croscopic viscosity can be used to predict the lifetime of $[DMIC^+PF_6^-]^{*1}$.

In summary, Kramers' theory does not describe the dynamic behavior of $[DMIC^+PF_6^-]^{*1}$. However, solvent molecular weight correlates surprisingly well with observed excited-state lifetimes. An explanation based simply on transfer of momentum seems to account for the findings. This approach may also assist in the interpretation of data reported previously for related systems.[7,8,14]

Acknowledgment. This work was supported by a grant from the National Science Foundation for which we are thankful. We are grateful to Professor J. Jonas of this department for his helpful comments.

Supplementary Material Available: Tables of the experimentally determined relaxation rates for $[DMIC^+PF_6^-]^{*1}$ in various solvents and plots of the data taken from refs 7, 8, and 14 against solvent molecular weight (12 pages). Ordering information is given on any current masthead page.

(14) Rice, A.; Kenney-Wallace, G. A. *Chem. Phys.* **1979**, *47*, 161. Waldeck, D. H.; Fleming, G. R. *J. Phys. Chem.* **1981**, *85*, 2614-2617. Osborne, A. D.; Winkworth, A. C. *Chem. Phys. Lett.* **1982**, *85*, 513-517. Lee, M.; Bain, A. J.; McCarthy, P. J.; Han, C. H.; Haleltine, J. N.; Smith, A. B., III; Hochstrasser, R. M. *J. Chem. Phys.* **1986**, *85*, 4341-4347. Ben-Amotz, D.; Harris, C. B. *J. Chem. Phys.* **1987**, *86*, 4856-4870. Bowman, R. M.; Eisenthal, K. B.; Millar, D. P. *J. Chem. Phys.* **1988**, *89*, 762-769. Sun, Y.-P.; Satiel, J. *J. Phys. Chem.* **1989**, *93*, 8310-8316. Aberg, U.; Sundström, V. *Chem. Phys. Lett.* **1991**, *185*, 461-467.

Silicon-Directed Aldol Reactions. Rate Acceleration by Small Rings

Andrew G. Myers,* Susan E. Kephart, and Hou Chen

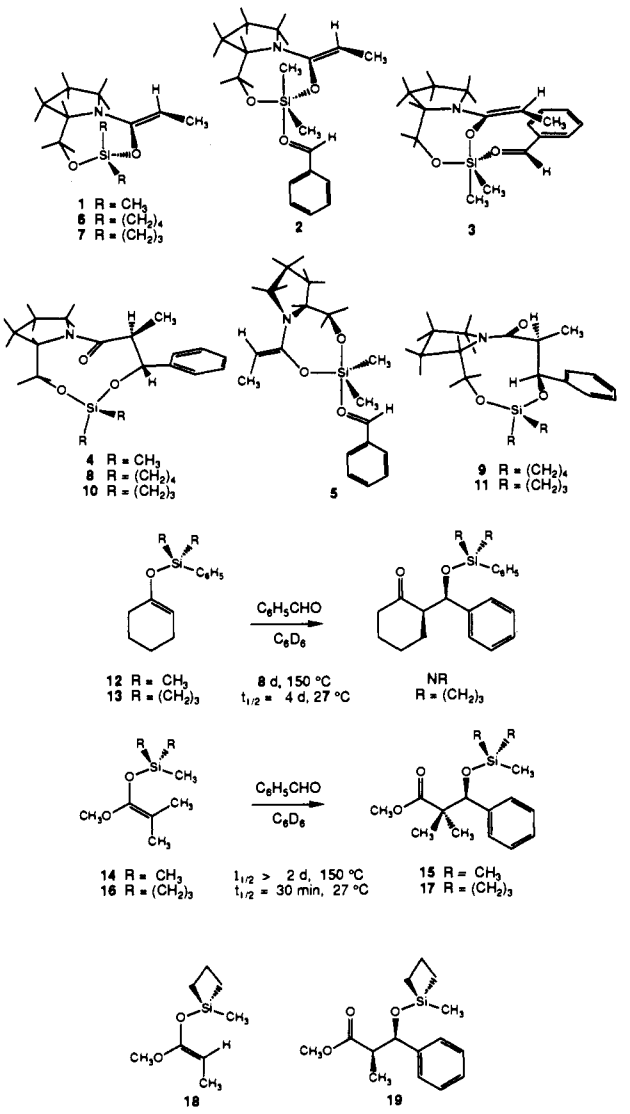
Contribution No. 8652, Arnold and Mabel Beckman Laboratories of Chemical Synthesis California Institute of Technology Pasadena, California 91125

