

Pressure dependent OH yields in the reactions of CH_3CO and HOCH_2CO with O_2

Cite this: *Phys. Chem. Chem. Phys.*,
2014, 16, 10990

C. B. M. Groß, T. J. Dillon† and J. N. Crowley*

OH-formation in the reactions of CH_3CO (R1) and HOCH_2CO (R4) with O_2 was studied in He, N_2 and air (27 to 400 mbar) using OH-detection by laser induced fluorescence (LIF). 248 nm laser photolysis of COCl_2 in the presence of CH_3CHO or HOCH_2CHO was used as source of the acyl radicals CH_3CO and HOCH_2CO . The LIF-system was calibrated in back-to-back experiments by the 248 nm laser photolysis of H_2O_2 as OH radical precursor. A straight-forward analytical expression was used to derive OH yields (α) for both reactions. A Stern–Volmer-analysis results in $\alpha_{1b}^{-1}(\text{N}_2) = 1 + (9.4 \pm 1.7) \times 10^{-18} \text{ cm}^3 \text{ molecule}^{-1} \times [\text{M}]$, $\alpha_{1b}^{-1}(\text{He}) = 1 + (3.6 \pm 0.6) \times 10^{-18} \text{ cm}^3 \text{ molecule}^{-1} \times [\text{M}]$ and $\alpha_{4b}^{-1}(\text{N}_2) = 1 + (1.85 \pm 0.38) \times 10^{-18} \text{ cm}^3 \text{ molecule}^{-1} \times [\text{M}]$. Our results for CH_3CO are compared to the previous (divergent) literature values whilst that for HOCH_2CO , for which no previous data were available, provide some insight into the factors controlling the yield of OH in these reactions.

Received 14th March 2014,
Accepted 15th April 2014

DOI: 10.1039/c4cp01108b

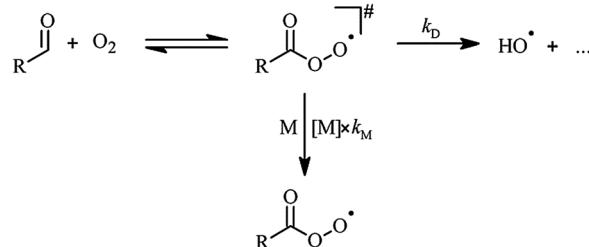
www.rsc.org/pccp

1 Introduction

Acetyl radicals (CH_3CO) play an important role in atmospheric chemistry. Important sources of acetyl radicals are the photolysis of acetone in the upper troposphere and the reaction of acetaldehyde with OH in the troposphere. The hydroxyl-substituted hydroxy acetyl radicals (HOCH_2CO) are formed in the reaction of OH with glycol aldehyde (HOCH_2CHO). The only significant reaction of acetyl and hydroxy acetyl radicals in the atmosphere is with O_2 , forming (mainly) peroxy radicals. Accompanying peroxy radical formation, (R1) displays a second reaction pathway forming OH and an organic by-product. The branching ratio (α) for formation of OH increases from small values (<2%) at standard pressure to unity at pressures close to zero.^{1,2}



Reaction (R1) is considered to proceed *via* an excited peroxy radical $\text{CH}_3\text{C}(\text{O})\text{O}_2^\#$ that is either stabilised by collisions with the bath gas molecules M or decomposes to form OH.^{2–9} This is illustrated in reaction Scheme 1 (R = CH_3). The pressure dependence of α thus originates from the competition between the pressure- and bath gas-dependent quenching rate $[\text{M}] \times k_{\text{M}}$ and the pressure-independent decomposition rate k_{D} . A kinetic

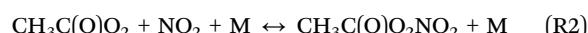


Scheme 1 Generalised mechanism for the reactions of CH_3CO ($\text{R} = \text{CH}_3$) and HOCH_2CO ($\text{R} = \text{HOCH}_2$) with O_2 .

(Stern–Volmer) analysis of the reaction scheme leads to eqn (1) which can be used to parameterise α :

$$\alpha^{-1} = 1 + \frac{k_{\text{M}}}{k_{\text{D}}} [\text{M}] \quad (1)$$

Although OH yields are low at pressures typical for the troposphere, (R1b) has an indirect impact on atmospheric chemistry because of its occurrence in laboratory experiments. The OH product of (R1b) has, for example, been used as spectroscopic marker for CH_3CO formation in the determination of photo-dissociation quantum yields for acetone,¹⁰ an important source of HOx radicals and PAN ($\text{CH}_3\text{C}(\text{O})\text{O}_2\text{NO}_2$) in the upper troposphere.^{11,12} Recent studies on the yield of OH in the reaction between $\text{CH}_3\text{C}(\text{O})\text{O}_2$ and HO_2 observed OH from (R1).¹³ The title reaction will also have occurred in and potentially impacted on the results of studies of PAN formation in (R2) at low pressures where the yield of OH is large.



Max-Planck-Institut für Chemie, 55128 Mainz, Germany.

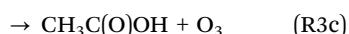
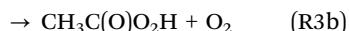
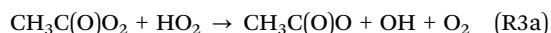
E-mail: john.crowley@mpic.de

† Present address: Department of Chemistry, University of York, York, YO10 5DD, UK.



For example, in their study of PAN formation, Bridier *et al.*¹⁴ generated CH₃CO radical in the presence of O₂ to examine the kinetics of the reaction of CH₃C(O)O₂ + NO₂ (R2) at pressures down to 20 mbar. As the results of the present publication show, at such pressures 18% of CH₃CO reacting with O₂ forms OH instead of CH₃C(O)O₂. Data recorded at low pressure by Bridier *et al.* might thus be subject to systematic error since reaction channel (R1b) was not known to take place in 1991.

The reaction of CH₃C(O)O₂ with HO₂ (R3), which competes with (R2) at low NO_x levels,¹⁵ has drawn considerable interest in recent years.^{13,16–18} Its main reaction channel (R3a) preserves a HO_x species (HO_x is OH + HO₂) and an organic radical and is hence radical-propagating, which helps sustain atmospheric oxidation capacity.



In experiments on (R3), CH₃C(O)O₂ and HO₂ are usually generated by reaction of Cl atoms with CH₃CHO and CH₃OH in air involving intermediate generation of CH₃CO and CH₂OH radicals. Therefore, OH-generation influences the initial [CH₃C(O)O₂]/[HO₂]-ratio in these experiments. In product studies that do not allow for an experimental separation between different OH-formation routes, (R1b) must be well known so that discrimination between OH formed in (R1b) and (R3a), respectively, is possible.

In the present work we employ a new experimental approach to quantify the pressure-dependence of the OH forming channels (R1b) and (R4b) of the reactions of O₂ with CH₃CO and its OH-substituted analogue HOCH₂CO.



We assume that, for reaction (R4), the same pathways are available as in (R1), *i.e.* competition between peroxy-radical formation and OH (see Scheme 1, R = HOCH₂). The formation of the peroxy radical, its UV-absorption spectrum and its reaction with HO₂ will be subject of a future publication from this group.

