reduced pressure gave 3.5 g (41% yield) of **8** with a purity by GC of 87%. Column chromatography (silicAR cc-7) with petroleum ether (bp 30–60 °C) followed by redistillation gave an analytically pure sample as a colorless oil: bp 103–105 °C (21 mmHg); IR 1740 (C=O) and 1625 cm^{-1} (C=C); NMR δ 5.88 (ragged t, C=CH), 3.70 (s, OCH_3), 2.67–2.20 (m, CH_2CH_2); mass spectrum, *m/e* (rel intensity) 182 (M^+ for Cl = 35, 20.5), 122 (100). Anal. Calcd for $C_6H_8Cl_2O_2$: C, 39.37; H, 4.41; Cl, 38.74. Found: C, 39.56; H, 4.34; Cl, 38.51.

With THF as the solvent, **7** (10 mmol) gave **8** in a 59% yield after one distillation. The purity of the distilled sample was 85%.

5,5-Dichloro-4-pentenoic Acid (2). A mixture of pure **8** (0.549 g, 3 mmol) in MeOH (6 mL) and KOH (1.18 g, 21 mmol) was stirred at 5 °C for 30 min and then at room temperature for 2 h (Ar atmosphere). The mixture was concentrated on a rotary evaporator and the semisolid residue was dissolved in water. The aqueous phase was washed with hexane, acidified to pH 1 with 1 N HCl, and extracted with methylene chloride. The organic phase was washed with a saturated solution of NaCl and dried (Na_2SO_4). Evaporation of the solvent gave **2** (456 mg, 90%) as a colorless oil: IR 1710 (C=O) and 1625 cm^{-1} (C=C); NMR δ 9.92 (s, COOH, exchanged with D_2O), 5.92 (m, C=CH), 2.73–2.20 (m, CH_2CH_2). Acid **2** was found to slowly decompose on storage at room temperature as indicated from the appearance of NMR signals near 3.5 ppm. At 4 °C, the compound appeared to be stable for several months. After **2** (400 mg) was stirred in hexane (10 mL) and 1 N sodium carbonate (3 mL) for 1 h, the aqueous phase was removed and treated with methanol (30 mL) and THF (60 mL). The mixture was cooled at 4 °C, then filtered, and evaporated. Lyophilization of the concentrated filtrate gave a sodium salt of **2** (390 mg) as a white, crystalline power: mp 180–185 °C.

6,6-Dichloro-5-hexen-2-one (13). According to the general Wittig procedure, **11** (11.5 g, 80 mmol)[9] was reacted with **4** in benzene solution (100 mL) for 24 h. The crude product (~18.5 g) isolated after filtration and evaporation of the solvents showed two main peaks by GC. This sample (a mixture of **12** and **13**) was dissolved in THF (150 mL) and 5 N HCl (50 mL) was added. After 4 h at room temperature, the solution was neutralized to pH 7 with $NaHCO_3$. The THF was removed on a rotary evaporator and a saturated solution of NaCl (80 mL) was added. The product was extracted with ether and the organic extract was dried ($MgSO_4$). Distillation under reduced pressure gave **13** (9.44 g, 70.8%) as a nearly colorless oil: bp 37–38 °C (0.2 mm); IR 1715 (C=O) and 1620 cm^1 (C=C); NMR δ 5.88 (ragged t, C=CH), 2.80–2.33 (m, CH_2CH_2), 2.17 (s, CH_3); mass spectrum, *m/e* (rel intensity) 166 (M^+, 35.5), 131 (100). Anal. Calcd for $C_6H_8Cl_2O$: C, 43.14; H, 4.83; Cl, 42.45. Found: C, 43.44; H, 5.02; Cl, 42.21.

This experiment was repeated with 39, 63.8, and 69.4 mmol of **11**. The respective yields, based on distilled samples of **13**, were 50, 60, and 75%. The purity by GC was ~85%.

