1,2-Versus 1,4-Reduction of α,β -Unsaturated Carbonyl Compounds in the Gas Phase

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The regioselectivity involved in the gas-phase hydride reduction of α,β -unsaturated carbonyl compounds by pentacoordinate silicon hydride ions is investigated. The kinetics and product distributions of the reactions of acrolein, methyl vinyl ketone and cyclohex-2-enone with monoalkoxysiliconate ions of the general composition RSiH₃(OR')⁻ were examined with the flowing afterglow-triple quadrupole technique. All three substrates react by hydride transfer and by formation of a siliconate adduct in which hydride reduction of the organic reactant has occurred. The structures of these adducts and the hydride transfer products were identified by various tandem mass spectrometric protocols, including analysis of competitive collision-induced dissociation (CID) reactions and comparisons of CID spectra obtained from reference ions with known structures. 1,4-Reduction forming an enolate ion product is found to be the dominant or exclusive process with all three substrates, i.e. acrolein (70 ± 5%), methyl vinyl ketone (72 ± 5%) and cyclohex-2-enone (100%). Comparisons are made between these gas-phase results and the regioselectivity reported for analogous condensed-phase reactions. The observed behavior is discussed in terms of the reaction thermochemistry.

INTRODUCTION

Regiochemical and stereochemical control are central concerns in organic and organometallic synthesis. The organic synthetic literature is replete with experimental strategies for achieving regioselectivity and stereoselectivity in the formation of complex, polyfunctional molecules.¹⁻³ Extending established reactivity patterns and deciphering the lessons of newly discovered reactivity often involves implicit consideration of 'intrinsic' chemical behavior, i.e. reactivity due to inherent features of the isolated reactants and products. However, this is often complicated by uncertainties regarding the influence of extrinsic factors on reactivity, such as solvation and ion pairing. This is especially true of reactions involving polar and ionic reagents carried out in polar or hydrogen-bonding solvents.⁴

Hydride reduction reactions of α,β -unsaturated carbonyl compounds are a familiar and important case in point. These reactions occur by hydride attachment to either the carbonyl carbon ('1,2-reduction'), giving allylic alcohol derivatives, or to the β -carbon of the unsaturated moiety ('1,4-reduction'), yielding enolates and their derivatives⁵ (Scheme 1). Moreover, depending on the substitution in the substrate, different stereoisomeric products can be formed in both reaction channels. Most of the common reducing agents used for these reactions are polar, ionic and/or oligomeric species such as the borohydrides and aluminum hydrides.^{6,7} In many instances these reactions display pronounced counter-ion and solvent effects on the kinetics and product distributions, although the reasons for this behavior are poorly understood.⁵ For example, whereas alcoholic solutions of NaBH₄ tend to give nearly equal mixtures of 1,2- and 1,4-reduction products

CCC 0030-493X/93/281658-07 © 1993 by John Wiley & Sons, Ltd. with most α,β -unsaturated ketones, adding metal salts such as MCl₂ (M = Mg, Ca, Sr, Ba) leads to nearly exclusive 1,2-reduction.⁸ In contrast, changing the ligand R in KR₃BH reagents from *sec*-butyl (i.e. K-Selectride) to phenyl causes the regioselectivity for reduction of mesityl oxide to change from 86% (1,2-) to 94% (1,4-).⁹ Lithium aluminium hydride and its derivatives typically give 1,2-reduction.⁵

Progress in controlling the regioselectivity and stereoselectivity of these types of reductions has been achieved mainly by means of empirical optimizations based on systematic variation of the reducing reagents and the reaction conditions.^{5–7} Molecular orbital (MO) and molecular mechanics-type calculations have become useful tools for investigating carbonyl group reduction and addition reactions. Numerous successes in the correct prediction of regioselectivity and diastereoselectivity in hydride reductions and related nucleophilic addition reactions have been reported.^{10–15} Nevertheless, because these calculations ultimately refer to isolated chemical species, their relationship to the



Scheme 1.

