 mmol), MeOH (2.5 mL), THF (2.5 mL), 30°C, 5.5 h; d) 1) Ac_2O/pyridine; 2) HPLC analysis (Daicel chiral AD column, *i*PrOH/Hex 10%, flow rate 1.0 mL min^{-1}).

One of the most crucial demands for the acetyl group protection lies in the carbohydrate chemistry.[13] Table 5 shows the usefulness of our method for selective cleavage of the primary acetyl ester. α-D-Glucose pentaacetate **31** underwent deprotection exclusively at the 6-position (entry 1). This is quite unique in that only the primary acetyl ester could be cleaved leaving the secondary acetyl groups intact.[14] Moreover, the anomeric acetyl group is usually cleaved in the presence of secondary acetyl groups,[15] and no reaction took place at the anomeric position in the present protocol. It

Table 5. Selective deprotection of the primary acetyl ester in various carbohydrates and nucleosides.[a]

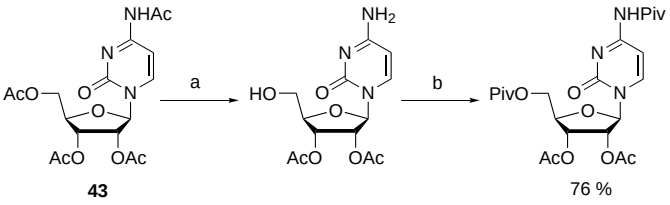
	Substrate	Reaction [°C/h]	Yield [%][b]	Product[c]
1	 **31**	30/4	88	
2	 **32**	0/24	81	
3	 **33**	30/24[d]	96	
4	 **34**	0/24	55	
5	 **35**	20/7	82	
6	 **36**	0/20[d]	88	
7	 **37**	0/24	44	
8	 **38**	0/18	47	 **44**
9	 **39**	30/3	86	
10	 **40**	30/4	91	
11	 **41**	30/2[d]	85	
12	 **42**	30/24[d]	89	
13	 **43**	0/24	77	 **45**

[a] Reaction conditions: **1** (5.0 mol%); acetyl ester (1.0 mmol); MeOH (5.0 mL); THF (5.0 mL). [b] Isolated yield of the product with the primary hydroxyl group. [d] Without THF.

0947-6539/01/0715-3324 $ 17.50+.50/0 *Chem. Eur. J.* **2001**, *7*, No. 15

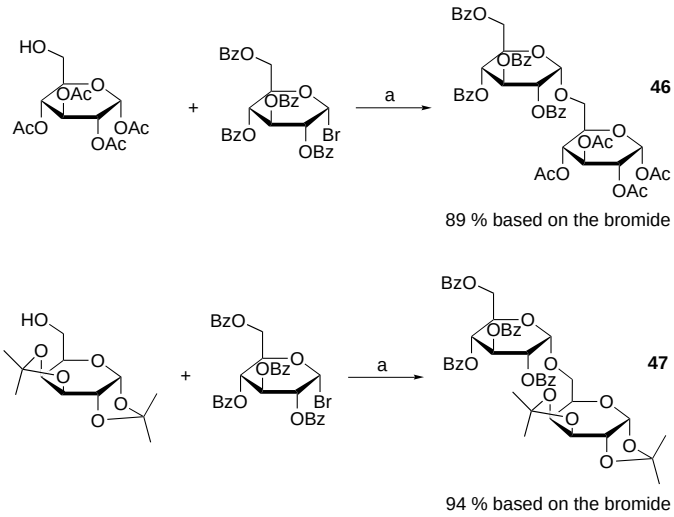
should be noted, however, that no clean outcome was obtained with β-D-glucose pentaacetate; this is probably due to the interaction between the acetyl groups at the anomeric center and 6-positions. Tri-*O*-acetyl-D-glucal **32** was somewhat labile under the same conditions but in this case a satisfactory yield was attained by lowering the reaction temperature to 0 °C (entry 2). The acetonide in **33** was completely inert (entry 3), yet a D-xylofuranose derivative **34** gave rise to a lower yield (entry 4). The substitution of the anomeric acetyl group of α-D-glucose or mannose pentaacetate with methoxy group **35** and **36** showed no influence (entries 5 and 6). Notably, the corresponding β-methoxy derivative **37**, in contrast to the pentaacetate, was deprotected, though the yield was modest, probably because of suppression of the acetyl transfer (entry 7). The unique selectivity is highlighted in entry 8 where solely the primary acetyl ester is cleaved. The problem at the anomeric position was completely overcome by use of chemically stable thiosugars. Thus, the 1-phenylthio derivatives of glucose, galactose, and mannose **39**–**41** underwent smooth deprotection of the primary acetyl ester even for the β-isomers (entries 9–11). No epimerization was detected in all cases. Finally, it was revealed that nucleosides could be successfully employed resulting in exclusive deprotection of the primary acetyl ester for example in tri-*O*-acetyluridine **42** (entry 12). With tetraacetylcytidine **43**, both the primary and *N*-acetyl groups were cleaved leaving the secondary ones intact (entry 13).