Haloform Oxidation of 13. Ketone **13** (13.55 g, 81 mmol) was dissolved in dioxane (100 mL) and cooled to 2 °C. To this solution was added dropwise during 15 min a cold solution of NaOBr, prepared by adding Br_2 (51.62 g, 323 mmol) to an ice-cold solution of NaOH (38.93 g) in water (200 mL). The mixture was stirred mechanically for 1 h and then at room temperature for 5 h. A solution of sodium sulfite (9.9 g) in water (90 mL) was added to the faint-yellow mixture and the pH was adjusted to 12 with NaOH pellets. After extraction with ether, the aqueous phase was adjusted to pH 2 with HCl. The mixture was saturated with NaCl and then extracted with ether. The combined ether extracts were washed with a saturated solution of NaCl and dried ($MgSO_4$). Removal of the dioxane by distillation left a crude yellow product (9.2 g). A portion of the residue was purified by column chromatography (silicAR cc-7). A middle fraction, obtained by elution with hexane–ether (5:1, v/v), gave 5,5-dichloro-4-pentenoic acid (20.1% yield) as determined by NMR spectral comparison to **2** from Scheme I.

A sample of **2** (100 mg) was treated with 10 mL of a methanolic solution of HCl and heated under reflux for 15 h. After addition of water, the mixture was extracted with hexane. Evaporation of the dried ($MgSO_4$) organic extracts gave 104 mg of an oil (63% pure by GC). The major component was isolated by column chromatography (silicAR cc-7) with hexane and was identified as **8** by GC and mass spectral comparison to **8** obtained by the sequence in Scheme I.

Acknowledgment. I thank Mr. Art Hewitt for technical assistance and Mr. Jim Elder for recording the mass spectra.

Registry No. 2, 4189-05-3; **2**·Na, 78019-16-6; **4**, 6779-08-4; **5**, 591-80-0; **6**, 818-57-5; **7**, 13865-19-5; **7** 2,4-dinitrophenylhydrazone, 15903-35-2; **8**, 38666-11-4; **11**, 24108-29-0; **12**, 78019-17-7; **13**, 57054-18-9; $CBrCl_3$, 75-62-7.

Selective Reductive Carbonyl Couplings with Titanium

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Considerable interest recently has been shown in the reductive coupling of ketones and aldehydes to olefins, using low-valent titanium reagents,[1] accessible from $TiCl_3$ or $TiCl_4$ by reduction with Zn,[3,4] Mg,[5] Zn–Cu couple,[6] K, Li,[6a,7] or $LiAlH_4$.[8] Intramolecular dicarbonyl coupling to cycloalkenes is also possible in high yield, including medium sized rings.[6a] This formal reverse of a double bond ozonolysis appears to have great synthetic potential. However, the reagent also reacts with other functional groups.[9] Its use was therefore assumed to be limited to cases where functional groups other than alcohols, ethers, and olefins are not present.[6a]

We now report our results on the selective reductive coupling of aromatic aldehydes and ketones having carboxylate or tosylate ester functionalities to the corresponding stilbenes (Schemes I and II). Contrary to what was expected on the basis of previous works,[5,6a,7] in most cases the ester groups remained unaffected under the reaction conditions.

In connection with another project we needed to prepare the phenolic stilbene **1**. The most simple approach seemed to be the reductive coupling of a suitably protected benzaldehyde. We first tried the *O*-benzyl-protected benzaldehyde **2a**, the corresponding stilbene **3a** resulting in a high yield on reaction of **2a** with $TiCl_3$ and Zn–Cu.

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[1] The so-called low-valent titanium species seem in most cases to be active Ti^0, as can be inferred from the work of R. D. Rieke, *Acc. Chem. Res.*, **10**, 301 (1977) and ref 6a. (π-C_6H_6)$_2Ti^0$ has also been used.[2]

[2] H. Ledon, I. Tkatchenko, and D. Young, *Tetrahedron Lett.*, 173 (1979).

[3] T. Mukaiyama, T. Sato, and J. Hanna, *Chem. Lett.*, 1041 (1973); D. Lenoir and P. Lemmon, *Chem. Ber.*, **113**, 3112 (1980).

[4] J. Drabowicz and M. Mikolajczyk, *Synthesis*, 138 (1978).

[5] S. Tyrlik and I. Wolochowick, *Bull. Soc. Chim. Fr.*, 2147 (1973).