Received 13 July 1993 Revised 1 October 1993 Accepted 3 October 1993 actual mechanisms of condensed-phase reduction reactions and, therefore, the origin of their success in predicting the outcomes remain unclear. One way of calibrating these isolated-molecule models for reactivity is to compare theoretical predictions with the more closely related experimental results of gas-phase reactions. A few investigations of gas-phase ion-molecule reactions involving anionic nucleophiles and α,β unsaturated aldehydes, ketones, esters and nitriles have been reported; in some of these studies the products arising from 1,2- and 1,4-addition could be identified and distinguished.¹⁶⁻²⁴ As with the corresponding condensed-phase reactions, widely varying reactivity is also evident in the gas phase that appears to depend on several factors, including the nature of the nucleophile, the substrate and the presence of ancillary solvent molecules with the reactant ion. Relatively little is known about the corresponding hydride reductions. Bernasconi et al.24 examined hydride transfer reactions of cyclohexadienyl anion with acrolein, methyl vinyl ketone, methyl acrylate and other activated olefins, and reported the formation of 1,4-reduction products in each case. The hydride transfer reactions of HNO^- and CH_3O^- with acrolein have been investigated,^{16,17,21} both ions are believed to react by 1,4-reduction. Van der Wel et al.²³ reported both 1,2- and 1,4-reduction in reactions of BH₄⁻ with maleic anhydride and some of its derivatives.

We recently described an experimental method for determining the stereochemical outcome of gas-phase hydride reduction reactions of substituted cyclo-hexanones.²⁵ The method makes use of pentacoordinate silicon hydride anions²⁶ as the gas-phase hydride reducing reagents, and a tandem mass spectrometric protocol for distinguishing and quantitating the diastereometric reduction products. The basic approach is also applicable to a wider variety of reactions, including hydride reductions of α,β -unsaturated carbonyl compounds. In this paper we present an investigation of the regioselectivity for reduction of model α,β -unsaturated carbonyl compounds by pentacoordinate silicon hydride ions.

EXPERIMENTAL

All experiments were carried out in a flowing afterglowtriple quadrupole instrument that has been described in detail previously.²⁷ Unless noted otherwise, the standard operating conditions in the 100 cm \times 7.3 i.d. flow reactor were P(He) = 0.4 Torr (1 Torr = 133.3 Pa), flow rate = 190 STP cm³ s⁻¹, flow velocity = 100 m s⁻¹ and $T = 296 \pm 2$ K. Kinetic measurements were carried out by established procedures^{27,28} using fixed-position neutral reagent inlets located at calibrated distances from the ion sampling orifice of 38 and 48 cm. Neutral reagent flow rates were determined from the observed pressure increase with time when the gas flow was diverted to a gas bulb with a calibrated volume. Rate coefficients were determined with a typical precision better than 10% and an estimated uncertainty of $\pm 20\%$. Product branching ratios for ion-molecule reactions were determined from plots of normalized product ion signal intensities versus the percentage conversion of the reactant ion, or from the relative product ion signal intensities in cases where secondary reactions were insignificant. No corrections for differences in ion diffusion or detection efficiency were applied and the detector resolution was kept as low as possible to minimize mass discrimination.

Collision-induced dissociation (CID) experiments were carried out in the triple quadrupole mass analyzer with argon as target gas. The target pressure in the central quadrupole collision chamber (Q2) was maintained at pressures in the 0.06-0.08 mTorr range, which corresponds to multiple collision conditions in our instrument.²⁹ Collision energies in the 15-20 eV (laboratory frame) range were used, with the voltage bias of the third quadrupole (Q3) adjusted so as to optimize product ion collection. Mass-analyzed ions were detected with a Channeltron electron multiplier operated in pulse-counting mode. For quantitative measurements of CID product yield ratios, the Q3 mass resolution and other tuning conditions of the triple quadrupole analyzer were varied so as to achieve maximum reproducibility ($\pm 10\%$ absolute).

Hydroxide ions were formed in the ion source region of the flow tube by electron impact ionization of an N_2O-CH_4 mixture. The alkoxide ions were formed by deprotonation of the corresponding alcohol by HO⁻ and, in a few cases, by base-induced elimination with the corresponding dialkyl ether.

Gas purities were He 99.995%, Ar 99.995%, N_2O 99% and CH_4 99%. *n*-Butyl- and *n*-hexysilane were obtained from Silar. All other liquid samples were obtained from various commercial sources and used as supplied, other than degassing just prior to use.

