promoted additions involve chelation control. The Cornforth model satisfactorily explains the facial selectivity of BF_3-promoted additions.[14]

The present findings are complimentary to previous studies on additions of achiral (γ-alkoxyallyl)stannanes to α-alkoxy aldehydes.[9] The use of stannanes **3**-(*S*) and **3**-(*R*) enable products with a stereochemically defined *E* double bond to be obtained. Further, stereocontrolled hydroxylation of the double bond in these products could lead to ω-deoxy sugars. Studies along these lines will be reported in due course.

Typical Experimental Procedure: (-)-(*E*)-(2*S*,3*R*,4*S*,5*R*)-2,3-Bis(benzyloxy)-1-[(*tert*-butyldimethylsilyl)oxy]-5-(methoxymethoxy)-6-octen-4-ol (14). To a solution of 83.0 mg (0.205 mmol) of stannane **3**-(*S*) and 79.4 mg (0.191 mmol) of aldehyde **13** in 0.5 mL of dry CH_2Cl_2 at -78 °C was added, dropwise, 31 μL (0.248 mmol) of $BF_3{\cdot}Et_2O$. After 40 min at -78 °C, the reaction was quenched with saturated aqueous $NaHCO_3$ and allowed to warm to room temperature. The mixture was then diluted with ether and additional $NaHCO_3$. After the layers were separated, the aqueous layer was reextracted twice with ether. The combined ether extracts were dried over $MgSO_4$ and concentrated. The crude material was purified by flash chromatography on silica gel. Gradient elution from 5 to 10 to 15 to 20% ethyl acetate-hexanes afforded 72.8 mg (72%, 81% based on 8.9 mg of recovered **13**) of alcohol **14**: $[\alpha]_D^{27}$ -38.1° (*c* 1.24, $CHCl_3$); IR (film) ν 3499, 3030, 2929, 1454, 1256, 1095, 1028, 837, 777, 734, 698 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.36-7.26 (10 H, m, Ar H), 5.70 (1 H, dq, J = 15.5, 6.4 Hz, H-7), 5.52 (1 H, ddd, J = 15.5, 8.3, 1.5 Hz, H-6), 4.73, 4.54, 4.72, 4.66, 4.63, 4.59 (6 H, AB, J = 6.7, 11.7, 10.4 Hz, OCH_2O, benzylic H's), 4.22 (1 H, d, J = 8.0 Hz, H-5), 3.86-3.76 (5 H, m, H-2,3,4,5), 3.37 (3 H, s, OCH_3), 3.06 (1 H, d, J = 6.3 Hz, OH), 1.69 (3 H, dd, J = 6.3, 1.4 Hz, vinyl CH_3), 0.865 (9 H, s, $SiC(CH_3)_3$), 0.0033 (6 H, s, $Si(CH_3)_2$); EIMS *m/z* (relative intensity) 415 (4), 303 (5), 181 (25), 117 (17), 91 (100). Anal. Calcd for $C_{30}H_{46}O_6Si$: C, 67.89; H, 8.74. Found: C, 67.95; H, 8.75.

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Supplementary Material Available: ^1H NMR spectra of **5, 6, 7, 8, 10, 13, 14, 15, 16, 17, 19**, and iii and ^{13}C NMR spectrum of **16** (16 pages). Ordering information is given on any current masthead page.

(14) Cornforth, J. W.; Cornforth, R. H.; Mathew, K. K. *J. Chem. Soc.* **1959**, 112.

Resolution, Asymmetric Transformation, and Configuration of Tröger's Base. Application of Tröger's Base as a Chiral Solvating Agent†

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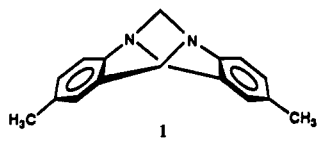
Summary: Tröger's base, **1**, has been resolved by diastereomeric salt formation with a strongly acidic resolving agent, **2**. The resolution is attended by an asymmetric transformation. Enantiopure **1** acts as a chiral solvating agent toward several secondary and tertiary alcohols. The configuration of **1** has been determined by X-ray crystallography on salt **3** to be (5*S*,11*S*)-(+) which is contrary to that previously established from the circular dichroism spectrum by the method of exciton chirality.

