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Ion–Molecule Reactions in the Gas Phase. Collision Energy Influence on the Competitive S_Ni/S_N2 Orientation from Adduct Ions of Epimeric 1,2-Indanediols Prepared by Ammonia Chemical Ionization

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Under chemical ionization (CI) conditions, *cis* and *trans* 1,2-indanediols mainly react with the NH_3/NH_4^+ system *via* a nucleophilic substitution process. In the CI source several mechanisms can occur yielding the substituted $[M + NH_4–H_2O]^+$ ions at *m/z* 150. Collisionally activated reaction (CAR) spectra provide additional information concerning the structure of selected low kinetic energy species. These ion–molecule reactions with methylamine are performed for $[M + NH_4–H_2O]^+$ ions in the collision cell of a triple quadrupole mass spectrometer. In this way, the nucleophilic substitution process is demonstrated to depend on the stereochemistry of the indanediol precursor. Stereospecific S_N2 and S_Ni pathways operate for the *cis* and *trans* derivatives, respectively. Such competitive orientations are explained by considering hydrogen bonds and the steric hindrance due to the homobenzylic group. © 1997 John Wiley & Sons, Ltd.

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Several investigations have been reported involving ammonia chemical ionization (CI), and concerning the production of the $[M + NH_4–H_2O]^+$ ions (denoted as M_SH^+) from hydroxylic compounds. Several reviews have been published.[1–3] Knowing the initial relative configuration of functional groups borne by the epimeric compounds, structure determination of the product ions throws light on the nucleophilic substitution mechanism. This can be achieved by using tandem mass spectrometry (MS/MS) experiments under collision-induced dissociation (CID) conditions, since many stereochemical effects have been described and rationalized in the literature.[4] In particular, two nucleophilic substitution processes mainly occur in the gas phase (Eqn (1)). The S_Ni mechanism (Eqn 1(a)) corresponds to direct water elimination from the adduct ion $(ROH + NH_4)^+$, proceeding with retention of stereochemistry.[5–9] The bimolecular S_N2 reaction of NH_3 with $(ROH + NH_4)^+$ (Eqn 1(b)), characterized by a configuration inversion, is also envisaged[10–15] to occur.

$$ROH + NH_4^+ \rightleftharpoons (ROH{+}NH_4)^{+*} \xrightarrow{S_Ni} RNH_3^+ + H_2O \quad (1a)$$

$$(ROH{+}NH_4)^{+*} \xrightarrow{+NH_3} RNH_3^+ + H_2O + NH_3 \quad (1b)$$

Less frequently, the following stepwise pathway (Eqn (2)) is implicated as a nucleophilic attachment via the formation of carbonium R^+ species:[16,17]

$$(ROH + NH_4)^{+*} \longrightarrow R^+ + H_2O + NH_3 \xrightarrow{+NH_3} RNH_3^+ \quad S_N1 \quad (2)$$

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This reaction, proposed to account for the racemization of the product ion RNH_3^+, is considered as a 'like S_N1' mechanism.

The stereochemistry of the inserted $–NH_3^+$ group in the M_SH^+ ions can be determined by analysis of these substituted species under collision processes, as noted above. Indeed, CID spectra provide useful information about the ion structures.[6–9,13–15] This method allows one to specify the nucleophilic substitution mechanism operating in the high pressure source. The origin of the substituted M_SH^+ ions prepared by ammonia CI from epimeric 1,2-indanediols[18] (or higher-membered-ring homologues[19]) has been approached by using such a methodology. In the bifunctional M_SH^+ ions thus produced, the stereochemistry of the intact –OH group in relation to the charged $–NH_3^+$ group specifically appeared *trans*, regardless of which diastereoisomer is considered. This conclusion has been reached from: (i) mass-analysed ion kinetic energy (MIKE)-CID spectra and charge reversal spectra which displayed similar fingerprints for M_SH^+ product ions and synthesized standards, (ii) comparison of dependence of M_SH^+ ion formation efficiency (i.e. measurement of the $M_SH^+/[M + NH_4]^+$ abundance ratios) upon ammonia pressure, from both *cis/trans* epimers. Furthermore, the nucleophilic substitution process has been shown to take place regioselectively at the benzylic position.[18,19] This was considered to result from the particular polarizability of the benzylic C–O bond.[18] Finally, production of a common *trans*-protonated amino-alcohol from both the *cis* and *trans* diols required that the reaction proceeded via S_N2 (Scheme 1a) and S_Ni (Scheme 1b) pathways, respectively.

