81. Loss of H_2O from $M + t$-Butyl Complex Ions of Benzyl Alcohol in Isobutane Chemical Ionization Mass Spectrometry[1])

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Summary

In isobutane chemical ionization mass spectrometry *benzyl alcohol* exhibits ions at *m/z* 147 ('$M+39$') that arise by a loss of H_2O from $[M+C_4H_9]^+$, *i.e.* '$M+57$' complex ions. Electrophilic aromatic substitution of a proton at an *ortho*-position of neutral $C_6H_5CH_2OH$ with $[t\text{-}C_4H_9]^+$ and, alternatively, nucleophilic substitution of H_2O at the benzylic carbon in $C_6H_5CH_2\overset{+}{O}H_2$ with $CH_2{=}C(CH_3)_2$ are discussed as possible pathways. Evidence in favor of the latter is derived from the analysis of $C_6D_5CH_2OH$ and $C_6H_5CD_2OH$ for the origin of the H-atoms lost in H_2O. The inferred ion structure of *m/z* 147 is verified by mass-analyzed ion kinetic energy (MIKE.) measurements of its collision-activated (CA.) decomposition. MIKE./CA. spectra of mass-selected *m/z* 147 ions, once generated by $CI(i\text{-}C_4H_{10})$ from *benzyl alcohol* and, once, from *2-methyl-4-phenyl-2-butanol* match closely and, thus, reflect identical ion structures. With reference to the simple genesis of this ion from the latter precursor, the structure in question can be concluded to be $C_6H_5CH_2CH_2\overset{+}{C}(CH_3)_2$.

Introduction. - Owing to its mild protonating properties, chemical ionization (CI.) using isobutane reagent gas is widely employed in analytical and structural studies. The resulting mass spectra are relatively simple with the notable exception of fragment ion formation from $[M+t\text{-}C_4H_9]^+$ complex ions[3]). Such complexes

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[3]) The subject has been discussed in [1].

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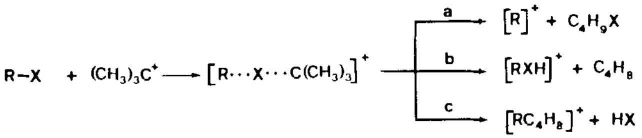
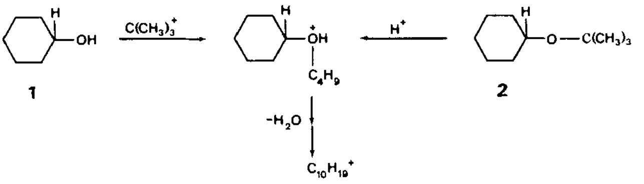
may be formed in addition to, or even instead of, the customary $[MH]^+$ ions when the proton affinity of the substrate relative to that of the corresponding base (i-C_4H_8) of the reactant ion (t-C_4H_9)$^+$ becomes critically low. This situation prevails, *e.g.*, in simple alcohols R–OH [2]. The fragmentation of $[M+t\text{-}C_4H_9]^+$ complexes is not in all cases well understood.

Scheme 1



Generally, it has been recognized that $[M+t\text{-}C_4H_9]^+$ complexes, *i.e.* '$M+57$' ions, decompose *via* three major modes *(Scheme 1)* in which, invariably, a neutral molecule is lost: a) by *heterolysis*, b) by *elimination*, and c) by *substitution*. Reactions of type c, prone to be mechanistically more complex than its competitors, have been observed for alcohols [2–4], acetates [5–8], halides and thiols [4]. *Munson et al.* studied the loss of H_2O from '$M+57$' ions of aliphatic alcohols in some detail [3]. The results from ^{2}H-labeling experiments on *cyclohexanol* (**1**, *Scheme 2*) suggest that the initial (probably *O*-bonded) complex decomposes along a complicated expulsion route(s) involving H-abstraction from more than one site within the substrate [3].

Scheme 2



Interestingly, it was shown later [9] that $[MH]^+$ ions of *t-butyl cyclohexyl ether* (**2**), for which identity with the '$M+57$' ions would be anticipated, also exhibit the requisite H_2O-elimination. An interpretation of the underlying (single-route) processes appears possible on the basis of a new concept advanced by *Bowen & Williams* [10] for related 'onium' ion fragmentation under electron impact (EI.) conditions. This concept considers long-lived ion/molecule complexes which may repeatedly rearrange prior to final breakdown^4).