Since the above deacetylation is so clean that the product could be used for further reaction without purification. Such advantage was exemplified in two cases. The first example is the facile preparation of cytidine with two different protective groups in a selective manner (Scheme 4). Tetraacetylcytidine **43** was deacetylated as already described and the solvents were evaporated after filtration through a thin pad of silica gel. Treatment of the residue directly with pivaloyl chloride in pyridine afforded cytidine with primary and *N*-pivaloyl groups together with the secondary acetyl groups in 76% overall yield.



Scheme 4. Deacetylation of tetraacetylcytidine followed by pivalation: a) **1** (5 mol%), MeOH/THF, 30 °C, 24 h; b) *t*BuCOCl, pyridine, RT, 24 h.

The second example is the glycosylation with the crude deacetylated products (Scheme 5). The crude glucose and galactose products as obtained above were, upon exposure to tetra-*O*-benzoate-α-D-glucopyranosyl bromide in the presence of AgOTf,[16] efficiently converted to dissacharides **46** and **47**. The respective carbohydrate units are installed by completely different protecting groups. The catalyst utilized in the deacetylation could be separated by a simple filtration through a thin pad of silica gel.



Scheme 5. Glycosylation using crude deacetylated donor (obtained from 1.3 mmol fully protected monosaccharide) and 1.0 mmol bromide): a) AgOTf (1.3 mmol), tetramethylurea (2.0 mmol), 3 Å MS, CH_2Cl_2, RT, 18 h.

Finally, it should be noted that the simple operation has another advantage of the present protocols. The catalyst **1** is stable in the air and thus inert atmosphere is not necessary. Thus, the reaction is carried out for example in the following fashion: The methanol solution of an acetyl ester is stirred at an ambient temperature or 30 °C in the presence of a catalytic amount of **1**. Upon the completion of the reaction, the solvent is evaporated and the residue is purified by distillation or column chromatography. The catalyst remains in the reaction flask or on the silica gel. Thus, no aqueous workup was required.

In conclusion, **1** has proven to be a highly efficient catalyst for the deprotection of acetyl esters despite its virtually neutral character. On the basis of the unique examples disclosed in this study, the catalyst will find a wide spectrum of synthetic applications.