The present work concerns reactivity of the same epimeric 1,2-indanediols (**1c** and **1t**) towards methylamine, CH_3NH_2. In this study, ion–molecule reactions are induced from the selected substituted M_SH^+ ions in

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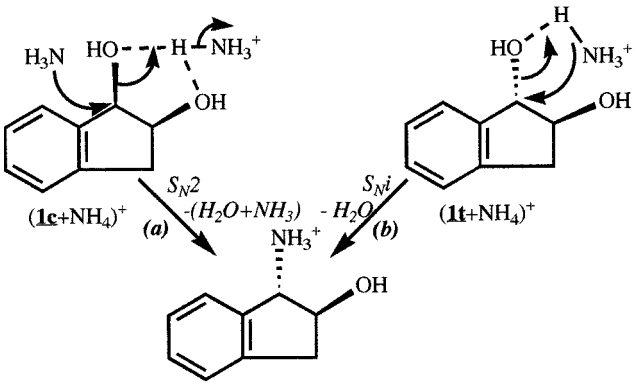


Scheme 1. (a) S_N2 and (b) S_Ni mechanisms occurring from the *cis* and *trans* indanediols, respectively.

the collision cell of a tandem mass spectrometer. Their respective structures are compared by investigation of the dependence of the produced species on the laboratory collision energy (ERMS: energy resolved mass spectrometry[20–26]). Under these conditions, several processes such as proton transfer, nucleophilic reagent attachment, and dissociation, occur competitively. However, stereochemical effects can be particularly analysed via collisionally activated reaction (CAR) spectra,[16,17,27,28] recorded from epimeric adduct ions $[\mathbf{1c} + NH_4]^+$ and $[\mathbf{1t} + NH_4]^+$.

EXPERIMENTAL

Mass spectrometric experiments were performed using a triple quadrupole instrument (Nermag R30-10, Rueil Malmaison, France). The samples (1 μL of a 1 μg/μL solution) were introduced into a high pressure ion source by using a direct desorption DCI probe without heating the tungsten filament. Source operating conditions were: electron energy 100 eV, emission current 100 μA, repeller 0 V. The low energy CID spectra of the selected species were obtained with argon as target gas (essentially single collision conditions, 2×10^{-3} torr) in the collision cell. Ion–molecule reactions (CAR spectra) were produced by introducing CH_3NH_2 (multiple collision conditions, 2×10^{-2} torr or 7×10^{-3} torr) in the RF-only quadrupole. The main factor which influences the abundance of the product ions, is the methylamine pressure in the collision cell. The potentials applied to the lens seemed to be less critical. In order to optimise the methylamine pressure, the following species: $CH_3NH_3^+$ (*m/z* 32), $(CH_3NH_3, NH_3)^+$ (*m/z* 49) and $(CH_3NH_2)_2H^+$ (*m/z* 63), prepared from the selected $N_2H_7^+$ ion, are considered. When the ratios of their abundances are maintained constant, the CAR spectra are reproducible, even the low intensity peaks. The eventual changes do not modify the observed trends, particularly for the nucleophilic substitution generated in the collision cell. Laboratory collision energy varied from 4 eV to 15 eV. Each mass spectrum corresponds to an average of fifty scans.

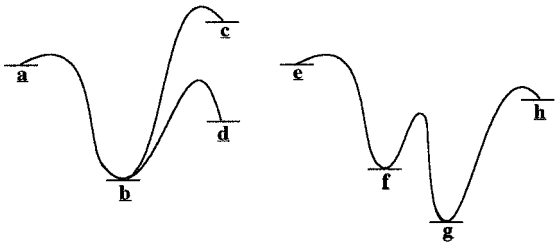
Cis and *trans* indanediols were synthesized according to methods described in the literature.[29]

RESULTS AND DISCUSSION

Under ammonia CI conditions, protonated molecules

Table 1. Relative abundances of the $[M+NH_4]^+$, M_SH^+ and $[M_SH–NH_3]^+$ ions displayed in the CI-NH_3 mass spectra of the epimeric 1,2-indanediols

epimer	$[M_SH–NH_3]^+$ *m/z* 133	M_SH^+ *m/z* 150	$[M+NH_4]^+$ *m/z* 168
1c cis	40	80	100
1t trans	33	73	100



Scheme 2. Simplified reaction coordinate-energy diagrams comparing protonation and nucleophilic substitution processes. a = $[M + NH_4^+]$, b = $[(M + NH_4)^+]$, c = $[MH^+ + NH_3]$, d = $[M_SH^+ + H_2O]$, e = $[(M + NH_4)^+ + NH_3]$, f = $[(H_3N...MNH_4)^+]$, g = $[(H_3N, H_2O, M_SH)^+]$, h = $[M_SH^+ + H_2O + NH_3]$.

