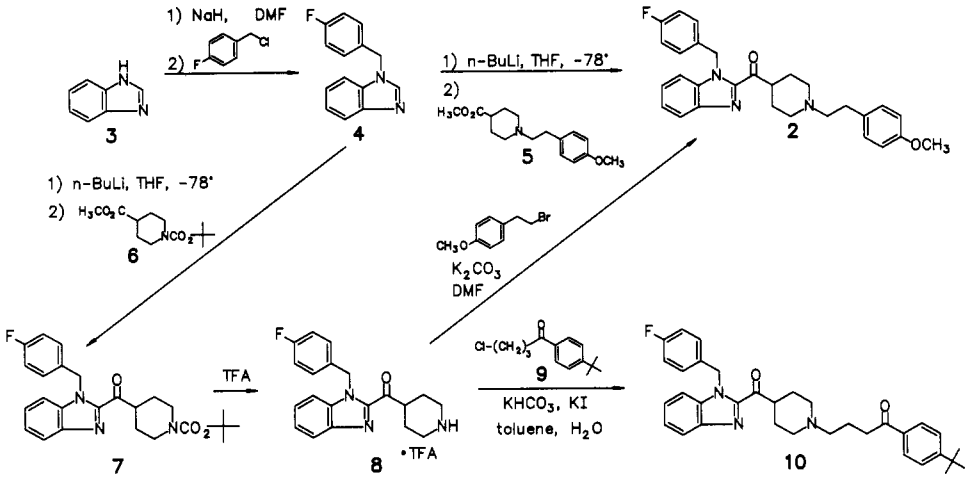
Scheme I



by suction. Crystallization from EtOH/Et_2O afforded colorless needles: 1.43 g (84%); mp 213–215 °C dec; IR (KBr) 1690, 1680 cm^{-1}; ^1H NMR (DMSO-d_6) δ 1.68–1.84 (m, 2 H), 2.05–2.18 (m, 2 H), 3.11 (dt, J = 12.6, 2.6 Hz, 2 H), 3.30–3.45 (m, 2 H), 4.13 (tt, J = 11.4, 3.5 Hz, 1 H), 5.86 (s, 2 H), 7.09–7.23 (m, 4 H), 7.37–7.51 (m, 2 H), 7.77 (d, J = 7.8 Hz, 1 H), 7.89 (d, J = 8.1 Hz, 1 H), 8.62 (br s, 1 H). Anal. Calcd for $C_{20}H_{20}FN_3O \cdot CF_3CO_2H$: C, 58.54; H, 4.69; N, 9.31. Found: C, 58.55; H, 4.77; N, 9.29.

[1-[(4-Fluorophenyl)methyl]-1*H*-benzimidazol-2-yl][1-[2-(4-methoxyphenyl)ethyl]-4-piperidinyl]methanone (2). To a stirred, −78 °C, solution of **4** (1.13 g, 5.00 mmol) and dry THF (12 mL) under argon was added via syringe a 2.5 M solution of *n*-butyllithium in hexane (2.1 mL, 5.2 mmol). After 15 min a solution of **5** (1.39 g, 5.01 mmol) and dry THF (6 mL) was added dropwise via syringe. After 5–10 min, the cooling bath was removed, and after 30 min the reaction was quenched by the addition of saturated aqueous NH_4Cl. The aqueous mixture was extracted twice with EtOAc. The EtOAc extracts were combined, washed with saturated aqueous NaCl, and dried over anhydrous Na_2SO_4. The drying agent was removed by filtration, and the filtrate was evaporated at reduced pressure leaving an oil. Purification of this oil by flash chromatography (EtOAc) and crystallization from cyclohexane afforded off-white, matted needles: 0.90 g (38%); mp 109–111 °C; IR (KBr) 1680 cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.71–1.88 (m, 2 H), 1.98 (br d, J = 11.9 Hz, 2 H), 2.24 (dt, J = 11.6, 2.5 Hz, 2 H), 2.54–2.62 (m, 2 H), 2.72–2.80 (m, 2 H), 3.05 (dt, J = 11.6, 3.2 Hz, 2 H), 3.78 (s, 3 H), 3.88 (tt, J = 11.5, 3.8 Hz, 1 H), 5.79 (s, 2 H), 6.79–6.86 (m, 2 H), 6.90–7.00 (m, 2 H), 7.06–7.17 (m, 4 H), 7.33–7.46 (m, 3 H), 7.87–7.96 (m, 1 H). Anal. Calcd for $C_{29}H_{30}FN_3O_2$: C, 73.86; H, 6.41; N, 8.91. Found: C, 73.98; H, 6.48; N, 8.90.

Alternate Preparation of 2. To a stirred, room temperature mixture of **8** (1.82 g, 4.03 mmol), K_2CO_3 (1.39 g, 10.0 mmol), and DMF (15 mL) was added 1-(2-bromoethyl)-4-methoxybenzene (0.87 g, 4.0 mmol). The reaction was then heated at 90 °C for 22 h. The reaction was poured into H_2O, and the aqueous mixture was extracted with a 2:1 mixture of EtOAc/toluene. The organic layer was washed twice with H_2O and once with saturated aqueous NaCl before being dried over anhydrous Na_2SO_4. The drying agent was removed by filtration, and the filtrate was evaporated at reduced pressure leaving an oil. Purification of this oil by flash chromatography (EtOAc) and crystallization from cyclohexane afforded off-white, matted needles: 1.08 g (57%). This material was spectroscopically identical with the previous sample of **2**. Anal. Calcd for $C_{29}H_{30}FN_3O_2$: C, 73.86; H, 6.41; N, 8.91. Found: C, 73.73; H, 6.50; N, 8.90.

