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Reaction of Distonic Aryl and Alkyl Radical Cations with Amines: The Role of Charge and Spin Revealed by Mass Spectrometry, Kinetic Studies, and DFT Calculations

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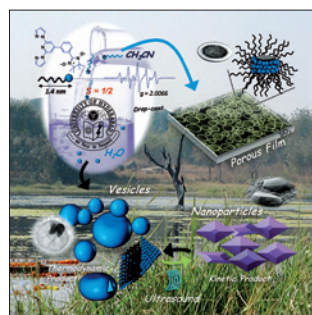
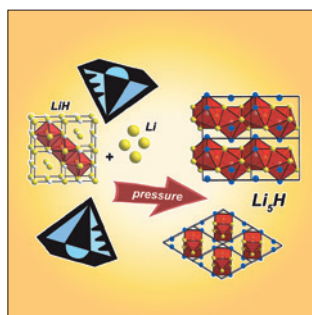
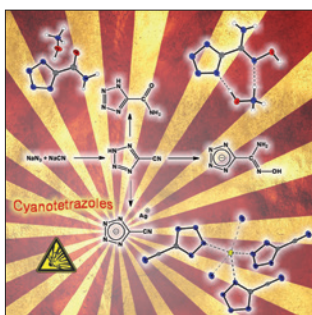
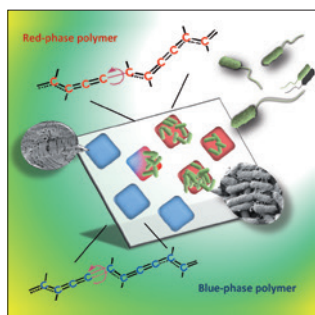
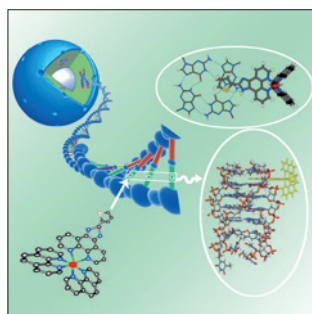
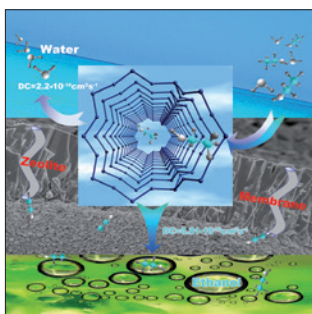
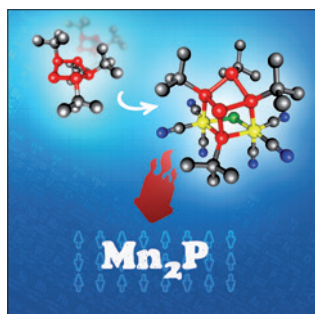
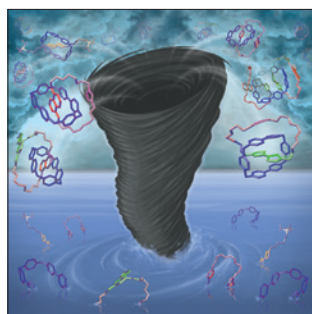
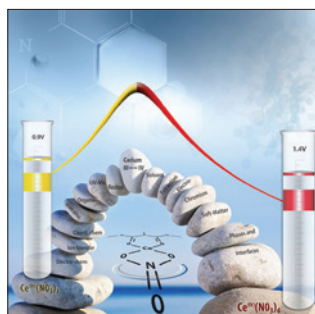
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Reaction of Distonic Aryl and Alkyl Radical Cations with Amines: The Role of Charge and Spin Revealed by Mass Spectrometry, Kinetic Studies, and DFT Calculations

Benjamin Andrikopoulos, Parvinder K. Sidhu, Bethany I. Taggart, Joses G. Nathanael, Richard A. J. O'Hair,* and Uta Wille*^[a]

Dedicated to Prof. Frances Separovic on the occasion of her 65th birthday and her retirement.

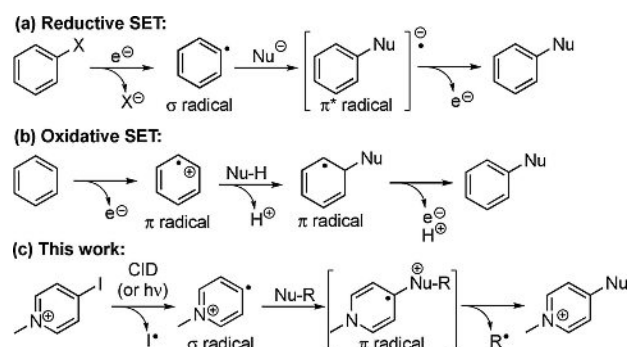
Gas-phase reaction of the aromatic distonic radical cations 4-Pyr⁺• and 3-Pyr⁺• with amines led to formation of the corresponding amino pyridinium ions 4-Pyr⁺NR₂ and 3-Pyr⁺NR₂ through amine addition at the site of the radical, followed by homolytic β-fragmentation. The reaction efficiencies range from 66–100% for 4-Pyr⁺• and 57–86% for 3-Pyr⁺•, respectively, indicating practically collision-controlled processes in some cases. Computational studies revealed that the combination of positive charge and spin makes nucleophilic attack by the amine at the site of the radical barrierless and strongly

exothermic by about 175 ± 15 kJ mol⁻¹, thereby rendering 'conventional' radical pathways through hydrogen abstraction or addition onto π systems less important. Exemplary studies with 4-Pyr⁺• showed that this reaction can be reproduced in solution. A similar addition/radical fragmentation sequence occurs also in the gas-phase reaction of amines with the aliphatic distonic radical cation Oxo⁺C•, showing that the observed charge-spin synergism is not limited to aromatic systems.

1. Introduction

Free radicals have found numerous applications in synthetic chemistry and are also involved in many biological systems, as well as intermediates in combustion and environmental transformation and degradation processes. Since the unpaired electron is considered as the most reactive site, it comes as no surprise that reactions involving radicals are commonly believed to proceed through radical pathways.

However, that this picture cannot be generalised is illustrated by several known reaction types where the unpaired electron seems to act as an 'observer' of non-radical processes occurring in the same molecule. The Sandmeyer reaction is an example of a radical-nucleophilic aromatic substitution (S_{RN}1) that was discovered by Bunnett in 1970 (Scheme 1a)^[1] and involves a nucleophile (Nu) replacing an existing substituent X (most commonly a halogen atom) on the aromatic ring. The reaction is initiated by reductive single electron transfer (SET), which is followed by dissociation to form a σ radical intermediate that is subsequently attacked by an N-, O- or C-nucleophile, such as sodium amide, an alkoxide or an enolate, respectively. During this addition the unpaired electron trans-



Scheme 1. Examples for reactions of nucleophiles with radicals and radical ions.^[1,2]

sitions into a π* orbital, from where it is transferred onto another substrate to propagate the radical chain.

Removal of an electron from a π system, as shown in Scheme 1b for benzene as example, leads to a π radical cation, which can be trapped by either another radical through radical recombination (not shown) or by a nucleophile at the positive charge site.^[2] In the latter case the unpaired electron acts as a spectator during the bond-forming process. In the case of aromatic substrates, the sequence is usually terminated by a second oxidation and deprotonation that restores the aromatic π system.

Here we present a variation of this concept, which we discovered during an ongoing research project aimed at gaining a better mechanistic understanding of environmental radical polymer degradation. These processes are initiated at the gas/solid interface, which can be experimentally simulated by performing gas-phase studies in multi-stage mass spectro-

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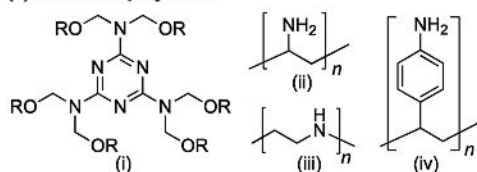
meters using the capability of ion traps to generate distonic radical ions, and then study their reactions with neutral compounds.^[3] The chemistry of reactant radical ions and charged reaction products can be directly monitored in a time resolved fashion to identify reactive intermediates associated with the formation of early degradation products,^[4] and to obtain kinetic data for individual reaction steps.