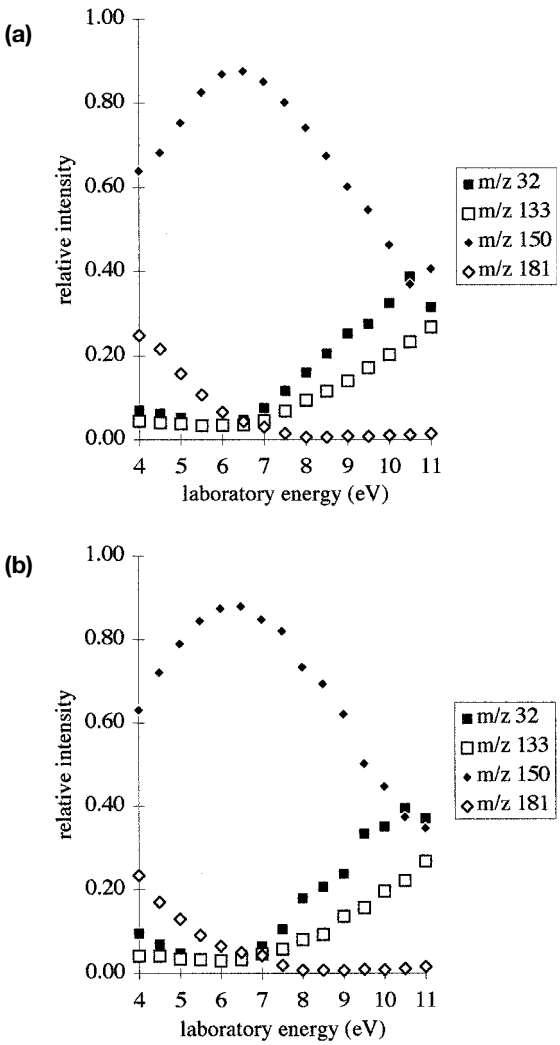


Figure 1. Energy dependence of reactive collisions induced by CH_3NH_2 with the selected M_SH^+ ions (*m/z* 150). $P_{CH_3NH_2} = 2 \times 10^{-2}$ torr, uncorrected value. (a) *cis* indane 1,2-diol **1c**, (b) *trans* indane 1,2-diol **1t**.

are not detected from the epimeric **1c** and **1t** diols. The adduct $[M + NH_4]^+$ ions constitute the major species (Table 1).

The inefficiency of the proton transfer reaction from ammonium ion to these analytes indicates that the protonation process must be significantly endothermic. This behaviour is consistent with the estimated proton affinities of the diastereoisomeric diols as lower than that of ammonia (see Appendix). Consequently, other ion–molecule reactions can be favoured, such as nucleophilic substitution processes, even if their tight transition state leads to an higher intrinsic barrier (Scheme 2).

In particular, the nucleophilic substitution reaction yielding the M_SH^+ ions at *m/z* 150, isobaric with the molecular $M^{+\bullet}$ species, can be enhanced. In the deuterated ammonia CI spectrum, the peak at *m/z* 150 is shifted to *m/z* 154 which is consistent with the loss of D_2O from the labelled adduct $(Md_2 + ND_4)^+$ ions at *m/z* 174. The $[(M_SH–NH_3)^+/M_SH^+]$ abundance ratios are very similar whatever the considered epimer may be. This could be a first indication that a common structure characterizes the substituted ions.

Stereochemistry of the substituted $[1c + NH_4–H_2O]^+$ and $[1t + NH_4–H_2O]^+$ species generated in the ion source

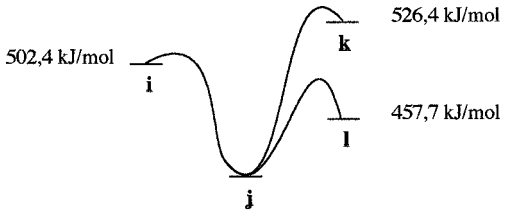
The structures of these substituted ions are compared in order to determine the nucleophilic substitution mechanisms operating in the high pressure source. For this purpose, ion–molecule reactions are induced in the collision cell with methylamine used as reagent gas. This investigation is performed from a beam of reactant ions possessing a variable low kinetic energy (see Fig. 1). These ERMS experiments should be useful for distinguishing very similar structures.[22,30–34] In addition to the dissociation producing the $[M_SH–NH_3]^+$ ions at *m/z* 133, different bimolecular processes are generated under these low collision energy conditions (Eqn (3)).

$$\underset{m/z\ 150}{RNH_3^+ + CH_3NH_2} \rightleftharpoons \{RNH_3^+, CH_3NH_2\}^* \rightleftharpoons \{RNH_2, CH_3NH_3^+\}^* \quad (3)$$

(3a) collisional stabilisation → $\{RNH_3^+, CH_3NH_2\}$ m/z 181

(3b) dissociation → $RNH_2 + CH_3NH_3^+$ m/z 32

Solvation of the protonated amine leading to $[M_SH + NH_2CH_3]^+$ at *m/z* 181 is enhanced at the lowest collision energies, as expected since this reaction is exothermic in relation to the initial state (Eqn 3(a)).[35,36] Under these multiple collision conditions, the excited adduct ions $[M_SH + NH_2CH_3]^+*$ are relaxed by near-thermal collision. At higher laboratory energies, the latter solvated species are more and more vibrationally excited so that they dissociate into protonated methylamine $[CH_3NH_3^+]$ at *m/z* 32 (Eqn 3(b)). This pathway is estimated as slightly endothermic by 24 kJ/mol from the initial state $[M_SH^+ + CH_3NH_2]$ (see Appendix and Scheme 3). Direct cleavage of the substituted M_SH^+ precursor ion also occurs, producing the *m/z* 133 carbonium ion.