1-[4-(1,1-Dimethylethyl)phenyl]-4-[4-[[1-[(4-fluorophenyl)methyl]-1*H*-benzimidazol-2-yl]carbonyl]-1-piperidinyl]-1-butanone (10). A stirred mixture of **8** (5.00 g, 11.1 mmol), **9** (6.20 g, 26.0 mmol), $KHCO_3$ (2.5 g, 25 mmol), KI (0.19 g, 1.1 mmol), toluene (50 mL), and H_2O (5 mL) was refluxed 72 h. The reaction was poured into H_2O, and the aqueous mixture was extracted with EtOAc. The EtOAc layer was washed with H_2O and saturated aqueous NaCl before being dried over anhydrous $MgSO_4$. The drying agent was removed by filtration, and the filtrate was evaporated at reduced pressure leaving an oil. Purification of this oil by flash chromatography (EtOAc) and crystallization from cyclohexane/hexane afforded colorless matted needles: 3.4 g (57%); mp 105–106 °C; IR (KBr) 1690, 1670 cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.34 (s, 9 H), 1.63–1.80 (m, 2 H), 1.87–2.01 (m, 4 H), 2.16 (dt, J = 11.8, 2.4 Hz, 2 H), 2.43 (t, J = 7.3 Hz, 2 H), 2.92–3.03 (m, 4 H), 3.85 (tt, J = 11.6, 3.8 Hz, 1 H), 5.79 (s, 2 H), 6.90–7.00 (m, 2 H), 7.07–7.15 (m, 2 H), 7.34–7.50 (m, 5 H), 7.89–7.94 (m, 3 H). Anal. Calcd for $C_{34}H_{38}FN_3O_2$: C, 75.67; H, 7.10; N, 7.79. Found: C, 75.65; H, 7.16; N, 7.78.

Registry No. **2**, 124461-07-0; **3**, 51-17-2; **4**, 124443-67-0; **5**, 124461-08-1; **6**, 124443-68-1; **7**, 124443-69-2; **8**, 124443-71-6; **9**, 43076-61-5; **10**, 124443-72-7; methyl 4-piperidinecarboxylate hydrochloride, 7462-86-4; 4-fluorobenzyl chloride, 352-11-4; 1-(2-bromoethyl)-4-methoxybenzene, 14425-64-0.

Direct Polynitroaliphatic Alcohol Addition to Alkenes. 1. Synthesis of New 2-Fluoro-2,2-dinitroethyl Acetals and Ethers[1]

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Received July 31, 1989

Acetal- and ether-compounds containing the 2-fluoro-2,2-dinitroethoxy structure represent an important class of energetic compounds for potential use in formulated propellant and explosive materials, but, their synthesis routes are severely limited. This limitation results from the inherent instability of the *gem*-2,2-dinitroaliphatic alcohol structure in alkaline or acidic solution[4] and from the very weak nucleophilic properties exhibited by this class of alcohol reactants.[5-7] Therefore, the usual alkaline or acidic conditions for converting alcohols into acetals or ethers cannot be used with *gem*-2,2-dinitroaliphatic alcohols like 2-fluoro-2,2-dinitroethanol (FDNEOH) because deformylation occurs, producing formaldehyde and either

(1) McGuire, R. R.; Cochoy, R. E.; Shackelford, S. A. US Patent 4,424,398, Jan 3, 1984.
(2) Present address: Lawrence Livermore National Laboratory, P.O. Box 808 (Code L-282), Livermore, CA 94550.
(3) To whom correspondence should be sent.
(4) Coburn, M. D. *Synthesis* **1977**, 570.
(5) Cochoy, R. E.; McGuire, R. R. *J. Org. Chem.* **1972**, *37*, 3041–3042.
(6) Shipp, K. G.; Hill, M. E., Kamlet, M. J. *NOLTR 62-68*, April 1962.
(7) Adolph, H. G.; Kamlet, M. J. *J. Org. Chem.* **1968**, *34*, 45–50.

Table I. 2-Fluoro-2,2-dinitroethanol Catalytic Addition to Unsaturated Hydrocarbons

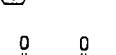
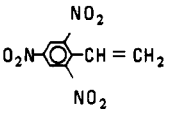
reactant	solvent	products	prod. no.	catalyst	% yield	prod. distribution
$HC\equiv COCH_2CH_3$	CH_2Cl_2	$H_3C-C(OFDNE)(COCH_2CH_3)-OFDNE$	1	$Hg(OCOCH_3)_2$	95	2 FOUND ONLY ONCE IN A MIXTURE OF 1 (73%) AND 2 (27%)
		AND				
		$H_2C=C(OFDNE)COCH_2CH_3$	2			
	CCl_4		3	— — —	100	— — —
$H_2C=CHOCH_2CH_3$	CH_2Cl_2	$H_3C-CH(OFDNE)OCH_2CH_3$	4	$HgSO_4$	73	— — —
$H_2C=CHOFDNE$	CH_2Cl_2	$H_3C-CH(OFDNE)OFDNE$	5	$HgSO_4$	61	— — —
$H_2C=C(CH_3)CH_2CH_2CH_3$	CH_2Cl_2	$H_3C-C(CH_3)(OFDNE)CH_2CH_2CH_3$	6	$HgSO_4$	74	— — —
				Hg_2SO_4	58	— — —
$H_2C=CHCH=CH_2$	CCl_4	$H_2C=CHCH(OFDNE)-CH_3$	7	$HgSO_4$	53	7 (77%) AND 8 (23%)
		AND				
		$H_3CCH=CHCH_2(OFDNE)$	8			
$H_2C=CHOCH=CH_2$	CH_2Cl_2	$H_2C=CHOCH(OFDNE)-CH_3$	9	$HgSO_4$	70	SEE TABLE III
$OFDNE\equiv -OCH_2C(NO_2)_2$		$H_3C-CHOCH(OFDNE)-CH_3$	AND 10	OR Hg_2SO_4	74	SEE TABLE III

the 2-fluoro-2,2-dinitromethyl anion ($FC(NO_2)_2^-$) or 2-fluoro-2,2-dinitromethane ($FC(NO_2)_2H$). In spite of this chemical instability, some 2-fluoro-2,2-dinitroethoxy-substituted esters, formals, ethers, amines, and oximes have been synthesized using FDNEOH;[5-13] synthesis strategies included Michael additions, Mannich condensations, and trifluoroacetic anhydride condensation. Indirect approaches using trifluoromethanesulfonate (triflate) ester intermediates recently expanded polynitroaliphatic ether syntheses[11-13] and sometimes permit a one-pot procedure. This paper reports the first direct, one-step addition of FDNEOH to certain unsaturated hydrocarbons to form new 2-fluoro-2,2-dinitroethoxy acetal and ether compounds in high yield. These nonaqueous mercury salt catalyzed Markovnikov additions with FDNEOH are achieved under the mild, neutral reaction conditions. The scope and limitations of this new polynitroaliphatic reaction as a complementary alternative to other polynitroaliphatic syntheses are discussed.