The distonic radical ion approach to study gas-phase radical reactions by mass spectrometry commonly considers the charge tag as innocent entity, which does not influence the mechanism by which the radical reacts, compared to the neutral counterpart. Distonic radical ions have therefore been successfully employed to investigate radical reactions in many different areas, for example atmospheric chemistry,^[5] organic synthesis,^[6] and biological chemistry.^[7] Our previous studies, where we used distonic radical cations to explore the gas-phase chemistry of peroxy, alkoxy and alkyl radicals,^[6,8] enabled identification of several new reaction pathways that could contribute to polymer degradation under environmental conditions.^[9] However, Kenttämäa *et al.* recently found that the radical reactivity of some distonic radical cations can be challenged by a competing nucleophilic reaction enabled by the positive charge.^[10]

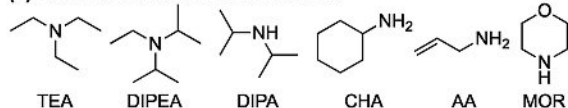
Amines are prevalent structural moieties in polymers (Figure 1a), for example in melamine formaldehyde resins or melamine crosslinked polyesters (i), in polyamines, such as polyvinyl amine (ii), polyethylene imine (iii) and poly(amino-styrene) (iv).

While hydrolytic degradation of melamine-containing polymers has been well studied,^[11] direct involvement of amine moieties in radical-mediated degradation has received considerably less attention. We have therefore explored the gas-phase reactions of the distonic aryl and alkyl radical cations 4-Pyr^{•+}, 3-Pyr^{•+} and Oxo^{•+}C⁺ with a series of primary, secondary and tertiary amines, *e.g.*, triethyl amine (TEA), diisopropylethyl amine (DIPEA), diisopropyl amine (DIPA), cyclohexyl amine (CHA), allyl amine (AA) and morpholine (MOR) (Figure 1b,c),

(a) Amines in polymers:



(b) Model amines studied in this work:



(c) Distonic alkyl and aryl radical cations studied in this work:

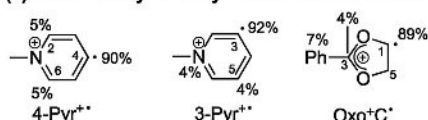


Figure 1. (a) Amine motifs in polymers and (b) model systems studied in this work; (c) spin densities in 4-Pyr^{•+}, 3-Pyr^{•+} and Oxo^{•+}C⁺ calculated with M062X/6-31 + G*.

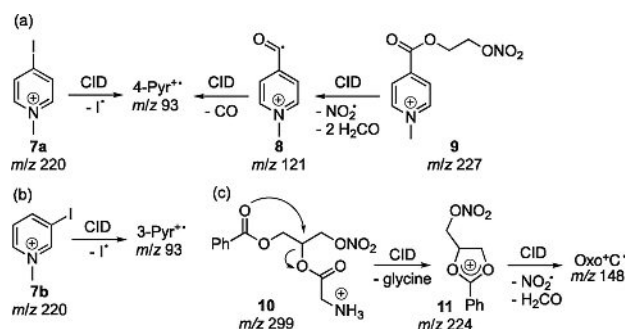
which represent simplified models for amine residues present in polymers with sufficient volatility to enable gas-phase studies in the ion trap mass spectrometer. Rapid nucleophilic addition of the amine to the distonic radical cation that is directed by the unpaired electron *in conjunction* with the charge is a key-finding (Scheme 1c), with 4-Pyr^{•+} reacting in a similar fashion also in solution. The experimental studies were augmented by DFT calculations to gain mechanistic understanding of these reactions, in particular to define the interplay between charge and spin in these transformations.

2. Results and Discussion

2.1. Radical generation in the mass spectrometer

The distonic aryl and alkyl radical cations 4-Pyr^{•+}, 3-Pyr^{•+} and Oxo^{•+}C⁺ were generated *in situ* in the ion trap mass spectrometer (see Experimental Methods for details of the experimental set-up). The isomeric pyridinium radicals 3-Pyr^{•+} and 4-Pyr^{•+} (*m/z* 93) were obtained from the respective *N*-methyl iodo pyridines **7a** and **7b** through collision-induced dissociation (CID), as described previously (Scheme 2a,b).^[8a]

The pyridinium ester **9** was originally designed to access an *O*-centred alkoxy radical through CID of the labile *O*–NO₂ bond but rapid sequential loss of two H₂CO molecules led to the acyl radical **8** at *m/z* 121, which upon a second CID produced 4-Pyr^{•+} (Scheme 2a). The synthetic procedure and CID mass spectra for compound **9** are provided in the Supporting Information (Figure S1). Comparison of the reactions of 4-Pyr^{•+} derived from precursors **7a** or **9** confirmed that its reactivity was independent of the generation method. We recently developed glycerol derivative **10** as precursor for Oxo^{•+}C⁺ (*m/z* 148), which is obtained through sequential CID *via* the cyclic tertiary carboxonium ion **11**,^[7d] followed by homolytic scission of the *O*–NO₂ bond and loss of formaldehyde (Scheme 2c).^[8b] According to DFT calculations (see below for details) the spin density in these distonic radical cations is predominantly (ca. 90%) located on the desired carbon atom (Figure 1c).



Scheme 2. Generation of the distonic radical cations 4-Pyr^{•+}, 3-Pyr^{•+} and Oxo^{•+}C⁺ in the mass spectrometer.

2.2. Gas-phase mass spectrometric studies

Reactions with $\text{Pyr}^{+\bullet}$: Figure 2 shows the mass spectra of the ion-molecule reactions of 4- $\text{Pyr}^{+\bullet}$ with TEA (a), DIPEA (b), DIPA (c), and CHA (d), which were taken at reaction times where the signal intensity of 4- $\text{Pyr}^{+\bullet}$ had dropped to about 20% (120–240 ms). Product assignment was accomplished using computational studies (see Section 2.3).

Interestingly, in the reaction with these amines the expected hydrogen atom abstraction (HAT) to give Pyr^+H at m/z 94 was only a very minor pathway.^[12] In the reaction with TEA the major product at m/z 165 could be assigned as the 4-diethylamino pyridinium ion **12a** resulting from formal addition of NEt_2^+ . The reaction with DIPEA led to a major product at m/z 179, which could be assigned as the 4-ethyl isopropylamino pyridinium ion **13a**, suggesting a reaction through addition of the amine to the aromatic ring and loss of an isopropyl moiety. A product resulting from loss of an ethyl group (which would appear at m/z 193) was not formed. Similarly, the product at m/z 151 in the reaction with DIPA corresponds to the 4-isopropyl amino pyridinium ion **14a**, resulting from formal addition of $\text{NH}i\text{Pr}^+$. In the reaction involving CHA, the product at m/z 109 could be assigned as the 4-amino pyridinium ion **15a**, which could be formed through formal addition of NH_2^+ . Products corresponding to addition of the amine to 4- $\text{Pyr}^{+\bullet}$ without elimination of an alkyl moiety were not detected in any of these

reactions. Isolation of **12a–15a** in the ion trap showed no further reaction with the respective amine over several seconds, suggesting closed-shell species. Fragmentation by CID only occurred at very high energies, which further confirmed their stability. It should be noted that the products at m/z 100 in the reaction of TEA, at m/z 128 in the reaction of DIPEA, at m/z 100 and 102 in the reaction of DIPA, and at m/z 98 in the reaction of CHA could be assigned to protonated and/or oxidized amines, which were likely formed under the experimental conditions and not further investigated.^[13]

The reaction of 3- $\text{Pyr}^{+\bullet}$ with these four amines also led to formation of the respective isomeric 3-substituted products **12b–15b** (the site of amine substitution was elucidated computationally, see Section 2.4). However, the HAT reaction to give Pyr^+H appeared to be more favourable than in the reactions with 4- $\text{Pyr}^{+\bullet}$. The mass spectra for the reaction of 3- $\text{Pyr}^{+\bullet}$ with TEA, DIPEA, DIPA and CHA are shown in Figures S2–S5.

