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Metal-Free Selective Synthesis of α,β-Unsaturated Aldehydes from Alkenes and Formaldehyde Catalyzed by Dimethylamine

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α,β-Unsaturated aldehydes are important building blocks for the synthesis of a wide range of chemicals, including polymers. The synthesis of these molecules from cheap feedstocks such as alkenes remains a scientific challenge, mainly due to the low reactivity of alkenes. Here we report a selective and metal-free access to α,β-unsaturated aldehydes from alkenes with formaldehyde. This reaction is catalyzed by dimethylamine and affords α,β-unsaturated aldehydes in yields of up to 80%. By combining Density Functional Theory (DFT) calculations and experiments, we elucidate the reaction mechanism which is based on a cascade of hydride transfer, hydrolysis and aldolization reactions. The reaction can be performed under very mild conditions (30–50 °C), in a theoretically 100% carbon-economical fashion, with water as the only by-product. The reaction was successfully applied to non-activated linear 1-alkenes, thus opening an access to industrially relevant α,β-unsaturated aldehydes from cheap and widely abundant chemicals at large scale.

Introduction

In the chemical industry, α,β-unsaturated aldehydes represent an important chemical platform for preparing a wide range of valuable chemicals such as polymers, bioactive ingredients, flavors, and fragrances.[1] Acrolein, as the simplest α,β-unsaturated aldehyde, is produced at large scale by the oxidation of propene in the presence of Bi–Mo catalysts,[2] but this advantageous route is not applicable to longer-chain alkenes. More generally, α,β-unsaturated carbonyl compounds are synthesized by the Horner-Wadsworth-Emmons/Wittig reaction,[3] aldol or Knoevenagel condensation,[4] Saegusa-oxidation[5] or the carbonylation of unsaturated hydrocarbons in the presence of a transition metal catalyst, a topic which has been recently reviewed by Beller[6] and Bäckwall.[7] From an industrial standpoint, carbonylation[6] and oxidative carbonylation[7] are of particular interest because these catalytic routes rely on CO and unsaturated hydrocarbons as very cheap and readily available starting materials. However, to the best of our knowledge, α,β-unsaturated aldehydes have only been obtained by the Pd or Rh-catalyzed formylation of alkynes, which are unfortunately less abundant and more expensive than alkenes.[6] As an alternative, the two-step (metal catalyzed) hydroformylation of alkenes to aldehydes followed by (acid or base-catalyzed) aldol condensation has been developed (Figure 1, route 1). This reaction can be even advantageously performed in a one pot fashion with a high chemo-, regio- and stereoselectivity by combining rhodium phosphine complexes with an acid-base system in a single reactor.[8]

All the above reactions rely on the use of noble metal catalysts, most of them being expensive and with limited availability and / or future risks to supply.[9] Interestingly, however, in the late 1980s, Maninnen reported a stoichiometric metal-free pathway to α,β-unsaturated aldehydes by reacting styrene, paraformaldehyde and dimethylammonium chloride in the presence of acetic acid.[10] Except for a very recent report on this reaction (use of a stochiometric amount of $ZnCl_2$ and an excess of LiCl, Figure 1, route 2),[11] this work went almost unnoticed (only five citations) probably because the 1980s were the golden age of metal-based catalysts and, at that time, our society was not really concerned about metal scarcity.

The methodology initially developed by Manninen was inspired by hydroaminomethylation reactions (Figure 1, route 3).[12] The key ingredient of such reactions is the generation of the *N*,*N*-dimethylmethaniminium, $[CH_2NMe_2^+]$ ion which, in combination with an iodide counterion, is also known as Eschenmoser's salt. This ion is generated by the reaction of an aldehyde with a secondary amine. As a strong electrophile, Maulide reported that it readily reacts with various nucleophiles

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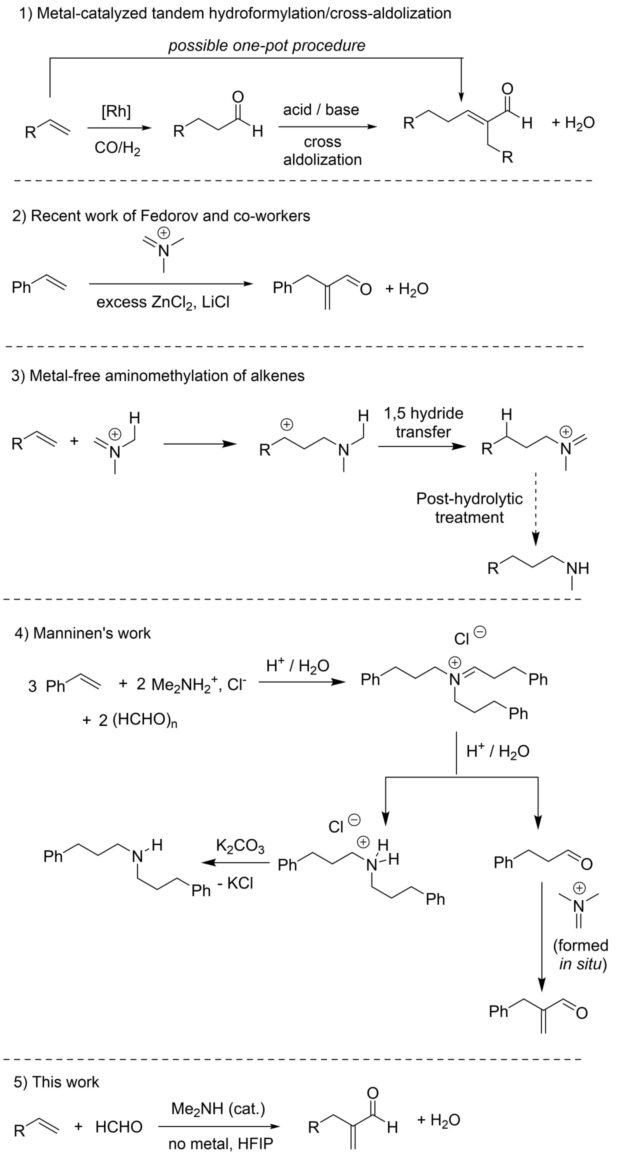