Results and Discussion

Direct addition of weakly nucleophilic 2-fluoro-2,2-dinitroethanol (FDNEOH) to unsymmetrically substituted hydrocarbons by mercury salt catalysis proved to be a general one-step method when the carbon–carbon double or triple bond is activated by an electron-donating atom or substituent. Mercury(II) sulfate, mercury(I) sulfate, mercury(II) acetate, red mercury(II) oxide, and phenylmercury(II) chloride all catalyzed this addition reaction, but generally, the two sulfate salts produced the best results. While this reaction system is similar to the mercury-catalyzed solvomercuration–demercuration olefin additions reported for the more common aliphatic alcohols,[14] it differs because the poorly nucleophilic FDNEOH forms Markovnikov acetal and ether derivatives in CH_2Cl_2 or CCl_4 solvent without requiring an alkaline sodium boro-

Table II. Alkynes/Alkenes Resistant to 2-Fluoro-2,2-dinitroethanol Catalytic Addition at the Milder Ambient Pressure Conditions

$H_2C=C(H)C\equiv CH$	$H_2C=C(CH_3)C\equiv CH$	
$N(-CH_2C\equiv CH)_3$	$HOCH_2C\equiv CCH_2OH$	$HOC(=O)C\equiv CC(=O)OH$
$H_2C=CHOC(=O)CF_3$	$H_2C=CH(CH_2)_2CH_3$	$H_2C=CHBr$
		

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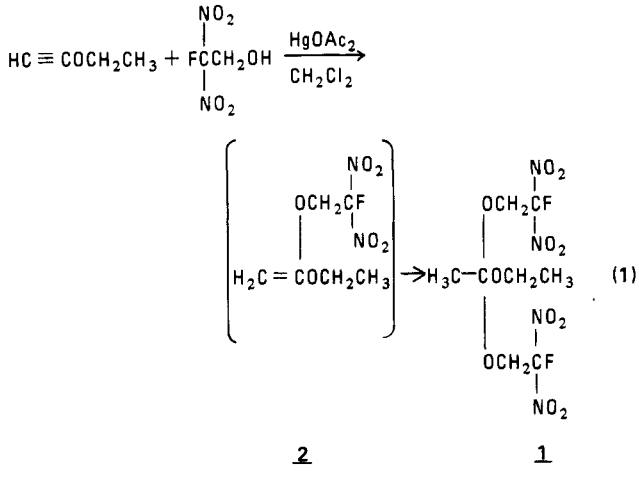
(9) Adolph, H. G. *J. Org. Chem.* **1971**, *36*, 806–809.
(10) Grakauskas, V. *J. Org. Chem.* **1972**, *38*, 2999–3004.
(11) Beard, C. D.; Baum, K.; Grakauskas, V. *J. Org. Chem.* **1973**, *38*, 3673–3677.
(12) Chapman, R. D.; Andreshak, J. L.; Shackelford, S. A. *J. Org. Chem.* **1988**, *53*, 3771–3775.
(13) Chapman, R. D.; Andreshak, J. L.; Herrlinger, S. P.; Shackelford, S. A.; Hildreth, R. A.; Smith, J. P. *J. Org. Chem.* **1986**, *51*, 3792–3798.
(14) (a) Brown, H. C.; Geoghegan, P. J., Jr., *J. Am. Chem. Soc.* **1967**, *89*, 5646–5647. (b) Brown, H. C.; Kurek, J. T.; Rei, M. H.; Thompson, K. L. *J. Org. Chem.* **1985**, *50*, 1171–1174, and references therein.

hydride reduction of the mercurial intermediate. Reaction conditions usually require an overnight reflux in CH_2Cl_2 or CCl_4 for 16 to 19 h, followed by a simple filtration and in vacuo solvent removal. High yields of the desired fluorodinitroethoxy-substituted products are obtained. As discussed later, addition to butadiene required more severe reaction conditions. Table I displays the unsaturated hydrocarbon substrates, reaction conditions, and yields achieved with this simple reaction procedure. Together, Tables I and II permit a comparison of the subtle structural variations that determine whether this mercury salt catalyzed FDNEOH Markovnikov addition occurs under the milder reaction conditions outlined.

Mercury(II) salts form a Hg^{2+} π complex with an alkyne's triple bond and permit nucleophilic Sn2-like attack.[15] In the presence of mercury(II) acetate catalyst, ethoxyacetylene readily added 2 mol of FDNEOH even at room temperature to form the bis(2-fluoro-2,2-dinitroethyl)-ethoxy ethyl orthoester product **1** in 95% yield (Table I). During the first reaction attempt, ethoxyacetylene was placed into the CH_2Cl_2 solvent as a 62% hexane solution, and two addition products resulted. The higher boiling orthoester diadduct **1** formed as 73% of the product mixture, while the lower boiling vacuum-distilled product represented 27% of the products and proved to be the ethoxy 2-fluoro-2,2-dinitroethyl vinyl acetal **2**. Subsequent systematic attempts to produce monoadduct product **2** were unsuccessful (eq 1). Such behavior contrasts with



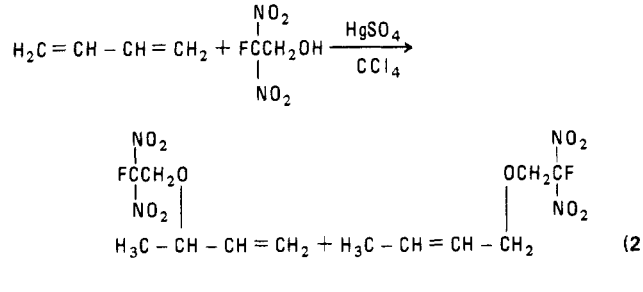
(1)

2 **1**

a recently reported mercury(II) chloride catalyzed oxidative methoxymercuration between either a monoalkyl or monoalkoxy acetylene with the highly nucleophilic alcohol, methanol, which adds only once to form methoxy vinyl ethers or methoxyacrolein acetal products, respectively.[16] Apparently, the Hg^{2+} π complex of the unsymmetrical vinyl 2-fluoro-2,2-dinitroethoxy acetal intermediate **2** is highly reactive and is not easily intercepted prior to Sn2 attack by a second FDNEOH molecule. Phenylmercury(II) chloride also produced the ethoxyacetylene orthoester diadduct **1** in a lower (43%) yield, after stirring at room temperature in CH_2Cl_2 for 21 h. Other less reactive acetylenic compounds without an electron-donating alkoxy substituent at the acetylenic carbon fail to add FDNEOH. Apparently, an electron-donating substituent or oxygen-atom-containing group is needed at the unsaturated carbon position to form a sufficiently stabilized acetylenic or olefinic mercury complex that is reactive enough for attack by the weak FDNEOH nucleophile.