Background

Investigating the regioselectivity of hydride reduction reactions of unsaturated carbonyl compounds requires an ionic reducing agent that reacts cleanly and efficiently with a range of substrates, and some means for distinguishing and quantitatively analyzing the isomeric product ions that are formed. Some time ago, we described the formation of pentacoordinate silicon hydride ions from gas-phase reactions of bare hydride ion with primary, secondary, tertiary and quaternary alkylsilanes under flowing afterglow conditions:²⁶

$$H^- + R_4 Si \rightarrow R_4 Si H^-$$
(1)

Pentacoordinate silicon anions have been known for some time in solution^{30,31} and in the gas phase.^{32,33} We previously demonstrated that the corresponding hydrides are reactive gas-phase reducing agents that are capable of rapidly transferring H⁻ to CO₂, transition metal carbonyls, boranes and even to SiH₄.^{26,34,35} The reactions of pentacoordinate silicon hydride anions with simple aldehydes and ketones proceed somewhat differently in that adducts, formulated as monoalkoxysiliconate ions, are formed as the major or exclusive product,²⁵ e.g.

$$R_4SiH^- + Me_2C=O \rightarrow [Me_2CH-O-SiR_4^-]$$
 (2)
↑
 $Me_2CHO^- + SiR_4$

The occurrence of carbonyl group reduction in these addition reactions is shown by the formation of the free alkoxide ion [i.e. Me₂CHO⁻ in Eqn (2)] as the major fragment ion from CID of the adducts, and by the fact that the CID spectra are identical with those of the corresponding reference ions formed by directly adding the pre-formed alkoxide ion to the same silane. In the course of these studies, it became evident that monoalkoxysiliconates ions are also reactive hydride reducing agents with aldehydes and ketones, forming adducts that possess two alkoxy ligands, i.e. dialkoxysiliconate ions. These ions undergo characteristic CID by elimination of both alkoxides with a yield ratio that is an extremely sensitive function of the relative basicities and structural details of the two fragment ions. Moreover, in all cases examined the measured CID product ratios were found to be independent of the synthetic order in which the two alkoxy groups become attached in the dialkoxysiliconate ion, an effect attributable to the known fluxionality of pentacoordinate silicon ions.^{30,31,36} We were able to use this CID behavior as a means for determining the diastereoselectivity of reactions involving substituted cycloreduction hexanones.²⁵ This same basic approach was used in this work to determine the regioselectivity of hydride reduction reactions of the model unsaturated carbonyl compounds acrolein, methyl vinyl ketone and cyclohex-2-enone with various monoalkoxysiliconate ions.

Acrolein

The reducing agents used were monoalkoxysiliconate ions formed by addition of different primary and secondary alkoxide ions to either *n*-butyl- or *n*-hexylsilane, e.g.

$$PrO^{-} + BuSiH_3 \rightarrow BuSiH_3(OPr)^{-}$$
 (3)

These presumably termolecular association reactions are relatively efficient under flowing afterglow conditions, producing the alkoxysiliconate ion adduct in high yield along with lesser amounts of a proton transfer product. Reaction of the *n*-propoxysiliconate ion formed as in Eqn (3) with acrolein yields two primary product ions, *a* and *b*:

BuSiH₃(OPr)⁻ + CH₂=CHCHO
→ C₃H₅O⁻ + BuSiH₂(OPr) (4a)

$$a$$

→ BuSiH₂(OPr)(OC₃H₅)⁻ (4b)
 b

The overall reaction is relatively efficient, with an apparent bimolecular reaction rate coefficient, $k_{app}(4)$, at 0.4 Torr total pressure of $7.5 \pm 0.5 \times 10^{-10}$ cm³ s⁻¹ (efficiency = $k_{app}/k_{coll} = 0.3$).³⁷ The measured yields $(\pm 5\%)$ at 0.4 Torr are 70% hydride transfer [Eqn (4a)] and 30% addition [Eqn (4b)]. In order to evaluate the regioselectivity of these reactions, the structures of product ion *a* and the C₃H₅O ligand in the adduct *b* must be identified. 1,4-Reduction of acrolein produces propanal enolate ion, possibly as a mixture of *Z* and *E* diastereomers, while 1, 2-reduction gives allyl alkoxide