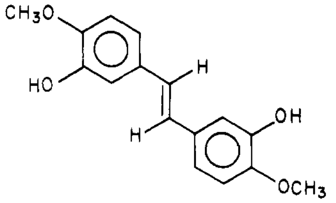
[6] (a) J. E. McMurry, M. P. Fleming, K. L. Kees, and L. R. Krepski, *J. Org. Chem.*, **43**, 3255 (1978); (b) J. A. Marshall, R. E. Bierenbaum, and K. H. Chung, *Tetrahedron Lett.*, 2081 (1979).

[7] S. C. Welch and M. Walters, *J. Org. Chem.*, **43**, 4797 (1978).

[8] J. E. McMurry and M. P. Fleming, *J. Am. Chem. Soc.*, **96**, 4708 (1974); H. Wynberg, K. Lammerstsma, and L. A. Hulshot, *Tetrahedron Lett.*, 3749 (1975); R. F. Langler and T. T. Tidwell, *ibid.*, 777 (1975); D. S. Bomse and T. H. Morton, *ibid.*, 781 (1975); A. L. Baumstark, E. J. H. Bechara and H. J. Semigram, **ibid.**, 3265 (1976); P. D. Mollere, K. N. Houk, D. L. Bomse, and T. H. Morton, *J. Am. Chem. Soc.*, **98**, 4732 (1976).

[9] Low-valent titanium species are known to react with esters,[5,6a,7] acid chlorides, 1,2-diketones, α-bromo and α-phenyl sulfenyl ketone enolates, ketals[6a], thioketals, organic halides[10], epoxides[2,10], sulfoxides,[4] and enol phosphates.[7]

[10] T. Mukaiyama, *Angew Chem., Int. Ed. Engl.*, **16**, 817 (1977), and references therein.



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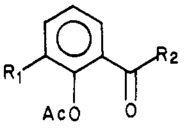
However, attempts to remove its *O*-benzyl protecting groups by acid treatment gave unacceptable yields of the desired stilbene 1 because of competing polymerization.[11] Consequently, we turned our attention to a benzaldehyde derivative with an *O*-protecting group which is labile under basic conditions. When the *O*-acetyl-protected benzaldehyde **2b** was submitted to reductive coupling as above, a high yield of the corresponding stilbene **3b** (Table I) resulted.

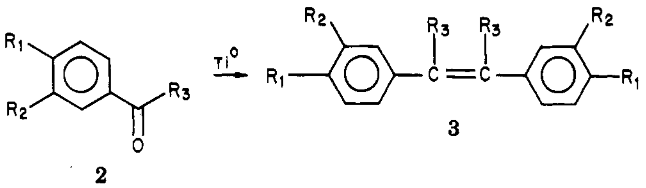
The results in Table I indicate that the reductive coupling takes place selectively in good to excellent yields,[12] provided that the acyloxy group is at the meta or para position. It can be argued that as only a 2-fold molar excess of Ti^0 is used, the available Ti^0 could first react with the aldehyde or ketone moiety, without leaving any surplus reagent to react further with the ester. However, we also found that although optimum yields are achieved with 2- to 4-fold molar excess, it was necessary to use up to a 10-fold molar excess of Ti^0 to obtain a substantial decrease in the yield.

In those cases where the ester is ortho to the carbonyl (compounds **4a,b**) only complex mixtures of products were obtained. Some of the products isolated from these mixtures were shown to be mono or diphenolic,[13] suggesting that the intermediate glycolate[6a] suffered intramolecular transesterifications, thereby preventing the formation of the desired protected ortho phenolic stilbenes.



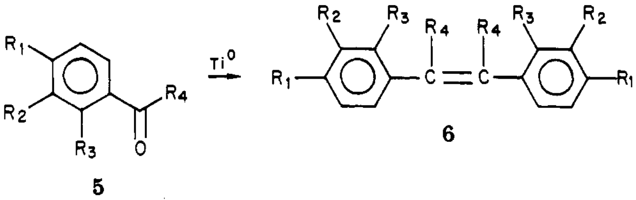
4a, $R_1 = CH_3O; R_2 = H$
b, $R_1 = H; R_2 = CH_3$