Monofunctional alkenes also add FDNEOH under these mild reaction conditions whenever their localized olefinic bond is substituted unsymmetrically with an electron-donating entity. The slight electron-donating properties of the methyl group are sufficient to cause FDNEOH addition with 2-methyl-1-pentene to form product **6** (Table I), but the absence of a 2-substituted methyl in 1-pentene (Table II) renders this alkene inert to FDNEOH attack. The methyl group activation is offset when the localized double bond's electron density can be delocalized by conjugation with another unsaturated bond. This is shown by 2-methyl-1-buten-3-yne's inertness to FDNEOH addition (Table II). Vinyl ethers possessing an electron-donating alkoxy substituent readily react and produce acetal derivatives. So reactive is 2,4-dihydropyran that no catalyst is required for a quantitative yield of the 2-fluoro-2,2-dinitroethoxy acetal adduct **3** when reacted in refluxing CCl_4; however, this is the only example found that needs no mercury salt catalysis. While 2,4-dihydropyran and ethyl vinyl ether readily form their corresponding acetal products, **3** and **4**, respectively, even the 2-fluoro-2,2-dinitroethoxy ethyl vinyl ether reactant **11** produces its bis(2-fluoro-2,2-dinitroethyl) ethyl acetal, **5**, in good yield (Table I). In spite of the highly electronegative 2-fluoro-2,2-dinitroethoxy ($-OCH_2C(NO_2)_2F$) substituent at the vinyl position of **11**, electron donation from the oxygen atom to the adjacent carbon–carbon double bond must form a stabilized Hg^{2+}–olefin complex reactive enough for FDNEOH attack. Although vinyl ether **11** adds FDNEOH, the vinyl trifluoroacetate ester with a highly electronegative $OCOCF_3$ substituent does not. It would appear this ester's nonreactivity results from the trifluoroacetate group's oxygen atom at the vinylic position being in a resonant α position with the carbonyl moiety. Under mild ambient pressure CH_2Cl_2 or CCl_4 solvent reflux conditions, any vinylic, acetylenic, aromatic, or carbonyl conjugation apparently delocalizes an alkene's unsaturated site enough that the mercury ion complex is not sufficiently reactive for attack by FDNEOH. Under these same reaction conditions, simple alkenes without an electron-donating vinyl substituent do not add FDNEOH; this includes strained alkenes like norbornene. Under more stringent higher pressure reaction conditions, alkenes without an electron-donating vinyl substituent or with a conjugated olefinic bond possibly can react with FDNEOH; butadiene represents one example.

Conjugated butadiene and unconjugated divinyl ether are two difunctional alkenes that behave quite differently in their catalytic FDNEOH addition reactions. In the presence of mercury(II) sulfate catalyst, the weakly nucleophilic alcohol adds once to excess butadiene in CCl_4 solvent when heated 16 h under pressure at 55 °C in a shaking Paar pressure bottle. A Markovnikov-directed 1,2- or 1,4-addition (eq 2) occurs, giving two vinyl ether prod-



(2)

7 **8**

ucts, the 3-(2-fluoro-2,2-dinitroethoxy)but-1-ene 1,2-adduct

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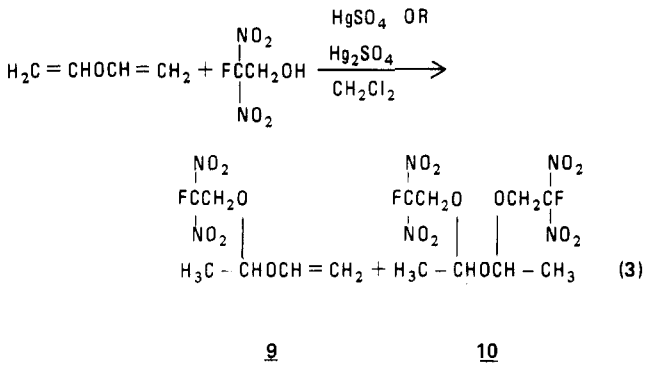
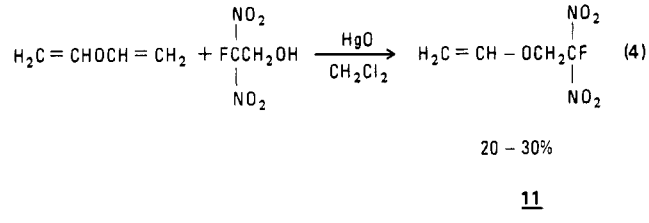
(16) Barlenga, J.; Anzar, F.; Bayod, M. *Synthesis* **1988**, *144*–146.

7 (77%) and 1,4-adduct, 1-(2-fluoro-2,2-dinitroethoxy)-but-2-ene, 8 (23%). No diadduct products were found with butadiene; this contrasts with divinyl ether, which produces both monoadduct 9 and diadduct 10 products (eq 3).



9 10

The addition of FDNEOH to divinyl ether (DVE) proceeds under milder conditions in refluxing CH_2Cl_2 solvent over 16 h with either mercury(II) or mercury(I) sulfate catalysis. The product distribution of 9 versus 10 is easily varied by the DVE/FDNEOH stoichiometry used. A detailed GLPC/MS analysis of the crude oil isolate of 2:1 DVE/FDNEOH stoichiometry using mercury(II) sulfate catalyst reveals the increasing retention time–product distribution: 2-fluoro-2,2-dinitroethyl vinyl ether (11) (6%), monoadduct 9 (70%), ethyl vinyl ether adduct 4 (3%), bis(2-fluoro-2,2-dinitroethyl) ethyl acetal 5 (1%), and the diadduct 10 (20%). The diadduct 10 appears as two overlapping peaks in the 30-m capillary HP SE-30 column and apparently represents a diastereomeric pair caused by the two asymmetric carbon atoms on each side of the bridging oxygen atom. The diastereomer of lower GLPC retention time predominates (56 to 44%) regardless of the DVE/FDNEOH reactant stoichiometry. This diastereomeric mixture apparently causes the ^1H NMR spectrum of 10 to give a multiplet resembling a pentet for the single hydrogen (δ 5.07) on each asymmetric carbon; theoretically, a quartet is expected. The three minor products 4, 5, and 11 all result from minor competing transetherification reaction pathways like that shown in eq 4. Under different