ion. These ions can be easily distinguished on the basis of their differing basicities: $\Delta H_{acid}(CH_3CH_2CHO) =$ mol⁻¹ 1528 ± 10^{38} $\Delta H_{\rm acid}$ (Ref. 38); kJ $(CH_2 = CHCH_2OH) = 1562 \pm 4$ kJ mol⁻¹ (Ref. 39). The apparent basicity of ion a was determined by analyzing the CID spectra obtained from its clusters with selected neutral alcohols, ROH, i.e. from CID of 'proton-bound dimer' ions, $(C_3H_5O^-)(RO^-)H^+$. ⁴⁰ For these experiments the initial reduction was carried out with the *n*-butoxysiliconate ion, $BuSiH_3(OBu)^-$, instead of n-propoxysiliconate [Eqn (4)] in order to avoid certain ion mass overlaps that were encountered during the analysis. When relatively high concentrations of the n-BuOH precursor for the n-BuO⁻ ions are present in the flow tube, the $C_3H_5O^-$ reduction product forms an abundant cluster ion, $(C_3H_5O^-)(BuO^-)H^+$:

$$C_{3}H_{5}O^{-} + BuOH \rightarrow (C_{3}H_{5}O^{-})(BuO^{-})H^{+}$$
 (5)

CID of this ion with argon target and 20 eV (laboratory frame) collision energy produces only $C_3H_5O^-$ (m/z 57) and no BuO⁻ (m/z 73).

Identical behavior is observed with the reference cluster ion formed from deprotonated propanal and nbutanol, which is consistent with the significantly greater basicity of n-BuO⁻ compared with propanal enolate $(\Delta H_{acid}(n-BuOH) = 1571 \pm 10 \text{ kJ mol}^{-1}).^{38}$ In contrast, the reference cluster ion formed from deprotonated allyl alcohol and n-butyl alcohol undergoes under identical conditions to give both CID $CH_2 = CHCH_2O^-$ and *n*-BuO⁻ in a 4:1 yield ratio, consistent with the slightly greater basicity of the latter. On this basis, ion a is identified as propanal enolate ion. Further support for this structure assignment is obtained from an examination of one of the observed secondary products of the reduction reaction (4). Ion a is observed to form an adduct with the background BuSiH₃ that is present in the flow reactor:

 $C_3H_5O^-$ [from Eqn (4a)] + BuSiH₃ \rightarrow

 $BuSiH_3(OC_3H_5)^-$ (6)

CID of this adduct gives $C_3H_5O^-$ (m/z 57) as the only observed product ion. Identical behavior is observed with the reference species formed by adding authentic propanal enolate ions to BuSiH₃, whereas the reference species formed by adding $CH_2 = CHCH_2O^-$ to BuSiH₃ undergoes CID to produce three different fragment ions arising from loss of BuSiH₃, allyl alcohol and propene (alkene loss is a general reaction of collisionally activated siliconate anions with α,β -unsaturated alkoxyl ligands⁴¹). This confirms the conclusion derived from the cluster ion CID experiments: the product of reaction (4a) is propanal enolate formed by 1,4-reduction of acrolein.

The structure of the C_3H_5O ligand in adduct b was similarly identified by comparing its CID behavior with that of reference species possessing authentic propanal enolate and allyl alkoxyl ligands. Reaction of BuSiH₃ with authentic propanal enolate yields an adduct BuSiH₃(OCH=CHCH₃)⁻. Reduction of neutral propanal with this species in a downstream region of the flow tube produces a reference ion c that undergoes lowenergy CID to yield only CH₃CHCHO⁻ (m/z 57) and no PrO⁻ (m/z 59). In contrast, addition of authentic CH₂=CHCH₂O[−] ions to BuSiH₃ followed by reduction of propanal gives the dialkoxysiliconate ion d, which undergoes CID to produce CH₂=CHCH₂O[−] (m/z 57) and PrO[−] (m/z 59) with a measured yield ratio of 2.7 ± 0.2. CID of b under identical conditions produces C₃H₅O[−] and PrO[−] with a measured yield ratio of 2.8 ± 0.2. Therefore, ions b and d are identical, and the C₃H₅O ligand formed in reaction (4b) has the allyl alkoxy structure derived from 1, 2-reduction of acrolein.

$$BuSiH_{2}(OCH=CHCH_{3})(OPr)^{-}$$

$$c$$

$$BuSiH_{2}(OCH_{2}CH=CH_{2})(OPr)^{-}$$

$$d$$

Thus, for acrolein, the hydride transfer reaction (4a) proceeds entirely by 1,4-reduction, while the addition reaction (4b) occurs exclusively by 1, 2-reduction. Combining this information with the measured branching ratio for reaction (4) leads to the conclusion that acrolein reacts with the alkoxysiliconate ion by $70 \pm 5\%$ 1,4-reduction and $30 \pm 5\%$ 1,2-reduction. A summary of these results, to be discussed later, is given in Table 1.