To compare the chemical reactivity of the isomeric $\text{Pyr}^{+\bullet}$, we analysed the mass spectrometric yields obtained for the reaction with each amine at the same time point. Since mass discrimination could be excluded the peak area of each ionic species directly reflected their concentration. While the overall reactivity of both $\text{Pyr}^{+\bullet}$ with the amines is similar, compared with 4- $\text{Pyr}^{+\bullet}$ the reaction of 3- $\text{Pyr}^{+\bullet}$ gave a higher yield of the HAT product Pyr^+H (m/z 94) at the expense of amine adduct

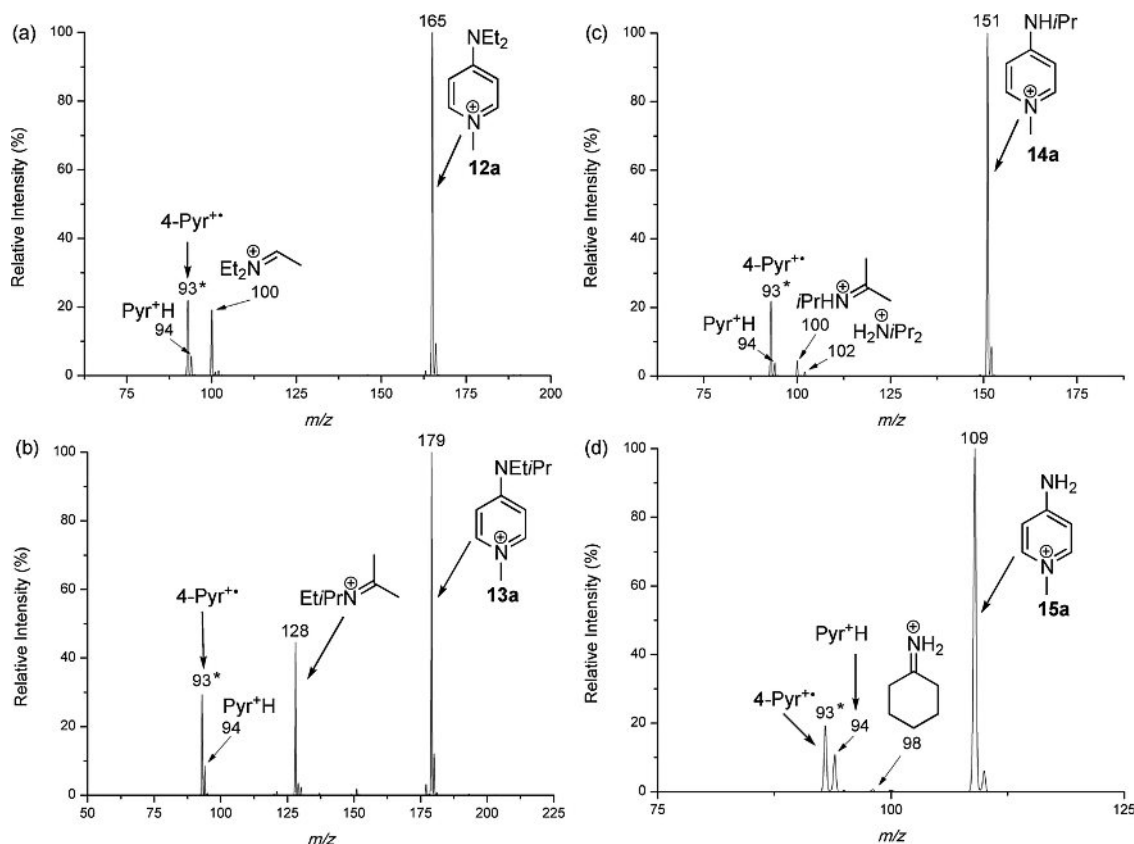


Figure 2. Mass spectra of the ion-molecule reactions of 4- $\text{Pyr}^{+\bullet}$ (m/z 93) with (a) TEA after 135 ms ([TEA] ca. 1.2×10^{10} molecules cm^{-3}), (b) DIPEA after 240 ms ([DIPEA] ca. 1.1×10^{10} molecules cm^{-3}), (c) DIPA after 120 ms ([DIPA] ca. 1.2×10^{10} molecules cm^{-3}), and (d) CHA after 120 ms ([CHA] ca. 1.2×10^{10} molecules cm^{-3}). The mass-selected precursor ion is indicated by an asterisk (*).

formation, indicating a higher *radical* reactivity of the latter (Table S1).

To further explore this finding, we studied the reaction of AA, which could support radical pathways through both HAT (allylic C–H bonds) and addition (π -system). The mass spectra obtained after 110 ms for the reaction of AA with 4-Pyr⁺• and 3-Pyr⁺• revealed clear differences between these two radical cations (Figure 3; the mass spectrometric yields at this time point are included in Table S1).

Thus, while the major product at m/z 109 in the reaction of 4-Pyr⁺• could be assigned as the 4-amino pyridinium ion **15a** resulting from formal addition of the amine and loss of an allyl moiety (Figure 3a), the isomeric **15b** was obtained only as a minor product in the reaction of 3-Pyr⁺•. Instead, the major product appeared at m/z 120, which could be assigned as the vinyl pyridinium ion **16b** (Figure 3b). In addition, small amounts of a product at m/z 134 also appeared, which could correspond to the allyl pyridinium ion **17b**. In the reaction of 4-Pyr⁺•, on the other hand, the isomeric vinyl pyridinium **16a** was a minor product and only trace amounts of **17a** at m/z 134 were formed. Both products **16** and **17** indicate radical addition of Pyr⁺• to the π -system in AA. Products from oxidation and/or protonation of AA could not be detected, because their masses were below the mass cut-off of the ion trap. Overall, formation of Pyr⁺H at m/z 94 through HAT was a minor reaction of both

Pyr⁺• but slightly more important for 3-Pyr⁺• than for 4-Pyr⁺•.^[14]

On the other hand, in the reaction of MOR with 3-Pyr⁺• HAT and formation of Pyr⁺H was found as the major pathway. HAT also occurred in the reaction with 4-Pyr⁺•, but several unidentifiable products appeared at higher m/z values that suggest MOR addition, followed by fragmentation (see Figure S6).

Reactions with Oxo⁺C•: Compared with both isomeric Pyr⁺• the reaction of Oxo⁺C• with amines was considerably slower. Figure 4 shows the mass spectrum of the reaction with TEA after 500 ms, where the signal intensity of unreacted Oxo⁺C• was about 30%. The mass spectra of the reactions involving DIPEA and DIPA showed a similar outcome and are provided in Figure S7. While all reactions were characterised by significant amounts of protonation and/or oxidation side-products of the respective amines, none gave a product at m/z 149 corresponding to Oxo⁺CH, clearly excluding a pathway through HAT.

The adduct at m/z 220 formed in the reaction with TEA formally results from addition of NEt₂⁺ to Oxo⁺C•. Computational studies revealed the likely structure of the product as the open-chain iminium ion **19a** (see Section 2.4). CID of **19a** showed fragmentation into an ion at m/z 105, which can be assigned as the phenylacetylium ion PhC≡O⁺ (**21**). In addition, a product at m/z 206 was also formed, which was tentatively assigned as the acylammonium ion **18a**.^[15] We believe that the latter results from ring-opening of Oxo⁺C• to **20**, followed by fragmentation into the acylium ion **21**,^[8b] which is subsequently trapped by the amine (Scheme 3). This assignment could be confirmed by CID on isolated **18a** in the ion trap, which revealed fragmentation into **21**.