11

reaction conditions, the competing transetherification illustrated by eq 4 alternatively can become the exclusive reaction pathway and produce polynitroalkyl vinyl ethers by reaction of DVE with various β-substituted 2,2-dinitro alcohols.[17,18] DVE contains ethanol as a stabilizer (4%) even when purified, and the minor transetherification reaction between DVE and the ethanol stabilizer produces the intermediate ethyl vinyl ether that adds FDNEOH to form 4. Similarly, FDNEOH produces a trace of 11, and some 11 continues adding FDNEOH to yield 5. Such transetherification reactions are known in mercury(II)-catalyzed reactions between vinyl ethers and the more common nucleophilic alcohols.[19] Depending upon reaction stoichiometry, either the monoadduct product 9 or the diadduct 10 selectively predominates. Essentially, a 1:1 DVE/FDNEOH molar ratio with either mercury(I) or mercury(II) sulfate catalyst produces twice as much diadduct 10 as monoadduct 9, while a 2:1 DVE/FDNEOH ratio reverses this distribution. Table III provides a more detailed correlation of 9 and 10 product distribution as a function of reactant ratio, catalyst used, and product analysis method. A 3:1 DVE/FDNEOH reactant stoichiometry provides no significant increase in the monoadduct 9.

Table III. 2,2,2-Fluorodinitroethanol/Divinyl Ether Mono- and Diadduct Product Percentages

DVE/FDNEOH	catalyst[a]	% 9	% 10	anal. method
0.75	A	18	82	isoltd wt
0.93	A	27	73	^1H NMR
0.99	A	36	64	GLPC/MS
1.00	B	37	63	^1H NMR
2.00	B	68	32	^1H NMR
2.00	A	63	37	^1H NMR
2.00	A	60	40	GLPC/MS
2.00	A	78	22	GLPC/MS
2.00	B	59	47	isoltd wt

[a] A, $HgSO_4$; B, Hg_2SO_4.

While a change from mercury(II) to mercury(I) sulfate catalysis has little affect upon product distribution of the DVE and FDNEOH addition (Table III), altering the mercury salt anion displays a marked impact. Mercury(II) acetate catalyzes ambient temperature addition of FDNEOH to ethoxyacetylene and provides a high yield of the bis(2-fluoro-2,2-dinitroethyl) ethoxy ethyl orthoester 1, but little reaction occurs with DVE. Refluxing 40 h in CH_2Cl_2, less than 15% reaction occurs between DVE and FDNEOH with $Hg(OAc)_2$ catalyst. Analysis by GLPC/MS reveals only two minor reaction products, the vinyl ether 11 (3%) and the DVE monoadduct 9 (5%), plus unreacted alcohol (85%) and product 4 (7%) from the ethanol stabilizer. No trace of the diasteromeric diadduct 10 was observed even though some monoadduct 9 forms. Phenylmercury(II) chloride, which produces the orthoester 1 with ethoxyacetylene, also yields no appreciable amount of 9, 10, or 11 with DVE and FDNEOH even when reacted 68 h at room temperature followed by 5-h reflux in CH_2Cl_2 solvent. Catalysis of the reaction between DVE and FDNEOH by red mercury(II) oxide in refluxing CH_2Cl_2 produces only a transetherification reaction in which 11 is the exclusive product;[18] a 20–30% isolated yield indicates that the reaction does not proceed to completion (eq 4). This incomplete transetherification initially is driven by the elimination of the ethenol structural fragment from the DVE molecule to form ethenol's acetaldehyde tautomer as a reaction byproduct.[18] Reflux beyond 20 h fails to improve the yield of 11 and product degradation occurs. This important reaction can be driven to completion by modifing the reaction conditions and much higher yields of 11 result.[17,18] This reaction modification and the scope this novel transetherification are addressed in a future paper.

Conclusions

Markovnikov-directed additions of the weakly nucleophilic 2-fluoro-2,2-dinitroethanol (FDNEOH) to a variety of reactive unsaturated hydrocarbons is achieved by mercury salt catalysis under neutral, nonaqueous reaction

(17) Shackelford, S. A.; McGuire, R. R.; Cochoy, R. E. US Patent 4,426,540, Jan 17, 1984.
(18) Shackelford, S. A.; Cochoy, R. E.; Loving, B. A.; McGuire, R. R. *FJSRL-TR-77-0018*, Dec 1977.
(19) Watanbe, W. H.; Conlon, L. E. *J. Am. Chem. Soc.* **1957**, *79*, 2828–2833.

conditions. This finding expands the scope of potentially available 2-fluoro-2,2-dinitroethoxy acetal and ether compounds that suffer from severe limitations in possible synthesis strategies. Both the product yield or the specific 2-fluoro-2,2-dinitroalkoxy compound produced can depend upon the FDNEOH/alkene reactant stoichiometry or the specific mercury salt catalyst used. Under overnight ambient pressure reflux in CH_2Cl_2 or CCl_4 solvent, unsaturated hydrocarbons must possess an electron-donating substituent or oxygen atom at its C_2 or vinylic position. Otherwise, addition of the poor FDNEOH nucleophile fails to occur; but, more stringent reaction conditions in a sealed Paar pressure bottle may extend this reaction to less reactive alkynes and alkenes as shown by butadiene's reaction with FDNEOH. Demonstration of the subject reaction further opens the possibility of producing analogous new energetic acetal and ethers using other weakly nucleophilic 2,2-dinitroalkyl-substituted alcohols that also are subject to the facile deformylation reaction under alkaline or acidic conditions.