Figure 1. Synthesis of α,β-unsaturated aldehydes from alkenes. Contribution of our work to the state of the art (R = Alkyl or phenyl group).

(Mannich-type reaction), including π-systems such as alkynes or alkenes, to form an iminium cation through a 1,5-hydride shift.[13] This reaction is catalyzed by an acid, thus avoiding the use of transition metals. The as-formed iminium cation can be subsequently converted to an amine by a post hydrolytic work up. Manninen reported that successive additions of an alkene to an *in situ* formed Eschenmoser salt led to the formation of a tertiary iminium cation (Figure 1, route 4). The latter can be then hydrolyzed to yield an aldehyde and a secondary amine. The aldehyde reacts in turn with the aforementioned Eschenmoser salt, yielding the targeted α,β-unsaturated aldehydes in yields of up to ~50%.[10] Despite its interest, this pathway has important shortcomings such as the stoichiometric use of dimethylammonium chloride (or the combination of *N*,*N*,*N*′,*N*′-tetramethyldiaminomethane with sulfuric acid), leading to the generation of salts, and a poor atom economy due to the formation of a secondary amine as byproduct.

With growing concerns about sustainability, we decided, with the help of DFT calculations, to revisit the mechanism of this reaction, leading us to discover a catalytic one-pot and metal-free alternative pathway to α,β-unsaturated aldehydes (up to 83% yield), without forming the secondary amine as a co-product (Figure 1, route 5). Notably, we found that it was possible to directly use dimethylamine in a catalytic amount (by *in situ* generation and regeneration of Eschenmoser's salt), thus avoiding the side generation of salt. From a practical viewpoint, this optimized pathway couples two cheap and abundant feedstocks (alkene, formaldehyde) without any transition metal, at low temperature (30–50 °C) and in a theoretically 100% carbon economical fashion, with water as the only by-product.

Results and Discussion

Screening of Reaction Conditions

Styrene was selected as a model alkene as it is known to react with Eschenmoser's salt to form an iminium cation.[13] It was reacted at 30 °C with 4 eq. of formalin (37 wt% HCHO in water) and 1 eq. of dimethylamine (DMA, 38 wt% in water) for 20 h (see Table S1 which shows that this molar ratio led to the highest selectivity towards the desired α,β-unsaturated aldehyde). Different from Manninen who carried out the reaction in acetic acid at 115 °C,[10] we selected hexafluoroisopropanol (HFIP) as a solvent for two reasons. First, Maulide previously reported that styrene reacted with Eschenmoser's salt in HFIP to form an iminium cation at temperatures below 75 °C.[13] Secondly, several reports showed that HFIP was a solvent of choice to generate and stabilize cationic species, essentially through H-bond interaction, and thus to promote reactions at low temperatures.[14] As expected, while no reaction was observed at 30 °C in solvents such as acetic acid, toluene, methanol, nitromethane or trifluoroethanol (Table 1, entries 1–5), the conversion of styrene was complete in HFIP and 2-benzylacrylaldehyde, the targeted α,β-unsaturated aldehyde, was formed in 78% yield after 20 h (Table 1, Entry 6). The α-methylenation was confirmed by ^{1}H NMR with a doublet corresponding to the $=CH_2$ group at 6.14 ppm (in $CDCl_3$). The $-CH_2$ (singlet) and -CHO (singlet) groups appear at 3.57 and 9.59 ppm, respectively. The complete structural characterization of the α,β-unsaturated aldehyde (^{1}H/^{13}C NMR and HRMS) is provided in Fig. S1–S3). Note, that under the best conditions reported in Table 1 (entry 6), the reaction was already complete after 9 h, as determined by ^{1}H NMR.

Other secondary amines such as diethyl- or dibutylamine can also be used instead of DMA, but the selectivity towards the targeted α,β-unsaturated aldehyde (56-64%) is lower (Table 1, entries 7, 8). Hence, in the following experiments, dimethylamine was selected.

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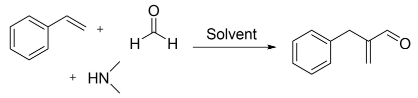
Table 1. Screening of reaction conditions.[a]



Entry	Solvent	Conv./%	Selectivity/%	
			A	Others[b]
1	CH_3COOH	< 5	0	0
2	Toluene	< 5	0	0
3	CH_3OH	< 5	0	0
4	CH_3NO_2	< 5	0	0
5	CF_3CF_2OH	< 5	0	0
6	HFIP	100	78	22
7[c]	HFIP	83	64	36
8[d]	HFIP	96	56	44
9[e]	HFIP	0	0	0
10[f]	HFIP	0	0	0

[a] Reaction conditions: styrene (2 mmol), HCHO (8 mmol, 37 wt% aqueous, formalin), DMA (2 mmol, 38 wt% aqueous), 0.1 M solvent, air (1 bar), 30 °C, 20 h; [b] Others are mainly N-methyl-3-phenylpropan-1-amine, bis(3-phenylpropyl)amine, N-methyl-bis(3-phenylpropyl)amine; [c] Diethylamine replaced DMA;[d] Dibutylamine replaced DMA ; [e] without DMA; [f] without HCHO.