2.3. Kinetic studies of the gas-phase reaction of Pyr⁺• with amines

Absolute rate coefficients for the consumption of Pyr⁺• through reaction with TEA, DIPEA, DIPA, CHA and AA according to: Pyr⁺• + amine → products, were obtained under quasi-thermal

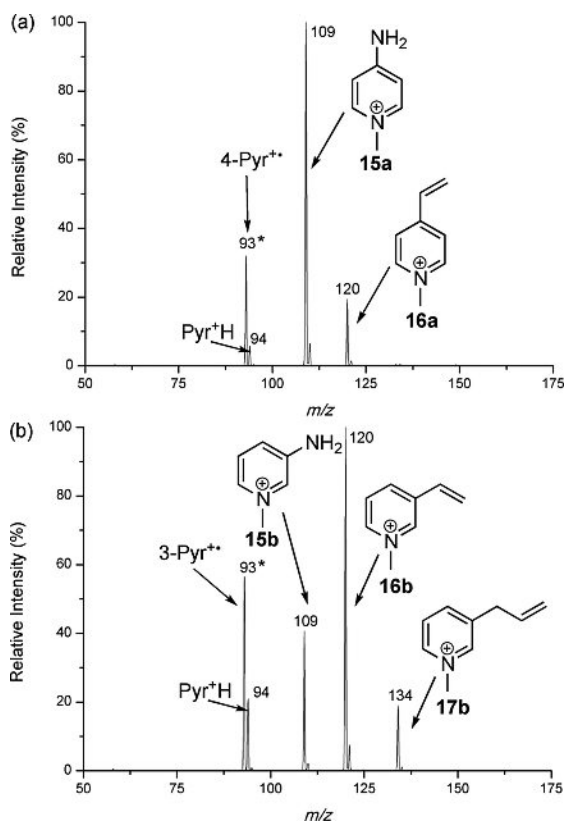


Figure 3. Mass spectra of the reaction of AA with (a) 4-Pyr⁺• (m/z 93) and (b) 3-Pyr⁺• (m/z 93) after 110 ms ([AA] ca. 1.2×10^{10} molecules cm^{-3}); the mass-selected precursor ion is indicated by an asterisk (*).

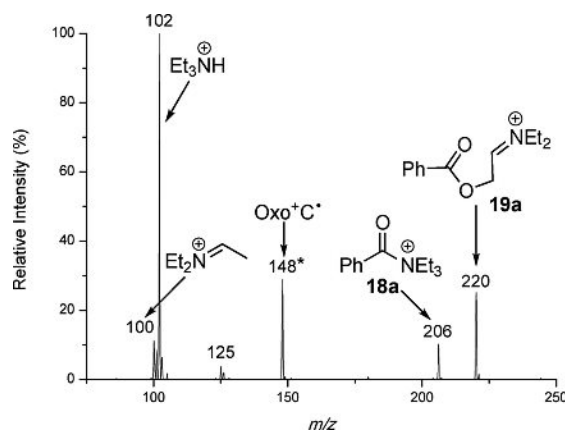
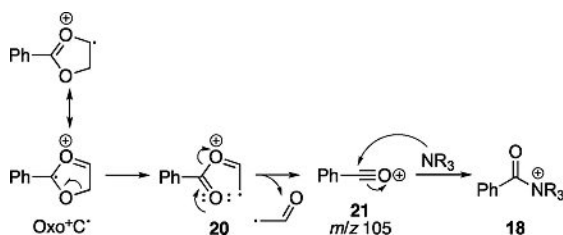


Figure 4. Mass spectrum of the reaction of Oxo⁺C• (m/z 148) with TEA after 500 ms ([TEA] ca. 8.5×10^9 molecules cm^{-3}). The mass-selected precursor ion is indicated by an asterisk (*).



Scheme 3. Proposed mechanism for formation of the acyl ammonium ion **18** in the reaction of Oxo^+C^* with amines.

conditions by monitoring the decay of the $\text{Pyr}^{+\bullet}$ signal at m/z 93 ($[\text{M}]^{+\bullet}$) as a function of reaction time under pseudo-first order conditions.^[8b] The rate coefficients for product formation, *i.e.*, Pyr^+H , the adducts Pyr^+-NR_2 as well as **16**, **17** and amine oxidation products were obtained from kinetic modelling of the experimental concentration-time profiles using the program Dynafit 4.^[16] Details are given in the Experimental Section.^[17] The rate data are presented in Table 1. An exemplary concentration-time profile is shown in Figure S11, and the kinetic data for amine oxidation are compiled in Table S2. It should be noted that the concentration-time profiles for all products did not show any induction period, suggesting that they result from either a one-step reaction or from multistep processes, where intermediates are transformed into the products on faster timescales than can be resolved in the mass spectrometer. The mechanism will be discussed in Section 2.4.

Overall, the reactions of both $\text{Pyr}^{+\bullet}$ with amines were very fast with the rate coefficients for the consumption of 4- $\text{Pyr}^{+\bullet}$ being about 20% higher than for 3- $\text{Pyr}^{+\bullet}$. The reaction efficiencies, which were calculated from the trajectory collision rate, k_{ador} derived from the average dipole orientation (ADO) theory^[18] for all amines (except for DIPEA for which polarizability data were not available from literature), range from 66–100%

Table 1. Absolute second-order rate coefficients k for the reaction of 4- $\text{Pyr}^{+\bullet}$ and 3- $\text{Pyr}^{+\bullet}$ with amines at 298 K.^[a,b,c]

Amine	$k \times 10^{-10}$ ($\text{cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$) $\text{Pyr}^{+\bullet}$ consumption	Pyr^+H formation	Pyr^+-NR_2 formation	$k_{\text{Add}}/k_{\text{Rad}}$ ^[d]	Efficiency ^[e]
TEA	8.9	0.8	9.1	11.4	70%
	7.3	2.1	6.8	3.2	57%
DIPEA	9.3	0.9	7.3	7.9	— ^[f]
	8.0	1.4	4.2	3.0	
DIPA	10	1.0	9.8	9.8	66%
	8.1	2.3	8.4	3.7	58%
CHA	15	2.7	15	5.6	100%
	12	5.0	10	2.0	86%
AA ^[g]	9.3	0.6	8.3	2.4	69%
	8.2	0.7	3.3	0.4	61%

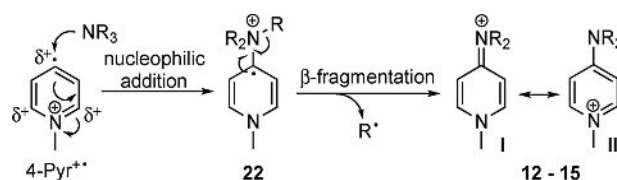
[a] Data in first line for 4- $\text{Pyr}^{+\bullet}$, in second line (in italics) for 3- $\text{Pyr}^{+\bullet}$. [b] Rate coefficients for $\text{Pyr}^{+\bullet}$ consumption from pseudo-first order measurements; rate data for product formation were fitted using the Dynafit 4 program (see Experimental Methods). [c] Rate coefficients have an experimental error of 25%. [d] k_{Rad} = all radical processes (see text). [e] Determined from $\text{Pyr}^{+\bullet}$ decay rate using trajectory collision rate k_{ado} ($\times 10^{-9} \text{ cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$): TEA = 1.28, DIPA = 1.40, CHA = 1.40, AA = 1.35. [f] Not available (see text). [g] Rate coefficient (in $\text{cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$) for formation of **16a**: $(2.8 \pm 0.7) \times 10^{-10}$, **16b**: $(5.8 \pm 1.5) \times 10^{-10}$, **17b**: $(1.0 \pm 0.3) \times 10^{-10}$.

for 4- $\text{Pyr}^{+\bullet}$ and 57–86% for 3- $\text{Pyr}^{+\bullet}$, respectively, indicating practically collision-controlled reactions in some cases. Within error, the decay rate coefficients for $\text{Pyr}^{+\bullet}$ are similar to the sum of the rate coefficients for product formation, *i.e.*, Pyr^+H , Pyr^+-NR_2 and amine oxidation (see Table S2), confirming that no major pathway resulting in loss of the charge tag occurred, which would render the product undetectable by mass spectrometry.

Comparison of the rate coefficients k_{Add} for the formation of Pyr^+-NR_2 with that for the 'conventional' radical pathways k_{Rad} through HAT or addition to π -systems (formation of Pyr^+H , as well as **16a**, **b** and **17b** in the reaction involving AA) confirmed the differences in the chemical behaviour of both $\text{Pyr}^{+\bullet}$ observed in the product studies (Section 2.2). For the reaction with the tertiary and secondary amines TEA, DIPEA and DIPA with 4- $\text{Pyr}^{+\bullet}$ an average value for $k_{\text{Add}}/k_{\text{Rad}}$ of 9.7 is obtained, whereas it is only 3.3 for 3- $\text{Pyr}^{+\bullet}$, clearly showing the higher reactivity of 4- $\text{Pyr}^{+\bullet}$ for amine addition at the expense of conventional radical reactivity. This finding was confirmed by comparing $k_{\text{Add}}/k_{\text{Rad}}$ for the reaction involving AA (where several sites are available to promote radical chemistry), which revealed a value of 2.4 for 4- $\text{Pyr}^{+\bullet}$ and only 0.4 for 3- $\text{Pyr}^{+\bullet}$. For the reaction involving the less nucleophilic primary CHA, the ratio $k_{\text{Add}}/k_{\text{Rad}}$ is about 50% smaller for both $\text{Pyr}^{+\bullet}$ compared with TEA, DIPEA and DIPA, respectively, which further supports the suggestion that formation of Pyr^+-NR_2 involves nucleophilic amine addition to $\text{Pyr}^{+\bullet}$.