Received June 10, 1992

Noncatalyzed aldol addition reactions of silyl enol derivatives of ketones and esters with aldehydes do not occur or are exceedingly slow, even at elevated temperatures.[1] By contrast, silyl enol derivatives of amides (*O*-silyl *N,O*-ketene acetals) react readily with aldehydes, without catalysis, to form aldol addition products in a simple bimolecular process.[2] In further mechanistic studies of the latter transformation, we have learned that the rate of this reaction is dramatically accelerated by incorporation of the silicon atom within a four-membered ring. This observation extends to silyl enol derivatives of ketones and esters as well and likely represents a general strategy for carbon–carbon bond formation with organosilicon intermediates.

We were led to these discoveries in the course of mechanistic studies of the reaction of *O*-silyl *N,O*-ketene acetal **1** with benzaldehyde. In order to further distinguish between a mechanism proposed in earlier work (**1** → **2** → **3** → **4**)[2] and an alternative pathway (**1** → **5** → **3** → **4**), the effect of constraining the silicon atom and silicon-bound carbon atoms within a small ring was examined.[3] In the proposed pathway, this change should lead to an accelerated reaction, whereas the alternative pathway involving **5** is predicted to be prohibitively strained. Silacyclopentane and silacyclobutane derivatives **6** and **7**, respectively, were prepared in analogy to **1**[2a] and were found to react with benzaldehyde at accelerated rates versus **1** to form mixtures of syn and anti aldol addition products (**8**–**11**).[4] Whereas the observed rate acceleration at 40 °C with silacyclopentane derivative **6** is roughly 10-fold ($k = (4.3 \pm 0.2) \times 10^{-4}$ and $(4.2 \pm 0.9) \times 10^{-5}$ M^{-1} s^{-1}, respectively, ^1H NMR analysis), reaction of the homologous silacyclobutane analog **7** is accelerated to such an extent that the reaction must be conducted at −80 °C to conveniently measure its rate ($k = (2.6 \pm 0.1) \times 10^{-4}$ M^{-1} s^{-1}, ^1H NMR analysis). From activation parameters previously determined,[2b] the rate of reaction of **1** and benzaldehyde at −80 °C can be estimated ($k \approx 1.2 \times 10^{-10}$ M^{-1} s^{-1}), leading to a calculated rate acceleration of $\sim 2 \times 10^6$ upon linking the silylmethyl groups of **1** with a carbon atom. Interestingly, across the series of substrates **1**, **6**, and **7**, the syn:anti ratio of benzaldehyde adducts is observed to increase uniformly (2:98, 50:50, 85:15, respectively). The origin of this variation in stereoselectivity is presently unclear, but is believed to be a consequence of bond angle distortion within the respective hypervalent transition states (Chart I).

Chart I



The results above suggest a general strategy for promotion of the aldol reaction of silyl enol derivatives of carbonyl compounds. Silyl enol derivatives of ketones, for example, do not react with aldehydes under simple thermal conditions. Thus, cyclohexanone

(1) Silyl ketene acetals: Creger, P. L. *Tetrahedron Lett.* **1972**, 79. We are unaware of any precedent for noncatalyzed thermal aldol addition reactions of ketone silyl enol ethers with aldehydes.

(2) (a) Myers, A. G.; Widdowson, K. L. *J. Am. Chem. Soc.* **1990**, *113*, 9672. (b) Myers, A. G.; Widdowson, K. L.; Kukkola, P. J. *J. Am. Chem. Soc.* **1992**, *114*, 2765.

(3) This strategy is well-precedented in the study of phosphate ester hydrolysis: (a) Westheimer, F. H. *Acc. Chem. Res.* **1968**, *1*, 70. (b) Holmes, R. R. *Pentacoordinated Phosphorus*; American Chemical Society: Washington, D.C., 1980; Vol. 2, and references therein.

(4) Not surprisingly, silacyclobutane ethers are, in some cases, quite sensitive to hydrolysis (e.g., on silica gel); products **10** and **11** represent such a case.

