which on X-ray analysis fully confirmed the preceding and subsequent stereochemical assignments.[11] Hydrogenation of the two enone diester *E* isomer mixture (**6c,d**) followed by C-3 epimerization, methylenation, and *i*-Bu$_2$AlH as described also gave ca. 10% of pure diol **10**.

The somewhat unstable dialdehyde **12** in DME was added by syringe pump over 24 h to a refluxing suspension of McMurry Ti reagent from Zn-Cu and TiCl$_3$ in DME.[14] After a further 18 h at reflux, neutral workup and chromatography over Si gel/AgNO$_3$ using 15:1 hexane-ether gave the single taxane triene **13**[15] in 20% yield, accompanied by ca. 10% of a C$_{20}$H$_{32}$O$_2$ diene diol established by NMR and by X-ray analysis of its crystalline (enol) monoacetate as the stable enol **15**, arising from vinylogous reductive coupling of dialdehyde **12**[16] (Scheme I).

The convergent phase of our synthesis leads from acetal **3** in 10 steps and 5% yield to the key dialdehyde **12**, from which the sterically encumbered eight-membered B-ring can uniquely be formed by McMurry cyclization. To our knowledge this is the first direct cyclization of the taxane B-ring from any bicyclic seco-B intermediate. Moreover, triene **13** is not only the first synthetic compound containing the stereochemically correct taxane structure but offers attractive potential for taxusin synthesis. Thus **13** underwent selective allylic oxidation with CrO$_3$/2,5-dimethylpyrazole[17] to give enone **14**[18] in ca. 44% yield. Enone **14** with MCPBA (5 equiv, CH$_2$Cl$_2$, room temperature, 1 h) undergoes smooth epoxidation at the C-4 methylene group, suggesting fruitful possibilities for selective B- and C-ring functionalizations.[19]

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(14) (a) McMurry, J. E.; Kees, K. L. *J. Org. Chem.* **1977**, *42*, 2655. (b) Review: McMurry, J. E. *Acct. Chem. Res.* **1983**, *16*, 405.

(15) **13**: 400-MHz, ^{1}H NMR, (CDCl$_3$, partial) δ 5.90 (1 H, br d, J = 11.6 Hz), 5.15 (1 H, d, J = 11.6 Hz), 4.86 (1 H, s), 4.64 (1 H, s), 1.72 (3 H, s), 1.07, 1.03, and 0.86 (each 3 H, s).

(16) Evidence for structure **15** will be detailed in our full paper.

(17) Salmond, W. G.; Barta, M. A.; Havens, J. L. *J. Org. Chem.* **1978**, *43*, 2057.

(18) **14**: 400-MHz, ^{1}H NMR (CDCl$_3$, partial) δ 6.01 (1 H, br d, 12.5), 5.27 (1 H, d, 12.5), 4.86 (1 H, s), 4.64 (1 H, s), 2.90 (1 H, dd, J = 19.5, 6.5 Hz), 2.10 (1 H, d, J = 19.5 Hz), 1.82 (3 H, s), 1.19, 1.14, and 0.92 (each 3 H, s). The δ and J values for the C-14 α- and β-protons at 2.9 and 2.1 parallel those given for a related enone system by: Woods, M. C.; Nakanishi, K.; Bhacca, N. S. *Tetrahedron* **1966**, *22*, 243.

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Ab Initio Predictions and Experimental Confirmation of Large Tunneling Contributions to Rate Constants and Kinetic Isotope Effects for Hydrogen Atom Transfer Reactions

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The interpretation of kinetic isotope effects (KIE's) involves potential energy barrier heights, vibrational effects of stretches and bends, and competition between overbarrier and tunneling mechanisms.[1] In favorable cases, KIE's provide some of the most compelling evidence for or against detailed interpretations of the dynamics of reactive events. The present paper reports such a case in which the detailed question is the role of tunneling[2] in hydrogen atom transfer reactions in the gas phase. Since many features of H transfer are similar to proton and hydride transfer,[3] the role of tunneling in this kind of reaction has far reaching implications for reactions in solution as well as in gas-phase applications, such as combustion and atmospheric chemistry. In this communication we report new calculations and experiments on the bimolecular rate constant ratio k_3/k_4

$$\mathrm{O + HD \xrightarrow{3} OH + D}$$

$$\mathrm{O + HD \xrightarrow{4} OD + H}$$

which, together with earlier results[4-9] for k_1 and k_2

$$\mathrm{O + H_2 \xrightarrow{1} OH + H}$$

$$\mathrm{O + D_2 \xrightarrow{2} OD + D}$$

provide strong evidence for the dominance of tunneling in all four reactions at temperatures below 500 K.

The KIE's were measured in two complementary experiments. In the first study[6] k_1, k_2, and $k_3 + k_4$ were measured with a flash photolysis apparatus,[10] using atomic resonance fluorescence to monitor the decay of O(^{3}P) in real time. In the new experiment the branching ratio k_3/k_4 was measured with a discharge flow apparatus using laser-induced fluorescence to determine the ratio of the steady-state concentrations of OH and OD products. Oxygen atoms were generated in a microwave discharge of N$_2$ containing 0.01% O$_2$ and combined far downstream with a mixture of either HD and N$_2$ or H$_2$, D$_2$, and N$_2$. The OH and OD fluorescence intensities observed with the H$_2$/D$_2$ mixtures were used to normalize the fluorescence ratio obtained with HD.

