Unimolecular Reactions of Ionised 4-Methoxyheptane

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The dissociation of metastable ionised 4-methoxyheptane has been examined by means of extensive ^2H-labelling experiments. Only two significant fragmentations are observed, corresponding to loss of either methanol or propane. Each of these processes involves a hydrogen transfer step in which a pronounced site-selectivity is observed. However, the site-selectivities found for the two fragmentations are distinctly different. Expulsion of methanol, which is characterised by a rather small kinetic energy release, takes place after a unidirectional 1,4-hydrogen transfer to oxygen has occurred; this step is subject to a very large isotope effect. In contrast, loss of propane involves ejection of an intact propyl group, together with an α-hydrogen atom from the second propyl group, *via* a formal 1,2-elimination. Primary and secondary isotope effects of comparable magnitudes intervene in propane loss from ionised methoxyheptanes in which either or both propyl groups carry ^2H-labels on the α-carbon atom. The possibility that ion–neutral complexes are important in the reactions of these $C_8H_{18-n}D_nO^{+\bullet}$ species is discussed.

An extremely large number of isolated organic ions fragment *via* cleavage of a single bond with an associated hydrogen transfer between the groups originally connected by that bond.[1] These hydrogen transfer processes, which sometimes show unexpected site selectivities, often can be logically explained in terms of ion–neutral complexes (INCs).[2–4] In an INC, the charged and neutral components are not joined by a conventional covalent bond, but they remain held together by a combination of ion–dipole attractions and related ionic forces. The distinctive feature of an INC is that the components are freed from the geometric restraints that a covalent bond would impose upon their movement with respect to one another. As a result, each component displays a reactivity which resembles that of the 'free' species; in particular, mutual rotation of the partners is possible, thus allowing reactions between the components to take place.

Single hydrogen transfers which have been interpreted in terms of mechanisms involving INCs include alkene (C_nH_{2n}) elimination from $R^+Z{=}CR^1R^2$ onium ions[5] ($R = C_nH_{2n+1}$, $n \geq 2$; Z = O, NH, NCH_3, S; $R^1,R^2 = C_mH_{2m+1}$) or $ArOR^{+\bullet}$ radical cations,[6] and alkane (C_nH_{2n+2}) expulsion from ionised alkanes ($[RCHR^1R^2]^{+\bullet}$),[7] ketones ($RR^1CO^{+\bullet}$),[8] alcohols ($RR^1CHOH^{+\bullet}$) or ethers ($[RR^1CHOR^2]^{+\bullet}$).[9] Special attention has been given to the interesting rearrangement steps that precede loss of alkanes, alkyl radicals and alcohols from ionised dialkyl ethers.[9–12] Some of these reactions are influenced by strong isotope effects. The present study of the dissociation of metastable ionised 4-methoxyheptane was initiated in order to probe these processes in more detail.

Results and Discussion

Metastable ionised 4-methoxyheptane, $\mathbf{1}^{+\bullet}$, fragments *via* loss of methanol or propane in approximately equal abundance. No other decay routes (*e.g.*, loss of a propyl radical) are observed in measurable quantities. Table 1 contains data for the dissociation of $\mathbf{1}^{+\bullet}$ and eight ^2H-labelled analogues.

It is apparent that expulsion of methanol and propane from $\mathbf{1}^{+\bullet}$ both involve well-defined, but quite different, selectivities in the hydrogen transfer steps. Isotope effects clearly come into play when these steps involve transfer of a deuterium as opposed to a protium atom. The isotope effects influence the relative abundance (RA) of the labelled and unlabelled molecules expelled by either dissociation route. In addition, the total relative abundances of methanol and propane loss [$\Sigma RA(CH_{4-n}D_nO)$ and $\Sigma RA(C_3H_{8-n}D_n)$, respectively] are also affected by isotope effects.

The kinetic energy (KE) releases that accompany elimination of methanol and propane show only a marginal variation with deuteriation. Both fragmentations produce Gaussian metastable peaks. The $T_{\frac{1}{2}}$ values (KE releases estimated from the width at half-height of the associated metastable peaks) lie in the ranges 0.38–0.46 kJ mol^{-1} and 1.38–1.52 kJ mol^{-1} for methanol and propane loss, respectively. Deuteriation may produce a slight increase in the $T_{\frac{1}{2}}$ values, but any such changes are at most only comparable in magnitude to the estimated uncertainties (0.05 and 0.10 kJ mol^{-1}, respectively) of the data. The invariance of the $T_{\frac{1}{2}}$ values is circumstantial evidence that neither methanol nor propane loss occurs *via* a route in which a bond to hydrogen is broken or formed in the final step. If such a bond were suddenly and completely cleaved in the final step, a significant isotope effect on the KE release accompanying fragmentation might be anticipated.