Throughout this work the branching ratios of the OH-forming reaction channels are defined as follows: $k_{1b}/k_1 = \alpha_{1b}$ and $k_{4b}/k_4 = \alpha_{4b}$.

2 Experimental

2.1 Experimental set-up

The experiments detailed in this publication were performed using the pulsed laser photolysis-laser induced fluorescence (PLP-LIF) apparatus that has been described previously^{19,20} and only a short description is given here. Experiments were conducted in a 500 cm³ reactor at room temperature. The pressure was monitored with a capacitance manometer, and gas flow rates were selected such that a fresh gas sample was available for photolysis at each laser pulse. Reactions were performed at

pressures between 27 and 400 mbar in nitrogen and helium bath gases with added O₂ or in air.

Reactions were initiated by the 248 nm photolysis of H₂O₂ (8–12 × 10¹⁴ molecule cm^{−3}) or COCl₂ (3–11 × 10¹⁵ molecule cm^{−3}) using an excimer laser (Lambda Physik). Laser fluences of 39–55 mJ cm^{−2} per pulse resulted in formation of 0.3–0.5 × 10¹² OH radicals cm^{−3} or 1–5 × 10¹² Cl-atoms cm^{−3}. Two absorption cells located upstream of the reactor enabled on-line concentration measurements of the reactants at 185 nm and 214 nm. The optical path-lengths of the absorption cells are $l_{185} = 43.8$ cm and $l_{214} = 34.8$ cm.

Fluorescence from OH was detected by a photomultiplier tube shielded by a 309 nm interference filter and a BG 26 glass cut-off filter. The frequency doubled emission from a Nd-YAG-pumped dye laser (Quantel, Lambda Physik) was used to excite the A²Σ(ν = 1) ← X²Π(ν = 0), Q₁₁ (1) transition of OH at 281.997 nm.

2.2 Chemicals

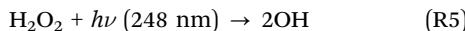
Liquid samples of CH₃CHO (Roth, ≥99.5%) were degassed by repeated evacuation, and stored in a blackened glass bulb as ~1% mixture in N₂. HOCH₂CHO was prepared during the experiments from its dimer (Sigma-Aldrich) by heating the solid sample to 50–75 °C and eluting gaseous HOCH₂CHO by a continuous flow of N₂. COCl₂ (Fluka, >99%) was stored in a stainless steel canister as ~4% mixture in N₂ or He. H₂O₂ (AppliChem, 50%) was concentrated in vacuum to >80% and used as liquid sample. He (Westfalen, 99.999%), N₂ (Westfalen, 99.999%) and O₂ (Westfalen, 99.999%) were used as supplied.

3 Results

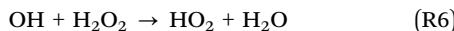
3.1 Experimental approach

We performed back-to-back experiments in reaction mixtures containing either H₂O₂ or COCl₂ as photolytic sources of OH radicals or Cl atoms. Addition of CH₃CHO or HOCH₂CHO to the COCl₂ experiments converted Cl atoms into CH₃CO or HOCH₂CO, which reacted with O₂ to form OH. This allowed us to compare OH formation *via* title reactions (R1b) and (R4b) directly with OH production from H₂O₂-photolysis, a well-characterized source of OH radicals. Formation of acyl radicals by the reaction of Cl atoms with CH₃CHO ($\Delta H = -58$ kJ mol^{−1})¹⁸ or HOCH₂CHO ($\Delta H = -49$ kJ mol^{−1})^{18,21} are exothermic processes and the nascent fragments are expected to be vibrationally and rotationally hot. Assuming an energy transfer efficiency of 300 cm^{−1} per collision with N₂, hot CH₃CO would be deactivated within 16 collisions, ensuring that, at the high pressures of bath gases used in this study, acetyl should, to a good approximation, be thermalized before reaction with O₂ takes place. Experiments in which N₂ was mixed with 1% O₂ yielded the same results as those with 21% O₂, so that no evidence was obtained for reaction of non-thermalised CH₃CO with O₂. Even in the experiments in He (presumably a less efficient energy transfer medium than N₂) no dependence of the OH-yield on O₂ partial pressure was obtained. We note also that the existence of a direct channel for OH-formation from excited CH₃CO and O₂ is considered unlikely.⁹

3.1.1 Determination of α . The OH-LIF system was calibrated by photolysing H_2O_2 that, at 248 nm, generates OH radicals with a quantum yield of 2.²²



Quasi-instantaneous photolytic OH-formation and subsequent OH loss *via* (R6) result in a mono-exponential decay of [OH] that was recorded by OH-LIF.



The LIF-signal is proportional to [OH] and was fitted by eqn (2) where f_{cal} is a calibration factor that quantifies the sensitivity of the LIF-system.

$$\text{LIF}(t) = f_{\text{cal}} \times [\text{OH}](t) = s_{\text{OH}} \times e^{-\alpha_{\text{OH}} \cdot t} \quad (2)$$

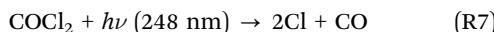
where α_{OH} and s_{OH} represent the fitted parameters. Due to the low conversion of H_2O_2 (<0.1%) its concentration, $[\text{H}_2\text{O}_2]$, can be considered constant over the course of the reaction. With $k_6' = k_6 \times [\text{H}_2\text{O}_2]$, and $[\text{OH}]_0$ as the initial OH concentration, the temporal evolution of [OH] can be described by the integrated rate law for first-order kinetics:

$$[\text{OH}](t) = [\text{OH}]_0 \times e^{-k_6' \cdot t} \quad (3)$$

Combining eqn (2) and (3) we get:

$$f_{\text{cal}} [\text{OH}]_0 = s_{\text{OH}} \quad (4)$$

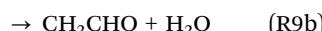
In back-to-back experiments, H_2O_2 was replaced by COCl_2 and an acyl radical source (CH_3CHO or HOCH_2CHO). Photolysis of COCl_2 generates Cl atoms with a quantum yield of 2.^{23,24}



Reaction of Cl with CH_3CHO (R8) forms CH_3CO with a yield very close to unity ($k_8 = 8.0 \times 10^{-11} \text{ cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$).¹⁷



OH formation in reaction (R1b) and its main loss *via* reaction (R9) are both resolved on the time-scale of our experiments and a bi-exponential time-dependence of the LIF-signal is observed ($k_9 = 1.5 \times 10^{-11} \text{ cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$).^{17,18}



Reaction with OH generates mainly CH_3CO ($\alpha_{9a} = 0.95$) which is accounted for in the analytical expression of the [OH] time evolution presented below. Only 5% of the OH formed in (R1) is thus converted *via* (R9b) into CH_2CHO . Even if CH_2CHO were converted with unity yield into OH radicals, this would result in a maximum overestimation of no more than 5% in the value of α_{1b} .

