Supporting Information for "New Insights into the Radical Chemistry and Product Distribution in the OH-initiated Oxidation of Benzene"

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S1: Experimental Conditions

Benzene (99.8% Sigma-Aldrich), CH_3ONO (synthesized following Taylor et al.[1]), and NO (1993±20 ppmv, Matheson) are injected into the chamber in a similar fashion. Briefly, the standard is firstly introduced to an evacuated gas-tight 500 cm^3 glass bulb, and then undergoes serial dilution with N_2 to achieve the desired mixing ratio. The analyte in the glass blub is quantified by FTIR spectroscopy using tabulated cross section and then injected into the chamber. 8 UV lights (Sylvania F40/350BL) are used. The measured j_{CH_3ONO} and inferred j_{NO_2} are 1.1×10^{-3} s^{-1} and 4.4×10^{-3} s^{-1}, respectively. The experimental conditions are summarized in Table S1.

Table S1: Experimental conditions.

Expt No.	initial concentration (ppb)				Ox Time (min)	$[OH]^b$ ($\times10^8$)	Δ[Benzene] (ppb)	note
	Benzene	OH source[a]	NO	NO_2				
1	785	2000	0	0	2400	0.033	55	
2	1473	501	4673	300	52	0.11	53	
3	1525	542	1225	60	12	0.62	61	
4	1456	557	593	19	12.5	1.14	100	
5	1446	527	289	10	6.5	1.54	100	
6	1509	525	168	5	5	1.61	108	
7	1428	537	35	1	5.5	1.72	121	
8	1487	509	0	0	7	1.79	128	c
9	1422	568	0	0	7	1.71	112	d
10	1463	576	2100	127	30	0.21	67	d
11	1429	490	0	0	40	0.21	98	d,e
12	1408	492	729	17	12	0.65	80	d
13	1580	517	727	28	12	0.73	92	d

[a] H_2O_2 is used as OH source for Expt 1 and CH_3ONO is used as OH source for all other experiments.

[b] unit: molecule cm^{-3}. Determined from the measured decay rate of benzene.

[c] Continuous injection of isotopically labeled benzene (benzene-d_6, 99%, Sigma Aldrich) with constant concentration into the CIMS, to better quantify the reaction amount of benzene in the reaction chamber. However, benzene-d_6 is an isobaric compound of $C_4H_4O_2$ and interferes the quantification of $C_4H_4O_2$.

[d] GC column condition changed so that the chromatograms can only be compared between experiments 9-13, not with experiments 1-8.

[e] Only one light bulb is used.

S2: CIMS operation and sensitivity

The CIMS is operated in two alternating modes: negative mode with CF_3O^- as reagent ion and positive mode with $NO{\cdot}H_2O^+$. The negative mode with CF_3O^- has been well documented in the literature[2,3]. In brief, 1 ppmv CF_3OOCF_3 (in N_2) flows through a radioactive ^{210}Po source and CF_3O^- is generated via the following reactions:

$$^{210}\mathrm{Po} \rightarrow \alpha + {}^{206}\mathrm{Pb} \tag{1}$$

$$\alpha + \mathrm{N_2} \rightarrow \mathrm{N_2}^+ + \mathrm{e}^- + \alpha \tag{2}$$

$$\mathrm{e}^- + \mathrm{CF_3OOCF_3} \rightarrow \mathrm{CF_3O}^- + \mathrm{CF_3O}\cdot \tag{3}$$

CF_3O^- selectively interacts with multifunctional oxygenated products to generally produce either cluster ion (reaction 4) or fluoride transfer ion (reaction 5):

$$\mathrm{M} + \mathrm{CF_3O} \rightleftharpoons \mathrm{M} \cdot \mathrm{CF_3O}^- \tag{4}$$

$$\mathrm{M} + \mathrm{CF_3O} \rightarrow \mathrm{M\text{-}H}^- \cdot \mathrm{HF} + \mathrm{CF_2O} \tag{5}$$

For the negative mode, the instrument is calibrated for phenol, glycoaldehyde, and H_2O_2, all of which are commercially available. When the authentic standards are not commercially available, we estimate the instrumental sensitivity based on the ion-molecule collision rate coefficients[4,5]. In brief, the conformer-weighted dipole moment and the lowest-energy conformer polarizability of the compound of interest are calculated at the B3LYP/cc-pVTZ level of theory. Next, the dipole moment and polarizability are used to calculate the ion-molecular collision rate coefficients based on an empirical approach[6]. Finally, the ion-molecular collision rate coefficient is related to instrumental sensitivity by using glycoaldehyde as reference compound, the sensitivity of which is experimentally determined. The instrumental sensitivities of major oxidation products are summarized in Table S2.

In the positive mode, $NO{\cdot}H_2O^+$ is produced by flowing 1993±20 ppmv NO (in N_2, Matheson) through the same ^{210}Po source as used in negative mode. The $N_2{}^+$ generated by reaction 2 reacts with NO to form NO^+. Under the trace amount of H_2O in the instrument, the NO^+ is present as $NO \cdot H_2O^+$ and $NO \cdot (H_2O)_2^+$. In contrast to CF_3O^-, $NO \cdot H_2O^+$ is sensitive to less oxygenated compounds, including aromatics, alkanes, and carbonyl species[7–10].

$$N_2{}^+ + NO \rightarrow NO^+ + N_2 \tag{6}$$

$$NO^+ + H_2O \rightleftharpoons NO \cdot H_2O^+ \tag{7}$$

$$M + NO \cdot H_2O^+ \rightleftharpoons M \cdot NO^+ + H_2O \tag{8}$$

The instrumental sensitivity in the positive mode is calibrated for benzene (commercially available), CH_3ONO (synthesized following Taylor et al.[1]), and glyoxal (prepared by following the procedure in Kroll et al.[11]). The sensitivities vary between compounds, but are on the order of 1×10^{-3} ncts/ppbv (normalized by the sum of the signal of $NO \cdot H_2O^+$ and $NO \cdot (H_2O)_2^+$) under dry condition (roughly 10 ppmv water vapor in the flow tube). The instrumental sensitivities for other compounds detected in the positive mode are assumed to be the average of that of benzene and glyoxal. For the compounds calibrated here, cluster with NO^+ via reaction 8 is the dominant product ion. This observation is consistent with Guimbaud et al.[12] who measured $C_2H_2O_2{\cdot}NO^+$ as the only product ion for the reaction of glyoxal with NO^+, but inconsistent with Španél et al.[10] who showed that $C_6H_6{\cdot}NO^+$ only accounts for 15% of the benzene + NO^+ products. However, caution is required when applying knowledge on NO^+ ion chemistry to $NO{\cdot}H_2O^+$, because the H_2O molecule can influence the ionization chemistry by carrying away excess energy and minimizing fragmentation. In addition, the instrument configuration and tuning also influence the ion-molecule reaction.

The uncertainty in the instrumental sensitivity is the most important factor hindering the quantification of product yields. For the compounds without authentic standards, their sensitivities are estimated based on ion-molecule collision rate coefficients in the negative mode and based on the average sensitivity of glyoxal and benzene in the positive mode. We evaluate the uncertainty of the estimated sensitivity by comparing the yields of compounds that are detected in both the positive ($NO{\cdot}H_2O^+$) and negative modes (CF_3O^-). Compounds with chemical formula C_6H_6O, $C_6H_6O_2$, $C_6H_6O_3$, $C_4H_4O_3$, which are of interest to this study, are detected in both modes. The sensitivity of phenol (C_6H_6O) in the negative mode is calibrated based on standard, and the sensitivities of other compounds are estimated as discussed above.

Figure S1 compares the yields of four masses between the negative and positive modes. The C_6H_6O yield agrees within 25% between two modes. For the other three masses, the agreement is generally within 50% for the majority of experiments. For $C_6H_6O_2$, $C_6H_6O_3$, and $C_4H_4O_3$, each mass has multiple isomers, which likely have different sensitivities. This could introducing compensating errors and complicate the comparison. Nonetheless, the reasonable agreement in product yields between positive and negative modes suggests that the estimated sensitivity is on the right order of magnitude and the uncertainty in instrumental sensitivity does not alter the major conclusions of this study, such as the small yields of C6-epoxydicarbonylene.

S3: Yield calculation

The molar yield of a product X is defined as follows

$$Y_X = \frac{\Delta[X]^{\text{corrected}}}{\Delta[\text{benzene}]} = \frac{F \cdot \Delta[X]}{\Delta[\text{benzene}]} \tag{9}$$

where $\Delta[X]$ and $\Delta[X]^{\text{corrected}}$ represent the amount of X formed before and after correction for secondary loss, respectively. $\Delta[\text{benzene}]$ represents the reacted amount of benzene. F is the correction factor for secondary loss of X. The determination of F follows the procedure

Table S2: Instrumental sensitivity and reaction kinetics of major oxidation products in benzene oxidation

Compound	Formula	sensitivity[a] ($\times 10^{-4}$)	k_{OH}[b] ($\times 10^{-11}$)	j[c] ($\times 10^{-5}$)	mode	note
phenol	C_6H_6O	0.94	2.8	N/A	CF_3O^-	d
C-nitrate	$C_6H_7NO_4$	1.6	2.8	N/A	CF_3O^-	e
BCE-nitrate	$C_6H_7NO_5$	1.8	2.8	N/A	CF_3O^-	e
BCP-nitrate	$C_6H_7NO_6$	1.5	2.8	N/A	CF_3O^-	e
2,4-hexadienedial	$C_6H_6O_2$	1.0	7.4	5.4	CF_3O^-	f
C6-epoxydicarbonylene	$C_6H_6O_3$	1.3	7.4	5.4	CF_3O^-	g
fumaraldehydic acid	$C_4H_4O_3$	2.0	3.7	79.2	CF_3O^-	h
epoxy-butandial	$C_4H_4O_3$	2.0	3.0	0.8	CF_3O^-	i
glyoxal	$C_2H_2O_2$	26	1.0	3.9	$NO \cdot H_2O^+$	j
butenedial	$C_4H_4O_2$	24	5.2	79.2	$NO \cdot H_2O^+$	k
benzene	C_6H_6	23	0.12	N/A	$NO \cdot H_2O^+$	l
methyl nitrite	CH_3ONO	12	N/A	110	$NO \cdot H_2O^+$	m

[a] The unit of sensitivity is ncts pptv^{-1} and ncts ppbv^{-1} for negative mode and positive mode, respectively. In the negative mode, the signal is normalized to the sum of the count rates for $^{13}CF_3O^-$ and $^{13}CF_3O^- \cdot H_2O$. In the positive mode, the signal is normalized by the sum of the count rates of $NO \cdot H_2O^+$ and $NO \cdot (H_2O)_2^+$

[b] k_{OH} unit is cm^3 molecule^{-1} s^{-1}. Values at 298 K.

[c] j unit is s^{-1}. Values correspond to light intensity in this study.

[d] Sensitivity is from calibration. k_{OH} is from MCM.

[e] Sensitivity is from theoretical calculation and averaged over all stereo-isomers. k_{OH} is assumed to be the same as phenol.

[f] Sensitivity is from theoretical calculation. k_{OH} and j are for the E,E-$C_6H_6O_2$ isomer from Klotz et al.[13].

[g] Sensitivity is from theoretical calculation. k_{OH} and j are assumed to be same as 2,4-hexadienedial.

[h] Sensitivity is from theoretical calculation. k_{OH} is adapted from Wang et al.[14], which is calculated using traditional transition-state theory. j is assumed to be the same as butenedial.

[i] Sensitivity is assumed to be the same as fumaraldehydic acid. k_{OH} is assumed to be twice the k_{OH} of acetaldehyde. j is assumed to be 0.01 of $j_{\mathrm{butenedial}}$.

[j] Sensitivity is from calibration. k_{OH} and j are from MCM.

[k] Sensitivity is assumed to be the average of benzene and glyoxal. k_{OH} and j are for the Z-$C_4H_4O_2$ isomer from Newland et al.[15].

[l] Sensitivity is from calibration. k_{OH} is from MCM.

[m] Sensitivity is from calibration. j is from measurement.

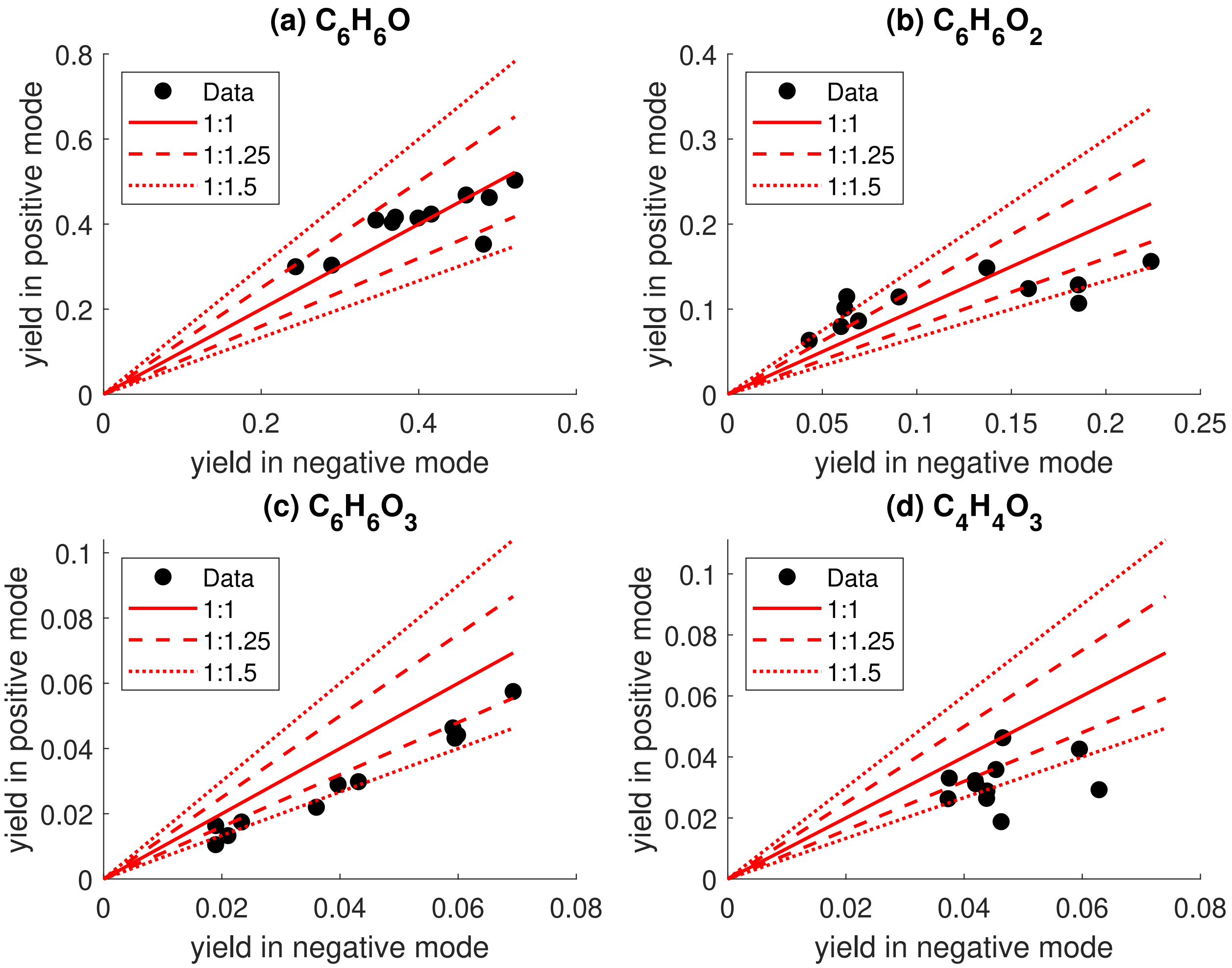


Figure S1: Yield comparison for compounds that are measured in both positive and negative modes.

in Atkinson et al.[16]. In brief, the time-dependent concentrations of benzene and products are governed by

$$\frac{d[\mathrm{benzene}]}{dt} = -\mathrm{k_{benzene+OH}}[\mathrm{benzene}][\mathrm{OH}] \tag{10}$$

$$\begin{aligned}\frac{d[\mathrm{X}]}{dt} &= \mathrm{Y_X} \cdot \mathrm{k_{benzene+OH}}[\mathrm{benzene}][\mathrm{OH}] - \mathrm{k_{X+OH}}[\mathrm{X}][\mathrm{OH}] - \mathrm{j_X}[\mathrm{X}] \\ &= \mathrm{Y_X} \cdot \mathrm{k_{benzene+OH}}[\mathrm{benzene}][\mathrm{OH}] - \mathrm{k_{X,loss}}[\mathrm{X}][\mathrm{OH}]\end{aligned} \tag{11}$$

where $\mathrm{k_{benzene+OH}}$, $\mathrm{k_{X+OH}}$, and $\mathrm{j_X}$ are the rate coefficients for benzene+OH, X+OH, photolysis of X, respectively. $\mathrm{k_{X,loss}} = \mathrm{k_{X+OH}} + \mathrm{j_X}/[\mathrm{OH}]$ represents the effective loss rate of product X, combining its reaction with OH and photolysis. OH concentration in each experiment is determined by fitting the loss rate of benzene. The above two equations can be integrated to obtain

$$\mathrm{F} = \left(\frac{\mathrm{k_{benzene+OH}} - \mathrm{k_{X,loss}}}{\mathrm{k_{benzene+OH}}}\right)\left(\frac{1 - \frac{[\mathrm{benzene}]_t}{[\mathrm{benzene}]_0}}{\frac{[\mathrm{benzene}]_t}{[\mathrm{benzene}]_0}^{\mathrm{k_{X,loss}}/\mathrm{k_{benzene+OH}}} - \frac{[\mathrm{benzene}]_t}{[\mathrm{benzene}]_0}}\right) \tag{12}$$

The related reaction kinetics of oxidation products are summarized in Table S2.

In the main text, when comparing the phenol yield between different studies, we correct the phenol production from C-yl + $\mathrm{NO_2}$ reaction, based on Eqn. S13, which is obtained by re-arranging Eqn.3 in the main text. The correction is to facilitate comparison between studies, because both NO and $\mathrm{NO_2}$ concentrations influence the bimolecular lifetime of the radical pool (i.e., C-yl and C-peroxy), but they have different impacts on phenol yield.

$$\mathrm{Y_{phenol}^{corr,NO_2}} = \mathrm{Y_{phenol}} - \frac{\Phi_{\mathrm{phenol}}\frac{\mathrm{k_6}}{\mathrm{K_{eq2}}}\frac{[\mathrm{NO_2}]}{[\mathrm{O_2}]}}{\mathrm{k_{phenol}} + \frac{\mathrm{k_6}}{\mathrm{K_{eq2}}}\frac{[\mathrm{NO_2}]}{[\mathrm{O_2}]} + \mathrm{k_{endo,eff}} + \mathrm{k_9}\frac{\sum_1^4 \mathrm{K_{eqi}}}{\mathrm{K_{eq2}}}[\mathrm{NO}]} \tag{13}$$

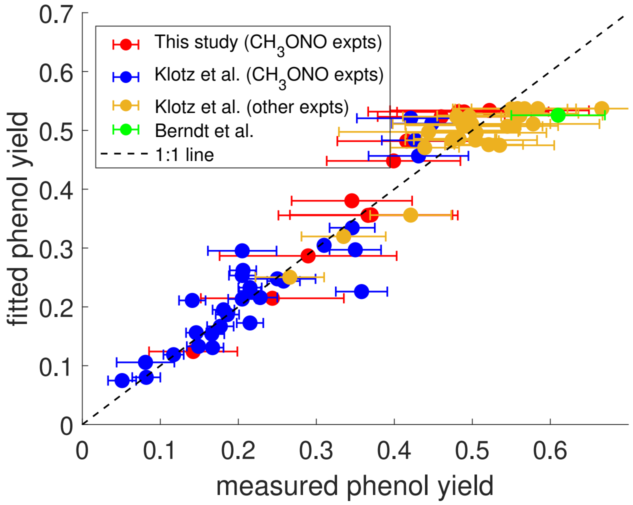


Figure S2: Fitting of phenol yield according to Eqn.3

S4: GC operation and chromtograms

Analytes are sampled from the chamber reactor and cryo-trapped on the head of a 2 m Restek RTX-1701 column at -20°C. After trapping for certain time (5 - 20 min, depending on the analyte concentration), elution is enabled by programmed heating with N_2 as carrier gas. The temperature profile is ramping from -20°C to 50°C at a rate of 20°C min^{-1}; ramping from 50°C to 130°C at a rate of 3°C min^{-1}; held at 130°C for 10 min.