Two of the $T_{\frac{1}{2}}$ values for methanol loss (CH_3OD and CH_3OH elimination from $\mathbf{1}$-2,2-$^2H_2^{+\bullet}$ and $\mathbf{1}$-2,2,6,6-$^2H_4^{+\bullet}$, respectively) lie well outside the usual range. This anomaly can be explained by attributing these very minor signals (RA < 2%) to contributions from the ^{13}C-satellite peak of $[M - H]^+$. In the conventional mass spectrum of **1**, the intensities of the $[M - H]^+$ and $M^{+\bullet}$ peaks are similar; furthermore, the $C_8H_{17}O^+$ oxonium ion $(CH_3CH_2CH_2)_2C{=}O^+CH_3$, formed by $H^\bullet$ loss from $\mathbf{1}^{+\bullet}$, expels CH_3OH with a KE release ($T_{\frac{1}{2}} \approx 1.4$ kJ mol^{-1}) comparable to those associated with the 'abnormal' methanol losses of Table 1. Similar complications have recently been uncovered in the elimination of water from ionised *n*-propanol.[13]

(a) *Isotope Effects on the Competition Between Elimination of Methanol and Propane.*—Metastable ionised ethers derived from secondary alcohols in which the side chains are insufficiently long to contain δ-hydrogen atoms generally fragment exclusively *via* alkane expulsion. Thus, both $(CH_3CH_2)_2CHOCH_3^{+\bullet}$ and $[(CH_3)_2CH]_2CHOCH_3^{+\bullet}$ eliminate only C_2H_6 and C_3H_8, respectively. Consequently, $\mathbf{1}^{+\bullet}$ is the lowest symmetrical ionised ether of this homologous series of radical-cations in which the competition between methanol and alkane loss can be studied.

The ratio, *x*, of $\Sigma RA(CH_{4-n}D_n):\Sigma RA(C_3H_{8-n}D_nO)$ loss is

Table 1 Dissociation of metastable $C_8H_{18-n}D_nO^{+\bullet}$ ions generated from 4-methoxyheptanes

	Neutral molecule lost														
	CH_3OH		CH_3OD		CD_3OH		C_3H_8		C_3H_7D		$C_3H_6D_2$		$C_3H_5D_3$		
Precursor structure	RA[a]	$T_{\frac{1}{2}}$[b]	RA[a]	$T_{\frac{1}{2}}$[b]	RA[a]	$T_{\frac{1}{2}}$[b]	RA[a]	$T_{\frac{1}{2}}$[b]	RA[a]	$T_{\frac{1}{2}}$[b]	RA[a]	$T_{\frac{1}{2}}$[b]	RA[a]	$T_{\frac{1}{2}}$[b]	$\Sigma RA(CH_{4-n}D_nO)$: $\Sigma RA(C_3H_{8-n})$
$CH_3CH_2CH_2CH(OCH_3)CH_2CH_2CH_3$ (1)	48	0.39					52	1.38							0.91
$CH_3CH_2CH_2CH(OCD_3)CH_2CH_2CH_3$ (1-*O*-C^2H_3)					36	0.39	64	1.38							0.56
$CH_3CH_2CH_2CD(OCH_3)CH_2CH_2CH_3$ (1-4-$^2H_1$)	54						46	1.38							1.2
$CH_3CH_2CD_2CH(OCH_3)CH_2CH_2CH_3$ (1-3,3-$^2H_2$)	72	0.45							14	1.45	14	1.49			2.5
$CH_3CH_2CHDCH(OCH_3)CHDCH_2CH_3$ (1-3,5-$^2H_2$)	69								24	1.50	6	1.5			2.2
$CH_3CH_2CD_2CH(OCH_3)CD_2CH_2CH_3$ (1-3,3,5,5-$^2H_4$)	89	0.45											11	1.52	8.3
$CH_3CH_2CD_2CD(OCH_3)CD_2CH_2CH_3$ (1-3,3,4,5,5-$^2H_5$)	89.5	0.45											10.5	1.51	8.5
$CH_3CD_2CH_2CH(OCH_3)CH_2CH_2CH_3$ (1-2,2-$^2H_2$)	31	0.42	<2	1.62			44	1.47			22	1.44			0.47
$CH_3CD_2CH_2CH(OCH_3)CH_2CD_2CH_3$ (1-2,2,6,6-$^2H_4$)	<1	1.29	5	0.46							94	1.43			0.054

[a] RA = Relative abundance, measured by ion counts (corresponding to metastable peak areas) and normalized to a total metastable ion current of 100 units for ions dissociating in the second field-free region. [b] $T_{\frac{1}{2}}$ = kinetic energy release (kJ mol^{-1}), estimated from the width at half-height of the corresponding metastable peak. Some data are quoted to three significant figures merely to avoid rounding errors.