Experimental Section

General methods: All reactions of deacylation were carried out in the air, unless otherwise noted. MeOH and EtOH was distilled from the corresponding magnesium alkoxide, and kept under molecular sieves (4 Å MS). Allyl alcohol, $(CH_3)_2CHOH$, CF_3CH_2OH, and CCl_3CH_2OH were used without any further removal of residual moisture. Tetrahydrofuran (THF) and Et_2O were distilled from sodium/benzophenone. Dimethoxyethane (DME), toluene, CH_3CN, and acetone were distilled from CaH_2. NMR spectra were recorded at 25 °C on Varian Gemini-300, JEOL Lambda 300 and JEOL Lambda 500 instruments and calibrated with tetramethylsilane (TMS) as an internal reference. Mass spectra were recorded on a Jeol MStation JMS-700 spectrometer. GC analysis was performed on Shimadzu GC17A attached with CBP1 and CBP5 capillary columns. HPLC analysis was performed on Shimadzu LC-10AS and SPD-10A UV detector attached with Daicel chiral OD or AD column. Elemental analyses were performed by the Perkin–Elmer PE 2400. Silica gel (Daiso gel IR-60) was used for column chromatography. All the tin clusters were prepared according to the literature methods: **1**,[7] **2**,[5] **3**,[5] **4**,[5] **5**[4, 8] and **6**.[9] Bu_2SnCl_2, $BuSnCl_3$, Bu_2SnO, $(Bu_3Sn)_2O$, $(Me_3SnOH)_2$, $Sc(OTf)_3$, KOTf, TMSOTf, $BF_3 \cdot OEt_2$, and TfOH were commercially available. $Bu_2Sn(OTf)_2$[17] and $Bi(OTf)_3$[18] were prepared according to the

literature methods. α-D-Glucopyranosyl bromide tetrabenzoate was commercially available.

Preparation of the acetyl esters: Acetyl esters **7**–**24** were prepared by acetylation of the corresponding alcohol using Ac_2O/pyridine. The starting alcohols to acetyl esters **7**–**11**, **17**, **18**, **21**, **23**, and **24** were commercially available. Acetyl esters **12**, **13**, and **15** were prepared from mono-*tert*-butyldimethylsilyl-protected butanediol[19] and heptanediol,[20] and acetonide-protected propandiol,[21] respectively. Acetyl ester **14** was accessible by acetylation of THP-protected heptanediol.[22] Acetyl ester **16** was prepared by acetylation of methyl 12-hydroxydodecanoate[23] which was obtained by methyl esterification of 12-hydroxyl acid utilizing trimethylsilyldiazomethane in MeOH. Ethyl 12-acetoxydodecanoate[24] was prepared by acetylation of 12-hydroxyl ester which was derived from hydroxyl acid by treatments of $SOCl_2$ and ethanol. Acetyl esters **19** and **20** were prepared by acetylation of pentadecan-8-ol[25] and 1,2,3,4-tetrahydronaphthol[26] derived by the $LiAlH_4$ reduction of 8-pentadecanone and 1-tetralone. Acetyl esters **22** was prepared by acetylation of 2-methyl-2-undecanol[27] which was obtained by the treatment of 2-undecanone with MeMgBr. 2-Phenylethyl esters **25**–**29** were obtained by the reaction of 2-phenylethanol with the corresponding acid chloride, respectively, in pyridine in the presence of dimethylaminopyridine (DMAP). Optically active acetyl esters (*S*)-**17** and (*S*)-**30** were prepared by acetylation of commercially available (*S*)-1-phenylethanol and (*S*)-2-phenylglycinol with Ac_2O in pyridine. Polyacetyl esters such as **31**, **32** and **36** were commercially available. Other acetyl esters such as **33**–**35**, **37**, **38**, **42**, and **43** were prepared by acetylation of the corresponding commercially available pyranose, furanose, and nucleoside with Ac_2O in pyridine. 1-Phenylthio-D-glucopyranoside such as **39**, **40**, and **41** were prepared from the corresponding pyranose pentaacetate according to the procedure reported before.[28]

Deacetylation of 2-phenylethyl acetate (7) (Representative procedure): 2-Phenylethyl acetate (**7**; 82.1 mg, 0.5 mmol), **1** (14.3 mg, 0.025 mmol) and methanol (5 mL) were added to a round-bottomed flask, and the mixture was stirred at 30 °C for 3.5 h. After addition of AcOEt, the reaction mixture was filtered through a thin pad of silica gel, and GC analysis showed the formation of 2-phenylethanol in 97% yield. All the alcohols produced by deacetylation in Table 3 are commercially available or reported before. See the Section of preparation of acetyl esters described above.