Scheme 3. Competitive proton transfer reaction and nucleophilic substitution processes for the system: i = $[(RNH_3^+ + CH_3NH_2]$. j = $[(RNH_3 + CH_3NH_2)^+]$, k = $[RNH_2 + CH_3NH_3^+]$, l = $[RNH_2CH_3^+ + NH_3]$.

$$\underset{m/z\ 150}{RNH_3^+ + CH_3NH_2} \rightleftharpoons \{RNH_3^+, CH_3NH_2\} \xrightarrow{S_N2} \underset{m/z\ 164}{RNH_2CH_3^+ + NH_3} \quad (4)$$

It should be noted that the formation of $RNH_2CH_3^+$ at *m/z* 164 does not occur by nucleophilic substitution (Eqn (4)) under these collisional conditions in spite of the exothermicity of this process, estimated to be 44.7 kJ/mol (see Appendix and Scheme 3). This behaviour can be rationalized by considering that the $C–NH_3^+$ bond is insufficiently polarized. Consequently, the nucleophilic CH_3NH_2 approach at the activated

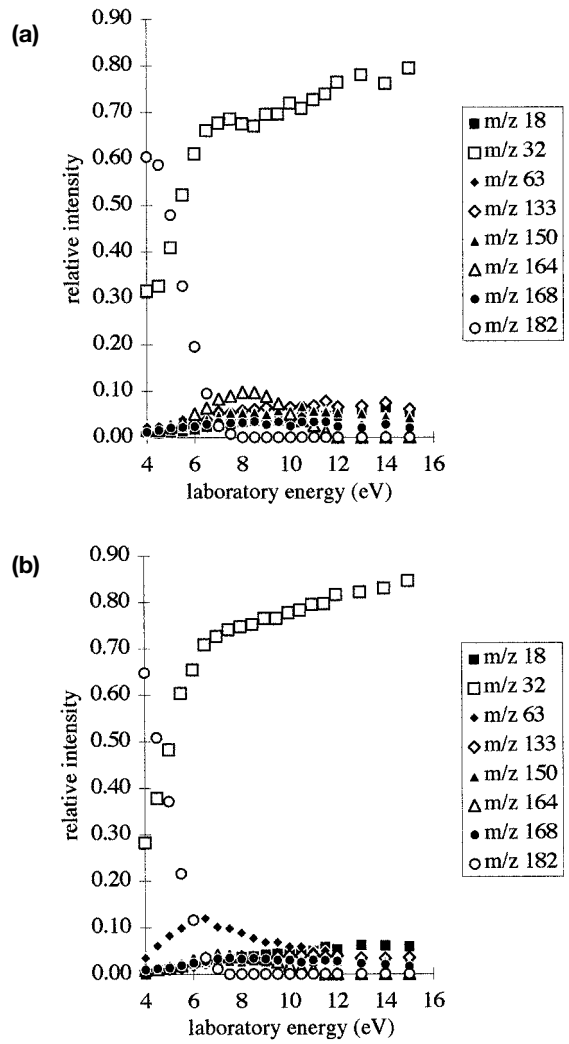


Figure 2. Energy dependence of reactive collisions induced by CH_3NH_2 for the selected $[M + NH_4]^+$ species at *m/z* 168. $P_{CH_3NH_2} = 7 \times 10^{-3}$ torr, uncorrected value. (a) *cis* indane 1,2-diol **1c**, (b) *trans* indane 1,2-diol **1t**.

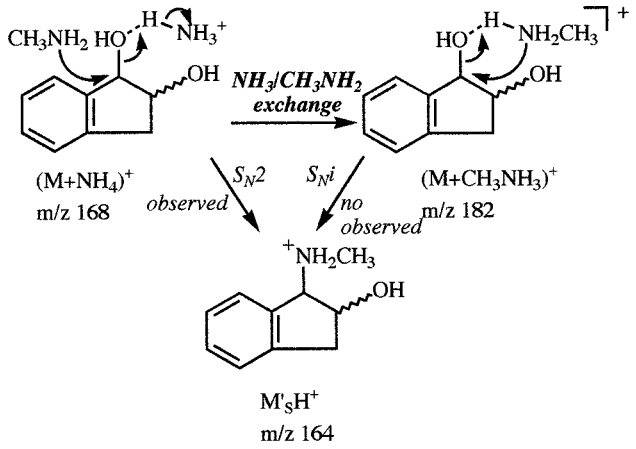
benzylic carbon atom is inefficient, since this C atom is not sufficiently positively charged. On the other hand, this implies that ammonia is not a good leaving group in this context, as expected because of the relatively high proton affinity of amines.[37]