Figures S3 to S8 show the chromatograms and the yields of key oxidation products detected in the negative mode of CIMS. Multiple isomers are resolved for each oxidation product. Regarding $C_6H_7NO_6$ (Figure S5), the 2 m GC column is not efficient in fully separating the two isomer eluting at 1680 s and 1720 s. To separate these two isomers, we represent the two peaks as equal-width Gaussian and fit the chromtograms by employing the peakfit.m function by Dr. Tom O'Haver (https://terpconnect.umd.edu/∼toh/spectrum /Introduction.html). Figure S11 shows the output of the algorithm for one representative chromatogram. The GC transmission efficiencies of $C_6H_7NO_6$ and $C_6H_6O_3$ are measured to be 82% and 80%, respectively, by comparing the total chromatogram signal to the amount of analyte trapped in the GC. The GC transmission efficiency would affect the estimated yields of BCP-nitrate and C6-epoxydicarbonylene, because their yields depend on the isomer separation. The reported yields in the main text are based on the assumption that isomers with the same *m*/*z* have the same GC transmission efficiency. To place an upper limit of the yields of BCP-nitrate and C6-epoxydicarbonylene, we assume that they are the only isomers partially lost in the GC and other isomers have 100% GC transmission efficiency. Under this assumption, the yields of BCP-nitrate and C6-epoxydicarbonylene are estimated to be 0.1% and 1.8%, under atmospherically relevant conditions. This does not change the conclusions that the BCP-nitrate yield is unexpectedly low and the C6-epoxydicarbonylene production from BCP-yl is negligible.

To aid the chemical identification of products, we perform H/D exchange analysis and O_3 test. By adding D_2O (D, 99.9%, Cambridge Isotope Laboratories, Inc.) to the GC eluent, the H/D exchange reaction can reveal the number of exchangeable H atoms (-OH, -OOH, and -C(O)OH groups) in the product. The H/D exchange analysis is only performed in the negative mode, not in the positive mode, because high D_2O concentration forms $NO^+ \cdot (D_2O)_n$ clusters. The O_3 test examines the presence of the C-C double bond in the product. After the photooxidation ceases, the oxidation products are evacuated from the chamber and collected in a cold trap at -60°C. Then the trapped analytes are warmed and transferred to a clean chamber using a flow of purified air. 2-4 ppmv O_3 and approximately 90 ppmb cyclohexane (as an OH scavenger) are injected into the chamber. Products with C-C double bond(s) will be quickly consumed by O_3.

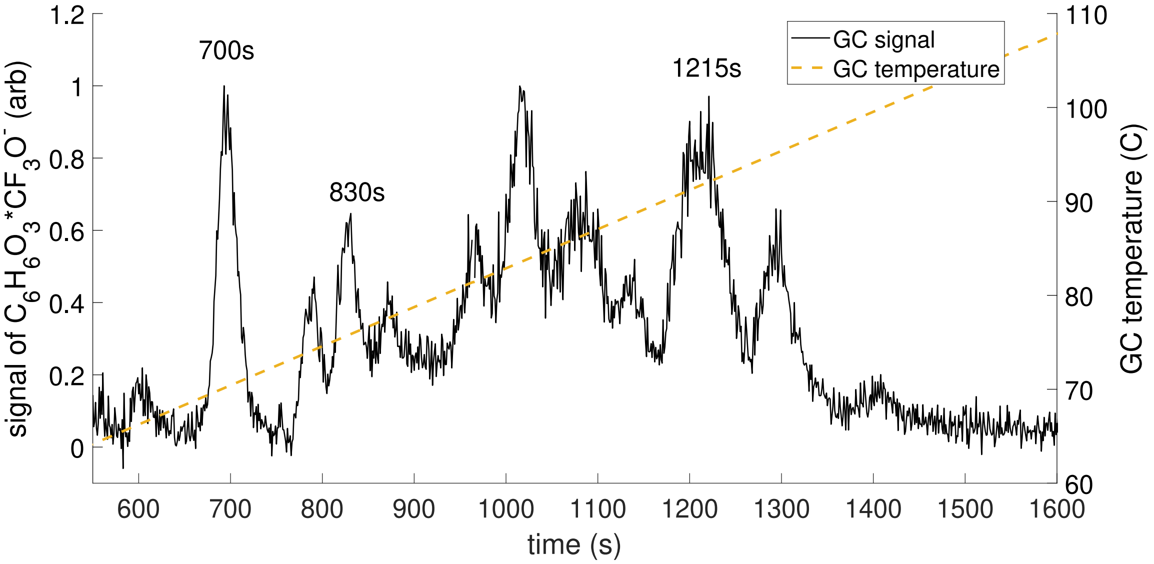


Figure S3: Chromatogram of $C_6H_6O_3 \cdot CF_3O^-$ from an experiment with $\tau_{RO_2,\mathrm{bimolecular}} \approx$ 0.05s.

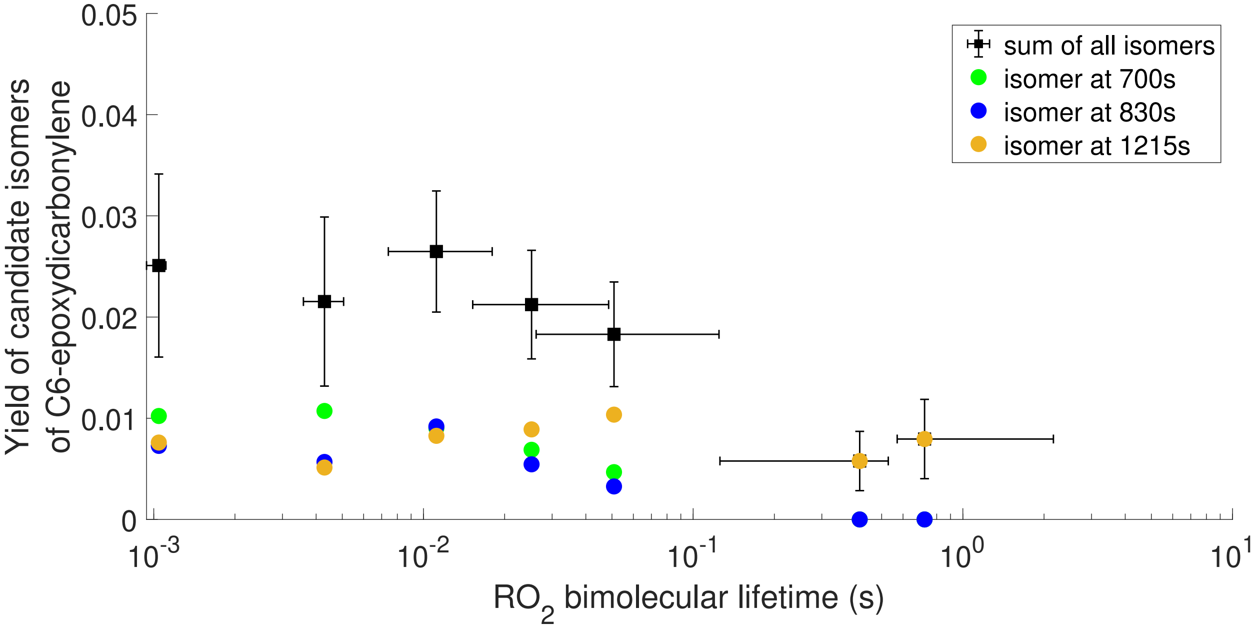


Figure S4: Yield of candidate isomers for C6-epoxydicarbonylene as a function of RO_2 bimolecular lifetime.

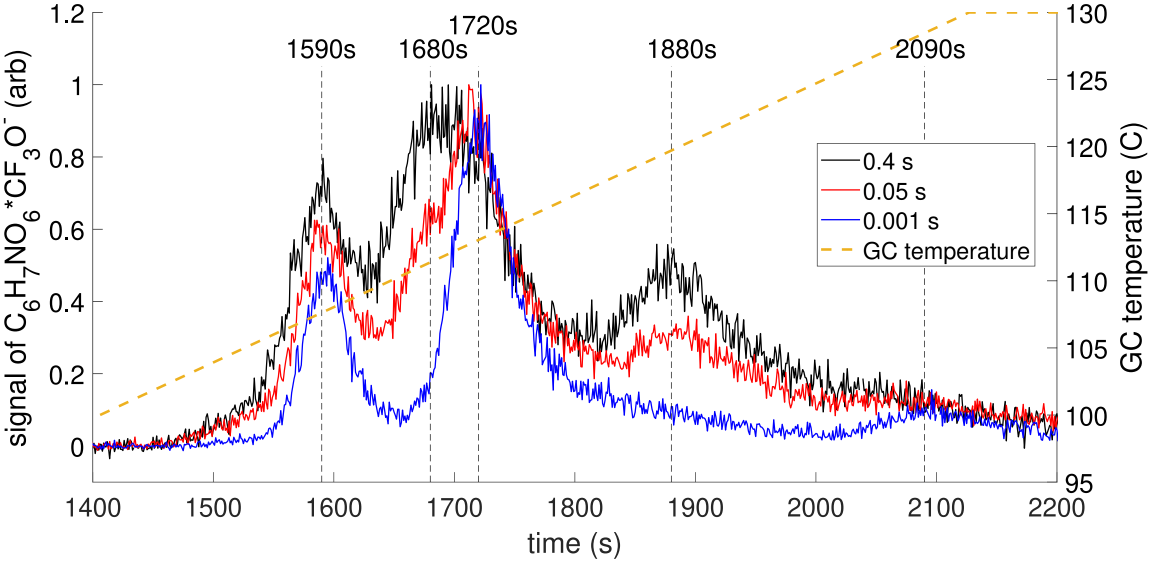


Figure S5: Chromatogram of $C_6H_7NO_6 \cdot CF_3O^-$ from three experiments with different RO_2 bimolecular lifetime. The signals are scaled by the maximum signal of each chromatogram.

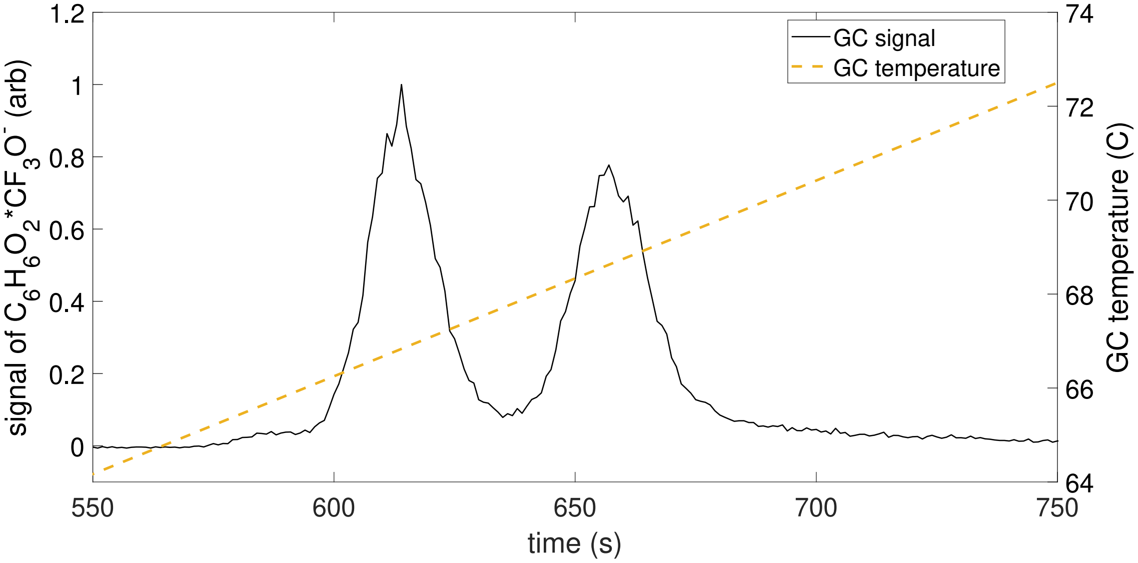


Figure S6: Chromatogram of $C_6H_6O_2 \cdot CF_3O^-$ from an experiment with $\tau_{RO_2,\text{bimolecular}} \approx 0.001\text{s}$.

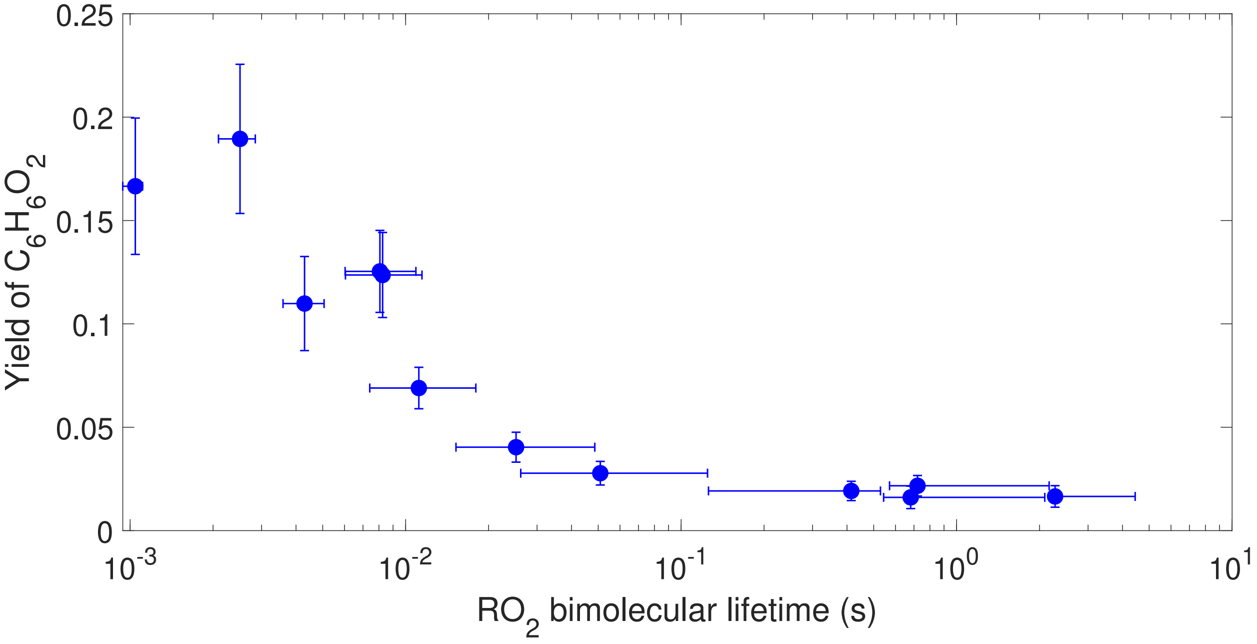


Figure S7: Yield of $C_6H_6O_2$ as a function of RO_2 bimolecular lifetime.

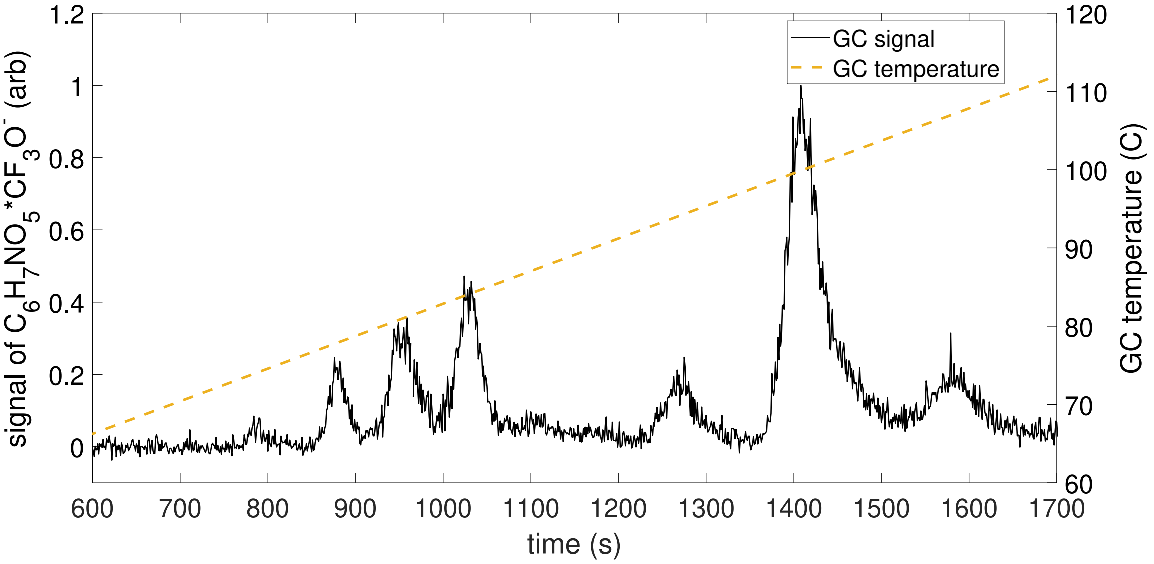


Figure S8: Chromatogram of $C_6H_7NO_5 \cdot CF_3O^-$ from an experiment with $\tau_{RO_2,\mathrm{bimolecular}} \approx 0.05$s.

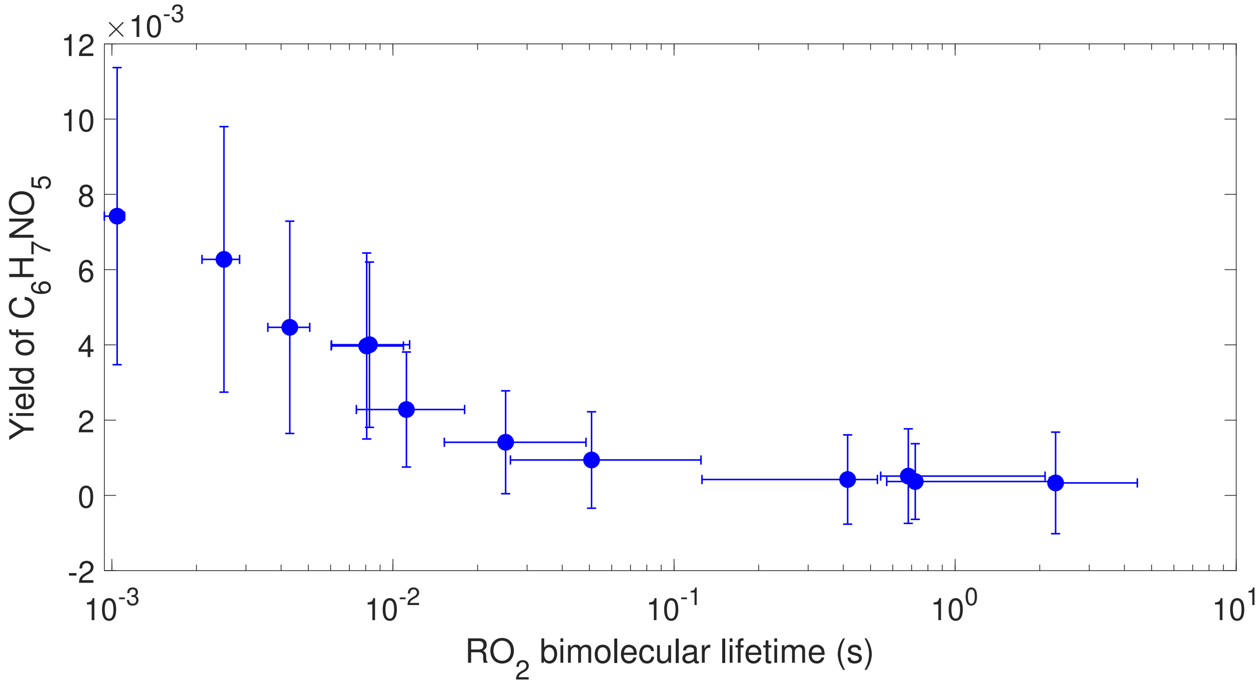


Figure S9: Yield of $C_6H_7NO_5$ as a function of RO_2 bimolecular lifetime.