0002-7863/92/1514-7922$03.00/0

dimethylphenylsilyl enol ether (**12**) and benzaldehyde (0.5 M each, benzene) showed no evidence of reaction after 200 h at 150 °C. In contrast, silacyclobutane analog **13**[5] reacts with benzaldehyde even at 27 °C, albeit slowly ($t_{1/2} \approx 4$ days, 0.8 M each, benzene), to form efficiently a mixture of syn and anti aldol addition products (12:1, respectively).[6] At 100 °C, complete conversion is attained within 34 h, with a slight erosion in syn selectivity (7:1, 84% yield).[7] Both *E*- and *Z*-rich mixtures of 3-pentanone phenylsilacyclobutane enol ethers react with benzaldehyde at 100 °C to form predominantly the syn aldol adduct (4 days, 66:34 *E*:*Z* → 7.6:1 syn:anti, 95%; 15:85 *E*:*Z* → 2.8:1 syn:anti, 86%),[8] indicating that both isomers are syn-selective, although the *E* isomer is more so. Interestingly, in the examples described, the methylsilacyclobutane derivative[9] is found to react at roughly half the rate of the corresponding phenylsilacyclobutane derivative, suggesting an electronic factor for further study. At present, the useful range of substrates with ketone silacyclobutane enol ethers appears to be limited to reactive aldehydes; reaction of **13** with isobutyraldehyde, for example, is found to be impractically slow (ca. one-tenth the rate of reaction with benzaldehyde).

Noncatalyzed aldol addition reactions of *O*-silacyclobutane ketene acetals are also dramatically accelerated versus their acyclic counterparts and may represent the most useful demonstration of the silacyclobutane-mediated aldol strategy. For example, the reaction of *O*-trimethylsilyl ketene acetal **14** with benzaldehyde is reported to require heating at 150 °C (neat, 18 h) for completion and affords the addition product **15** in 81% yield.[1] As a control, **14** was heated with benzaldehyde in benzene solution (0.2 M each, 150 °C), forming less than 25% of the aldol product **15** after 24 h as well as several unidentified byproducts. In marked contrast, methylsilacyclobutane derivative **16**[10] reacted completely and cleanly with benzaldehyde within 4 h at 27 °C (0.2 M each, benzene) to afford the adduct **17** quantitatively. This derivative also undergoes smooth addition with less reactive carbonyl substrates such as isobutyraldehyde (0.2 M, benzene, 1 day, 60 °C, 80%) and acetone (excess, benzene, 3 days, 65 °C, 85%). (*E*)-*O*-Methylsilacyclobutane ketene acetal **18**[10] reacted efficiently with benzaldehyde at 23 °C to afford the syn adduct **19** with good stereocontrol (19:1 syn:anti, quantitative). Though the reactions described were performed with distilled silyl ketene acetals in benzene solution, preliminary experiments have shown that aldol reactions of silacyclobutane ketene acetals prepared in situ in tetrahydrofuran are also feasible. In a process that is almost certainly mechanistically distinct, but nevertheless of interest, each of these silacyclobutane-accelerated aldol reactions is found to be catalyzed by potassium *tert*-butoxide and, presumably, by other nucleophiles as well.[11]

As a working hypothesis, it is suggested that silacyclobutane-mediated aldol reactions proceed by way of a pentavalent (tbp or square pyramidal) organosilicon species where a boatlike transition state is preferred (**1**, **13**, **18**), though a chairlike transition state is readily accessible and, in some cases (**7**, (*Z*)-silyl enol ether from 3-pentanone), may dominate.[2] The preliminary studies described herein suggest a general strategy[3] for the development of new bond-forming processes, both stoichiometric and catalytic, wherein a potential transition state involving hypervalent silicon is made energetically accessible by the simple expedient of incorporation of the silicon atom within a four-membered ring.

Acknowledgment. Generous financial assistance from the National Science Foundation and American Cyanamid Company and NSF predoctoral fellowship support for S.E.K. and H.C. are gratefully acknowledged.

Supplementary Material Available: ^{1}H and ^{13}C NMR and IR spectra of each new compound and X-ray coordinates for compound **6** (48 pages). Ordering information is given on any current masthead page.

(5) Prepared in 92% yield (distilled) by reaction of 1-chloro-1-phenylsilacyclobutane (Auner, N.; Grobe, J. *J. Organomet. Chem.* **1980**, *188*, 25) with the lithium enolate of cyclohexanone.

(6) It is noteworthy that this stereoselectivity is opposite that of the $TiCl_4$-induced reaction (Mukaiyama aldol reaction: Mukaiyama, T.; Banno, K.; Narasaka, K. *J. Am. Chem. Soc.* **1974**, *96*, 7503).

(7) Yields are determined by integration of ^{1}H NMR spectra employing an internal standard.

(8) Prepared in 81% yield (distilled) by trapping of the kinetic mixture of lithium enolates formed from 3-pentanone and lithium diisopropylamide (LDA) with 1-chloro-1-phenylsilacyclobutane (ref 5). The *Z*-rich mixture arose adventitiously by isomerization of this mixture during a distillation, presumably catalyzed by a basic impurity.