No stereochemical effect was observed from the substituted $[\mathbf{1c} + NH_4–H_2O]^+$ and $[\mathbf{1t} + NH_4–H_2O]^+$ ions. In particular, a similar efficiency characterizes the production of the protonated methylamine. From previous measurements, the proton affinities of *cis* bifunctional epimers have been shown to be higher than those of the *trans* isomers.[38–40] Such proton transfer reactions, from selected even-electron charged molecular species of various substrates to neutral reagents like methyl, di- and trimethylamines in a quadrupole collision cell, have been already used to provide information complementary to that obtained under CI conditions.[27] Ion–molecule reactions produced in a low-energy collision cell from a selected ion allow assignment of a specific structure according to its reactivity. Thus, several *cis/trans* protonated bifunctional compounds have been distinguished in this way.[36] Since the substituted $[\mathbf{1c} + NH_4–H_2O]^+$ and $[\mathbf{1t} + NH_4–H_2O]^+$ ions are closely similar in their reactivities towards the methylamine reagent, the relative stereochemistries of the OH/NH_3^+ groups may be considered as most probably identical. To provide such a result, different mechanisms must operate for the two epimers in the ion source. A previous study[18] has shown that the intramolecular nucleophilic substitution (i.e. S_Ni) was significantly disadvantaged in the case of the *cis* $[\mathbf{1c} + NH_4]^+$ isomer, because of ammonium chelation involving both neighbouring OH groups. Indeed, this chelation hinders the formation of the four-centre transition state. Consequently, the *cis* derivative preferably reacts *via* bimolecular nucleophilic substitution (i.e. S_N2). On the contrary, the steric effect due to the homobenzylic group prevents this mechanism for the *trans* compound, and the S_Ni pathway preferentially occurs in the ion source.

Reactivity of the epimeric adduct $[M + NH_4]^+$ ions towards methylamine in the collision cell

This section describes a comparison of nucleophilic substitution processes yielding the substituted $[M + NH_4–H_2O]^+$ ions at *m/z* 150 and $[M + CH_3NH_3–H_2O]^+$ ions at *m/z* 164 in the collision cell, particularly the effects of collision energy. Reactive collisions of selected $[M + NH_4]^+$ ions with CH_3NH_2 in the collision cell should allow distinction between the *cis/trans* epimeric structures (Fig. 2).

Unfortunately, methylamine as reagent gas mainly produces proton transfer from the adduct ions, and the nucleophilic substitution pathways occur at lower efficiencies. However, competitive bimolecular and intramolecular nucleophilic substitution processes give rise to formation of the substituted $[M + CH_3NH_3–H_2O]^+$ ions (denoted as M'_SH^+) at *m/z* 164, and to $[M + NH_4–H_2O]^+$ species (M_SH^+) at *m/z* 150, respectively. The production of M'_SH^+ ions (*m/z* 164) directly via S_Ni reaction from the adduct $[M + CH_3NH_3]^+$ ions at *m/z* 182 has been ruled out. Such solvated species prepared under methylamine CI conditions, and subjected to CID ($E_{Lab} = 10$ eV, argon) lead to $CH_3NH_3^+$ rather than to $[M + CH_3NH_3–H_2O]^+$, which was not detected even at lower collision energies. Such an unfavourable tendency for S_Ni reactions can be explained by considering that the tight transition state (low frequency factor) constitutes the 'bottleneck' of the S_Ni reaction. This contrasts with the loose transition



Scheme 4. Formation of the substituted M'_SH^+ ions (*m/z* 164).

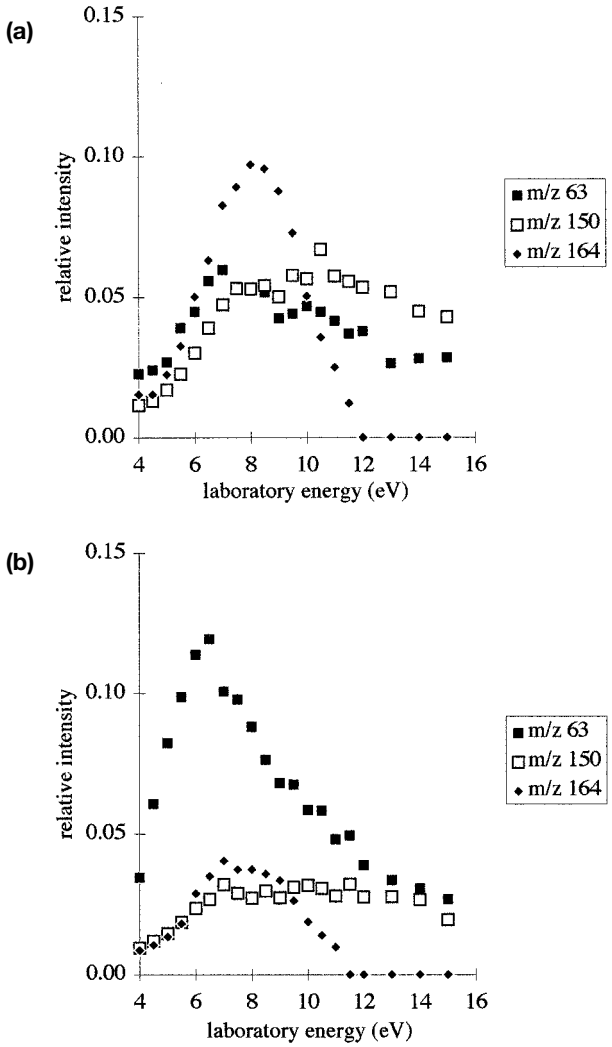


Figure 3. Energy dependence of the abundances of minor product ions produced by reactive collisions of the selected $[M + NH_4]^+$ ions at *m/z* 168 with CH_3NH_2. $P_{CH_3NH_2} = 7 \times 10^{-3}$ torr, uncorrected value. (a) *cis* indane 1,2-diol **1c**, (b) *trans* indane 1,2-diol **1t**.