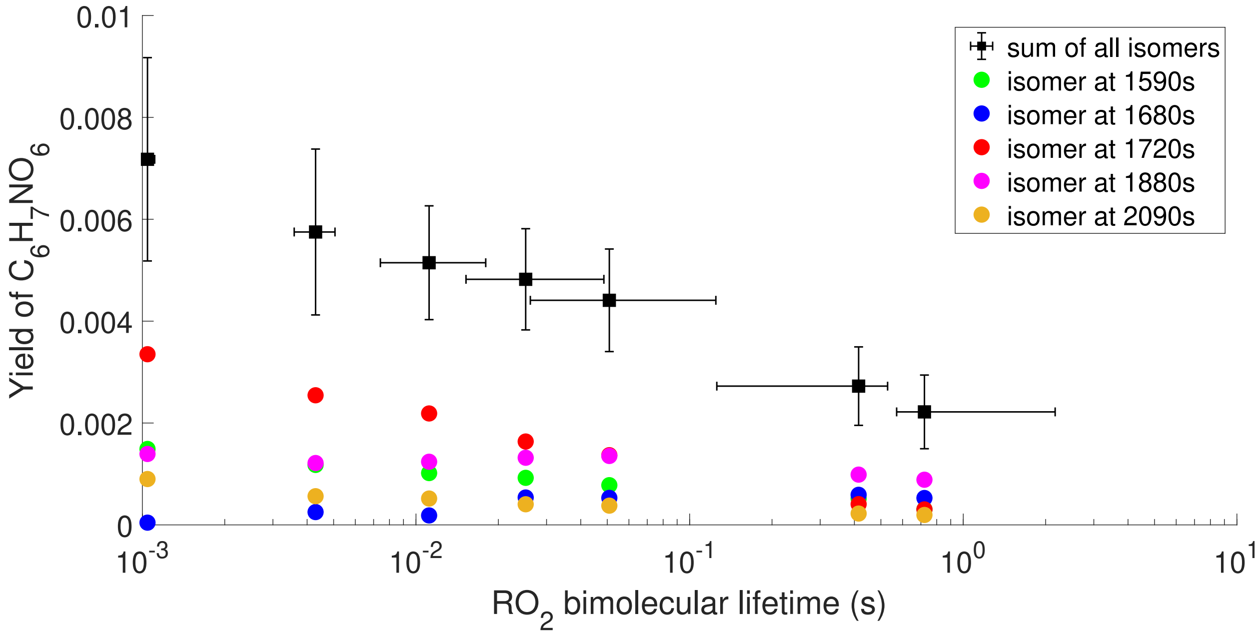


Figure S10: Yield of $C_6H_7NO_6$ as a function of RO_2 bimolecular lifetime.

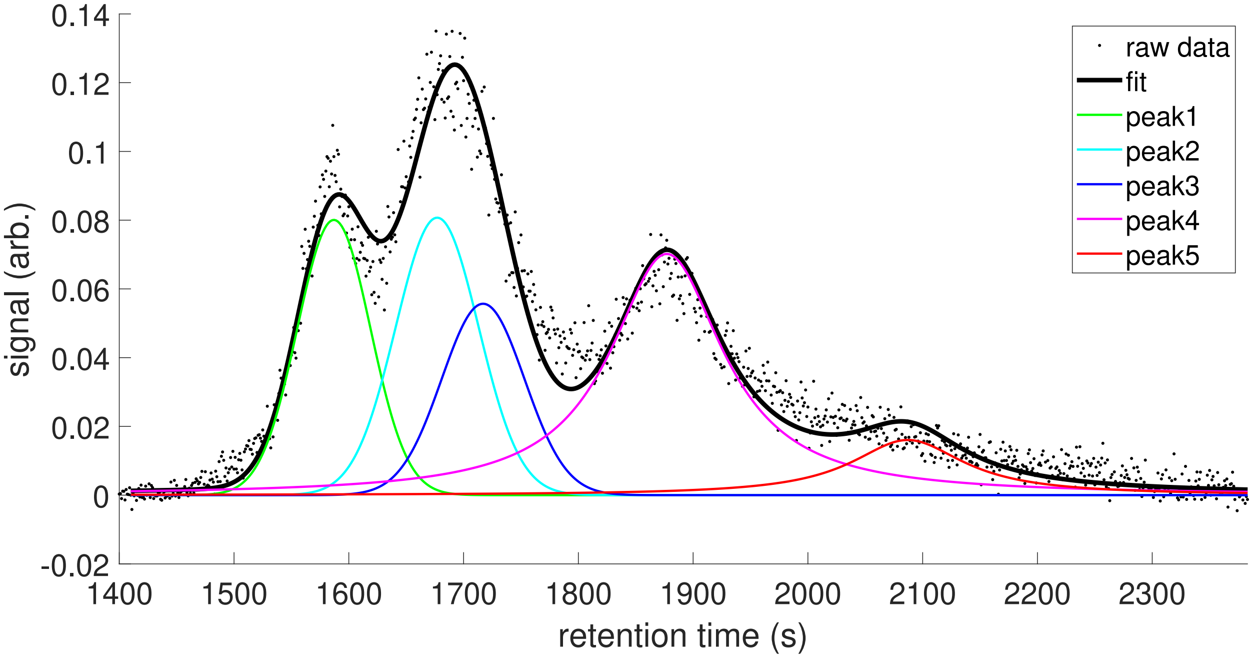


Figure S11: Representative chromatogram of $C_6H_7NO_6 \cdot CF_3O^-$ from an experiment with $\tau_{RO_2,\mathrm{bimolecular}} \approx 0.4$s. The peak shapes of peaks 1-3 and peaks 4-5 are represented by a Gaussian and a Lorentzian, respectively.

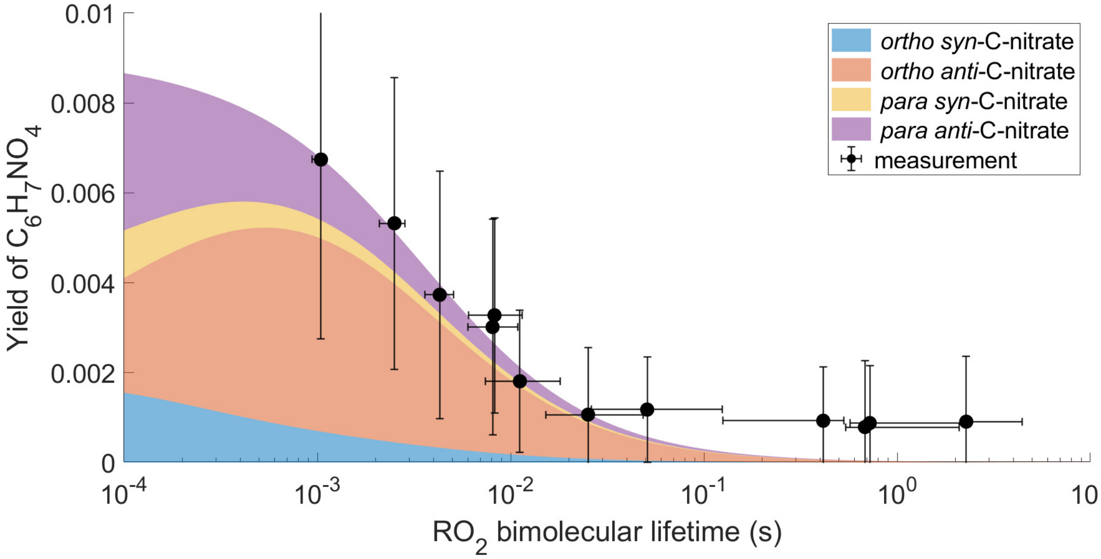


Figure S12: Yield of $C_6H_7NO_4$ as a function of RO_2 bimolecular lifetime ($\tau_{\mathrm{radical,bimolecular}}$). The measured yield represents the sum of all four C-nitrate isomers. The isomer-specific yields are obtained from a kinetic model based on Schemes 1 and 2. The nitrate branching ratio of C-peroxy+NO reaction is optimized to match the measured $\tau_{RO_2,\mathrm{bimolecular}}$-dependent C-nitrate yield. The optimal nitrate branching ratio is 0.9%.

S5: RO_2 bimolecular lifetime

Peroxy radical bimolecular lifetime ($\tau_{RO_2,bimolecular}$) is defined as

$$\tau_{RO_2,bimolecular} = \frac{1}{k_{RO_2+NO}[NO] + k_{RO_2+HO_2}[HO_2]} \tag{14}$$

The values of k_{RO_2+NO} and $k_{RO_2+HO_2}$ are 9.15×10^{-12} and 2.39×10^{-11} cm^3 $molecule^{-1}$ s^{-1}, respectively[17], unless otherwise noted. [NO] and [HO_2] are determined from an updated benzene oxidation mechanism. In the mechanism, the chemistry following a single OH reaction with benzene is based on findings and discussions in the main text. The chemistry of the first-generation closed-shell products is kept the same as that in MCM. However, the model develop and calculation of $\tau_{RO_2,bimolecular}$ are interrelated. On one hand, $\tau_{RO_2,bimolecular}$ is calculated based on model output (i.e., [NO] and [HO_2]). On the other hand, model development requires the radical reaction kinetics, such as k_{phenol}, which are determined based on $\tau_{RO_2,bimolecular}$. Therefore, the determination of radical reaction kinetics and the calculation of $\tau_{RO_2,bimolecular}$ are iterative. We firstly implement theoretically calculated k_{phenol} and $k_{endo,eff}$ into model to obtain initial estimate of $\tau_{RO_2,bimolecular}$. This initial estimate is combined with measured phenol yield to update k_{phenol} and $k_{endo,eff}$. After two iterations, the changes in k_{phenol} and $k_{endo,eff}$ are within 1%. We then obtain the final estimates of $\tau_{RO_2,bimolecular}$, k_{phenol} and $k_{endo,eff}$.

S6: Computational approach

Reaction rate coefficients, *k*, of selected unimolecular reactions are calculated using multi-conformer transition state theory (MC-TST):[18–21]

$$k = \varkappa \frac{k_B T}{h} \frac{\sum_{i}^{\text{TS conf.}} \exp\left(\frac{-\Delta E_i}{k_B T}\right) Q_{TS_i}}{\sum_{j}^{\text{R conf.}} \exp\left(\frac{-\Delta E_j}{k_B T}\right) Q_{R_j}} \exp\left(-\frac{E_{TS} - E_R}{k_B T}\right) \tag{15}$$

$\varkappa$ is the tunneling coefficient calculated using the Eckart approach (see below).[22] k_B is the Boltzmann constant, T is the temperature and h is Planck's constant. The two sums run over the conformers of transition states and reactants, respectively, and sum their partition functions, Q, weighted by their relative zero-point corrected energy, ΔE. The partition functions are evaluated at the lowest-energy vibrational level. The final term depends on the zero-point corrected energy difference between the lowest-energy conformers of TS and reactant, i.e., the reaction barrier.

Conformers, partition functions, and energies are generally calculated as described in Møller et al.[21]. The structure of an arbitrary conformer is optimized using B3LYP/6-31+G(d) in Gaussian 16, rev. C.01.[23–28] Based on this structure, a systematic conformer search is done using MMFF in Spartan'18 with a neutral charge enforced on the radical center.[21,29,30] For the conformer sampling of the transition states, three bond lengths are constrained to their optimized values from the B3LYP/6-31+G(d) optimizations. For peroxy radical H-shifts, these are the O-H bond being formed, the O/C-H bond being broken and the peroxy O-O bond. The conformers from the conformational sampling are optimized at the B3LYP/6-31+G(d) level in Gaussian 16. For the transition states, the TS optimization is preceded by an optimization towards a minimum with the same constraints as used for the conformer search.

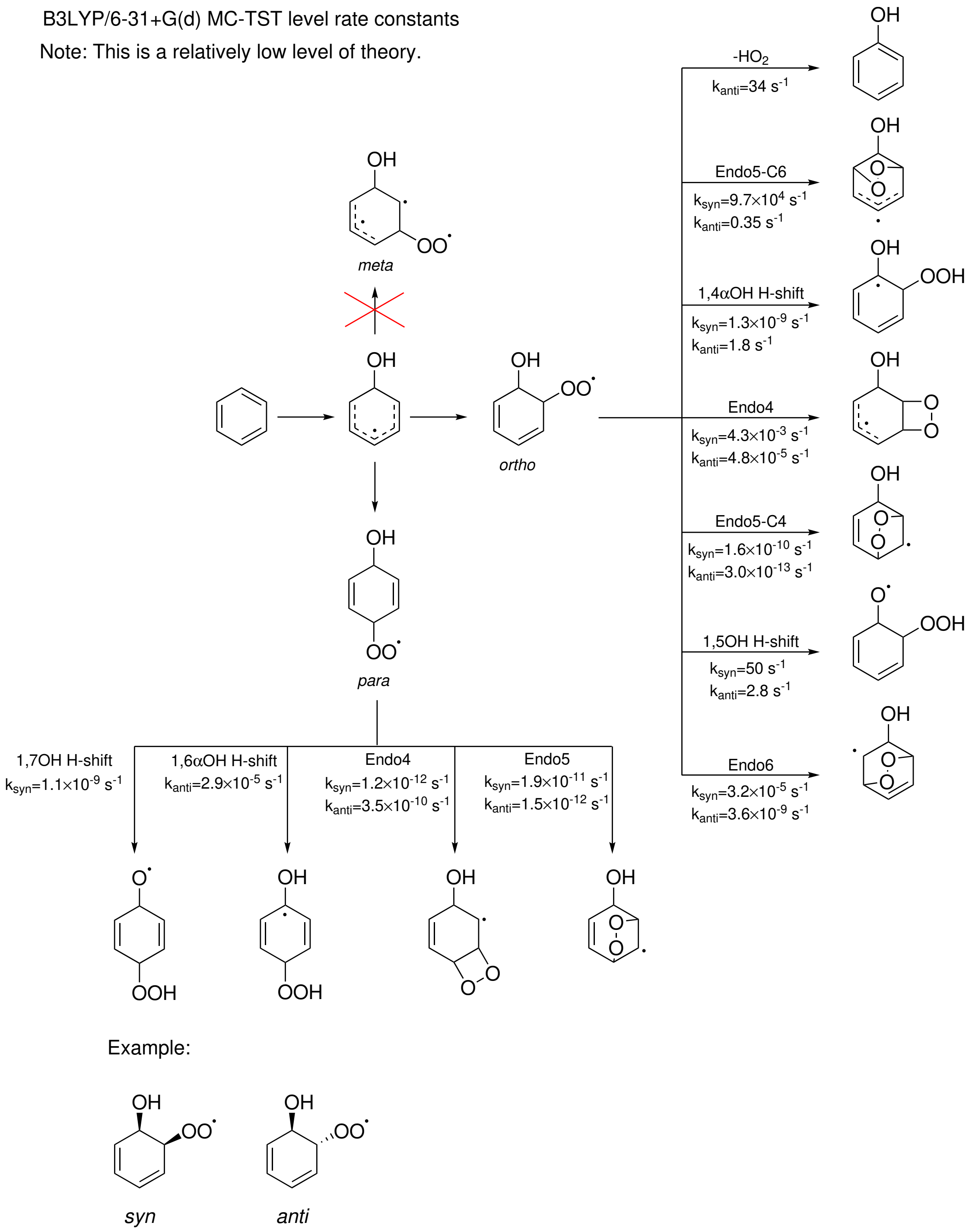
Unique conformers within 2 kcal mol^{-1} in electronic energy of the lowest-energy conformer at the B3LYP/6-31+G(d) level are further optimized using ωB97X-D/aug-cc-pVTZ.[21,31–33] For the lowest-energy conformers at this level, an RO-CCSD(T)-F12a/VDZ-F12 (abbreviated F12) single-point calculation is done in Molpro2012.[34–39] The barrier height in the MC-TST equation (Eq. 15) is calculated at the RO-CCSD(T)-F12a/VDZ-F12//ωB97X-D/aug-cc-pVTZ level with ωB97X-D/aug-cc-pVTZ zero-point corrections, while the relative energies between conformers and the partition functions are calculated using omegaB97X-D/aug-cc-pVTZ.

For the tunneling, an IRC is run at the B3LYP/6-31+G(d) level for the TS conformer lowest in energy at the ωB97X-D/aug-cc-pVTZ level. The end-points are optimized using first B3LYP/6-31+G(d) and subsequently ωB97X-D/aug-cc-pVTZ. Finally, an F12 single-point energy is calculated. The tunneling coefficient is then calculated using the Eckart approach with ωB97X-D/aug-cc-pVTZ imaginary frequency and F12//ωB97X-D/aug-cc-pVTZ Eckart barriers with ωB97X-D/aug-cc-pVTZ zero-point corrections. All rate coefficients are calculated at 298.15 K and are high-pressure limit values.

For the alkoxy radicals, no F12 calculations are done due to potential issues with the HF reference wave function[40] and instead, the ωB97X-D values are used. For the ωB97X-D of the reactions of the BCP-oxy radical, the 6-311+G(d,p) basis set is used instead of the aug-cc-pVTZ basis set as no TS could be located for the 1,5 aldehydic H-shift with the aug-cc-pVTZ basis set.

S7: Unimolecular reactions of C-peroxy

We calculate the unimolecular reaction rate coefficients of C-peroxy isomers using MC-TST. Calculation results at the B3LYP/6-31+G(d) level, summarized in Scheme S1, show that the endo-cyclization and HO_2 elimination are the dominant reactions for *ortho-syn*-C-peroxy and *ortho-anti*-C-peroxy, respectively. These two reaction pathways are re-evaluated at the F12 level. The rate coefficients of all studied unimolecular reactions of *para*-C-peroxy are below 3×10^{-5} s^{-1} at the B3LYP/6-31+G(d) level, suggesting these unimolecular reactions are negligible under atmospheric conditions.



B3LYP/6-31+G(d) MC-TST level rate constants

Note: This is a relatively low level of theory.

Scheme S1: Calculated unimolecular reaction rate coefficient for C-peroxy isomers at the B3LYP/6-31+G(d) MC-TST level. The HO_2 elimination rate of *ortho*-*anti*-C-peroxy is calculated at the at the ωB97X-D/6-31+G(d) level.

Table S3: Calculated unimolecular reaction rate coefficients of C-peroxy. All values are calculated at 298 K, except for this study at 298.15 K.

reaction	rate coefficient (s^{-1})	reference[a]	note
ortho-syn-C-peroxy → BCP-yl	2.5×10^5	Raoult et al.[41]	b
	3.07×10^3	Glowacki et al.[42]	c
	3.6×10^2	Olivella et al.[43]	d
	8.1×10^2	this study	e
ortho-anti-C-peroxy → phenol	4.3×10^1	Glowacki et al.[42]	f
	1.3×10^2	this study	e

[a] Lay et al.[44] also calculated the unimolecular reactions of C-peroxy, but are not included in this table because of the relatively low level of theory used in that study.

[b] TST, B3LYP/6-31G(d) with the activation enthalpy corrected by the empirical "Intrinsic-Method" (IM).

[c] Bartis-Widom Eigenvalue-Eigenvector Analysis, 760 Torr, barriers calculated using CASPT2 on PES adjusted within expected uncertainties to best fit experimentally observed decay of C-yl (Benzene-OH)

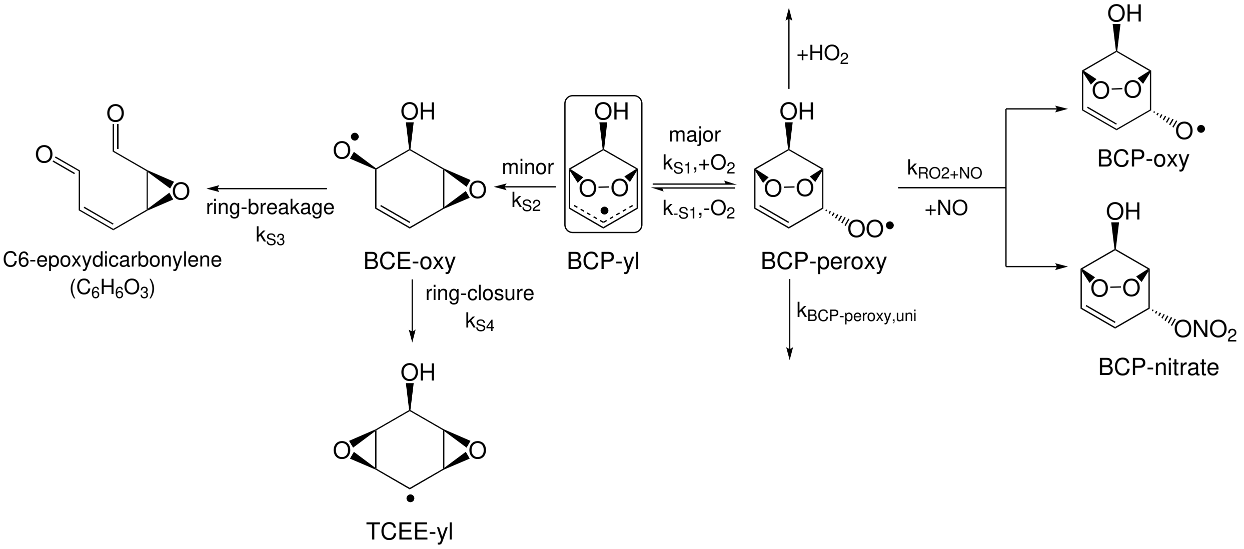
[d] TST, ROCCSD(T)/6-311+G(2df,2p)// B3LYP/6-31G(d).

