









Structures and reactivity of peroxy radicals and dimeric products revealed by online tandem mass spectrometry

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Organic peroxy radicals (RO₂) play a pivotal role in the degradation of hydrocarbons. The autoxidation of atmospheric RO₂ radicals produces highly oxygenated organic molecules (HOMs), including low-volatility ROOR dimers formed by bimolecular RO₂ + RO₂ reactions. HOMs can initiate and greatly contribute to the formation and growth of atmospheric particles. As a result, HOMs have far-reaching health and climate implications. Nevertheless, the structures and formation mechanism of RO₂ radicals and HOMs remain elusive. Here, we present the in-situ characterization of RO₂ and dimer structure in the gas-phase, using online tandem mass spectrometry analyses. In this study, we constrain the structures and formation pathway of several HOM-RO₂ radicals and dimers produced from monoterpene ozonolysis, a prominent atmospheric oxidation process. In addition to providing insights into atmospheric HOM chemistry, this study debuts online tandem MS analyses as a unique approach for the chemical characterization of reactive compounds, e.g., organic radicals.

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Atmospheric aerosols adversely affect human health¹ and have important climate effects. They impact Earth's radiative balance by directly interacting with light, or indirectly by acting as cloud condensation nuclei (CCN)^{2,3}. Their effects on cloud formation and physical properties remain one of the most important uncertainties in climate models^{3,4}. Up to 50% of global CCN formation could be attributed to new particle formation (NPF)^{5–7}. Rapidly and widely formed, highly oxygenated organic molecules (HOMs)^{8–11} have been identified to be critical for NPF and growth, and therefore for CCN formation^{12–15}.

HOM formation proceeds via autoxidation of the peroxy radical (RO₂), which undergoes intramolecular hydrogen abstraction (H-shift), yielding an alkyl radical (R) with a hydroperoxyl functional group (–OOH). Addition of O₂ to R produces a new RO₂ radical, which may undergo termination reactions or further autoxidation reactions^{8,16,17}. Autoxidation can therefore yield a plethora of multifunctional products with low or extremely low saturation vapor pressures within seconds^{10,18,19}. Studies have also reported rapid gas-phase formation of dimeric accretion products (i.e., organic peroxides, ROOR) produced from RO₂ + RO₂ reactions^{8,16,20,21}, which can initiate and contribute to NPF²² and particle growth^{20,23}. However, little is known about the molecular structures of the gas-phase HOMs, including RO₂ and ROOR, making their formation pathways uncertain. HOMs' contribution to NPF is directly dependent on their volatility, which can vary by orders of magnitude for isomeric compounds with different structures and functional groups^{24,25}.

While quantum chemical calculations and online high-resolution mass spectrometry (MS) analyses using isotopic labeling and deuterium-hydrogen exchange have provided valuable information on HOMs, direct assessment of their molecular structures remains elusive^{26–29}. Existing online tandem MS (MS/MS) studies on low-volatility compounds are restricted to the aerosol phase^{30–32}. Offline analysis requires sample collection and extensive sample preparation³³, which can be prone to artifacts from chemical degradation and contamination³⁴. Nevertheless, MS/MS measurements in the particle phase^{30,35–37} have provided precious insights into the structure of stable compounds but also unstable gas-phase precursors, for example the identification of stable ester dimers produced from α -pinene ozonolysis^{36,38}. α -Pinene is one of the most abundant biogenic volatile organic compounds in the atmosphere, with global emission reaching up to 66.1 Tg yr^{–1}, and one of the key precursors for organic aerosol³⁹. Similarly, the ozonolysis of limonene (structural isomer of α -pinene) is also expected to play a major role in NPF, despite the lower emission rate (11.4 Tg yr^{–1}), due to its greater reactivity toward ozone and a higher HOM yield than α -pinene¹⁰. In addition, limonene is found in cleaning and personal care products, and might be a significant source for indoor secondary organic aerosols (SOAs)^{40–43}. Limonene has a single cyclic structure as opposed to the bicyclic structure of α -pinene, making it a model compound for the elucidation of monoterpene oxidation mechanisms due to the comparatively simple product structures.

In this study, we report the in-situ structural characterization of gas-phase HOMs, RO₂ radicals, and dimeric products of α -pinene and limonene ozonolysis based on online MS/MS using an ultrahigh-resolution Orbitrap mass spectrometer equipped with a NO₃[–] chemical ionization (CI) source^{44,45}. Using online MS/MS data, aided by known structure-specific fragmentation patterns from existing offline MS/MS literature, we are able to infer the most plausible isomers of different compounds. We propose the most plausible oxidation product structures, autoxidation mechanisms, and dimer formation pathways based on the

observed MS/MS product ions and neutral losses for the two monoterpene precursors.

