Ab Initio Study of the Homolytic Additions of Aminyl Radicals and Ammoniumyl Cation Radicals to Alkenes

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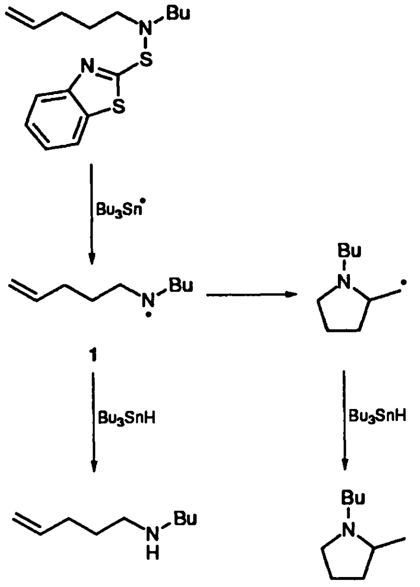
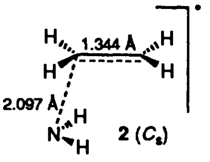
High-level *ab initio* molecular orbital calculations predict that the inter- and intra-molecular addition reactions of aminyl radicals and ammoniumyl cation radicals to alkenes are irreversible.

The inter- and intra-molecular addition reactions of carbon-centred radicals to carbon–carbon and carbon–heteroatom (N, O, S) multiple bonds has been the subject of intense activity from both mechanistic and synthetic viewpoints.[1] However, the analogous processes of aminyl radicals and to a lesser extent ammoniumyl cation radicals, have received considerably less attention.[2] In this context, we reported recently that even low levels (≈ 1 mol%) of bis(tributyltin) oxide have a profound accelerating influence on the homolytic cyclization of *N*-butyl-*N*-pent-4-enylaminyl **1** and that this process is irreversible under the prescribed reaction conditions (Scheme 1).[3] These results are in qualitative agreement with the data of Bowman and co-workers[4] who failed to observe cyclization of **1** in the presence of low concentrations of tributylstannane in boiling cyclohexane and the results of Maeda and Ingold, who report that the intramolecular addition of aminyl radicals to alkenes is immeasurably slow at room temperature.[5] Recently, however, Newcomb studied the cyclization of **1** in the presence of tributylstannane and concluded, in contrast with our findings, that **1** undergoes reversible cyclization at 50 °C.[2d,2e,2i] We now report the results of high-level *ab initio* molecular orbital calculations which predict that aminyl radicals add slowly and irreversibly to alkenes, while the corresponding protonated species add substantially more rapidly in the analogous reaction.



Scheme 1

Ground and transition states on the potential energy surface for the attack of aminyl and ammoniumyl at ethene were fully optimized in the usual way[6] using the Gaussian 92 system of programs[7] and the 6-311G** basis set with the inclusion of electron correlation at the MP2 level[8] (MP2/6-311G**). Further electron correlation was included as QCISD(T) single-point calculations [QCISD(T)/6-311G**//MP2/6-311G**]. For the cyclization reactions studied, all geometries were optimized using the 6-31G* basis set with MP2 electron correlation included as single-point calculations (MP2/6-31G*//UHF/6-31G*). Spin contamination did not appear to be a problem, as values of $\langle S^2 \rangle$ never exceeded 0.80 before annihilation of quartet contamination. The evaluation of the complete set of harmonic frequencies in each optimization proved that the located structures do indeed correspond to the correct stationary point.



2 (C_s)

Transition structure **2** (C_s symmetry) was located for the reaction of aminyl with ethene [eqn. (1)]. Structure **2** was