Deacetylation of ethyl 12-acetoxydodecanoate with MeOH [Eq. (1)]: Ethyl 12-acetoxydodecanoate (286.4 mg, 1.0 mmol), **1** (28.6 mg, 0.05 mmol), methanol (5 mL), and THF (5 mL) were added to a round-bottomed flask, and the mixture was stirred at 0 °C for 20 h. After addition of AcOEt, the reaction mixture was filtered through a thin pad of silica gel, and GC analysis showed the formations of ethyl and methyl 12-hydroxydodecanoate in 21% and 60% yield, respectively.

Competitive deacetylation of 2-phenylethyl acetate (7) and (1*S*)-phenylethyl acetate (17) (Representative procedure): Acetate **7** (82.1 mg, 5.0 mmol), **17** (82.1 mg, 0.5 mmol), **1** (14.3 mg, 0.025 mmol), THF (5 mL), and methanol (5 mL) were added to a round-bottomed flask. Then, the mixture was stirred at 0 °C for 30 h. After addition of AcOEt, the reaction mixture was filtered through a thin pad of silica gel, and GC analysis showed the formations of 2- and 1-phenylethanol in 96% and 6% yield, respectively.

Deacetylation of (*S*)-1-phenylethyl acetate [(*S*)-17] (Representative procedure): Acetate (*S*)-**17** (82.1 mg, 0.5 mmol), **1** (14.3 mg, 0.025 mmol) and methanol (2.5 mL) were added to a round-bottomed flask, and the mixture was heated at reflux for 24 h. After addition of AcOEt, the reaction mixture was filtered through a thin pad of silica gel, and the filtrate was concentrated. The crude product was subjected to a column chromatography on silica gel to give pure (*S*)-1-phenylethanol in 90% yield. The treatment of (*S*)-1-phenylethanol obtained here with Ac_2O (5 mL) and pyridine (10 mL) gave acetyl ester (*S*)-**17**, quantitatively, which showed 100% *ee* of optical purity on HPLC analysis (Daicel chiral OD column, *i*PrOH/hexanes 10%, flow rate 1.0 mL min^{-1}).

Deacetylation of α-D-glucose pentaacetate (31) (Representative procedure): Pentaacetate **31** (390 mg, 1.0 mmol), **1** (28.5 mg, 0.05 mmol), THF (5 mL) and methanol (5 mL) were added to a round-bottomed flask, and the mixture was stirred at 30 °C for 4 h. After addition of AcOEt, the reaction mixture was filtered through a thin pad of silica gel, and the filtrate was concentrated. The crude product was subjected to a column chromatography on silica gel to give pure 1,2,3,4-tetra-*O*-acetyl-α-D-glucose[29] in 88% yield. The deacetylated products obtained by treatment of **31**,[29] **32**,[30] **34**,[31] **35**,[29] **36**,[32] **37**,[33] and **41**[34] with methanol in the presence of catalyst **1** are reported previously, and the deacetylated pyranose derived from **33** is a commercially available.

5-Acetyl-α-chlorarose (44): ^{1}H NMR ($CDCl_3$, 25 °C, TMS): $\delta = 6.13$ (d, $J = 3.8$ Hz, 1H), 5.56 (d, $J = 3.1$ Hz, 1H), 5.34 (s, 1H), 5.11–5.06 (m, 1H), 4.93 (dd, $J = 3.1$, 9.5 Hz, 1H), 4.68 (d, $J = 3.8$ Hz, 1H), 4.04–3.70 (m, 2H), 2.08 (s, 3H), 2.05 (s, 3H), 1.98–1.85 (br, 1H); ^{13}C NMR ($CDCl_3$, 25 °C, TMS): $\delta = 170.2$, 169.3, 107.4, 105.6, 97.0, 85.3, 78.3, 73.9, 69.9, 62.4, 20.9, 20.6; elemental analysis calcd (%) for $C_{12}H_{15}O_8Cl_3$: C 36.62, H 3.84; found C 36.78, H 4.05.

