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Reactions of Iron Carbenes with α,β-Unsaturated Esters by Using an Umpolung Approach: Mechanism and Applications

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Abstract: An Umpolung approach, in which a phosphorus ylide moiety was introduced to increase the electron density of the double bond, was developed to activate electron-deficient alkenes for reaction with electrophilic iron carbenes. In tandem with the Wittig reaction, the reactions of α,β-unsaturated esters with in situ generated Fe–carbene complexes delivered formal C–H insertion products through cyclopropanation/ring-opening reactions. DFT calculations and cross-experiments indicate that, in this process, the ring opening of the cyclopropylmethyl ylide intermediate is rapid and reversible and the subsequent proton transfer is the rate-determining step. Further studies revealed that, based on the choice of the ylide and ester groups, as well as the base, the reaction could be steered towards either the ring-opening pathway or to the production of vinyl cyclopropanes.

Keywords: carbenes · cyclopropanation · iron · Umpolung reaction · ylides

Introduction

Transition-metal-catalyzed carbene transfer from diazo compounds to olefins is a useful and important type of transformation in organic synthesis.[1,2] However, aside from the properties of the metal carbenes or carbenoids, the reaction type, reactivity, and the regio- and stereoselectivity of the transfer are usually heavily influenced by the electronic nature of the alkene, steric hindrance, and the adjacent functionality.[1–3] For example, in the cyclopropanation reaction, great success has been achieved with electron-rich and terminal olefins.[1,4] However, electron-deficient alkenes, such as α,β-unsaturated carbonyl compounds, and sterically hindered olefins, such as 1,2-disubstituted, trisubstituted, and tetrasubstituted olefins, are far less reported, owing to the electrophilic nature and structural sensitivity of most metal–carbene intermediates.[1–3]To realize the reaction of electron-deficient alkenes with metal carbenes (carbenoids), extensive studies have been performed, but with quite limited success. To the best of our knowledge, only a few direct catalytic carbene-transfer reactions for the cyclopropanation of electron-poor alkenes have been reported and large amounts of excess olefin are always employed.[4] The most successful example[5] reported so far is probably the radical cobalt–porphyrin system reported by Zhang and co-workers.[6] We recently introduced an Umpolung activation approach for electron-deficient alkenes, in which the iron–porphyrin complex catalyzed carbene transfer to α,β-unsaturated esters and produced unusual formal C_{sp2}–H insertion products through a cyclopropanation/ring-opening process.[7] Herein, we report this reaction and a mechanistic study in detail, together with an extension of this Umpolung method to a tandem cyclopropanation/Wittig reaction.

Results and Discussion

Fe–porphyrin complexes have shown excellent stability and efficiency in the cyclopropanation reactions of alkenes[8] and they have even been employed under aqueous and strongly basic conditions,[8a–d] thus suggesting their high potential for practical use. However, Fe–porphyrin-derived carbenes are strongly electrophilic and inactive toward electron-deficient olefins, such as methyl crotonate.[9] Although both steric hindrance and electron deficiency are possible reasons for this inactivity, we hypothesized that, in the cases of inactive 1,2-disubstituted alkenes, such as α,β-unsaturated carbonyl esters, their electronic nature might be the main cause.[10] Considering that electron-deficient olefins usually contain an acidic allylic proton, we conceived that deprotonation with an appropriate base would produce an allylic carbanion and probably reverse its polarity, thus making the double bond electron-rich enough to react with electrophilic metal carbenes (Scheme 1). However, in our initial study, subjecting methyl crotonate to basic conditions (with lithium bis(trimethylsilyl)amide (LiHMDS) as a base) in the presence of methyl diazo acetate (MDA) and a catalytic amount of

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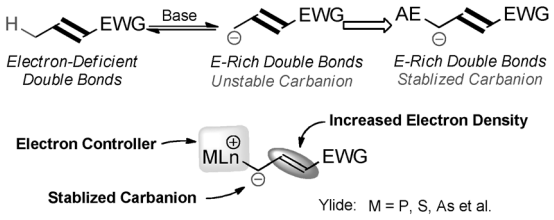
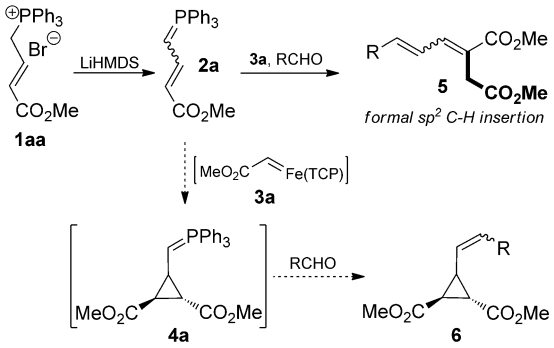


Scheme 1. Umpolung strategy for the activation of electron-deficient alkenes.