Compared with saturated alcohols, the reaction of t-butyl cations with alcohols containing π-systems, *e.g. benzyl alcohols* (**3**), may represent, in terms of the multiplicity of available reaction paths, the more intricate problem. Conceptually, however, it may be the better amenable case. On one hand, the π-system may

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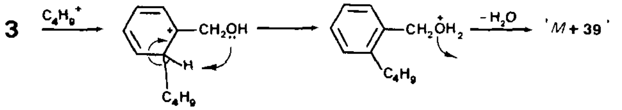
[4]) Analogous ion/radical complexes have been inferred recently in the EI.-induced decomposition of odd-electron molecular ions of phenyl alkyl ethers [11].

expose sites other than oxygen to the attack of the complexing reactant ions on grounds of possibly similar *t*-butyl ion affinities[5]). As a result, a multiple reactivity might ensue. On the other hand, the requisite C,C-bonding, in this case between an unsaturated substrate, **3**, and the $[C_4H_9]^+$ reactant ion, would be readily understood when proceeding *via* electrophilic aromatic substitution *(Scheme 3)*, being independent of the (subsequent) H_2O-elimination: For the saturated substrates **1** and **2**, which require, in the net result, skeletal rearrangement [9] concomitant with H_2O-expulsion, this is not the case unless the process is interpreted according to the *Bowen-Williams* concept (see above).

Scheme 3



Aromatic substitution of this type has, in fact, been proposed in an early study by *Field* on various substituted benzyl acetates [7] [8]. '$M-3$' ions in their isobutane spectra were shown to arise from '$M+57$' ions due to loss of CH_3COOH in analogy to the above loss of H_2O. In view of some remaining uncertainties (no substituent effects on the ease of CH_3COOH loss; missing isotope labeling experiments) we chose to subject **3** as a simple analogue of the acetates to the following more detailed investigation. Emphasis is given to elucidating the substitution mechanism(s) by determining both the atoms transferred in the process as well as the structure of the product ion.

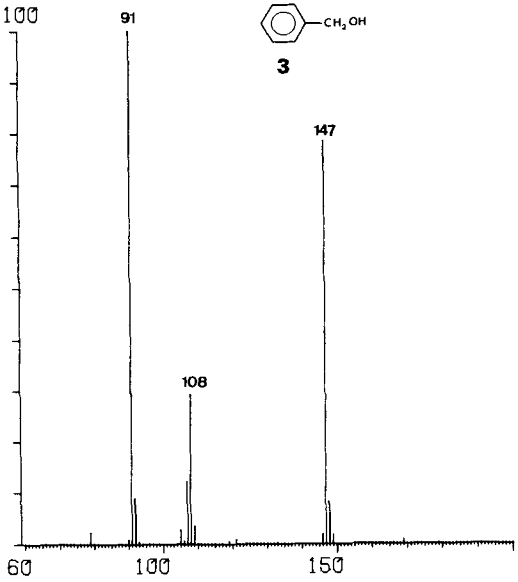


Fig. 1. *CI. (i-C_4H_{10}) spectrum of benzyl alcohol* (**3**)

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[5]) For alkyl ion affinities, see *e.g.* [12]. The proton affinity of benzene is about 769 kJ/mol [13], that of methanol about 756 kJ/mol [14].

Results and Discussion. - The isobutane chemical ionization mass spectrum of *benzyl alcohol* (**3**) is characterized by its dominant benzyl ion, *m/z* 91 *(Fig. 1)*. Only one other ion is of relative abundance above 50%: *m/z* 147, the dehydration product of the '$M+57$' adduct ion under study. Obviously due to a quantitative decomposition of the latter, no '$M+57$' signal (*m/z* 165) is observed as such.

