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A McLafferty Rearrangement in an Even-electron System: C_3H_6 Elimination from the *α*-Cleavage Product of Tri-*n*-butylamine[†]

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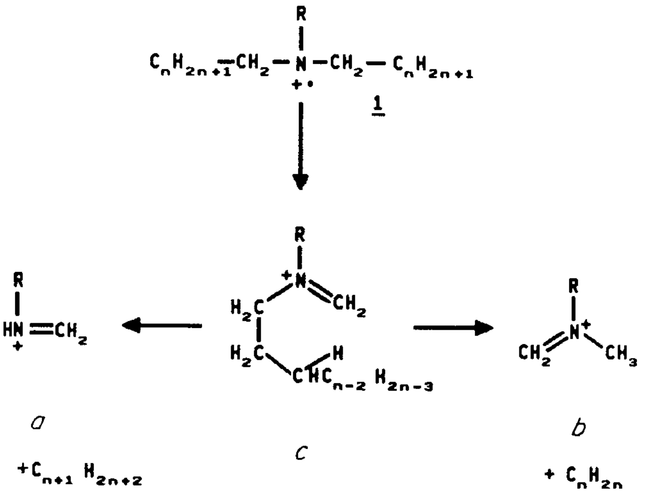
It is shown by deuterium labelling, linked-scan measurements and collision activation that the $[M - C_3H_7^{\cdot}]^+$ (α-cleavage) ion in the electron impact ionization spectrum of tributylamine loses C_3H_6 with transfer of one hydrogen specifically from the γ-position. The experimental data point towards a mechanism which involves the intermediate formation of a distonic diradical ion from an excited α-cleavage ion which then eliminates the neutral alkene.

INTRODUCTION

The α-cleavage products of di- and tri-alkylamines decompose further by alkene elimination.[2–4] Two competing processes have been observed (Scheme 1), viz. loss of the complete chain (*a*) with non-specific back-transfer of one H (so-called 'onium' reaction) or alkene loss with retention of the α-carbon (*b*). The latter process has been described as a McLafferty rearrangement. The importance of *b* as compared with *a* increases (i) with increased steric hindrance (tri- > di-alkylamines; increasing chain length) and (ii) with the nature of the γ-H ($CH > CH_2 > CH_3$; cf. Refs 5 and 6) (examples can be found in Ref. 7).



Scheme 1. Fragmentation sequences of aliphatic amines.

Zollinger and Seibl[8] claimed that McLafferty rearrangements are unlikely in even-electron systems. Therefore, except for very special cases, no example could be found in the literature where for a McLafferty rearrangement formulated in such a system unambiguous proof according to the following three criteria has been offered: (i) the cyclic transition state depicted in Scheme 1 must be possible (the main obstacle could be a distance between the γ-H and the acceptor atom exceeding 180 pm;[9] this is not relevant for purely aliphatic systems and will not be considered further in this context); (ii) the transferred hydrogen must come exclusively from the γ-position; and (iii) it is essential that the fragment ion is formed directly (i.e. without any intermediate) from the decomposing species (this does not exclude a two-step mechanism where the γ-H is transferred first to the acceptor atom and the alkene is eliminated subsequently).

For aliphatic amines, only one deuterium-labelling study (for *n*-butylmethylisopropylamine) has been reported.[10] However, the specificity of the γ-H transfer cannot be demonstrated unambiguously in this case because two different fragmentation paths lead to ions of the same mass, *m/z* 72: (i) $CH_3CH_2\overset{+}{N}(CH_3)=CH_2$ arising from the assumed McLafferty rearrangement and starting from $[M - {}^{\cdot}CH_3]^+$ formed via the loss of methyl from one of the isopropyl groups; (ii) $(CH_3)_2C=\overset{+}{N}HCH_3$ arising from an 'onium' reaction of $[M - H^{\cdot}]^+$ formed by the loss of H from the secondary position of one of the isopropyl groups. We wish now to show that the $[M - C_3H_7^{\cdot}]^+$ (α-cleavage) ion of tri-*n*-butylamine (Fig. 1) (**1**, R = C_4H_9, *n* = 3) loses C_3H_6 by a process which satisfies the three postulates mentioned above. This demonstrates the occurrence of a McLafferty rearrangement in an even-electron system even under the criteria proposed in Ref. 8.