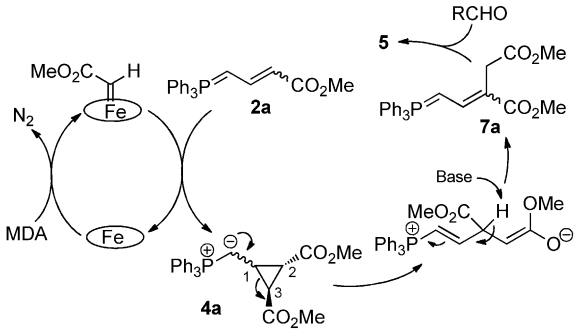
tetra(4-chlorophenyl)porphyrin iron chloride [Fe(TCP)Cl] led to a dirty reaction, probably owing to the instability or basicity of the carbanion and to side reactions, such as Michael reactions, the oligomerization of methyl crotonate, etc. Thus, we envisioned that the introduction of an electron-accepting group to stabilize the carbanion could be a potential solution to our original proposal (Scheme 1).

During the course of our studies on ylide chemistry,[11] we recognized that a classical ylide (L_nM^+–C^-RR′) could be regarded as a carbanion that contains a unique leaving group. Thus, the neighboring positively charged group (L_nM^+) could be employed as an "electron controller" to stabilize the carbanion (Scheme 1). Inspired by these structural features, we designed crotonate-derived allylic phosphorus ylide **2a** as a model substrate for our investigation. Interestingly, attempts to generate ylide **4a** and subsequently trap it with aldehydes delivered the formal C_{sp2}–H insertion products, namely 1,1,4-trisubstituted 1,3-butadienes (**5**), rather than their corresponding vinyl cyclopropanes (**6**; Scheme 2).[7]



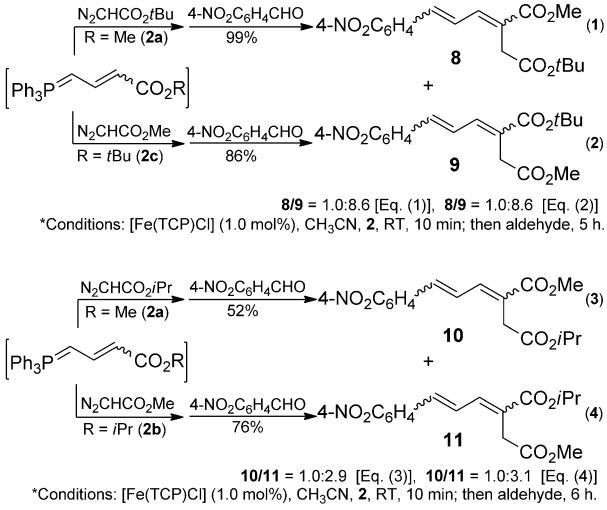
Scheme 2. Reaction of ylide **2a** with iron carbenoid **3a**.

However, in this reaction, cross-experiments and the successful trapping of intermediate **4a** suggested that the cyclopropanation of crotonate-derived phosphorus ylides did occur;[7] thus, we proposed a plausible mechanism, as shown in Scheme 3: The cyclopropanation of ylide **2a** by an iron carbene gives cyclopropylmethyl ylide intermediate **4a**, which then rapidly undergoes an ylide-triggered ring-opening reaction and subsequent proton transfer to afford ylide **7a**. Finally, treatment with aldehydes gives the ring-opened 1,3-butadiene products (**5**).



Scheme 3. Proposed mechanism for the diene formation.