In order to identify the H-atoms incorporated in the H_2O molecule lost, benzyl-*ar*-d_5 (**3a**) and benzyl-*a*,*a*-d_2 alcohol (**3b**) were analyzed by CI.(*i*-C_4H_{10}). The results should indicate the substitution site(s), *i.e.* determine whether **3** indeed undergoes aromatic substitution at all, or whether it follows more closely the behaviour of the cyclohexyl derivatives **1** and **2** *(Scheme 1)* in undergoing 'aliphatic' substitution at the benzylic site.

Inspection of the spectrum of **3a** *(Fig. 2)* shows immediately that aromatic *o*-substitution with subsequent 1,3-elimination of H_2O according to *Scheme 3* is ruled out. The quantitative shift of *m/z* 147 to 152 in **3a** is irreconcilable with the abstraction of an H-atom from any aromatic site. Analysis of **3b** *(Fig. 3)* shows that *no* hydrogen of the substrate other than O–*H* is lost, as *m/z* 147 is quantitatively shifted to 149. Hence, the second of the two H_2O H-atoms ought to be derived exclusively from the $[C_4H_9]^+$ reactant ion[6]. This evidence is compatible with the following mechanism *(Scheme 4)* which specifies the generalized route outlined already in *Scheme 2*.

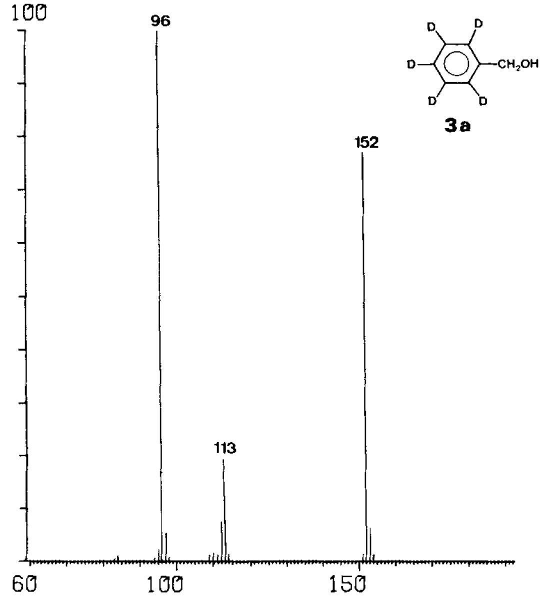

Fig. 2. *CI. (i-C_4H_{10}) spectrum of 2,3,4,5,6-d_5-benzyl alcohol* (**3a**)

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[6] Relying on the exclusion principle (all relevant abstraction sites are accounted for), no ²H-labelling of the reactant ion (use of C_4D_{10} as reagent gas) was performed. Reaction of $[C_4D_9]^+$ with *3-hydroxybenzyl alcohol* ($M=124$) in an earlier experiment had established the prevalence of HOD loss from the '$M+66$' complex within the usual limits of certainty posed by isotopic impurities of the reagent gas (*cf.* also [3]) and/or kinetic isotope effects. Instead of a 'clean' shift of *m/z* 163 to 171 for exclusive HOD loss, an isotope distribution pattern *m/z* 169 (4%), 170 (46%), 171 (100%), 172 (25%, partial H/D exchange at the 3-hydroxyl group?) was observed.

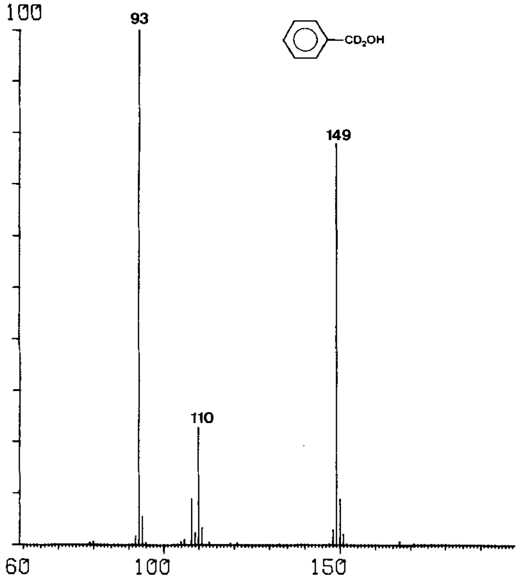
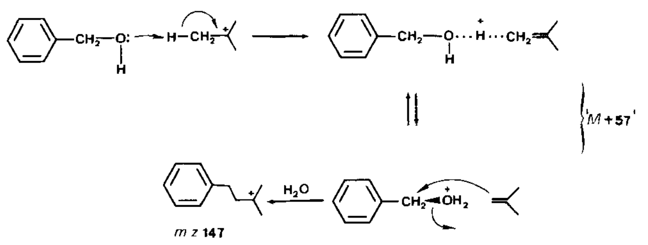