EXPERIMENTAL

Electron impact (EI) mass spectra were obtained with a Kratos MS 25 RF instrument (source temperature 150 °C, source pressure 10^{-3} Pa, electron energy 70 eV, accelerating voltage 4 kV) coupled with a Carlo Erba HRGC 5150 gas chromatograph. Linked-scan measurements were performed with the same instrument, but

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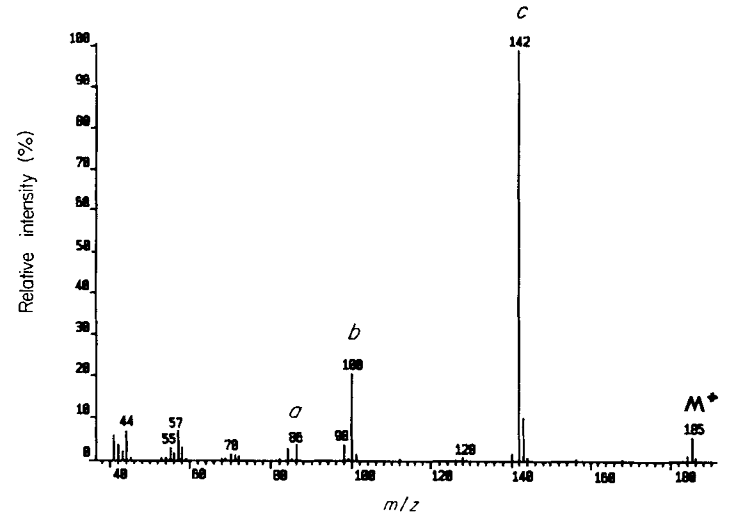


Figure 1. Electron impact ionization mass spectrum (70 eV) of tributylamine.

the samples were introduced with the direct inlet system. For the collisional activation (CA) spectra a Finnigan MAT HSQ-30 (BEQQ) mass spectrometer was used (source temperature 150 °C, source pressure 10^{-4} Pa, electron energy 70 eV, accelerating voltage 3 kV, scan rate 10 u s^{-1}, collision gas argon, collision energy 70 eV, attenuation of the main beam 50%).

The amines were obtained from ammonia and the appropriate alkyl bromides.[11] The deuterium-labelled butyl bromides were synthesized by standard procedures according to the following schemes (details may be obtained upon request from the authors: see also Ref. 10):

$$(C_3H_7CO)_2O \xrightarrow[\text{(ii) PBr}_3]{\text{(i) LiAlD}_4;} C_3H_7CD_2Br$$

$$(C_2H_5CO)_2O \xrightarrow[\text{(ii) PBr}_3]{\text{(i) LiAlD}_4;} C_2H_5CD_2Br$$

$$\xrightarrow{[\text{Mg/CO}_2]} C_2H_5CD_2COOH$$

$$\xrightarrow[\text{(ii) PBr}_3]{\text{(i) LiAlH}_4;} C_2H_5CD_2CH_2Br$$

$$CH_3CH(COOC_2H_5)_2 \xrightarrow{\text{NaOD}} CH_3CD_2COOD$$

$$\xrightarrow[\text{(iii) Mg/CO}_2\text{; (iv) LiAlH}_4\text{; (v) PBr}_3]{\text{(i) LiAlH}_4\text{; (ii) PBr}_3\text{;}} CH_3CD_2CH_2CH_2Br$$

$$CD_3COOH \xrightarrow[\text{(ii) PBr}_3]{\text{(i) LiAlH}_4;} CD_3CH_2Br$$

$$\xrightarrow[\text{(ii) PBr}_3]{\text{(i) Mg/(CH}_2)_2\text{O;}} CD_3(CH_2)_3Br$$

$(C_4H_9)_2NCH_2CH_2CD_2CH_3$ was obtained from $(C_4H_9)_2NH$ and $CH_3CD_2CH_2CH_2Br$.