state (higher frequency factor), which is close in structure to the final state, yielding $CH_3NH_3^+$ by hydrogen-bond cleavage. An analogous competition has been described[41] in order to explain the decompositions of ammonia adduct ions generated from norbornyl acetates. Formation of NH_4^+ was preferred[41] to the production of $[M + NH_4–CH_3CO_2H]^+$ ions from such solvated species. All of this discussion suggests that the $[M + CH_3NH_3–H_2O]^+$ ions must be exclusively produced via the S_N2 pathway from $[M + NH_4]^+$ rather than via S_Ni from $[M + CH_3NH_3]^+$ (Scheme 4). Furthermore, the total disappearance of M'_SH^+ (*m/z* 164) at collision energies above 12 eV confirms the bimolecular character of its formation, in contrast to the substituted M_SH^+ ion at *m/z* 150 which is still produced by the S_Ni process (CID pathway) from $[M + NH_4]^+$ (Fig. 3).

On the other hand, the difference of reactivity between RNH_3^+ and $[ROH + NH_4]^+$ illustrates the lower polarity of the benzylic C–NH_3^+ bond in relation to the (C–OH···H^+···NH_3) grouping, since only the latter form leads to bimolecular nucleophilic substitution.

The influence of proton affinities, on the efficiency of proton transfer processes from the adduct $[M + NH_4]^+$ ions, will now be considered. At low collision energy, the NH_3/CH_3NH_2 exchange reaction is very efficient in the $[M + NH_4]^+/CH_3NH_2$ system, yielding the solvated $[M + CH_3NH_3]^+$ species at *m/z* 182. The abundance of the latter species sharply decreases at higher laboratory energies, since the dissociation of this hydrogen-bonded cluster ion is thereby enhanced. Above 6 eV, protonated methylamine constitutes the major CID product ion. Under these experimental conditions, neither of the abundant $[M + CH_3NH_3]^+$ ions (*m/z* 182) or $CH_3NH_3^+$ (*m/z* 32) is influenced by the *cis/trans* stereochemistry. In order to differentiate the $[\mathbf{1c} + NH_4]^+$ and $[\mathbf{1t} + NH_4]^+$ epimers, the minor product ions (less than 15% of TIC) must be considered. (Fig. 3). In spite of the low abundances of these ions, the reproducibility is sufficient to confirm the ion–molecule reaction dependence upon the stereochemistry.

Protonated methylamine is produced with the same efficiency whatever the initial stereochemistry, in contrast to the $(CH_3NH_2)_2H^+$ proton-bound dimer at *m/z* 63. Under these multiple collision conditions, a favourable M/CH_3NH_2 exchange leads to $(CH_3NH_2)_2H^+$, more stable than the mixed dimer, i.e. $[M + CH_3NH_3]^+$. In general, the more similar the proton affinity (PA) values of the neutral constituents of proton-bound dimers, the more stable is the complex.[42] Knowing that $PA(CH_3NH_2) > PA(\mathbf{1c}) > PA(\mathbf{1t})$ (see Appendix), the adduct $[\mathbf{1c} + CH_3NH_3]^+$ ion is expected to be more stable than $[\mathbf{1t} + CH_3NH_3]^+$, and the $(CH_3NH_2)_2H^+$ dimer should be produced more abundantly from the *trans* derivative, as observed.

Stereochemical effects on the S_Ni/S_N2 orientation were indeed observed. Below 10 eV, the two nucleophilic substitution mechanisms occur competitively. From the selected $[\mathbf{1c} + NH_4]^+$ ion, the S_N2 process (formation of M'_SH^+ at *m/z* 164) is more favoured than the S_Ni pathway (production of M_SH^+ at *m/z* 150), in relation to the situation observed for the epimeric $[\mathbf{1t} + NH_4]^+$ species. Indeed, the $[\mathbf{1t} + CH_3NH_3–H_2O]^+$ and $[\mathbf{1t} + NH_4–H_2O]^+$ ions are generated in almost equal abundances at these collision energies, which suggests that the S_N2/S_Ni competition is less specific from the *trans* isomer. From the *cis* derivative, the S_N2 process occurs without steric interaction with the homobenzylic hydroxylic group, since CH_3NH_2 approaches on the opposite ring side. Alternatively, the S_Ni process via a four-centre transition state from the $[\mathbf{1c} + NH_4]^+$ species must be hindered by the ammonium ion chelation. In contrast, the homobenzylic OH group in the *trans* **1t** epimer provides steric hindrance for the methylamine attack at the activated site. Thus, the S_N2 intrinsic barrier is higher, and formation of the substituted $[\mathbf{1t} + CH_3NH_3–H_2O]^+$ ion is disadvantaged. Under CI conditions, a similar preference has been observed, and presumably the foregoing discussion can also be applied to reaction conditions in the CI source.