Results

Online MS/MS. Representative mass spectra of limonene and α -pinene ozonolysis products are shown in Supplementary Fig. 1. Online MS/MS was performed on NO₃[–] adducts of C₁₀H_{14–16}O_{6–10} monomers, C₁₀H₁₅O_{6,8,10} RO₂ radicals, and C_{18–20}H_{28–34}O_{6–16} dimers at different collision energies (normalized collision energy (NCE) from 2 to 10). Overall, as shown for C₁₀H₁₄O₇NO₃[–] and C₂₀H₃₀O₁₄NO₃[–] in Supplementary Figs. 2 and 3, respectively, MS/MS spectrum exhibits a higher signal intensity corresponding to the precursor ion at lower collision energies, while product ions and NO₃[–] (declustered CI reagent ion) dominate at higher collision energies. In general, dimers appear to bind more strongly to NO₃[–] than do monomers (Supplementary Figs. 2c and 3c)⁴⁴. In Fig. 1, we present an overview of most important neutral losses and product ions observed for HOMs. We infer the neutral loss pattern from the precursor and product ion formula (Fig. 1b). For closed-shell molecules, we observe a common fragmentation pattern involving HNO₃ loss, which is rare or insignificant for RO₂ radicals (Fig. 1a). We report the fragmentation patterns of RO₂ radicals (e.g., C₁₀H₁₅O_{8,10}), all of which undergo O₂ loss, corresponding to the loss of the peroxy functional group, as shown in Fig. 1a. NO₃[–] product ion is observed in all MS/MS spectra. While RO₂ radicals and closed-shell molecules share some common MS/MS fragments, predominately C_{3–6} ions (Fig. 1a), they exhibit distinct neutral loss patterns and share little spectral similarity (Supplementary Fig. 4b). In general, compounds produced from the same (VOC + O₃) reactions share spectral similarity with each other (Fig. 1b), which is also reflected in the unsupervised agglomerative hierarchical clustering results (Supplementary Fig. 4a). As discussed below, the neutral loss patterns such as OH, HO₂, CH₃O₂, and C₃H₆O observed for RO₂ radicals (Fig. 1a) are indicative of specific functional groups.

Autoxidation mechanism. An overview of limonene ozonolysis mechanism can be found in Fig. 2 and Supplementary Fig. 5. Briefly, limonene ozonolysis predominantly occurs by ozone addition onto the endocyclic double bond, forming an unstable primary ozonide, followed by the formation of two distinct Criegee intermediates^{46–49}. The major Criegee intermediate can evolve into RO₂ radicals, C₁₀H₁₅O₄, by two main channels: A and B (Supplementary Fig. 5), which can undergo further autoxidation via intramolecular H-shifts followed by O₂ addition, forming more oxidized RO₂ radicals (i.e., C₁₀H₁₅O_{6,8,10})^{17,47,48}. Earlier studies have showed that aldehydic H-shift is rapid enough (i.e., 10^{–2} to 10 s^{–1}) to be competitive against bimolecular reactions^{50–53}. Thus, for limonene, the aldehydic H-shift is anticipated to be a major formation pathway for C₁₀H₁₅O₆ via a 1,9- or a 1,7 H-shift for A and B routes, respectively (Supplementary Fig. 5). We note that while the formation of A/B 4 via endocyclization is also expected to be fast^{21,54}, the corresponding fragmentation patterns were not observed in our MS/MS spectra. Figure 2 and Supplementary Fig. 5 labels possible C₁₀H₁₅O₈ radicals from both routes as A1–A7 and B1–B7, respectively. It is possible that some RO₂ isomers may exist to varying extents. Nonetheless, offline ultra-performance liquid chromatography–electrospray ionization–tandem mass spectrometry (UPLC–ESI–MS/MS) analyses show that a limited number of isomers dominate the RO₂ termination products (Supplementary Fig. 6), consistent with previous studies using ion mobility MS⁵⁵. These prior studies suggest that a limited number of isomers are formed from the oxidation of monoterpenes. With this in mind, we demonstrate how MS/MS analyses can be utilized to constrain the most probable isomers and the corresponding H-shift pathways

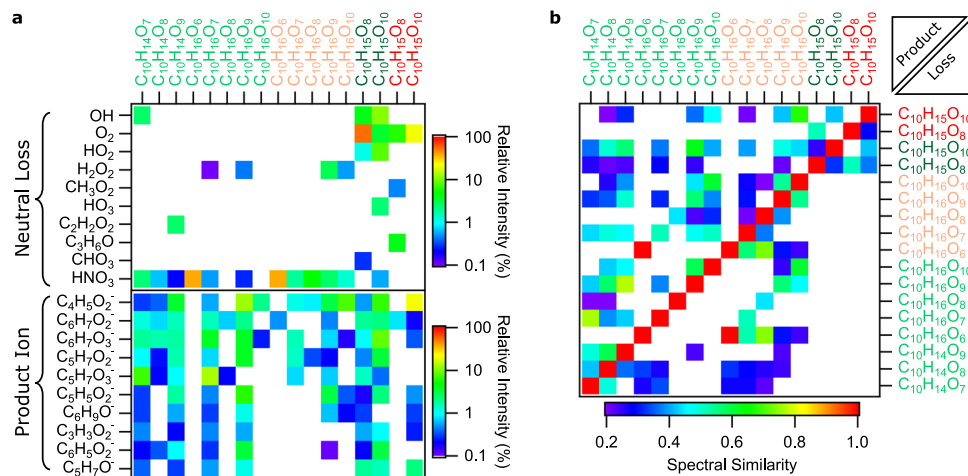


Fig. 1 Common MS/MS product ions and neutral losses observed. **a** Selected neutral loss patterns deduced from the formulae of the parent and product ions, and the ten most common product ions observed. **b** Pair-wise spectral similarities in MS/MS spectra. Corresponding MS/MS data were obtained at NCE 2 for NO₃⁻ adducts of limonene and α -pinene ozonolysis products. Parent molecular formulae are shown on the upper x-axis with labels for closed-shell limonene and α -pinene ozonolysis products in light green and light red, respectively. Labels for limonene and α -pinene RO₂ radical are in dark green and dark red, respectively. Inferred neutral losses and observed product ions with relative intensity $\geq 0.1\%$ are shown in log color in **a**. The upper triangle and lower triangle areas in **b** represent the cosine similarity between the observed product ions or neutral losses, respectively, among the MS/MS spectra. For clarity, only pairs with cosine similarity ≥ 0.2 are shown in linear color scale. Parent molecular formulae are also shown on the right y-axis in **b**.

given the observed product ions, neutral losses, and known fragmentation mechanisms.