Fig. 3. *CI.* (i-C_4H_{10}) *spectrum of α,α*-d_2-*benzyl alcohol* (**3b**)

Substitution at the benzylic C-atom in **3** is thought to proceed *via* O/H/C-bonded '*M* + 57' complexes in which the central proton is shared by the two neutral species **3** and isobutene[7]). Before these complexes eventually decompose into fully separated $[MH]^+$ ions of **3** and independent isobutene molecules (provided the energy requirements are met) another, 'loose' ion/molecule complex will have to be traversed by these two latter incipient species. If long-lived enough, such a complex would, once more, permit chemical interaction just as the initial $C_6H_5CH_2OH/C_4H_9^+$ ion/molecule complex did. This time, the substrate/reagent role is, however, reversed. In such a complex, the necessary C,C-bond formation at the (saturated) benzylic site should be greatly facilitated by both the protonated hydroxyl function being an excellent leaving group (H_2O), and the nucleophilicity of the dimethyl-substituted olefin. Whether nucleophilic displacement of H_2O

Scheme 4



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[7]) C/O-bonded complexes between **3** and $[C_4H_9]^+$, either loosely associated through electrostatic forces or covalently bonded *Lewis* acid adducts, are likely to co-exist in equilibria. For simplicity, they are neglected in this context.

occurs directly, as arbitrarily depicted, in an S_N2-like fashion, or whether it proceeds stepwise by dissociation of $[M\mathrm{H}]^+$ into benzyl cations reacting as an electrophile with the associated C_4H_8 remains, of course, an unsettled question. In the latter, S_N1-like case, the benzyl cation and isobutene neutral could be viewed as a 'new' reactant ion and a 'new' substrate, respectively, in a 'second-order' type chemical ionization. The reversed reactant/substrate relationship requires, of course, respective changes in the differences between proton and /or alkyl ion [12] affinities in order to become thermodynamically feasible[8]).

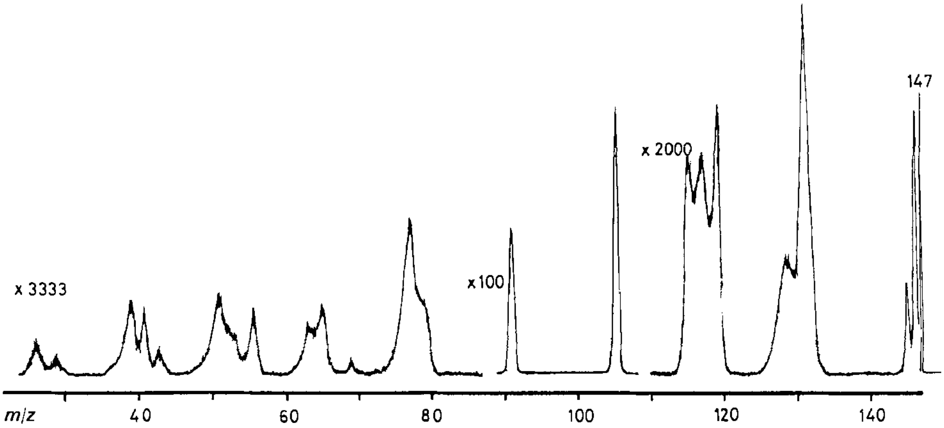

Fig. 4. *MIKE./CA. spectrum of* m/z *147 produced from benzyl alcohol* (**3**)

Strong support for this rationale of *t*-butyl substitution at the benzylic C-atom was derived from additional experiments. These were aimed directly at confirming the inferred integral structure of the product ion rather than the origin of single atoms mobilized in its genesis. For that purpose, mass-analyzed ion kinetic energy (MIKE.) spectroscopy under collisional activation (CA.) conditions was employed. In order to match the actual with the proposed ion structure, the CI. (i-C_4H_{10}) MIKE./CA. spectrum of *m/z* 147, produced from **3** *(Fig. 4)*, was matched with that of *m/z* 147, produced from *2-methyl-4-phenyl-2-butanol* (**4**, *Fig. 5*). This latter precursor can be expected to be a reliable source of the required reference ion of the inferred structure. It embodies the complete postulated C-skeleton and yields *m/z* 147 abundantly through heterolytic decomposition of, *inter alia*, $[M\mathrm{H}]^+$ by loss of H_2O in a simple and transparent genesis *(Scheme 5)*.