Tröger's base,[1] 2,8-dimethyl-6*H*,12*H*-5,11-methanodibenzo[*b*,*f*][1,5]diazocine (**1**) (TB), is a chiral heterocyclic amine whose chirality is solely due to the presence of two stereogenic nitrogen atoms. The chiral nature of **1** was first recognized by Prelog and Wieland, and this observation was confirmed by optical resolution of the racemate.[2] It is the first chiral tertiary amine devoid of non-nitrogen stereogenic centers to have been resolved.



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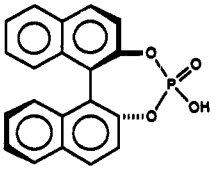

2

† Dedicated to Professor Vladimir Prelog.

Initial efforts to resolve *rac*-**1** with acidic resolving agents, e.g., 10-camphorsulfonic acid, led to the finding that partially resolved samples undergo racemization in acid medium. In order to circumvent the racemization, **1** was subjected to resolution by chromatography on an enantioselective stationary phase (lactose); indeed, **1** is one of the first chiral substances to have been resolved chromatographically.[2] All subsequent reports of resolutions of **1** have been to chromatographic resolutions[3] with the consequence that only small amounts of optically active **1** have been available for study or evaluation of properties. Moreover, it has been asserted that resolution of **1** through formation of diastereomeric salts is not feasible.[4]

There is something of a resurgence of interest in **1** due in large measure to the sharply folded geometry of the molecule, its C_2 symmetry, and its rigidity that makes it

(1) Tröger, J. *J. Prakt. Chem.* **1887**, *36*, 225-245.
(2) Prelog, V.; Wieland, P. *Helv. Chim. Acta* **1944**, *27*, 1127-1134.
(3) E.g.: Hesse, G.; Hargel, R. *Liebigs Ann. Chem.* **1976**, 996-1008. Lindner, K. R.; Mannschreck, A. *J. Chromatogr.* **1980**, *193*, 308-310. Saigo, K.; Chen, Y.; Kubota, N.; Tachibana, K.; Yonezawa, N.; Hasegawa, M. *Chem. Lett.* **1986**, 515-8. Yuki, Y.; Okamoto, I.; Shibata, T.; Nakamura, H. U.S. Patent 4,786,416, Nov. 22, 1988 (to Daicel Chemical Industries); *Chem. Abstr.* **1989**, *111*, 160,330.
(4) (a) Mason, S. F.; Vane, G. W.; Schofield, K.; Wells, R. J.; Whitehurst, J. S. *J. Chem. Soc. B* **1967**, 553-556. (b) Mason, S. F. *Molecular optical activity and the chiral discriminations*; Cambridge Univ. Press: Cambridge, U.K., 1982; p 191.

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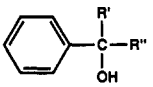
Table I. Chemical Shifts of Anisochronic Group Signals of Diastereomeric Complexes (A and B) Formed by Racemic Alcohols 4–8 and Tröger's Base (+)-1[a]



compd	R′	R″	observed group	δ_A[b]	δ_B[b]	multiplicity
4	CH_3	H	CH	4.89	4.91	q
				4.87	4.88	
				4.85	4.86	
				4.82	4.84	
5	CH_3	C≡CH	≡CH	2.63	2.66	s
6	H	CH_2CH_3	CH_3	0.91[c]	0.92	t
				0.89	0.90	
				0.86	0.87	
7	H	CH_2OH	CH	4.78[d]	4.80[d]	q
				4.76	4.77	
				4.73	4.74	
8	H	$CH(OH)C_6H_5$[e]	CH	4.63	4.66	s

[a] (±)-Alcohol (0.1 mmol) and (+)-1 (0.1 mmol) in $CDCl_3$ (0.2 M) at 25 °C [1:1 ratio]. [b] ^1H NMR chemical shifts referred to TMS as internal standard (300 MHz). [c] Ratio = 2:1 (Tröger's base:alcohol). [d] Two overlapping quartets with the center peaks having 2× the intensity of the outer doublets. [e] (±)-Hydrobenzoin.

especially suited to incorporation in molecular systems that mimic enzymes and to studies of molecular recognition phenomena.[5-7] Availability of the enantiomers of 1 in larger quantities might lead to a substantial increase in the use of this compound in biomimetic systems. It is also a good candidate substance for studies of inclusion compound formation.