2.4. Computational mechanistic studies

In recent gas-phase studies of isomeric distonic pyridinium radical cations with amino acids Kenttämä *et al.* reported outcomes similar to those shown in Figures 2–4. They proposed that the reaction is initiated by nucleophilic addition of the amine to the pyridinium radical, where the efficiency of the transfer of the amino group was found to increase with the electron affinity of the radical cation; however, an 'active' role of the unpaired electron during the addition was not considered.^[10a,d,g] Thus, in the reaction with 4- $\text{Pyr}^{+\bullet}$ addition of NR_3 could occur at the radical site C-4, which should also be activated for nucleophilic attack, to form adduct **22**, followed by homolytic β -fragmentation to give the amino pyridinium ions **12–15** with release of $\text{R}^{\bullet}$ (Scheme 4).^[19] In the reaction involving 3- $\text{Pyr}^{+\bullet}$, where the sites of positive polarisation and unpaired electron do not coincide, NR_3 addition might occur at



Scheme 4. Proposed mechanism for formation of the amino-substituted pyridinium ions **12–15** through non-radical addition of amines to $\text{Pyr}^{+\bullet}$, followed by homolytic β -fragmentation (shown exemplary for the reaction of 4- $\text{Pyr}^{+\bullet}$).

C-3 (radical site) as well as C-2 and C-4, which are activated by positive polarisation (not shown).

To better understand the interplay between charge and unpaired electron in these reactions, DFT calculations were performed at the M062X/6-31 + G* level of theory,^[20a,21] which has been previously shown to provide sufficiently accurate energies to identify the most likely reaction pathways.^[8b,22] The energies of the gas-phase calculations are given as enthalpies, as they best describe chemical reactivity under low-pressure bimolecular conditions,^[23] whereas for the reactions in solution (see Section 2.5) free energies are considered. The Gaussian archive entries for all optimized stationary points, energies and imaginary frequencies for transition states are given in the SI.

Table 2 compiles the energies for the different reaction pathways of Pyr⁺• with TEA, DIPEA and MOR. The reaction proceeds through formation of an initial ion-molecule association complex (reactant complex A) that is 40–60 kJ mol^{−1} lower in energy than the free reactants, or 'entrance channel', which is defined as reference point and set to 0 kJ mol^{−1}. Pathways with energies above the entrance channel are too slow to occur on the timescale of the experiment.^[24]

A transition state TS1 for the addition of the amine to the radical centre in 4-Pyr⁺• (C-4) and in 3-Pyr⁺• (C-3) could not be located,^[26] suggesting a barrierless step. Amine addition at C-4 in 3-Pyr⁺• will be discussed below. Formation of the Pyr⁺•-amine adducts B is strongly exothermic with 158–189 kJ mol^{−1} (entries 1–4). The subsequent homolytic β-fragmentation via TS2 is associated with a barrier of about 60–100 kJ mol^{−1} and leads to the product association complex C in an essentially energy-neutral or in the case of 3-Pyr⁺• slightly endothermic reaction. However, since B, TS2 and C are energetically well below the entrance channel, the β-fragmentation should be very fast. These findings support the mass spectrometric data that adducts B could not be detected even at very short

reaction times. Relief of steric strain in the case of DIPEA is likely responsible for the higher exothermicity of step B→C (entry 2), where the calculations confirm the experimentally observed exclusive release of the more stable secondary radical iPr• over the primary Et• (see Figure 2b).

Although HAT from the α-carbon atom in amines is thermodynamically highly favourable, this pathway is associated with a barrier (TS3) of 15–27 kJ mol^{−1} for the reaction of 4-Pyr⁺• with TEA and DIPEA, which cannot compete with the barrier-less formation of the amine adduct B. On the other hand, TS3 is considerably lower for the reaction involving 3-Pyr⁺• (27 vs 8 kJ mol^{−1}, entries 1 vs 4), which is in line with the experimentally observed higher radical reactivity of 3-Pyr⁺•. In MOR the N-CH₂ moiety is the kinetically most favourable site for HAT, with TS3 being about 15 kJ mol^{−1} (entry 3). The computations predict also a barrierless addition of MOR to 4-Pyr⁺• via the N atom. As mentioned above and shown in the mass spectrum in Figure S6a, the signals at higher m/z values suggest that addition of MOR to 4-Pyr⁺• occurred, but it was not possible to assign the various products that result from subsequent fragmentation of the 4-Pyr⁺•-MOR adduct.

To evaluate the role of the radical site in 4-Pyr⁺•, we calculated the addition of TEA to C-4 in the closed-shell Pyr⁺H (similar to a nucleophilic aromatic substitution, S_NAr). The data in entry 5 show that this addition is associated with a barrier of some 20 kJ mol^{−1} and is endothermic. On the other hand, for the addition of TEA to C-4 in the neutral 4-Pyr• (similar to an S_{RN}1 mechanism; see Scheme 1a) both TS1 and adduct B are located above the entrance channel, making this reaction too slow to occur under our experimental conditions (entry 6). These findings show that the unpaired electron in Pyr⁺• in conjunction with the positive charge facilitate amine attack on the aromatic ring at the site of the unpaired electron. A similar accelerating effect on the amine addition was found, when the

Table 2. Gas-phase reaction of Pyr⁺• with amines. M062X/6-31 + G* enthalpies in kJ mol^{−1}, relative to the free reactants.

Entry	Pyr ⁺ •	amine	A	Reaction site in Pyr ⁺ •	TS1	B	TS2	C	TS3 ^[a]	D
1	4-Pyr ⁺ •	NEt ₃ (TEA)	−56.3	C-4	— ^[b]	−188.4	−104.7 ^[c]	−183.0 ^[c]	−28.9	−191.0
2	4-Pyr ⁺ •	NEtPr ₂ (DIPEA)	−51.9	C-4	— ^[b]	−157.9	−95.6 ^[c]	−193.2 ^[c]	— ^[d]	—
3	4-Pyr ⁺ •	morpholine (MOR)	−46.8	C-4	— ^[b,g] −26.3 ^[h]	−157.6 ^[g] −45.3 ^[h]	— —	— —	−37.4 ^[f] −31.3	−215.1 ^[f] −154.0
4	3-Pyr ⁺ •	NEt ₃	−44.7	C-3 C-4	— ^[b] −41.1	−179.8 −50.4	−80.1 ^[c] —	−154.5 ^[c] —	−36.9	−198.5
5	Pyr ⁺ H	NEt ₃	−43.3	C-4	−25.7	−28.1	—	—	—	—
6	4-Pyr•	NEt ₃	−14.6	C-4	32.7	16.4	—	—	—	—
7	⊖...4-Pyr•	NEt ₃	−187.2 ^[k]	C-4	— ^[b]	−194.3	—	—	—	—

[a] HAT from N-CH₂. [b] No barrier (could not be located). [c] R•=Et•. [d] Not determined. [e] R•=iPr•. [f] (R-H)•=iPr•. [g] N addition. [h] O addition. [j] HAT from O-CH₂. [k] Geometry differed considerably from that of the other reactant complexes A.^[25]

charge-causing methyl group in 4-Pyr⁺ was replaced by a positive point charge (+1.0), i.e., $\oplus\cdots 4\text{-Pyr}^+$, to simulate an electric field (entry 7 vs 1).^[27]