Measured LIF-profiles were analysed using eqn (5).

$$\text{LIF}(t) = f_{\text{cal}} \times [\text{OH}](t) = s_{\text{Cl}} \frac{a_{\text{Cl}1}}{a_{\text{Cl}1} - a_{\text{Cl}2}} (e^{-a_{\text{Cl}1} t} - e^{-a_{\text{Cl}2} t}) \quad (5)$$

where $a_{\text{Cl}1}$, $a_{\text{Cl}2}$ and s_{Cl} represent the fitted parameters. Under the assumptions that (R1) is fast compared to (R8) and (R9) and

that $[\text{CH}_3\text{CHO}]$ remains constant on the experimental time-scale, an analytical expression for the temporal evolution of [OH] can be derived.

$$[\text{OH}](t) = \frac{\alpha_{1b} k_8' [\text{Cl}]_0}{(1 - \alpha_{1b} \alpha_{9a}) k_9' - k_8'} (e^{-k_8' t} - e^{-(1 - \alpha_{1b} \alpha_{9a}) k_9' t}) \quad (6)$$

In this expression, $k_8' = [\text{CH}_3\text{CHO}] \times k_8$, $k_9' = [\text{CH}_3\text{CHO}] \times k_9$ and $[\text{Cl}]_0$ is the Cl-concentration initially formed by photolysis. Conditions were chosen such that reaction (R1) was 5.2–250 times faster than (R8), and 28–1300 times faster than (R9) and thus fast on the experimental time-scale of ~ 1 ms. Combining eqn (5) and (6) we get:

$$\alpha_{1b} f_{\text{cal}} [\text{Cl}]_0 = s_{\text{Cl}} \quad (7)$$

f_{cal} can be eliminated from eqn (7) by insertion of eqn (4) because experiments were conducted back-to-back.

$$\alpha_{1b} = \frac{s_{\text{Cl}}}{s_{\text{OH}}} \times \frac{[\text{OH}]_0}{[\text{Cl}]_0} \quad (8)$$

This assumes that fluorescence quenching is dominated by the bath gas and that the contribution of reactants is negligible so that switching between H_2O_2 and COCl_2 /aldehyde does not change the detection sensitivity to OH. The experiments performed in He, which is a weak quencher of OH-fluorescence, are the most likely to be influenced, should this not be the case. In Section 3.3 we show however that such quenching effects did not have a measurable effect on the results obtained.

The initial concentrations $[\text{OH}]_0$ and $[\text{Cl}]_0$ were calculated from $[\text{H}_2\text{O}_2]$ and $[\text{COCl}_2]$, the respective 248 nm cross sections and the number of photons per photolysis pulse n_{Phot} . We then derive:

$$\begin{aligned} \alpha_{1b} &= \frac{s_{\text{Cl}}}{s_{\text{OH}}} \times \frac{\Phi_{\text{H}_2\text{O}_2}^{248} n_{\text{Phot}} (1 - e^{-\sigma_{\text{H}_2\text{O}_2}^{248} [\text{H}_2\text{O}_2]})}{\Phi_{\text{COCl}_2}^{248} n_{\text{Phot}} (1 - e^{-\sigma_{\text{COCl}_2}^{248} [\text{COCl}_2]})} \\ &= \frac{s_{\text{Cl}}}{s_{\text{OH}}} \times \frac{1 - e^{-\sigma_{\text{H}_2\text{O}_2}^{248} [\text{H}_2\text{O}_2]}}{1 - e^{-\sigma_{\text{COCl}_2}^{248} [\text{COCl}_2]}} \end{aligned} \quad (9)$$

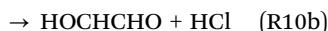
Since the laser intensity remained stable (within $\sim 1\%$) during back-to-back experiments, n_{Phot} cancels out as do the quantum yields of OH formation ($\Phi_{\text{H}_2\text{O}_2}^{248}$) and Cl formation ($\Phi_{\text{COCl}_2}^{248}$) that both equal 2. The precursor concentrations $[\text{H}_2\text{O}_2]$ and $[\text{COCl}_2]$ were calculated from the respective optical depths $OD_{\text{H}_2\text{O}_2}^{214}$ and $OD_{\text{COCl}_2}^{214}$ measured at 214 nm in a separate absorption cell (see Section 2.1).

$$[\text{precursor}] = \frac{OD_{\text{precursor}}^{214}}{\sigma_{\text{precursor}}^{214} l_{214}} \quad (10)$$

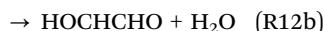
HOCH_2CHO was used as acyl radical precursor in experiments for the determination of α_{4b} . Reaction of Cl atoms with HOCH_2CHO (R10) forms HOCH_2CO with a yield of



$\alpha_{10a} = 0.65$ ($k_{10} = 7.5 \times 10^{-11} \text{ cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$).^{25,26} Reaction of HOCHCHO with O₂ (R11), is not known to form OH.^{25,26}



Reaction with HOCH₂CHO (R12) is the main OH loss channel in these experiments.



Reaction with OH generates HOCH₂CO with a higher yield ($\alpha_{12a} = 0.80$) than reaction with Cl. Based on this kinetic scheme, one again expects a bi-exponential time profile of [OH] that can be analysed by eqn (5). The temporal evolution of [OH] is described by the integrated rate law (11) which was derived analytically assuming reaction (R4) to be fast compared to reactions (R10) and (R12) and that [HOCH₂CHO] was not significantly depleted during the experiments.

$$[\text{OH}](t) = \frac{\alpha_{10a}\alpha_{4b}k_{10}'[\text{Cl}]_0}{(1 - \alpha_{4b}\alpha_{12a})k_{12}' - k_{10}'} \left(e^{-k_{10}'t} - e^{-(1 - \alpha_{4b}\alpha_{12a})k_{12}'t} \right) \quad (11)$$

with $k_{10}' = [\text{HOCH}_2\text{CHO}] \times k_{10}$ and $k_{12}' = [\text{HOCH}_2\text{CHO}] \times k_{12}$. Under the experimental conditions applied in this work and assuming the rate coefficients of (R1) and (R4) to be equal, (R4) was 12 to 280 times faster than (R10) and 110 to 2700 times faster than (R12) and, thus, fast on the experimental time-scale of ~ 1 ms. As for the CH₃CO + O₂ system we can derive an analytical expression for α_{4b} from eqn (4) and (11).

$$\alpha_{4b} = \frac{1}{\alpha_{10a}} \cdot \frac{s_{\text{Cl}}}{s_{\text{OH}}} \cdot \frac{1 - e^{-\sigma_{\text{H}_2\text{O}_2}^{248}[\text{H}_2\text{O}_2]}}{1 - e^{-\sigma_{\text{COCl}_2}^{248}[\text{COCl}_2]}} \quad (12)$$

α_{4b} can thus be derived from measurement of $OD_{\text{H}_2\text{O}_2}^{214}$, $OD_{\text{COCl}_2}^{214}$, s_{OH} and s_{Cl} , the absorption cross sections of COCl₂ and H₂O₂ at 214 nm and 248 nm and the branching ratio α_{10a} .