Experimental Section

General. The divinyl ether (DVE) used was purchased from PCR, Inc., Gainesville, FL,[20] and initially was used without further purification. Later purchases came from Marshallton Research Laboratory, Winston-Salem, NC. In later reactions, the ethanol stabilizer was enriched by DVE evaporation. The ethanol stabilizer was reduced to 4% (^{1}H NMR analysis) by two distillations (7 in. Vigereaux column), the second over CaH_2. Other alkenes and alkynes were distilled only when necessary. The 2-fluoro-2,2-dinitroethanol (FDNEOH) was purchased from the Naval Surface Warfare Center/White Oak Laboratory, Silver Spring, MD, as a 30% by-weight solution in CH_2Cl_2 solvent.[21] Prior to use, the CH_2Cl_2 was removed by rotary evaporation to yield a slightly yellow oil. (*Caution! The FDNEOH during solvent removal goes through a sensitivity maximum between 30% solution and neat compound; this operation should be conducted behind appropriate shielding.*) The viscous FDNEOH was vacuum distilled in a short path column (bp 36.0–38.8 °C at 0.1 mmHg). *Caution! FDNEOH can be explosive under the proper stimulus and also causes severe burns to the skin. Proper shielding and skin protection should be used when handling it or when working up reactions containing this reagent.* The distilled FDNEOH always contained a trace of 2-fluoro-2,2-dinitroethyl methyl formal. The mercury(I) and -(II) sulfate catalysts were obtained from J. T. Baker Chemical Co. ("Baker Analyzed" reagent) as was the red mercury(II) oxide. Mercury(II) acetate came from Fisher Scientific Co. (A.C.S. grade). Neutral aluminum oxide used in the purification and workup was "Baker Analyzed" purity (pH 6.9–7.4 water slurry). The CH_2Cl_2 and CCl_4 solvents were MCB spectrometric grade. Nuclear magnetic resonance ^{1}H spectra were taken either on a Varian A-60, T-60, or JOEL FXQ90 instrument ($CDCl_3$ solvent and TMS internal reference). Infrared spectra were obtained as a neat liquid film (NaCl plates) on a Beckman IR-20 spectrophotometer. Mass spectra were taken on a Dupont 21-491 double focusing mass spectrometer or with a Hewlet Packard 5985 GC/MS system. Elemental analyses were performed by Galbraith Laboratories, Knoxville, TN.

Addition of 2-Fluoro-2,2-dinitroethanol to Unsaturated Aliphatic Compounds (General Procedure). The alkene/alkyne was weighed into CH_2Cl_2 or CCl_4 solvent contained in an appropriate-sized round-bottom flask with a Teflon-coated stir bar. FDNEOH was added to the stirred solution; then, the solid Hg(I) or -(II) salt catalyst was added. The reaction flask was fitted with a water-cooled reflux condenser topped with a Drierite filled drying tube. The reaction was sometimes stirred at room temperature, but usually required reflux for 16–19 h. Reaction solution filtration and the solvent removal by rotary evaporation followed. The remaining oil was taken up in 1–3 mL of CCl_4 and was eluted through a short neutral aluminum oxide column to remove unreacted FDNEOH. This column was prepared by packing 2.5 g of aluminum oxide slurried in CCl_4 into a 15-mL "course" glass sintered Buchner funnel. CCl_4 removal afforded the addition product(s). Vacuum distillation provided further product purification.

Addition of 2-Fluoro-2,2-dinitroethanol to Ethoxyacetylene (Products 1 and 2). A flask charged with 1.05 g (15 mmol) of distilled ethoxyacetylene, 25 mL of CH_2Cl_2, 3.08 g (20 mmol) of FDNEOH, and 100 mg of mercury(II) acetate was stirred overnight at room temperature (ca. 16 h). Solvent removal and filtration of the resulting oil through 23 g of alumina (pH = 7.2) with CH_2Cl_2, followed by CH_2Cl_2 removal, afforded 3.59 g (95%) of clear yellow oil **2**. Vacuum distillation (molecular still), 90 °C/0.05 mm for 4 h, gave 3.26 g of less pure oil: density 1.42 g/mL; NMR (dd, 4.64, 4 H) with $J_{vic\text{-}HF}$ = 17 Hz, (q, 3.57, 2 H), (s, 1.54, 3 H), (t, 1.22, 3 H); IR (neat film) cm^{-1} 2990, 2950, 2900 (sat. CH), 1600, 1310 (NO_2). Anal. Calcd for $C_8H_{12}N_4O_7F_2$: C, 25.4; H, 3.20; N, 14.8; F, 10.1). Found: C, 25.4; H, 3.19; N, 14.7; F, 10.1). In one experiment, 27% vinyl acetal **2** was obtained by distillation (48 °C/0.2 mm) of the crude oil mixture with **1**: NMR (dd, 4.94, 2 H) with $J_{vic\text{-}HF}$ = 16.5 Hz (q, 3.96, 2 H), (q 3.37, 2 H), (t, 1.33, 3 H).

Addition of 2-Fluoro-2,2-dinitroethanol to 3,4-Dihydropyran (Product 3). A flask charged with 1.00 g (11.9 mmol) of 3,4-dihydropyran, 10 mL of CCl_4, and 1.00 g (6.5 mmol) of FDNEOH was stirred under reflux for 17 h. CCl_4 solvent removal afforded 1.56 g (100%) of light yellow oil: NMR (m, 4.82, 1 H), (dd, 4.70, 2 H), (m, 3.72, 2 H), (m, 1.68, 6 H).

Addition of 2-Fluoro-2,2-dinitroethanol to Ethyl Vinyl Ether (Product 4). A flask charged with 2.15 g (30 mmol) of ethyl vinyl ether, 25 mL of CH_2Cl_2, and 3.08 g (20 mmol) of FDNEOH was cooled with stirring in an ice bath before 200 mg of $HgSO_4$ was added. The solution was stirred for 16 h at room temperature. Workup gave 4.65 g of crude oil; vacuum distillation through a 6-in. Vigreaux column at 34–35 °C/0.10 mm yielded 3.29 g (73%) of product **4** as a colorless oil: NMR (q, 4.92, 1 H), (dd, 4.60, 2 H) with $J_{vic\text{-}HF}$ = 18 Hz, (m, 3.60, 2 H), (m, 1.26, 6 H); IR (neat film) cm^{-1} 2995, 2940, 2900 (sat. CH), 1600, 1315 (NO_2); mass spectrum, characteristic m/e 225 (M − 1), 211, 183, 181, 155, 134, 91, 77, 73, 45 (base), 30, 29. Anal. Calcd for $C_5H_{11}N_2O_6F$: C, 31.9; H, 4.87; N, 12.4; F, 8.41. Found: C, 31.9; H, 4.69; N, 12.2; F, 8.35.