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[8]) For a 'reverse' electrophilic addition of the benzyl ion to the 'new' substrate isobutene

$$C_6H_5CH_2^+ + CH_2{=}C(CH_3)_2 \rightarrow C_6H_5CH_2CH_2\overset{+}{C}(CH_3)_2$$

an approximate exothermicity of $\Delta H = -105$ kJ/mol follows from the standard heats of formation, ΔH_f, of the species involved. $\Delta H_f(C_6H_5CH_2CH_2\overset{+}{C}(CH_3)_2$ is estimated to be 785 kJ/mol by using *Franklin*'s group equivalent approach [15]; $\Delta H_f(C_6H_5CH_2)^+$and ΔH_f (isobutene) are taken as being 907 and -17 kJ/mol, respectively [16].

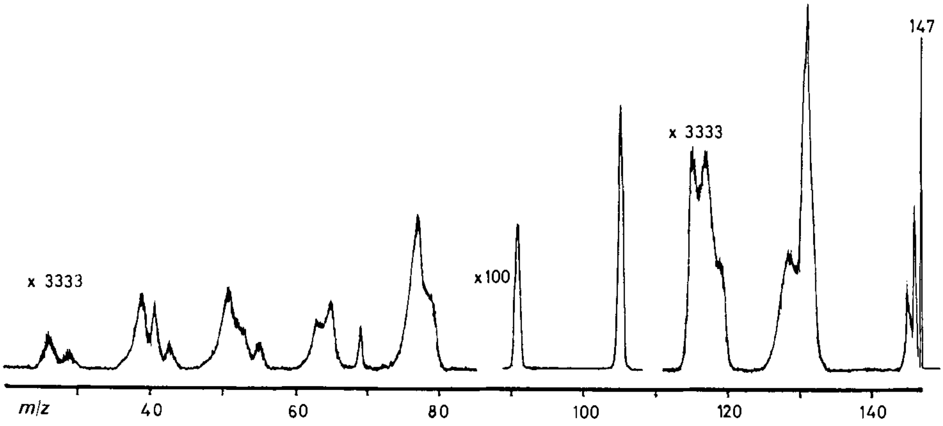
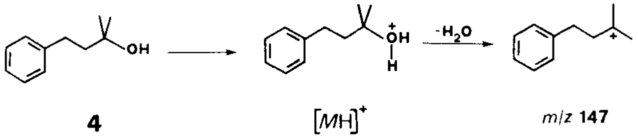


Fig. 5. *MIKE./CA. spectrum of* m/z *147 produced from 2-methyl-4-phenyl-2-butanol* (**4**)

Using the CA. method, identical fragmentation patterns of mass-selected ions of different provenance indicate identical ion structures, independent of differences in their original internal energy content and distribution due to formation from different precursors [17]. On interaction of the selected ions with the collision gas, a portion of their high kinetic energy is converted into internal energy [18]. The average amount of energy conveyed in this manner is large compared with the original internal energy distribution of the ion prior to collision [19]. A close inspection of the MIKE./CA. spectra of the two *m/z* 147 ions indeed shows a close match of the fragmentation patterns. This piece of evidence in favor of identity fully supports the ion structure of *m/z* 147 in the CI. (i-C_4H_{10}) spectrum of **3**.

Scheme 5



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Experimental Part

Materials and Methods. Benzyl alcohol, 3-hydroxybenzyl alcohol and $LiAlD_4$ were purchased from *Fluka AG*, Buchs, Switzerland; 2,3,4,5,6-pentadeuteriobenzyl alcohol from *E. Merck AG*, Darmstadt. Mass spectral measurements were performed using these chemicals without further purification. Hydrocinnamic acid and methyl iodide were obtained from *Aldrich Chemical Co.*, Milwaukee, Wisconsin, USA. Isobutane (99.95%) used as CI. reagent gas was purchased from *L'Air Liquide*, Geneva.