Natural bond orbital (NBO) population analyses^[20b,28] revealed that in both 3- and 4-Pyr⁺ the SOMO is submerged below the MOs of the aromatic π -electrons to become the fourth-highest energy molecular orbital (Figure 5a with 4-Pyr⁺ as example, only the HOMO is shown, HOMO-1 and HOMO-2 on the remaining centres of the aromatic system are similar). The electron spin density plot shown exemplary for 4-Pyr⁺ confirms the sp^2 character of the SOMO on C-4, which is unrelated to the three higher lying occupied orbitals of the π system. On the other hand, the SOMO interacts with the σ^* orbitals of neighbouring C–C bonds (LUMO+3 and LUMO+4), enabling delocalisation so that about 10% of the spin density in 4-Pyr⁺ can be found on C-2 and C-6, and in 3-Pyr⁺ on N and C-5, respectively (see also Figure 1).^[29,30]

Figure 5b shows the optimised geometry of adduct **B** in the reaction of 4-Pyr⁺ with TEA. Only 5% of the spin density is located on the amine moiety, which is characterised by all four C–N bonds being slightly elongated compared with typical C–N single bonds (ca. 1.479 Å).^[31] The remaining 95% spin density is distributed over the pyridinium ring involving two p-shaped SOMOs at both C-4 and N (which are now also the two highest occupied MOs) and the π^* orbitals of the connecting carbon framework (not shown), suggesting that adduct **B** could be described through the resonance forms **III** and **IV**. In the transition state (**TS2**) of the subsequent homolytic β -fragmentation, the SOMO (=HOMO) interacts with the σ^* orbital (LUMO) of the breaking N–C bond (Figure 5c). **TS2** occurs comparatively late on the potential energy surface with about 50% of the spin density on the leaving Et[•] fragment. The bond scission is

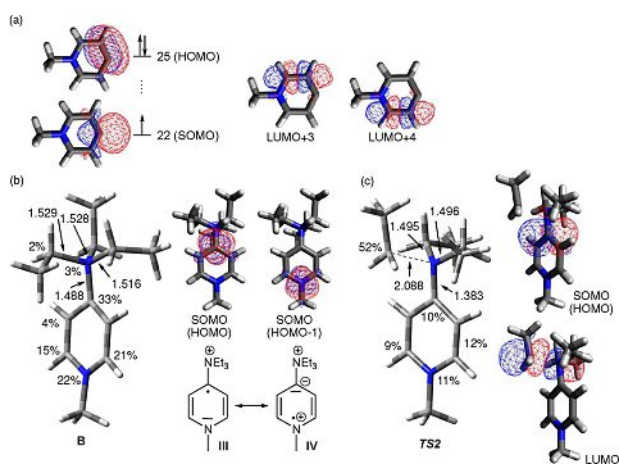


Figure 5. Reaction of 4-Pyr⁺ with TEA. Geometries optimised with M062X/6-31+G*. (a) Electronic arrangement and MO configuration in 4-Pyr⁺; NBO population analysis with ω B97x/6-31+G*. (b) Geometry and MO configuration in adduct **B**; NBO population analysis with ω B97x/6-31+G*. (c) Geometry and MO configuration of transition state **TS2**; NBO analysis with M062X/6-31+G*. Bond lengths in Å, the percentage numbers are spin densities. The α electron spin density, highest doubly occupied molecular orbital (HOMO), singly occupied molecular orbital (SOMO), and selected lowest unoccupied molecular orbitals (LUMO) are indicated. The numbering of molecular orbitals is assigned in the order of increasing energy.

accompanied by considerable contraction of the remaining N–Et bonds to practically single bond length, as well as of the N–Pyr bond, which at 1.383 Å is close to that of a partial C–N double bond (1.352 Å)^[31] and already resembles the product resonance structure **I** in Scheme 4.

As mentioned above, the addition of amines to 3-Pyr⁺ could principally occur at the radical site C-3, as well as at C-2 and C-4, since both latter positions would be expected to be activated for nucleophilic attack. We will focus our discussion on the reaction at C-3 and C-4. The calculations reveal that amine addition at C-3 is not only barrier-less but also thermodynamically clearly more favourable than at C-4, despite being the less electropositive site (Table 2, entry 4).

Figure 6a shows that the optimised geometries for **B** and **TS2** after initial amine addition at C-3 closely resemble those found for the addition at C-4 in 4-Pyr⁺ with regards to both geometry and spin density. On the other hand, nucleophilic amine addition at C-4 in 3-Pyr⁺ is associated with a small barrier (**TS1**) of 3 kJ mol^{−1}. Analysis of the orbitals revealed that the bond forming process involves interaction of the lone pair at N (in HOMO-1) with the LUMO at C-4 (MO not shown), without any contribution by the unpaired electron that is located in HOMO-4 (Figure 6b; HOMO, HOMO-2 and HOMO-3 are occupied by the six π electrons of the Pyr system). The adduct **B** is only slightly lower in energy than the reactant complex **A** and characterised by a long C–N bond of 1.619 Å and 90% spin density on C-3 (as in 3-Pyr⁺) and only 5% on the TEA moiety, clearly indicating that the unpaired electron is not involved in the amine addition at C-4.

The calculated energy profile for the reaction of Pyr⁺ with AA revealed that the radical processes for 3-Pyr⁺ through HAT and addition to the π system are lower in energy than for 4-Pyr⁺, confirming the experimentally found higher preference for 3-Pyr⁺ to undergo ‘conventional’ radical chemistry. The data are presented in Scheme S1.

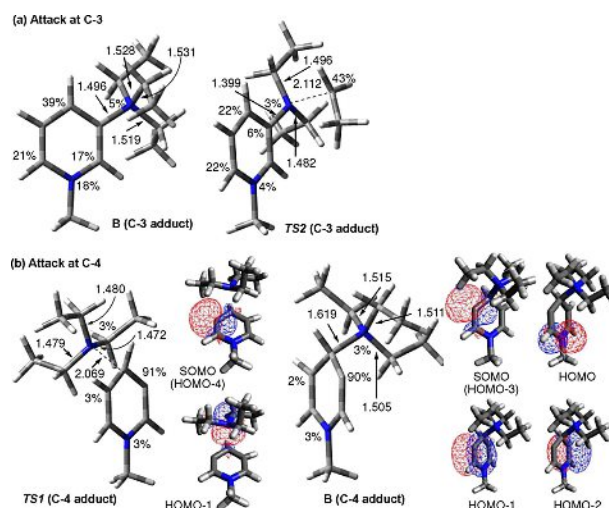


Figure 6. Reaction of 3-Pyr⁺ with TEA. Geometries optimised with M062X/6-31+G*. (a) Adduct **B** and **TS2** during reaction at C-4. (b) **TS1** and adduct **B** during reaction at C-3. NBO population analysis of MO configuration analysed with M062X/6-31+G*. Bond lengths in Å, the percentage numbers are spin densities. The α electron spin density of relevant MOs is shown.

To conclude, upon amine addition to the radical site in either 3- or 4-Pyr^{•+} the SOMO transitions from an sp² orbital (σ radical) to a p orbital (π radical), enabling spin delocalisation over the Pyr ring that leads to stabilisation of adduct **B** by about 150–200 kJ mol⁻¹, compared to the reactions with the closed-shell (Pyr⁺H) or neutral (4-Pyr[•]) counterparts, respectively (Table 2, entry 1 vs 5 and 6). The unpaired electron is ejected *via* an alkyl radical in the subsequent homolytic β -fragmentation, leading to formation of the amino substituted pyridinium [Pyr–NR₂]⁺.

In contrast to $\text{Pyr}^{+\bullet}$, amine addition to $\text{Oxo}^{+\text{C}\bullet}$ occurs at a carbon centre that is not a part of an aromatic π system. Scheme 5a shows the calculated energies of the stationary points of the reaction of $\text{Oxo}^{+\text{C}\bullet}$ with TEA and DIPEA. Amine addition to form the adduct **F** via **TS4** is kinetically considerably more favourable than HAT from the α -CH group in the amines via **TS8**, confirming the experimental finding that $\text{Oxo}^{+\text{CH}}$ (m/z 149) was not formed (see Figure 4). The geometry of **TS4** is shown in Scheme 5b for the reaction involving TEA, the geometries of all stationary points for this reaction are presented in Figure S19. **TS4** is characterised by a long C–N distance of 2.308 Å consistent with an early transition state. MO analysis revealed a strong interaction between the SOMO (= HOMO-1) and the LUMO on the tertiary carbon atom (C-3) of the dioxolane ring, enabling spin delocalisation. In the C–N bond forming process the SOMO accepts one electron of the lone pair at nitrogen, *i.e.*, $\text{LP}_{\text{N}} \rightarrow \text{SOMO}$, leaving the non-

participating electron on N (11% spin density). Formation of the adduct **F**, which has the SOMO centred on C-3, is strongly exothermic by about 120 kJ mol⁻¹. For comparison, the addition of TEA to the neutral radical OxoC• (see Scheme 5a) is predicted to be highly endothermic by ca 168 kJ mol⁻¹ (data not shown), clearly revealing the role of the positive charge in Oxo⁺C• on the reaction energetics.