Experimental Validation of Reaction Intermediates

To gain insight into the reaction mechanism, in particular the role of DMA, several experiments were carried out, starting with control reactions in the absence of DMA or HCHO (Table 1, entries 9, 10). In both cases, no reaction took place, indicating that the combination of styrene, DMA and HCHO is mandatory. Indeed, the formation of the *N*,*N*-dimethylmethaniminium ion from DMA and HCHO is a prerequisite for the reaction, as explained in the introduction section. Note that using paraformaldehyde instead formalin failed. Importantly, in the conditions of Table 1, entry 6, *N*-methyl-3-phenylpropan-1-amine (7% yield, m/z = 149.1199) was also detected by gas chromatography coupled to High Resolution Mass Spectrometry (HRMS) (Figure 2, Fig. S4), as well as trace amounts of phenylpropanal.

Next, to validate the key role of the *N*,*N*-dimethylmethaniminium intermediate, we reacted styrene with 1 eq. of the commercially available *N*,*N*-dimethylmethaniminium iodide (Eschenmoser's salt) in aqueous HFIP (1 wt% of H_2O was added in HFIP to mimic water brought by formalin in the above-described experiments) at 30 °C, in the absence of formaldehyde (Figure 3). After 6 h of reaction, 2-benzylacrylaldehyde was formed in 81% yield. The aforementioned *N*-methyl-3-phenylpropan-1-amine was also detected by GC (Fig. S5). This experiment strongly suggests that the reaction mechanism for 2-benzylacrylaldehyde formation from styrene occurs *via* the *in situ* formation of the *N*,*N*-dimethylmethaniminium cation, obtained by the reaction of DMA with HCHO in aqueous HFIP.

To assess whether the detected *N*-methyl-3-phenylpropan-1-amine was a co-product or a reaction intermediate in the above reaction, it was reacted at 30 °C in HFIP with 1 eq. of aqueous HCHO (Figure 4) but in the absence of styrene. Under these conditions, 2-benzylacrylaldehyde was obtained in 43% yield, supporting that *N*-methyl-3-phenylpropan-1-amine is not a by-product but a reaction intermediate, albeit the rate of the reaction was quite low. Importantly, this experiment suggests that alternatives may exist to the reaction pathway proposed by Manninen (Figure 1, route 4), otherwise styrene would have been required to convert *N*-methyl-3-phenylpropan-1-amine to 2-benzylacrylaldehyde. Instead, we may propose that this amine reacted with HCHO to form an iminium cation which is then rearranged through a 1,3-hydride transfer (Figure 4), *without* styrene intervening. Intuitively, an intramolecular H transfer would require an unfavorable 4-membered ring transition state structure.[11] However, amines have been shown to act as hydride transfer agents toward iminium ions.[15] The rearranged iminium ion is then hydrolyzed to phenylpropanal and DMA. Phenylpropanal can be further converted into 2-benzylacrylaldehyde, potentially through two different routes. Route 1 involves an aldol condensation of phenylpropanal with HCHO, a reaction known to be catalyzed by amines.[16] To support this hypothesis, phenylpropanal was reacted with 4 eq. of HCHO and 1 eq. of DMA in HFIP at room temperature (Figure S6). As anticipated, phenylpropanal was readily converted into 2-benzylacrylaldehyde in 66% yield, supporting that it is one of the possible reaction intermediates. The very high reactivity of

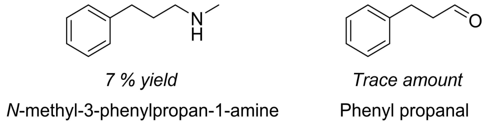


Figure 2. Byproducts detected by GC-HRMS (conditions of Table 1, entry 6).

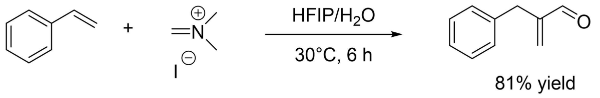


Figure 3. Test reaction of styrene and the *N*,*N*-Dimethylmethaniminium iodide salt.

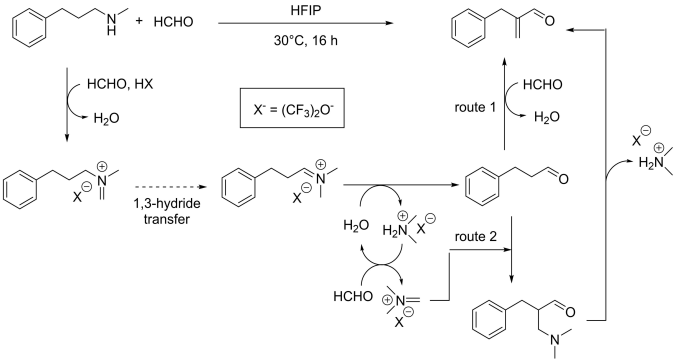


Figure 4. Test reaction of *N*-methyl-3-phenylpropan-1-amine and 1 eq. of HCHO.