In a recent study, Greenberg et al.[8] sought evidence for an iminium ion suggested by Prelog and Wieland as being the intermediate responsible for the racemization of 1. Although these investigators were unable to find evidence for such an intermediate, their study implied that racemization might not be as facile in concentrated acid as it is in dilute acid. Their study encouraged us to consider whether a diastereomer-mediated resolution might be feasible after all with a strongly acidic resolving agent.

Reaction of 1[5c] with (−)-1,1′-binaphthalene-2,2′-diyl hydrogen phosphate, 2[9] (1:1), in ethanol led to formation of salt (+)-1·(−)-2 (3) from which (+)-1 was recovered with high enantiomer purity. When the crystallization was coupled to careful control of the crystallization rate, we realized a yield of 3 in excess of 50%. We subsequently established that the optimal yield of salt 3 leading to (+)-1 is 93% (186% based on the amount of (+)-TB initially present in the racemate being resolved).[10] This finding requires that, during the resolution, the (−)-1 racemizes and, eventually, nearly all the (−)-1 initially present in the racemate is converted to (+)-1 in the precipitated diastereomeric salt. The resolution is thus attended by a crystallization-induced asymmetric transformation of salt 3.[11a,12] We have reasonable evidence that the (+)-1 isolated from diastereomeric salt 3 is enantiomerically pure.[13]

Thus, contrary to the assertion that such a resolution is not feasible,[4] the resolution is straightforward and multigram quantities of optically active 1 (both enantiomers) can be readily prepared by our method.[14] Although optimal results have been achieved with just the first resolving agent tried (as well as with its enantiomer), we have evidence that other resolving agents also lead to resolution of 1.[15] The resolving agent used, 2, is readily available (in either optically active or racemic form),[9] and it is recovered from the resolution in 79% yield.

Two aspects of our work merit comment: (1) Selection of the resolving agent, although intuitive, was deliberate. We sought a strongly acidic resolving agent in order to facilitate salt formation and we chose one bearing aromatic groups to optimize diastereomer discrimination between the diastereomeric salts. (2) Our results exemplify the contention that resolution of easily racemizable compounds by crystallization of diastereomers not only is not precluded, but may actually be facilitated by the attendant crystallization-induced asymmetric transformation.

As first evidence that 1 can participate in stereoisomer discrimination phenomena, we have observed that enantiopure 1 may serve as a chiral solvating agent (CSA)[17]

(5) (a) Wilcox, C. S. *Tetrahedron Lett.* **1985**, *26*, 5749–5752. (b) Wilcox, C. S.; Greer, L. M.; Lynch, V. *J. Am. Chem. Soc.* **1987**, *109*, 1865–67. (c) Sucholeiki, I.; Lynch, V.; Phan, L.; Wilcox, C. S. *J. Org. Chem.* **1988**, *53*, 98–104. (d) Webb, T. H.; Wilcox, C. S. *J. Org. Chem.* **1990**, *55*, 363–365.

(6) Weber, E.; Müller, U.; Worsch, D.; Vögtle, F.; Will, G.; Kirfel, A. *J. Chem. Soc., Chem. Commun.* **1985**, 1578–1580.

(7) Katz, H. E. *J. Chem. Soc., Chem. Commun.* **1990**, 126–127.

(8) Greenberg, A.; Molinaro, N.; Lang, M. *J. Org. Chem.* **1984**, *49*, 1127–1130.

(9) Jacques, J.; Fouquey, C. *Org. Synth.* **1989**, *67*, 1–12.