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Table I. Arrhenius Parameters for Reactions 1–4[a]

i	j	T, K	ICVT	ICVT/LAG	CEQB/G	experiment[b]
1		1400–1900	36, 14.0	35, 13.6	48, 14.4	37, 14[c]
		318–471	6.0, 10.7	0.6, 7.9	0.7, 7.95	0.4 ± 0.1, 7.8 ± 0.1[d]
1	2	422–472	1.4, 0.8	0.7, 1.8	0.4, 2.3	0.3 ± 0.2, 2.4 ± 0.5
1	3 + 4	422–472	1.3, 0.2	1.3, 0.2	0.9, 0.5	2.3 ± 1.1, −0.3 ± 0.4
3	4	373–500	1.1, 0.5	0.4, 1.9	0.3, 2.1	0.5 ± 0.1, 1.5 ± 0.2

[a] Left entry, A_i in 10^{-11} cm^3 molecule^{-1} s^{-1} or unitless A_{ij}; right entry, E_i or E_{ij} in kcal/mol. [b] Uncertainties are one standard deviation. [c] The results of ref 4 over the T range indicated and of a fit over the same T range to the rate constants of ref 9 agree to the two significant figures shown. [d] Reference 6.

Combining the new measurements with previous data[5,6] on reactions 1 and 2 yields rate constants and their ratios for all four reactions. Further details will be published elsewhere.[11]

Three theoretical approaches are employed: improved canonical variational theory with classical reaction coordinate motion (ICVT),[2g] ICVT with a least-action ground-state transmission coefficient to account for tunneling (ICVT/LAG),[2o] and reduced-dimensionality quantum calculations with an adiabatic incorporation of bending motion (denoted more specifically as collinear exact quantum with ground-state bend or CEQB/G).[7] Details of the calculations for k_3 and k_4 are identical with those for k_1 and k_2 reported elsewhere.[7,8] The ICVT/LAG and CEQB/G calculations are our best theoretical estimates of the three-dimensional rate constants, whereas the ICVT calculations provide our best estimate of the classical reaction coordinate overbarrier contribution. Rate constants correspond to a sum of contributions from the $^3A'$ and $^3A''$ potential energy surfaces and are based on analytic fits[7,8] of ab initio calculations[7,12] of these surfaces with no semiempirical parameters. The classical barrier height for both surfaces is 12.58 kcal/mol.

For the present report previous results for reactions 1 and 2 and new results for 3 and 4 are fit to Arrhenius forms $k_i = A_i \exp(-E_i/RT)$ and $k_i/k_j = A_{ij} \exp(E_{ij}/RT)$. Since the parameters depend on the temperature range used for the fit, this is indicated in every case.

Tabel I first compares the experimental and theoretical Arrhenius parameters for k_1 at high and low temperatures. At 1400–1900 K, theory and experiment[4,9] agree well, whether or not tunneling is included. At 318–471 K the preexponential factor and the activation energy are lower and the inclusion of tunneling lowers them further. The lower values are in much better agreement with experiment than are the ICVT values calculated without tunneling. We turn to the KIE's for a further confirmation of theory. In two of the three examples (k_1/k_2 and k_3/k_4) the difference in activation energies and the ratio of preexponential factors seen in the experimental data can be explained only if tunneling is included. In the third case the predicted correction due to tunneling is too small to be discerned experimentally.

In general there is good agreement between the ICVT/LAG and CEQB/G calculations and the experimental results. This provides confidence in the LAG method which can be used to estimate for each reaction the percentage of ground-state reactive events that occur by tunneling. At 400 K the estimated percentages are 76%, 57%, 80%, and 58% for reactions 1–4, respectively. The trends in Table I also indicate that the ICVT/LAG method actually somewhat underestimates the tunneling effect so these are approximate lower bounds. We conclude that tunneling dominates these hydrogen-atom transfers at 400 K, and it must be included in interpreting the KIE's or in understanding or modeling the detailed dynamics. The LAG method predicts further that the percentage of reaction occurring by tunneling increases as the temperature is lowered, e.g., for reaction 1, to 86% at 350 K and 94% at 300 K.

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Efficient Preparations of 8- and 9-Membered Cyclic Ethers

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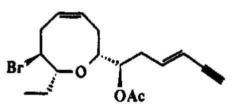
The preparation of medium rings remains one of the more difficult problems in organic synthesis since cyclization reactions are compromised both by entropic effects and developing transannular interactions.[2] The isolation[3] of a variety of medium-ring cyclic ethers from marine sources, e.g., laurencin (**1**), has heightened interest in developing efficient methods for preparing these heterocycles. Progress in this area has recently been recorded[4] by, among others, the groups of Trost,[4a] Kocienski,[4b] Schreiber,[4c] and Nicolaou.[4d] In this paper we demonstrate for the first time that eight- and nine-membered cyclic ethers containing Δ^4 unsaturation can be prepared in good yields by direct cyclization of simple unsaturated acetals. We report also that the alkyl side chains characteristic of many eight-membered ring oxacyclic marine natural products[2] can be stereoselectivity introduced in the cyclization step.



1

The method is illustrated by treatment of the (methoxyethoxy)methyl ether[5,6] of 5-hexen-1-ol (**2**) with 2 equiv of $SnCl_4$ at −20 °C for 13 h to give, in 83% yield, a 2:1 mixture of *cis*-3,6,7,8-tetrahydro-2*H*-oxacin (**3**) and 4-chlorooxocane (**4**).[7]

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