Figure 3a shows that the radical C₁₀H₁₅O₈NO₃⁻ (m/z 325.0644) first undergoes O₂ elimination during fragmentation, forming the alkyl radical-anion C₁₀H₁₅O₆NO₃⁻ (m/z 293.0748), followed by the simultaneous loss of HNO₃ and OH, yielding C₁₀H₁₃O₅⁻ (m/z 213.0766) (Fig. 3c). This can only occur if the carbon adjacent to the alkyl radical is not quaternary, therefore excluding structures A/B 4, 5, 6 and B7. The H₂O elimination from the resulting C₁₀H₁₃O₅⁻ to form C₁₀H₁₁O₄⁻ (m/z 195.0667) likely occurs on the hydroperoxide functional group (Fig. 3c), a known negative ion fragmentation pathway⁵⁶. The C₉H₁₁O₂⁻ (m/z 151.0764) product ion results from C₁₀H₁₁O₄⁻ via a charge migration elimination of CO₂, which is indicative of a carboxylic functional group, related to a peroxy acid moiety formed from the aldehydic H-shift. Finally, the formation of C₁₀H₁₄O₇NO₃⁻ (m/z 308.0616) from C₁₀H₁₅O₈NO₃⁻ through an intramolecular H-abstraction from the peroxy radical moiety, followed by OH elimination and ketone formation, is not possible for tertiary alkylperoxy radicals such as A/B 3. Based on the MS/MS analysis, A/B 1 and 2 and A7 from 1,4, 1,6, or 1,7 H-shift emerge as the most plausible structures for C₁₀H₁₅O₈, under the assumption that the A/B O₆ peroxy radical structures were the precursors of the O₈ radicals. Additionally, if we consider rapid H-shift scrambling (scrb)⁵⁷, B1-3 and 7-scrb structures (with B7-scrb corresponding to A7) may also be plausible structures for C₁₀H₁₅O₈, as these structures can accommodate the observed MS/MS fragmentation pathways.

Assuming A/B 1,2 and A7 as the main structures of C₁₀H₁₅O₈, several C₁₀H₁₅O₁₀ structures are possible (Fig. 1 and Supplementary Figs. 7 and 8). In the MS/MS spectrum of C₁₀H₁₅O₁₀NO₃⁻ (m/z 357.0543, Fig. 3b), the product ion C₁₀H₁₄O₉NO₃⁻ (m/z 340.0515) is likely formed via OH elimination similar to that depicted in Fig. 3d, which is not possible for tertiary alkyl peroxy radicals, thereby eliminating several potential candidates (A1–6, A2–5, A7–1, A7–5, B1–6, and B2–6). The formation of C₁₀H₁₄O₈NO₃⁻ (m/z 324.0565) from C₁₀H₁₅O₁₀NO₃⁻ via HO₂ elimination occurs if the carbon next to the RO₂ radical is not quaternary, limiting the potential precursor structures to A/B 1–1, A/B 1–2, A/B 2–1, and A 7–2. Following O₂ elimination from C₁₀H₁₅O₁₀NO₃⁻, the subsequent

CHO₃ elimination from C₁₀H₁₅O₈NO₃⁻ to form C₉H₁₄O₅NO₃⁻ (m/z 264.0725) can follow a radical recombination mechanism described in Fig. 3d. Such recombination is possible if the radical is near a peroxy functional group, excluding the A/B 1–2 structures. Therefore, A/B 1–1, 2–1, and A 7–2 are likely the only candidates for C₁₀H₁₅O₁₀, corresponding to 1,5 and 1,6 H-shift from saturated carbon atoms, for which all observed loss processes are feasible. Lastly, we note that if H-scrambling between an RO₂ site and hydroperoxide functional groups occurs in C₁₀H₁₅O₈ and C₁₀H₁₅O₁₀ radicals, up to 14 additional potential structures may also explain the observed O₁₀ MS/MS fragmentation pattern.

As previously described and discussed in the Supplementary Information (Supplementary Figs. 9–11), the MS/MS spectrum of C₁₀H₁₅O₈ from α -pinene ozonolysis (Supplementary Fig. 10a) exhibits similar fragmentations (i.e., O₂ and CO₂ eliminations corresponding to the RO₂ radical moiety and the peroxy acid functional group, respectively) but also some notable differences compared to products from limonene oxidation. Previous works investigated the fragmentation of compounds bearing a peroxy acid functional group and described a common fragmentation loss via CH₂O₂ elimination through a two-step fragmentation process (H₂O + CO)^{58,59}, which is not observed for either α -pinene or limonene. In addition, the MS/MS spectrum of α -pinene C₁₀H₁₅O₈⁻ RO₂ radical displays two distinct fragmentation losses, CH₃O₂ and C₃H₆O, which are indicative of the methyl group specific to α -pinene RO₂, i.e., quaternary carbon bonded to two methyl groups (Supplementary Fig. 9, highlighted in blue), which is not present in the case of limonene RO₂.