0.91 for **1**$^{+\bullet}$. Slightly smaller and larger values (0.56 and 1.2, respectively) are found for **1**-O-$^{2}H_{3}{}^{+\bullet}$ and **1**-4-$^{2}H_{1}{}^{+\bullet}$. Consequently, deuteriation on the *O*-methyl group slightly suppresses methanol expulsion, whereas deuteriation on C-4 leads to a marginal enhancement of this reaction. These changes are insufficient to permit any firm conclusions to be made. However, much more profound effects are induced by deuteriation on C-3 (and/or C-5) or C-2 (and/or C-6). The former strongly suppresses propane loss (x = 8.3 and 8.5, respectively, for **1**-3,3,5,5-$^{2}H_{4}{}^{+\bullet}$ and **1**-3,3,4,5,5-$^{2}H_{5}{}^{+\bullet}$), but the latter suppresses methanol elimination, especially when both the C-3 and C-5 methylene groups are deuteriated (x = 0.054 for **1**-2,2,6,6-$^{2}H_{4}{}^{+\bullet}$). The large variations in x reflect the contrasting selectivities in the hydrogen transfer steps which are involved in elimination of methanol or propane. Methanol loss requires abstraction of a hydrogen atom from C-2 or C-6. Since this fragmentation is suppressed by deuteriation on C-2 or C-6, fission of a C(2)–H or C(6)–H bond must be involved in the rate-limiting step. On the other hand, the reduction of $\Sigma RA(C_3H_{8-n}D_n)$ caused by deuteriation on C-3 or C-5 suggests that a C(3)–H or C(5)–H bond is partially broken in the transition state for propane expulsion. The selectivities shown in the hydrogen transfer steps indicate that loss of methanol and propane are 1,3- and 1,2-eliminations, respectively.

(b) *Loss of Methanol.*—1. *Site selectivity of methanol loss.* The specific expulsion of CD_3OH from **1**-O-$C^{2}H_{3}{}^{+\bullet}$ shows that the intact methoxy group is retained in the eliminated methanol. Similarly, the loss of predominantly CH_3OD from **1**-2,2,6,6-$^{2}H_{4}{}^{+\bullet}$ establishes that the remaining hydrogen originates mainly or exclusively from those attached to C-2 and C-6. This conclusion is consistent with the suppression of methanol loss, compared to propane expulsion, that is induced by deuteriation on these sites.

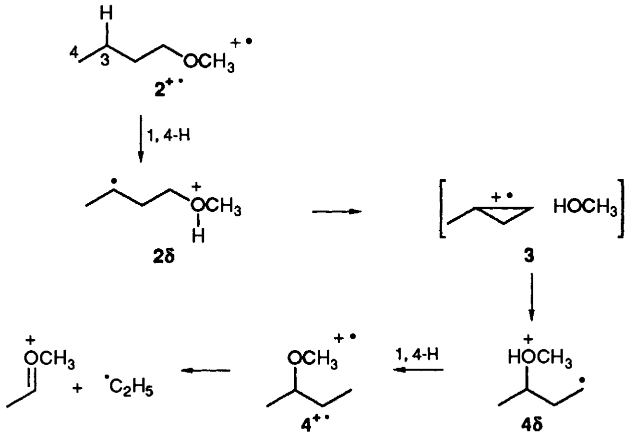
It is possible that a minor channel for methanol expulsion involves abstraction of a hydrogen atom from C-1 or C-7. However, as discussed previously, the small amount of CH_3OH that is apparently lost from **1**-2,2,6,6-$^{2}H_{4}{}^{+\bullet}$ is characterized by a KE release which is abnormally large, but comparable to that found for CH_3OH loss from $(CH_3CH_2CH_2)_2C{=}O^{+}CH_3$. Even if the CH_3OH loss does occur from **1**-2,2,6,6-$^{2}H_{4}{}^{+\bullet}$, as opposed to the ^{13}C satellite of the derived $[M - H]^{+}$ oxonium ion, it is clear that this route involving 1,5-hydrogen transfer becomes noticeable only when the C-2 and C-6 positions are fully deuteriated. In other circumstances, 1,5-hydrogen transfer is swamped or entirely pre-empted by 1,4-hydrogen transfer.

This overwhelming preference for 1,4-hydrogen transfer is significant. The 1,5-hydrogen transfer might have been expected to dominate since, on a naïve assumption, it involves a less strained six-membered ring transition state. Such 1,5-hydrogen transfers are often preferred over their 1,4-counterparts in the fragmentation of metastable onium ions.[14] In the present system, however, the 1,5-transfer requires hydrogen abstraction from a methyl group and formation of the corresponding primary radical, whereas the 1,4-route yields a secondary radical. This difference is sufficient to offset any advantageous features of the 1,5-hydrogen transfer. Thus, the discrimination against forming a primary radical is so strong that methanol loss *via* 1,4-hydrogen transfer is not observed in the fragmentation of metastable $(CH_3CH_2)_2CHOCH_3{}^{+\bullet}$ or $[(CH_3)_2CH]_2CHOCH_3{}^{+\bullet}$.