Addition of 2-Fluoro-2,2-dinitroethanol to 2-Fluoro-2,2-dinitroethyl Vinyl Ether (Product 5). A flask charged with 1.50 g (8.3 mmol) of 2-fluoro-2,2-dinitroethyl vinyl ether,[18] 20 mL of CH_2Cl_2, 1.28 g (8.3 mmol) of FDNEOH, and 250 mg of $HgSO_4$ was stirred under reflux for 24 h. The isolated crude oil was molecular distilled at 68.0–68.4 °C/0.2 mm to yield 1.71 g (61%) of product **5**. Colorless oil with a density = 1.55 g/mL: NMR (q, 5.02, 1 H), (dd, 4.64, 4 H) with $J_{vic\text{-}HF}$ = 17 Hz, (d, 1.43, 3 H); IR (cm^{-1}) 3000, 2950, 2900 (sat. CH), 1600, 1310 (NO_2); mass spectrum, m/e 333 (M − 1), 319, 181, 147, 133, 91, 75, 73, 57, 45, 44, 30 (base), 29. Anal. Calcd for $C_4H_8N_4O_{10}F_2$: C, 21.6; H, 2.40; N, 16.8; F, 11.4. Found: C, 21.6; H, 2.5; N, 16.6; F, 11.2.

Addition of 2-Fluoro-2,2-dinitroethanol to 2-Methyl-1-pentene (Product 6). (a) A flask charged with 2.52 g (30 mmol) of 2-methyl-1-pentene, 25 mL of CH_2Cl_2, 3.08 g (20 mmol) of FDNEOH, and 200 mg of $HgSO_4$ was stirred under reflux for 16 h. The purple solution yielded 2.95 g of crude product. Vacuum distillation at 47–48 °C/0.2 mm (6-in. Vigreaux column) gave 3.51 g (74%) of nearly colorless oil **6**. Redistillation, 45 °C/0.2 mm, was done with a 12-in. glass bead column: NMR (dd, 4.42, 2 H), (s amid a mult, 1.17, 13 H); IR (cm^{-1}) 2970, 2940, 2880 (sat. CH), 1600, 1315 (NO_2). Anal. Calcd for $C_7H_{15}N_2O_5F$: C, 40.4; H, 6.36; N, 11.8; F, 7.98. Found: C, 40.4; H, 6.37; N, 11.7; F, 7.76.

(b) A flask charged with 1.00 g (12 mmol) of 2-methyl-1-pentene, 20 mL of CH_2Cl_2, 1.85 g (12 mmol) of FDNEOH, and 550 mg of Hg_2SO_4 was stirred under reflux for 48 h. Workup gave 1.58 g of purple oil (58%) **6**: NMR (dd, 4.42, 2 H), (s amid a mult, 1.17, 14 H).[22]

(20) Divinyl ether is no longer available from this source. Later, quantities were obtained from Marshallton Research Laboratory, P.O. Box 11646, Winston-Salem, NC 27106.

(21) This material is available from Fluorochem, Inc., 680 S. Ayon Ave., Azusa, CA 91702.

(22) This integration should be 13 H; the product possesses a slight unidentified impurity.

Addition of 2-Fluoro-2,2-dinitroethanol to 1,3-Butadiene (Products 7 and 8). A Paar pressure bottle charged with 40 mL of CCl_4 was cooled in an ice bath before 4.2 g (7.8 mmol) of 1,3-butadiene was bubbled into the solvent. Next, 3.08 (2.0 mmol) of 2-fluoro-2,2-dinitroethanol and 100 mg of $HgSO_4$ were added to the Paar bottle. The bottle, stoppered with a Teflon-brand wrapped rubber stopper, was shaken at 55 °C for 16 h. The reaction product was then washed through 23 g of alumina (pH = 7.2) with CCl_4. The CCl_4 was removed; the product was again filtered through 23 g of alumina with a CCl_4 wash. CCl_4 removal provided 4.05 g of light reddish brown oil. Vacuum distillation (6-in. Vigreaux column) at 35 °C/0.10 mm gave 2.19 g (53%) of light yellow oil. The distillate contained mainly the 1,2-adduct 7 with some 1,4-adduct 8. Distillation (51.0–51.5 °C/1.6 mm) (12-in. glass bead column) provided nearly pure (90%) 1,2-adduct 7; the 1,4-adduct would not distill even with a diethyl succinate pot chaser. Analytical samples of the two adducts were obtained by preparative GLPC (8 ft. by $^1/_2$ in. 20% Dow 710 silicon oil column) at 148 °C. **1,2-Adduct 7**: NMR (m, 5.55, 3 H), (dd, 4.48, 2 H) with $J_{vic\text{-}HF}$ = 18 Hz, (pent, 4.02, 1 H), (d, 1.25, 3 H); IR (cm^{-1}) 3090 (=CH), 2990, 2930, 2890 (sat. CH), 1600, 1310 (NO_2). Anal. Calcd for $C_5H_9N_2O_5F$: C, 34.6; H, 4.36; N, 13.5; F, 9.13. Found: C, 34.85; H, 4.39; N, 13.3; F, 9.16. **1,4-Adduct 8**: NMR (m, 5.62, 2 H), (dd, 4.49, 2 H) with $J_{vic\text{-}HF}$ = 18 Hz, (d, 1.76, 3 H); IR (cm^{-1}) 3010 (=CH), 2985, 2960, 2920, 2870 (sat. CH), 1600, 1315 (NO_2). Anal. Calcd for $C_5H_9N_2O_5F$: C, 34.6; H, 4.36; N, 13.5; F, 9.13. Found: C, 34.85; H, 4.39; N, 13.6; F, 8.71.

Addition of 2-Fluoro-2,2-dinitroethanol to Divinyl Ether (Products 9 and 10). **(a)** A flask charged with 1.05 g (15 mmol) of divinyl ether (DVE), 25 mL of CH_2Cl_2, 3.08 g (20 mmol) of FDNEOH, and 200 mg of $HgSO_4$ was stirred under reflux for 16 h. Short-path vacuum distillation (43.2–43.4 °C/0.3 mmHg) of the isolated oil afforded 0.4 g (12%) of monoadduct **9**. The pot residue was taken up in CCl_4 and passed through a short alumina (pH = 7.2) column. CCl_4 removal gave 2.20 g (58%) of pure diadduct 10, density = 1.42 g/mL. Diadduct **10**: NMR (pent, 5.07, 2 H), (dd, 4.57, 4 H) with $J_{vic\text{-}HF}$ = 18 Hz, (d, 1.39, 6 H); IR (cm^{-1}) 3000, 2940 (sat. CH), 1600, 1310 (NO_2); mass spectrum, characteristic m/e 181 (higher GLPC diastereomer), 147, 133, 119, 105, 91, 75, 73, 45 (base), 44, 30, 29. Anal. Calcd for $C_6H_{12}N_4O_{11}F_2$: C, 25.4; H, 3.20; N, 14.8; F, 10.1. Found: C, 25.6; H, 3.20; N, 14.7; F, 10.0.