Gas-phase dimer formation mechanism. The reaction rate coefficient between RO₂ radicals can range from 10⁻¹⁷ to 10⁻¹¹ cm³ molecule⁻¹ s⁻¹⁶⁰, with recent studies reporting values on the order of 10⁻¹⁰ cm³ molecule⁻¹ s⁻¹ for selected HOM-RO₂^{21,61}. While kinetic studies show that the RO₂ + RO₂ \rightarrow ROOR + O₂ reaction rate coefficients generally increase with the RO₂ oxygen content⁶², further enhanced by intramolecular hydrogen bonds that may help with transition state stabilization²⁸, the contribution of different RO₂ radicals to dimer formation remains

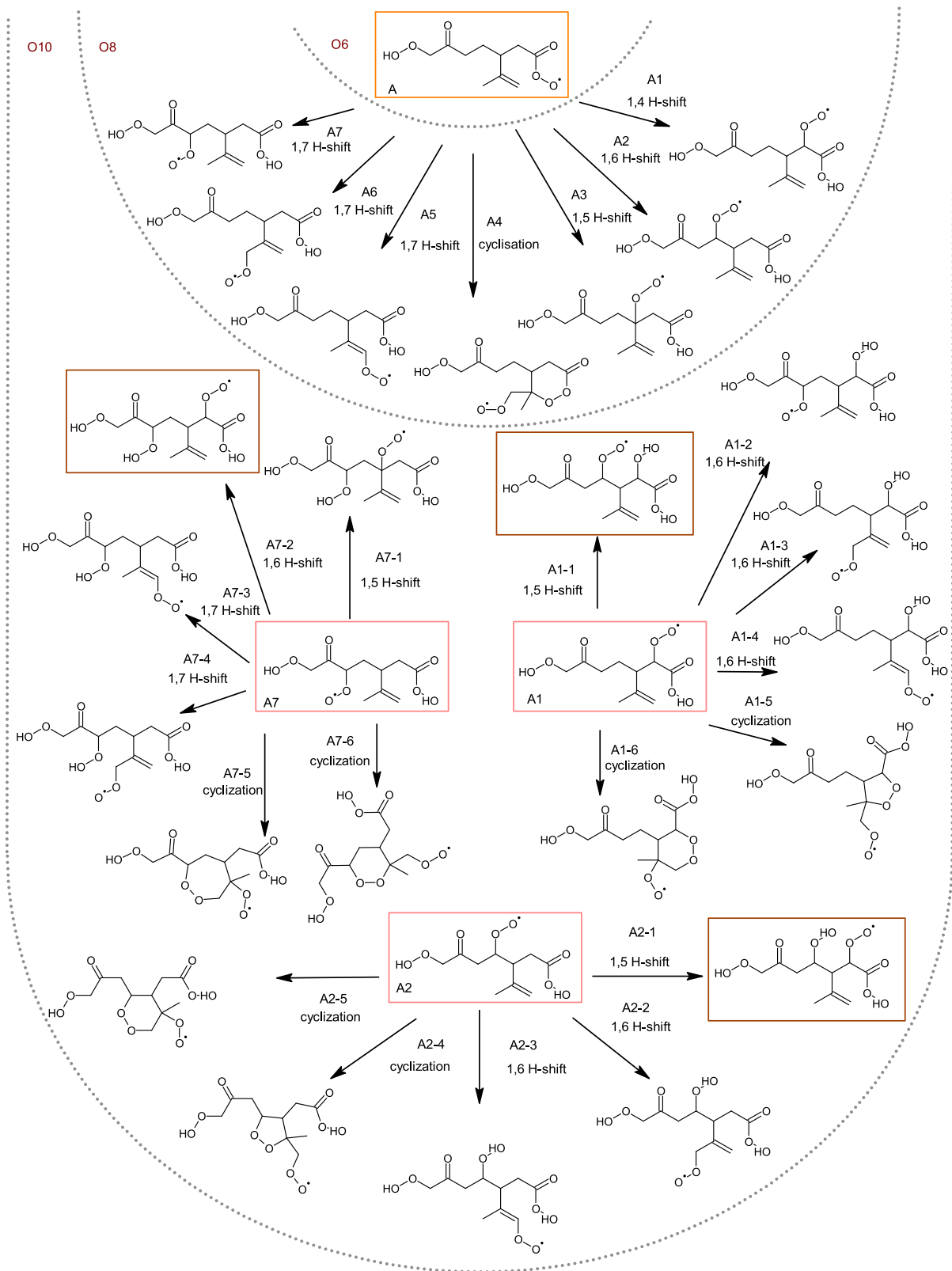


Fig. 2 Proposed limonene autooxidation pathways and products. Potential structures and proposed formation mechanisms of the O₆, O₈, and O₁₀ RO₂ radicals from the A route of the ozonolysis of limonene. Most plausible identified structures are boxed in orange, pink, or brown for O₆, O₈, and O₁₀ RO₂ radicals, respectively.