Methyl vinyl ketone

Three primary products are formed in the reaction of the monoalkoxysliconate ion $BuSiH_3(O^iPr)^-$ with methyl vinyl ketone at 0.4 Torr: 63% $C_4H_7O^-$ by hydride transfer (product *e*), 25% of an adduct *f* and 12% of t protolytic cleavage product $C_4H_5O^-(g)$:

BuSiH₃(O^{*i*}Pr)⁻ + CH₂=CHCOCH₃

$$\rightarrow$$
 C₄H₇O⁻ + BuSiH₂(O^{*i*}Pr) (7a)

е

$$\rightarrow \operatorname{BuSiH}_{2}(\operatorname{O}^{i}\operatorname{Pr})(\operatorname{OC}_{4}\operatorname{H}_{7})^{-}$$
(7b)
$$f$$

$$\rightarrow C_4 H_5 O^- + BuSiH_2(O^i Pr) + H_2 \quad (7c)$$

Reaction (7) is less efficient than reaction (4), with a measured rate coefficient for the overall reaction at 0.4 Torr of $2.7 \pm 0.3 \times 10^{-10}$ cm³ s⁻¹ ($k_{app}/k_{coll} = 0.1$).³⁷

Table 1. Kinetics and product distributions for hydride reduction of α , β -unsaturated carbonyl compounds by alkoxysiliconate ions in the gas phase.^a

Substrate	1,2-Reduction (%) ^b	1,4-Reduction (%) ^b	د (efficiency)d
Acrolein	30	70	7.5 ± 0.5 (0.3)
Methyl vinyl ketone	28	72	$2.7 \pm 0.3 (0.1)$
Cyclohex-2-enone	0	100	e

^aAll measurements carried out at 296 \pm 2 K, total pressure 0.4 Torr. ^b Estimated uncertainty $\pm 5\%$

 $^{\rm c}$ Total apparent bimolecular reaction rate coefficient in units of $10^{-10}~\text{cm}^3~\text{s}^{-1}.$

^d Efficiency = k_{app}/k_{coll} , where k_{coll} is the calculated collision rate coefficient from variational transition state-trajectory theory.³⁷ ^e Kinetics not determined.

Protolytic cleavage [reaction (7c)] is commonly observed when pentacoordinate silicon hydride ions react with Brønsted acids²⁶ The absence of this reaction with acrolein but its occurrence with methyl vinyl ketone suggests that the methyl hydrogens in the latter compound are responsible for the siliconate ion protolysis and, therefore, that product ion g has the structure $CH_2 = CHCOCH_2^-$. The structures of the hydride transfer product e and the adduct f were determined in an analogous manner as that used for the acrolein system. 1,4-Reduction of methyl vinyl ketone would give a Z, E mixture of butan-2-on-3-yl enolates, whereas 1,2-reduction would produce a racemic mixture of but-3-en-2-ol alkoxide ions. Formation of a protonbound dimer from product ion e and pentan-3-ol $(\Delta H_{acid}(Et_2CHOH) = 1559 \pm 11 \text{ kJ mol}^{-1})^{38}$ followed by CID produces only $\overline{C_4}H_7O^-$ (m/z 71) and no Et_2CHO^- (m/z 87). For comparison, the reference ion formed from deprotonated butan-2-one and pentan-3-ol also yields only $C_4H_7O^-$ upon CID. Although deprotonation of butan-2-one is known to give a mixture of isomeric enolates,⁴² these ions all have a similar basicity that is significantly less than that of $Et_2CHO^{-}(\Delta H_{acid}(butan-2-one) = 1540 \pm 8 \text{ kJ mol}^{-1}).^{38}$ Therefore, exclusive formation of $C_4H_7O^-$ product from CID of cluster ions of butan-2-one enolates with pentan-3-ol is expected in any case. In contrast, the reference cluster ion made from deprotonated but-3-en-2ol and pentan-3-ol yields both alkoxide ions (m/z 71 and 87) upon CID in a 2:1 yield ratio. These results indicate that ion e has the same effective basicity relative to Et₂CHO⁻ as does deprotonated butan-2-one. Similarly, the secondary production ion, $BuSiH_3(OC_4H_7)^-$, formed when higher concentrations of BuSiH₃ are present in the flow tube, shows CID behavior identical with that of the ion produced by adding deprotonated butan-2-one to BuSiH₃, but distinctly different behavior from the ion produced by adding deprotonated but-3-en-2-ol to BuSiH₃. Hence, as with the acrolein system, the hydride transfer product e is the enolate ion arising from 1,4-reduction.