3.1.2 Error estimation. The exponentials in eqn (9) and (12) can be expanded in a Taylor series that is stopped after the second term. By insertion of eqn (9) and (10) thus becomes

$$\alpha_{1b} \approx \frac{s_{\text{Cl}}}{s_{\text{OH}}} \cdot \frac{\sigma_{\text{H}_2\text{O}_2}^{248} \cdot \sigma_{\text{COCl}_2}^{214} \cdot OD_{\text{H}_2\text{O}_2}^{214}}{\sigma_{\text{COCl}_2}^{248} \cdot \sigma_{\text{H}_2\text{O}_2}^{214} \cdot OD_{\text{COCl}_2}^{214}} \quad (13)$$

Similarly, eqn (12) becomes

$$\alpha_{4b} \approx \frac{1}{\alpha_{10a}} \cdot \frac{s_{\text{Cl}}}{s_{\text{OH}}} \cdot \frac{\sigma_{\text{H}_2\text{O}_2}^{248} \cdot \sigma_{\text{COCl}_2}^{214} \cdot OD_{\text{H}_2\text{O}_2}^{214}}{\sigma_{\text{COCl}_2}^{248} \cdot \sigma_{\text{H}_2\text{O}_2}^{214} \cdot OD_{\text{COCl}_2}^{214}} \quad (14)$$

This allows us to separate statistical errors, *i.e.* reading errors or uncertainties in the determinations of s_{OH} and s_{Cl} which are small, from the systematic errors originating from uncertainties in literature values of the absorption cross sections and, in the case of α_{4b} , the branching ratio $\alpha_{10a} = 0.65 \pm 0.05$.²⁵ To reduce systematic error, absorption cross sections were taken from literature sources that specify values for both wavelengths used in this work. Values for

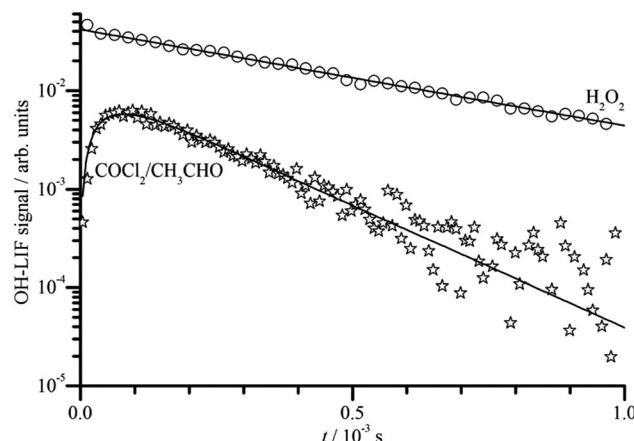


Fig. 1 OH-LIF profiles measured in back-to-back experiments in 133 mbar of N₂ bath gas with 1% O₂. The solid lines are fits to expressions (2) and (5).

H₂O₂ were taken from Vaghjiani *et al.*,²⁷ values for COCl₂ were taken from Meller *et al.* whose data are published in the MPI-Mainz UV/VIS Spectral Atlas²⁸ ($\sigma_{\text{H}_2\text{O}_2}^{214} = 33.0 \pm 2.2$, $\sigma_{\text{H}_2\text{O}_2}^{248} = 9.23 \pm 0.70$, $\sigma_{\text{COCl}_2}^{214} = 11.3 \pm 1.1$ and $\sigma_{\text{COCl}_2}^{248} = 8.96 \pm 0.90$ all values given in units of $10^{-20} \text{ cm}^2 \text{ molecule}^{-1}$).

3.2 CH₃CO + O₂ (N₂/O₂)

Back-to-back PLP-LIF-experiments on (R1) were performed at pressures between 133 and 270 mbar of N₂ or at 27 and 270 mbar of air. Fig. 1 shows a pair of OH-profiles recorded at 133 mbar in N₂. Both OH-profiles display the expected kinetics and were analysed using eqn (2) or (5), respectively. Although this work was not performed to re-measure the rate-coefficients of reactions (R8) and (R9), we did derive them from the fit-parameters and the respective [CH₃CHO] as a check of our experimental approach. We obtained $k_8 = (7.4 \pm 1.1) \times 10^{-11} \text{ cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$, and $k_9 = (1.8 \pm 0.2) \times 10^{-11} \text{ cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$ where the uncertainties represent statistical errors (2σ) in the fit-parameters only. [CH₃CHO] was determined barometrically and carries an additional uncertainty of $\sim 20\%$. Our values are, within these uncertainties, in accordance with the currently recommended literature values of $k_{8,\text{Lit}} = (8.0^{+1.4}_{-1.2}) \times 10^{-11} \text{ cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$, and $k_{9,\text{Lit}} = (1.5 \pm 0.2) \times 10^{-11} \text{ cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$.^{17,18}

Fig. 2 shows the results of all single experiments as a plot of the reciprocal of α_{1b} against [M]. A linear regression of the data resulted in (all errors statistical, 2σ)

$$\alpha_{1b}^{-1}(\text{N}_2) = (0.55 \pm 1.81) + (9.52 \pm 0.72) \times 10^{-18} \text{ cm}^3 \text{ molecule}^{-1} [\text{M}]$$

As expected^{3,5,29} the intercept is 1 within statistical uncertainty. We then re-fitted the data using eqn (1), *i.e.* we performed another linear regression with the intercept being fixed to 1 (thick solid line in Fig. 2). From this we obtain $\frac{k_M}{k_D} = (9.4 \pm 0.48) \times 10^{-18} \text{ cm}^3 \text{ molecule}^{-1}$ (error statistical only, 2σ). We applied eqn (13) to incorporate the systematic uncertainties (2σ) and derive a final value of $\frac{k_M}{k_D} = (9.4 \pm 1.7) \times 10^{-18} \text{ cm}^3 \text{ molecule}^{-1}$. In Fig. 2 these error margins are represented by thin solid lines.

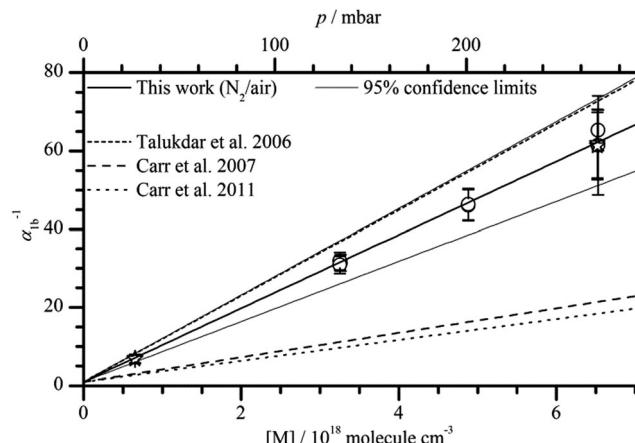


Fig. 2 Plot of α_{1b}^{-1} versus bath gas number density [M] at 296 K. Talukdar *et al.* (2006),³⁴ Carr *et al.* (2007),³ Carr *et al.*, (2011).² The stars represent data obtained in air, the circles represent data obtained in a mixture of oxygen (1%) in N₂.

We note that the data show no dependence on the O₂ concentration and that values of α_{1b} determined in air would be higher if CH₃CO were not thermalized and if there were an additional OH-formation route *via* CH₃CO[#] + O₂. This observation rules out a significant contribution of hot acetyl radicals.