2. *Isotope effects on methanol loss.* An approximate value of 31:1.8 ≈ 17:1 for the isotope effect favouring H-transfer over D-transfer to oxygen prior to methanol loss can be deduced from the behaviour of **1**-2,2-$^{2}H^{+\bullet}$. The calculation of this value is based on the assumptions that 1,5-transfer is of negligible importance and that the small quantity of CH_3OD apparently expelled from **1**-2,2-$^{2}H_{2}{}^{+\bullet}$ is not an artefact. If, as is very likely, some or all of the CH_3OD loss actually occurs from the ^{13}C-satellite signal of the $[M - H]^{+}$ peak formed from **1**-2,2-$^{2}H_{2}{}^{+\bullet}$, the true isotope effect must be even greater than the calculated value.

The apparent isotope effect is extremely large, but it is by no means unique in 1,4-hydrogen transfers from carbon to oxygen in radical-cation systems. Thus, for example, water loss from ionised *n*-propanol is subject to an isotope effect (44:1) of still greater magnitude favouring 1,4-H over 1,4-D transfer.[13]

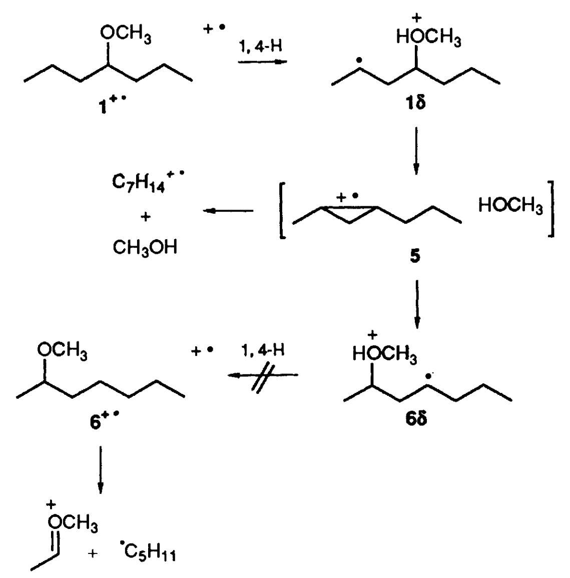
3. *Mechanism of methanol loss.* Both the high selectivity of the hydrogen transfer step and the associated isotope effect point to a mechanism involving unidirectional and rate-limiting 1,4-hydrogen transfer to oxygen in the mechanism of methanol expulsion from **1**$^{+\bullet}$ and its ^{2}H-labelled analogues. Many skeletal rearrangements in ionised ethers derived from primary alcohols are known to be initiated by a 1,4-hydrogen shift to oxygen.[8–11] In some instances, the transferred hydrogen is returned to another carbon atom before dissociation of the isomerised radical-cation takes place. Thus, $CH_3CH_2CH_2CH_2OCH_3{}^{+\bullet}$, **2**$^{+\bullet}$, eliminates $C_2H_5{}^{\bullet}$ *via* steps which result in transfer of a hydrogen atom from C-3 to oxygen ($\mathbf{2}^{+\bullet} \longrightarrow \mathbf{2\delta}$) and thence to either C-1 or C-2 ($\mathbf{4\delta} \longrightarrow \mathbf{4}^{+\bullet}$), Scheme 1. This route certainly involves the distonic[15] ions[16] (DIs) **2δ** and **4δ**; rearrangement of **2δ** ⟶ **4δ** may occur directly, but this step is perhaps more readily envisaged in terms of the INC **3**, which comprises ionised methylcyclopropane and methanol. Convincing evidence supporting the intermediacy of the analogous INC in the chemistry of low-energy $CH_3CH_2CH_2OR^{+\bullet}$ species (R = CH_3, C_2H_5) has been presented.[17]



Scheme 1

Although **1**$^{+\bullet}$ bears some structural resemblance to **2**$^{+\bullet}$ (the length and nature of the hydrocarbon chains attached to the carbon atom bearing the methoxy substituent is the same in both cases), **1**$^{+\bullet}$ does not undergo the later stages of the rearrangement steps that precede some fragmentations of **2**$^{+\bullet}$. Thus, no loss of an alkyl radical (*e.g.*, $C_5H_{11}{}^{\bullet}$ *via* $\mathbf{1}^{+\bullet} \longrightarrow \mathbf{1\delta} \longrightarrow \mathbf{5} \longrightarrow \mathbf{6\delta} \longrightarrow \mathbf{6}^{+\bullet} \longrightarrow$ products, Scheme 2) is observed from **1**$^{+\bullet}$. Moreover, the hydrogen atom transferred to oxygen retains its identity and it is specifically lost in the eliminated methanol. Therefore, any steps which would return this oxygen-bound hydrogen to carbon ($\mathbf{6\delta} \longrightarrow \mathbf{6}^{+\bullet}$, or similar conversions of DIs accessible to **5** to their conventional isomers) are pre-empted by methanol loss. If **5** does isomerise to **6δ** or related DIs, then these DIs must revert to **5** more rapidly than they undergo 1,4-hydrogen shifts, since the latter would destroy the positional integrity of the hydrogen attached to oxygen.