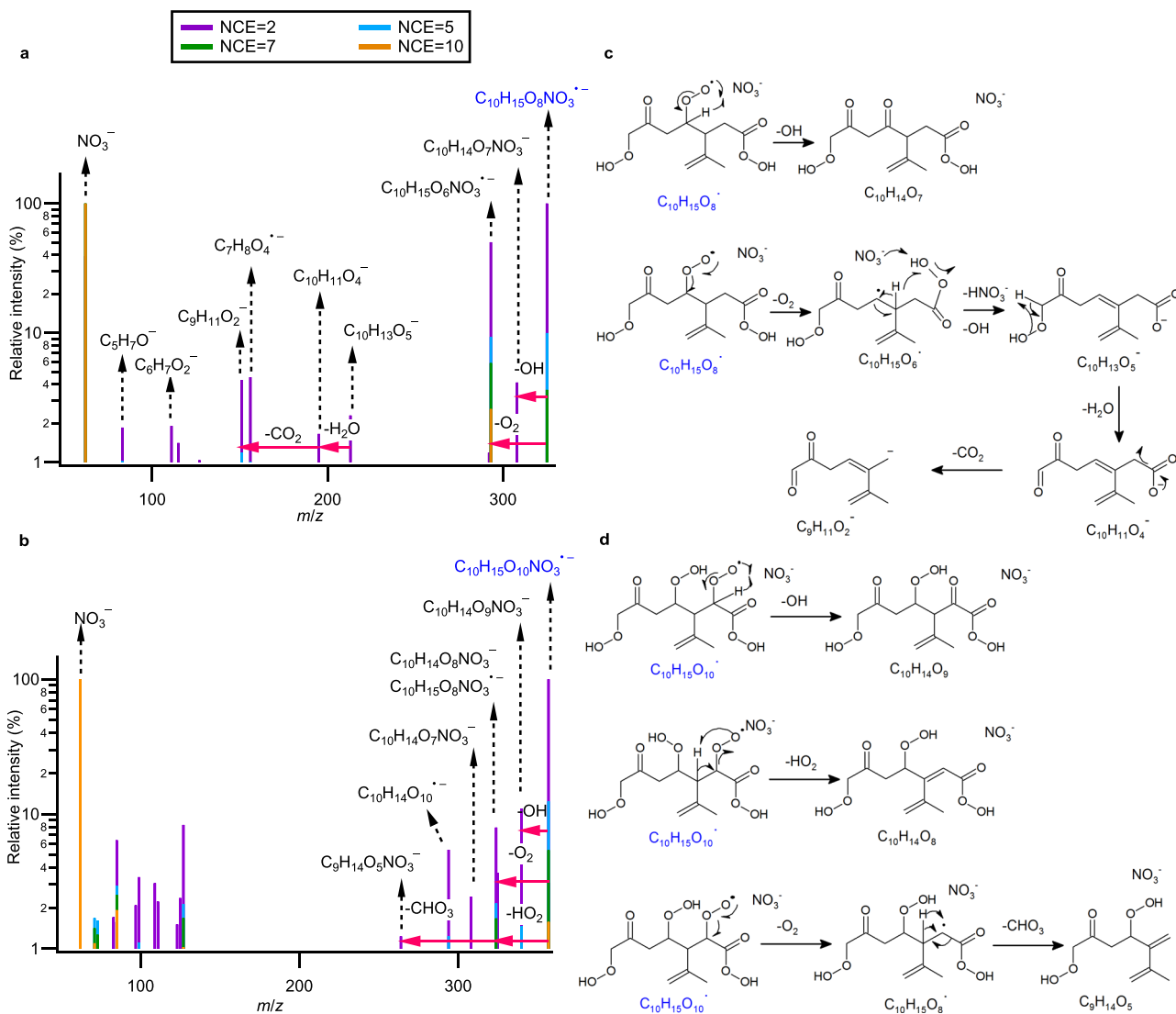


Fig. 3 MS/MS spectra of two limonene ozonolysis RO₂ radicals at various NCE (2–10). **a** MS/MS spectra of C₁₀H₁₅O₈NO₃•⁻. **b** MS/MS spectra of C₁₀H₁₅O₁₀NO₃•⁻. **c** MS/MS fragmentation routes to product ions, C₁₀H₁₄O₇NO₃⁻ and C₉H₁₁O₂⁻ from the A2 structure of C₁₀H₁₅O₈NO₃•⁻ as depicted in Fig. 2. **d** MS/MS fragmentation route to product ions, C₁₀H₁₄O₉NO₃⁻, C₁₀H₁₄O₈NO₃⁻, and C₉H₁₄O₅NO₃⁻, from the structure B2-1 of C₁₀H₁₅O₁₀NO₃•⁻ as depicted in Supplementary Fig. 7. The parent radical anions are highlighted in blue.

unknown. Online MS/MS analysis provides insights into the dimer structure and formation, as shown for C₂₀H₃₀O₁₂NO₃⁻ (*m/z* 524.1608) and C₂₀H₃₀O₁₄NO₃⁻ (*m/z* 556.1520) in Fig. 4 for limonene ozonolysis and in Supplementary Fig. 12 for α -pinene ozonolysis. C₂₀H₃₀O₁₂ can be formed from reactions of O₄ with O₁₀ or O₆ with O₈ peroxy radicals; C₂₀H₃₀O₁₄ can be formed from reactions of O₈ with O₈, or O₆ with O₁₀ peroxy radicals. As shown in Fig. 4a and b, both limonene ozonolysis dimers produce the C₁₀H₁₄O₇NO₃⁻ (*m/z* 308.0617) product ion, which is likely formed from the cleavage of the peroxide (i.e., RO–OR bond) into an alkoxy radical (RO) combined with H-exchange, as illustrated in Fig. 4c. The presence of C₁₀H₁₄O₇NO₃⁻ suggests that C₁₀H₁₅O₈ may be the main precursor for C₂₀H₃₀O₁₂ and C₂₀H₃₀O₁₄. This is also supported by the absence of O₉ fragments and the presence of C₁₀H₁₃O₇⁻ (*m/z* 245.0663). This is further reinforced by hierarchical clustering analyses (Supplementary Fig. 13), which consistently group C₁₀H₁₆O₈ (termination product of C₁₀H₁₅O₈), C₂₀H₃₀O₁₂, and C₂₀H₃₀O₁₄ together based on their MS/MS spectral similarity. The hierarchical clustering analysis also reveals that the MS/MS spectrum of C₁₀H₁₆O₇NO₃⁻ is