3.3 CH₃CO + O₂ (He)

Back-to-back PLP-LIF-experiments on (R1) were performed at pressures between 33 and 400 mbar of He. From the fit-parameters and the respective [CH₃CHO] we derived $k_8 = (7.6 \pm 0.4) \times 10^{-11} \text{ cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$, and $k_9 = (1.9 \pm 0.1) \times 10^{-11} \text{ cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$ where the uncertainties represent statistical errors (2σ) in the fit-parameters, only. As described above, [CH₃CHO] was determined from barometric and mass flow readings and carries an additional uncertainty of $\sim 20\%$. These values are, within combined uncertainties, in accordance with the currently recommended literature values.

Fig. 3 shows the results of all experiments performed in He with an addition of 2.7 (or 1.3) mbar of O₂ as a plot of the reciprocal of α_{1b} against He number density [M]. For the experiments with 2.7 mbar O₂, a linear regression of the data resulted in (all errors statistical, 2σ)

$$\alpha_{1b}^{-1}(\text{He}) = (2.13 \pm 0.35) + (3.52 \pm 0.19) \times 10^{-18} \text{ cm}^3 \text{ molecule}^{-1} [\text{M}]$$

The two data points obtained using 1.3 mbar of O₂ reveal the expected trend, slightly enhanced yields (but a similar slope) due to the quenching effect of O₂. With 2.7 mbar of O₂ we expect α_{1b}^{-1} to approach 1.6 ± 0.11 (the value we derive from $\frac{k_M}{k_D}$ -value for N₂ and air) at zero pressure. Within the statistical uncertainties the intercept (2.13 ± 0.35) is however slightly higher than this. In the experiments in He, the main contribution to OH-fluorescence quenching is O₂ and not the H₂O₂ and CH₃CHO and Cl₂CO reactants. The fact that the two datasets obtained with different O₂ concentrations are in good agreement, supports this.

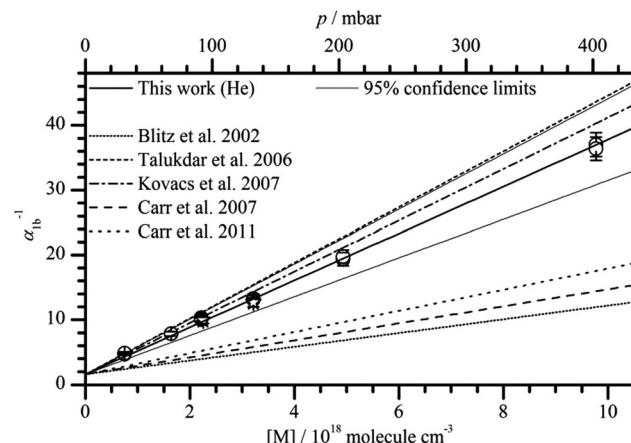


Fig. 3 Plot of α_{1b}^{-1} against bath gas number density [M] or pressure. Data were recorded in He with addition of 1.3 mbar (stars) or 2.7 mbar (circles) of O₂. Note that the literature data are plotted with an intercept of 1.6 to take into account the effect of quenching by O₂ (see text for details). Blitz *et al.* (2002).⁴ Talukdar *et al.* (2006).³⁴ Kovács *et al.* (2007).⁶ Carr *et al.* (2007).³ Carr *et al.* (2011).²

We therefore re-fitted the data using eqn (1), *i.e.* we performed another linear regression with the intercept being fixed to 1.6 (thick solid line in Fig. 3). From this we derived $\frac{k_M}{k_D} = (3.62 \pm 0.05) \times 10^{-18} \text{ cm}^3 \text{ molecule}^{-1}$ (error statistical only, 2σ). We applied eqn (13) to incorporate the systematic uncertainties (2σ) and derived a final value of $\frac{k_M}{k_D} = (3.6 \pm 0.6) \times 10^{-18} \text{ cm}^3 \text{ molecule}^{-1}$. In Fig. 3 these error margins are represented by thin solid lines.

3.4 HOCH₂CO + O₂ (N₂/O₂)

Back-to-back PLP-LIF-experiments using HOCH₂CHO as acyl radical precursor were performed at pressures between 33 and 269 mbar in N₂ or air. Fig. 4 shows a pair of OH-LIF time profiles recorded at 133 mbar in N₂ which were fitted using eqn (2) or (5), respectively. As a check for possible error sources

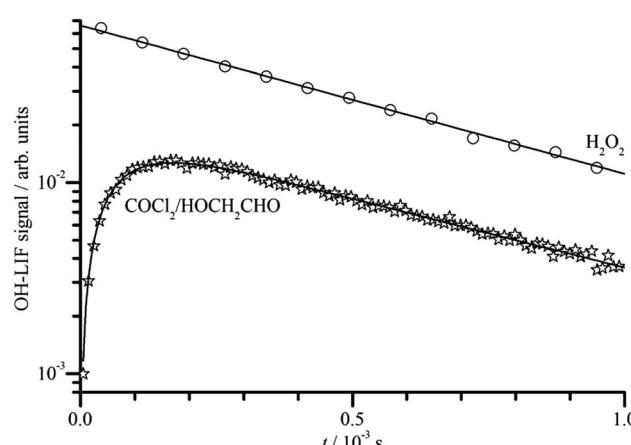


Fig. 4 OH-LIF profiles measured in back-to-back experiments at 133 mbar of N₂ bath gas containing 2.7 mbar of O₂. The solid lines are fits using equations (2) and (5).



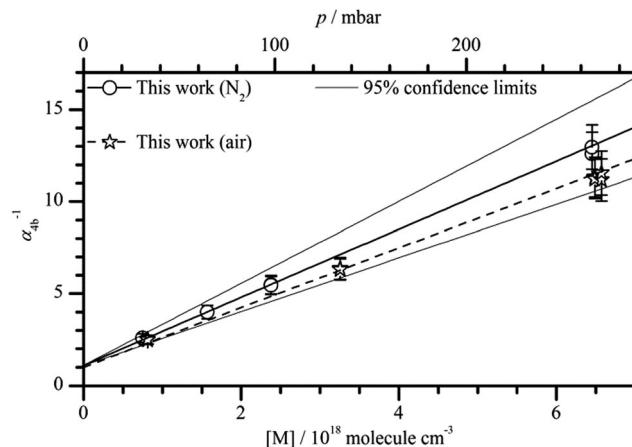


Fig. 5 Plot of α_{4b}^{-1} versus bath gas number density [M] or pressure, respectively.

of our experimental approach, we derived the rate-coefficients of reactions (R10) and (R12) from the fit-parameters and the respective $[\text{HOCH}_2\text{CHO}]$, we get $k_{10} = (6.6 \pm 0.3) \times 10^{-11} \text{ cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$, and $k_{12} = (1.0 \pm 0.2) \times 10^{-11} \text{ cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$ where the uncertainties represent statistical errors (2σ) in the fit-parameters, only. $[\text{HOCH}_2\text{CHO}]$ was derived by measuring its absorption at 185 nm using a literature value for the absorption cross section of HOCH_2CHO ($\sigma_{\text{HOCH}_2\text{CHO}}^{185} = (3.85 \pm 0.20) \times 10^{-18} \text{ cm}^2 \text{ molecule}^{-1}$)³⁰ and carries an additional uncertainty of $\sim 10\%$. Our values are, within combined uncertainties, in accordance with the currently recommended literature values of $k_{10,\text{Lit}} = (7.6 \pm 1.5) \times 10^{-11} \text{ cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$ ²⁶ and $k_{12,\text{Lit}} = (0.80^{+0.33}_{-0.23}) \times 10^{-11} \text{ cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$ ^{17,18}.