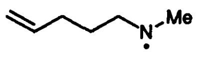
$$\dot{N}H_2 + H_2C{=}CH_2 \xrightarrow{\Delta E^\ddagger} \mathbf{2} \longrightarrow H_2NCH_2\dot{C}H_2 \qquad (1)$$

calculated to lie 37.8 kJ mol^{-1} above the energy of the reactants and 131.9 kJ mol^{-1} above the energy of the product at the MP2/6-311G** level of theory. Inclusion of single-point correlation at the QCISD(T) level reduced these barriers to 16.6 and 107.8 kJ mol^{-1}, respectively. These data are to be compared with the results of Peyerimhoff and co-workers who predict a barrier of 146–167 kJ mol^{-1} for the reverse reaction using less sophisticated *ab initio* techniques.[9] It is highly unlikely, therefore, that the reaction of aminyl with ethene is reversible under laboratory conditions. Interestingly, no transition state could be located at the MP2/6-311G** level of theory for the reaction of ammoniumyl with ethene [eqn. (2)]. Indeed, this

$$\overset{+\bullet}{N}H_3 + H_2C{=}CH_2 \longrightarrow H_3\overset{+}{N}CH_2\dot{C}H_2 \qquad (2)$$

reaction is predicted to proceed without barrier and to be exothermic to 230 kJ mol^{-1}; single-point QCISD(T) correction reduces this value to 218 kJ mol^{-1}.

We then turned our attention to the intramolecular addition processes of *N*-methyl-*N*-pent-4-enylaminyl (**3**) and *N*-methyl-*N*-pent-4-enylammoniumyl (**4**). The *exo* and *endo* modes of homolytic cyclization of **3** and **4** were examined as described



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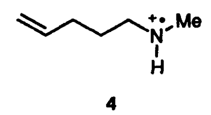

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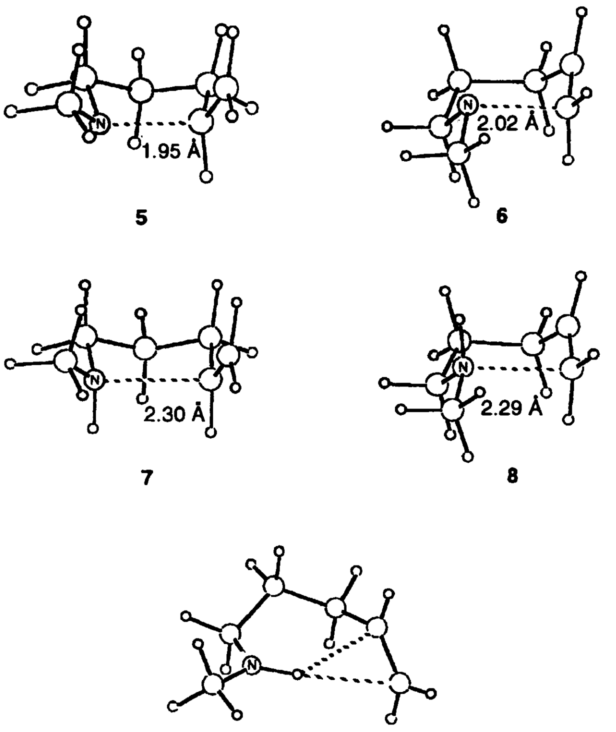


5 **6** **7** **8** **9**

Fig. 1

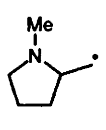
Table 1 Calculated energy barriers ($\Delta E^{\ddagger}$/kJ mol^{-1}) and enthalpies ($\Delta H^{\ddagger}$/kJ mol^{-1}) for the *exo* and *endo* modes of cyclization of **3** and **9**

		$\Delta E^{\ddagger}$		$\Delta H^{\ddagger}$	
Reaction	TS	UHF[a]	MP2[b]	UHF[a]	MP2[b]
3 ⟶ **10**	**5**	85.1	59.0	−14.9	−57.4
3 ⟶ **11**	**6**	96.6	86.6	−31.8	−75.4
9 ⟶ **12**	**7**	21.1	5.0	−66.3	−109.2
9 ⟶ **13**	**8**	31.1	11.5	−74.3	−115.7

[a] UHF/6-31G*. [b] MP2/6-31G*//UHF/6-31G*.