CONCLUSION

The present work deals with the reactivity of *cis/trans* indane diols towards the NH_3/NH_4^+ system. In the high pressure source, S_Ni and S_N2 pathways occur from $[\mathbf{1t} + NH_4]^+$ and $[\mathbf{1c} + NH_4]^+$ ions, respectively. Indeed, the substituted M_SH^+ ions, $[\mathbf{1t} + NH_4–H_2O]^+$ and $[\mathbf{1c} + NH_4–H_2O]^+$, have a common structure independent of the initial stereochemistry. This conclusion is supported by the similar trends of the reactive collisions with methylamine in the RF-only quadrupole. Such behaviour was expected from previous results.[18] On the other hand, the adduct $[M + NH_4]^+$ ions react with CH_3NH_2 via a nucleophilic substitution process in the collision cell, in contrast with the substituted M_SH^+ species. Water is a better leaving group than ammonia in the present context. Furthermore, the reactivity of the adduct ions depends on the initial stereochemistry of the diol. If the S_N2 pathway is favoured over S_Ni in the collision cell for $[\mathbf{1c} + NH_4]^+$, the reverse orientation characterizes $[\mathbf{1t} + NH_4]^+$. This distinction has been demonstrated despite the high efficiency observed for the competing proton transfer to methylamine.

REFERENCES

1. J. B. Westmore and M. M. Alauddin, *Mass Spectrom. Rev.* **5**, 381 (1986).
2. J. C. Tabet, *Fundamentals of Gas Phase Ion Chemistry*, K. R. Jennings (Ed.), Elsevier, Netherlands, p.351 (1991).
3. A. Mandelbaum, *Mass Spectrom. Rev.* **2**, 223 (1983).
4. J. S. Splitter and F. Turecek, *Methods in Stereochemical Analysis: Applications of Mass Spectrometry to Organic Stereochemistry*, VCH, New York (1994).
5. T. Keough and A. J. DeStefano, *Org. Mass Spectrom.* **16**, 527 (1981).
6. K. G. Das, R. A. Swamy, J. van Thuijl, W. Onkenhout, D. Fraisse and J. C. Tabet, *Org. Mass Spectrom.* **18**, 34 (1983).
7. H. Nakata, Y. Hoshino, N. Takeda and A. Tatematsu, *Org. Mass Spectrom.* **20**, 467 (1985).
8. D. Promé, J. C. Promé and D. Stahl, *Org. Mass Spectrom.* **20**, 525 (1985).
9. K. P. Madhusudanan, S. Durani, R. S. Kapil and D. Fraisse, *Org. Mass Spectrom.* **25**, 265 (1990).
10. J. Bastard, D. Do Khac Manh, M. Fetizon, J. C. Tabet and D. Fraisse, *J. Chem. Soc., Perkin Trans II*, 1591 (1981).
11. R. Houriet and J. C. Tabet, *Nouv. J. Chim.* **6**, 565 (1982).
12. F. O. Gülaçar, F. Mermoud, F. J. Winkler and A. Buchs, *Helv. Chim. Acta* **67**, 488 (1983).
13. J. C. Tabet, M. Bertranne, J. C. Beloeil and D. Stahl, *Org. Mass Spectrom.* **19**, 363 (1984).