Scheme I



a, $R_1 = CH_3O; R_2 = C_6H_5CH_2O; R_3 = H$
b, $R_1 = CH_3O; R_2 = AcO; R_3 = H$
c, $R_1 = R_3 = H; R_2 = AcO$
d, $R_1 = AcO; R_2 = R_3 = H$
e, $R_1 = AcO; R_2 = CH_3O; R_3 = H$
f, $R_1 = H; R_2 = AcO; R_3 = CH_3$
g, $R_1 = AcO; R_2 = H; R_3 = CH_3$
h, $R_1 = CH_3O; R_2 = COOCH_3; R_3 = H$
i, $R_1 = CH_3O; R_2 = CH_3OOCCH_2CH_2OCO; R_3 = H$

Scheme II



a, $R_1 = CH_3O; R_2 = p\text{-}CH_3C_6H_4SO_3; R_3 = R_4 = H$
b, $R_1 = R_4 = H; R_2 = CH_3O; R_3 = p\text{-}CH_3C_6H_4SO_3$
c, $R_1 = R_2 = H; R_3 = p\text{-}CH_3C_6H_4SO_3; R_4 = CH_3$

Table I. Couplings of Benzaldehydes and Acetophenones by Ti^0 [a]

starting compd	solvent	reacn time, h	stilbene	% yield	mp, °C
2b [f]	DME	16	3b [b]	97	259-260
2c [f]	DME	16	3c [b]	87	131-132
2d	THF	17	3d [b]	94	214-217 [c]
2e	THF	16	3e [b]	87	227-229 [d]
2f [f]	DME	16	3f	75	94.5-95.5
2g	DME	16	3g	64	123-124 [e]
2h [f]	THF	13	3h [b]	74	138.5-140
2i [f]	DME	16	3i [b]	60	118-120
4a	DME	14	complex mixture		
4b	DME	21	complex mixture		
5a [f]	THF	16	6a [b]	80	217-218.5
5b [f]	THF	16	6b [b]	92	251-253
5c [f]	THF	16	6c	64	138-141

[a] Reaction conditions were not optimized. [b] UV data supports trans stereochemistry, although the presence of minor amounts of cis stilbenes cannot be completely excluded. [c] Lit. mp 215-18 °C: W. S. Johnson, C. A. Erickson and J. Ackerman, *J. Am. Chem. Soc.*, 74, 2251 (1952). [d] Lit. mp 227-29 °C: J. Gierer, J. Lenic, I. Norén, and I. Szabo-Din, *Acta Chem. Scand., Ser. B*, 28, 717 (1974). [e] Lit. mp 123-24 °C: S. H. Zaheer, B. Singh, B. Bhushan, P. M. Bhargava, I. K. Kaaker, K. Ramachandran, V. D. N. Sastri, and N. R. Rao, *J. Chem. Soc.*, 3360 (1954). [f] Satisfactory analytical data (±0.4% for C, H, and S when present) were provided for compounds 3b,c,f,h,i and 6a-c.

Although tosylates should obviously remain unaffected by this transesterification step, there were doubts about their capacity to withstand the reductive conditions (tosylates are known to be reduced by one-electron donors such as Na–Hg/EtOH, Na/liquid NH_3, and sodium naftalidide).[14] Fortunately, as shown in **5a–c** (Table I) the tosyloxy group turned out to be totally compatible with the reaction conditions, thus providing a unique way to generate protected ortho phenolic stilbenes (Scheme II).

In summary, this work shows that in most cases aromatic aldehydes and ketones having acyloxy, carbomethoxy, or tosyloxy groups give Ti^0-induced carbonyl reductive cou-

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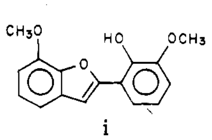
[11] Attempted catalytic hydrogenolysis of compound **3a** caused an undesired reduction of the central double bond of stilbene 1.

[12] It is worth noting that coupling of the benzaldehyde **2i** with two ester groups (aromatic and aliphatic) also gives a good yield of the corresponding stilbene **3i**.

[13] From the reaction mixture of compound **4a** we have isolated three products to which we have tentatively assigned (on the basis of spectral data) structures i, ii, and iii. They were obtained in 8, 18, and 2.5% yields, respectively.