[e] MC-TST, RO-CCSD(T)-F12a/VDZ-F12//ωB97X-D/aug-cc-pVTZ.

[f] Bartis-Widom Eigenvalue-Eigenvector Analysis, 760 Torr, barriers calculated using G3X(MP2)-RAD but adjusted within its estimated uncertainty limit (~ 5 kJ mol^{-1}) to best fit experimentally observed decay of C-yl (Benzene-OH)

Table S4: Kinetic parameters adopted from the literature and used in Eqn.3

Parameter	Value	Unit	Reference
$\Phi_{\mathrm{phenol,NO_2}}$	5.9	%	Klotz et al.[45]
k_1	2.8×10^{-15}	cm^3 $molecule^{-1}$ s^{-1}	Glowacki et al.[42]
k_{-1}	9.8×10^4	s^{-1}	Glowacki et al.[42]
k_2	8.4×10^{-16}	cm^3 $molecule^{-1}$ s^{-1}	Glowacki et al.[42]
k_{-2}	2.8×10^3	s^{-1}	Glowacki et al.[42]
k_3	4.2×10^{-14}	cm^3 $molecule^{-1}$ s^{-1}	Glowacki et al.[42]
k_{-3}	2.6×10^6	s^{-1}	Glowacki et al.[42]
k_4	2.6×10^{-14}	cm^3 $molecule^{-1}$ s^{-1}	Glowacki et al.[42]
k_{-4}	4.8×10^5	s^{-1}	Glowacki et al.[42]
k_6	2.8×10^{-11}	cm^3 $molecule^{-1}$ s^{-1}	Knispel et al.[46]
k_9	1.7×10^{-11}	cm^3 $molecule^{-1}$ s^{-1}	Klotz et al.[45]



Scheme S2: Reaction scheme of BCP-yl.

S8: Loss rate of BCP-yl

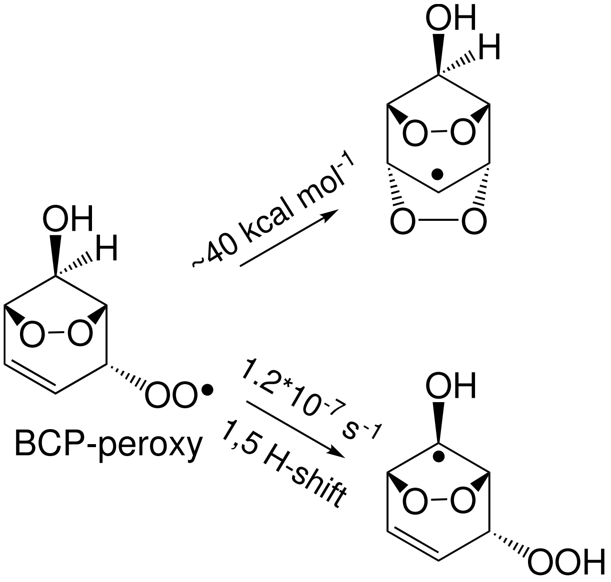
This section compares the effective loss rate of BCP-yl by O_2 addition (denoted as $k_{eff,BCP\text{-}peroxy}$) and by isomerization channel (k_{S2}). By considering the reversible O_2 addition to BCP-yl and assuming reaction with NO as the sole fate of BCP-peroxy (Scheme S2),

$$k_{eff,BCP-peroxy} = k_{RO_2+NO}[NO]\frac{k_{S1}[O_2]}{k_{-S1}} = k_{RO_2+NO}K_{eq,S1}[NO][O_2] \tag{16}$$

where k_{RO_2+NO} = 9.15×10^{-12} cm^3 s^{-1} $molecule^{-1}$. The equilibrium constant ($K_{eq,S1}$ = k_{S1}/k_{-S1}) is uncertain. We estimate its value by using three different approaches. First, the calculated $K_{eq,S1}$ is 2.4×10^{-17} at ωB97X-D/aug-cc-pVTZ level of theory. Second, the calculated $K_{eq,S1}$ is $5.9 \times 10^{-15} cm^3 molecule^{-1}$ at RO-CCSD(T)-F12a/VDZ-F12// ωB97X-D/aug-cc-pVTZ level of theory. Third, by analogizing to equilibrium between BCP-yl and BCP-peroxy to that of isoprene system, $K_{eq,S1}$ is on the order of $10^{-13} cm^3 molecule^{-1}$ (i.e., $2 \times 10^{-12}/20$ from Teng et al.[47]). By applying the estimated range of $K_{eq,S1}$ and assuming 1 ppbv NO and atmospheric O_2 concentration, $k_{eff,BCP\text{-}peroxy}$ is calculated to range from 30 to 10^5 s^{-1}. We also theoretically calculate the isomerization rate of stabilized BCP-yl (k_{S2}) to be 0.02 s^{-1}. Thus, regardless of the uncertainty, $k_{eff,BCP\text{-}peroxy}$ is orders of magnitude faster than the k_{S2}.

S9: Unimolecular reactions of BCP-peroxy

Two unimolecular reactions have been theoretically investigated as shown in Scheme S3.

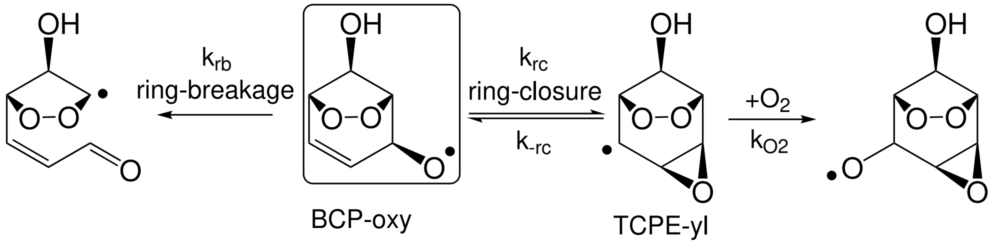


Scheme S3: Explored unimolecular reactions of BCP-peroxy. The rate coefficient of H-shift is calculated using the MC-TST approach by Møller et al.[21] with barriers at the F12 level. The barrier height of endo-cyclization is calculated by Motta et al.[48].

S10: BCP-oxy chemistry

Uncertainties in theoretical calculation of BCP-oxy reaction

Wang et al.[49] calculated the branching ratio of BCP-oxy chemistry and suggested ring-closure to be preferential. However, new calculation results from the same group suggest less than 2% of BCP-oxy undergoes ring-closure (Figure 1 in Wang et al.[14]). The theoretical calculation is highly uncertain because of the reversibility of BCP-oxy ring-closure reaction and the unknown O_2 addition rate to TCPE-yl (Scheme S4).



Scheme S4: Reaction pathways of *syn*-BCP-oxy.

The effective removal rate of BCP-oxy by ring-closure ($k_{\mathrm{eff,rc}}$) can be represented as

$$k_{\mathrm{eff,rc}} = \frac{k_{O_2}[O_2]k_{\mathrm{rc}}}{k_{-\mathrm{rc}} + k_{O_2}[O_2]} \tag{17}$$

where k_{O_2} represents the O_2 addition rate coefficient to TCPE-yl. k_{rc} and $k_{-\mathrm{rc}}$ represent the forward and reverse rate coefficients of ring-closure of BCP-oxy, which are calculated to be 2.84×10^9 and 3.97×10^9 s^{-1}, respectively, by Wang et al.[49]. $[O_2]$ represents the atmospheric O_2 concentration. Using a value of 6×10^{-12}cm^{3}molecule^{-1}s^{-1} for k_{O_2}, $k_{\mathrm{eff,rc}}$ is calculated to be equal to the ring-breakage rate coefficient of BCP-oxy (i.e., $k_{\mathrm{rb}} = 2.2 \times 10^7$ s^{-1}). This leads to the ratio of ring-closure to ring-breakage to be 1, which is the predicted value in Wang et al.[49]. However, k_{O_2} is poorly constrained. If k_{O_2} was 1×10^{-12} cm^3 molecule^{-1} s^{-1}, the ratio of ring-closure to ring-breakage would decrease to 0.17. Therefore, the theoretically predicted fate of BCP-oxy is highly sensitive to the O_2 addition rate coefficient.

The fate of BCP-oxy is expected to be stereospecific. Wang et al.[49] only studied the *syn* isomer, because this isomer is proposed to be produced from the isomerization of *syn*-BCP-peroxy and the stereo-structure is inherited. The reactions of other stereoisomers generated from C-oxy channel require further investigation.

Uncertainties in experimental estimate of BCP-oxy fate

To experimentally investigate the fate of BCP-oxy, we use the measurement of epoxy-butandial, a unique product from BCP-oxy ring-closure pathway. This constraint is only applicable under low NO conditions (i.e., NO $<$ a few ppbv) when BCP-oxy is the dominant source of epoxy-butandial. Under high NO conditions when C-peroxy+NO is substantial, epoxy-butandial can also be produced from TCEE-yl (Scheme S10). Another to note is taht epoxy-butandial and fumaraldehydic acid are structural isomers with the same chemical formula $C_4H_4O_3$. Their separation based on gas chromatography will be discussed in next section.

One uncertainty in using epoxy-butandial yield to constrain the BCP-oxy fate is the unstudied photochemical reaction rates of epoxy-butandial. We assume that the k_{OH} of epoxy-butandial is twice the $\mathrm{k_{OH}}$ of acetaldehyde, as epoxy-butandial has two aldehyde functionality. We assume $\mathrm{j_{epoxy-butandial}} = 0.01 \times \mathrm{j_{butenedial}}$ because Newland et al.[15] noted that the photolysis rate of unsaturated aldehyde is roughly 100 times larger than that of saturated aldehyde. Even assuming that epoxy-butandial has the same fast secondary loss as butenedial, the epoxy-butandial yield only increases from 0.2% to 0.3%. The instrumental sensitivity of epoxy-butandial also influences the estimate of BCP-oxy fate. However, even if we assume the instrumental sensitivity of epoxy-butandial is 10 times of current assumption, the epoxy-butandial yield increases from 0.2% to 2%, suggesting only 4% of BCP-oxy undergoing ring-closure. In conclusion, these uncertainties unlikely alter the conclusion that ring-closure is a minor reaction of BCP-oxy and ring-breakage is its dominant fate.

Separation of epoxy-butandial and fumaraldehydic acid

Epoxy-butandial and fumaraldehydic acid are structural isomers with the same chemical formula $C_4H_4O_3$. They are separated based on gas chromatography and their different ion-chemistry with CF_3O^-. It is expected that epoxy-butandial reacts with CF_3O^- mainly via clustering chemistry ($C_4H_4O_3 \cdot CF_3O^-$ at *m/z* 185), while fumaraldehydic acid could potentially react both by clustering ($C_4H_4O_3 \cdot CF_3O^-$ at *m/z* 185) and fluoride transfer ($C_4H_4O_3 \cdot F^-$ at *m/z* 119). The chromtograms of $C_4H_4O_3 \cdot CF_3O^-$ and $C_4H_4O_3 \cdot F-$ have two peaks each. We infer both $C_4H_4O_3 \cdot F^-$ peaks represent fumaraldehydic acid and $C_4H_4O_3 \cdot$

CF_3O^- peak eluting at 720s represents epoxy-butandial based on the following analysis. First, the H/D exchange analysis reveals that the $C_4H_4O_3 \cdot CF_3O^-$ peak eluting at 720s does not contain any exchangeable acidic H, consistent with the structure of epoxy-butandial. Both $C_4H_4O_3 \cdot F^-$ peaks have one acidic H, consistent with the structure of fumaraldehydic acid. Second, in benzene-d$_6$ oxidation experiments, two $C_4D_3HO_3 \cdot F^-$ peaks (i.e., replacing three hydrogen atoms in $C_4H_4O_3 \cdot F^-$ with deuterium atoms) are observed, which is consistent with their proposed formation mechanism (Scheme S5). However, we note that the two peaks of $C_4H_4O_3 \cdot F-$ unlikely arise from the same molecule, because they exhibit different ion-chemistry with CF_3O^-. The molecule eluting at 720s reacts with CF_3O^- via only fluoride transfer, while the molecule eluting at 1000s undergoes both fluoride transfer and clustering reactions with CF_3O^- (i.e., both $C_4H_4O_3 \cdot CF_3O^-$ and $C_4H_4O_3 \cdot F^-$ have a peak eluting at 1000s). Without authentic standard, the further peak assignment is challenging. We assume both peaks represent fumaraldehydic acid and use the summed signal to obtain an upper bound of fumaraldehydic acid yield. Authentic standard of fumaraldehydic acid will be critical to improve its quantification and hence constrain the fate of BCP-oxy.

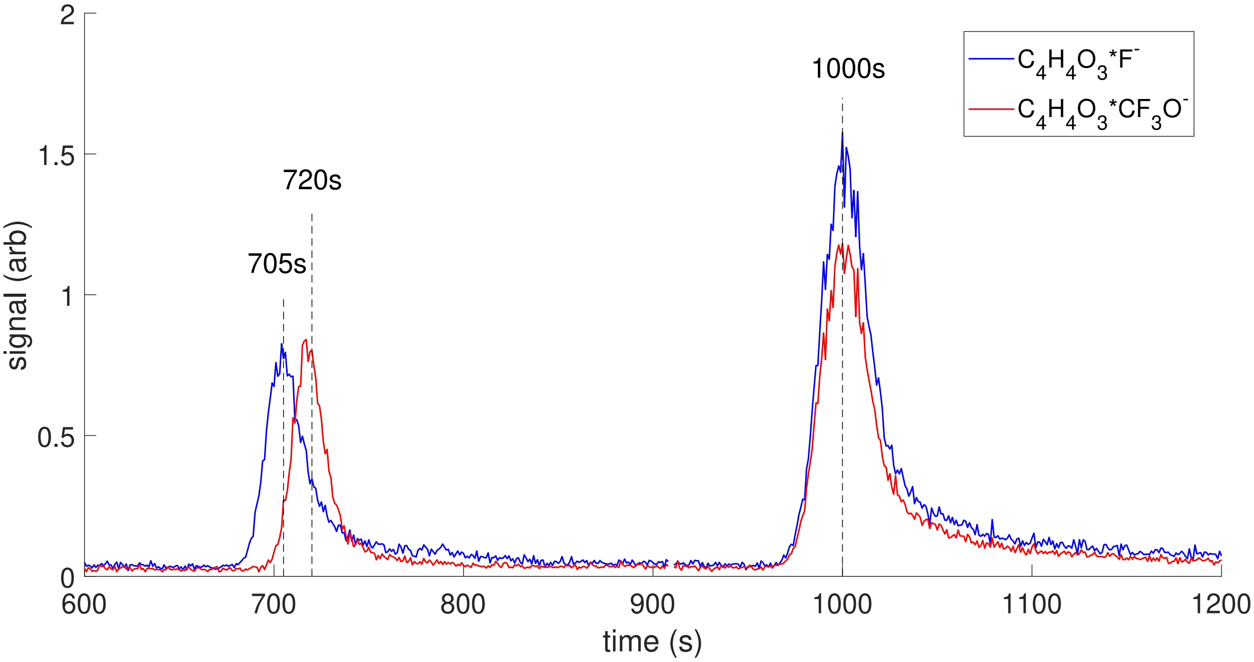
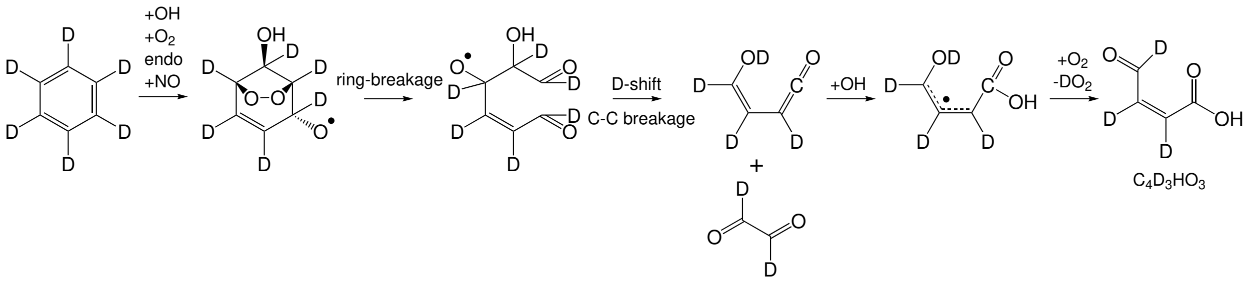


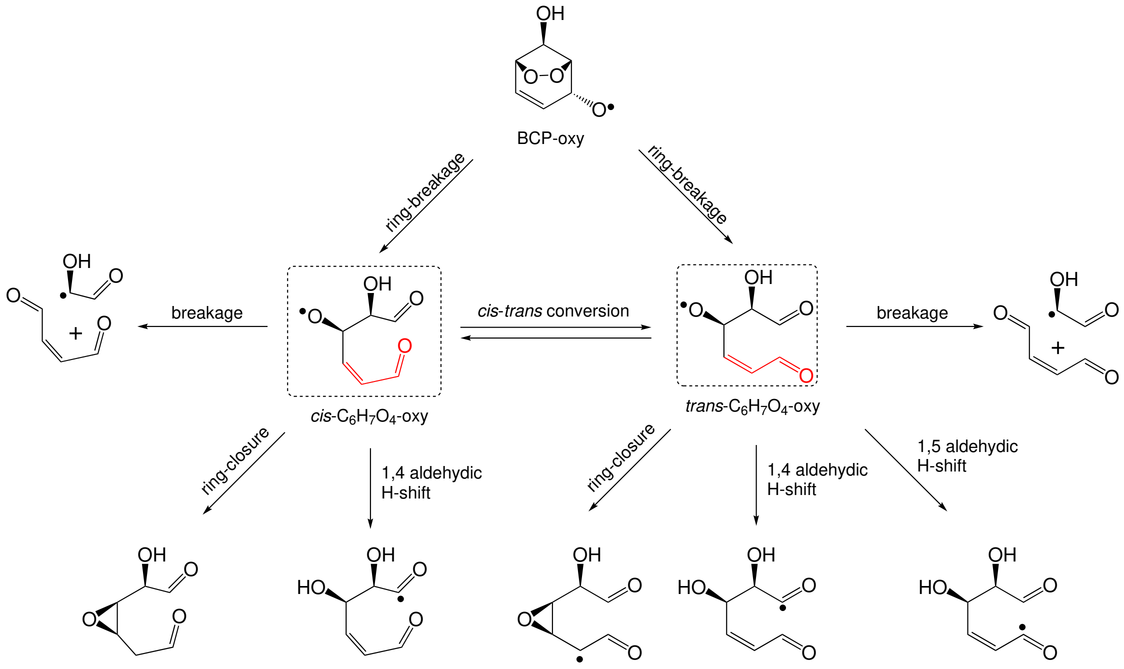
Figure S13: Chromatograms of $C_4H_4O_3 \cdot CF_3O^-$ and $C_4H_4O_3$ fluoride transfer product from an experiment with $\tau_{RO_2,\mathrm{bimolecular}} \approx 0.001$s.



Scheme S5: Formation of $C_4D_3HO_3$ from the oxidation of d6-benzene.

Theoretical study of BCP-oxy, $C_6H_7O_4$-oxy and $C_6H_7O_4$-yl reactions

In this section, we discuss our theoretical study of the BCP-oxy, $C_6H_7O_4$-oxy, and $C_6H_7O_4$-yl reactions. C-C bond scission is the initial step in the conversion of BCP-oxy to $C_6H_7O_4$-oxy. Intrinsic Reaction Coordinate (IRC) calculations for this reaction at the ωB97X-D/6-31+G(d) level lead to a structure in which the newly formed aldehyde group is perpendicular to the double bond. This suggests that the $C_6H_7O_4$-oxy radical will be formed as both *cis* and *trans* isomers with respect to the central bond in the conjugated aldehyde group (Scheme S6) which have ωB97X-D/6-311+G(d,p) zero-point corrected energies within 0.05 kcal mol^{-1} of each other. The ωB97X-D/6-311+G(d,p) barrier for the interconversion between these is about 5 kcal mol^{-1}. This barrier is higher than the barriers for some of the other unimolecular reaction pathways available (Table S5) and therefore these two isomers may react independently. Decomposition is calculated to be the dominant pathway for *cis*-$C_6H_7O_4$-oxy, yielding gloyxal and butenedial. In contrast, for *trans*-$C_6H_7O_4$-oxy, the 1,5-aldehydic H-shift leading to $C_6H_7O_4$-yl is also expected to be an important pathway, as the barrier is ~3 kcal mol^{-1} lower than that for the decomposition (Table S5). The isomer-specific chemistry of $C_6H_7O_4$-oxy is not specifically discussed by Wang et al.[14].