Phenyl 2,3,4-tri-*O*-acetyl-1-thio-D-glucopyranoside: ^{1}H NMR ($CDCl_3$, 25 °C, TMS): $\delta = 7.51$–7.46 (m, 2H), 7.37–7.30 (m, 3H), 5.27 (t, $J = 9.5$ Hz, 1H), 5.03–4.95 (m, 2H), 4.76 (d, $J = 10.1$ Hz, 1H), 3.77–3.73 (m, 1H), 3.62–3.54 (m, 2H), 2.20–2.17 (br, 1H), 2.09 (s, 3H), 2.04 (s, 3H), 2.00 (s, 3H); ^{13}C NMR ($CDCl_3$, 25 °C, TMS): $\delta =$ 170.2, 169.9, 169.3, 132.7, 131.7, 129.0, 128.4, 85.6, 78.2, 73.8, 70.1, 68.4, 61.4, 20.7, 20.6, 20.5; elemental analysis calcd (%) for $C_{18}H_{22}O_8S$: C 54.26, H 5.57; found C 54.28, H 5.75.

Phenyl 2,3,4-tri-*O*-acetyl-1-thio-D-galactopyranoside: ^{1}H NMR ($CDCl_3$, 25 °C, TMS): $\delta = 7.46$–7.51 (m, 2H), 7.30–7.37 (m, 3H), 5.40 (d, $J = 3.3$ Hz, 1H), 5.28 (t, $J = 9.9$ Hz, 1H), 5.09 (dd, $J = 3.3$, 9.9 Hz, 1H), 4.76 (d, $J = 9.9$ Hz, 1H), 3.86–3.67 (m, 2H), 3.60–3.44 (m, 1H), 2.33–2.20 (br, 1H), 2.14 (s, 3H), 2.10 (s, 3H), 2.00 (s, 3H); ^{13}C NMR ($CDCl_3$, 25 °C, TMS): $\delta =$ 171.1, 167.0, 169.5, 132.4, 132.2, 129.0, 128.1, 86.5, 77.3, 72.0, 68.0, 67.5, 60.8, 20.8, 20.7, 20.6; elemental analysis calcd (%) for $C_{18}H_{22}O_8S$: C 54.26, H 5.57; found C 54.42, H 5.68.

2,3-Diacetyluridine: ^{1}H NMR ($CDCl_3$, 25 °C, TMS): $\delta = 9.40$–9.30 (br, 1H), 7.78 (d, $J = 8.2$ Hz, 1H), 6.08 (m, 1H), 5.80 (d, $J = 8.2$ Hz, 1H), 5.55–5.42 (m, 2H), 4.22 (s, 1H), 4.08–3.67 (m, 2H), 3.20–3.00 (br, 1H), 2.14 (s, 3H), 2.09 (s, 3H); ^{13}C NMR ($CDCl_3$, 25 °C, TMS): $\delta = 170.2$, 169.9, 163.7, 150.7, 140.9, 103.1, 87.1, 83.5, 73.0, 71.2, 61.6, 20.6, 20.4; MS (FAB): *m*/*z* (%): 329 (14) $[M+H]^+$, 217 (100).

2,3-Diacetylcytidine: ^{1}H NMR ([D$_6$]DMSO, 25 °C, TMS): $\delta = 7.81$ (d, $J = 7.5$ Hz, 1H), 7.30 (br, 2H), 6.01 (d, $J = 5.5$ Hz, 1H), 5.75 (d, $J = 7.5$ Hz, 1H), 5.33–5.27 (m, 2H), 4.08 (d, $J = 3.1$ Hz, 1H), 3.66–3.54 (m, 2H), 2.07 (s, 3H), 2.00 (s, 3H); ^{13}C NMR ([D$_6$]DMSO, 25 °C, TMS): $\delta = 169.7$, 169.4, 165.7, 155.0, 141.5, 94.9, 86.7, 82.5, 72.7, 70.8, 60.8, 20.5, 20.3; MS (FAB): *m*/*z* (%): 328 (65) $[M+H]^+$, 217 (100).

