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1 The capability of CI-Orbitrap for gas-phase analysis in
2 atmospheric chemistry:

3 A comparison with the CI-API-TOF technique

4
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10

11 **Abstract**

12 Chemical ionization Orbitrap mass spectrometry (CI-Orbitrap) represents a promising new technique
13 for gas-phase analysis in analytical and atmospheric chemistries mainly due to its very high mass
14 resolving power. In this work, we performed the first side-by-side comparison between a CI-Orbitrap
15 and the widely used atmospheric pressure interface time-of-flight mass spectrometry (CI-APi-TOF)
16 using two different chemical ionization methods, i.e., acetate-ion-based (CH_3COO^-) and aminium-ion-
17 based ($\text{n-C}_3\text{H}_7\text{NH}_3^+$) schemes. The capability of the CI-Orbitrap at accurately measuring low
18 concentrations of gaseous species formed from the oxidation of α -pinene was explored. Although this
19 study reveals a lack of linearity of the CI-Orbitrap when measuring product ions at very low
20 concentrations ($< 1 \times 10^6$ molecules cm^{-3}), very good agreement between both techniques can be
21 achieved by applying a newly developed linearity correction. It is experimentally shown that the
22 correction function is independent of the reagent ion used. Thus, accurate quantification of organic
23 compounds at concentrations as low as 1×10^5 molecules cm^{-3} by the CI-Orbitrap can be achieved.
24 Finally, by means of tandem mass spectrometry, the unique capability of the Orbitrap allows the direct
25 determination of the binding energy of cluster ions between analyte and reagent ions, that is needed
26 for the assessment of a chosen ionization scheme.

27 **Introduction**

28 Biogenic and anthropogenic activities constantly release a wide variety of volatile organic compounds
29 (VOCs) into the atmosphere.^{1,2} Once emitted, VOC are rapidly oxidized to form oxidized VOCs
30 (OVOCs) spanning a broad range of chemical formulas, and, thus, volatilities.^{1,3,4} As a result, organic
31 compounds play a key role in the formation of atmospheric aerosol by either condensing onto pre-
32 existing aerosol particles or by forming new particles.^{1,2,5,6} VOC emissions strongly impact
33 atmospheric chemistry, human health, and Earth's climate. More specifically, a critical starting point in
34 new particle formation (NPF) and growth is the generation of highly oxygenated multifunctional
35 organic molecules (HOMs) through a process usually referred to as autoxidation.⁷⁻⁹ In the course of
36 the autoxidation process, peroxy (RO₂) radicals, formed via the oxidation of a VOC, undergo an
37 intramolecular hydrogen shift reaction, ROO → QOOH, followed by the addition of molecular oxygen
38 resulting in the formation of a new R'O₂ radical: QOOH + O₂ → OOQOOH (R'O₂) ("Q" stands for
39 the organic group "R" after intermolecular H shift). This chain reaction can be repeated, yielding a
40 broad diversity of products depending on the RO₂ radical termination steps.^{8,10-12} As a result, HOMs
41 can be formed efficiently at high enough yields to consider them as a significant source of condensing,
42 or, in certain cases, even nucleating, organic components.^{6-8,13-15} Finally, RO₂ chemistry not only
43 controls the formation of HOMs and NPF but also impacts the production of secondary pollutants
44 including O₃ and NO₂.¹⁶ While in the last decade major breakthroughs have been achieved within the
45 field of atmospheric oxidation processes and new particle formation,^{6-8,17} a complete understanding of
46 how VOC oxidation products contribute to new particle and SOA formation remains poorly
47 constrained. Indeed, gas-phase oxidation processes of biogenic and anthropogenic VOCs yield a
48 number of oxidized products resulting in extremely complex mixture of oxygenated VOCs (OVOCs).
49 These span a wide range of chemical formulas, structures, and physicochemical properties and pose a
50 critical challenge in detecting, quantifying, and characterizing key atmospheric species including RO₂
51 radicals and HOMs.

52 Mass spectrometric techniques have recently made enormous improvements in detecting and
53 quantifying gaseous oxygenated species.¹⁸⁻²⁰ In particular, chemical ionization mass spectrometry
54 (CIMS) has emerged as a prevailing tool due to its very low detection limits, good sensitivity, and

55 capability of measuring a wide variety of gaseous organic and inorganic species.^{8,10,10,21} Chemical
56 ionization (CI) is a soft ionization technique where the analyte is ionized via a clustering process with
57 the reagent ion with minimal fragmentation or via proton transfer processes.²¹⁻²⁴ As part of the rapid
58 development, multiple reagent ion schemes have been tested over the last few years. Due to the
59 improvements in sensitivity and/or selectivity, a wide variety of oxygenated species, including RO₂
60 radicals and stabilized Criegee intermediates, can now be directly analyzed.^{10,11,19,20,25,26} However,
61 most of the CI mass spectrometers offer a rather limited mass resolving power (i.e., from 2 000 to 14
62 000), hindering yet a complete and unambiguous identification of the compounds of interest.
63 Consequently, the presence of multiple overlapping ions leads to significant uncertainties that can only
64 be partly resolved by computational techniques. To overcome these limitations, we have recently
65 coupled a high-resolution mass spectrometer (Orbitrap) with a CI source.³⁰ The CI-Orbitrap combines
66 the benefits of soft atmospheric pressure ionization with a unique mass resolving power ($R \geq 140\ 000$
67 at m/z 200). In our first study we demonstrated the applicability of this new analytical method and
68 evaluated its ability in detecting and characterizing OVOCs formed during the oxidation of two
69 monoterpenes using nitrate-based (NO₃⁻) CI.³⁰ Nonetheless, a direct comparison with the widely used
70 atmospheric pressure interface time-of-flight mass spectrometry (CI-APi-TOF) has not been
71 performed hitherto. Hence, the sensitivity as well as the linearity of the CI-Orbitrap with different
72 reagent ions operated in the positive or negative mode need to be determined and compared to those of
73 the CI-APi-TOF.

74 Within the present study, we performed the first side-by-side comparison between a CI-
75 Orbitrap and a CI-APi-TOF applying two different chemical ionization schemes i.e., the acetate-ion-
76 based (CH₃COO⁻)^{10,11} and the aminium-ion-based (n-C₃H₇NH₃⁺)¹¹ product ionization. Unlike our
77 initial study, we performed our experiments in a free-jet system designed to probe the early stage of a
78 given reaction. A very short residence time was used as well as very low reactant conversion. As a
79 result, RO₂ radicals are the main products and experiments are performed within atmospheric reaction
80 conditions, where bimolecular steps are only important for relatively high RO₂/ HO₂ levels or in the
81 presence of high enough concentrations of additives (e.g., NO). Hence, very low concentrations of
82 RO₂ radicals and OVOCs are produced from the ozone and OH radical initiated oxidation of α -pinene

83 in order to ascertain the benefit and the limitation of the CI-Orbitrap. We also explored the potential of
84 the CI-Orbitrap in evaluating the binding energies of RO₂ radicals and OVOCs clustered with acetate
85 and aminium (n-C₃H₇NH₃⁺) by means of tandem mass spectral analyses (MS²).