Table 1. Isotopic purities of the α-cleavage products of the deuterium-labelled analogues of tributylamine

Precursor	Position	D_2	D_4	D_6
α, α′, α″-D_6-1	α, α′, α″			95.7 ± 0.3
β, β′, β″-D_6-1	β, β′		96.7 ± 0.4	
γ, γ′, γ″-D_6-1	γ, γ′		90.5 ± 0.9	
γ-D_2-1	γ	95.0 ± 1.0		
δ, δ′, δ″-D_9-1	δ, δ′		96.4 ± 0.3	

The isotopic purity was determined for the α-cleavage ions *c* by comparing the intensity of the fully deuterated fragments (D_6 for the α- and the δ-; D_4 for the β- and the γ-deuterated analogues) with that of the two species 1 and 2 mass units lower (after correction for ^{13}C) taking a mean of five mass spectrometric runs. The intensity of the '*c* − 2' ion was in every case less than 1% of that of *c*. The results are given in Table 1.

RESULTS AND DISCUSSION

Although the deuterium content of all labelled analogues was better than 90% D_n (less than 10% D_{n-1} and less than 1% D_{n-2}), for a correct evaluation the isotope effect, especially for the transfer from the γ-position, had to be determined (D atoms are usually transferred less readily than H atoms owing to their higher bond energy and their smaller van der Waals radius.[12] For the range of observed isotope effects for McLafferty rearrangements, see Ref. 13). The isotope effect (i.e. the amount of D transferred for one transferred H)[14] for the process $c \rightarrow b$ with respect to the γ-position was determined in three ways. In the mass spectrum of $(C_4H_9)_2NCH_2CH_2CD_2CH_3$ two α-cleavage ions can be formed, viz. $(C_4H_9)_2\overset{+}{N}{=}CH_2$ (*m/z* 142) and $(CH_3CD_2CH_2CH_2)(C_4H_9)\overset{+}{N}{=}CH_2$ (*m/z* 144). While the former can lose C_3H_6 only (yielding *m/z* 100), the latter will lose both C_3H_6 (*m/z* 102) and C_3H_5D (*m/z* 101). When calculating the isotope effect from the *m/z* 102 to *m/z* 101 intensity ratio, the following corrections are necessary: (i) the ^{13}C contributions and (ii) the contributions from incomplete labelling. $(CH_3CHDCH_2CH_2)(C_4H_9)\overset{+}{N}{=}CH_2$ can eliminate C_3H_6 from both the labelled and the unlabelled chain (*m/z* 101) and C_3H_5D (*m/z* 100). Iterative calculation is necessary since an isotope effect operates here also. The value thus obtained is 0.76 ± 0.06. Integration of the *m/z* 102 and *m/z* 101 peak areas for both the metastable and the collision-activated decay of *m/z* 144 in the collision quadrupole gave a ratio of 1.00 : 0.80. This value was used for subsequent calculations. These calculations

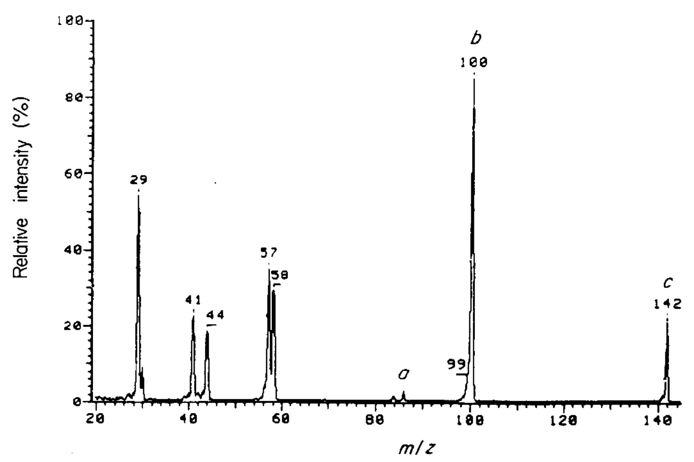


Figure 2. CA mass spectrum of the ion of m/z 142 from tributylamine.

imply that *c* is the only source of *b*. This assumption is justified for the following reason: in the constant B^2/E scan of m/z 100 (*b*) obtained from unlabelled tributylamine, only m/z 142 (*c*) was observed, and in the CA spectrum of m/z 142 (Fig. 2) no ions were found in the region between m/z 100 and 142. Both experiments exclude any precursor of *b* other than *c*. Analogous experiments with the labelled compounds confirmed this conclusion.