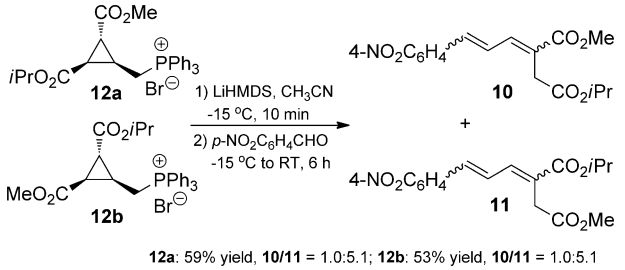
To further verify this proposed mechanism, cross-experiments by using ylides **2a** and **2c** with MDA and *tert*-butyl diazo acetate (BDA) were performed (Scheme 4, Equations (1) and (2)). In each case, both products **8** and **9** were obtained in a 1:8.6 ratio (**8**/**9**). Similar results were also observed in the corresponding cross-experiments with isopropyl diazo acetate and ylide **2b** (Scheme 4, Equations (3) and (4)). These results indicated that the reaction most likely proceeded through a tandem cyclopropanation/ring-opening/Wittig process, as proposed in Scheme 3, rather than through a direct C_{sp2}–H insertion, which should exclusively lead to compound **8** (**10**) or **9** (**11**).[12] Moreover, different ester groups lead to different product distributions in the cross-experiments (Scheme 4), thus suggesting that the relative configurations and/or steric hindrance of the substituents in the cyclopropylmethyl ylide intermediates might affect the relative fission of the C1–C2 versus C1–C3 bonds in compound **4a** (Scheme 3).



Scheme 4. Cross-experiments.

To determine the influence of the configuration of the cyclopropylmethyl ylide on the product distribution, we prepared salts **12a** and **12b** with a defined relative configuration that could afford cyclopropylmethyl ylide intermediates

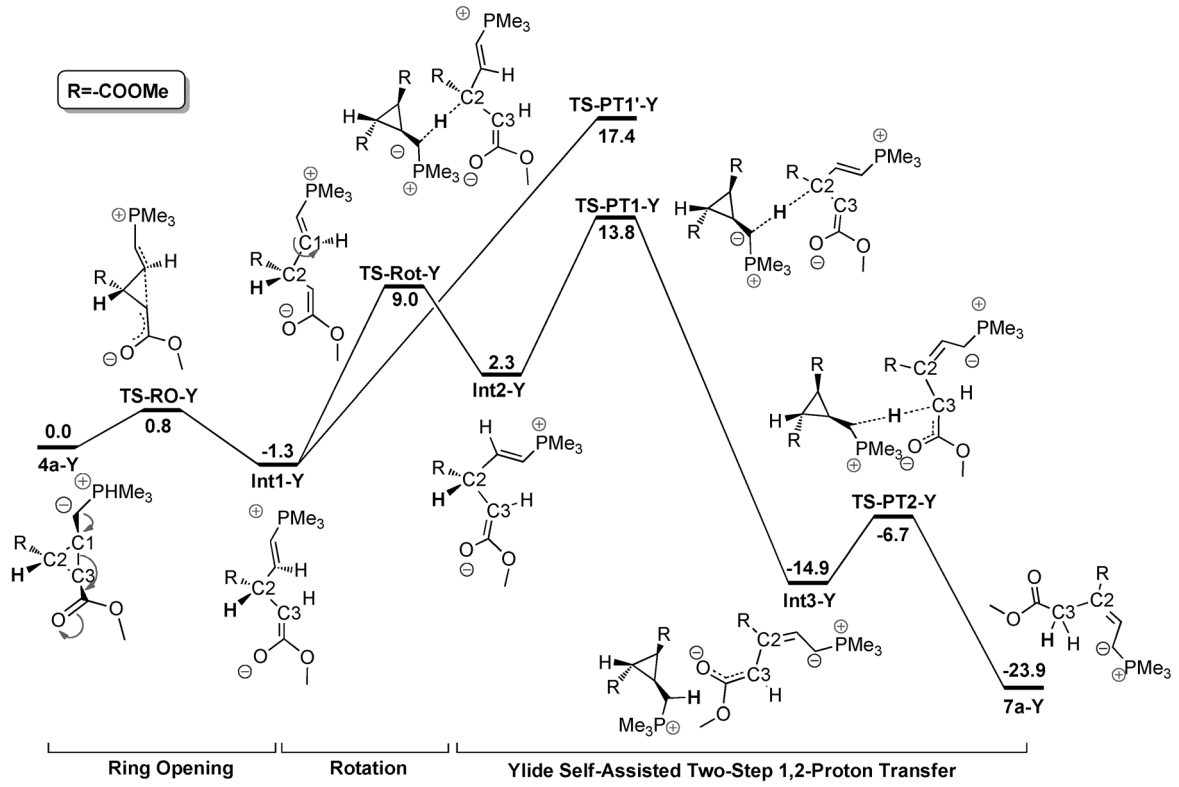
upon treatment with a base (Scheme 5). Although diastereoisomers **12a** and **12b** had a different relative configuration, when treated with LiHMDS, 1,3-butadiene **11** was obtained as the major isomer in both cases and with the same ratio of compounds **10**/**11** (Scheme 5), thus indicating that the configuration of compound **4a** had a negligible effect on the product distribution, whereas the steric hindrance of the substituents on the cyclopropylmethyl ylide could be the cause. To further understand the reaction mechanism and, in particular, to gain insight into the selectivity of the ring-opening step and the factors that influence the product distribution, density functional theory (DFT)[13] calculations were performed.