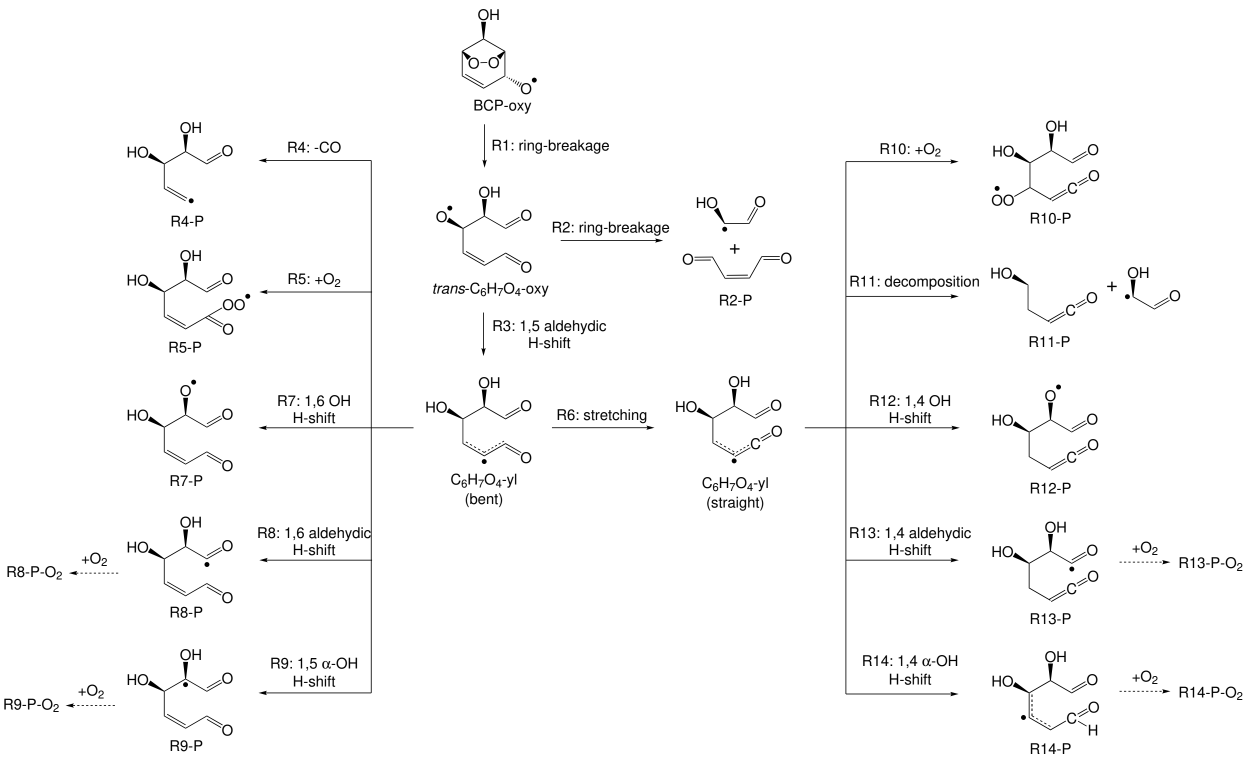


Scheme S6: Overview of BCP-oxy ring-breakage leading to *cis* and *trans*-$C_6H_7O_4$-oxy and their unimolecular reactions.

Table S5: ωB97X-D/6-311+G(d,p) zero-point corrected barrier heights (in kcal mol^{-1}) for the unimolecular reactions of the *cis* and *trans*-$C_6H_7O_4$-oxy radicals shown in Scheme S6.

Reaction	ΔE_{cis}	ΔE_{trans}
Cis-trans-conversion	5.1	5.1
1,4 aldehydic H-shift	7.5	10.7
1,5 aldehydic H-shift	N/A	-0.3
Ring-breakage	1.5	2.8
Ring-closure	7.1	5.7

The 1,5-aldehydic H-shift of *trans*-$C_6H_7O_4$-oxy produces an alkyl radical $C_6H_7O_4$-yl (R3 and R6 in Scheme S7). Wang et al.[14] suggested that the $C_6H_7O_4$-yl exclusively decomposes into a ketene-enol accompanied by gloyxal (R11 in Scheme S7), rather than reacting with O_2. In agreement with Wang et al.[14], we find that the $C_6H_7O_4$-yl radical is about 70 kcal mol^{-1} lower in energy than BCP-oxy and thus is unlikely to react with O_2 before undergoing unimolecular reactions via the excess energy. However, given the amount of excess energy and multiple substituents in the $C_6H_7O_4$-yl, the decomposition is not the only possible unimolecular reaction of $C_6H_7O_4$-yl.



Scheme S7: Overview of studied unimolecular reactions for the $C_6H_7O_4$-yl radical formed from the 1,5 aldehydic alkoxy H-shift of the *trans*-$C_6H_7O_4$-oxy radical. An IRC calculation shows that the 1,4 α-OH H-shift (R14) is connected to $C_6H_7O_4$-yl (straight) rather than the bent isomer. The relative energies of the species and transition states are given in Table S6. The ring-breakge of BCP-oxy (R1) can also produce *cis*-$C_6H_7O_4$-oxy radical, which is not included in the RRKM-ME modeling.

Table S6: ωB97X-D/6-311+G(d,p) zero-point corrected energy (in kcal mol^{-1}) of transition states, E_{TS}, products, E_{P}, and products after O_2-addition, $E_{\mathrm{P-O_2}}$, of the reactions shown in Scheme S7 calculated relative to BCP-oxy.

Reaction	E_{TS}	E_{P}	$E_{\mathrm{P-O_2}}$
R1	8.4	-52.3	
R2	-49.5	-69.8	
R3	-52.6	-69.5	a
R4	-44.0	-45.6	
R5		-94.0	
R6	-68.9	-74.2	b
R7	-46.8	-51.4	
R8	-50.4	-66.0	-91.4
R9	-58.4	-78.4	-88.8
R10		-88.2	
R11	-54.6	-66.9	
R12	-43.4	-56.6	
R13	-47.5	-69.7	-97.9
R14	-51.7	-84.6	-85.6

[a] Corresponds to R5-P
[b] Corresponds to R10-P

The possible unimolecular reactions of $C_6H_7O_4$-yl is outlined in Scheme S7 and modeled with Rice-Ramsperger-Kassel-Marcus Master Equation methods (RRKM-ME) using the Master Equation Solver for Multi Energy-well Reactions (MESMER) version 6.0.[50] The stationary points used for the simulations are the lowest-energy conformers at the ωB97X-D/6-311+G(d,p) level and the modeling is based on energies at that level. This level is selected because the TS for the 1,5 alkoxy H-shift from *trans*-$C_6H_7O_4$-oxy could not be optimized with the aug-cc-pVTZ basis set (a scan suggests that the reaction is barrierless at that level). For products of decomposition reactions, the optimized IRC end-point conformer is used. For products of O_2-addition reaction, an arbitrary conformer is used rather than the lowest-energy conformers but this is not expected to impact the simulations as these are modelled as sinks. The modeling starts from BCP-oxy, but includes only ring-breakage to the *trans*-$C_6H_7O_4$-oxy, as the branching between the *trans* and *cis* $C_6H_7O_4$-oxy isomers is unknown. If one assumes *cis*-$C_6H_7O_4$-oxy as the only isomer produced from $C_6H_7O_4$-oxy ring-breakage, the yields reported here represent the upper limits from BCP-oxy channel.

The following parameters are used for the modeling:

- $k(R\cdot+O_2) = 1.4\times10^{-11}$ cm^3 molecule^{-1} s^{-1}. Based on experimental results for cyclohexyl at 298 K.[51] This value may be an upper limit as most of the alkyl radicals are delocalized and thus likely react slower.
- Atmospheric O_2 concentration of 5.36×10^{18} molecules cm^{-3}.
- Exponential energy decay with an average energy transfer per collision (ΔE_{down} = 278.89 cm^{-1}) based on experimental results for toluene with N_2 as the bath gas.[52]
- Lennard-Jones parameters for the benzene-derived species: $\sigma = 5.92$ Å and $\varepsilon/k = 410$ K. Values for toluene.[52,53]
- Bath gas = N_2 ($\sigma = 3.919$ Å, $\varepsilon/k_B = 91.85$ K).[54]
- P = 760 Torr, T = 298.15 K
- Grain size = 100 cm^{-1} and automatically determined upper limit to the span of energy grains with threshold population of 1×10^{-15}. A test done with a grain size of 75 cm^{-1} for a subsystem yielded negligible differences suggesting that a grain size of 100 cm^{-1} is suitable.
- Numerical precision = qd. This was found to be necessary for reliable modeling.

Simulation 1

To assess if any of the reversible unimolecular reactions in Scheme S7 are negligible, we did a RRKM-ME modeling of the system treating the products of the unimolecular reaction (excluding R3 and R6) as sinks. The results indicate that the OH H-shifts abstracting the H from a hydroxy group (R7 and R12) are negligible (Table S7) and these are excluded from the final simulation.

Table S7: Final fractional populations in the RRKM modelling of the system outlined in Scheme S7 without the dashed O_2 addition steps and treating all products as sinks. The species with a final fractional population of zero are the only ones not treated as sinks. Treating the products of the reversible H-shifts as sinks likely leads to (potentially significant) overestimation of their importance, see Table S8 for the corresponding results when not treating them as sinks.

Compound	Final Fractional Population
BCP-oxy	0.0
R1-P: *trans*-$C_6H_7O_4$-oxy	0.0
R2-P	5.6×10^{-1}
R3-P: $C_6H_7O_4$-yl (bent)	0.0
R4-P	1.1×10^{-1}
R5-P	1.7×10^{-4}
R6-P: $C_6H_7O_4$-yl (straight)	0.0
R7-P	1.4×10^{-3}
R8-P	1.6×10^{-2}
R9-P	9.9×10^{-2}
R10-P	8.7×10^{-4}
R11-P	2.0×10^{-1}
R12-P	8.4×10^{-4}
R13-P	6.9×10^{-3}
R14-P	1.1×10^{-2}

Simulation 2

Treating the unimolecular H-shifts as sinks likely leads to an overestimation of their importance, as they are reversible. Therefore, we redid the modeling allowing these reactions to be reversible and instead adding an irreversible O_2-addition step as shown by the dashed arrows in Scheme S7. The results from this simulation are shown in Table S8, Figure S14. and summarized in Scheme S8. This MESMER modeling suggests that about 56% of the *trans*-$C_6H_7O_4$-oxy undergoes the dissociation reaction (R2) leading to butenedial and glyoxal and about 44% undergoes the 1,5-aldehydic H-shift to form $C_6H_7O_4$-yl. This result is largely in overall agreement with the results presented by Wang et al.[14], if the $C_6H_7O_4$-oxy in Wang et al.[14] refers to the *trans* isomer. Regarding the reactions of $C_6H_7O_4$-yl, Wang et al.[14] suggests that it exclusively decomposes to ketene-enol, but our calculation suggests that a fraction of $C_6H_7O_4$-yl undergoes CO-loss (R4), which constitutes 14% of the total product from the reactions of *trans*-$C_6H_7O_4$-oxy (Table S8). Thus, CO-loss is an important pathway. The CO-loss is accompanied by a product with five carbon atoms, which provides an alternative pathway to produce lower-carbon-containing products. Zaytsev et al.[55] detected a plethora of C6 products and C8 products in the oxidation of toluene (C7) and 1,2,4-trimethylbenzne (C9), respectively, and noted their formation mechanism is unclear. A few percent of $C_6H_7O_4$-yl undergoes some H-shifts, which could lead to the formation of HOMs.

Table S8: Final fractional populations in the RRKM modelling of the system outlined in Scheme S7 excluding R7 and R12. Decomposition reactions and O_2-additions are modelled as being irreversible. The time profile of the species population is shown in Figure S14. Major pathways are highlighted in bold.

Compound	Final Fractional Population
BCP-oxy	0.0
R1-P: *trans*-$C_6H_7O_4$-oxy	0.0
R2-P	**5.6×10^{-1}**
R3-P: $C_6H_7O_4$-yl (bent)	0.0
R4-P	**1.4×10^{-1}**
R5-P	2.6×10^{-4}
R6-P: $C_6H_7O_4$-yl (straight)	0.0
R8-P	0.0
R8-P-O_2	2.1×10^{-4}
R9-P	0.0
R9-P-O_2	1.2×10^{-2}
R10-P	1.7×10^{-3}
R11-P	**2.7×10^{-1}**
R13-P	0.0
R13-P-O_2	2.8×10^{-3}
R14-P	0.0
R14-P-O_2	1.3×10^{-2}

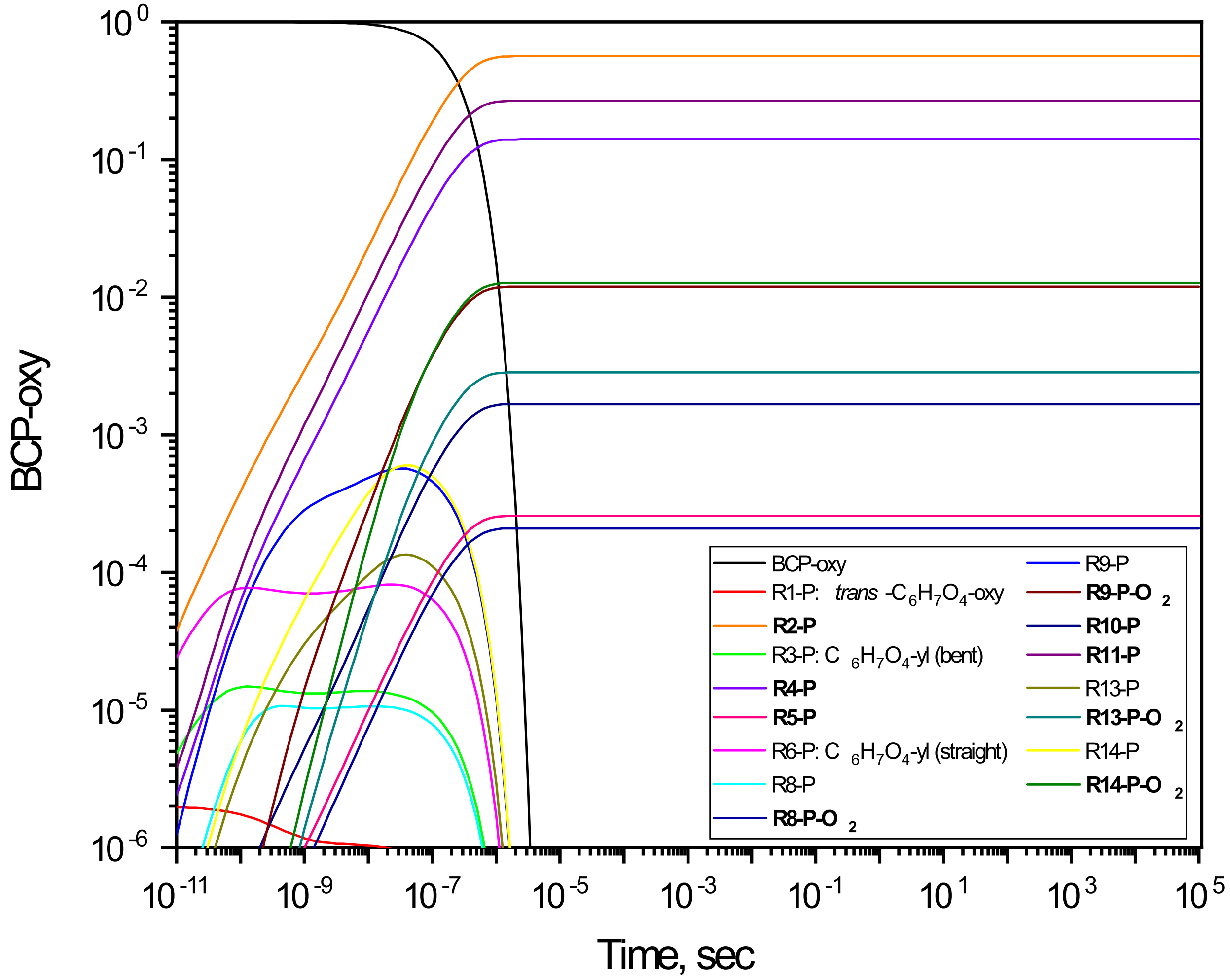
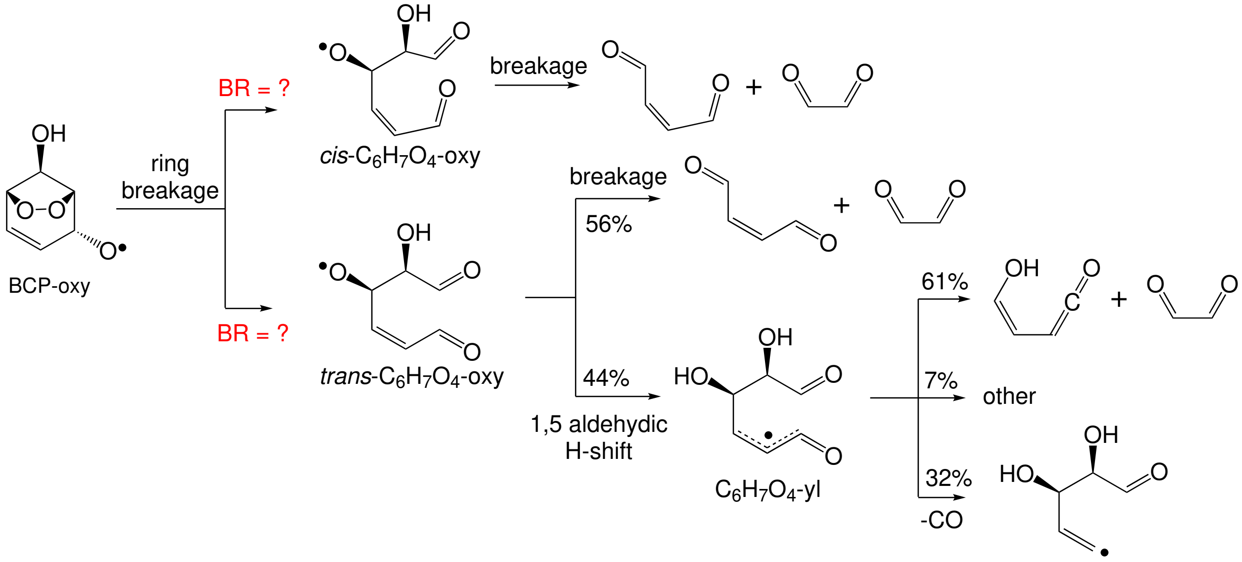


Figure S14: Fractional product population as a function of time in the RRKM-ME modeling of the system shown in Scheme S7 excluding R7 and R12. Products of decomposition reactions and O_2-additions (highlighted in bold in the legend) are treated as sinks. The final product distribution is presented also in Table S8.

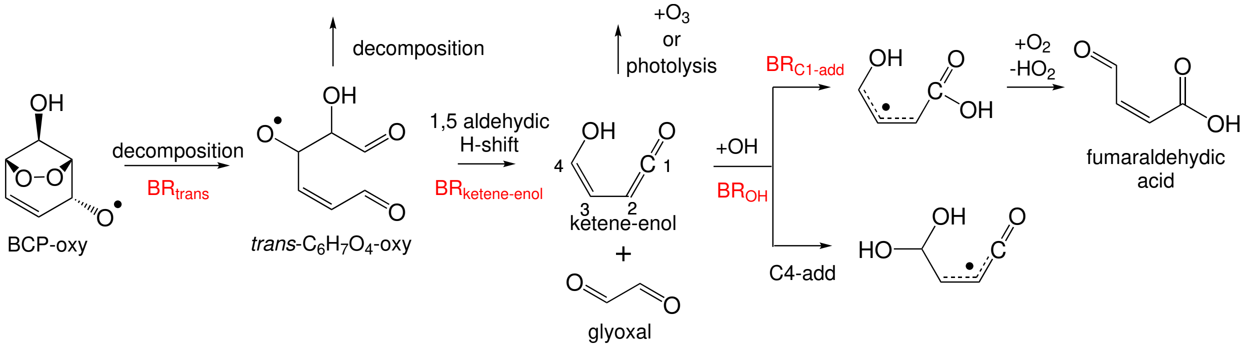
The theoretical findings are summarized in Scheme S8. Our theoretical study suggests that the decomposition of BCP-oxy produces both *cis* and *trans* $C_6H_7O_4$-oxy isomers (Scheme S6). The *cis* isomer dominantly undergoes decomposition, but the *trans* isomer can undergo both decomposition and 1,5-aldehydic H-shift (Table S5). However, the distribution of *cis* and *trans* isomers is unclear and the isomer-specific chemistry is not discussed in Wang et al.[14]. Further, theoretical calculation suggests that about 56% of the *trans*-$C_6H_7O_4$-oxy undergoes the dissociation reaction leading to butenedial and glyoxal and about 44% undergoes the 1,5-aldehydic H-shift to form $C_6H_7O_4$-yl (Table S8). This is largely in overall agreement with the results presented by Wang et al.[14]. In contrast to Wang et al.[14] which suggested that $C_6H_7O_4$-yl exclusive decomposes to ketene-enol, we find that about 30% of $C_6H_7O_4$-yl undergoes CO-loss and an additional 7% undergoes other reactions. The CO-loss constitutes 14% of the total product from the reactions of *trans*-$C_6H_7O_4$-oxy (Table S8).