(10) Racemic 1[5c] (2.504 g, 10 mmol) and (−)-2 (3.483 g, 10 mmol) were dissolved together in 50 mL of absolute ethanol (heating 1 h) and gradually cooled to 0 °C (3 h). Two crops of salt 3[19] (6.0 g, 93%), mp 161–2 °C were obtained. (+)-1 (2.28 g in three crops; 91%) was recovered on treatment of the salt with aqueous NaOH and recrystallization from methanol; mp 131–132 °C (lit.[2] 127–28 °C), $[\alpha]^{25}_{589}$ +287 ● 2° (*c* 0.29, hexane) (lit.[2] $[\alpha]^{17}_{589}$ +287 ± 7° (*c* 0.281, hexane)). Comparable resolution of *rac*-1 with (+)-2 gave (−)-1; the first crop had mp 130–131.5 °C and $[\alpha]^{25}_{589}$ −307° (*c* 0.31, hexane).

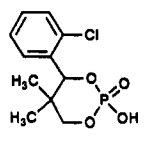
(11) Jacques, J.; Collet, A.; Wilen, S. H. *Enantiomers, Racemates and Resolutions*; Wiley: New York, 1981; (a) Chapter 6; (b) pp 37–41, 151–159.

(12) Review: Arai, K. *Yuki Gosei Kagaku Kyokaishi* **1986**, *44*, 486–498.

(13) (+)-1 was estimated to be of >98% ee based on the optical rotation. However, absence of a eutectic peak in the differential scanning calorimetric trace[11b] of (+)-1, ΔH^f_{rac} = 5.94 kcal mol^{-1} and ΔH^f_{enant} = 4.77 kcal mol^{-1}, leads us to conclude that its enantiomer purity is in excess of 99%.

(14) The resolution/asymmetric transformation has been accomplished also on a 50-mmol scale. The preparative details will be submitted to *Organic Synthesis*.

(15) We have evidence (not optimized) that 4-(2-chlorophenyl)-5,5-dimethyl-2-hydroxy-1,3-dioxaphosphorinane 2-oxide[16] (a) may also serve as resolving agent for 1.



a

(16) ten Hoeve, W.; Wynberg, H. *J. Org. Chem.* **1985**, *50*, 4508–4514.

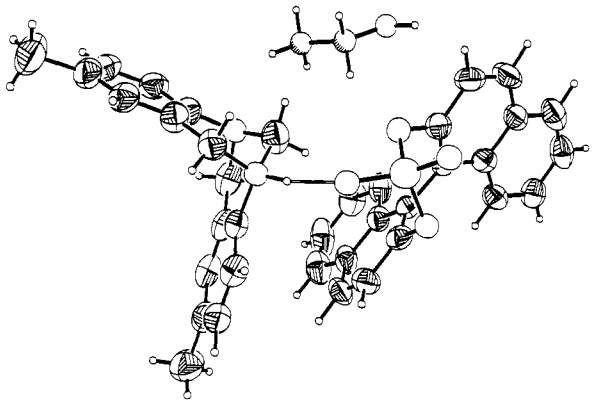


Figure 1. Thermal ellipsoid plot of the (+)-1·(−)-2 salt (3) molecular structure.

toward chiral alcohols. Comparison of ^{1}H NMR spectra of racemic alcohols 4–8 run alone in $CDCl_3$ with spectra of these alcohols run in the presence (+)-1 led to the observation of anisochrony of at least one set of peaks in the case of five alcohols, all containing at least one phenyl group, at room temperature (Table I). Enantiopure 1 generates intrinsically nonidentical chemical shifts in some of the sensor nuclei of the diastereomeric association complexes formed between the CSA and the alcohol enantiomers. In addition, enantiopure 1 may exhibit stronger nonbonded interaction with one of the enantiomers of each of these alcohols than with the other *in solution*, i.e., the equilibrium constants for formation of the diastereomeric complexes may be unequal.[18] Under appropriate conditions, enantiopure 1 may serve in the determination of the enantiomer purity of such alcohols. Our results are comparable to and complementary with those observed when quinine is used as CSA.[19]

The availability of nice crystals of salt 3 [(+)-1·(−)-2][20] made it possible for us to undertake an X-ray structural analysis (Figure 1) and to determine independently the absolute configuration of Tröger's base.[21] Since the absolute configuration of acid (−)-2 is known to be *R*,[22] the latter being the configuration shown in the figure, the configuration of (+)-1 in the crystal was established relative to that of (−)-2 as being 5*S*,11*S*. This experimental finding is inconsistent with the configurational assignment 5*R*,11*R*-(+) based on exciton chirality (coupled oscillators) calculation.[4a] The incontrovertible assignment based on crystallography requires that the configuration of Tröger's base that has been cited in the literature since 1967 must be reversed.