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phenylpropanal with HCHO might explain its detection in trace amount. Route 2 is the methylenation of phenylpropanal by reaction with the *N*,*N*-dimethylmethaniminium cation, as also indirectly suggested in Figure 3. This hypothesis is further supported by the detection of an intermediate with a molecular mass of 190.1236 uma (HRMS, [M-H$^+$]), which could correspond to the addition of *N*,*N*-dimethylmethaniminium cation to phenylpropanal.(Fig. S7). This intermediate can be then converted into the targeted α,β-unsaturated aldehyde through a classical Hofmann elimination, a reaction even accelerated under basic conditions.[17] Presumably, both routes 1 and 2 co-exist.

DFT Calculations

So far, from our experimental results, two different mechanisms are plausible (1) the one proposed by Manninen which is based on consecutive additions of styrene on Eschenmoser's salt (Figure 1, route 4) but also (2) a 1,3-hydride transfer as suggested in Figure 4. To obtain further insight, a series of DFT calculations was performed at the M06-2X/def2-QZVP level (Figures 5 and 6, see the SI for computational details).

Consecutive 1,5-hydride Transfers by Reaction with Styrene

Consistent with literature,[11,12f,13] we find that the first step is the nucleophilic attack of the electron-rich double bond of styrene on the electron-poor $=CH_2$ moiety of the *N*,*N*-dimethylmethaniminium ion (Eschenmoser's salt, **1**, formed *in situ* by the reaction of DMA and HCHO) to generate a cationic intermediate (**2**) (Figure 5a). The latter is stabilized by 53 kJ/mol *vs.* separate styrene and **1**, and it is formed *via* a low energy ($\triangle G^{\ddagger} = +78$ kJ/mol) concerted transition state with a favorable 6-membered ring structure. Formally this process corresponds to a 1,5-hydride transfer from one of the methyl groups of **1** to the benzylic carbon of styrene. An alternative stepwise pathway to the same product *via* a benzylic cation was found 10 kJ/mol higher in energy (less favorable). Hydrolysis of **2** to *N*-methyl-3-phenylpropan-1-aminonium (**3-H$^+$**) and HCHO is unfavorable (+16 kJ/mol *vs.* **2**), hence it is not expected to be a dominant pathway. In contrast, in the same way as **2** was formed from iminium ion **1** and styrene, the reaction of iminium **2** with a second molecule of styrene to form iminium ion **4** is favored by −46 kJ/mol. The lowest energy pathway to **4** goes through intermediate **2**–**4** which result from the nucleophilic attack of the terminal carbon of the electron-rich double bond of styrene on the electrophilic methylenic carbon of **2**. A barrier-free hydride transfer from the methyl group of **2**–**4** to the cationic benzylic carbon then yields **4**. The overall process again formally corresponds to a 1,5 hydride transfer. Similar to **2**, **4** can undergo hydrolysis, affording bis(3-phenylpropyl)amine (**6**) and HCHO, a process which is thermodynamically favoured by −10 kJ/mol. Alternatively, *via* still another 1,5-hydride transfer, **4** can react with a third molecule of styrene to form iminium species **5** in a highly favourable reaction (−66 kJ/mol *vs.* **4**). For this reaction step, we were able to locate a concerted 6-