Fig. 5 shows the results of all single determinations of α_{4b} plotted as α_{4b}^{-1} against [M]. Except for the data measured at the lowest pressure of 33 mbar, the values for α_{4b} determined in air are slightly higher than those measured in nitrogen. We therefore evaluated data recorded in N_2 or air separately to check if the final results differ within their statistical uncertainties. A linear regression of the data obtained in N_2 gave (all errors statistical, 2σ)

$$\alpha_{4b}^{-1}(\text{N}_2) = (1.23 \pm 0.42) + (1.78 \pm 0.26) \times 10^{-18} \text{ cm}^3 \text{ molecule}^{-1} [\text{M}]$$

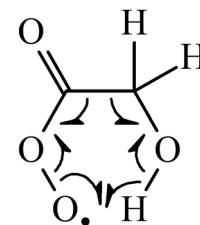
A linear regression of the data obtained in air resulted in (all errors statistical, 2σ)

$$\alpha_{4b}^{-1}(\text{air}) = (1.24 \pm 0.43) + (1.55 \pm 0.19) \times 10^{-18} \text{ cm}^3 \text{ molecule}^{-1} [\text{M}]$$

Assuming that (R4b) forms OH with unity yield at pressures approaching 0 mbar, we expect the intercept to be unity in air which, within statistical uncertainty, is the case. In the N_2 -experiments a constant amount of 2.7 mbar of O_2 was added. Thus, at $[\text{M}] = 0 \text{ molecule cm}^{-3}$ we expect α_{4b}^{-1} to approach ~ 1.1 , *i.e.* the value we derived using $[\text{M}] = 6.5 \times 10^{16} \text{ molecule cm}^{-3}$

and $\frac{k_M}{k_D} = 1.6 \times 10^{-18} \text{ cm}^3 \text{ molecule}^{-1}$. This is also confirmed by

the data. In both cases we performed linear regressions according to eqn (1), with the intercept being fixed to 1.1 for the data recorded in N_2 , and to unity for the air-data. We derived



Scheme 2 Possible transition state for OH formation in (R4b).

$\frac{k_M}{k_D} = (1.85 \pm 0.16) \times 10^{-18} \text{ cm}^3 \text{ molecule}^{-1}$ (solid black line in Fig. 5) for the data recorded in nitrogen and $\frac{k_M}{k_D} = (1.62 \pm 0.14) \times 10^{-18} \text{ cm}^3 \text{ molecule}^{-1}$ (dashed black line) for the data recorded in air (errors are statistical, 2σ). Within combined uncertainties measurements in nitrogen and air resulted in the same values of $\frac{k_M}{k_D}$ and, accordingly, α_{4b} .

The slightly larger α_{4b} -values observed at higher pressures in air are potentially due to experimental scatter. Our data do not however allow us to completely rule out the existence of an additional, O_2 -dependent OH-source as the cause. Therefore, we decided to rely exclusively on the data recorded in N_2 (with 1–10% of O_2 added) which would be less impacted by such an additional OH-source. Doing so we commit a maximum error of 7% in α_{4b} compared to values derived from all data. The fact that the data obtained at a fixed O_2 -to- N_2 ratio of 21%, but at various pressures (and thus at different O_2 concentrations), display no significant deviation from the expected behaviour, suggests that an additional OH forming channel that is dependent on the O_2 partial pressure is not significant. Incorporation of systematic uncertainties (2σ), results in a final value of $\frac{k_M}{k_D} = (1.85 \pm 0.38) \times 10^{-18} \text{ cm}^3 \text{ molecule}^{-1}$. The error margins that also enclose the data recorded in air are presented in Fig. 5 by thin solid lines.

Our studies on OH formation in the reactions of CH_3CO (R1) and HOCH_2CO (R4) with O_2 reveal a strong dependence of the yield on substituents, with $\frac{k_M}{k_D}$ for (R4) a factor of 5 smaller than for (R1). Under the assumption that the collisional quenching of both activated peroxy radicals proceeds at a similar rate this large difference can be attributed to a more efficient decomposition of $\text{HOCH}_2\text{C}(\text{O})\text{O}_2^\#$ compared to $\text{CH}_3\text{C}(\text{O})\text{O}_2^\#$. This may be rationalized in terms of a more favourable reaction pathway in which the hydroxyl group of $\text{HOCH}_2\text{C}(\text{O})\text{O}_2$ enables formation of a six-membered transition state as illustrated in Scheme 2 in which highly stable products (formaldehyde and CO_2) are formed along with OH.

4 Comparison with literature

4.1 $\text{CH}_3\text{CO} + \text{O}_2$

Several experimental studies have reported OH formation *via* (R1b) in N_2 , O_2 and He .^{2–6} Table 1 and Fig. 2 and 3 summarise

Table 1 Summary of results (all room temperature) and comparison with literature

M	This work	Tyndall (1997)	Blitz (2002)	Talukdar (2006)	Kovács (2007)	Carr (2007)	Carr (2011)	Groß (2014)
CH ₃ CO								
k_M/k_D^a	N ₂	9.4 ± 1.7	(5.9) ^b		11.0 ± 2.5		3.59 ± 0.60	2.67 ± 1.40
	He	3.6 ± 0.6		1.06 ± 0.05	4.3 ± 1.0	3.9 ± 0.6 ^c	1.31 ± 0.51	1.63 ± 0.54
Ratio N ₂ /He		2.6			2.6		2.7	1.6
HOCH ₂ CO								
k_M/k_D^a	N ₂	1.85 ± 0.38						

Tyndall (1997),⁵ Blitz (2002),⁴ Talukdar (2006),³⁴ Kovács (2007),⁶ Carr (2007),³ Carr (2011),² Groß (2014).¹³ ^a Units of $10^{-18} \text{ cm}^3 \text{ molecule}^{-1}$. ^b The cited value is based on a correction from G. S. Tyndall that was published by Carr *et al.*³ ^c Value obtained by applying eqn (1) to the data of Kovács *et al.*⁶ ^d Value derived from a single experiment at 233 mbar in N₂/O₂.

the $\frac{k_M}{k_D}$ -values from these studies as well as those from our work. Note that in Fig. 3 the literature data are plotted with an intercept of 1.6 to take into account the presence of O₂ in our experiments at extrapolated zero mbar of He.