distinct from that of C₂₀H₃₀O₁₂NO₃⁻ and C₂₀H₃₀O₁₄NO₃⁻ (Supplementary Fig. 13). Similarly, the importance of the O₆-radical (i.e., C₁₀H₁₅O₆) in the formation of the C₂₀H₃₀O₁₂ is supported by the detection of C₁₀H₁₅O₅⁻ (*m/z* 215.0921). While C₂₀H₃₀O₁₄NO₃⁻ produces a C₁₀H₁₆O₇NO₃⁻ (*m/z* 310.0773) product ion (Fig. 4b), C₂₀H₃₀O₁₂NO₃⁻ does not (Fig. 4a). This difference indicates that C₁₀H₁₅O₆ is an acylperoxy radical, which is consistent with the structure proposed in Fig. 4d. As a result, only one RO–OR cleavage pathway for C₂₀H₃₀O₁₂NO₃⁻ is possible with the H-exchange only taking place in one side of the peroxide, in contrast to C₂₀H₃₀O₁₄NO₃⁻ (Fig. 4c). This result also supports the structures A/B proposed in Fig. 2 and Supplementary Fig. 5.

The fragmentation patterns of α -pinene dimers are distinct from those of limonene, suggesting a considerable difference in the reactivity of their RO₂ radicals (as discussed below). For example, the reaction between C₁₀H₁₅O₁₀ and C₁₀H₁₅O₄ RO₂ radicals clearly contributes to the formation of C₂₀H₃₀O₁₂ dimer from α -pinene ozonolysis, according to the presence of C₁₀H₁₆O₉NO₃⁻ (*m/z* 342.0676) and C₁₀H₁₅O₉⁻ (*m/z* 279.0722)