Scheme 5. Compounds **12a** and **12b** as probes to study the selectivity in the ring-opening step.

Theoretical study: DFT calculations were performed with the Gaussian 03[14] program. The geometries were fully optimized at the B3LYP[15]/6-31G* level of theory; harmonic vibration frequency calculations confirmed that the optimized structures were either minima (with no imaginary vibrations) or transition states (with one imaginary vibration). To determine more-accurate energies, single-point energies and solvent effects were calculated by using the IEFPCM[16] model (UAHF radii) in THF ($\varepsilon = 7.59$) at the B3LYP/6-311+G** level of theory. The final relative free energies (ΔG_{sol}, in kcal mol^{-1}) were obtained by adding the single-point energies and the solvent-effect corrections, as well as the thermal corrections at the B3LYP/6-31G* level. The phosphinyl PMe_3 group was used in the models to accelerate the calculations. Reaction pathways that proceeded from cyclopropylmethyl ylide **4a** to intermediate **7a** (Scheme 3) have been studied in detail.[17] These results showed that the direct intramolecular 1,2-proton transfer was unlikely, owing to the high energy barrier (30.1 kcal mol^{-1}).[17] The most favorable mechanism was the ylide-self-assisted ring-opening and intermolecular proton transfer, in which the assisting ylide acted as a proton shuttle.

As shown in Scheme 6, structure **4a-Y** contains two molecules of ylide **4a**. Surprisingly, the ring-opening step occurs very easily, with a small barrier of 0.8 kcal mol^{-1}, thus leading to a relatively stable intermediate, **Int1-Y** (−1.3 kcal mol^{-1}). After a conformational change with rotation of the C1−C2 bond (**TS-Rot-Y**, 9.0 kcal mol^{-1}), proton abstraction from the C2 position in **Int2-Y** occurs via transition state



Scheme 6. Calculated reaction pathways in the self-assisted mechanism for ylide **4a** (in some structures, the assisting ylide is omitted for clarity).

TS-PT1-Y (13.8 kcal mol^{-1}), thus leading to intermediate **Int3-Y**. Subsequently, protonation at the C3 position in **Int3-Y** (**TS-PT2-Y**, −6.7 kcal mol^{-1}) fulfills a formal 1,2 proton transfer and leads to intermediate **7a-Y**, which can be trapped by aldehydes to give 1,3-butadiene derivatives. Direct proton abstraction from the C2 position in **Int1-Y** by the cyclopropylmethyl ylide is less favorable (**TS-PT1′-Y**, 17.4 kcal mol^{-1}).

The calculated results given in Scheme 6 show that the ring-opening process is very fast and reversible. In structure **4a-Y**, the C1−C2 and C1−C3 bond lengths are 1.536 Å and 1.546 Å, respectively, longer than the C2−C3 bond (1.523 Å). Clearly, it is the electron-donating ylidic carbanion and the electron-withdrawing ester groups that make the cyclopropane highly polarized, thus facilitating the ring-opening step. Based on the calculated results, proton transfer from **Int2-Y** to **Int3-Y** is the rate-determining step and is irreversible under the reaction conditions. Therefore, the distribution of the ring-opened products in cross-experiments is governed by transition state **TS-PT1-Y**.

To gain more insight into the ester effect, by which the cyclopropane always opens from the side of the less-hindered ester group (Scheme 4 and Scheme 5), calculations were performed for the self-assisted proton-transfer reaction of ylide **4b**. Considering the orientation of the phosphorus group and the ester groups, a conformational search was performed for transition states that corresponded to ring opening from the MeO (**TS-PT-Y-Me**) and *t*BuO sides (**TS-PT-Y-*t*Bu**) and eight structures were calculated.[14] As shown in Figure 1, the most-stable transition state, **TS-PT-Y-Me**, was