Attempts to compute a direct pathway from amine adduct **F** to the amino substituted dioxolanes **K** through homolytic β -fragmentation failed, but instead revealed the open-chain iminium complex **H**, which could be formed through a concerted ring-opening/ β -fragmentation.^[32] However, since the barrier *TS7* lies close to or even above the entrance channel, respectively, this pathway should be too slow to occur under our experimental conditions.

On the other hand, a stepwise mechanism consisting of radical ring-opening via **T55** to yield the radical cation **G**, followed by homolytic β -fragmentation via **T56** to give **H** is highly feasible with all computed ground and transition states lying well below the entrance channel. It should be noted that for the reaction with DIPEA the predicted preferred radical scission of an N-*i*Pr bond over an N-Et bond in the fragmentation **G**→**H** is in agreement with the experimental findings (see Figure S7a).

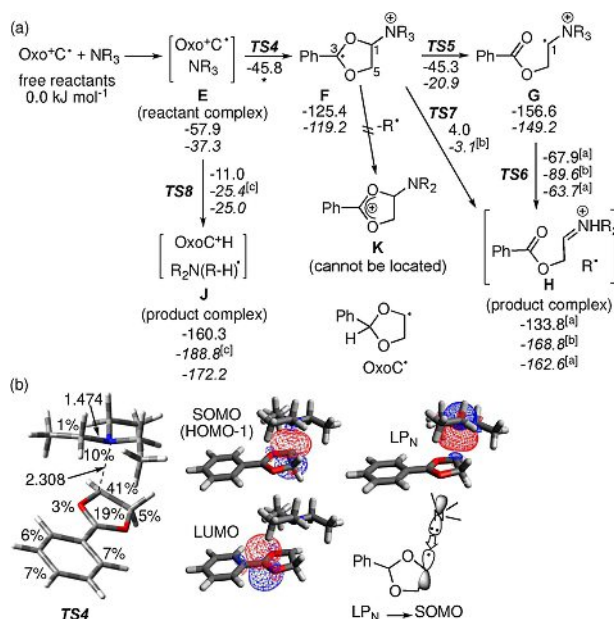
2.5. Reaction of 4-Pyr⁺ with amines in solution

Since Kenttämäa *et al.* showed in previous work that distonic pyridine radical cations react with ethers, such as THF, in the condensed phase through both radical and non-radical pathways,^[10c,f] we explored whether the results from our mass spectrometric studies could also be reproduced in solution.^[33]

The experiments were performed by irradiating a solution of the radical precursor **7a** and the amine in acetonitrile in a Rayonet photoreactor with $\lambda = 350 \text{ nm}^{[10c]}$ at 35°C for 24 hours. The reaction mixture was analysed by direct injection ESI high-resolution mass spectrometry (HRMS, see Table S3), which provided confident assignment of the molecular formulae of the products. Generation of $4\text{-Pyr}^{+\bullet}$ under these conditions was confirmed by irradiating a solution of **7a** in acetonitrile in the presence of two equivalents of the radical trap TEMPO. A product at m/z 249 was formed, which was confirmed by HRMS as the adduct $4\text{-Pyr}^+ \text{-OTEMP}$ (Figure S8).

The mass spectrum in Figure 7a shows that the reaction with TEA indeed led to formation of the adduct **12a** at m/z 165. No reaction occurred between **7a** and TEA in the absence of light under otherwise identical conditions (Figure S9), clearly excluding an S_NAr mechanism.

The major signal at m/z 102 could be assigned to protonated TEA that was present in excess. We also observed formation of a new product at m/z 110, which could be assigned as the hydroxy pyridinium ion **23** that could possibly result from reaction of 4-Pyr⁺• with residual water in the solvent, which acts as the nucleophile. Product **12a** was isolated and its structure confirmed by ¹H NMR spectroscopy (Figure S20), providing further support for the proposed



Scheme 5. (a) M062X/6-31 + G* enthalpies (in kJ mol⁻¹) of the stationary points for the various pathways in the reaction of Oxo⁺C[•] with TEA (top number) and DIPEA (bottom number in *italics*), relative to the free reactants. HAT pathway calculated for abstraction from the amine α -carbon. [a] R[•]=Et[•], [b] R[•]=iPr[•], [c] HAT from secondary C–H in *i*Pr. ***T54** for the addition of DIPEA cannot not be located, suggesting a barrier-less process. (b) Optimised geometry and MO configuration of **T54** for the addition of TEA to Oxo⁺C[•]; NBO analysis with ω B97X/6-31 + G*. Bond lengths in Å, the percentage number are spin densities. The α electron spin density, and selected molecular orbitals are indicated.

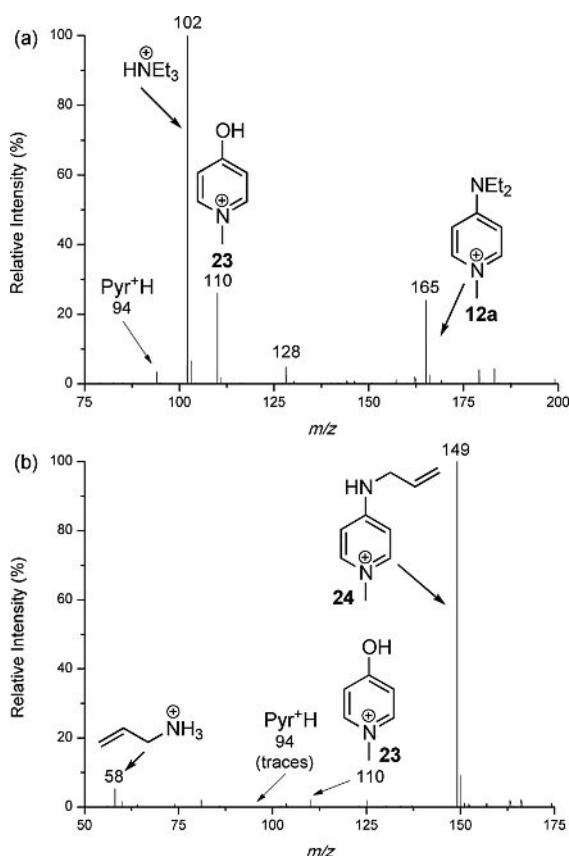
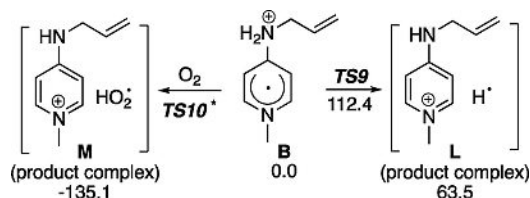


Figure 7. Mass spectra of the reaction of 4-Pyr⁺• (**7a**, *m/z* 220, 0.086 mmol) in the Rayonet photoreactor ($\lambda = 350$ nm, 24 hrs, 35 °C). (a) Reaction with TEA (1.79 mmol in 15 mL MeCN), (b) Reaction with AA (3.34 mmol in 15 mL MeCN). The HRMS data of the products are given in Table S3.

mechanism. Similar to the reactions in the gas phase, HAT and formation of Pyr⁺H was only a very minor pathway in the reaction with amines in solution. Interestingly, the outcome of the reaction of 4-Pyr⁺• with the primary amines AA and CHA in the condensed phase was different from that in the gas phase. In the reaction involving AA a product appeared at *m/z* 149 (Figure 7b), which could be assigned as the allylamine-substituted pyridinium **24**. Likewise, the product at *m/z* 191 formed in the reaction of 4-Pyr⁺• with CHA corresponds to 4-cyclohexylamine pyridinium (**25**; shown in Figure S10a). Using the reaction with AA as example, the mechanism in Scheme 6



Scheme 6. Reaction of 4-Pyr⁺• with AA in solution. M062X/6-31+G* free energies in acetonitrile (in kJ mol⁻¹) of the stationary points relative to the free reactants or relative to the adduct complex **B** – O₂ for the reaction involving O₂. *TS could not be located.

suggests that **24** result from the initially formed amine adduct **B** through hydrogen loss.