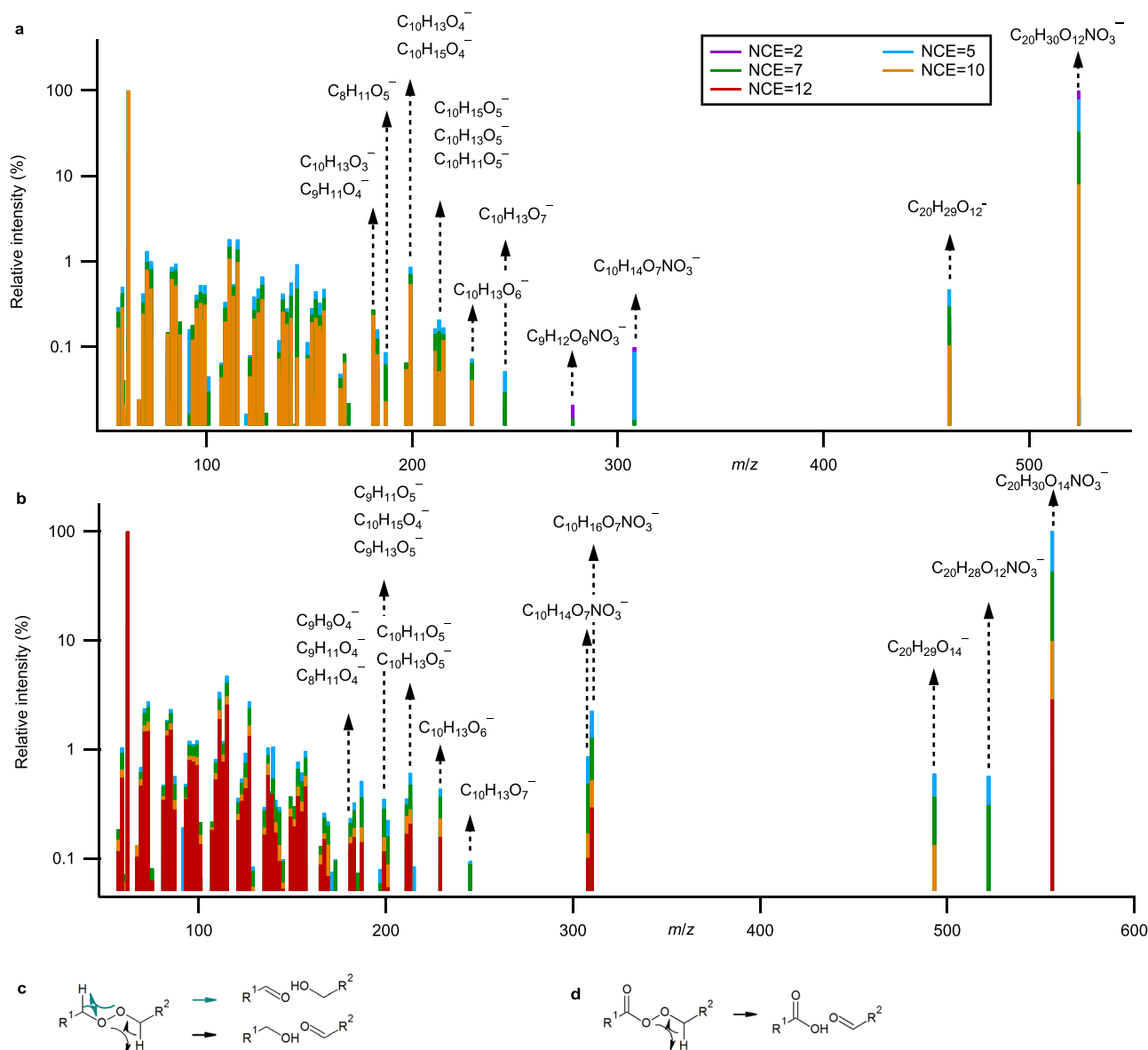


Fig. 4 MS/MS spectra of two limonene ozonolysis dimers at various NCE (2–10). **a** MS/MS spectra of $C_{20}H_{30}O_{12}NO_3^-$. **b** MS/MS spectra of $C_{20}H_{30}O_{14}NO_3^-$. **c** MS/MS fragmentation mechanism of RO–OR for dimers produced from the reaction involving two peroxy radical precursors, which can proceed via either of the black or green pathways. **d** MS/MS fragmentation mechanism of RO–OR for dimers produced from the reaction involving an acylperoxy radical and a peroxy radical, where only one pathway is available.

product ions in the MS/MS spectrum, as shown in Supplementary Fig. 12. The $C_{10}H_{15}O_6^-$ (m/z 231.0874) product ion observed in the MS/MS spectrum might suggest that RO_2 radicals other than O_4 and O_{10} may contribute to the formation of dimer, although this product ion may have also originated from further fragmentation of a larger product ion. Hence, reactions between $C_{10}H_{15}O_6$ and $C_{10}H_{15}O_8$ radicals may also contribute to the formation of $C_{20}H_{30}O_{12}$ dimers, though the corresponding RO–OR product ions, e.g., $C_{10}H_{16}O_5NO_3^-$ and $C_{10}H_{16}O_7NO_3^-$, were not observed under our experimental conditions. The greater importance of the O_4 α -pinene RO_2 radical compared to the O_4 limonene RO_2 radical is also reflected in the dimer concentration distributions (Supplementary Fig. 1d), with less oxygenated dimers being more abundant during α -pinene ozonolysis ($C_{20}H_{30}O_{10}$ and $C_{20}H_{30}O_{12}$) than during limonene ozonolysis ($C_{20}H_{30}O_{12}$ and $C_{20}H_{30}O_{14}$). Ozonolysis experiment with varying α -pinene concentration further indicates that the O_4 α -pinene RO_2 radical is a key participant in the formation of

$C_{20}H_{30}O_8$ (with $C_{10}H_{15}O_6$), $C_{20}H_{30}O_{10}$ (with $C_{10}H_{15}O_8$), and $C_{20}H_{30}O_{12}$ (with $C_{10}H_{15}O_{10}$) dimers (see Supplementary Figs. 15, 16 and Supplementary Information).

Discussion

We have shown that the structures A/B-1, A/B-2, and A-7 may be potential RO_2 radicals formed during limonene autoxidation. The formation of these structures requires 1,6-, 1,7-, and 1,4-H shifts, respectively. For A1 and B1, the required 1,4-H-shifts are typically thought to be slow, due to steric hindrance¹⁰, but theoretical calculations show that 1,4-H-aldehydic migration has significantly lower energy barriers than other H-shift pathways on unsubstituted aliphatic carbons⁶³. The presence of adjacent functional groups such as alkyl, carbonyls, hydroxyl, hydroperoxyl, and ether can further enhance H-abstraction^{10,64}. Unlike 1,4-H-shifts, 1,6 and 1,7 H-shifts are not expected to cause steric strains, though H-abstraction from a saturated carbon atom is

likely slow⁶³. Structures resulting from a saturated carbon H-shift were shown to be good candidates and could explain MS/MS fragmentation for both limonene and α -pinene peroxy radicals in our work, despite their structural differences. Our data also highlight the presence of peroxy acid functional groups for both limonene and α -pinene peroxy radicals, which has also been suggested for other VOCs^{16,65}. This is further supported by offline UHPLC–ESI–MS/MS analyses of C₁₀H₁₆O_{7–8} and C₁₀H₁₆O_{5–6} (termination products of the O₈ and O₆ peroxy radicals, respectively), largely detected in the negative ion mode (Supplementary Fig. 6), which is consistent with the presence of an acidic hydrogen from the peroxy acid functional group^{58,59}.

When applied to gaseous dimers, online MS/MS reveals unique RO–OR dimer fragmentation pathways that help identifying main RO₂ radical precursors, which is further supported by hierarchical clustering analyses. Our results show that HOM dimer formation during limonene ozonolysis is driven by the O₈ peroxy radical (Fig. 4 and Supplementary Figs. 14 and 16), whereas the O₄ peroxy radical appears to be a key component for dimer formation during α -pinene ozonolysis (Supplementary Figs. 12, 14, and 16). Consequently, dimers produced from α -pinene ozonolysis were on averaged less oxidized than those produced from limonene ozonolysis (Supplementary Fig. 1d) despite seemingly similar RO₂ radical distribution (O₈ > O₁₀ > O₆, Supplementary Fig. 1c), with potential implications of reduced NPF due to the higher vapor pressure of α -pinene dimers²². Furthermore, our results show that the RO₂ + RO₂ reaction rate coefficient is not only driven by the degree of oxidation⁶¹ (Supplementary Fig. 16) but also by the structure/reactivity of each RO₂ radicals. Overall, our findings advance the understanding of atmospheric radical chemistry, which can help constraining model representation of autoxidation pathways and dimer formation kinetics. The online approach employed here can be readily applied to, and is beneficial for, the investigation of short-lived or labile organic compounds in the gas phase present in low concentrations, demonstrably organic radicals that are otherwise inaccessible by offline techniques.