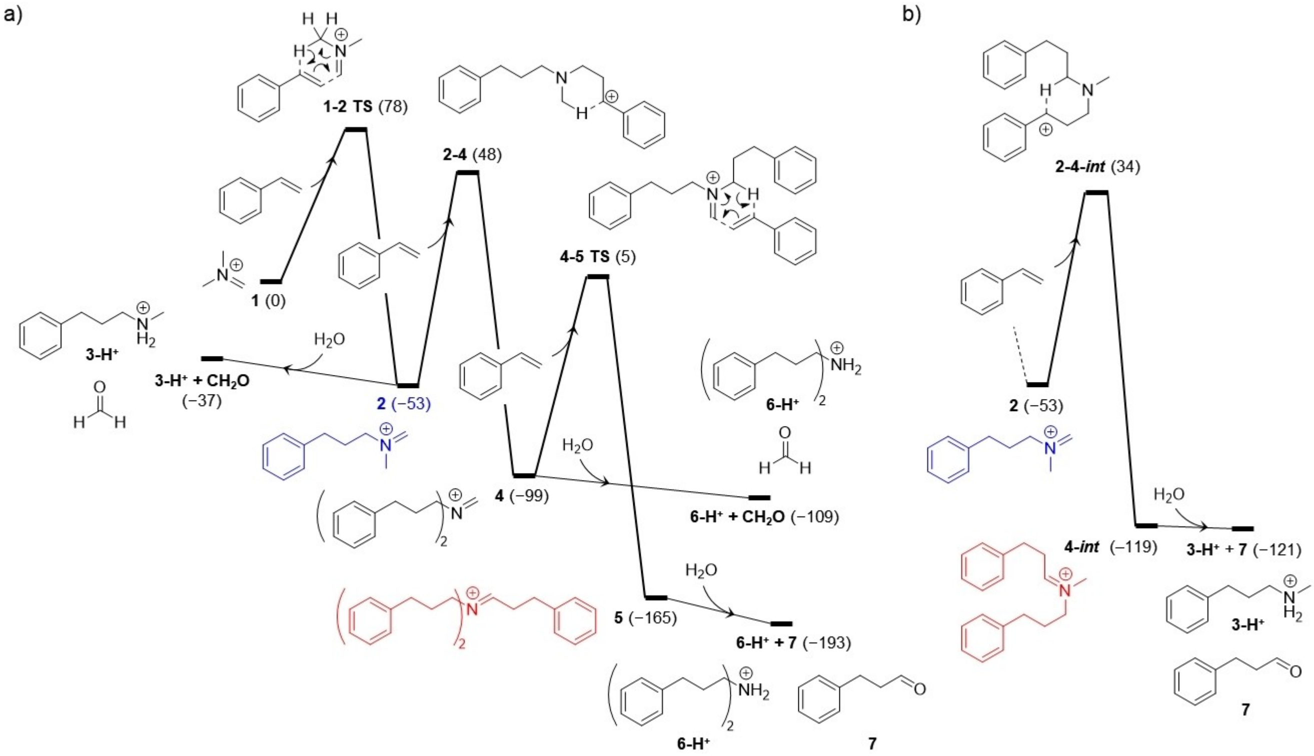

Figure 5. DFT calculated free energy profile (298 K, 1 bar, HFIP solvent) for a) the reaction mechanism proposed by Manninen; b) an alternative mechanism involving an isomer of intermediate **4**.

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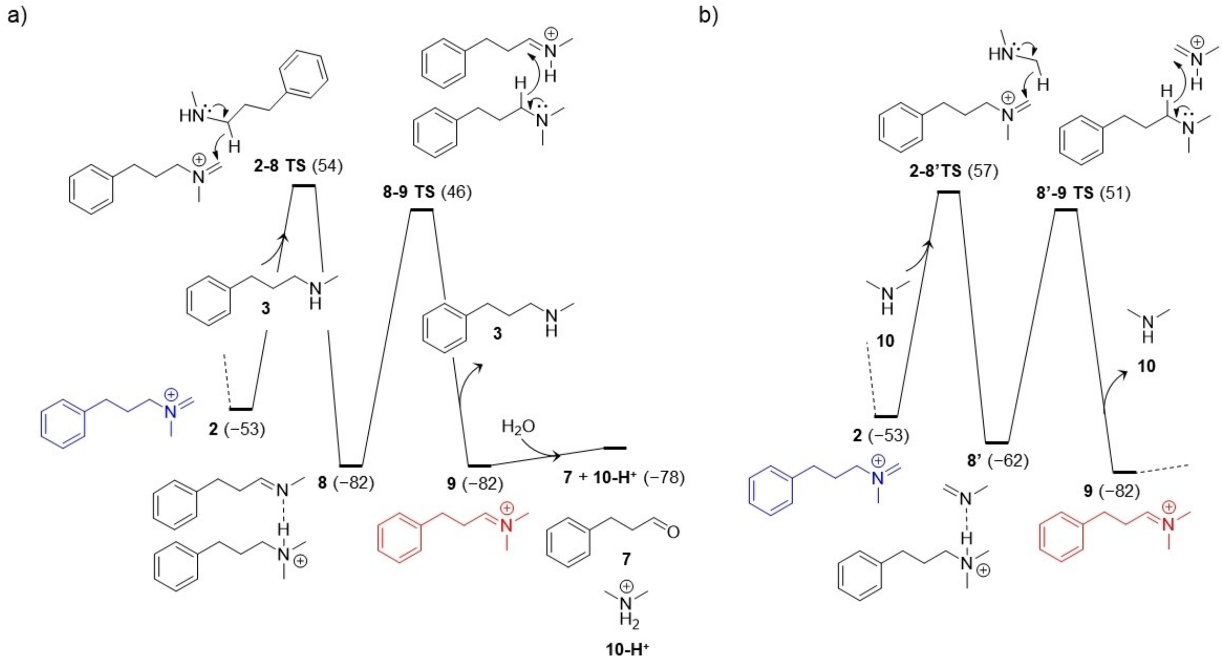

Figure 6. DFT calculated free energy profile (298 K, 1 bar, HFIP solvent) for the intermolecular 1,3-hydride transfer of intermediate **2** to **9** catalyzed by a) *N*-methyl-3-phenylpropan-1-amine (**3**) or b) dimethylamine.

membered ring transition state (**4**–**5 TS**). Finally, hydrolysis of **5** to 3-phenylpropanal (**7**) and bis(3-phenylpropyl)ammonium (**6-H**$^+$) is favored by −28 kJ/mol.

While the mechanism proposed by Manninen appears plausible, key intermediate **4** is a terminal iminium, and we surmised that an isomer with an internal double bond would be more stable. As expected, **4-int** is indeed significantly more stable than **4** (by 20 kJ/mol, Figure 5b), making it more likely than **4** from a thermodynamic point of view. Kinetic arguments are also in favour of **4-int**, with intermediate **2**–**4-int** being 14 kJ/mol more stable than **2**–**4**. Finally, **4-int** can hydrolyze to *N*-methyl-3-phenylpropan-1-amine (**3**) and 3-phenylpropanal (**7**), the latter affording the desired 2-benzylacrylaldehyde.

1,3-Hydride Transfer Mediated by Amines

As suggested from our experiments (see Figure 4 and the corresponding discussion), 3-phenylpropanal, and subsequently 2-benzylacrylaldehyde, might be also obtained from **2** through an 1,3-hydride transfer, *not* mediated by the presence of styrene but by amines. Therefore, we assessed whether *N*-methyl-3-phenylpropan-1-amine **3** (Figure 6a) or DMA (Figure 6b) could act in such capacity.