(9) 1-Chloro-1-methylsilacyclobutane was prepared from commercially available (3-chloropropyl)dichloromethylsilane by a modification (Baker, K. V.; Brown, J. M.; Hughes, N.; Skarnulis, A. J.; Sexton, A. *J. Org. Chem.* **1991**, *56*, 698) of the literature procedure: Damrauer, R.; Davis, R. A.; Burke, M. T.; Karn, R. A.; Goodman, G. T. *J. Organomet. Chem.* **1972**, *43*, 121.

(10) Prepared by kinetic trapping of the lithium enolate (LDA) with 1-chloro-1-methylsilacyclobutane (ref 9) with purification by Kugelrohr distillation (70–85% yield). In the case of **18**, approximately 40% of the C-silylated product is present as a contaminant; this compound is inert under the reaction conditions.

(11) Reactions described as "noncatalyzed" were performed with distilled reagents in neutral glassware and followed reproducible, bimolecular kinetics.

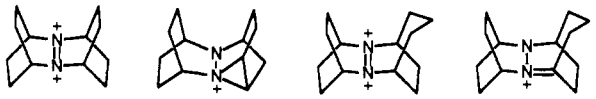
Bicyclic Ring Size Effect on β- vs α-Deprotonation of Diazenium Dications

Stephen F. Nelsen* and Yichun Wang

S. M. McElvain Laboratories of Organic Chemistry
Department of Chemistry, University of Wisconsin
Madison, Wisconsin 53706

Received June 15, 1992

Sesquibicyclic diazenium dication $\mathbf{1}^{2+}$ is a rather strong CH acid which is deprotonated slowly by chloride and more rapidly by pyridine at a carbon β to nitrogen to give the thermally labile *N*-aminoaziridinium cation **2**.[1] We report here that expanding one of the dimethylene bridges of $\mathbf{1}^{2+}$ to three and four carbons greatly increases acidity and causes a switch from β proton loss to α and that these changes may be understood using AM1 semiempirical MO calculations.[2]



$\mathbf{1}^{2+}$ **2** $\mathbf{3}^{2+}$ **4**

$\mathbf{3}^{2+}$ is isolable at room temperature[3] but is far more acidic than $\mathbf{1}^{2+}$. In contrast to $\mathbf{1}^{2+}$, reaction of $\mathbf{3}^{2+}$ with water is rapid, although it produces substantial amounts of $\mathbf{3}^{\bullet+}$, making NMR characterization of the initial products difficult. Basic workup gives 2,3-diazabicyclo[2.2.2]oct-2-ene and 1,4-cycloheptanedione in low yield, but no 6,7-diazabicyclo[3.2.2]non-6-ene. These products are most easily explained by hydrolysis of the α-deprotonation product, *N*-aminoimmonium cation **4**. We were surprised to see evidence for α-deprotonation of $\mathbf{3}^{2+}$ because we expected only a rather small weakening of its C_α—H bonds. The H—C_α,N(p) dihedral angle θ is calculated to be 77.0°, and if bond weakening followed a $\cos^2\theta$ relationship (as the hyperconjugative contribution to ESR splitting constants does), its C_α—H bond would only be weakened 5% as much as that for a perfectly aligned hydrazine dication C_α—H bond. However, AM1 calculations predict that significant $N^+{=}C_\alpha$ bonding is present for α-deprotonation product **4**, as summarized in Table I. The N^+C_α bond length for **4** corresponds to 92% of the change from $\mathbf{1}^{2+}$-H_α (which as expected has essentially no double bonding, as indicated by its pyramidal atoms and large twist angle) to the unstrained acyclic model, and α-deprotonation of $\mathbf{3}^{2+}$ is estimated to be about 30 kcal/mol more

(1) Nelsen, S. F.; Wang, Y. *J. Am. Chem. Soc.* **1991**, *113*, 5905.

(2) (a) Dewar, M. J. S.; Zoebisch, E. G.; Healy, E. F.; Stewart, J. J. P. *J. Am. Chem. Soc.* **1985**, *107*, 3902. (b) Structures were optimized using the substantially improved programs VAMP 4.30 or 4.40 (on a Stardent 3000 computer) or SCAMPIBM 4.30 (on an IBM 6000), made available to us by their author, T. Clark, Universität Erlangen-Nürnberg.

(3) $\mathbf{3}^{2+}(PF_6^-)_2$ was isolated in 97% yield by oxidation with $NOPF_6$ in acetonitrile (see supplementary material).

0002-7863/92/1514-7923$03.00/0