Scheme S8: Summary of key theoretical findings on BCP-oxy chemistry.

Theoretical yield of fumaraldehydic acid

Under low NOx conditions, the theoretical yield of fumaraldehydic acid (Y_{FAA}) is equal to the product of branching ratios along its formation pathway (Scheme S9 and Eqn. S18)



Scheme S9: Simplified formation mechanism of fumaraldehydic acid from the 1,5-aldehydic H-shift of BCP-oxy based on Wang et al.[14].

$$Y_{FAA} = Y_{BCP-oxy} \cdot BR_{trans} \cdot BR_{ketene-enol} \cdot BR_{OH} \cdot BR_{C1-add} \quad (18)$$

where $Y_{BCP-oxy}$ represents the yield of BCP-oxy, BR_{trans} represents the branching ratio for BCP-oxy decomposition to produce *trans*-$C_6H_7O_4$-oxy isomer, $BR_{ketene-enol}$ represents the branching ratio for ketene-enol formation from *trans*-$C_6H_7O_4$-oxy, BR_{OH} represents the branching ratio for ketene-enol undergoing OH addition, and BR_{C1-add} represents branching ratio for OH addition to the ketene carbon connected to the oxygen (Scheme S9). $Y_{BCP-oxy}$ is roughly 47% under low NO conditions (i.e., NO $<$ a few ppbv) as discussed in the main text. BR_{trans} is unknown and assumed to be 50%. $BR_{ketene-enol}$ is theoretically calculated to be 0.27 (44% × 61% in Scheme S8). BR_{OH} is estimated to be 0.8 based on the [OH] (1.75×10^8 molecule cm^{-3}), [O_3] (∼50 ppb), and $j_{ketene-enol}$ (3.2×10^{-3} s^{-1}) in low NOx experiments (Expts. 8 and 9) in this study. BR_{C1-add} is theoretically calculated to be 0.64 by Wang et al.[14]. Therefore, the theoretical yield of fumaraldehydic acid (FAA) under low NOx conditions is 3.5%.

Wang et al.[14] used formic acid measurement in an laboratory (E)-butenedial photooxidation experiment to evaluate the theoretically calculated fate of ketene-enol. However, the fate of $C_6H_7O_4$-oxy is not experimentally accessed in that study. Here, we select fumaraldehydic acid to constrain the fate of $C_6H_7O_4$-oxy, because it is a unique product following the $C_6H_7O_4$-oxy H-shift and subsequent $C_6H_7O_4$-yl decomposition. Formic acid is also measured in this study, but not used in this analysis because formic acid could be formed from the illumination of the chamber walls and unknown formation pathways.

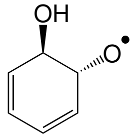
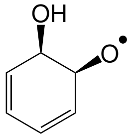
S11: C-oxy chemistry

C-oxy is subject to both ring-closure and ring-breakage. The ratio of two pathways is stereo-specific. The barrier heights of ring-closure and ring-breakage are calculated to be the same for *ortho-anti*-C-oxy (Table S9), suggesting both channels are likely of comparable importance. For *ortho-syn*-C-oxy, however, the barrier height of ring-closure is more than 4 kcal mol^{-1} lower than that of ring-breakage, suggesting ring-closure is likely the dominant fate of *ortho-syn*-C-oxy.

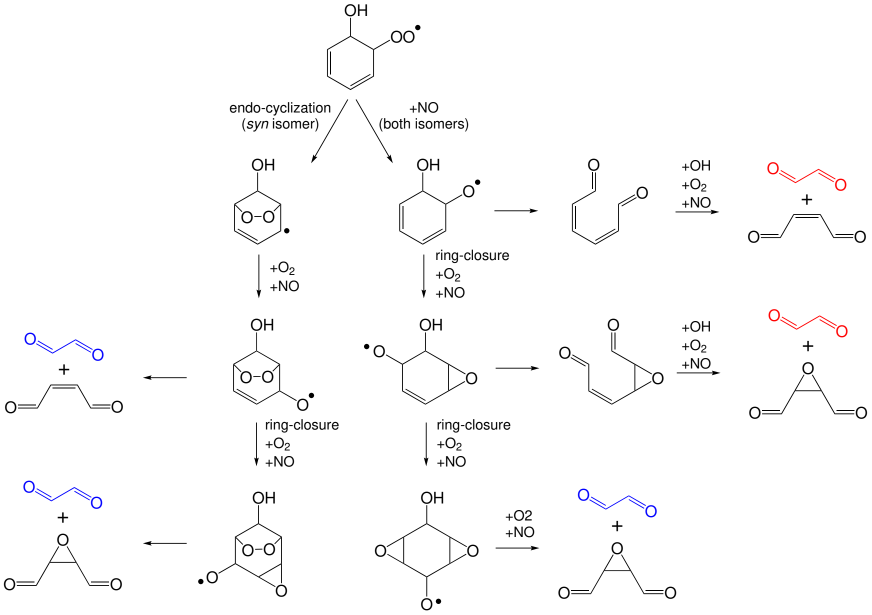
The ring-breakage of C-oxy, followed by O_2 addition and HO_2 elimination, produces 2,4-hexadienedial (muconaldehyde, $C_6H_6O_2$). GC-CIMS resolves two major peaks in the chromotogram of *m/z* 195 ($C_6H_6O_2 \cdot CF_3O^-$)(Figure S6) and the H/D exchange analysis reveals that neither peak has any exchangeable H, consistent with the chemical identify of 2,4-hexadienedial. 2,4-hexadienedial has Z,Z-, E,Z-, and E,E-isomers. Klotz et al.[56] showed that Z,Z-isomer thermally isomerize to the E,Z-isomer with a lifetime of 13 min, a time scale similar to the oxidation time and GC sampling in this study. Thus, the two major peaks resolved by GC-CIMS likely represent E,Z- and E,E isomers.

The total yield of 2,4-hexadienedial (i.e., sum of both isomers) increases with shorter $\tau_{RO_2,\text{bimolecular}}$ (Figure S7), consistent with C-oxy chemistry as its major source. At the shortest $\tau_{RO_2,\text{bimolecular}}$ (10^{-3} s) in this study, the yield is 17%, but still does not reach a plateau, as a result of the fast unimolecular reactions of C-peroxy. At the longest $\tau_{RO_2,\text{bimolecular}}$ (2 s), the yield is low (1%), but non-zero. This is unexpected as C-peroxy predominantly undergoes unimolecular reactions and the formation of C-oxy is negligible under this condition. This non-zero yield implies that some unknown pathway produces 2,4-hexadienedial without the involvement of NO.

Table S9: ωB97X-D/aug-cc-pVTZ barrier heights of the ring-breakage and ring-closure reactions for C-oxy isomers (kcal mol^{-1}).

Isomer	ring-breakage	ring-closure
 *ortho-anti*-C-oxy	2.3	2.3
 *ortho-syn*-C-oxy	5.0	0.8

S12: Literature values of glyoxal yields



Scheme S10: Formation pathways of glyoxal. Primary formation is marked blue and secondary formation is marked red.

Table S10 summarizes literature glyoxal yields and corresponding experimental conditions. To obtain the RO_2 bimolecular lifetime and hence compare the literature data in Figure 4, we input the initial concentrations of species, photolysis rate, oxidation time, as reported by each study, into the kinetic model described in section S5.

Table S10: Reported glyoxal yields at room temperature and pressure.

reference	yield (%)	benzene[a] (ppm)	NO[a] (ppb)	NO_2[a] (ppb)	OH source & conc. (ppm)	j_{NO_2} ($\times10^{-3}$ s^{-1})	ox. time (min)
Tuazon[57]	21±2	10	4.9×10^3	0	CH_3ONO (9.8)	4.4[b]	3
Volkamer[58]	35±10	10	80	40	HONO (0.08)	2.5	85
Berndt[59]	29±10	120-180	18-58	0	CH_3ONO (0.41)	4.7	10.4
Alvarez[60]	42±3	2	6	20	HONO (0.034)	6.7	30
Alvarez[60]	36±2	39	14	37	HONO (0.064)	6.5	30

[a] The concentrations refer to initial values before oxidation.
[b] A biacetyl photolysis rate of 1.25×10^{-4} s^{-1} is reported for 25 kW xenon arc. The j_{NO_2} is difficult to estimate, but assumed to be the same as this study.

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Environmental Science & Technology

New Insights into the Radical Chemistry and Product Distribution in the OH-Initiated Oxidation of Benzene

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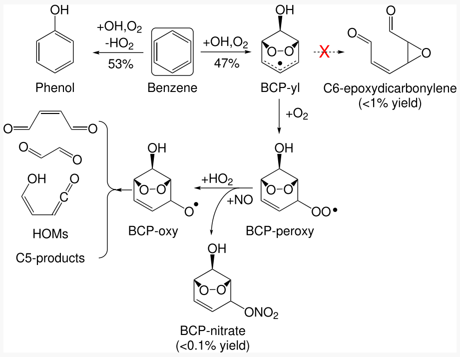
ABSTRACT: Emissions of aromatic compounds cause air pollution and detrimental health effects. Here, we explore the reaction kinetics and products of key radicals in benzene photo-oxidation. After initial OH addition and reaction with O_2, the effective production rates of phenol and bicyclic peroxy radical (BCP-peroxy) are experimentally constrained at 295 K to be 420 ± 80 and 370 ± 70 s^{-1}, respectively. These rates lead to approximately 53% yield for phenol and 47% yield for BCP-peroxy under atmospheric conditions. The reaction of BCP-peroxy with NO produces bicyclic hydroxy nitrate with a branching ratio <0.2%, indicating efficient NO_x recycling. Similarly, the reaction of BCP-peroxy with HO_2 largely recycles HO_x, producing the corresponding bicyclic alkoxy radical (BCP-oxy). Because of the presence of C−C double bonds and multiple functional groups, the chemistry of BCP-oxy and other alkoxy radicals in the system is diverse. Experimental results suggest the aldehydic H-shift and ring-closure to produce an epoxide functionality could be competitive with classic decomposition of alkoxy radicals. These reactions are potential sources of highly oxygenated molecules. Finally, despite the large number of compounds observed in our study, we are unable to account for ∼20% of the carbon flow.



INTRODUCTION

Aromatic compounds are an important class of atmospheric trace species. On a carbon basis, the global emissions of the most atmospherically abundant aromatic compounds, benzene, toluene, ethylbenzene, and xylenes (collectively known as BTEX), account for about 23% of the total anthropogenic non-methane hydrocarbons.[1] Atmospheric aromatics are emitted mainly from the use of fossil fuel (i.e., vehicles, gasoline evaporation, and solvent use) and biomass burning.[2,3] Some aromatic compounds and their oxidation products, such as benzene and nitroaromatics, are known carcinogens.[4,5] The oxidation of aromatics is a major source of secondary pollutants, including ozone and organic aerosol (OA).[6−11] In addition, recent studies reveal significant influences of aromatic chemistry in new-particle formation[12−15] and the chemical evolution of biomass burning smoke.[16−19]

Previous experimental and theoretical studies have extensively investigated the oxidation mechanism of aromatic compounds, as reviewed by Calvert et al.[20] and Vereecken.[21] Reversible, site-specific, and stereo-specific reactions, resulting from the aromaticity, complicate the study of aromatic oxidation.[21] As a result, a number of questions remain unsolved. First, the product yields are uncertain. The yield of phenol, a major product from benzene oxidation, varies from 23 to 61% in the literature.[22−25] Second, carbon mass balance is not achieved using measured product yields. Some products, even though not experimentally confirmed, have been added, ad hoc, to some chemical mechanisms to account for the missing carbon.[26,27] For example, the widely used near-explicit master chemical mechanism (MCM) assumes a yield of more than 10% for an epoxydicarbonylene product in benzene and other aromatic oxidation. However, there is growing evidence that this yield is largely over-estimated.[28,29] Third, the reaction kinetics of organic radicals are poorly constrained. Reaction pathways of key peroxy and alkoxy radicals have been investigated using quantum chemistry methods[28,30−33] but rarely constrained by experimental results.[34,35] Fourth, there have been only a few studies on the yields of hydroxy nitrates for aromatics.[36,37] This uncertainty impedes the prediction of O_3 formation in urban areas.[38] Finally, these uncertainties only grow as the structure of aromatic compounds becomes more complex.

In this study, we investigate the reaction kinetics of key intermediate radicals, reaction mechanisms, and product yields in the OH-initiated oxidation of benzene. Benzene, the simplest homocyclic aromatic compound, serves as a model molecule and provides insights into the chemistry of more structurally complex aromatics.

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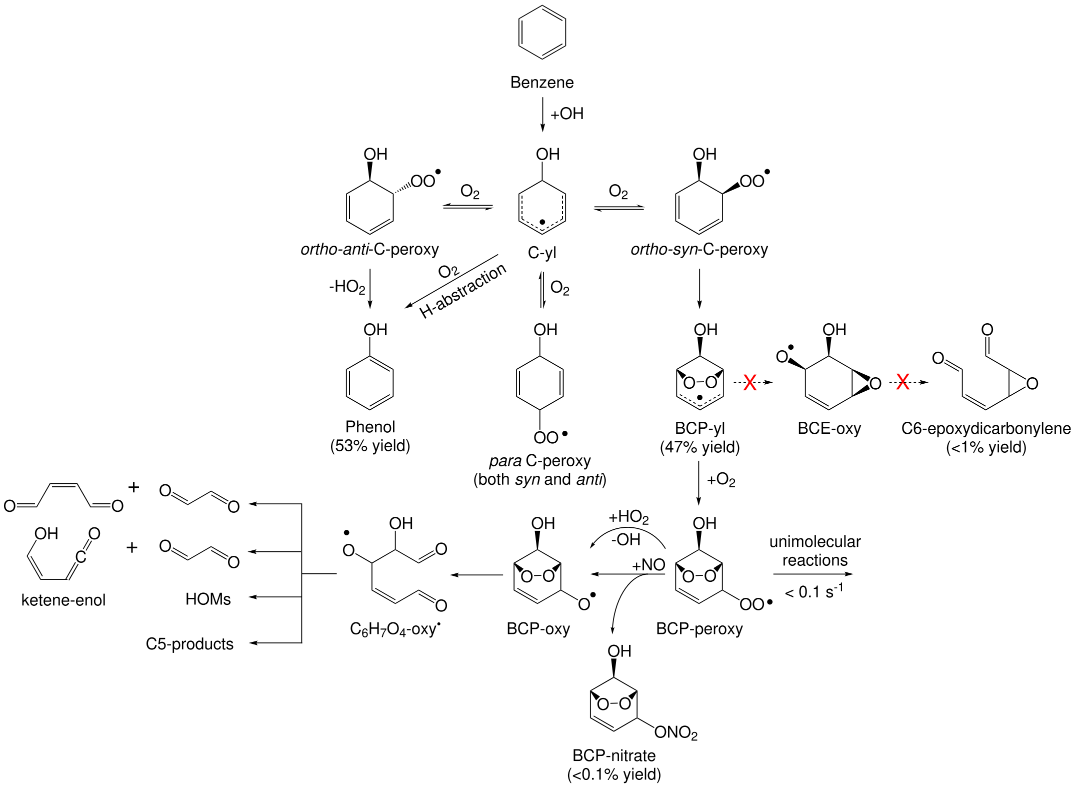
Scheme 1. Key Radicals Discussed in This Study[a]



[a]Some stereoisomers are not shown in the scheme. The naming convention is adopted from Vereecken.[21] "C" refers to ring with 6 carbon atoms and a hydroxy group, "B" refers to bicyclic ring, "P" refers to peroxide ring, and "E" refers to epoxide ring. "yl", "oxy", and "peroxy" refer to alkyl radicals, alkoxy radicals, and peroxy radicals, respectively.

■ METHODS

Experimental Methods. Benzene photo-oxidation experiments are conducted in a 0.8 m^3 FEP Teflon chamber at laboratory temperature (295 K) and pressure (~993 hPa). Experimental conditions are summarized in Section S1 and Table S1. Benzene (99.8% Sigma-Aldrich), CH_3ONO (synthesized following the procedure by Taylor et al.[39]), and NO (1993 ± 20 ppmv, Matheson) are injected into the chamber before oxidation starts. To probe the reaction kinetics of RO_2 chemistry, the initial NO concentration varies from 0 to 5 ppmv. High levels of benzene (i.e., initially roughly 1.5 ppmv) are chosen to minimize the extent of secondary chemistry. Nevertheless, even though only ~6% of the benzene is oxidized, secondary chemistry is inevitable because the OH reaction rate with oxidation products is much faster than with benzene. For the product yields reported here, we account for the secondary loss due to OH oxidation and photolysis by following the procedure by Atkinson et al.[40] (Section S3).

The main instrument used in this study is a customized gas chromatography time-of-flight chemical ionization mass spectrometer (GC-ToF-CIMS).[41] The CIMS is operated in two alternating modes: negative mode with CF_3O^- as the reagent ion and positive mode with $NO{\cdot}H_2O^+$. CF_3O^- selectively interacts with multifunctional oxygenated products to produce either cluster ions or fluoride transfer ions. $NO{\cdot}H_2O^+$ is sensitive to less oxygenated compounds, including aromatics, alkanes, and carbonyl species.[42−45] In the negative mode, the instrumental sensitivity is calibrated for phenol and estimated for compounds without authentic standard based on calculated ion-molecule collision coefficients (Section S2). In the positive mode, the instrumental sensitivity is calibrated for benzene, CH_3ONO, and glyoxal. Details about instrument operation and sensitivities are described in Section S2.

In addition to directly sampling analytes from the reaction chamber, CIMS is coupled with a gas chromatograph (GC). The use of chromatography enables the isomer-resolved detection of oxidation products. The analytes from the reaction chamber are first cryo-trapped on the head of a GC column (2 m Restek RTX-1701) and then eluted by programmed heating with N_2 as carrier gas. Details about the GC operation are in Section S4. The CIMS alternates between directly sampling from the reaction chamber and chromatographic sampling through the GC column.

A chemiluminescene NO_x monitor (Teledyne NO_x M200 EU) and an O_3 monitor (Teledyne O_3 M400E) are deployed alongside the GC-ToF-CIMS. The NO_x instrument is used to monitor the initial concentrations of NO and NO_2 prior to CH_3ONO injection, as CH_3ONO is an interference in both the NO and NO_x channels of this instrument.

To probe the RO_2 chemistry, we calculate the bimolecular lifetime of the peroxy radical ($\tau_{RO_2,\text{bimolecular}} = 1/k_{RO_2+NO}[NO] + k_{RO_2+HO_2}[HO_2]$). Determination of [NO], [HO_2], and reaction rate coefficients is described in Section S5.

Computational Approach. We use the multiconformer transition state theory (MC-TST)[46] approach reported by Møller et al.[47] to investigate the unimolecular reactions of key radicals in the benzene oxidation. Conformers are located using MMFF in Spartan'18 and optimized using B3LYP/6-31+G(d) in Gaussian 16.[48−55] Conformers with relative electronic energies of less than 2 kcal mol^{-1} are further optimized at the ωB97X-D/aug-cc-pVTZ level or ωB97X-D/6-311+G-(d,p).[47,56−58] For the lowest-energy conformer of reactant and TS, an RO-CCSD(T)-F12a/VDZ-F12 (abb. F12) single-point energy calculation is done using Molpro 2012.[59−64] We account for tunneling using the Eckart approach.[65] See Sections S6 and S10 for details.