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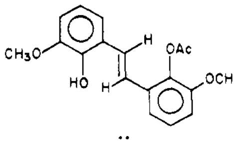

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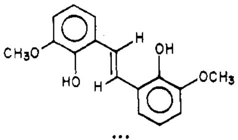

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[14] W. D. Closson, P. Wriede, and S. Bank, *J. Am. Chem. Soc.*, **88**, 1581 (1966), and references therein.

plings in high yield, suggesting that further work is necessary in this field to achieve selective reductive couplings in the presence of other reducible functional groups.

Experimental Section

General Procedures. All melting and boiling points are uncorrected. Proton NMR spectra were run with a Varian CFT-20 using Me_4Si as the internal standard. Mass spectra were recorded with a Kratos MS-25 instrument. IR spectra were recorded with a PYE UNICAM 1100 spectrometer and UV spectra with a PYE UNICAM 1700.

Starting acetates and tosylates were prepared by treatment with Ac_2O and TsCl, respectively, in dry pyridine of the corresponding commercial phenols. Compound **2h** was synthesized from 5-formylsalicylic acid[15] by treatment with diazomethane. The synthesis of benzaldehyde **2i** is described below. The Zn–Cu couple was prepared according to the procedure of McMurry et al.[6a] All sensitive materials were transferred under inert atmosphere conditions, using a dry box or Schlenk apparatus. Solvents were dried by reflux over Na or H_2Ca in an Ar atmosphere. All starting materials were purified by crystallization or distillation under low pressure.

Benzaldehyde 2i. 3-Hydroxy-4-methoxybenzaldehyde (2 g, 13.1 mmol), succinic anhydride (1.986 g, 19.8 mmol), and 4-(dimethylamino)pyridine (32 mg, 0.26 mmol) were dissolved in 10 mL of dry pyridine and left for 2 days at room temperature. After addition of 30 mL of CH_2Cl_2, the resulting solution was washed 4 times with HCl (10%), dried (Na_2SO_4), and concentrated to half its volume by gently warming at the rotary evaporator. The solution was then immediately cooled in an ice bath and an ether solution of diazomethane (excess) was added. After 20 min unreacted diazomethane was destroyed with acetic acid, and the solution was washed with NaOH (5%), dried (Na_2SO_4), and concentrated under reduced pressure, giving compound **2i** as a thick oil (2.5 g, 72% yield). Distillation in a Kugelrohr oven in vacuo produced an analytically pure sample of compound **2i**: bp 190–5 °C (2 mm); IR (film) 1745, 1695, 1605, 1275 cm^{-1}; UV (EtOH) λ_{max} ($\log \epsilon$) 271 (3.83); ^1H NMR ($CDCl_3$) δ 7.72 (dd, J = 1.7 and 8.1 Hz, 1, 6-H), 7.56 (d, J = 1.7 Hz, 1, 2-H), 7.02 (d, J = 8.1 Hz, 1, 5-H), 3.90 and 3.72 (two 3 H singlets, $\mathbf{CH_3}O_2C$ and $\mathbf{CH_3}OAr$), and 2.73 (A_2B_2 system, 4, $RO_2C\mathbf{CH_2}\mathbf{CH_2}CO_2Ar$); mass spectrum, m/e 266 (M^+, 2), 235 (5), 152 (23), 151 (20), 116 (100).

Anal. Calcd for $C_{13}H_{14}O_6$: C, 58.64; H, 5.30. Found: C, 58.77; H, 5.47.

General Procedure for the Titanium-Induced Couplings. $TiCl_3$ (1.03 g, 6.7 mmol) and 1.5 g of Zn–Cu couple[6a] were covered with 20 mL of dry solvent (see Table I). The mixture was refluxed for 1 h with effective stirring under Ar atmosphere. A solution of 3.35 mol of the carbonyl compound in 5 mL of dry solvent was added at once, and refluxing was continued for the amount of time indicated in Table I.

To the reaction mixture was added 25 g of silica gel, and the solvent was removed under vacuum, the residue being incorporated at the top of a silica gel column. Stilbenes were eluted with CH_2Cl_2, normally giving crystalline compounds.