We indeed found that *N*-methyl-3-phenylpropan-1-amine (**3**) could transfer a methylenic hydride in α-position of the N atom to the electrophilic -CH_2 carbon of **2** *via* a relatively low energy transition state (**2**–**8 TS**, +107 kJ/mol *vs.* **2**, Figure 6a). The nucleophilic character of the hydride is likely enhanced by electron donation from the adjacent N lone pair. While, in principle, a hydride transfer could also be initiated by the methyl group of **3**, the corresponding transition state was found 21 kJ/mol higher in energy (less favourable). The hydride transfer from **3** leads to a strongly stabilized acid-base adduct of a tertiary amine and a secondary imine (**8**, stabilized by −29 kJ/mol *vs.* **2**) which might explain why these individual compounds were not observed experimentally. Analogous to the first H-transfer, the tertiary amine then transfers a methylenic hydride to the electrophilic -CH_2 carbon of the iminium ion *via* a relatively high barrier (**8**–**9 TS**, +128 kJ/mol *vs.* **8**), leading to the isomerized iminium **9**, hereby regenerating *N*-methyl-3-phenylpropan-1-amine (**3**). Finally, hydrolysis of **9** to 3-phenylpropanal (**7**) and the dimethylammonium ion **10-H**$^+$ is thermodynamically feasible, as indicated by the slightly positive free energy of reaction of +4 kJ/mol.

In such mechanism, it is obvious that DMA could act in the same way as **2**. For this reason, we recomputed the energy profile with DMA (**10**) instead of *N*-methyl-3-phenylpropan-1-amine (Figure 6b). While overall similar, intermediate **8'** is less stable than **8** (−82 *vs.* −62 kJ/mol), probably due to the lower basicity of DMA. Indeed, in the 1,3-hydride pathway promoted by *N*-methyl-3-phenylpropan-1-amine, the rate-limiting step is the isomerization of **8** to **9** (barrier of 128 kJ/mol, *vide supra*), mainly due to the high stability of adduct **8**, resulting from the high basicity of the tertiary amine. In the case of DMA, the corresponding barrier is significantly lower (113 kJ/mol), suggesting that DMA is a more efficient hydride transfer agent than *N*-methyl-3-phenylpropan-1-amine.

Comparing now the different pathways, the mechanism going through the internal iminium ion **4-int** (Figure 5b) clearly features the lowest free energy barrier (87 kJ/mol), followed by Manninen's mechanism (104 kJ/mol; Figure 5a), going through the less stable terminal iminium ion **4**, and the 1,3-hydride shift promoted by either DMA (113 kJ/mol, Figure 6b) or *N*-methyl-3-

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phenylpropan-1-amine (128 kJ/mol, Figure 6a). The formation of **4**-int or **4** is indeed consistent with the observation of a peak with m/z = 265 in the mass spectrum (Figure S8). We did not observe the formation of bis(3-phenylpropyl)amine (**6**) (Figure 5a), which is consistent with the more favorable pathway going through intermediate **4-int**. Finally, note that the co-produced amine **3** can react back with the excess of HCHO (4 equiv. *vs* styrene are used, see Table 1) to regenerate **2**, thus likely explaining the high selectivity towards the α,β-unsaturated aldehyde and the detection of **3** only in trace amounts.

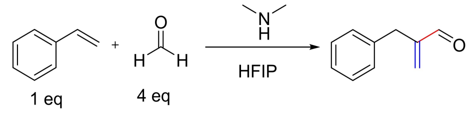
From Stoichiometric to Catalytic Reactions

If our mechanistic proposal is correct, DMA could be regenerated, opening the way to a potentially catalytic reaction. To our great delight, when the amount of DMA was reduced from 1 to 0.1 eq., the reaction was slowed down, but the selectivity remained unchanged, showing that DMA controls both the overall reaction rate and the selectivity of the reaction, as does a catalyst (Table 2). This result is of significant interest because, compared to previous reports, this work opens a catalytic and potentially 100% carbon economical route to α,β-unsaturated aldehyde from styrene and formaldehyde, the only co-product being water. In addition, this is a salt-free pathway to α,β-unsaturated aldehyde, thus drastically simplifying the work-up procedure and potentially improving the profitability as compared to the previously reported routes.

The most plausible Reaction Mechanism

To allow for a final comparison between the possible pathways, the reaction was carried out using two different styrene : HCHO molar ratios. Based on the theoretical stoichiometry of both pathways, styrene : HCHO molars ratio of 1:1 (2 molecules of styrene and 2 molecules of HCHO) and 1:2 (1 molecule of styrene and 2 molecules of HCHO) for the most favorable pathway found (via **4-int**) and the 1,3-hydride shift pathway catalyzed by DMA, respectively, were tested. In both cases, DMA was added in a catalytic amount (0.2 eq). The α,β-unsaturated aldehyde was formed nearly 4 times faster at a styrene : HCHO molar ratio of 1:1 (Fig. S9), suggesting that the pathway via **4-int** is the dominant one, a result in line with our DFT calculations which predict a significantly lower activation energy for the pathway relying on styrene (87 vs 113 kJ/mol, *vide supra*). To further support this hypothesis, we reproduced the experiment illustrated in Figure 4 from *N*-methyl-3-phenylpropan-1-amine but with 1 eq. of styrene added. In perfect agreement, the conversion of *N*-methyl-3-phenylpropan-1-amine to the α,β-unsaturated aldehyde was 50 times faster with styrene than without (Fig. S10), again showing that the styrene-mediated pathway is more favorable. A complete picture of the reaction mechanism is provided in the Figure 7. The first step is the generation of the iminium ion **1** by the reaction of DMA with HCHO. Then, **1** reacts with styrene to form the intermediate **2**. The existence of **2** is consistent with the observation of its hydrolysis product *N*-methyl-3-phenylpropan-1-amine **3**. Through the dominant styrene-mediated pathway, the addition of styrene on the cationic intermediate **2** generates **4-int**, followed by hydrolysis to **7**, and the aforementioned **3** which can re-inter the loop by reaction with HCHO. Alternatively, the less stable isomer **4** is formed, which reacts with an additional molecule of styrene to intermediate **5**. The latter is hydrolyzed to the aforementioned phenyl propanal (**7**), and **6**, which could be regenerated to **4** by reaction with HCHO. In a less favourable pathway, the cationic intermediate **2** could also undergo a 1,3-hydride transfer catalyzed by DMA, or by the secondary amine (**3**), yielding the cationic intermediate (**9**). *In situ* hydrolysis of (**9**) generates phenylpropanal (**7**) which is then converted to 2-benzylacrylaldehyde.