(b) DVE (2.10 g, 30.0 mmol), FDNEOH (2.31 g, 15.0 mmol), and 200 mg of $HgSO_4$ in 25 mL of CH_2Cl_2 refluxed 16 h produced 3.28 g of crude oil product. GC/MS analysis revealed the following crude product distribution: **11** (6%), **9** (70%), **4** (3%), **5** (1%), and **10** (20%). Prolonged or gradual heating during distillation causes apparent polymerization of **9**.

(c) A flask charged with 2.0 g (28.6 mmol) of DVE, 60 mL of CH_2Cl_2, 2.2 g (14.3 mmol) of FDNEOH, and 750 mg of Hg_2SO_4 was stirred under reflux for 26 h. Workup produced 2.63 g of crude oil containing both monoadduct **9** and diadduct **10**. Short-path vacuum distillation afforded 1.29 g (40%) of monoadduct **9**. The pot residue was dissolved in CH_2Cl_2 and eluted through a short alumina column. CH_2Cl_2 removal gave 0.91 g (34%) of diadduct **11**. **Monoadduct 9**: NMR (dd, 6.36, 1 H), (q, 5.14, 1 H), (dd, 4.62, 2 H) with $J_{vic\text{-}HF}$ = 18 Hz, (m, 4.50, 2 H), d, 1.40, 3 H); IR (cm^{-1}) 3120, 3070 (=CH), 3000, 2945 (sat. CH), 1645 (C=C), 1600, 1315 (NO_2); mass spectrum, characteristic m/e 181, 134, 105, 91, 87, 71, 45 (base), 44, 43, 30, 29. Anal. Calcd for $C_5H_9N_2O_6F$: C, 32.2; H, 4.05; N, 12.5, F, 8.48. Found: C, 32.0; H, 3.98; N, 12.5; F, 8.31.

Acknowledgment. We are deeply indebted to Dr. H. G. Adolph and Dr. M. J. Kamlet (deceased Feb 1988), NSWC/WOL, for their helpful technical discussions and encouragement. Mr. J. L. Pflug (FJSRL) provided extensive ^1H NMR and GLPC/mass spectral analyses; Dr. Clay M. Sharts (SDSU) and Dr. John E. Marlin (FJSRL) provided helpful manuscript comments, and Mrs. Linda Pukajilo (FJSRL) aided in manuscript preparation. The Air Force Office of Scientific Research through Dr. D. L. Ball, Director of Chemical and Atmospheric Sciences, generously provided financial support.

Registry No. 1, 88934-30-9; 2, 124618-93-5; 3, 124618-94-6; 4, 124618-95-7; 5, 124618-96-8; 6, 88934-26-3; 7, 88934-28-5; 8, 88934-29-6; 9, 88934-27-4; (±)-10, 124618-97-9; *meso*-10, 124618-98-0; 11, 52483-76-8; FDNEOH, 17003-75-7; DVE, 109-93-3; H_2C=CHOFDNE, 52483-76-8; EtOC≡CH, 927-80-0; EtOCH=CH_2, 109-92-2; H_2C=C(Me)$CH_2CH_2CH_3$, 763-29-1; H_2C=CH-H=CH_2, 106-99-0; $Hg(OAc)_2$, 1600-27-7; $HgSO_4$, 7783-35-9; Hg_2SO_4, 7783-36-0; HgO, 21908-53-2; 3,4-dihydropyran, 110-87-2.

A Short Enantiodivergent Synthesis of the Geissman–Waiss Lactone[1]

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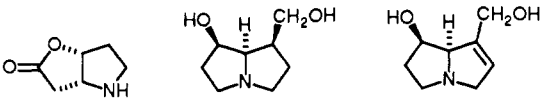
Received September 5, 1989

The Geissman–Waiss lactone (1) has been shown to be a useful intermediate in the synthesis of pyrrolizidine alkaloids such as retronecine.[2] In recent years, (+)-1 (with absolute stereochemistry as depicted in 1) has been used



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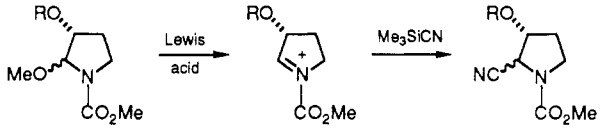
in the chirospecific synthesis of a number of pyrrolizidine alkaloids such as (−)-platynecine (2) and (+)-retronecine (3).[3] The enantioselective synthesis of (+)-1 from an optically active starting material has been achieved by several groups.[4] We here report a short synthesis of both (+)- and (−)-1[5] from a common intermediate, thus making it possible to synthesize both enantiomers of various pyrrolizidine alkaloids.

We recently reported on the preparation and reactivity of the *N*-acyliminium ion **5** (generated in situ from the electrochemically prepared α-methoxylated carbamate **4**).[6]



4b; R = Ac
c; R = TBDMS

5 **6**

It was shown that, on reaction with Me_3SiCN, the stereoselectivity could be controlled to give **6** in cis:trans ratios varying from 86:14 to 42:58 by using different O-protective groups. In addition, amidoalkylation occurred without racemization at C(3).[7,8] The synthon **5** incorporates the same absolute stereochemistry at C(3) as (+)-1, and in addition, C(2) is easily functionalized via reaction with a nucleophile. Thus, intermediate **5** is an ideal starting point for the enantioselective synthesis of (+)-1.

The introduction of the carbon chain at C(2) in **5** was achieved by using allyltrimethylsilane as the nucleophile[8,9] (Scheme I). Control of the stereoselectivity was again possible by using different O-protective groups. The cis:trans ratios varied from 77:23 (R = TBDMS) to 21:79 (R = Ac). Only very small effects on the stereoselectivity were observed when the temperature and the Lewis acid were changed (see Table I). The separation and identification[10] of the different allyl compounds were carried out

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0022-3263/90/1955-1406$02.50/0