Energy measurements indicate that the structure of the $C_4H_8{}^{+\bullet}$ species formed by methanol loss from **2**$^{+\bullet}$ at or near the threshold for dissociation must be either $CH_3CH{=}CHCH_3{}^{+\bullet}$ or $(CH_3)_2C{=}CH_2{}^{+\bullet}$.[10] This result can be interpreted by postulating isomerisation of the putative $C_4H_8{}^{+\bullet}$ radical-cation



Scheme 2

within the INC 3. It is possible that similar rearrangement of the initial $C_7H_{14}^{+\bullet}$ species in 5 occurs. However, any such isomerisation cannot proceed by reciprocal hydrogen transfer (RHT) between the components (*i.e.*, either by $[C_7H_{14}^{+\bullet}\ HOCH_3] \rightleftharpoons [C_7H_{15}^{+}\ {}^{\bullet}OCH_3]$ or by $[C_7H_{14}^{+\bullet}\ HOCH_3] \rightleftharpoons [C_7H_{13}^{\bullet}\ {}^{+}H_2OCH_3]$) because such RHTs would exchange the hydrogen attached to oxygen with those of the C_7H_{14} entity.

It is impossible to determine the structure of the $C_7H_{14}^{+\bullet}$ product ion because of the large number of isomers of this species that could be formed. The simplest explanation which covers all the known facts is that each of the steps $1^{+\bullet} \longrightarrow 1\delta \longrightarrow 5 \longrightarrow C_7H_{14}^{+\bullet} + CH_3OH$ is irreversible. Indeed, if methanol elimination affords ionised 1-propyl-2-methylcyclopropane, it is not strictly necessary to postulate the intermediacy of 5. Consequently, it is fair to conclude that the present data are consistent with the involvement of 5 in methanol loss from $1^{+\bullet}$, but they offer no compelling evidence in favour of this hypothesis.

(c) *Loss of Propane*.—1. *Site selectivity in propane loss*. Expulsion of propane proceeds *via* cleavage of the bond connecting C-4 to either C-3 or C-5, with an associated hydrogen atom transfer from C-5 or C-3, respectively. The selectivity of this process, which corresponds to a formal 1,2-elimination of one propyl group with an α-hydrogen atom from the other propyl group, is extremely high (≥99%). No measurable signals could be detected for loss of propane with a different selectivity in the hydrogen transfer step. Thus, for example, $1\text{-}3,3,5,5\text{-}{}^{2}H_4^{+\bullet}$ expels solely $C_3H_5D_3$ in propane elimination. Similar site selectivities have been found for alkane loss from ionised ethers derived from smaller secondary alcohols.[9–11]

The pronounced site selectivity for propane expulsion from $1^{+\bullet}$ suggests that hydrogen exchange processes do not take place prior to fragmentation. Reversible transfer of a hydrogen atom from one site to oxygen could in principle occur without eroding the positional integrity of the specifically labelled analogues of $1^{+\bullet}$. This possibility seems most unlikely, however, especially in view of the earlier discussion concerning the unidirectional nature of the 1,4-hydrogen shift to oxygen that precedes elimination of methanol.

2. *Isotope effects on propane loss*. There is a sizeable isotope effect on the hydrogen transfer step involved in this process. Thus, $1\text{-}3,5\text{-}{}^{2}H_2^{+\bullet}$, in which both the propyl substituents have a single α-deuterium atom, expels C_3H_7D (H-transfer) and $C_3H_6D_2$ (D-transfer) in the ratio 4.3 3:1. This observation sets a lower limit of *ca.* 4.3:1 for the primary isotope effect arising from cleavage of the bond connecting C-5 to the hydrogen atom that is transferred to the eliminated propyl group. Any secondary isotope effect on this step (*i.e.*, arising from the influence of the changing level of hybridisation from sp^3 to sp^2 of the C-5 carbon atom to which either a protium or deuterium atom remains attached) would operate against the primary isotope effect. The primary and secondary isotope effects are in conflict because H-transfer leaves behind a C–D bond in which the hybridisation of carbon changes from sp^3 to sp^2, whereas D-transfer leaves behind a C–H bond.

The behaviour of $1\text{-}3,3\text{-}{}^{2}H_2^{+\bullet}$ is also illuminating. This species loses C_3H_7D (D-transfer from C-3) and $C_3H_6D_2$ (H-transfer from C-5) in almost equal amounts. Taken in isolation, this result could be construed to indicate that propane loss is not subject to appreciable isotope effects. However, the detection of a moderately large isotope effect in propane elimination from $1\text{-}3,5\text{-}{}^{2}H_2^{+\bullet}$ refutes this naïve interpretation. Therefore, in the case of the dideuteriated isomer $1\text{-}3,3\text{-}{}^{2}H_2^{+\bullet}$, the primary and secondary isotope effects must almost exactly cancel each other. Assuming that the primary isotope is 4.3 3:1, the overall secondary isotope effect on propane loss is 4.33 × (14.19/14.07) = 4.39:1, or 2.09 [*i.e.*, $(4.39)^{\frac{1}{2}}$] per deuterium atom attached to C-3 (or C-5). The problem in evaluating the magnitude of the secondary isotope effect for the hydrogen transfer step is that the overall secondary isotope effect could arise from at least two other causes. First, elongation of the bond connecting C-3 (or C-5) to C-4 is probably subject to an isotope effect; secondly, the hyperconjugative interaction between the C(5)–H/D [or C(3)–H/D] bonds and the increasing charge density on C-4 may also be influenced by an isotope effect.