The crystal structure determination of salt 3 has also established that the binaphthyl phosphate and protonated TB counterions are hydrogen bonded and that interaction between these ions appears to take place from the top of the TB molecule.

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Supplementary Material Available: Representative DSC traces of (+)-1, (±)-1, and mixtures of (+)-1 and (−)-1; fusion phase diagram of (+)-1/(−)-1 mixtures; ^{1}H NMR spectra illustrating application of (+)-1 as a chiral solvating agent; and tables of atomic coordinates and temperature factors, bond lengths and angles, anisotropic thermal parameters, hydrogen coordinates and thermal parameters and torsion angles along with a labeled plot of the crystallographic, asymmetric unit for compound 3 (14 pages). Ordering information is given on any current masthead page.

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(19) Rosini, C.; Uccello-Barretta, G.; Pini, D.; Abete, C.; Salvadori, P. *J. Org. Chem.* **1988**, *53*, 4579–4581.

(20) Salt 3, mp 161–62 °C, $[\alpha]^{25}_{589}$ −336.6° (*c* 1.065, CH_3OH), analyzed as follows: calculated for $C_{39}H_{37}N_2O_5P$ [$(C_{17}H_{18}N_2)\cdot(C_{20}H_{13}O_4P)\cdot(C_2H_5OH$], 72.65% C, 5.79% H, 4.35% N, 4.80% P; found, 72.31% C, 5.95% H, 4.29% N, 4.76% P.

(21) Salt 3 [(+)-1·(−)-2] crystallized in the noncentrosymmetric, orthorhombic, space group $P2_12_12_1$. The unit cell parameters were determined to be a = 10.432 (3) Å, b = 16.164 (3) Å, and c = 19.879 (4) Å based upon least-squares fitting of 25 reflections in the range 24° < 2θ < 26°. The unit cell contains four asymmetric units of molecular formula [$(C_{17}H_{18}N_2)\cdot(C_{20}H_{13}O_4P)\cdot(C_2H_5OH$)] in a volume of 3351.9 (1.2) Å^3 which produces a calculated density of 1.28 g/cm^3. A total of 2857 reflections were recorded in the range 3.5° <2θ <47° with a Nicolet $R3_m/E$ crystallographic system using the θ–2θ scan routine and graphite monochromated Mo Kα radiation (λ = 0.71069 Å). After Lorentz and polarization corrections and an absorption correction based upon a crystal measurement (0.3 mm × 0.3 mm × 0.6 mm), the structure was solved by the SHELXTL 5.1 programs. All non-hydrogens were refined anisotropically except the terminal carbon of the somewhat disordered ethanol molecule. The approximate location of all hydrogen atoms was determined by Fourier difference synthesis. In the final stages of refinement the hydrogen atoms were placed in calculated positions and allowed to ride with the atom to which they are attached. The final agreement factors are R = 0.056 and R_w = 0.058 for 2407 unique, observed reflections [$F_o > 3\sigma(F_o)$] and 421 independent variables.

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Ruthenium-Catalyzed Allylation of Primary Alcohols by Allylic Acetates: A Novel Synthesis of α,β-Unsaturated Ketones

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Summary: Certain ruthenium complexes show high catalytic activity in the synthesis of α,β-unsaturated ketones from primary alcohols and allylic acetates. Here, π-allylruthenium intermediates apparently operate as nucleophiles rather than as electrophiles.

Among the carbon–carbon bond forming reactions promoted by transition-metal complexes, allylic alkylations, especially those catalyzed by palladium complexes, have been extensively studied and have been successfully applied in organic synthesis.[1] In contrast, comparatively

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