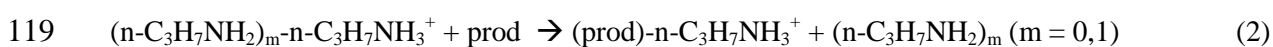
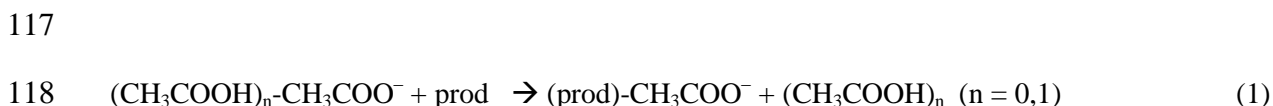
86 EXPERIMENTAL SECTION

87 Ozonolysis and OH radical initiated oxidation of α -pinene (C₁₀H₁₆) were performed under dry
88 conditions (RH < 0.1%) in air using a free-jet flow system at a temperature of 297 \pm 1 K and
89 atmospheric pressure.^{10,11} This flow system allows the investigation of VOC oxidation under
90 atmospheric conditions with negligible wall effects and a reaction time of 7.9 s. Ozone produced from
91 a low-pressure mercury lamp or isopropyl nitrite (IPN) was premixed with air (5 L/min (STP)) and
92 injected through the inner tube into the main gas stream (95 L/min (STP)) containing α -pinene diluted
93 in air. Ozonolysis experiments (dark reaction) were performed in the absence of an OH scavenger, i.e.,
94 the in-situ OH radical formation from ozonolysis led to a combined O₃/OH + α -pinene reaction. In the
95 pure OH experiments based on IPN photolysis, 8 NARVA 36W Blacklight Blue lamps were used for
96 illuminating the flow system. All gas flows were set by means of calibrated gas flow controllers (MKS
97 1259/1179). The concentration of α -pinene was maintained at 5.0 \times 10¹¹ molecules cm⁻³, while ozone
98 and IPN were ramping up from 2.5 \times 10¹⁰ to 5.6 \times 10¹¹ and from 1.7 \times 10¹⁰ to 6.7 \times 10¹¹ molecules cm⁻³, respectively.
99

100 The chemical composition of the oxygenated products was retrieved in real time by a Q-
101 Exactive Orbitrap Plus mass spectrometer (Thermo Scientific) and a chemical ionization - atmospheric
102 pressure interface - time-of-flight mass spectrometer (CI-APi-TOF, Tofwerk AG). Both instruments
103 have been described elsewhere and were equipped with a similar Eisele-type inlet.^{21,30-33} While the CI
104 inlet mounted on the APi-TOF is manufactured by Airmodus (Finland), the CI inlet installed on the
105 Orbitrap is a home-built version with minor modifications regarding to the commercially available
106 inlet (i.e., dimensions of the drift tube and specific flange, see for more details ref.³⁰). The sample flow
107 rate for both instruments was set at \sim 10 L/min (STP). Protonated n-propylamine (n-C₃H₇NH₃⁺) or
108 acetate (CH₃COO⁻) ions were produced using an X-ray source or an Am-241 source for the Orbitrap
109 and the APi-TOF, respectively. In the ion-molecule-reaction (IMR) zone, the reagent ions from a clean
110 sheath nitrogen flow were guided into the concentric sample flow by an electrical field without

111 turbulent mixing of both streams. The residence time within the IMR zone was in the range of 200 –
112 300 ms in both instruments.

113 The reagent ions were $(\text{CH}_3\text{COOH})_n\text{-CH}_3\text{COO}^-$ ($n = 0,1$) and $(n\text{-C}_3\text{H}_7\text{NH}_2)_m\text{-n-C}_3\text{H}_7\text{NH}_3^+$ (m
114 $= 0,1$) in the negative and positive mode, respectively. RO_2 radicals as well as closed-shell products,
115 called “prod” for all together, were detected as clusters with the respective reagent ions according to
116 the following reactions (1) and (2):



120
121 It is important to mention that the absolute calibration of the detected oxygenated products is
122 impossible due to a lack of authentic reference substances for RO_2 radicals and the majority of closed-
123 shell products. Thus, the product signals of both mass spectrometers were normalized to the sum of
124 the reagent ions, i.e., $\Sigma[(\text{CH}_3\text{COOH})_n\text{-CH}_3\text{COO}^-$ ($n = 0,1$)] or $\Sigma[(n\text{-C}_3\text{H}_7\text{NH}_2)_m\text{-n-C}_3\text{H}_7\text{NH}_3^+$ ($m =$
125 $0,1$)]. The resulting normalized signals were used for the comparison in order to evaluate the
126 performance of both techniques.

127 However, the lower end value of the calibration factor f can be calculated considering the ion-
128 molecule reaction within the CI-inlet, $f = 1 / (k \times t \times f_{\text{inlet}})$,³⁴ where k is the rate coefficient of the ion-
129 molecule reaction, t the reaction time and f_{inlet} corresponds to the “prod” loss in the sampling tube.
130 Diffusion loss of the RO_2 radicals and OVOCs in the sampling lines to the CI-API-TOF and the CI-
131 Orbitrap were calculated to be 12% and 38%, respectively, assuming diffusion-controlled wall
132 losses.¹⁰ Taking into account this diffusion loss, $f_{\text{inlet}} = 0.88$, and a reaction time of the ion-molecule
133 reaction $t = 0.2 - 0.3$ s (which is similar for both instruments), a calibration of $f_{\text{calc}} = (1.3 - 2.8) \times 10^9$
134 molecules cm^{-3} can be calculated. It should be mentioned that using the only reliable absolute
135 calibration technique (i.e., sulfuric acid) a calibration factor of $f_{\text{H}_2\text{SO}_4,\text{exp}} = 1.85 \times 10^9$ molecules cm^{-3}
136 was determined in previous experiments. This value is in good agreement with the range of f_{calc} . The
137 calibration factor f of reactions (1) and (2) was set equal to $f_{\text{H}_2\text{SO}_4,\text{exp}}$ by practical reasons. The

138 uncertainty of the lower end “prod” concentrations determined according to equation (1) or (2) is
139 assumed to be not higher than a factor of two due to the expected uncertainty of the used calibration
140 factor $f_{\text{H}_2\text{SO}_4, \text{exp}} = 1.85 \times 10^9$ molecules cm^{-3} , and possible inaccuracy connected with the duty cycle
141 correction. Therefore, only lower limit product concentrations are available based on this calculated
142 calibration factor.