The former effect apparently remains operative even at longer range. Thus, $1\text{-}2,2\text{-}{}^{2}H_2^{+\bullet}$ expels C_3H_8 and $C_3H_6D_2$ in the ratio 2.04:1; the corresponding isotope effect is 1.43 per deuterium atom attached to C-2. In this case, neither primary nor secondary isotope effects are involved in the hydrogen transfer step. The analogous effect per deuterium atom bound to C-3 could be appreciably greater. Indeed, it is quite possible that much of the overall secondary isotope effect of at least 2.09 per deuterium atom on C-3 arises from the influence of deuteriation on this position on the stretching of the C(3)–C(4) bond. According to this interpretation, the secondary isotope effects for the hydrogen transfer step and for the hyperconjugative interaction between the C(5)–H/D [or C(3)–H/D] bonds and the developing cationic site on C-4 are both relatively small.

Although there remains some doubt concerning the details of the isotope effects that intervene in propane expulsion, two points are clearly evident. First, there is a substantial primary isotope effect of at least 4.3 3:1 on the hydrogen transfer step. Secondly, an appreciable secondary isotope effect influences extension of the C–C bond which is eventually broken.

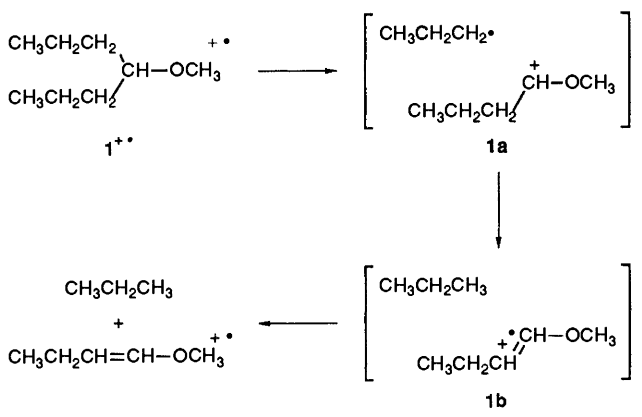
3. *Mechanism of propane loss*. Alkane elimination from ionised ethers of secondary alcohols has been explained in terms of INCs.[8,9,11,12] The analogous mechanism for C_3H_8 loss from $1^{+\bullet}$ is shown in Scheme 3. Stretching of the C(3)–C(4) bond in $1^{+\bullet}$ yields **1a**, which is an INC comprising the oxonium ion $CH_3CH_2CH_2CH^{+}OCH_3$ ($\longleftrightarrow CH_3CH_2CH_2CH{=}O^{+}CH_3$) and a propyl radical. Hydrogen transfer from the α-methylene group of the developing oxonium ion leads to **1b**, which is a second INC consisting of the ionised enol ether $CH_3CH_2\text{-}CH{=}CHOCH_3^{+\bullet}$ and a molecule of propane. Separation of **1b** to its constituent parts then results in propane elimination.

This mechanism is consistent with the observed site selectivity for hydrogen transfer in propane elimination, provided that **1a** ⟶ **1b** is unidirectional. If **1a** and **1b** could interconvert, exchange of the hydrogen atoms attached to C-3 and C-5 would precede propane loss. No such exchange occurs, however, as is

Table 2 Dissociation of metastable $C_8H_{18-n}D_nO^{+\cdot}$ ions generated from metastable 2,6-dimethyl-4-methoxypentanes

	Neutral molecule lost					
	C_3H_8		C_3H_7D		C_3HD_7	
Precursor structure	RA[a]	$T_{\frac{1}{2}}$[b]	RA[a]	$T_{\frac{1}{2}}$[b]	RA[a]	$T_{\frac{1}{2}}$[b]
$(CH_3)_2CHCH(OCH_3)CH(CH_3)_2$	100	1.70				
$(CH_3)_2CHCH(OCD_3)CH(CH_3)_2$	100	1.64				
$(CD_3)_2CHCH(OCH_3)CD(CH_3)_2$			$83._3$	1.80	$16._7$	1.86

[a,b] See footnotes to Table 1.



Scheme 3

shown most clearly by the contrasting behaviour of the dideuteriated isomers, **1**-3,3-$^2H_2^{+\cdot}$ and **1**-3,5-$^2H_2^{+\cdot}$. The kinetic energy release accompanying propane loss from $\mathbf{1}^{+\cdot}$ is also much larger than that associated with alkane loss in cases in which interconversion of the pair of INCs corresponding to **1a** and **1b** precedes dissociation.[12] This larger $T_{\frac{1}{2}}$ value confirms that hydrogen transfer is unidirectional.