The amount of D transferred from the various labelled positions was determined in the following way. The expected intensity ratios were calculated under the assumption of a specific transfer from the γ-position correcting for ^{13}C and the isotopic purity (Table 1), and taking into account the observed intensities in the m/z 100 region for unlabelled tributylamine. These calculated values were compared with the observed peak intensities. Any deviation must be due to a transfer from a position other than γ. The results in Table 2 show that more than 98% of the transferred hydrogen stems from the γ-position.

Two additional observations are of interest in this context. Tri(3,3-dimethylbutyl)amine, which does not possess γ-hydrogens, yields m/z 198 (α-cleavage product, $[M - C_5H_{11}^{\bullet}]^+$) as the most abundant fragment. This ion decomposes further by loss of C_6H_{12} to give *a* ($R = C_6H_{13}$) (m/z 114, 7% relative intensity), but the m/z 128 (the mass expected for *b*) peak has an intensity of less than 1%. An indirect argument for the specificity of the γ-H transfer can also be obtained from dibutyl[3,3-D_2]butylamine mentioned above: if the preferred transfer of H as compared with D was not due to an isotope effect but rather to a transfer of H atoms from other positions, it would be highly unlikely that the same value could be obtained for short-lived high-energy (source) and for long-lived low-energy (collision quadrupole) species, i.e. that the energy and time dependences were the same for H transfers from different positions in the butyl chain.

Table 2. Deuterium transfer during the formation of *b* ($R = C_4H_9$) from labelled analogues of tributylamine

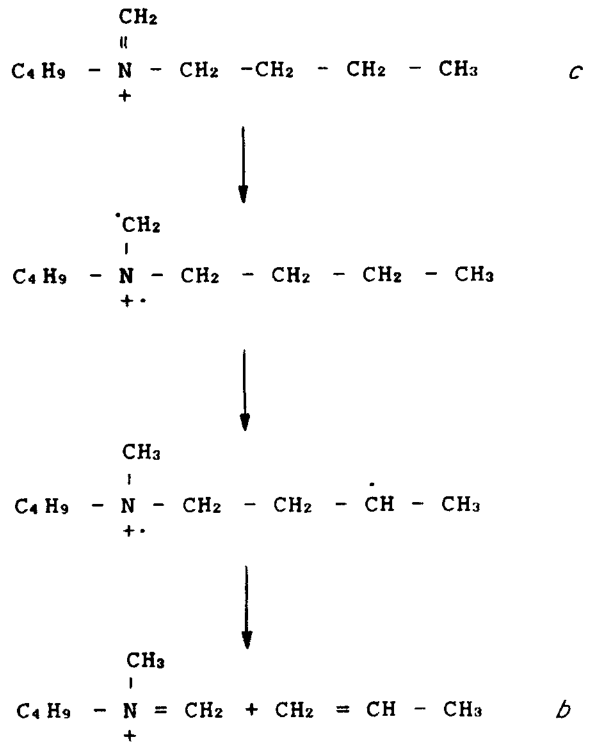
Labelled position	D transferred (%) Without correction for an isotope effect	With correction for an isotope effect (0.80)
$\alpha, \alpha', \alpha''$	0	0
β, β', β''	0.3 ± 0.4	0.4 ± 0.5
$\gamma, \gamma', \gamma''$	98.0 ± 1.0	98.3 ± 0.8
$\delta, \delta', \delta''$	0.6 ± 0.5	0.8 ± 0.6