143 Duty cycle correction was applied for the APi-TOF data in order to account for the m/z
144 discrimination during the ion extraction.^{10,24,35} In the case of the CI-Orbitrap, for each experiment, the
145 ion transmission was evaluated by comparing the loss of the number of charges of the reagent ions
146 with the increase of the number of charges of all the ions within the m/z 200 – 600 Th. This simple
147 method provides a rough estimate of the ion transmission for the compounds of interest relative to the
148 reagent ions. As a result, a factor of 2 was applied to correct for the lower ion transmission of the
149 reagent ions in order to determine the normalized signals.

150 In addition, we further evaluated the ion transmission of the Q Exactive Orbitrap in the m/z 53
151 – 800 Th using the depletion method described by Heinritzi et al.³⁶ This method takes into
152 consideration losses within the inlet as well as the different ion optics and C-Trap (see Figure S1). In
153 short, 4 different perfluorinated acids were introduced into the mass analyzer in order to deplete the
154 reagent ions. As a result, the relative transmission efficiency can be obtained by comparing the
155 decrease of signal strength of the reagent ions with the rising signals from the perfluorinated acids at
156 larger masses (see supplementary information for more details). The relative ion transmission was
157 only determined for the Q-Exactive Orbitrap using nitrate-ion based chemistry. It should be pointed
158 out that the depletion method leads to significantly different results for the ion transmission of a mass
159 spectrometer than absolute calibration methods.^{7,36-38} Nevertheless, the results of the depletion method
160 provide a first insight into the ion transmission of a Q Exactive Orbitrap.

161 The Q Exactive Plus Orbitrap (Orbitrap-Tropos) was used in positive (i.e., $\text{n-C}_3\text{H}_7\text{NH}_3^+$) and
162 negative mode (i.e., CH_3COO^-) and connected to the free-jet flow system. The Q Exactive Orbitrap
163 (Orbitrap-IRCELYON) was solely used in negative mode (NO_3^-) to determine the ion transmission
164 and to developed the linearity correction. Both instruments were operated using the same settings and
165 were run in full scan mode with a high mass resolving power of 140 000 (at m/z 200 Th), allowing an

166 identification of a wide variety of species. The instruments were operated in negative or positive
167 mode, scanning from m/z 50 to 750 Th with an automatic gain control (AGC) target of 1×10^5
168 charges, a maximum injection time of 1 s, resulting in a scan rate of 0.2 scans/s. Spectra were
169 averaged of 5 microscans (1 microscan corresponding to 1 ion injection). The stacked-ring ion guide
170 (or S-Lens) is a radio frequency (RF) device efficiently capturing and focusing the ions into a tight
171 beam. As previously described it contains a series of electrodes where voltages are applied in order to
172 focus the ions. The S-lens level was maintained at 60%, to maximize ion transmission and the limit of
173 detection. The C-Trap consist of a RF-based ion collecting trap (Figure S1), which is automatically
174 controlled by the AGC (automatic gain control) in order to prevent space-charge effects. In order to
175 evaluate the impact of the number of charges collected in the C-trap, the AGC target of the Orbitrap-
176 Tropos instrument was scanned from 5×10^4 to 1×10^6 charges. External mass calibrations were
177 performed prior to the experiments by injecting a 2 mM sodium acetate solution using an electrospray
178 ionization source. This procedure provided a suite of negative and positive adduct ions in the desired
179 mass range of m/z 59 – 700 Th. Tandem mass spectral (MS^2) analyses were performed by ramping up
180 the normalized collision energy (NCE) from 1 – 7 eV (i.e., normalized to singly charged ions at m/z
181 500). Thus, to retrieve the collision energy (CE) encountered by ions at any given m/z ratio within the
182 higher-energy collision dissociation (HCD) cell, the CE can be calculated as follows: $CE = (m/z / 500)$
183 \times NCE \times f, where f stands for the number of charges of the ion. To ensure an optimal detection of the
184 product ions, the mass spectra obtained using the CI-APi-TOF and the CI-Orbitrap were averaged over
185 10 minutes each. A time resolution of 5 min was used for the MS^2 analyses conducted by the Orbitrap.
186 The high-resolution Orbitrap data were analyzed by XCalibur 4.1 (Thermo Scientific) software
187 package to determine accurate composition and the abundance of the compounds of interest. Peak
188 fitting of the CI-APi-TOF data was performed by means of the Matlab-based toftools software.³⁷

189

190 RESULTS AND DISCUSSION

191 **Characterization of the CI-Orbitrap.** Despite the wealth of studies using the Orbitrap technique,
192 little is known about the capability of the Orbitrap in measuring compounds on-line at low
193 concentrations. For example it has been reported that the Orbitrap can provide a non-linear response,

194 potentially impacting isotope ratios, determination and the quantification of compounds present at
195 extremely low concentrations.³⁹ In view of these findings available from literature, we evaluated the
196 performance of the CI-Orbitrap by comparing the measured vs. the theoretical isotopic intensities
197 using product ions analyzed by the Orbitrap-Tropos using protonated n-propylamine ($n\text{-C}_3\text{H}_7\text{NH}_3^+$)
198 and acetate (CH_3COO^-). To further estimate the impact of different reagent ions, results from our
199 former study performed with the Orbitrap-IRCELYON using nitrate-ion based chemistry³⁰ are also
200 compared here. In both cases, OVOCs were continuously generated in the flow tube from either the
201 ozonolysis and/or OH radical initiated oxidation of α -pinene. Hence, the abundance of the main
202 OVOCs (e.g., $\text{C}_{10}\text{H}_{14,16}\text{O}_x$; $\text{C}_{20}\text{H}_{30,32}\text{O}_x$) and RO_2 radicals (e.g., $\text{C}_{10}\text{H}_{15,17}\text{O}_x$) at nominal masses M , (M
203 $+ 1$) and ($M + 2$), corresponding to their ^{13}C atom and ^{18}O atom fraction, were measured to cover a
204 wide range of normalized product signals in the range of 5×10^{-7} to 5×10^{-2} . Signal intensities
205 reported in Figure 1A were obtained with an AGC target of 1×10^5 charges. As depicted in Figure 1A,
206 when the ratio is equal to 1.0 for normalized signal $> \sim 4 \times 10^{-4}$ to ($\sim 1 \times 10^6$ molecules cm^{-3}), the
207 Orbitrap is providing a linear measure of the ion intensity. However, this ratio dropped significantly
208 for normalized signals below $\sim 4 \times 10^{-4}$. Such a situation occurs when the ion intensity is close to the
209 instrumental threshold, i.e., by using standard settings the Orbitrap mass analyzer records only signals
210 if $S/N > 1.3$. The ion signals below this threshold are treated as undetected by the acquisition software.
211 Due to the statistics, peaks with an average $S/N = 1.5$ for example will appear above this threshold
212 only in a limited amount of cases reducing the resulting peak intensity.⁴⁰ As a result, for a normalized
213 signal smaller than 1×10^{-5} , the CI-Orbitrap only detects 5 – 10 % of the “true ion number
214 distribution”. That means, using the instrumental parameters and the calibration factor employed here
215 (1.85×10^9 molecules cm^{-3}) the limit of quantification (LoQ, corresponding to lowest normalized
216 signal observed within the linear range) of the Orbitrap was evaluated to be $\sim 1 \times 10^6$ molecules cm^{-3}
217 at a 10-minute integration time. It is worth pointing out that the limit of detection (LoD, corresponding
218 to the lowest normalized signal observed) is likely one or two orders of magnitude lower than the LoQ
219 but due to the lack of linearity accurate numbers cannot be directly provided. By adjusting the AGC
220 target the linear range can be shifted towards lower ion concentrations as shown in Figure 1B. This
221 can be explained by larger number of ions trapped within the C-trap prior to the Orbitrap scan