Methods

General information and procedures. Ozonolysis experiments were performed in a 18-liter Pyrex glass flow tube reactor (12 cm i.d. × 158 cm length) at room temperature⁶⁶. Continuous injection of volatile organic compound (VOC) precursors, (+)-limonene (Sigma-Aldrich, 97% purity) or (+)- α -pinene (Sigma-Aldrich, >99%), ozone, and flow reactor carrier gas was regulated using mass flow controllers (MFC, Bronkhorst). Dry synthetic air (80:20 N₂:O₂) was used as the carrier gas for the flow tube and VOC injection. Total flow rate is kept at 21 L min⁻¹ and the total reaction time is 59.1 s. Input VOC concentrations, ranging from 45 to 227 ppbv for limonene and 214 to 749 ppbv for α -pinene, are estimated based on MFC settings and VOC evaporator temperature (5 °C). Ozone was generated via dielectric barrier discharge and was monitored with a Thermo 49C analyzer, ranging from 20 to 40 ppbv. Negligible particle formation (<100 cm⁻³) was observed by a condensation particle counter (TSI CPC 3772) during all experiments. A Q Exactive Orbitrap mass spectrometer (Thermo Scientific, US) coupled to an atmospheric pressure CI inlet⁴⁴ was used for online analysis of ozonolysis products. The Orbitrap has been used with an automatic gain control (AGC) and maximum injection time set to 1 × 10⁵ and 3000 ms, respectively. The mass resolution is set to 140,000 at m/z 200. The CI reagent nitrate ion (NO₃⁻) was generated from a nitric acid solution (Sigma-Aldrich, 65% purity) continuously flushed with pure N₂ (10 mL min⁻¹) and ionized with a soft X-ray photoionizer (Hamamatsu, I9491). The CI inlet total flow and sheath flow rates were set at 36 L min⁻¹ and 34 L min⁻¹, respectively. Further details of instrument setting and experimental conditions can be found in the Supplementary information.

Online tandem MS. Higher energy collision dissociation (HCD) was used to obtain targeted MS/MS spectra using a quadrupole ion isolation window width of 0.4 Da. No in-source collision-induced dissociation (CID) energy was applied. The HCD cell is located after the quadrupole capable of mass isolation within ±0.4 Da. The selectivity of the NO₃⁻ detection scheme toward acidic and highly oxidized compounds ensures that a single parent ion is selected for structural characterization using MS/MS acquisitions for the RO₂ radicals and dimeric products discussed in the main text within the mass isolation window. In the case that more

than one parent ion is isolated, the dominant parent ion is at least an order of magnitude more abundant than the other parent ion(s) in most cases. An NCE of 2 was applied to RO₂ and closed-shell monomers. An NCE value of 5 was applied to dimers, as well as to select RO₂ and monomers for comparison. Systematic ramping of NCE from 2–10 was also performed for a few targeted compounds. The Orbitrap was mass-calibrated using an aqueous sodium acetate solution (2 mM, Aldrich, >99% purity). During online CI-measurements, the drift in mass accuracy was negligible (i.e., <2 p.p.m.) based on the reported m/z of the CI reagent ions (NO₃⁻ and HNO₃NO₃⁻) and m/z values from MS/MS parent ions, which is within the specifications of the Orbitrap. Peak identification and assignment were performed using XCalibur 4.1 (Thermo Scientific). Identification of parent ion formula was constrained based on known oxidation chemistry and elemental composition, i.e., ions are assumed to contain only carbon, hydrogen, and oxygen atoms with up to two nitrogen atoms to account for adduction with NO₃⁻ or HNO₃NO₃⁻. Identification of MS/MS product ion is constrained by the parent ion elemental composition. Product ion intensities were normalized to the maximum ion intensity unless stated otherwise. A 5 p.p.m. m/z tolerance and a 0.1% relative intensity threshold were applied to refine the product ion lists. Agglomerative hierarchical clustering of the processed MS/MS spectra was performed in Spyder 3.3.2 using complete linkage of cosine distance of square root-transformed product ion relative intensities as recommended in the literature⁶⁷, excluding NO₃⁻ product ions, whose relative contribution reflects more the dissociation energy of NO₃⁻ adducts than the analyte structure or functionalization. The precursor ion signal is the most intense in all MS/MS spectra acquired at NCE ≤ 5 after excluding the NO₃⁻ ion. Clustering analysis results based on observed product ions alone or together with inferred neutral losses are detailed in the Supplementary Information. Details of the offline analysis of monoterpene ozonolysis products using high-performance liquid chromatography with Orbitrap are found in the Supplementary Information.

Data availability

The data supporting the finding of this study are available in this article and Supplementary information. Data presented in the main text are accessible via <https://doi.org/10.5281/zenodo.4276954>. Raw mass spectrometric data are available from the corresponding author on reasonable request.

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Author contributions

M.Riva conceived the work. S.T., D.W., N.Z., I.E.-H., and M.Riva designed the experiments and analyzed the data. S.T., D.W., N.Z., D.L., and M.Riva performed the flow tube experiments. F.B. and A.V. performed the offline analysis. S.T., D.W., I.E.-H., and M.Riva wrote the manuscript. N.Z., D.L., H.L., F.B., A.V., M.E.M., S.P., U.B., C.G., M.R., and M.E. commented on the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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