Methyl hydrocinnamate was prepared by standard esterification procedure in a methanol/thionyl chloride mixture [20]. *2-Methyl-4-phenyl-2-butanol* was prepared by reaction of methyl magnesium iodide with methyl hydrocinnamate using general *Grignard* reaction procedures [21]. *Benzyl-α,α*-d_2 *alcohol* was obtained by reduction of methyl benzoate with $LiAlD_4$.

Electron impact (EI.) mass spectra were obtained using a *Finnigan* 3200 GC./MS. system with integrated data system 6000 (6 ft. × 2 mm glass column, 3% OV-1 on Gas Chrom Q 100/200; initial temperature 100°, final temperature 290°, 10°/min, 70 eV). The EI. spectrum of *2-methyl-4-phenyl-2-butanol* contained the following ions [*m/z* (rel. int.)]: 149 (4), 147 (3), 146 (30), 132 (5), 131 (49), 129 (2), 117 (2), 116 (2), 115 (2), 106 (4), 105 (5), 104 (4), 103 (4), 92 (7), 91 (86), 89 (2), 79 (6), 78 (9), 77 (10), 65 (14), 63 (4), 60 (3), 59 (100), 58 (2), 55 (2), 51 (8), 50 (2). The EI. spectrum of the *trimethylsilyl ether* of *2-methyl-4-phenyl-2-butanol* contained the following ions [*m/z* (rel. int.)]: 221 (5), 147 (3), 146 (36), 145 (2), 132 (11), 131 (100), 117 (2), 115 (3), 105 (2), 92 (2), 91 (33), 80 (3), 79 (53), 78 (8), 77 (3), 76 (5), 75 (66), 74 (6), 65 (17), 61 (5), 53 (5), 52 (44), 51 (22), 50 (15).

Chemical ionization (CI.) mass spectra of the benzyl alcohols were obtained using a GC./MS.-system (*Carlo Erba* 2101 capillary gas chromatograph, *Finnigan* 3200 quadrupole mass spectrometer, *Incos* data system) described earlier [22]. Gas chromatographic analysis was based on the use of a 20 m × 0.33 mm persilylated [23] glass capillary column coated with OV-73. The ion source conditions were: 500 µA emission current, 130 eV ionizing energy, 120° ion source temperature. About 1 mbar of isobutane reagent gas pressure was maintained in the source. Chemical ionization spectra of *2-methyl-4-phenyl-2-butanol* were obtained using the direct inlet system under otherwise identical mass spectrometer conditions. The CI. (i-C_4H_{10}) spectrum of *2-methyl-4-phenyl-2-butanol* contained the following ions [*m/z* (% rel. int.)]: 166 (10), 165 (100), 149 (10), 148 (6), 147 (48), 146 (14), 145 (4), 134 (4), 133 (42), 131 (10), 129 (2), 106 (2), 105 (26), 104 (4), 91 (9).

Collision-induced MIKE. spectra were obtained using a *VG-Micromass* MM ZAB-2F 'reversed geometry' mass spectrometer [24] operated in the chemical ionization mode. The ion source was maintained at 120°, the electron energy at 100 eV, the emission current at 2 mA, the repeller potential at -0.5 V. The accelerating voltage was set at 5 kV for all measurements. The source pressure of the isobutane reagent gas and sample was adjusted so as to give a reading of about 10^{-5} mbar on the source ionization gauge which is estimated to correspond to a pressure of about 0.5 mbar within the source. The flow of collision gas (N_2) through the collision cell, located in the second field-free region, was adjusted so as to give a pressure indication of $2{,}5 \times 10^{-6}$ mbar on the ionization gauge, located below the collision cell and above one of the analyzer diffusion pumps (*Edwards Diffstak*, type 700). This was estimated to correspond to a pressure within the cell of about 10^{-3} mbar. At this pressure, the main beam of ions passing through the cell was attenuated to 50% of its original value.

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