222 resulting in more ions entering the Orbitrap mass analyzer. This leads to an enhanced S/N ratio and
223 better statistics. Hence, we have evaluated the impact of the AGC target (scanned from 5×10^4 to $1 \times$
224 10^6 charges) on the linearity and found that by optimizing the AGC target, the LoQ of the CI-Orbitrap
225 is anticipated to be greatly extended. However, as most of our previous experiments were performed
226 using an AGC target of 1×10^5 charges, we kept this setting to perform the side-by-side comparison.

227 **Comparison CI-Orbitrap vs CI-APi-TOF.** To evaluate the performance of the CI-Orbitrap
228 compared to the widely used CI-APi-TOF technique we directly performed side-by-side experiments.
229 Both instruments, equipped with a similar type of inlet originally designed by Eisele et al.³¹ and
230 running with the same reagent ion, sampled concurrently RO₂ radicals as well as OVOCs produced
231 under well-controlled reaction conditions. We focused on the detection of RO₂ radicals produced from
232 the oxidation of α -pinene. Using acetate and aminium ($n\text{-C}_3\text{H}_7\text{NH}_3^+$) as the reagent ions, the main RO₂
233 radicals from α -pinene oxidation, HO-C₁₀H₁₆(O₂) _{α} O₂ ($\alpha = 0, 1, 2$), were detected by means of the CI-
234 Orbitrap, in line with the findings of the CI-APi-TOF.^{24,30,35} As depicted in Figures 2 and S2, the mass
235 resolving power of the Orbitrap can accurately distinguish the different species, which is often
236 impossible with typical TOF mass analyzers. To further illustrate the difference, we have directly
237 compared ion signals measured by the CI-Orbitrap and by the CI-APi-TOF equipped with a high
238 resolution mass analyzer (HR-TOF, resolution ~ 3000) (Figure 2).

239 Figure 3 shows the results of the OH radical-initiated oxidation of α -pinene. The OH radicals
240 were generated by isopropyl nitrite (IPN) photolysis. The formation of the additional RO₂ radical HO-
241 C₁₀H₁₅(OH)(O₂)O₂ can be explained by the reaction of HO-C₁₀H₁₆(O₂)₂O₂ with NO and subsequent
242 radical isomerization as discussed in a former study.³⁵ NO is formed from the IPN photolysis. In
243 addition to the RO₂ radicals, also closed-shell products were detected including carbonyls and organic
244 nitrates produced from the RO₂ + NO reactions.¹⁶ Lastly, products arising from other bimolecular RO₂
245 reactions were not detected or were below the detection limit under the selected experimental
246 conditions due to the relatively low RO₂ radical concentrations $< 10^8$ molecules cm⁻³ and the very
247 short reaction time of 7.9 s.

248 As shown in Figure 3, for uncorrected normalized intensities above $(2 - 3) \times 10^{-4}$
249 (corresponding to $\sim (4 - 6) \times 10^5$ molecules cm⁻³) both techniques are in very good agreement. The lack

250 of linearity hampers the Orbitrap, unlike the APi-TOF, to accurately measure lower concentrations.
251 However, this lack of linearity appears to be independent of the instrument and the type of reagent
252 ions (Figure 1A). This behavior indicates that this instrumental limitation can be overcome in order to
253 retrieve the “correct” signal strength for peaks with lowest signal intensity. Indeed, using all
254 measurements from multiple experiments and reagent ions, a function named “sigmoidal correction
255 function” based on a fitting algorithm using a characteristic sigmoidal shape can be determined.
256 Therefore, raw normalized signals (corrected for sampling losses) measured with the CI-Orbitrap were
257 further corrected using the “sigmoidal correction function”, see also Figure 1. By applying this
258 method, all the data were corrected (open markers), which greatly helps maintaining the good
259 agreement between both techniques (Figure 3). However, for uncorrected signal intensities below a
260 threshold of $5 \times 10^{-6} - 1 \times 10^{-5}$ this approach results in an overestimation of the ion concentrations as
261 the signal is likely very close to the noise level of the instrument. As a result, such data points were
262 not included in Figures 3, 4, S3 and S4. While the APi-TOF can further help correcting this lack of
263 linearity we preferred to propose a method based only on the signal acquired by the Orbitrap. Hence,
264 the reported LoD is likely an upper limit and might be even pushed further with appropriate and
265 collocated instrumentations.

266 Overall, product signals measured by CI-Orbitrap and the CI-APi-TOF are mostly within a
267 factor of 2 (Figure 5) providing a good agreement between these two analytical techniques for
268 corrected normalized signal intensity ranging from $\sim 5 \times 10^{-5}$ to 1×10^{-2} (corresponding to $\sim 1 \times 10^5$ to
269 2×10^7 molecules cm^{-3}). Exception are the measurements of highly oxidized products using acetate
270 ionization. The reason for that is not clear at the moment. It is worth pointing out that the positive
271 mode measurements were less impacted by the lack of linearity compared to negative mode
272 measurements. This is explained by the fact that at a given product concentration, the resulting ion
273 intensity measured by aminium ($\text{n-C}_3\text{H}_7\text{NH}_3^+$) ionization is much greater than for acetate ionization. In
274 the case of the highest oxidized RO_2 radicals, i.e., $\text{HO-C}_{10}\text{H}_{16}(\text{O}_2)_2\text{O}_2$ and $\text{HO-C}_{10}\text{H}_{15}(\text{OH})(\text{O}_2)\text{O}_2$
275 bearing -OH and -OOH moieties, the obtained corrected signal intensities are almost identical within a
276 factor of two applying either acetate or aminium ($\text{n-C}_3\text{H}_7\text{NH}_3^+$) for product ionization. This fact is
277 obviously due to strong binding of these RO_2 radicals to both reagent ions. Thus, a near-maximum