The mother–daughter relationship of *c* and *b* postulated in Ref. 8 as an essential prerequisite for a McLafferty rearrangement could be demonstrated for tributylamine and its deuterated anlogue by constant B/E and constant B^2/E scans for metastable ions decomposing in the second field-free region. They also confirm the specificity of the H transfer from the γ-position, although the low abundance of the daughter ion formed by spontaneous alkene ejection in the field-free region (~5% of *c*) allows only a smaller reliability than the data obtained from ion-source processes. As has been mentioned before, *c* yields *b* on collision activation in the collision quadrupole of the BEQQ instrument. Here the specific transfer from the γ-position could be fully confirmed: no signals resulting from a D transfer from the β- or δ-position but only for an H transfer from the γ-position were observed for the appropriately labelled compounds.

The experimental results show that the formation of *b* from *c* in the case of tributylamine obeys the criteria for a 'true' McLafferty rearrangement, in particular an unambiguous mother–daughter relationship and a specific hydrogen transfer from the γ-position over the entire time and energy range. This raises the question of the detailed mechanism of the rearrangement.

The currently favoured mechanism for the McLafferty rearrangement of carbonyl compounds (specifically butanal[15]) implies a two-step process with the distonic ion $^{\bullet}CH_2CH_2CH_2CH{=}OH^+$ as an intermediate. A favourable transition state due to the highly directional radical orbital has been invoked to account for the γ-H specificity. For *c* the case is more complicated, however. This species formulated as an iminium ion (see Scheme 1) does not have an acceptor site (electron pair or radical) for the migrating H.[16] Proton or hydride transfer from the butyl chain to the CH_2 group would require zwitterionic intermediates, which are unlikely for energetic reasons. Therefore, one has to assume either a concerted quasi-aromatic transition state[17] (see, however, Ref. 15) or the intermediacy of a distonic diradical ion. This would explain the unusually high kinetic energy release (0.44 eV) observed in the case of *N*, *N*, *N*′, *N*′-tetrapropylbenzidine for $c \rightarrow b$ ($R = C_6H_4C_6H_4N(C_3H_7)_2$, $n = 2$)[8] (Scheme 2).

Veith[18] compared the CA spectra of *m*/*z* 142 from *N*,*N*-dibutylmethyleneiminium tetrafluoroborate (obtained by field desorption) and of the EI α-cleavage product *c* ($R = C_4H_9$) from tributylamine. He concluded that the stable non-decomposing portion of *c* has the *N*,*N*-dibutylmethyleneiminium structure. This species decomposes upon CA preferentially by alkane (C_3H_8, C_4H_{10}) elimination, whereas for the EI α-cleavage product alkene loss (C_3H_6, C_4H_8) predominates, and these two losses are the only ones observed after metastable decay of the *m*/*z* 142 ion obtained by fast atom bombardment from tetrabutylammonium iodide. Veith did not give any details regarding the conditions of the CA experiments with tributylamine. It can be inferred, however, that he used a Finnigan MAT 311 instrument (accelerating voltage 3 kV) with a collision chamber behind the ion source. This may explain why the CA spectra obtained with the Finnigan MAT HSQ-30 instrument (70 eV in the collision quadrupole) showed hardly any C_3H_8 elimination (< 1% of the loss of C_3H_6).



Scheme 2

These various observations can be reconciled by the assumption that upon α-cleavage both stable iminium ions (which can be induced by high-energy collision to decompose mainly by alkane elimination) and excited species are formed. The latter then loses C_3H_6 by the second McLafferty step to give *b* either spontaneously or upon low-energy activation. This would also explain the low abundance of the metastable ions observed by us in the third field-free region as compared with the high intensity in the first one mentioned by Veith.

CONCLUSION

The loss of an alkene from the α-cleavage product of an aliphatic amine ($c \rightarrow b$) fulfils all criteria postulated[8] for a McLafferty rearrangement. The specificity of the transfer of an γ-hydrogen is demonstrated for ions decomposing spontaneously in the ion source and in the second and third field-free regions in addition to for those decomposing by low-energy collision activation. A two-step mechanism with transfer of a γ-hydrogen to the methylene group giving a distonic diradical intermediate (which then eliminates the alkene) seems to be the best interpretation of the experimental data.

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