Deacetylation of cytidine tetraacetate (43) and the subsequent pivalation (Representative procedure): Tetraacetate **43** (411 mg, 1.0 mmol), **1** (28.5 mg, 0.05 mmol), THF (5 mL), and methanol (5 mL) were added to a round-bottomed flask, and the mixture was stirred at 30 °C for 24 h. After addition of CH_2Cl_2, the reaction mixture was filtered through a thin pad of silica gel, and the filtrate was concentrated to give a crude product of 2,3-di-*O*-acetylcytidine. To the crude product obtained were added *t*BuCOCl (4.0 mmol) and pyridine (5 mL), and the mixture was stirred at rt for 24 h. After usual aqueous workup (AcOEt/water), the organic layer was dried and evaporated to give a crude product of the pivalate, which was subjected to a column chromatography on silica gel to give pure 2′,3′-di-*O*-acetyl-5′-*O*,*N*^{6}-dipivaloylcytidine in 76% yield.

2′,3′-Di-*O*-acetyl-5′-*N*^{6},*O*-dipivaloylcytidine: ^{1}H NMR ($CDCl_3$, 25 °C, TMS): $\delta = 8.18$–8.10 (br, 1H), 7.91 (d, $J = 7.6$ Hz, 1H), 7.48 (d, $J = 7.3$ Hz, 1H), 6.25 (d, $J = 4.6$ Hz, 1H), 5.38 (t, $J = 4.9$ Hz, 1H), 5.33 (t, $J = 4.9$ Hz, 1H), 4.43 (dd, $J = 13.1$, 3.1 Hz, 2H), 4.34 (d, $J = 10.1$ Hz, 1H), 2.12 (s, 3H), 2.11 (s, 3H), 1.29 (s, 9H), 1.26 (s, 9H); ^{13}C NMR ($CDCl_3$, 25 °C, TMS): $\delta =$ 178.1, 177.8, 169.6, 169.5, 162.5, 154.9, 143.5, 96.8, 87.8, 80.0, 73.9, 69.7, 62.8, 40.3, 38.8, 27.2, 27.0, 20.5; MS (FAB): *m*/*z* (%): 496 (90) $[M+H]^+$, 301 (100).

Deacetylation of α-D-glucose pentaacetate (31) and the subsequent glucosylation (Representative procedure): Pentaacetate **31** (507 mg, 1.3 mmol), **1** (37.1 mg, 0.065 mmol), THF (7 mL) and methanol (7 mL) were added to a round-bottomed flask, and the mixture was stirred at 30 °C for 4 h. After addition of AcOEt, the reaction mixture was filtered through a thin pad of silica gel, and the filtrate was concentrated to give a crude product of α-D-glucose tetraacetate (484 mg). To another round-bottomed flask was added molecular sieves 3 Å (500 mg), which was heated to 150 °C under reduced pressure for 3 h. To this flask were added the crude 1,2,3,4-tetra-*O*-acetyl-α-D-glucopyranoside obtained above, tetra-*O*-benzoate-α-D-glucopyranosyl bromide (660 mg, 1.0 mmol) and CH_2Cl_2 (5 mL) followed by tetramethylurea (0.25 mL). After the mixture had been stirred at rt for

0947-6539/01/0715-3326 $ 17.50+.50/0 *Chem. Eur. J.* **2001**, *7*, No. 15

15 min, AgOTf (452 mg, 1.3 mmol) was added. Then, the mixture was stirred in the dark at rt for 18 h. After addition of CH_2Cl_2, the reaction mixture was filtered through a thin pad of celite. The filtrate was washed with sat. aq. $NaHCO_3$ (×3) and sat. aq. NaCl (×3), and dried over Na_2SO_4. After filtration and concentration, the crude product was subjected to a column chromatography on silica gel to give pure dissacharide in 89% yield.