Table 2. Experiments with catalytic amounts of DMA.[a]



Entry	DMA (eq.)	t/h	Conversion /%	Selectivity /%
1	1	20	100	78
2	0.4	20	96	84
3	0.2	54	96	87
4	0.1	115	80	80

[a] Reaction conditions: 2 mmol styrene, DMA aqueous (0.1-2 mmol DMA), formalin (8 mmol HCHO), HFIP (0.1 M with respect to styrene), air, 30 °C, 20 h, selectivity was determined by GC; [b] others are mainly *N*-methyl-3-phenylpropan-1-amine, bis(3-phenylpropyl)amine, *N*-methyl-bis(3-phenylpropyl)amine.

Scope of the Reaction

To assess the scope of the reaction, different alkenes were tested. (Figure 8). The final objective of this section was to demonstrate that this methodology was applicable to linear alkenes such as 1-octene, 1-decene and 1-dedecene for instance which are industrially available on a large scale and cheap, but also much less reactive. To this end, the reactivity of various styrene derivatives exhibiting a terminal C=C bond were first tested to get through the best conditions before testing linear alkenes. Styrenes with alkyl or phenyl substituents in *ortho*-, *meta*-, or *para*-position afforded the corresponding α,β-unsaturated aldehydes in 71–85% yield (**1 a-d**) after 15–24 h of reaction. With 1,1-diphenylethylene the reaction afforded the corresponding α,β-unsaturated aldehyde **1 e** in 78% yield after 24 h of reaction. The presence of halide substituents on styrene, such as F, Cl and Br, reduced the reactivity, in particular derivatives substituted in *ortho*- and *meta*- positions, as illustrated by an increase of the reaction time to 84 h (**1 f–j**), except for **1 f**. Having all these results in hand, linear alkenes were tested. To our delight, 1-octene, 1-decene and 1-dodecene were also successfully converted into the corresponding α,β-unsaturated aldehydes in 40–44% yield at only 50 °C (**1 k-m**).

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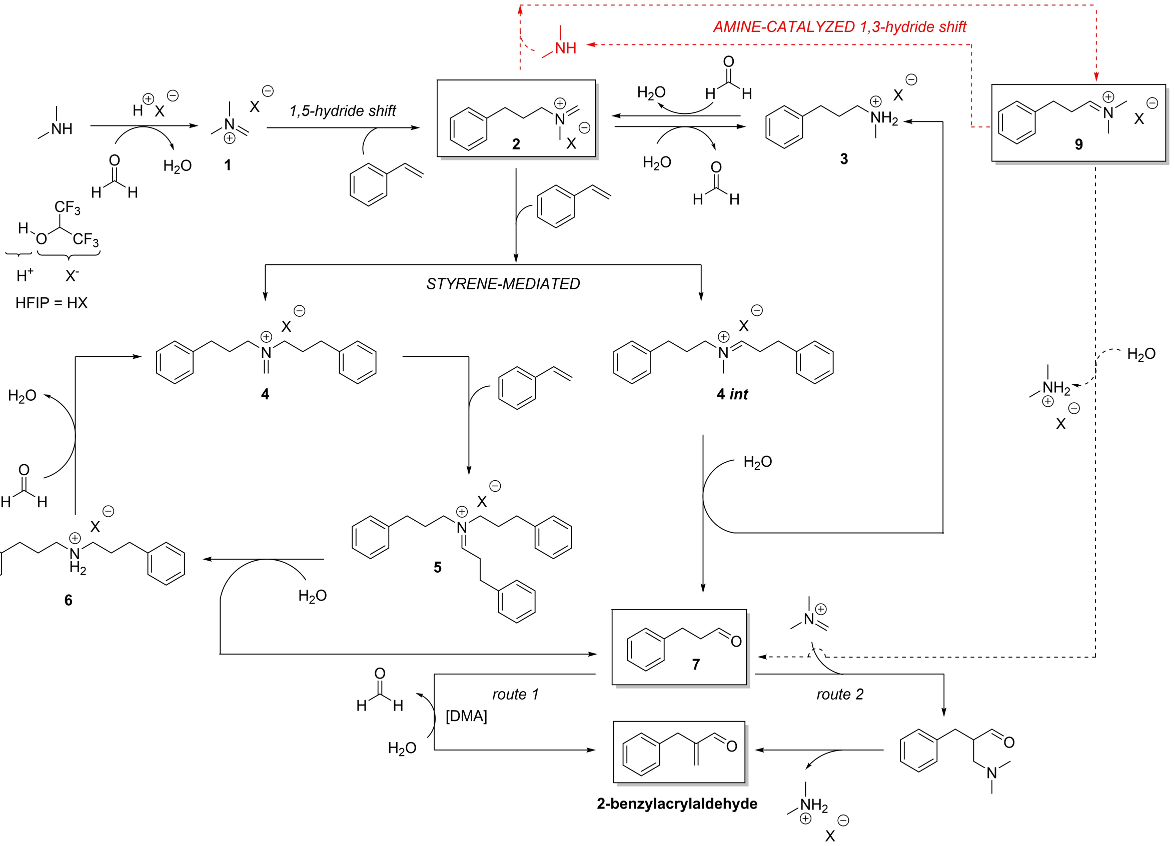
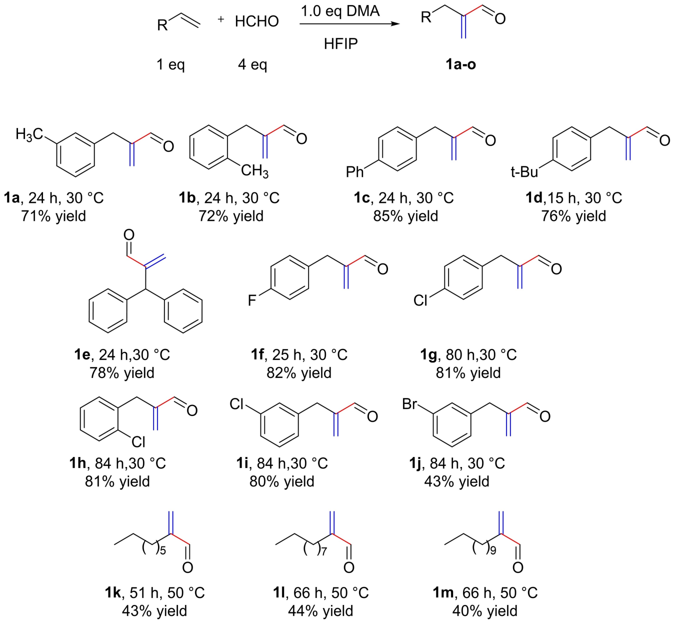