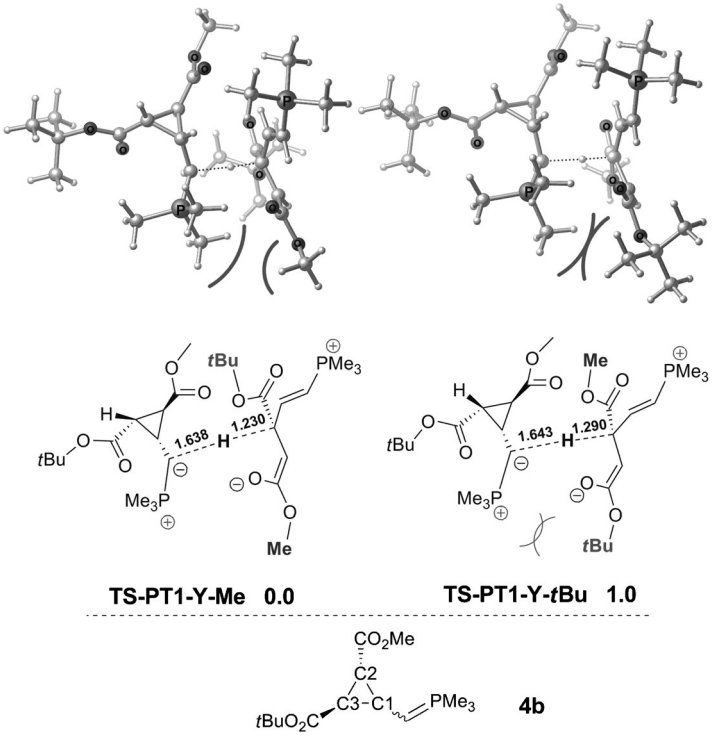
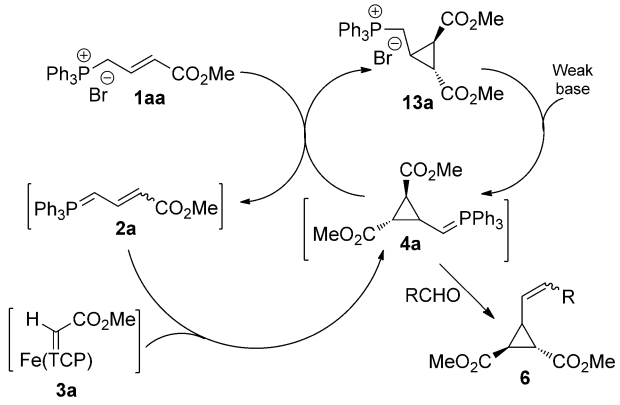


Figure 1. Ester effect in the self-assisted proton-transfer reaction of ylide **4b**.

1.0 kcal mol^{-1} more favorable than **TS-PT-Y-*t*Bu**, thus suggesting that the abstraction of a proton from **TS-PT-Y-Me** is much easier than from **TS-PT-Y-*t*Bu**, owing to the steric hindrance of the phosphonium moiety and the *tert*-butyl group. Thus, the ring opening mainly proceeds on the side of the methyl ester (fission of the C1−C2 bond), rather than on the side of the *tert*-butyl ester. This result is consistent with the experimental observations, thus explaining the steric effect of the ester on the product distribution.

Construction of vinylcyclopropanes through the catalytic cyclopropanation of allylic phosphonium compounds: In light of the calculated mechanism that the cyclopropylmethyl ylide intermediate itself can act as a base to promote the proton transfer and accelerate the ring-opening reaction, we envisioned that the best way to efficiently trap intermediate **4a** for the formation of the cyclopropane might be to keep it at a lower concentration than the trapping aldehyde. Taking notice of the stability of phosphonium salt **13a**,[7] we proposed that salt **13a** could be employed as a "reservoir" of the corresponding ylide (**4a**). Based on this concept, a new strategy is shown in Scheme 7. In this strategy, the ylide

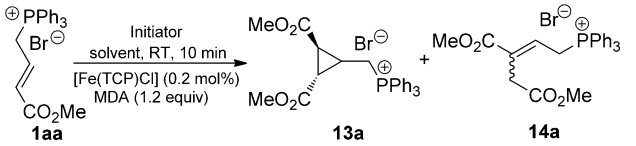


Scheme 7. Strategy for the cyclopropanation of allylide.

that is formed (**4a**) in situ through cyclopropanation will be quickly protonated by allylic phosphonium bromide **1aa** and is "stored" in the form of salt **13a** because compound **4a** is a stronger base than compound **2a**. Therefore, the ring opening of ylide **4a** would be effectively suppressed, whereas it can be released in a steerable way through an acid/base equilibrium reaction by a suitable base and, thus, maintain the relative concentration of compound **4a** to the aldehyde at a low (but productive) level.