2,3,4,6-Tetra-*O*-benzoyl-α-D-glucopyranosyl-(1→6)-1,2,3,4-tetra-*O*-acetyl-α-D-glucopyranoside (46): ^{1}H NMR ($CDCl_3$, 25 °C, TMS): $\delta = 8.03$ (d, $J =$ 7.3 Hz, 2H), 7.96 (d, $J = 7.1$ Hz, 2H), 7.90 (d, $J = 7.1$ Hz, 2H), 7.82 (d, $J =$ 7.1 Hz, 2H), 7.58–7.25 (m, 12H), 6.17 (d, $J = 3.7$ Hz, 1H), 5.90 (t, $J =$ 9.5 Hz, 1H), 5.67 (t, $J = 9.5$ Hz, 1H), 5.50 (dd, $J = 7.9$, 9.5 Hz, 1H), 5.37 (t, $J = 9.9$ Hz, 1H), 4.95–4.88 (m, 3H), 4.64 (dd, $J = 3.1$, 12.1 Hz, 1H), 4.49 (dd, $J = 4.7$, 12.1 Hz, 1H), 4.19–4.11 (m, 1H), 4.09–4.02 (m, 1H), 3.95 (dd, $J = 2.2$, 11.5 Hz, 1H), 3.67 (dd, $J = 6.6$, 11.5 Hz, 1H), 1.97 (s, 9H), 1.94 (s, 3H); ^{13}C NMR ($CDCl_3$, 25 °C, TMS): $\delta = 170.1$, 169.5, 169.4, 168.6, 166.1, 165.7, 165.2, 165.1, 133.4, 133.2 (2C), 133.1, 129.7 (2C), 129.6 (2C), 129.5, 129.1, 128.7, 128.6, 128.4 (2C), 128.3, 128.2, 101.0, 88.7, 72.7, 72.2, 71.5, 71.2, 69.6, 69.5, 69.2, 68.5, 67.5, 62.9, 20.7, 20.6, 20.5, 20.4; elemental analysis calcd (%) for $C_{48}H_{46}O_{19}$: C 62.20, H 5.00; found C 61.97, H 4.92.

2,3,4,6-Tetra-*O*-benzoyl-α-D-glucopyranosyl-1,2:3,4-di-*O*-isopropylidene-α-D-galactopyranoside (47): ^{1}H NMR ($CDCl_3$, 25 °C, TMS): $\delta = 8.05–8.00$ (m, 2H), 7.99–7.95 (m, 2H), 7.92–7.87 (m, 2H), 7.85–7.81 (m, 2H), 7.58–7.45 (m, 2H), 7.44–7.25 (m, 10H), 5.90 (t, $J = 9.7$ Hz, 1H), 5.67 (t, $J =$ 9.5 Hz, 1H), 5.53 (dd, $J = 7.9$, 9.7 Hz, 1H), 5.42 (d, $J = 5.1$ Hz, 1H), 5.04 (d, $J = 7.9$ Hz, 1H), 4.64 (dd, $J = 3.1$, 12.3 Hz, 1H), 4.49 (dd, $J = 5.1$, 11.9 Hz, 1H), 4.43 (dd, $J = 2.6$, 8.0 Hz, 1H), 4.21 (dd, $J = 2.4$, 5.0 Hz, 1H), 4.19–4.13 (m, 1H), 4.10 (d, $J = 8.0$ Hz, 1H), 4.02 (dd, $J = 3.0$, 10.1 Hz, 1H), 3.92–3.80 (m, 2H), 1.37 (s, 3H), 1.24 (s, 3H), 1.21 (s, 3H), 1.20 (s, 3H); ^{13}C NMR ($CDCl_3$, 25 °C, TMS): $\delta = 166.2$, 165.8, 165.2, 165.1, 133.4, 133.2, 133.0 (2C), 129.9, 129.8, 129.7 (2C), 129.6, 129.3, 128.9, 128.8, 128.5, 128.4, 128.3, 128.2, 109.2, 108.5, 101.2, 96.1, 72.9, 72.1, 71.8, 70.9, 70.5, 70.3, 69.8, 68.3, 67.5, 63.2, 25.9, 25.7, 24.8, 24.2; elemental analysis calcd (%) for $C_{46}H_{46}O_{15}$: C 65.86, H 5.53; found C 65.84, H 5.64.

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