However, the calculated free energies for this homolytic scission in acetonitrile using the Conductor-like Polarizable Continuum Model (CPCM) mode^[34] predict a barrier **TS9** of 112.4 kJ mol⁻¹ and an endothermicity of 63.5 kJ mol⁻¹, which seems to be unlikely to occur under the experimental conditions. We therefore propose that hydrogen abstraction proceeds with assistance of residual O₂ present in the solution. While a transition state for this abstraction could not be located, indicating a barrierless process, formation of the product complex **M** is strongly exothermic.^[35]

To explore whether the reaction is limited to amines, we performed the photolysis of **7a** in neat methanol and found formation of a product at *m/z* 124, which could be assigned as the 4-pyridinium methyl ether (**26**; shown in Figure S10b). When the reaction was performed in deuterated methanol, the mass shifted to *m/z* 127, confirming the proposed transfer of the OMe group onto 4-Pyr⁺•. However, in contrast to the reactions with the amines, a large amount of unconsumed radical precursor **7a** was still present after 24 hours. Furthermore, when the reaction was performed with MeOH dissolved in acetonitrile, formation of 4-pyridinium methyl ether did not occur. These findings suggest that interception of the photo-generated tight radical pair [4-Pyr⁺• I•] occurs more readily with the more nucleophilic amines allowing the reaction to be performed under dilute conditions using a solvent, whereas the lower nucleophilicity of MeOH requires partial separation of the ion pair for a reaction to occur, which can be achieved by performing the reaction in neat MeOH.^[36]

3. Conclusion

In this combined experimental and computational study, we have shown that the presence of a positive charge *in conjunction* with an unpaired electron considerably facilitates the nucleophilic addition of amines to pyridine. Using the isomeric distonic aryl radical cations 4-Pyr⁺• and 3-Pyr⁺•, the reaction was found to occur through amine attack exclusively at the site of the unpaired electron, which is followed by homolytic β -fragmentation, where the unpaired electron is ejected *via* an alkyl radical to give the amino substituted pyridinium [Pyr–NR₂]⁺. This reaction is the dominant pathway, rendering ‘conventional’ radical reactions through HAT or addition to π systems of minor importance. However, in 3-Pyr⁺•, where the site of spin and positive polarisation in the aromatic ring do not coincide, radical behaviour becomes slightly more important. The barrierless formation and particular stability of the amine adduct [Pyr–NR₂]⁺•, compared with the endothermic formation of the closed-shell cationic adduct [Pyr–NR₂]⁺ through an S_NAr-type reaction, or the neutral radical adduct [Pyr–NR₂][•] through an S_{RN}1-type reaction, respectively, can be rationalised by the gain in energy resulting from transformation of the largely localised sp²-type SOMO in Pyr⁺• into a p-type SOMO in [Pyr–NR₂]⁺ that enables delocalisation of the unpaired electron over the pyridine ring. Exemplary studies for 4-Pyr⁺•

revealed similar outcomes for the reaction with amines and even the weaker nucleophile methanol in solution.

A related amine addition/radical fragmentation sequence was also found in the reaction with the aliphatic distonic radical cation $\text{Oxo}^+\text{C}^\bullet$ in the gas phase. These findings show that the synergistic effects caused by the combination of charge and spin are not limited to aromatic systems.

Experimental Section

Mass Spectrometric Experiments. Gas-phase studies were conducted on a Thermo Scientific (Bremen, Germany) LTQ ESI mass spectrometer, modified to enable the introduction of volatile neutral reagents into the linear ion trap to perform ion-molecule reactions (IMRs). Briefly, a suitably volatile liquid reagent was injected at a rate of $5\text{--}20\ \mu\text{L}\ \text{hour}^{-1}$ directly into the helium line supplying helium bath gas to the linear ion trap. The helium line was heated and maintained at a temperature above the boiling point of the reagent, volatilizing the liquid before it reached the ion trap. The pressure regulator controlling the flow of helium into the ion trap under normal operating conditions was bypassed, with the helium pressure controlled manually to maintain an ion gauge pressure that was the same as under normal operating conditions (0.69×10^{-5} Torr), which was confirmed by testing against the relatively slow ion-molecule reaction of Br^- with CH_3I , as reported previously.^[37] Further details are given in refs.^[6,8,38] Ions undergoing ion-molecule reactions (IMRs) in the ion trap of the mass spectrometer are quasi-thermalized to the temperature of the helium bath gas (298 K).^[38a] When performing IMRs, an ion of interest was isolated inside the ion trap, where it was allowed to react with the neutral. Each neutral compound used in the IMRs was purified prior to use *via* distillation, with purity checked by NMR.

Compound samples were prepared to $75\text{--}100\ \mu\text{M}$ in methanol and were injected into the ESI source at a flow rate of $5\ \mu\text{L}\ \text{min}^{-1}$. The instrument was operated in positive ion mode, with the settings tuned to optimise the signal of the initial parent ion peak at the beginning of each data collection session. ESI source conditions included needle potentials between $2.5\text{--}4.7\ \text{kV}$, a capillary temperature of 250°C , capillary voltages between $0.0\text{--}34.0$, and tube lens voltages between $0.0\text{--}55.0\ \text{V}$. Ions of interest for MS^n experiments were isolated with a $2\text{--}5\ m/z$ window. The CID parameter was selected so that the parent ion being fragmented was reduced to $\sim 15\%$ abundance. Data were collected using three micro-scans and taking between $10\text{--}100$ spectra.

Kinetic Studies. Absolute rate coefficients were determined from the peak areas in the mass spectra, which directly reflect the concentration of the respective ionic species in the ion trap. The rate coefficients for the consumption of $\text{Pyr}^{+\bullet}$ through reaction with the amines were obtained at $298\ \text{K}$ by monitoring the decay of the $\text{Pyr}^{+\bullet}$ signal at $m/z\ 93$ ($[\text{M}]^{+\bullet}$) as a function of reaction time under pseudo-first order conditions. Four to five different excess concentrations^[39] of the amine were used on time scales that allowed the peak intensity of $\text{Pyr}^{+\bullet}$ to decrease to ca. 20% and to build up time-resolved decay profiles (8–13 reaction times). The pseudo-first order rate coefficient k_{obs} was obtained from the slope of the plot $\ln[\text{Pyr}^{+\bullet}]$ vs. reaction time. The second-order rate coefficient k was determined by plotting k_{obs} vs. [amine], see Figures S12 and S13. The rate coefficients for product formation were obtained from kinetic modelling of the experimental concentration-time profiles using the program Dynafit 4.^[16] The pseudo-first order rate coefficients for product formation, k'_{obs} , were fitted for the HAT pathway: $\text{Pyr}^{+\bullet} + \text{amine} \rightarrow \text{Pyr}^+\text{H} + [\text{amine-H}]^\bullet$, at m/z

94, for the amine addition to $\text{Pyr}^{+\bullet}$: $\text{Pyr}^{+\bullet} + \text{amine} \rightarrow \text{Pyr}^+\text{NR}_2$, at $m/z\ 165$ (12a/b), $m/z\ 179$ (13a/b), $m/z\ 151$ (14a/b), $m/z\ 109$ (15a/b), $m/z\ 120$ (16a/b) and $m/z\ 134$ (17b) and for the amine oxidation $\text{Pyr}^{+\bullet} + \text{amine} \rightarrow \text{amine-H}^+$ at $m/z\ 100$ (TEA and DIPA), $m/z\ 128$ (DIPEA) and $m/z\ 98$ (CHA). The second-order rate coefficient k for formation of each individual product was obtained from plotting k'_{obs} vs. [amine], which is shown in Figures S14–S17 in the Supporting Information.

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Keywords: DFT calculations · distonic ions · gas-phase chemistry · mass spectrometry · reaction mechanisms

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