To test this hypothesis, the cyclopropanation of allylic phosphonium salt **1aa** with methyl diazo acetate was performed in the presence of a catalytic amount of [Fe(TCP)Cl] and ylide **2a** as an initiator. Gratifyingly, phosphonium salts **13a** and **14a** were obtained in 35% yield, in a ratio of 81:19, as determined by ^{31}P NMR spectroscopy in $CDCl_3$ (Table 1, entry 2). Ylide **7a** could also initiate this reaction, thus giving similar results (Table 1, entry 3). In a control experi-

Table 1. Iron-catalyzed cyclopropanation of phosphonium salt **1aa**.



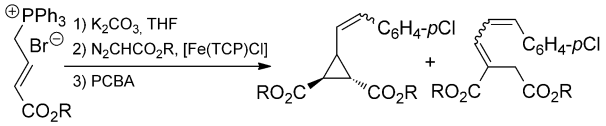
1aa **13a** **14a**

Entry	Initiator [mol%]	Solvent	Yield [%][a]	**13a**/**14a**[a,b]
1	–	THF	n.d.	–
2	**2a** (10)	THF	35	81:19
3[c]	**7a** (10)	THF	48	78:22
4	**2a** (10)	CH_2Cl_2	99	67:33
5	**2a** (2)	CH_2Cl_2	99	59:41
6[d]	K_2CO_3 (10)	CH_2Cl_2	99	59:41

[a] Determined by ^{31}P NMR spectroscopy; n.d. = not determined. [b] The *E*/*Z* ratio of compound **14a** was 85:15, as determined by ^{31}P NMR spectroscopy. [c] Compound **7a** was synthesized in situ according to the procedure in Ref. [5]. [d] [Fe(TCP)Cl] and MDA were added after the mixture of compound **1aa** and K_2CO_3 had been stirred for 10 min at room temperature.

ment without any basic initiator, no reaction was observed (Table 1, entry 1).

Salt **1aa** was poorly soluble in THF and low conversion was observed (Table 1, entry 2), whereas phosphonium salt **1aa** was completely consumed in CH_2Cl_2, albeit with slightly lower selectivity (Table 1, entry 4). Further studies demonstrated that this strategy was still efficient with 2 mol% of compound **2a** or 10 mol% of K_2CO_3 (Table 1, entries 5 and 6). Encouraged by these results, a one-pot procedure for the synthesis of vinylcyclopropanes was attempted by employing K_2CO_3 as the base and 4-chlorobenzaldehyde (PCBA) as the trapping agent (Scheme 8). With compound **1aa**, cinnamylcyclopropanes **6a** was isolated in 22% yield with a selectivity of 30:70 (**6a**/**5a**). To our delight, replacement of methyl groups by *tert*-butyl groups on both the crotonate and the diazo acetate improved the yield of cinnamylcyclopropane (**17a**) to 65%, together with much higher selectivity (**17a**/**18a**, 74:26). These results are consistent with the calculations, which showed that a bulky ester group could impede the proton transfer and, thus, afford a more-efficient trapping of the cyclopropylmethyl ylide.

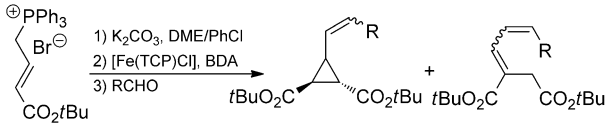


1aa, R = Me	**6a**, R = Me	**5a**, R = Me
	Yield = 22%	53%
	6a/**5a** = 30:70, *Z*/*E* = 85:15 (**6a**)	
1ba, R = *i*Pr	**15a**, R = *i*Pr	**16a**, R = *i*Pr
	Yield = 39%	49%
	15a/**16a** = 38:62, *Z*/*E* = 85:15 (**15a**)	
1ca, R = *t*Bu	**17a**, R = *t*Bu	**18a**, R = *t*Bu
	Yield = 65%	23%
	17a/**18a** = 74:26, *Z*/*E* = 81:19 (**17a**)	

Scheme 8. Effect of the ester groups on the reaction selectivity.