RESULTS AND DISCUSSION

The chemistry of key organic radicals generated following OH addition is outlined in Scheme 1. The naming convention of these radical intermediates is adopted from Vereecken,[21] as described in the scheme caption. In section C-yl and C-peroxy, we experimentally constrain the production rates of phenol and bicyclic peroxy alkyl radical (BCP-yl) after OH addition to benzene. For typical ambient NO levels, the production rates are similar and lead to a bifurcation with roughly 53% yield for phenol and 47% yield for BCP-yl. In section BCP-yl, we use both experimental results and theoretical calculations to suggest that previously proposed BCP-yl isomerization to C6-epoxydicarbonylene is negligible and the predominant fate of BCP-yl is O_2 addition leading to BCP-peroxy. In section BCP-peroxy, we estimate that the unimolecular reaction rate coefficient of BCP-peroxy is likely less than or equal to 0.1 s^{-1} but with large uncertainty. We also report that the yield of BCP-nitrate, produced from BCP-peroxy + NO reaction, is less than 0.1%. The bimolecular reactions of BCP-peroxy with NO and HO_2 both produce primarily the alkoxy radical BCP-oxy. In section BCP-oxy, we suggest, based on the low measured yield of epoxybutandial ($C_4H_4O_3$), that the major fate of BCP-oxy is ring-breakage, rather than ring-closure as predicted by a theoretical study.[33] The ring-breakage of BCP-oxy produces an aliphatic alkoxy radical $C_6H_7O_4$-oxy, the chemistry of which is discussed in section $C_6H_7O_4$-oxy. We present experimental evidence to support a newly discovered 1,5-aldehydic H-shift of $C_6H_7O_4$-oxy[66] and highlight the uncertainties in the $C_6H_7O_4$-oxy chemistry.

C-yl and C-peroxy. C-yl is produced from OH addition to the aromatic ring. Under atmospheric conditions, the redissociation of C-yl is negligible, and the dominant reactions of C-yl are direct H-abstraction by O_2 to form phenol and reversible O_2 addition to form C-peroxy.[30,35,67] The estimated loss rate of O_2 from C-peroxy is on the order of 10^3 to 10^6 s^{-1} at 298 K, suggesting that the equilibrium between C-yl and C-peroxy is quickly attained.[28]

The O_2 addition is site-specific. O_2 addition was calculated to be faster at the *para* position than the *ortho* position.[28] However, because the reactions of the *ortho*-C-peroxy leading to closed-shell products are calculated to be orders of magnitude faster than those of *para*-C-peroxy,[32] the *ortho* O_2 addition channels are believed to funnel the bulk of the carbon to closed-shell products under atmospheric conditions.

O_2 addition at the ortho position produces *ortho-syn*- and *ortho-anti*-C-peroxy isomers, where the −OH and −OO groups are on the same or opposite sides of the ring, respectively. Both *ortho-syn*- and *ortho-anti*-C-peroxy undergo fast but different unimolecular reactions. Previous theoretical studies suggested that *ortho-syn*-C-peroxy undergoes rapid endo-cyclization to form a five-membered ring with an O−O peroxide bridge (BCP-yl in Scheme 1).[28,30,32,68] This alkyl radical is the most stable among all unimolecular reaction pathways because it is resonance-stabilized, has intermediate ring-strain energy, and has a hydrogen-bonding interaction between the −OH and the −OO− bridge. As summarized in Table S3, the calculated endo-cyclization rate coefficients of *ortho-syn*-C-peroxy in the literature span an enormous range from 3.6×10^2 to 2.5×10^5 s^{-1}. At the F12 MC-TST level, we calculate the endo-cyclization rate coefficient to be 8.1×10^2 s^{-1} at 298.15 K. For α- and β-pinene-derived peroxy radicals, this level of theory agrees with experimental rate coefficients for reactions including comparable endo-cyclizations within a factor of 3.[69]

Possibly because of lack of interaction between −OH and −OO (as in *ortho-syn*-C-peroxy), the endo-cyclization reaction of *ortho-anti*-C-peroxy is calculated to be very slow (3.6×10^{-2} s^{-1} at the F12 level). In contrast, HO_2 elimination, leading to phenol formation, is the fastest unimolecular reaction for *ortho-anti*-C-peroxy, likely due to the weakened C−H bond by the α-OH. We calculate the HO_2 elimination rate to be 1.3×10^2 s^{-1} at 298.15 K, similar to that calculated by Glowacki et al.[28] (4.3×10^1 s^{-1}).

In this study, the measured phenol yield is 0.49 ± 0.13 in experiments under atmospheric NO_x levels, which agrees reasonably with 0.53 ± 0.07 reported by Klotz et al.[34] and 0.61 ± 0.07 reported by Berndt and Böge.[24] Figure 1 shows that the phenol yield decreases with shorter bimolecular lifetime of intermediate radicals ($\tau_{radical,bimolecular}$, which is controlled by C-peroxy + NO and C-yl + NO_2, as shown in Scheme 2), because the bimolecular reactions shorten the time available for the radicals to undergo unimolecular reactions and hence inhibit phenol formation. The $\tau_{radical,bimolecular}$-dependent phenol yield also shows good agreement with that reported by Klotz et al.[34] This $\tau_{radical,bimolecular}$-dependence is omitted in most chemical mechanisms. For example, MCM assumes a constant phenol yield of 0.53.[70] This assumption overestimates the yield of phenol and its oxidation products, which are critical precursors for OA, for laboratory experiments under high NO_x concentration.

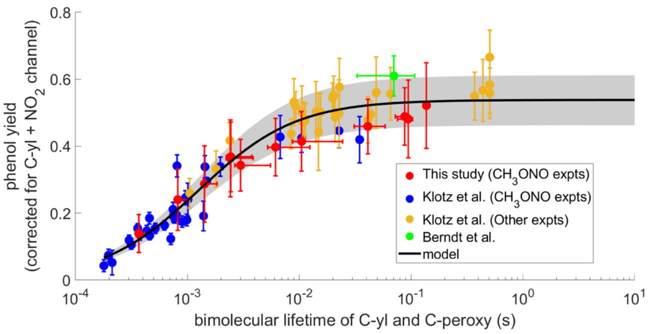
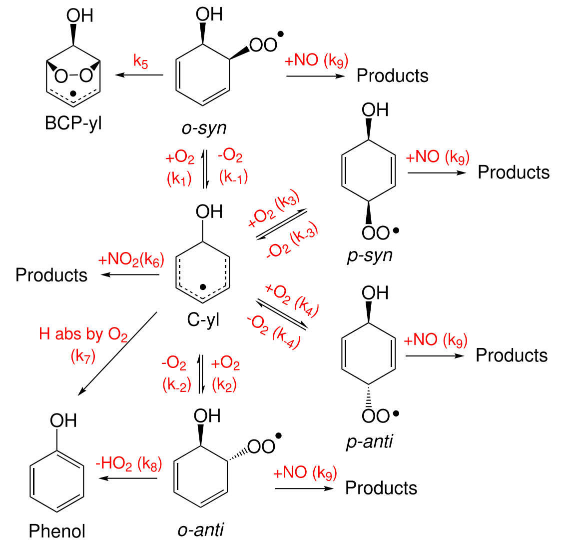


Figure 1. Phenol yield as a function of the bimolecular lifetime of intermediate radicals ($\tau_{radical,bimolecular} = \left(\frac{k_6}{K_{eq2}}\frac{[NO_2]}{[O_2]} + k_9\frac{\Sigma_1^4 K_{eqi}}{K_{eq2}}[NO]\right)^{-1}$). Phenol yields from all studies and theoretical values shown here are corrected for that produced via C-yl + NO_2, as further discussed in Section S3. The shaded region represents the range of uncertainty in k_{phenol} and $k_{endo,eff}$.

The reaction rate coefficients of C-yl and C-peroxy can be experimentally constrained based on the $\tau_{radical,bimolecular}$-dependent phenol yield, following the procedure reported by Klotz et al.[34] The phenol yield can be calculated by the ratio of the formation rate of phenol to the overall loss rate of intermediate radicals (Scheme 2 and eq 1). The intermediate radicals include C-yl ("Cyl" in eq 1) and the four C-peroxy isomers: *ortho-syn*-C-peroxy ("*o-syn*"), *ortho-anti*-C-peroxy ("*o-anti*"), *para-syn*-C-peroxy ("*p-syn*"), and *para-anti*-C-peroxy ("*p-anti*").

Scheme 2. Reaction Scheme of C-yl and C-Peroxy



$$Y_{\text{phenol}} = (k_8[o\text{-}anti] + k_7[\text{Cyl}][\text{O}_2] + k_6\Phi_{\text{phenol,NO}_2}[\text{Cyl}][\text{NO}_2]) / (k_8[o\text{-}anti] + k_7[\text{Cyl}][\text{O}_2] + k_6[\text{Cyl}][\text{NO}_2] + k_5[o\text{-}syn] + k_9([o\text{-}syn] + [o\text{-}anti] + [p\text{-}syn] + [p\text{-}anti])[\text{NO}]) \quad (1)$$

The formation pathways of phenol involve the HO_2 elimination of *ortho-anti*-C-peroxy (k_8), direct H-abstraction of C-yl with O_2 (k_7), and C-yl + NO_2 (k_6 with a phenol yield $\Phi_{\text{phenol,NO}_2}$). In addition to the three pathways leading to phenol, other losses of radicals include the endo-cyclization of *ortho-syn*-C-peroxy (k_5) and bimolecular reaction of C-peroxy + NO (k_9). The C-yl and C-peroxy radicals quickly attain equilibrium, with equilibrium constant $K_{\text{eq}i} = k_i/k_{-i}$ of reactions (i) and ($-i$). Substituting the equilibrium relationships between intermediate radicals into eq 1 leads to eq 2.

$$Y_{\text{phenol}} = \frac{k_8 + \frac{k_7}{K_{\text{eq2}}} + \Phi_{\text{phenol,NO}_2}\frac{k_6}{K_{\text{eq2}}}\frac{[\text{NO}_2]}{[\text{O}_2]}}{k_8 + \frac{k_7}{K_{\text{eq2}}} + \frac{k_6}{K_{\text{eq2}}}\frac{[\text{NO}_2]}{[\text{O}_2]} + k_5\frac{K_{\text{eq1}}}{K_{\text{eq2}}} + k_9\frac{\sum_4^4 K_{\text{eq}i}}{K_{\text{eq2}}}[\text{NO}]} \quad (2)$$

Further, we define the effective phenol formation rate coefficient $k_{\text{phenol}} = k_8 + \frac{k_7}{K_{\text{eq2}}}$ and the effective endo-cyclization rate coefficient $k_{\text{endo,eff}} = k_5\frac{K_{\text{eq1}}}{K_{\text{eq2}}}$ and obtain eq 3.

$$Y_{\text{phenol}} = \frac{k_{\text{phenol}} + \Phi_{\text{phenol}}\frac{k_6}{K_{\text{eq2}}}\frac{[\text{NO}_2]}{[\text{O}_2]}}{k_{\text{phenol}} + \frac{k_6}{K_{\text{eq2}}}\frac{[\text{NO}_2]}{[\text{O}_2]} + k_{\text{endo,eff}} + k_9\frac{\sum_1^4 K_{\text{eq}i}}{K_{\text{eq2}}}[\text{NO}]} \quad (3)$$

Equation 3 is effectively the same as that reported by Klotz et al.[34] but explicitly expresses the unimolecular reactions and the equilibrium relationships of C-yl and C-peroxy isomers. The k_{phenol} and $k_{\text{endo,eff}}$ are determined by fitting eq 3 to the measured yield of phenol under experimental [NO] and $[NO_2]$, together with the kinetic parameters adopted from the literature (Table S4).

Given the good agreement on the $\tau_{\text{radical,bimolecular}}$-dependent phenol yield between this and previous studies (Figure 1), measurements from all studies are exploited to improve the fitting. The optimized k_{phenol} and $k_{\text{endo,eff}}$ are 420 ± 80 and 370 ± 70 s^{-1}, respectively. The k_{phenol} is in excellent agreement with 421 ± 24 s^{-1} reported by Klotz et al.[34] The total loss rate for intermediate radicals, that is, the sum of k_{phenol} and $k_{\text{endo,eff}}$, is estimated to be 790 ± 100 s^{-1} in this study, which agrees within 5% to the measured value reported by Bohn and Zetzsch[35] (760 ± 80 s^{-1}). The endo-cyclization rate of *ortho-syn*-C-peroxy (k_5) is determined to be $(3.9 \pm 0.5) \times 10^3$ s^{-1}, assuming $K_{\text{eq1}}/K_{\text{eq2}}$, as given in Table S4. This value is close to that calculated by Glowacki et al.[28] (3.07×10^3 s^{-1} in Table S3) but a bit faster than the rate coefficient calculated here (8.1×10^2 s^{-1}). One caveat is that the experimentally constrained k_5 is indirectly inferred based on phenol measurement. In theory, k_5 represents the overall rate of all unimolecular reactions of *ortho-syn*-C-peroxy. We interpret $k_{\text{endo,eff}}$ as the effective endo-cyclization rate as guided by quantum chemical calculation that this reaction is the predominant fate of *ortho-syn*-C-peroxy, as discussed earlier in this section.

BCP-yl. The BCP-yl formation from the endo-cyclization of *ortho-syn*-C-peroxy is generally treated as irreversible because of the high barrier[28] (~24 kcal mol^{-1}) of the reverse reaction. BCP-yl can react with O_2 to produce BCP-peroxy. The O_2 addition is stereo-specific. Theoretical calculations suggested that O_2 *anti* addition (i.e., from the opposite side of the −OH and −OO− groups) is sterically favorable and predicted a ratio of 32:1 for *anti* vs *syn* addition.[28,33]

In addition to O_2 addition, one proposed chemistry of BCP-yl is isomerization to produce C6-epoxydicarbonylene ($C_6H_6O_3$, Scheme 1). This product is incorporated in many chemical mechanisms with significant yield (i.e., 11.8% in MCM).[27,70] However, the measured yield of C6-epoxydicarbonylene in this study is very low. Based on GC−CIMS measurements, we observed 10 distinct isomers at *m/z* 211 ($C_6H_6O_3 \cdot CF_3O^-$) (Figure S3). H/D exchange analysis reveals that three isomers do not contain any of the exchangeable H atoms, consistent with the structure of C6-epoxydicarbonylene. As an upper limit, assuming all three of these isomers represent C6-epoxydicarbonylene, the yield is only about 1% under atmospheric conditions (Figure S4). This observation is consistent with a recent study by Zaytsev et al.,[29] who measured the yield of epoxydicarbonylene analogue product in the 1,2,4-trimethyl benzene oxidation to be only 1%.

Two pieces of experimental evidence that were previously cited to qualitatively support the C6-epoxydicarbonylene formation are studies by Yu and Jeffries[71] and Birdsall et al.[72] However, these experiments were performed either under high NO concentration (0.67−10 ppmv), where C-peroxy + NO reaction contributes to C6-epoxydicarbonylene production (discussed in section C-oxy), or under reduced pressure, where the importance of prompt reaction of activated radicals is larger compared to ambient pressure.[28,73] Moreover, $C_6H_6O_3$ includes many isomers and likely confused product identification in previous studies. In conclusion, there is no experimental evidence to support the ~10% yield of C6-epoxydicarbonylene under atmospheric conditions.

Theoretical studies support the low yield of C6-epoxydicarbonylene. The formation of C6-epoxydicarbonylene involves two key reaction steps: the BCP-yl isomerization to BCE-oxy and the ring-breakage of BCE-oxy (Scheme 1). Neither reaction is able to compete with other reaction channels under stabilized conditions. We calculate the isomerization rate coefficient of stabilized BCP-yl to be 2×10^{-2} s^{-1}, orders of magnitude smaller than the effective removal rate of BCP-yl by O_2 addition (Section S8). For the second reaction step, Wang et al.[33] calculated that the ring-breakage of *syn*-BCE-oxy is not competitive with ring-closure (k_{S3} vs k_{S4} in Scheme S2). Therefore, theoretical calculations support experimental results that C6-epoxydicarbonylene production from BCP-yl is negligible.

BCP-peroxy. BCP-peroxy can undergo unimolecular and bimolecular reactions. We use the measurement of BCP-nitrate ($C_6H_7NO_6$, Scheme 1), a minor product from BCP-peroxy + NO reaction, to probe the unimolecular reaction of BCP-peroxy. GC−CIMS resolves five $C_6H_7NO_6$ peaks (Figure S5). Only one peak (eluting at ∼1680 s in Figure S5) is consistent with the structure of BCP-nitrate. This peak arises from molecule(s) with one acidic H atom based on H/D exchange reactions and disappears after adding O_3 to reaction chamber after photo-oxidation, suggesting the presence of a C−C double bond (Section S4). Other isomers are saturated with one acidic H and likely arise from the C-oxy chemistry, as discussed later.

The BCP-nitrate signal shows complex dependence on $\tau_{RO_2,bimolecular}$ (Figure 2), resulting from the conflicting effects of $\tau_{RO_2,bimolecular}$ on the formation and loss of BCP-nitrate precursor, BCP-peroxy. While shorter $\tau_{RO_2,bimolecular}$ (equivalently higher NO concentration) enhances the BCP-peroxy + NO reaction, shorter $\tau_{RO_2,bimolecular}$ inhibits the formation of BCP-peroxy by limiting the unimolecular reaction of *ortho-syn*-C-peroxy. To quantitatively evaluate the above relationship, we use a kinetic model based on Scheme 1. The model uses the reaction rate coefficients inferred from the previous section and treats the unimolecular reaction rate coefficient of BCP-peroxy ($k_{BCP\text{-}peroxy,uni}$) as the only tuning parameter. The major difference between model results with varying $k_{BCP\text{-}peroxy,uni}$ occurs when $\tau_{RO_2,bimolecular}$ is > 1 s, a region lacking experimental constraints (Figure 2). Based on the model and experiment comparison, the unimolecular chemistry of BCP-peroxy is likely less than or equal to 0.1 s^{-1}, though this is uncertain, and requires experiments at longer $\tau_{RO_2,bimolecular}$ to improve the constraint. Two unimolecular reactions of BCP-peroxy, that is, endo-cyclization and 1,5 H-shift of the H adjacent to the hydroxy group, are calculated to be negligibly slow (Scheme S3).

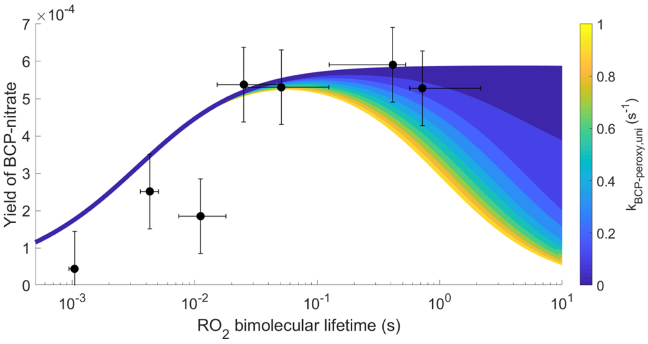


Figure 2. Yield of BCP-nitrate as a function of RO_2 bimolecular lifetime. Measurements are shown as black circles. Modeled yields with different unimolecular reaction rate coefficients of BCP-peroxy ($k_{BCP\text{-}peroxy,uni}$) are shown as contour.