CID of adduct f produces i-PrO⁻ and $C_4H_7O^-$ fragments with a 0.52 \pm 0.2 yield ratio. The reference ion formed by adding butan-2-one enolate to BuSiH₃ followed by reduction of acetone undergoes CID to give only $C_4H_7O^-$, while the dialkoxysiliconate ion formed from deprotonated but-3-en-2-ol and acetone yields both *i*-PrO⁻ and $C_4H_7O^-$ fragment ions in a 0.53 \pm 0.02 yield ratio. This indicates that the C_4H_7O ligand in adduct f has the but-3-en-2-alkoxyl structure and, therefore, that reaction (7b) occurs entirely by 1,2reduction of methyl vinyl ketone.

Combining the renormalized yields for reactions (7a) and (7b) with the ion structure assignments made above leads to the conclusion that methyl vinyl ketone undergoes $72 \pm 5\%$ 1,4-reduction and $28 \pm 5\%$ 1,2-reduction (Table 1).

Cyclohex-2-enone

Cyclohex-2-enone is a commonly used prototype for studies of regioselectivity in enone addition reactions in solution.⁵ This compound reacts with the 3-pentoxysiliconate ion, n-HexSiH₃(OCHEt₂)⁻, to form

(8b)

34% hydride transfer (product h), 51% addition (product i) and 15% protolytic cleavage (product j):

$$\text{HexSiH}_3(\text{OCHEt}_2)^- + \text{C}_6\text{H}_8\text{O}$$

$$\rightarrow C_6 H_9 O^- + \text{HexSiH}_2(\text{OCHEt}_2)$$
 (8a)

$$\rightarrow$$
 HexSiH₂(OCHEt₂)(OC₆H₉)⁻

i

$$\rightarrow C_6 H_7 O^- + HexSiH_2(OCHEt_2) + H_2 \quad (8c)$$

j

h

The kinetics of this reaction were not determined owing to the limited volatility of cyclohex-2-enone. As with methyl vinyl ketone, a protolytic cleavage product is observed (*j*), which could arise by loss of either the C(4) or C(6) hydrogens in the substrate.⁴³ CID of the proton-bound dimer made from ion h and pentan-3-ol produces only $C_6H_9O^-$ (m/z 97). Identical behavior is observed with the reference ion made from deprotonated cyclohexanone and pentan-3-ol, consistent with the lower basicity of the enolate $(\Delta H_{acid}(cyclohexanone) =$ $1544 \pm 12 \text{ kJ mol}^{-1}$.⁴⁴ In contrast, CID of the cluster made from deprotonated cyclohex-2-en-1-ol ($\Delta H_{acid} \approx$ 1552 kJ mol⁻¹, estimated) and pentan-3-ol gives both alkoxide fragments Et_2CHO^- and $C_6H_9O^-$ in a ratio of $\sim 2:3$. Therefore, h is identified as cyclohexanone enolate, formed by 1,4-reduction of the enone.

Likewise, the C_6H_9O ligand in adduct *i* is also found to have the cyclohexanone enolate structure. Lowenergy CID of *i* gives only $C_6H_9O^-$, as does the reference ion made by adding authentic cyclohexanone enolate ions to HexSiH₃ followed by reduction of pentan-3-one. In contrast, CID of the reference ion formed by adding deprotonated cyclohex-2-en-1-ol to HexSiH₃ followed by reduction of pentan-3-one produces both Et₂CHO⁻ and $C_6H_9O^-$ in a 0.63 \pm 0.02 yield ratio. Therefore, unlike with acrolein and methyl vinyl ketone, the hydride transfer and adduct-forming channels for cyclohex-2-enone both arise by 1,4reduction.