Based on these findings, further optimization of the one-pot reaction conditions was conducted by using *tert*-butyl-crotonate-derived phosphonium salt **1ca**, *tert*-butyl diazo acetate (BDA), and 4-chlorobenzaldehyde (PCBA) in the presence of a catalytic amount of [Fe(TCP)Cl]. Finally, the ratio of compounds **17a**/**18a** was improved to 94:6, with an 88% yield of compound **17a** when mixed solvent system 1,2-dimethoxyethane (DME)/PhCl (1:4, v/v) was used (Table 2, entry 1),[17] and the reaction scope was examined. As shown in Table 2, good-to-excellent yields of the desired vinylcyclopropanes (**17**) were obtained with moderate-to-good *Z* selectivities in the reactions of aromatic aldehydes. Notably, the selectivity (**17** versus **18**) was strongly dependent on the reactivity of the aldehyde, as well as on the substituents on the aromatic ring. In general, vinylcyclopropanes **17** were obtained with good-to-excellent selectivities when activated benzaldehydes that contained electron-withdrawing groups, such as halo, nitro, trifluoromethyl, and cyano group on the benzene ring, were used (Table 2, entries 1–10). This trend correlated well with the efficiency of trapping the cyclopropylmethyl ylide intermediate in the Wittig step, which heavily relied on the reactivity of the aldehyde. Lower selectivities for compound **17** were obtained with benzaldehyde and electron-rich benzaldehydes

Table 2. Synthesis of vinylcyclopropanes through the catalytic cyclopropanation of crotonate-derived phosphonium salts.[a]



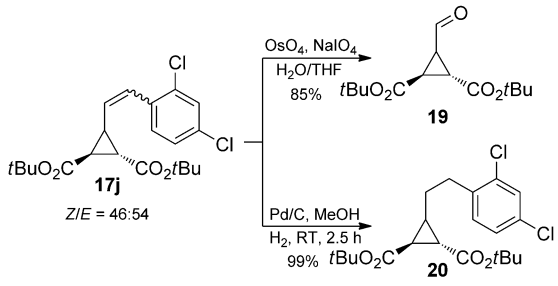
1ca **17** **18**

Entry	R	*t* [h]	**17**/**18**[b]	**17** [%][c]	*Z*/*E* (**17**)[b]
1	4-ClC_6H_4	7	94:6	88 (**17a**)	82:18
2	3-ClC_6H_4	7	90:10	87 (**17b**)	82:18
3	2-ClC_6H_4	7	90:10	76 (**17c**)	66:34
4	4-$NO_2C_6H_4$	7	95:5	79 (**17d**)	75:25
5	3-$NO_2C_6H_4$	7	95:5	87 (**17e**)	79:21
6	2-$NO_2C_6H_4$	7	87:13	73 (**17f**)	55:45
7	4-CNC_6H_4	10	94:6	94 (**17g**)	79:21
8	4-BrC_6H_4	7	93:7	90 (**17h**)	81:19
9	4-$CF_3C_6H_4$	10	94:6	93 (**17i**)	79:21
10	2,4-$Cl_2C_6H_3$	7	94:6	88 (**17j**)	46:54
11	C_6H_5	7	71:29	57 (**17k**)	86:14
12	4-$CH_3C_6H_4$	18	58:42	57 (**17l**)	88:12
13[d]	4-$CH_3OC_6H_4$	36	–	–[f]	–
14	(*E*)-PhCH=CH	22	65:35	63 (**17m**)	77:23
15	CO_2Et	24	–	81 (**17n**)	48:52
16[e]	2-HOC_6H_4	7	<1:99	– (**17o**)	–

[a] Reaction conditions: Phosphonium salt **1ca** (289.8 mg, 0.60 mmol), K_2CO_3 (99.4 mg, 0.72 mmol), [Fe(TCP)Cl] (1.7 mg, 0.002 mmol), BDA (152 μL, 1.2 mmol), aldehyde (0.4 mmol), DME/PhCl (1:4 v/v, 4.0 mL), 20 °C. For detailed procedures, see the Supporting Information. [b] Determined by ^1H NMR spectroscopy. [c] Yield of isolated product. [d] A complicated mixture was obtained and the yield of the cyclopropane was less than 17% by ^1H NMR analysis of the mixture after isolation. [e] Under the general cyclopropanation conditions: 91% yield (**18o**), **18o**/**17o** > 99:1. [f] A complicated mixture of products was obtained.

(Table 2, entries 11–13), whereas highly reactive ethyl glyoxalate afforded the desired product (**17n**) in excellent yield (Table 2, entry 14). On the other hand, steric effects were also found to play an important role in determining the *Z* selectivity of the vinylcyclopropanes (**17**). In comparison with the *meta*- or *para*-substituted substrates, a dramatic drop in the *Z* selectivity was observed in the reactions of *ortho*-substituted compounds (Table 2, entries 3, 6, and 10). As revealed by the calculations, proton transfer was the rate-limiting step in the cyclopropane ring-opening process and the presence of an active hydrogen source would probably accelerate the proton transfer and increase the diene formation. The case of salicylaldehyde provides a good support to this fact: Diene **18o** was obtained as the sole product in this reaction and no cyclopropane (**17o**) was detected by ^{1}H NMR analysis (Table 2, entry 16). The exclusive formation of diene **18o** could be ascribed to the presence of the *ortho*-acidic phenolic proton, which may have sped up the proton transfer and, thus, switch the reaction to the ring-opening/Wittig pathway to afford the diene products. In fact, protic solvents, such as *t*BuOH and *i*PrOH, were also found to favor the diene-formation process.