278 detection sensitivity can be expected for these reagent ions.^{41,42} On the other hand, for the less oxidized
279 RO₂ radicals HO-C₁₀H₁₆O₂ and HO-C₁₀H₁₆(O₂)O₂ the detection sensitivity based on aminium (n-
280 C₃H₇NH₃⁺) ionization is definitely higher compared to acetate ionization, i.e., by a factor of 500 –
281 1000 in the case of HO-C₁₀H₁₆O₂.⁴²

282 Ozonolysis experiments in the absence of an OH scavenger were conducted in order to
283 generate a larger variety of products, mainly RO₂ radicals, formed from the simultaneous ozone and
284 OH radical reactions of α -pinene. Accordingly, two types of RO₂ radicals have been formed, i.e., the
285 ozonolysis-derived RO₂ radicals O₂O-C₁₀H₁₅(O₂)_xO₂ (x = 0, 1, 2, 3) and the OH-derived RO₂ radicals
286 HO-C₁₀H₁₆(O₂) _{α} O₂ (α = 0, 1, 2).^{7,35} Figure 4 presents the signal intensities of both types of RO₂
287 radicals measured by means of aminium (n-C₃H₇NH₃⁺) ionization. While the agreement for the most
288 oxidized RO₂ radicals is again very good, the signals of the less oxidized species O₂O-C₁₀H₁₅O₂ and
289 HO-C₁₀H₁₆O₂ (Figures 3 and 4) are systematically higher using the CI-Orbitrap by a factor of two or
290 higher. In contrast, for the most oxidized RO₂ the difference between the two instruments was only ~
291 20%. Such a disparity might be explained by less efficient declustering of the relatively weakly bound
292 aminium clusters of O₂O-C₁₀H₁₅O₂ and HO-C₁₀H₁₆O₂ in the CI-Orbitrap compared to the CI-API-TOF.
293 This results in a more sensitive detection of the initially formed RO₂ radicals with relatively low
294 oxygen content. It is important to mention that by applying the transmission curve to the CI-Orbitrap
295 data, a larger discrepancy exist between the results of both instruments, see Figure S6. This
296 discrepancy is obviously due to the different ion transmission corrections. Indeed, using the
297 parameters selected in this study the ion transmission within the Orbitrap exhibit a steep increase
298 between from m/z 60 to 300 Th (SI). However, much more experimental effort is needed in the future
299 for a reliable determination of the ion transmission of both instruments and for different reagent ions.
300 Hence it would be possible to determine i) how good the duty cycle correction accounts for the overall
301 ion transmission of the CI-API-TOF and ii) what is the accuracy of the depletion methods in
302 comparison to absolute calibration methods.

303 Overall, the side-by-side comparison displays a very good agreement of the results of the CI-
304 Orbitrap and the CI-API-TOF with the exception of the lowest oxidized reaction products. By using
305 the “sigmoidal correction function”, 1.85×10^9 molecules cm⁻³ as the calibration factor for an AGC

306 target of 1×10^5 charges, the LoQ of the CI-Orbitrap can be as low as 1×10^5 molecules cm^{-3} at a 10-
307 minute integration time.

308 **Determination of cluster binding energy.** In common CI-APi-TOF approaches, the organic
309 molecules of interest are observed as molecular clusters with the reagent ion (e.g., with CH_3COO^- or
310 $n\text{-C}_3\text{H}_7\text{NH}_3^+$), see also eq. (1) and (2). In order to provide an accurate quantification of the compounds
311 of interest it is essential to constrain the sensitivity of the reagent ion to OVOCs. To reach this goal,
312 characterizing any limitations when detecting the compounds of interest, including the ion–molecule
313 collision limit and the ion–molecule reaction time is critical. The proficiency of any neutral molecule
314 to bind to the reagent ion is directly linked to the binding energy of the adduct.

315 Accordingly, a weakly bound adduct can undergo declustering, i.e., collision-induced
316 dissociation (CID), during the flight through the mass analyzer. Ultimately, the binding energy of the
317 adduct and the energy of the collisions with gas molecules in the mass spectrometer will define the
318 survival probability of the adduct ions. To constrain this parameter, procedures based on CID
319 measurement coupled to quantum chemical methods have been proposed to investigate the behavior of
320 adducts at different collision energies.^{43,44} Nonetheless, carrying out such measurements is challenging
321 for the hundreds of different molecular ions, typically observed with a CI-APi-TOF, especially when
322 molecular structures remain unknown and/or are highly complex. Therefore, to quantitatively
323 constrain the effective binding energies of a wide range of OVOCs and RO_2 radicals, we employed the
324 capability of the Orbitrap analyzer to perform untargeted MS^2 analyses. Hence, all ions were injected
325 into the HCD cell, where they collide at a defined collision energy with N_2 molecules. The NCE was
326 ramped up from 1 to 7 eV. During the declustering scans, all potentials upstream the HCD cell
327 remained identical and only the NCE within the HCD cell incremented, thereby avoiding any changes
328 in the ion transmission of the mass spectrometer.

329 An example of the declustering analysis is presented in Figure 6A for a set of typical oxidation
330 products, for which the remaining fraction of individual ions is plotted as a function of the CE
331 (retrieve for each ion based on their m/z). Following the approach previously proposed for iodide-
332 based clusters,^{43–45} a sigmoidal fit was applied to the acquired data (Figure S7), in order to obtain the
333 following parameters: i) the collision energy at which half of the signal is removed (CE_{50}), and ii) the

334 maximum amplitude of the sigmoidal function (S_0), corresponding to the relative signal intensity that
335 would be measured in absence of declustering processes during the transmission through the mass
336 spectrometer. In Table S1, the CE_{50} values of the OH-derived OVOCs and OH-derived RO_2 produced
337 from the OH radical-initiated oxidation of α -pinene are reported. While direct comparison with
338 quantum chemical calculations is not directly possible due to the absence of information on the studied
339 OVOCs, earlier studies indicate that the values reported in Table S1 are within a fairly good
340 agreement for binding energies determined for isoprene-derived oxidation products measured with CI-
341 APiTOF using protonated n-propylamine or acetate.^{41,42} For example, Berndt et al.⁴² have estimated
342 binding energies of the HPALD-(n-C₃H₇NH₃⁺) cluster (C₃H₈O₃) cluster and HPALD-CH₃COO⁻
343 cluster of 28.5 and 31.9 kcal mol⁻¹, respectively, which is close to the values determined for OVOCs
344 and RO_2 radicals containing 3 oxygen atoms (Table S1) within this present study.