Figure 7. A proposed complete picture of the reaction mechanism. The amine-catalysed mechanism is illustrated with DMA.



1a, 24 h, 30 °C 71% yield
1b, 24 h, 30 °C 72% yield
1c, 24 h, 30 °C 85% yield
1d,15 h, 30 °C 76% yield
1e, 24 h,30 °C 78% yield
1f, 25 h, 30 °C 82% yield
1g, 80 h,30 °C 81% yield
1h, 84 h,30 °C 81% yield
1i, 84 h,30 °C 80% yield
1j, 84 h, 30 °C 43% yield
1k, 51 h, 50 °C 43% yield
1l, 66 h, 50 °C 44% yield
1m, 66 h, 50 °C 40% yield

Figure 8. Transposition of the proposed pathway to different alkenes. Reaction conditions: alkene (2 mmol), HCHO (8 mmol, 37 wt% aqueous), DMA (2 mmol, 33 wt% aqueous), 30 °C, 20 mL HFIP (0.1 M with respect to olefin). Yields were determined by GC.

These slightly lower yields as compared to styrene derivatives are due to incomplete conversion. Higher yields could be theoretically obtained by extending the reaction time. These results are of particular interest as they open a straightforward access to industrially relevant α,β-unsaturated aldehydes from cheap and abundant chemicals. Please note that, in these examples, DMA can be used in a catalytic amount but, as discussed above (Table 2), the reaction time is logically slower in this case. For instance, **1 b** was obtained in 70% yield after 72 h of reaction when 0.1 eq. of DMA was used *vs* 72% yield after 24 h with 1 eq. of DMA.

Conclusions

In this work, we report a metal-free access to α,β-unsaturated aldehydes from alkenes and formaldehyde. Through a theoretical-experimental investigation, we clarified the reaction mechanism and discovered a mean to use DMA in a catalytic amount, thus allowing to avoid the generation of salts. Importantly, this reaction can be transposed to linear alkenes such as 1-octene, 1-decene and 1-dodecene, opening an access to industrially relevant α,β-unsaturated aldehydes from cheap and widely abundant chemicals at large scale. From a practical point of view, this reaction proceeds at low temperature (30–50 °C), in a theoretically 100% carbon economical fashion with water as the only by-product.

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Conflict of Interests

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Keywords: α,β-unsaturated aldehydes · alkenes · metal free · HFIP · salt free

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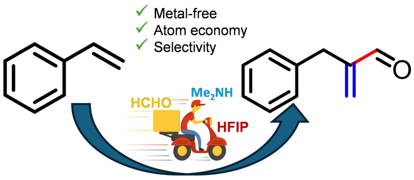
RESEARCH ARTICLE

We report here a selective and metal-free pathway to α,β-unsaturated aldehydes from cheap alkenes and formaldehyde. The reaction occurs at 30–50 °C and only releases water as a by-product. Through a combined theoretical-experimental study, we discovered that this reaction could be advantageously catalyzed by dimethylamine.



Dr. G. Peng, Dr. N. Ullah, Dr. S. Streiff, Prof. K. De Oliveira Vigier, Prof. M. Pera-Titus, Dr. R. Wischert, Dr. F. Jérôme**

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Metal-Free Selective Synthesis of α,β-Unsaturated Aldehydes from Alkenes and Formaldehyde Catalyzed by Dimethylamine