Acknowledgment. To the Comisión Asesora de Investigatión Científica y Técnica (Spain) for its financial support, to INAPE for a grant to G.T., and to Professor M. Gayoso (Inorganic Department) (Santiago) for technical assistance.

Registry No. 2b, 881-57-2; **2c**, 34231-78-2; **2d**, 878-00-2; **2e**, 881-68-5; **2f**, 18749-47-8; **2g**, 7398-52-9; **2h**, 78515-16-9; **2i**, 78515-17-0; (*E*)-**3b**, 78515-18-1; (*E*)-**3c**, 78515-19-2; (*E*)-**3d**, 47241-75-8; (*E*)-**3e**, 7329-59-1; **3f**, 78515-20-5; **3g**, 78515-21-6; (*E*)-**3h**, 78515-22-7; (*E*)-**3i**, 78515-23-8; **4a**, 7150-01-8; **4b**, 7250-94-4; **5a**, 78515-24-9; **5b**, 7740-04-7; **5c**, 70188-11-3; (*E*)-**6a**, 78515-25-0; (*E*)-**6b**, 78515-26-1; **6c**, 78515-27-2; 3-hydroxy-4-methoxybenzaldehyde, 621-59-0; succinic anhydride, 108-30-5; Ti, 7440-32-6.

Supplementary Material Available: Table II, reporting the physical properties of compounds **3b**,**c**,**f**,**h**,**i** and **6a–c** (1 page). Ordering information is given on any current masthead page.

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Measurement and Estimation of the Heats of Vaporization of Hydrocarbons

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Studies of the strain and resonance energies of organic compounds involve the heats of formation of the given species and that of the reference species to which it is compared.[4] Thermochemical logic suggests consideration of the ideal gas phase at STP as the standard reference state for comparison. The absence of the required ΔH_f and/or ΔH_v or ΔH_s has seemingly hindered many studies. For a given compound, the energy (enthalpy) of the condensed and gaseous phases are related by the heats of vaporization (ΔH_v) and sublimation (ΔH_s). Determination of these heats is often achieved by measuring the equilibrium vapor pressure of the compound at various temperatures. Direct measurement of vapor pressure has been used for both volatile solids and liquid. The measurement of low vapor pressures has been accomplished by a variety of methods.[5] Accurate measurement of low vapor pressures is more difficult and/or tedious, and the presence of systematic errors and disagreement between alternative approaches has rendered many of the reported results subject to question. Recently we reported on an equilibration technique which affords reliable ΔH_s results by measurement of vapor pressure as a function of temperature.[5] All previous results were obtained on solids of low volatility. We now report results which extend the range of this technique to liquid hydrocarbons of low to moderate volatility. We also elaborate on a simple empirical procedure for estimating heats of vaporization in instances where insufficient data are available in the literature.

The applicability of the equilibration technique to liquids of moderate volatility was demonstrated by comparison to vapor pressures obtained directly as a function of temperature. Four hydrocarbons were studied: 1-hexyne, 1-octene, phenylacetylene, and mesitylene. Direct measurement of vapor pressures was achieved by allowing a degassed sample to equilibrate with its vapor at a constant temperature. The vapor pressure was measured directly on a mercury manometer by using a cathetometer. A minimum of 5 min was allowed for each temperature equilibration. Null readings following each measurement were obtained by condensing the sample at −178 °C. Generally the vapor pressure measured at each temperature was obtained in triplicate.

Vapor pressure measurements by equilibration were obtained by slightly modifying the collection tube used previously.[5,6] The collection tube consisted of a U-shaped tube to which vacuum Teflon stopcocks had been attached at each end. The collection tube was attached to the apparatus and vacuum line by using O-ring seals. The

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(4) See, For example: Benson, S. W. "Thermochemical Kinetics: Methods for the Estimation of Thermochemical Data and Rate Parameters", 2nd ed.; Wiley: New York, 1976. Greenberg, A.; Liebman, J. F. "Strained Organic Molecules"; Academic Press: New York, 1978.

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(6) Sandman, D. J.; Epstein, A. J.; Chickos, J. S.; Ketchum, J.; Fu, J. S.; Scheraga, H. A. *J. Chem. Phys.* **1979**, *70*, 305.

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