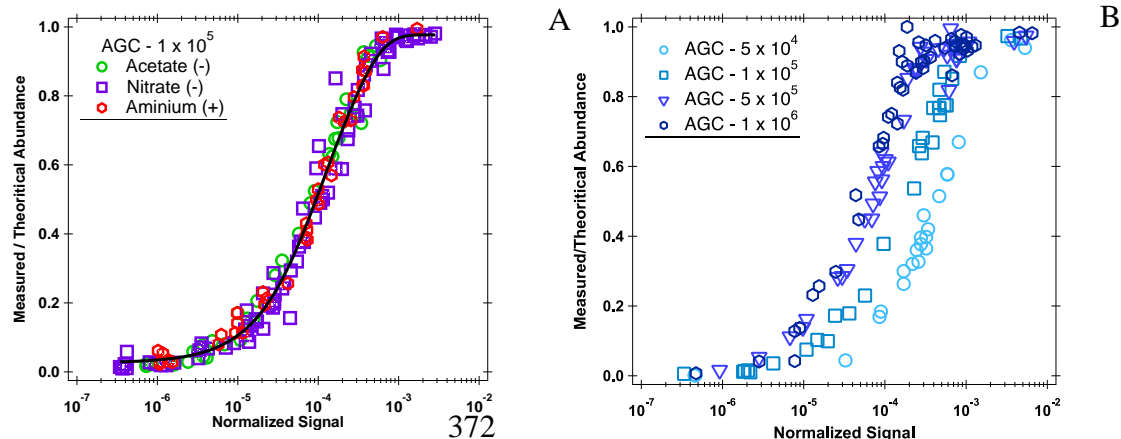
345 Following the method proposed in former studies,^{43,44} we found that the maximum possible
346 transmission for each compound clustered with protonated n-propylamine (n-C₃H₇NH₃⁺) is reached at
347 a binding energy of ~ 35 kcal mol⁻¹. This indicates that for cluster ions having a greater binding
348 energy, the stability of the adduct will be sufficient to transit through the different ion optics without
349 significant declustering losses. These results are in line with the side-by-side comparison, where the
350 largest discrepancy is observed for the lowest oxygenated species (e.g., O,O-C₁₀H₁₅O₂; HO-C₁₀H₁₆O₂),
351 i.e., the compounds with the lowest binding energy (Table S1). By optimizing the different voltages,
352 the declustering processes occurring within the APi-TOF and/or within the Orbitrap can be reduced.
353 Finally, it is interesting to note that earlier work, performing CID experiments using iodide-based
354 chemistry, determined a similar threshold, i.e., ~ 30 kcal mol⁻¹.⁴⁴

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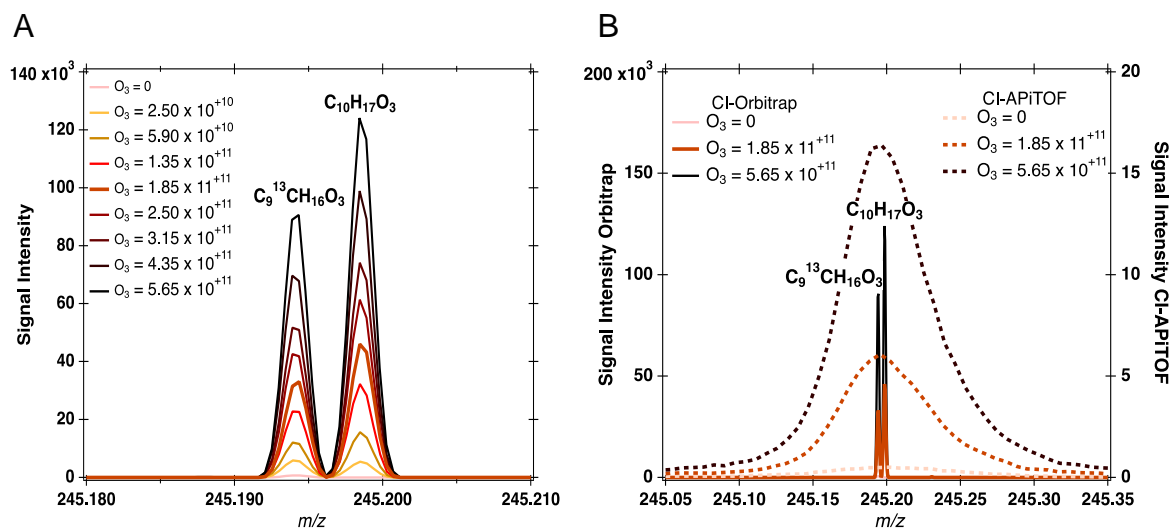
356 CONCLUSIONS

357 In this work, we demonstrated the capability of the CI-Orbitrap in measuring RO_2 radicals as well as
358 OVOCs at atmospherically relevant concentrations and compared them to simultaneous CI-APi-TOF
359 measurements. We explored the current limitations of this new analytical technique and demonstrated
360 that these can be partially overcome through a careful determination of a sigmoidal correction
361 function. In addition, to unambiguously identify OVOCs formed in the gas phase, the analysis by

362 means of the CI-Orbitrap is able to accurately quantify organic species at concentration down to $1 \times$
363 10^5 molecules cm^{-3} . This LoQ is \sim one order of magnitude higher in comparison to the APi-TOF used
364 in this study. In addition to the much greater mass resolving power, another clear advantage over the
365 APi-TOF technique is the capability of performing MS^2 analyses needed to retrieve information on the
366 chemical structure of the compounds of interest and to determine the binding energy of the clusters.
367 Overall, the combination of high-mass resolving power of the Orbitrap and high sensitivity of the
368 aminium/ammonium CI represents a powerful analytical tool that can improve our current knowledge
369 regarding the complexity of the atmospheric gaseous composition. Thus, this new technique can help
370 to answer some of the questions that so far were unable to be answered due to the pre-existing
371 instrument limitations.