Tyndall *et al.*⁵ studied the reaction of Cl atoms with CH₃CHO by irradiation of Cl₂-CH₃CHO-mixtures in N₂ or O₂ in environmental chambers and analysed the reaction mixtures by infra-red absorption spectroscopy. They found a pressure-dependence of the apparent rate coefficient of (R8) when the experiments were performed in O₂ but none for the measurements in N₂. The value measured in O₂ increased if the experimental pressure was decreased; at 1.6 mbar the apparent rate coefficient was 2.7 times higher than that derived in N₂. The authors attributed these findings to OH formation in (R1b). Thus, they did not directly detect OH, but their kinetic and product studies provided strong evidence for OH formation. The $\frac{k_M}{k_D}$ -value shown in Table 1 was derived by Carr *et al.*³ based on a personal communication with Tyndall *et al.*⁵

Blitz *et al.*⁴ used the 248 nm pulsed laser photolysis of CH₃C(O)CH₃ in He to generate CH₃CO and used OH-LIF for the detection of hydroxyl radicals formed in (R1b) at pressures between 13–533 mbar. Calibration of the LIF-system was achieved by fixing α_{1b} at zero pressure to unity, which neglects to take into account the fact that the acetyl radical yield is pressure dependent as a significant (but variable) fraction thermally decomposes to CH₃ and CO, at least in nitrogen bath gas.^{31–33} Blitz *et al.* could thus have underestimated the value of KM/KD by about 16%.³

Talukdar *et al.*³⁴ used different photolytic schemes (photolysis of acetone, Cl + CH₃CHO and OH + CH₃CHO) for CH₃CO generation coupled to OH-LIF to investigate OH-formation or modification of OH kinetics due to (R1) at experimental pressures between 27–800 mbar in He, N₂ and O₂. The resulting $\frac{k_M}{k_D}$ values are in good agreement with our results.

Kovács *et al.*⁶ used two low-pressure fast discharge flow tubes (operated at pressures between 1.3 and 11 mbar in helium) that were equipped with LIF or resonance fluorescence detection of OH radicals. CH₃CO was formed by reacting CH₃CHO with OH that was generated from H and NO₂, or from F and H₂O. The authors compared decay rates of OH radicals with or without O₂ present in the reaction mixture. We applied

eqn (1) to the α_{1b} -data provided by Kovács *et al.* to derive a value of $\frac{k_M}{k_D}$ that is in good agreement with those presented by Talukdar *et al.* and this work.

Carr *et al.*³ used the 248 nm pulsed laser photolysis of CH₃C(O)OH to generate prompt OH and CH₃CO radicals in equal amounts. Detection of OH radicals was achieved by OH-LIF. Experiments were restricted to pressures of <138 mbar of He, or <34 mbar of N₂. The approach is self-calibrated since it allows comparison of prompt OH formed in the photolysis step to OH formed from acetyl + O₂ and thus requires only separation of the LIF signal into prompt and slow components. Errors in the separation of prompt and slower OH contributions would thus affect α_{1b} two-fold and would be manifest at higher pressures of N₂ where the yield of OH is small. The resulting value for $\frac{k_M}{k_D}$ agrees well with the previous one of Blitz *et al.* from the same lab but accordingly differs by a factor of ~3 from our values.

Carr *et al.*² photolysed acetone at 248 nm to form CH₃CO and used OH-LIF detection. The resulting OH time profiles were fitted by a bi-exponential equation similar to the one presented here. Relative values of α_{1b} were measured in the pressure range of 7–400 mbar and based on an absolute scale by setting α_{1b} at 0 mbar to unity. Data were corrected by 25–35% for a pressure-dependence^{23,31} in the CH₃CO yield of acetone photolysis. In their N₂-experiments the authors needed to make an additional correction since they observed a decrease of LIF-sensitivity at elevated pressures. The correction factors were derived in separate experiments by measuring OH-formation from 248 nm photolysis of *t*-butylhydroperoxide at the same pressure.

Although not a detailed study of the OH yield in the title reaction, we recently published data on OH formation in the reaction of HO₂ with CH₃C(O)O₂ (ref. 13) and also observed (in this case “unwanted”) OH-formation *via* (R1b). This work was conducted in a different apparatus and used a different CH₃CO-formation scheme (355 nm-pulsed photolysis of CH₃CHO-CH₃OH-Cl₂-O₂-N₂-mixtures). OH was detected by an OH-LIF-unit that was calibrated by measuring OH from the reaction of HO₂ with NO. In spite of the different experimental approach we could accurately simulate the OH signals due to reaction (R1b) with the OH yield presented in the current work (see Fig. 8 in Groß *et al.*¹³). Use of α from the more recent publication of Carr *et al.*² would have resulted in an overestimation of initial OH-formation by a factor of 3.



Our results are in good agreement with those of Talukdar *et al.*³⁴ and Kovács.⁶ We cannot explain the differences between our work and that of Blitz *et al.*⁴ and Carr *et al.*^{2,3} but we highlight the fact that no correction needs to be applied to our data.

In Table 1 we also show the ratio of the respective $\frac{k_M}{k_D}$ values in N₂ and He bath gases. From our data we derive a value of 2.6 which is in agreement with those of Talukdar *et al.* (2.7) and the 2007 study of Carr *et al.* 2007 (2.6). From the 2011 dataset of Carr *et al.* we derive a lower value of 1.6.

4.2 HOCH₂CO + O₂

Butkovskaya *et al.*³⁵ investigated the OH-initiated oxidation of HOCH₂CHO in a turbulent flow reactor at 267 mbar of N₂. A chemical ionisation mass spectrometer was used to detect OH and derive a yield of $\alpha_{4b} = 22\%$. This high yield may reflect the fact that Butkovskaya *et al.*³⁵ were unaware that the reaction of HOCH₂C(O)O₂ with HO₂ (formed at a yield of 20% from OH + HOCH₂CHO in the presence of O₂) forms OH with a yield of $\sim 70\%$.^{16,36}

OH formation has also been observed³⁷ in the reaction of O₂ with CH₃OCO, which is isomeric with HOCH₂CO. Similar to (R4), OH-formation is accompanied by CH₂O and CO₂ by-products. The value of $\frac{k_M}{k_D}$ reported, $(7.4 \pm 1.9) \times 10^{-18} \text{ cm}^3 \text{ molecule}^{-1}$, is four times larger than our value for HOCH₂CO. Given that the products of decomposition are identical the difference must be related to energetic differences in the transition state leading to dissociation.

5 Conclusion

We determined the pressure-dependence of the OH-forming branching ratios α_{1b} of reaction (R1a) and α_{4b} reaction (R4b) using a novel experimental approach. The values for α_{1b} are in accordance with some earlier studies^{6,34} but clearly differ from those from the Leeds group^{2–4} that derive much higher OH yields. Our data for α_{4b} show that hydroxylation of CH₃CO enhances OH-formation in the reaction with O₂ by approximately a factor of five.

Acknowledgements

We thank Jim Burkholder (National Oceanic and Atmospheric Administration, Boulder, CO) for sending us a copy of a poster “Determination of the OH Radical Yield in the CH₃CO + O₂ + M Reaction” presented at the 19th International Symposium on Gas Kinetics in 2006. C. B. M. G. thanks the International Max Planck Research School for Atmospheric Chemistry and Physics for financial support.