DISCUSSION

The results summarized in Table 1 indicate a clear preference for 1,4-reduction of the three α,β -unsaturated carbonyl compounds by alkoxysiliconate ions. As noted in the Introduction, the limited number of previous studies of gas-phase hydride transfers involving unsaturated carbonyl compounds also suggest a general preference for 1,4-reduction, although this has not been extensively quantitated.^{16–24} A wider range of behavior is evident with other nucleophiles. Bernasconi *et al.*²⁴ reported that 1,4-addition (Michael addition) dominates in reactions between delocalized carbanions such as benzyl anion and methyl acrylate, but that 1,2-addition is competitive with acrolein and methyl vinyl ketone. Localized nucleophiles such as F^- and HO^- do not react with these compounds by addition, except when they are partially solvated.^{17,21,22,24} McDonald and Chowdhury²⁰ examined the reactions of phenyl nitrene anion, PhN⁻, with a variety of α,β -unsaturated carbonyl compounds, and concluded that 1,2-addition was the kinetically preferred pathway. Similarly, Bowie and coworkers²¹ demonstrated the occurrence of a 1,2addition–elimination pathway in the reaction between CD_3O^- and methyl acrylate carried out in an ion cyclotron resonance spectrometer.

The factors controlling competition between 1,2- and 1,4-addition to α,β -unsaturated carbonyl compounds are traditionally interpreted in terms of hard-soft acidbase (HSAB) theory, i.e. 'hard' nucleophiles generally react by adding to the carbonyl carbon, whereas 'soft' nucleophiles add to the β -carbon site.⁴⁵ In this context, the preference for 1,4-reduction by the alkoxysiliconates classifies them as 'soft.' However, the regioselectivity observed in these gas-phase reactions is probably better understood in terms of the prevailing thermochemistry. With the three compounds examined in this study, 1,4addition of H⁻ is exothermic by $\sim 238-259$ kJ mol⁻¹, whereas 1.2-addition of H^- is estimated to be exothermic by $151-176 \text{ kJ mol}^{-1}$. The hydride affinities of alkoxysilanes are estimated to be in the range 84-125 kJ mol⁻¹. ⁴⁶ Therefore, the greater observed yields for 1,4reduction are probably a reflection of a lower energy barrier for the thermodynamically favored H⁻ transfer pathway. The fact that the measured reaction efficiencies for acrolein and methyl vinyl ketone are less than unity confirms the presence of an energy barrier or some other kinetic bottleneck in these reactions.

It should be noted in this regard that 1,2-reduction is irreversible, ie.. once the (di)alkoxysiliconate species has formed, it never reverts to the carbonyl compound and the silicon hydride ion. This is apparent from the absence of any D–H exchange in reactions between deuterated silicon hydride ions and saturated aldehydes and by the lack of any label scrambling during either the formation or decomposition of partially labelled dialkoxysiliconate ions. This rules out otherwise plausible explanations for the dominance of 1,4-reduction in terms reversible 1,2-addition–elimination followed by irreversible 1,4-reduction.

It is interesting to note that 1,2-reduction of acrolein and methyl vinyl ketone results only in net addition (forming dialkoxysiliconate ions) rather than H⁻ transfer (forming the free alkoxide ions), despite the fact that the latter channel is exothermic in both cases. This same behavior characterizes most saturated aldehydes and ketones: only net addition occurs under flowing afterglow conditions, despite the fact that overall hydride transfer is thermodynamically allowed. Although this might suggest a four-center mechanism for 1,2reduction, this symmetry-forbidden process has been shown by Wu and Houk⁴⁷ using *ab initio* calculations to have a high activation barrier. Rather, adduct formation probably occurs in a stepwise fashion: hydride transfer from silicon to carbon followed by rapid addition of the resulting localized, strongly nucleophilic alkoxide ion to the Lewis acidic silane. Collisions with the helium bath gas then remove the excess energy in the siliconate ion, preventing dissociation of the alkoxide ligand. In contrast, 1,4-reduction by hydride transfer to the β -position of the substrates not only releases considerably more energy into the intermediate ionmolecule complex (~84 kJ mol⁻¹), but also produces a more weakly nucleophilic, delocalized enolate ion that has a lesser tendency to add to the nascent silane. Consequently, prompt dissociation of the 1,4-reduction intermediate occurs faster than quenching by the helium bath gas. In support of this hypothesis, we note that reactions of alkoxysiliconate ions with saturated ketones such as CF₃COCH₃ that have especially high hydride affinities produce significant yields of free alkoxide ion product.