14. J. C. Tabet, Y. Tondeur, Y. Hirano, A. Wegmann, P. Tecon and C. Djerassi, *Org. Mass Spectrom.* **19**, 473 (1984).
15. J. C. Tabet, C. Prevost, A. Bouillot, J. Bastard, D. Do Khac Manh and Y. Tondeur, *Helv. Chim. Acta* **69**, 806 (1986).
16. E. L. White, J. C. Tabet and M. M. Bursey, *Org. Mass Spectrom.* **22**, 132 (1987).
17. T. Cairns, E. G. Siegmund and J. J. Stamp, *Rapid. Comm. Mass Spectrom.* **1**, 74 (1987).
18. J. C. Tabet, H. E. Audier and J. P. Denhez, *Tetrahedron* **43**, 873 (1987).
19. K. P. Madhusudanan, M. Prasad, S. N. Rastogi and D. Fraisse, *Org. Mass Spectrom.* **20**, 680 (1985).
20. G. L. Glish, P. H. Hemberger and R. G. Cooks, *Anal. Chim. Acta* **119**, 137 (1980).
21. S. A. McLuckey, G. L. Glish and R. G. Cooks, *Int. J. Mass Spectrom. Ion Phys.* **39**, 219 (1981).
22. D. D. Fetterolf and R. A. Yost, *Int. J. Mass Spectrom. Ion Phys.* **44**, 37 (1982).
23. W. F. Sun and P. H. Dawson, *Org. Mass Spectrom.* **18**, 396 (1983).
24. D. D. Fetterolf, R. A. Yost and J. R. Eyler, *Org. Mass Spectrom.* **19**, 104 (1984).
25. K. L. Busch, G. L. Glish and S. A. McLuckey, *Mass Spectrometry/ Mass Spectrometry: Techniques and Applications of Tandem Mass Spectrometry*, VCH, New York (1988).
26. S. J. A. Curtis and A. G. Harrison, *J. Am. Soc. Mass Spectrom.* **1**, 301 (1990).
27. R. B. Cole and J. C. Tabet, *J. Mass Spectrom.* **32**, 413 (1997).
28. V. Gervat, F. Fournier, M. C. Perlat and J. C. Tabet, *J. Am. Soc. Mass Spectrom.* **8**, 610 (1997).
29. W. E. Rosen, L. Dorfman and M. P. Linfield, *J. Am. Chem. Soc.* **29**, 1723 (1964).
30. D. D. Fetterolf and R. A. Yost, *Int. J. Mass Spectrom. Ion Processes* **62**, 33 (1984).
31. A. G. Harrison, *Org. Mass Spectrom.* **22**, 637 (1987).
32. A. G. Harrison, S. Nacson and A. Mandelbaum, *Org. Mass Spectrom.* **22**, 283 (1987).
33. J. S. Brodbelt, H. I. Kenttämaa and R. G. Cooks, *Org. Mass Spectrom.* **23**, 6 (1988).
34. S. K. Chowdhury and A. G. Harrison, *Int. J. Mass Spectrom. Ion Processes* **92**, 135 (1989).
35. M. T. Kinter and M. M. Bursey, *J. Am. Chem. Soc.* **108**, 1797 (1986).
36. W. J. Meyerhoffer and M. M. Bursey, *Org. Mass Spectrom.* **24**, 169 (1989).
37. I. Jardine and C. Fenselau, *J. Am. Chem. Soc.* **98**, 5086 (1976).
38. F. J. Winkler and D. Stahl, *J. Am. Chem. Soc.* **101**, 3685 (1979).
39. R. Houriet, H. Rüfenacht, P. A. Carrupt, P. Vogel and M. Tichy, *J. Am. Chem. Soc.* **105**, 3417 (1983).
40. R. Houriet, H. Rüfenacht, D. Stahl, M. Tichy and P. Longevaille, *Org. Mass Spectrom.* **20**, 300 (1985).
41. D. Desperyroux, R. B. Cole and J. C. Tabet, *Org. Mass Spectrom.* **27**, 300 (1992).
42. M. Meot-Ner (Mautner), *J. Am. Chem. Soc.* **106**, 1257 (1984).
43. C. Guenat, R. Houriet, D. Stahl and F. J. Winkler, *Helv. Chim. Acta* **68**, 1647 (1985).
44. S. G. Lias, J. E. Bartmess, J. F. Liebman, J. L. Holmes, R. D. Levin and W. G. Mallard, *J. Phys. Chem.* Ref. Data 17, Suppl. 1 (1988).

APPENDIX: ESTIMATES OF THERMOCHEMICAL VALUES

The proton affinity (PA) values of epimeric indanediols were estimated as follows,

(i) The PA of *trans* cyclopentanediol[43] (822.6 kJ/mol) is higher by 24.6 kJ/mol than that of *n*-propanol[44] (798 kJ/mol). Supposing that a similar increment can be used in order to estimate PA(**1t**) from that of benzylic alcohol[44] (789 kJ/mol), PA(**1t**) can be considered to be approximately 813.6 kJ/mol.

(ii) A PA increase of 16.3 kJ/mol characterizes *cis* cyclopentanediol in relation to *trans* cyclopentanediol.[43] Then, the *cis* indanediol has a PA(**1c**) of about 829.9 kJ/mol (i.e. 813.6 + 16.3 kJ/mol).

The heats of formation and PA values found in the literature[44] are: $\Delta H^\circ_f(CH_3NH_2)$ = –23 kJ/mol, $\Delta H^\circ_f(CH_3NH_3^+)$ = 611 kJ/mol, $\Delta H^\circ_f(H^+)$ = 1530 kJ/mol, $\Delta H^\circ_f(NH_3)$ = –45.9 kJ/mol, $PA(NH_3)$ = 854 kJ/mol and $PA(CH_3NH_2)$ = 896 kJ/mol.

The heats of formation for the *trans* amino alcohol and the methyl amino alcohol are determined from Benson's method as $\Delta H^\circ_f(RNH_2)$ = –84.6 kJ/mol and $\Delta H^\circ_f(RNHCH_3)$ = –82.4 kJ/mol.

For *trans* β-amino alcohols (with $120^\circ < \Theta(CO–CN) < 180^\circ$), such as twistane, cyclohexane and bicyclooctane, the PA values do not depend on the polycyclic compound.[39] Thus, the PA is taken as 920 kJ/mol for the *trans* amino indanol, and $\Delta H^\circ_f(RNH_3^+)$ is estimated as $\Delta H^\circ_f(RNH_2) + \Delta H^\circ_f(H^+)–PA(RNH_2)$ = –84.6 + 1530–920, i.e. 525.4 kJ/mol.

A difference[4] of 24 kJ/mol between the primary and secondary amines, [$PA(H_2NCH_2CH_2NH_2)$ = 923 kJ/mol, $PA(H_2NCH_2CH_2NHCH_3)$ = 947 kJ/mol], leads to a $PA(RNHCH_3)$ = 944 kJ/mol (i.e. 920 + 24 kJ/mol). Thus, $\Delta H^\circ_f(RNH_2CH_3^+)$ = –82.4 + 1530–944, i.e. 503.6 kJ/mol.