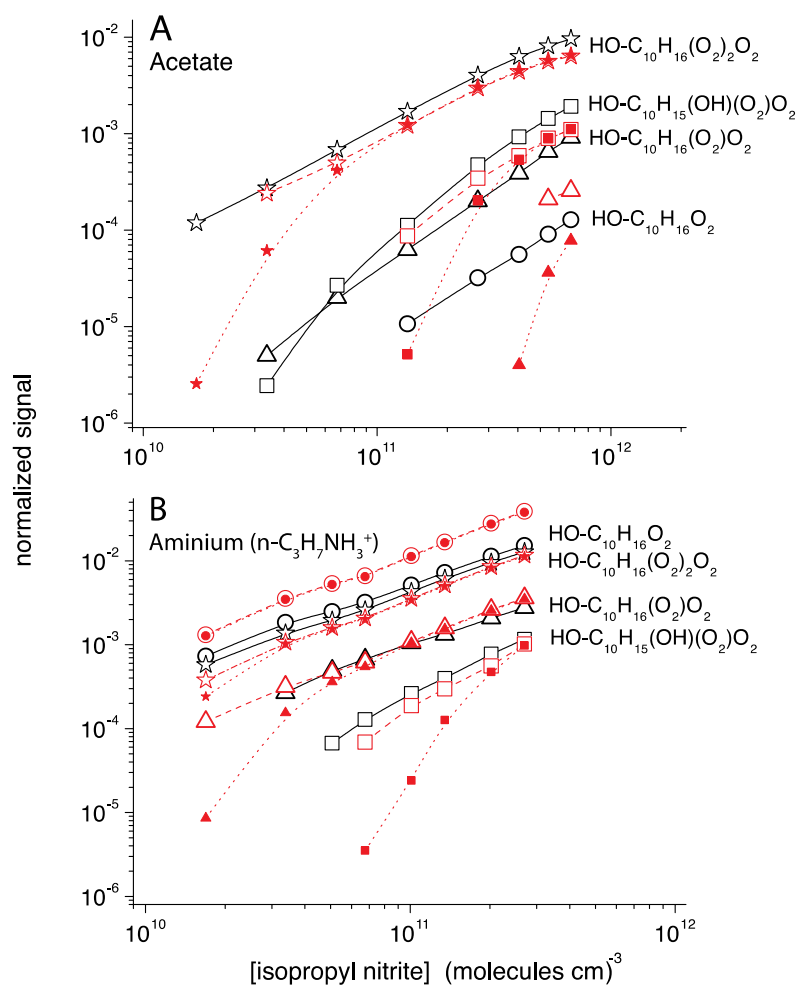


373 **Figure 1.** (A) Linearity of the Orbitrap as a function of normalized signal measured with protonated n-
 374 propylamine ($n\text{-C}_3\text{H}_7\text{NH}_3^+$) and acetate (CH_3COO^-) reagent ions with the Orbitrap-Tropos and nitrate-
 375 ion based chemistry with the Orbitrap-IRCELYON, using identical parameter settings. All signal
 376 intensities were corrected with respect to the sum of $(\text{CH}_3\text{COOH})_n\text{-CH}_3\text{COO}^-$ ($n = 0,1$) at nominal 59
 377 Th and 119 Th; to the sum of $(n\text{-C}_3\text{H}_7\text{NH}_2)_m\text{-n-C}_3\text{H}_7\text{NH}_3^+$ ($m = 0,1$) at nominal 60 Th and 119 Th; and
 378 to the sum of $(\text{HNO}_3)_p\text{-NO}_3^-$ ($p = 0,1,2$) at nominal 62, 125, 188 Th, for the respective reagent ions.
 379 The black fit is the “sigmoidal correction function” based on a sigmoidal fitting algorithm. (B) Impact
 380 of the AGC target on the linearity of the CI-Orbitrap-Tropos using aminium ($n\text{-C}_3\text{H}_7\text{NH}_3^+$) as the
 381 reagent ion.
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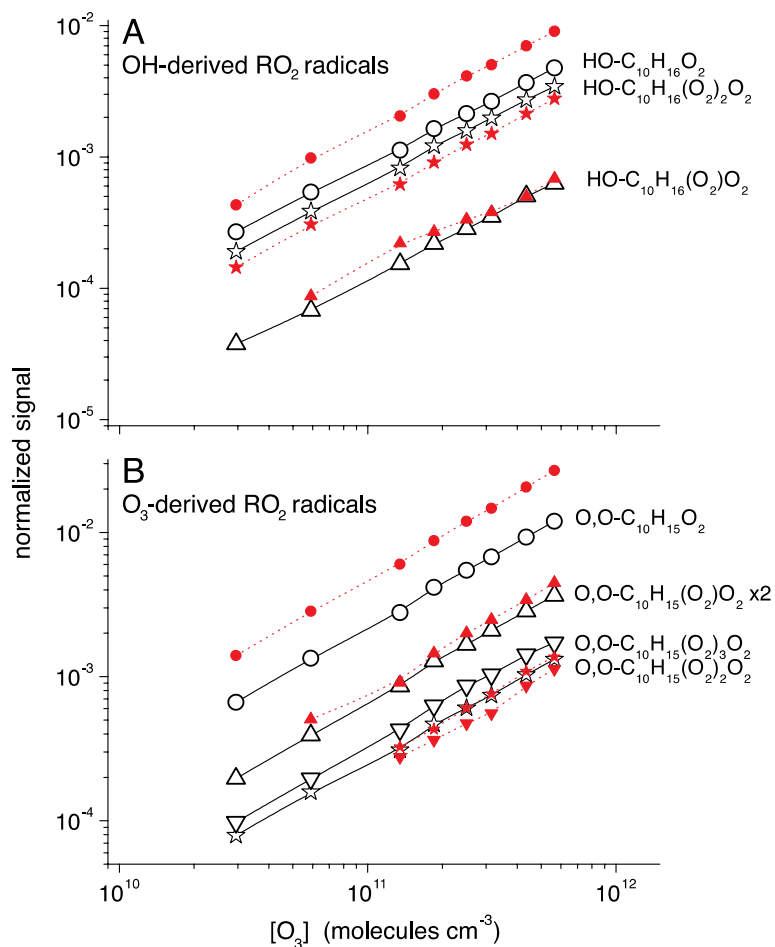