The nitrate product yield for aromatic oxidation has only been studied sparsely. To the best of our knowledge, the only reported BCP-nitrate yield is 3.4% reported by Elrod.[36] The maximum yield of BCP-nitrate is 0.06% in this study (Figure 2). The discrepancy is seemingly dramatic. However, the yield in Elrod[36] could be over-estimated by a factor of 40 because of isomer interference, instrumental sensitivity, and isotope effects on nitrate formation. First, the CIMS used reported by Elrod[36] is unable to resolve structural isomers so that the nitrate product yield represents the sum of all $C_6H_7NO_6$ isomers. Under similar NO_x levels as reported by Elrod,[36] our GC−CIMS measurement suggests that BCP-nitrate only accounts for ∼10% of the total $C_6H_7NO_6$ signal. Second, Elrod[36] used the response factor of 3-nitrato-2-butanol to calibrate BCP-nitrate but noted that the use of *o*-cresol response factor decreases the nitrate yield by a factor of 2. While the instrumental sensitivity of BCP-nitrate in this study is also uncertain, we estimate it to be ∼30% based on calibrations of a suite of hydroxy nitrates produced from small alkenes. Third, the nitrate yield measured by Elrod[36] is from the oxidation of benzene-d_6. We find that the $C_6H_7NO_6$ yield from benzene-d_6 oxidation is 1.8 times that from benzene oxidation under the same experimental condition, an enhancement similar in magnitude to what has been observed previously for α-D substituted peroxy radicals.[74,75] Combining the three effects discussed above, the yield of BCP-nitrate in Elrod[36] could be as low as 0.1%, similar to that reported here. The reason for the unexpectedly low nitrate yield is unclear, but the observation is consistent with a hypothesis that peroxy radicals attached to a ring with an internal alkene have a much lower nitrate yield compared to peroxy radicals of linear terminal alkene with the same number of carbon atoms.[69,76]

In addition to reaction with NO, another important bimolecular reaction of BCP-peroxy is with HO_2. Potential closed-shell products from BCP-peroxy + HO_2 include bicyclic peroxide ($C_6H_8O_5$), bicyclic carbonyl ($C_6H_6O_4$), and bicyclic alcohol ($C_6H_8O_4$). In one experiment, where H_2O_2 photolysis is used as the OH source and BCP-peroxy dominantly reacts with HO_2, the combined yield of all three products is less than 1%. Although the estimated yield is highly uncertain because of instrumental sensitivities, we suggest that the alkoxy radical is likely the major product of the reaction of BCP-peroxy with HO_2. This conjecture is in line with some recent findings and hypotheses.[29,77−79]

BCP-oxy. Two potential reactions of BCP-oxy are ring-breakage and ring-closure (Figure 3a).[24,33,80] The ratio between the two channels is unclear. Wang et al.[33] used computational chemistry methods and suggested ring-closure to be preferential. However, new calculation results from the same group suggest less than 2% of BCP-oxy undergoes ring-closure.[66] Here, we use the measurement of epoxy-butandial ($C_4H_4O_3$), a unique product from BCP-oxy ring-closure pathway, to probe the fate of BCP-oxy. GC−CIMS measurement resolves a peak in $C_4H_4O_3{\cdot}CF_3O^-$, which does not contain any exchangeable H atoms (Section S10) and is consistent with the structure of epoxy-butandial. The yield of this compound is less than 0.2% in experiments under atmospheric conditions (Figure 3a), suggesting that ring-closure is a negligible fate of BCP-oxy. Several factors, including instrumental sensitivity and photochemical reaction rates of epoxy-butandial, introduce uncertainty to the measured yield of epoxy-butandial. These uncertainties are discussed in Section S10 but are not expected to alter the conclusion that ring-breakage is the dominant fate of BCP-oxy.

$C_6H_7O_4$-oxy. The ring-breakage of BCP-oxy produces an alkoxy radical $C_6H_7O_4$-oxy (Figure 3a). Current mechanism assumes that $C_6H_7O_4$-oxy exclusively undergoes decomposition.[33,70,80,81] However, a recent study by Wang et al.[66] calculated that a substantial fraction of $C_6H_7O_4$-oxy undergoes a 1,5-aldehydic H-shift and subsequent decomposition to an

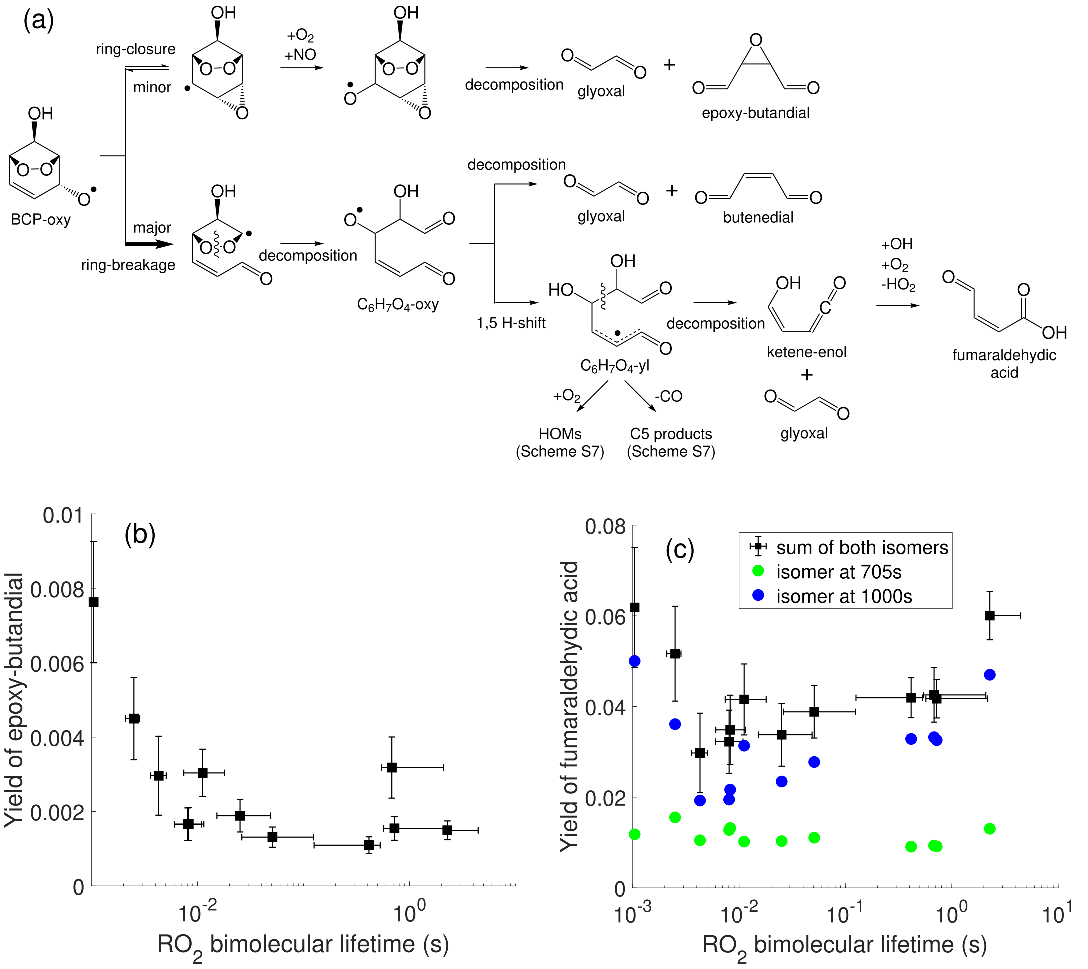
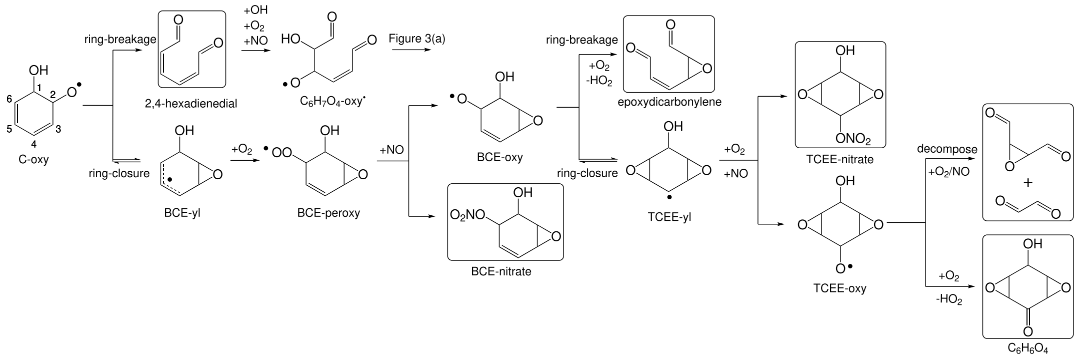


Figure 3. (a) Reactions and products of BCP-oxy. The yields of epoxy-butandial (b) and fumaraldehydic acid (c) as a function of RO_2 bimolecular lifetime. Theoretical investigation on the $C_6H_7O_4$-oxy and $C_6H_7O_4$-yl chemistry is discussed in detail in Section S10.

Scheme 3. Reactions and Products of C-Oxy[a]



[a] O_2 addition to BCE-yl is site- and stereo-specific. Only the C6 addition is shown in the scheme, while the C4 addition leads to isomeric compounds of C6 addition. Products consistent with observed signals are shown in black boxes.

intermediate ketene-enol compound. Here, we test the proposed mechanism based on the measurement of a product from ketene-enol chemistry. Under the experimental conditions in this study, 80% of the ketene-enol is estimated to react with OH (Section S10), and this reaction produces fumaraldehydic acid ($C_4H_4O_3$)[66] (Figure 3a). GC−CIMS resolves two $C_4H_4O_3$ peaks that contain one acidic H atom and decrease after adding O_3 to reaction chamber after photo-oxidation (Section S10). Therefore, these two peaks are consistent with the structure of fumaraldehydic acid. Without standard, the further peak assignment is challenging and we assume both peaks represent fumaraldehydic acid. The summed yield of two peaks is ∼6% under atmospheric conditions (Figure 3c), which agrees reasonably with the theoretically predicted yield of 3.5% (Section S10). As $\tau_{RO_2,\mathrm{bimolecular}}$ decreases, the experimental yield of fumaraldehydic acid shows an initial decrease and then increase. The decrease in fumaraldehydic acid yield is consistent with its proposed formation mechanism, as short $\tau_{RO_2,\mathrm{bimolecular}}$

suppresses the formation of BCP-oxy (via suppressing the endocyclization of *ortho-syn*-C-peroxy). As $\tau_{\mathrm{RO_2,bimolecular}}$ decreases further, reactions other than BCP-oxy chemistry could produce fumaraldehydic acid and cause the increase in its yield. For example, the OH-initiated oxidation of 2,4-hexadienedial ($C_6H_6O_2$) produces $C_6H_7O_4$-oxy (Scheme 3), and the $C_6H_6O_2$ yield is substantially enhanced when $\tau_{\mathrm{RO_2,bimolecular}}$ is shorter than 0.01 s (Figure S7). Overall, experimental results support the occurrence of the alkoxy H-shift of $C_6H_7O_4$-oxy,[66] but we note the branching ratios for $C_6H_7O_4$-oxy reactions require further quantification, as discussed in detail in Section S10.

While our understanding of benzene oxidation is improved by the newly discovered chemistry of $C_6H_7O_4$-oxy, we still cannot identify all pathways. In the presence of a few ppbv NO, the $C_6H_7O_4$-oxy yield is expected to be ~47% based on the branching ratios along its formation pathway, which include (1) 47% of C-yl that produces BCP-peroxy (section C-yl and C-peroxy); (2) reaction of BCP-peroxy with NO almost exclusively produces BCP-oxy (section BCP-peroxy); and (3) BCP-oxy almost exclusively undergoes decomposition to $C_6H_7O_4$-oxy. Given the current understanding, the consumption of one $C_6H_7O_4$-oxy, via either classic decomposition or newly discovered 1,5-aldehydic H-shift, produces one glyoxal molecule (Figure 3a). This leads to an expected yield of glyoxal to be 47%. However, the observed glyoxal yields under a few ppbv NO are much lower (20−30% in Figure 4) and, as a result, roughly 20% of the carbon in the $C_6H_7O_4$-oxy channel is missing. Because in much of the atmosphere, the RO_2 bimolecular lifetime will be longer than 10 s, additional measurements of the glyoxal yield at longer RO_2 lifetimes are recommended.

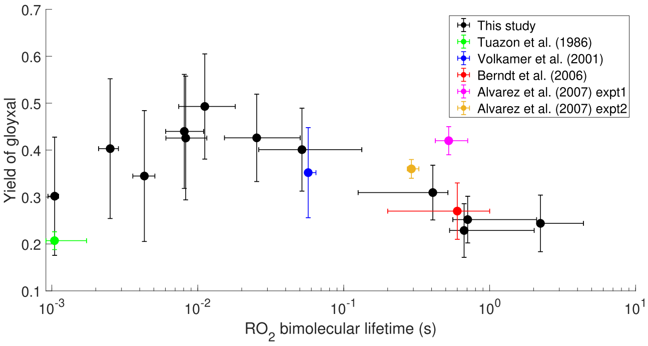


Figure 4. Yield of glyoxal as a function of RO_2 bimolecular lifetime. Details about literature values can be found in Section S12.

We hypothesize that the missing carbon may be attributable to the uncertain chemistry of the BCP-oxy channel. In Section S10, we theoretically investigate the unimolecular reactions of BCP-oxy, $C_6H_7O_4$-oxy, and $C_6H_7O_4$-yl. Following the decomposition of BCP-oxy, the $C_6H_7O_4$-oxy will be formed as both cis and trans isomers with respect to the central bond in the conjugated aldehyde group (Scheme S6). The reaction pathways of these two isomers are different. Decomposition is calculated to be the dominant pathway for *cis*-$C_6H_7O_4$-oxy, while the 1,5 aldehydic H-shift is an important pathway for *trans*-$C_6H_7O_4$-oxy (Scheme S8). The isomer-specific chemistry is not discussed by Wang et al.[66] The isomer distribution of $C_6H_7O_4$-oxy is unknown, but it will determine the distribution of further oxidation products. Regarding $C_6H_7O_4$-yl, it can potentially access a number of unimolecular reactions, given its excess energy and multiple substituents. For example, besides decomposition into ketene-enol, as suggested by Wang et al.,[66] we find that ~30% of $C_6H_7O_4$-yl undergoes CO-loss (Section S10 and Scheme S7) and produces lower-carbon-containing products. ~7% percent of $C_6H_7O_4$-yl undergoes H-shift reactions, which may produce HOMs and is in line with recent detection of HOMs from benzene oxidation.[13,14] The chemistry of these radicals is highly uncertain and warrants further investigation.

C-oxy. Because of the fast unimolecular reactions of C-peroxy, the bimolecular C-peroxy + NO is only important under high NO conditions (>100 ppbv). The C-peroxy + NO reaction produces C-oxy and C-nitrate. Based on the $\tau_{\mathrm{RO_2,bimolecular}}$-dependent C-nitrate yield, we estimate the nitrate branching ratio of C-peroxy + NO to be ~0.9% (Figure S12). This low branching is consistent with that of BCP-peroxy + NO reaction, as discussed in section BCP-peroxy. C-oxy is subject to ring-closure and ring-breakage (Scheme 3). C-oxy chemistry is stereo-specific but is simplified in the following discussion.

Products from Ring-Breakage Reaction. The ring-breakage of C-oxy, followed by O_2 addition and HO_2 elimination, produces 2,4-hexadienedial ($C_6H_6O_2$). GC−CIMS resolves two major peaks in the chromotogram of *m/z* 195 ($C_6H_6O_2 \cdot CF_3O^-$) (Figure S6), which likely represent the *E*,*Z*- and *E*,*E* isomers (Section S11). The total yield of 2,4-hexadienedial (i.e., sum of both isomers) increases with shorter $\tau_{\mathrm{RO_2,bimolecular}}$ (Figure S7), consistent with C-oxy chemistry as its major source.

Products from Ring-Closure Reaction. The ring-closure of C-oxy generates an allylic radical with an epoxide functionality (BCE-yl). Similar to other alkyl radicals discussed in this study, the subsequent O_2 addition to BCE-yl is site- and stereo-specific. BCE-peroxy produced from O_2 addition to C6 of BCE-yl is used as an example in the following discussion. As BCE-peroxy is produced under high NO condition, its dominant fate is reaction with NO, producing BCE-nitrate ($C_6H_7NO_5$) and BCE-oxy. Several isomers of BCE-nitrate are resolved by GC−CIMS (Figure S8), and their yields increase with NO concentration (Figure S9), consistent with the proposed formation pathway.

BCE-oxy is subject to both ring-breakage and ring-closure. The ring-breakage will produce C6-epoxydicarbonylene ($C_6H_6O_3$). The measured yield of C6-epoxydicarbonylene increases with shorter $\tau_{\mathrm{RO_2,bimolecular}}$ (i.e., higher NO concentration), as shown in Figure S4. The $\tau_{\mathrm{RO_2,bimolecular}}$-dependent yield suggests that the formation C6-epoxydicarbonylene involves C-oxy chemistry, instead of previously proposed BCP-yl isomerization, as discussed in section BCP-yl.

The ring-closure of BCE-oxy produces a tricyclic hexyl radical with two epoxide functionalities (TCEE-yl). The formation of TCEE-yl is implied by the detection of its nitrate product (TCEE-nitrate, $C_6H_7NO_6$). Among the five peaks of $C_6H_7NO_6$ resolved by GC−CIMS (Figure S5), four peaks are consistent with TCEE-nitrates, as they only contain one exchangeable H atom and do not decay in the presence of excess ozone (Section S4). TCEE-nitrate is a structural isomer of BCP-nitrate. Without isomer-resolved measurements, product identification based solely on *m/z* would lead to over-estimating the BCP-nitrate yield (section BCP-peroxy).

Glyoxal. Glyoxal is known to be produced in benzene oxidation. We observe a complex dependence of glyoxal yield on $\tau_{\mathrm{RO_2,bimolecular}}$ (Figure 4). The glyoxal yield is about 25% under atmospheric conditions and increases to a maximum of ∼50% when $\tau_{RO_2,bimolecular}$ is about 0.01 s. This $\tau_{RO_2,bimolecular}$-dependence is not contradicted by previous measurements of the glyoxal yields (Figure 4). The $\tau_{RO_2,bimolecular}$-dependent yield arises from the diversity of glyoxal formation pathways (Scheme S10). At long $\tau_{RO_2,bimolecular}$, glyoxal is only produced from the *ortho-syn*-C-peroxy and subsequent BCP-yl chemistry. As $\tau_{RO_2,bimolecular}$ becomes shorter, *ortho-anti*-C-peroxy starts to contribute to glyoxal production via reaction with NO and subsequent C-oxy channel chemistry, thereby increasing the glyoxal yield. When $\tau_{RO_2,bimolecular}$ is shorter than 0.01 s, glyoxal yield decreases with decreasing $\tau_{RO_2,bimolecular}$, likely due to the growing importance of *para*-C-peroxy + NO reaction, which does not lead to primary formation of glyoxal.

ATMOSPHERIC IMPLICATIONS

In this study, we investigate the oxidation mechanism of benzene by means of experimental studies and quantum chemical calculations. The effective production rates of phenol (via direct H-abstraction of C-yl with O_2 and HO_2 elimination of *ortho-anti*-C-peroxy) and BCP-yl (via endo-cyclization of *ortho-syn*-C-peroxy) are estimated to be 420 ± 80 and 370 ± 70 s^{-1}, respectively, at room temperature. These similar rates lead to approximately 53% yield for phenol and 47% yield for BCP-yl under atmospheric conditions. The closed-shell products from the BCP-yl, accounting for ∼47% of the reacted carbon, have not previously been fully characterized. As a consequence, non-experimentally confirmed products, such as C6-epoxydicarbonylene, are included in widely used chemical mechanisms to achieve carbon closure. In this study, however, we measure 1% as the upper limit of the C6-epoxydicarbonylene yield under atmospheric conditions. This is substantially lower than the ∼10% yield assumed in MCM to achieve carbon balance.[70] The negligible yield of epoxydicarbonylene emphasizes that a substantial pool of carbon is missing from the current aromatic oxidation mechanism.

The missing carbon is partly attributable to the BCP-oxy channel, an area of significant uncertainty. The ring-breakage is likely the dominant fate of BCP-oxy, as opposed to ring-closure, based on the low measured yield of BCP-oxy ring-closure product, epoxy-butandial. The ring-breakage of BCP-oxy produces an aliphatic alkoxy radical $C_6H_7O_4$-oxy, the chemistry of which was recently proposed to be more diverse than previously assumed. The proposed 1,5-aldehydic H-shift reaction of $C_6H_7O_4$-oxy[66] is supported by the potential detection of fumaraldehydic acid in this study. However, the branching ratio of $C_6H_7O_4$-oxy reactions is highly uncertain and requires further experimental investigation.

Because of the presence of C−C double bonds and carbonyl groups, the chemistry of alkoxy radicals in aromatic oxidation is more diverse than that in alkane oxidation. In addition to aldehydic H-shift as discussed above, another important pathway for alkoxy radical is ring-closure to produce epoxide functionality. Several epoxide-containing compounds are structural isomers of peroxide-ring containing compounds, for example, TCEE-nitrate versus BCP-nitrate. Product identification based solely on the mass-to-charge ratio could erroneously assign signals and lead to errors in the inferred chemical mechanism.

The aromatic nitrate yield is poorly known and significantly influences the prediction of O_3 production.[38,82] We find here that the branching ratio to form hydroxy nitrates from C-peroxy + NO and BCP-peroxy + NO reactions are approximately 0.9% and 0.2%, respectively. We expect the nitrate yields in the OH-initiated oxidation of toluene and xylenes to be similarly low, given their structure and previously observed trends in nitrate yields.[36] The low nitrate yield in the oxidation of aromatic compounds results in efficient NO_x recycling.

ASSOCIATED CONTENT

SI Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.0c04780.

> Experimental conditions; CIMS operation and sensitivity; yield calculation; GC operation and chromatograms; RO_2 bimolecular lifetime; computational approach; unimolecular reactions of C-peroxy; loss rate of BCP-yl; unimolecular reactions of BCP-peroxy; BCP-oxy chemistry; C-oxy chemistry; and literature values of glyoxal yields (PDF)

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Notes

The authors declare no competing financial interest.

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