The differences in the kinetics and product distributions for the three substrates are also instructive (cf. Table 1). First, it should be noted that the effective reducing reagents used for each of the three substrates are different: $BuSiH_2(OBu)^-$ for acrolein, $BuSiH_2$ - $(O^iPr)^-$ for methyl vinyl ketone and $HexSiH_2$ $(OCHEt_2)^-$ for cyclohex-2-enone, as dictated by the requirements of the CID protocol and the need to avoid mass overlaps. That is, a single, universal reducing reagent of this type was not used. However, because previous experience²⁵ has shown that minor variations in either the ancillary silane alkyl chain or the reference alkoxide group do not significantly effect the diastereochemical outcome of siliconate reductions involving prochiral ketones, we do not believe that these changes will introduce any differential effects on the regioselectivities. Hence, the results with the different reagents are fairly compared. The greater reaction efficiency for acrolein compared with methyl vinyl ketone is consistent with the relative reactivities of these compounds towards nucleophilic reactions in solution⁵ and with the difference in their total rates of reaction with PhNreported by McDonald and Chowdhury.20 The same reactivity ordering is also apparent in reactions of alkoxysiliconate ions with saturated ketones and aldehydes, although the differences are more pronounced. The two structurally similar acyclic carbonyl compounds acrolein and methyl vinyl ketone show essentially the same 1,4- vs. 1,2-regioselectivity (about 2:1). This casts doubt on the usefulness of HSAB theory for rationalizing the intrinsic regioselectivity, since these two compounds have different 'hardness' according to the usual criteria.45

Cyclohex-2-enone reacts entirely by 1,4-reduction. Moreover, unlike the other two substrates, it yields 1,4reduction products as both the free enolate ion and as the siliconate adduct. This difference is likely to be a result of the greater size of cyclohex-2-enone, which can lead to a longer lifetime for the intermediate enolatesilane complex and, therefore, a greater probability for collisional cooling by the helium and formation of adducts. The differing regioselectivity observed for cyclohex-2-enone must have kinetic origins since the estimated thermochemistry for reduction of the three substrates does not differ significantly. We note with interest the report by Chopra and Martin⁴⁸ of identical (1,4-) regioselectivity in the solution-phase reduction of cyclohex-2-enone by a novel pentacoordinate hydridosiliconate complex formed in tetrahydrofuran. Although the α,β -unsaturated carbonyl system of cyclohex-2-enone is constrained by the ring to an s-trans conformation, this is unlikely to be the origin of the differing regioselectivity since acrolein and methyl vinyl ketone also exist predominantly in their s-trans forms at room temperature.49 A relevant fact is that, in solution, cyclohex-2-enone derivatives generally show greater selectivity for axial attack by nucleophiles than do the corresponding cyclohexanones.⁵⁰ This has been attributed by Wu et al.⁵¹ to an unfavorable torsional interaction between the attacking nucleophile and one of the C(6) hydrogens in the transition state for equatorial addition to cyclohexenones that is not present with the saturated analogs. Implicit in this interpretation, and a natural consequence of the reactivityselectivity principle, is the conclusion that cyclohexenones are inherently less reactive than cyclohexanones towards carbonyl addition. Because these unfavorable torsional interactions would be either avoidable or absent altogether in methyl vinyl ketone and acrolein, 1,2-addition can occur with little or no hinderance.

The important question of diastereoselectivity in the 1,4-reduction reactions of the acyclic substrates remains unanswered. That is, addition of H⁻ to the β -position of acrolein and methyl vinyl ketone can produce the Z and E forms of the product enolate ions in either kinetically or thermodynamically controlled mixtures.⁵² Although distinguishing Z and E enolates in solution is relatively routine,⁵³ it is an especially challenging and unsolved problem for the corresponding gas-phase ions. We are currently pursuing experimental procedures for distinguishing diastereomeric enolate ions in the gas phase by means of competitive CID strategies analogous to those described here for regioisomers.

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