Analysis of the isotope effects encountered in propane loss sheds some more light on the mechanism of this fragmentation. The preference shown by **1**-2,2-$^2H_2^{+\cdot}$ for expelling C_3H_8 rather than $C_3H_6D_2$ supports the view that the C(3)–C(4) or C(4)–C(5) bond is elongated in the transition state for the rate-limiting step. Similarly, the elimination of more C_3H_7D than $C_3H_6D_2$ from **1**-3,5-$^2H_2^{+\cdot}$ suggests that a C(3)–H or C(5)–H bond is partially broken in this transition state. The first of these isotope effects is obviously consistent with the mechanism of Scheme 3. However, in order to explain the second isotope effect by means of the mechanism involving INCs, it is necessary to propose that the C–H bond in the α-methylene group of the putative oxonium ion in **1a** is partially broken in the transition state for propane loss. Taken in combination, the two isotope effects point to a mechanism in which progressive reorganisation of $\mathbf{1}^{+\cdot}$, *via* elongation of the C(3)–C(4) bond and a gradual fission of a C(5)–H bond in the part of $\mathbf{1}^{+\cdot}$ which becomes the developing oxonium ion. This process leads to **1b**, which breaks down to yield the corresponding products. Some circumstantial evidence for the existence of **1b** as a discrete entity is furnished by the absence of an appreciable isotope effect on the KE release accompanying expulsion of ^2H-labelled propanes from labelled analogues of $\mathbf{1}^{+\cdot}$. Such an isotope effect might be detected if the cleavage of a C–H/D bond was still being completed in the final step of the reaction resulting in propane elimination.

In conclusion, propane loss from $\mathbf{1}^{+\cdot}$ can be logically explained by means of a mechanism involving INCs. However, formation of the INC comprising $CH_3CH_2CH{=}CHOCH_3^{+\cdot}$ and C_3H_8 proceeds *via* a transition state in which the C(3)–C(4) and C(5)–H bonds are both significantly stretched. This part of the mechanism could possibly be envisaged as a concerted but not necessarily synchronous 1,2-elimination. The evidence for the participation of the INC **1b** is perhaps somewhat stronger than that supporting the involvement of **1a**.

4. *Propane loss from* $[(CH_3)_2CH]_2CHOCH_3^{+\cdot}$. The branched isomer of $\mathbf{1}^{+\cdot}$ also expels C_3H_8; relevant data are given in Table 2. This process is subject to a sizeable isotope effect, as is shown by the behaviour of $(CH_3)_2CDCH(OCH_3)$-$CH(CD_3)_2^{+\cdot}$, which loses C_3H_7D [H-transfer from the $CH(CD_3)_2$ group] and C_3HD_7 [D-transfer from the $CD(CH_3)_2$ group] in the ratio 5.01:1. The overall isotope effect probably represents a combination of an appreciable primary isotope effect on the hydrogen transfer step, together with two secondary isotope effects on the C(2)–C(3) [or C(3)–C(4)] bond stretching. One such effect (discrimination against extension of a bond to a carbon atom to which CD_3 groups are attached) should reinforce the primary isotope effect on the hydrogen transfer. The other [different hyperconjugative stabilisation of the developing cationic centre at C-3 by the alternative residual isopropyl groups $-CH(CD_3)_2$ and $-CD(CH_3)_2$] is more difficult to assess. If interaction with the C–H or C–D bond is the most important contribution to this stabilisation, it would be preferable to leave behind the $CH(CD_3)_2$ substituent, thus further reinforcing the primary isotope effect.

Both the methine hydrogens are lost in the expelled propane. Consequently, the specificity of propane loss does not exclude the possibility that these hydrogens undergo reversible exchange prior to dissociation. Strictly speaking, neither does the overall isotope effect because it could be argued that this arises solely from the secondary isotope effects on stretching the C(2)–C(3) [or C(3)–C(4)] bond. However, this possibility seems remote. Moreover, the $T_{\frac{1}{2}}$ value for propane elimination of *ca.* 1.7 kJ mol^{-1} is characteristic of alkane loss with unidirectional hydrogen transfer. Propane loss from $[(CH_3)_2CH]_2$-$CHOCH_3^{+\cdot}$ shows similar features to those encountered for the corresponding reaction of $\mathbf{1}^{+\cdot}$, but a less detailed analysis of the nature and significance of the isotope effects is feasible.