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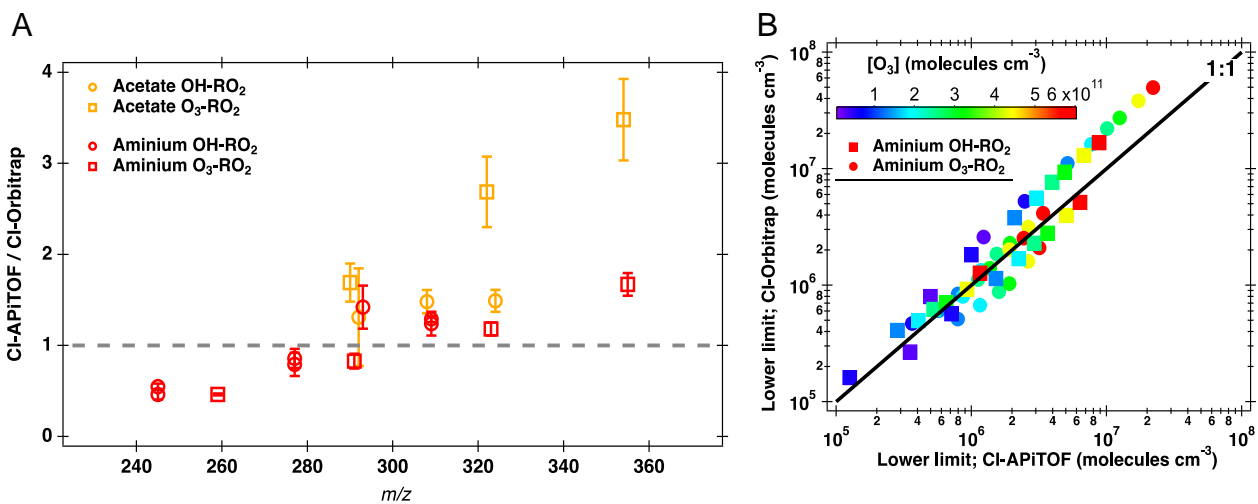
385 **Figure 2.** Mass spectra of ions at nominal m/z 245 from the combined ozonolysis and OH radical386 reaction of α -pinene for different reaction conditions (A) measured with the CI-Orbitrap and (B)387 comparison of the ion signals recorded by the CI-Orbitrap and the CI-APi-TOF. C₉¹³CH₁₆O₃388 represents most likely the ¹³C-isotope of pinonaldehyde and C₁₀H₁₇O₃ the initial RO₂ radical from the389 OH attack, HO-C₁₀H₁₆O₂. Concentrations are given in molecules cm⁻³.



390
 391 **Figure 3.** Normalized signals of RO₂ radicals produced from the OH radical-initiated oxidation of α -
 392 pinene as a function of initial IPN concentration measured by the CI-API-TOF (black) and the CI-
 393 Orbitrap (red). OH radicals have been formed via IPN photolysis. Full and open markers in red
 394 correspond to raw and corrected (using the sigmoidal correction function) signals measured with the
 395 Orbitrap, respectively. **(A)** Acetate and **(B)** aminium ($n\text{-C}_3\text{H}_7\text{NH}_3^+$) served as the reagent ion for
 396 otherwise identical reaction conditions in both cases.
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399
 400 **Figure 4.** Normalized signals of **A)** OH-derived RO₂ radicals and **B)** O₃-derived RO₂ radicals
 401 produced from the O₃/OH + α-pinene reaction as a function of the ozone concentration. Results
 402 obtained by the CI-API-TOF are given in black and those from the CI-Orbitrap in red using aminium
 403 (n-C₃H₇NH₃⁺) ionization in both cases. The Orbitrap data were corrected using the sigmoidal
 404 correction function.
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406
 407 **Figure 5.** (A) Comparison between lower limit RO₂ radical concentrations measured with the CI-
 408 APiTOF and the CI-Orbitrap in the different experiments. (B) Correlation of the concentrations of
 409 RO₂ radicals formed from the O₃/OH + α -pinene reaction measured by the CI-API-TOF and the CI-
 410 Orbitrap using aminium (n-C₃H₇NH₃⁺) ionization.

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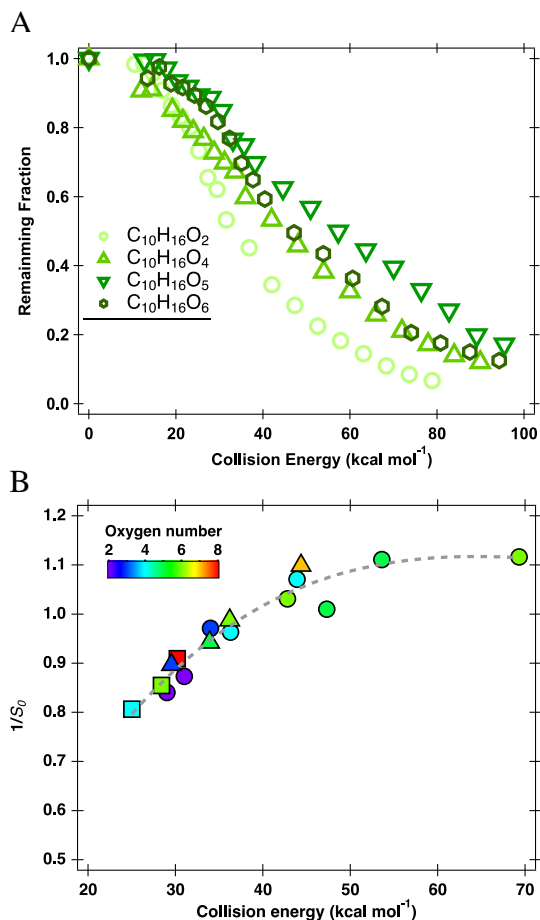


Figure 6. Declustering scans of (A) C₁₀H₁₆O₂₋₆ measured from the OH-initiated oxidation of α -pinene with the CI-Orbitrap using aminium (n-C₃H₇NH₃⁺). (B) Relationship between fitting declustering scans (1/S₀) as a function of collision energy. CE₅₀ is used as a measured of the relative binding energy and corresponds to the collision energy where half of the signal is removed. S₀ is the maximum amplitude obtained from the sigmoidal fit of declustering scans (e.g., Figure S7) of RO₂ radicals (triangle markers) and OVOCs (ON: square markers; non-ON: circle markers) formed from OH-initiated oxidation of α -pinene with the CI-Orbitrap using aminium (n-C₃H₇NH₃⁺).

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450

451 SUPPORTING INFORMATION

452 Figure S1 depicts the schematic of a Q Exactive mass spectrometer. Figure S2 shows the mass spectra
453 of ions at m/z 245 and 260 measured during the oxidation of α -pinene. Figures S3 and S4 present the
454 normalized signals of the organic nitrates and carbonyls produced from the OH-initiated oxidation of
455 α -pinene, respectively. Figure S4 shows the correlation of the concentration measured species using
456 both instruments and formed from the OH radical initiated oxidation of α -pinene using acetate-ion-
457 based (CH_3COO^-) ionization. Figure S6 presents the normalized signals of RO_2 generated from the
458 oxidation of α -pinene measured using aminium ($n\text{-C}_3\text{H}_7\text{NH}_3^+$). Figure S7 presents the declustering
459 experiments performed on OVOCs formed from α -pinene ozonolysis. Figure S8 shows the mass
460 Spectra of the different perfluorinated acids measured with CI-Orbitrap. Figure S9 presents the relative
461 ion transmission fit determined using the depletion method. The Supporting Information is available
462 free of charge on the ACS Publications website.

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