References

- 1 G. S. Tyndall, T. A. Staffelbach, J. J. Orlando and J. G. Calvert, *Int. J. Chem. Kinet.*, 1995, **27**, 1009–1020.
- 2 S. A. Carr, D. R. Glowacki, C.-H. Liang, M. T. Baeza-Romero, M. A. Blitz, M. J. Pilling and P. W. Seakins, *J. Phys. Chem. A*, 2011, **115**, 1069–1085.
- 3 S. A. Carr, M. T. Baeza-Romero, M. A. Blitz, M. J. Pilling, D. E. Heard and P. W. Seakins, *Chem. Phys. Lett.*, 2007, **445**, 108–112.
- 4 M. A. Blitz, D. E. Heard and M. J. Pilling, *Chem. Phys. Lett.*, 2002, **365**, 374–379.
- 5 G. S. Tyndall, J. J. Orlando, T. J. Wallington and M. D. Hurley, *Int. J. Chem. Kinet.*, 1997, **29**, 655–663.
- 6 G. Kovács, J. Zádor, E. Farkas, R. Nádasdi, I. Szilágyi, S. Dóbé, T. Bérces, F. Márta and G. Lendvay, *Phys. Chem. Chem. Phys.*, 2007, **9**, 4142–4154.
- 7 J. Lee, C.-J. Chen and J. W. Bozzelli, *J. Phys. Chem. A*, 2002, **106**, 7155–7170.
- 8 H. Hou, A. Li, H. Hu, Y. Li, H. Li and B. Wang, *J. Chem. Phys.*, 2005, **122**, 224304.
- 9 A. Maranzana, J. R. Barker and G. Tonachini, *Phys. Chem. Chem. Phys.*, 2007, **9**, 4129–4141.
- 10 M. A. Blitz, D. E. Heard, M. J. Pilling, S. R. Arnold and M. P. Chipperfield, *Geophys. Res. Lett.*, 2004, **31**, L06111.
- 11 H. B. Singh, M. Kanakidou, P. J. Crutzen and D. J. Jacob, *Nature*, 1995, **378**, 50–54.
- 12 S. A. McKeen, T. Gierzak, J. B. Burkholder, P. O. Wennberg, T. F. Hanisco, E. R. Keim, R.-S. Gao, S. C. Liu, A. R. Ravishankara and D. W. Fahey, *Geophys. Res. Lett.*, 1997, **24**, 3177–3180.
- 13 C. B. M. Groß, T. J. Dillon, G. Schuster, J. Lelieveld and J. N. Crowley, *J. Phys. Chem. A*, 2014, **118**, 974–985.
- 14 I. Bridier, F. Caralp, H. Loirat, R. Lesclaux, B. Veyret, K. H. Becker, A. Reimer and F. Zabel, *J. Phys. Chem.*, 1991, **95**, 3594–3600.
- 15 G. J. Phillips, N. Pouvesle, J. Thieser, G. Schuster, R. Axinte, H. Fischer, J. Williams, J. Lelieveld and J. N. Crowley, *Atmos. Chem. Phys.*, 2013, **13**, 1129–1139.
- 16 D. Taraborrelli, M. G. Lawrence, J. N. Crowley, T. J. Dillon, S. Gromov, C. B. M. Groß, L. Vereecken and J. Lelieveld, *Nat. Geosci.*, 2012, **5**, 190–193.
- 17 R. Atkinson, D. L. Baulch, R. A. Cox, J. N. Crowley, R. F. Hampson, R. G. Hynes, M. E. Jenkin, M. J. Rossi and J. Troe, *Atmos. Chem. Phys.*, 2006, 3625–4055.
- 18 M. Ammann, R. A. Cox, J. N. Crowley, M. E. Jenkin, A. Mellouki, M. J. Rossi, J. Troe and T. J. Wallington, IUPAC Task Group on Atmospheric Chemical Kinetic Data Evaluation, 2014, <http://iupac.pole-ether.fr/index.html>.
- 19 T. J. Dillon, M. E. Tucceri and J. N. Crowley, *Phys. Chem. Chem. Phys.*, 2006, **8**, 5185–5198.
- 20 T. J. Dillon, A. Horowitz and J. N. Crowley, *Chem. Phys. Lett.*, 2007, **443**, 12–16.
- 21 A. Galano, J. R. Alvarez-Idaboy, M. E. Ruiz-Santoyo and A. Vivier-Bunge, *J. Phys. Chem. A*, 2005, **109**, 169–180.
- 22 R. Atkinson, D. L. Baulch, R. A. Cox, J. N. Crowley, R. F. Hampson, R. G. Hynes, M. E. Jenkin, M. J. Rossi and J. Troe, *Atmos. Chem. Phys.*, 2004, **4**, 1461–1738.
- 23 V. Khamaganov, R. Karunanandan, A. Horowitz, T. J. Dillon and J. N. Crowley, *Phys. Chem. Chem. Phys.*, 2009, **11**, 6173–6181.
- 24 C. Maul and K.-H. Gericke, *Int. Rev. Phys. Chem.*, 1997, **16**, 1–79.



25 H. Niki, P. D. Maker, C. M. Savage and M. D. Hurley, *J. Phys. Chem.*, 1987, **91**, 2174–2178.

26 C. Bacher, G. S. Tyndall and J. J. Orlando, *J. Atmos. Chem.*, 2001, **39**, 171–189.

27 G. L. Vaghjiani and A. R. Ravishankara, *J. Geophys. Res.: Atmos.*, 1989, **94**, 3487–3492.

28 H. Keller-Rudek, G. K. Moortgat, R. Sander and R. Sørensen, *Earth Syst. Sci. Data*, 2013, **5**, 365–373.

29 J. V. Michael, D. G. Keil and R. B. Klemm, *J. Chem. Phys.*, 1985, **83**, 1630–1636.

30 R. Karunanandan, D. Hölscher, T. J. Dillon, A. Horowitz, J. N. Crowley, L. Vereecken and J. Peeters, *J. Phys. Chem. A*, 2007, **111**, 897–908.

31 V. Khamaganov, R. Karunanandan, A. Rodriguez and J. N. Crowley, *Phys. Chem. Chem. Phys.*, 2007, **9**, 4098–4113.

32 H. Somnitz, T. Ufer and R. Zellner, *Phys. Chem. Chem. Phys.*, 2009, **11**, 8522–8531.

33 B. Rajakumar, T. Gierczak, J. E. Flad, A. R. Ravishankara and J. B. Burkholder, *J. Photochem. Photobiol. A*, 2008, **199**, 336–344.

34 R. K. Talukdar, M. E. Davis, L. Zhu, A. R. Ravishankara and J. B. Burkholder, *19th International Symposium on Gas Kinetics*, Orleans, France, 2006.

35 N. I. Butkovskaya, N. Pouvesle, A. Kukui and G. Le Bras, *J. Phys. Chem. A*, 2006, **110**, 13492–13499.

36 C. B. M. Groß, Fachbereich Chemie der Johannes-Gutenberg-Universität Mainz, Kinetische Studien zur OH-Bildung über die Reaktionen von HO₂ mit organischen Peroxyradikalen, PhD thesis, 2013.

37 J. C. Hansen, Y. Li, C. M. Rosado-Reyes, J. S. Francisco, J. J. Szente and M. M. Maricq, *J. Phys. Chem. A*, 2003, **107**, 5306–5316.