Conclusions

Expulsion of methanol and propane from $\mathbf{1}^{+\cdot}$ proceed *via* mechanisms that have several points in common. Both processes involve an extremely high site selectivity in the hydrogen transfer step; furthermore, these steps are unidirectional and subject to isotope effects. The route for expulsion of methanol involves a rate-limiting 1,4-hydrogen shift to oxygen, with formation of a distonic ion. The initial 1,4-shift involves a very large isotope effect ($\geq$ 17:1). In contrast, propane loss proceeds *via* a 1,2-elimination and there is no evidence for the participation of distonic ions. The isotope effects for propane expulsion are more complicated and difficult to interpret than those affecting methanol loss. In particular, the C(3)–C(4) and the C(5)–H bonds both appear to be stretched in the transition state for elimination of propane. In contrast, the data for methanol loss are consistent with extensive or complete fission

1 $CD_3OD \xrightarrow{i} CD_3I$

2 $(CH_3CH_2CH_2)_2CO \xrightarrow{ii} (CH_3CH_2CH_2)_2CDOH$

3 $(CH_3CH_2CH_2)CO \xrightarrow{iii} (CH_3CH_2CD_2)_2CO \xrightarrow{iv} (CH_3CH_2CD_2)_2CHOH$

4 $CH_3CH_2CHO \xrightarrow{v} CH_3CH_2CHDOH \xrightarrow{i} CH_3CH_2CHDI \xrightarrow{vi, vii} (CH_3CH_2CHD)_2CHOH$

5 $CH_3CH_2COCl \xrightarrow{v} CH_3CH_2CD_2OH \xrightarrow{i} CH_3CH_2CD_2I \xrightarrow{vi, vii} (CH_3CH_2CD_2)_2CHOH$

6 $CH_3CH_2CH_2CHO \xrightarrow{viii} CH_3CH_2CD_2CHO \xrightarrow{ix} CH_3CH_2CD_2CH(OH)CH_2CH_2CH_3$

7 $CH_3CH_2CHO \xrightarrow{viii} CH_3CD_2CHO \xrightarrow{x} CH_3CD_2CH_2OH \xrightarrow{i} CH_3CD_2CH_2I \xrightarrow{vi, vii} (CH_3CD_2CH_2)_2CHOH$

8 $CH_3CD_2CH_2I \xrightarrow{vi, xi} CH_3CD_2CH_2CH(OH)CH_2CH_2CH_3$

9 $(CH_3)_2CHCHO \xrightarrow{xii} (CH_3)_2C{=}CHOCOCH_3 \xrightarrow{xiii} (CH_3)_2CDCHO$

10 $(CD_3)_2CO \xrightarrow{x} (CD_3)_2CHOH \xrightarrow{i} (CD_3)_2CHI \xrightarrow{vi, xiv} (CD_3)_2CHCH(OH)CD(CH_3)_2$

Scheme 4 *Reagents and conditions:* i, Red P, I_2, warm; ii, $LiAlD_4$, $(C_2H_5)_2O$; iii, $NaOD/D_2O$, $(C_4H_9)_4N^+Br^-$; repeat four times; iv, $LiAlH_4$, $(C_2H_5)_2O$; v, $LiAlD_4$, triglyme [triethylene glycol dimethyl ether, $CH_3O(CH_2CH_2O)_3CH_3$]; tetragol [tetraethylene glycol, $HO(CH_2CH_2O)_4H$]; vi, Mg, $(C_2H_5)_2O$; vii, 0.4 equivalents $HCO_2C_2H_5$; saturated aq. NH_4Cl; viii, D_2O, pyridine, reflux 48 h; repeat twice; ix, addition to 1.5 equivalents of $CH_3CH_2CH_2MgI$ in $(C_2H_5)_2O$; x, $LiAlH_4$, triglyme; tetragol; xi, 0.8 equivalents $CH_3CH_2CH_2CHO$; xii, $(CH_3CO)_2O$, $KOCOCH_3$, reflux; xiii, D_2O, D_2SO_4 (catalyst), reflux; xiv, 0.8 equivalents $(CH_3)_2CDCHO$

of the C(2)–H [or C(6)–H] bond prior to cleavage of the C–O bond. Thus, the timing of hydrogen transfer and rupture of the C–O or C–C linkages is evidently different for the two reactions. Both processes are logically interpreted in terms of mechanisms involving ion-neutral complexes (at later and earlier stages, respectively, in methanol and propane loss), but in neither case is there unequivocal evidence for the intermediacy of these species.

Experimental

The ethers required for this work were synthesised by condensation of the alkoxide derived from the corresponding alcohol with a slight deficiency (0.80 equivalents) of CH_3I or CD_3I. Details of the general procedure have been published elsewhere.[18] The labelled alcohols were prepared according to the routes shown in Scheme 4; further particulars are available on request.

The mass spectra were recorded by the MIKES[19] technique on a double-focusing research mass spectrometer ('MMM') of unusually large dimensions.[20] Typical conditions were: source pressure, 0.5–2.0 × 10^{-6} Torr; ionising electron energy, 70 eV; accelerating voltage, 8065–8070 V. The fragmentation of metastable ions in the second field-free region (between the magnetic and electric sectors) was measured by repetitive microcomputer-controlled sweeping of the electric sector voltage over the range of voltages needed to transmit the appropriate product ions. The voltage required to transmit the main beam of parent ions was 270 V. The quoted data corresponding to integrated spectra obtained from 50–500 individual scans. Kinetic energy release data were estimated from the width at half-height of the requisite metastable peak, by means of a one-line formula,[19,21] after application of the usual correction for the width at half-height of the main beam.[22]

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