above. The lowest energy conformation transition states **5**–**8** were located at the UHF/6-31G* level of theory and are displayed in Fig. 1. Structure **5** for *exo* mode of cyclization of **3** was found to lie some 85.1 kJ mol^{-1} above the reactant, while **6**, the transition state for the *endo* mode of cyclization, was calculated to lie 96.6 kJ mol^{-1} above **3** ($\Delta E^{\ddagger}$, Table 1). Inclusion of electron correlation (MP2/6-31G*//UHF/6-31G*) reduces the barriers for the *exo* and *endo* modes of cyclization to 59.0 and 86.6 kJ mol^{-1}, respectively. Inclusion of higher-order electron correlation is likely to reduce further the barrier as was observed in the addition of aminyl to ethene. The reverse reactions, namely the ring opening of **10** and **11** were calculated to have barriers of 100.0 and 128.4 kJ mol^{-1}, respectively, at the lower level and 116.4 and 162.0 kJ mol^{-1}, respectively, at the higher level ($\Delta E^{\ddagger}$ + $\Delta H^{\ddagger}$, Table 1). Clearly, these calculated data are consistent with slow, irreversible cyclization of **3** with preference for the *exo* mode of ring closure.

The potential energy surface for the ring-closure of the analogous cation radical **4** revealed several interesting features. The open-chain form of **4** was found to lie above the transition state **7** for cyclization. Indeed, at the higher level of theory, **4** was found to lie 23.4 kJ mol^{-1} above **7**. Extensive searching of the potential energy surface revealed the existence of a lower energy form of the reactant, namely **9**, in which the proton on nitrogen is coordinated to the alkene. Consequently, the barrier for the *exo* mode of cyclization of **9** was calculated to be 21.1 and 5.0 kJ mol^{-1} at the UHF/6-31G* and MP2/6-31G*//UHF/6-31G* levels, respectively, while the similar barrier for the formation of **13** was calculated to be 31.1 and 11.5 kJ mol^{-1} at the lower and higher levels, respectively. The reverse reactions, namely the ring-opening of **12** and **13**, were calculated to be accompanied by substantial barriers, 87.4 and 114.2 kJ mol^{-1}, respectively, at the lower level and 105.4 and 127.2 kJ mol^{-1} at the higher level ($\Delta E^{\ddagger}$ + $\Delta H^{\ddagger}$, Table 1). Our calculations, therefore, predict that intramolecular additions of ammoniumyl cation radicals are facile, irreversible and proceed with a preference for the *exo* mode of cyclization, in agreement with experimental observation.[2j,2l]



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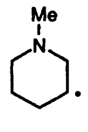

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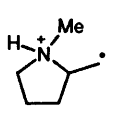

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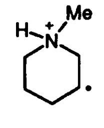

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14

The structures of the transition states **7** and **8** are subtly different to those for the cyclization of the neutral radical **3**. Fig. 1 indicates that the 'attack distance' is longer in **7** than in **5**, with values of 2.30 and 1.95 Å, respectively, indicative of later transition states involved in the reaction of the neutral species. Similar data are obtained for the *endo* mode of cyclization (2.29 *vs.* 2.02 Å). Not surprisingly, Fig. 1 also reveals that the transition states in this study are structurally similar to the transition states involved in the cyclization of the hex-5-enyl radical **14** as proposed by Beckwith.[10,11]

The similarities between the inter- and intra-molecular reactions are not to be overlooked. The aminyl in each case is predicted to add to the alkene slowly and in an irreversible manner. The ammoniumyl is predicted to add without barrier to ethene, while the intramolecular analogue is predicted to add with a very small barrier to the alkene, presumably due to the strain engendered in the cyclic nature of the transition state **7**. Each reaction is predicted to be facile and substantially exothermic, in good agreement with experimental observations.[2e,2j,2l]

We have already speculated on the unprecedented Lewis acid type complexation between **1** and bis(tributyltin) oxide; that this interaction is chelative in nature, however, is open for discussion.[3] Aminyls have been shown to be nucleophilic in nature.[12] Indeed, this has been corroborated by the expediency with which they add to electron deficient π-systems such as carbonyls[2c] and by their slow additions to unactivated (electron rich) alkenes.[2e,3,5,13] Accordingly, it could be argued that the role of bis(tributyltin) oxide in the cyclization reactions of aminyl radicals, such as **1**, is to produce a less nucleophilic nitrogen radical, thus facilitating cyclization.

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