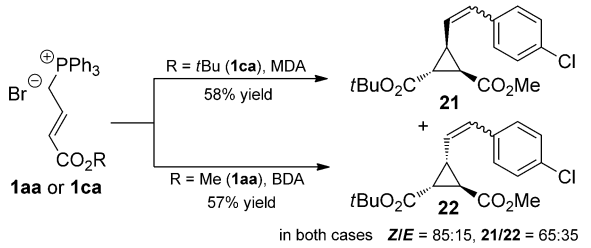
Because the ^{1}H NMR spectra of the obtained cyclopropanes indicated the presence of two isomers, oxidative cleavage and hydrogenation of the double bond were separately performed on vinylcyclopropane **17j** to determine the reason for the isomerization (Scheme 9). In both transformations, only a single product was obtained (compounds **19** and **20**, respectively), thus suggesting that the two isomers were the *Z* and *E* isomers of the double bond, rather than the diastereoisomers of the cyclopropanes. These results also indicate excellent diastereoselectivity in the cyclopropanation step.



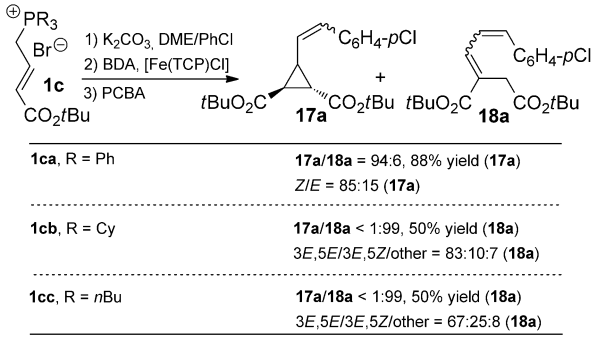
Scheme 9. Oxidation and hydrogenation of vinylcyclopropane **17j**.

Because the ring opening of the cyclopropylmethyl ylide intermediate is rapid and reversible, the cross-experiments under standard cyclopropanation conditions should lead to similar diastereoselectivities in the cyclopropanes. As shown in Scheme 10, the expected ratios of compounds **21**/**22** were observed in the two reactions. This result is also in agreement with the calculated mechanistic data.

Further improvement of the ring-opening process: According to the ring-opening mechanism of this reaction, the electron-accepting ability of the phosphonium group should also affect the proton-transfer step and vary the selectivity between the cyclopropanation products and the diene products. As shown in Scheme 11, a dramatic change in the reaction selectivity (**17a** versus **18a**) was found when the triphenyl phosphine was replaced by tricyclohexyl phosphine or tri-*n*-butyl phosphine. In the cases of trialkyl-phosphine-derived phosphonium salts (**1cb** and **1cc**), only 1,1,4-trisubstituted 1,3-butadiene **18a** was observed, in stark contrast to the predominant formation of vinylcyclopropanes in the reaction of salt **1ca.** These results also demonstrated the high tunability of this reaction, which provides a simple way to selectively synthesize disubstituted vinylcyclopropanes and 1,3-butadienes. Upon further optimization, the yield of 1,1,4-trisubstituted 1,3-butadiene **18a** was improved to 96%, together with high selectivity, by using tricyclohexyl-phosphine-derived phosphonium salt **1cb** and *t*BuOK as a base (Table 3, entry 1). As shown in Table 3, various aromatic and aliphatic aldehydes worked well under these conditions, thus providing the desired butadienes in excellent yields and high selectivities.



Scheme 10. Cross-experiments under the cyclopropanation conditions.

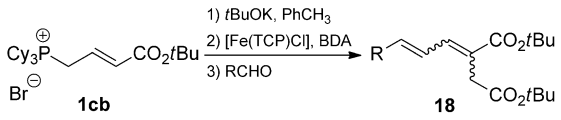


Scheme 11. Selectivity for vinylcyclopropanes and 1,3-butadienes with different phosphines.

Conclusion

We have successfully applied an Umpolung approach to activate electron-deficient alkenes (α,β-unsaturated esters) for reaction with electrophilic iron carbenes, thus confirming

Table 3. Synthesis of 1,3-butadienes through the catalytic cyclopropanation/ring-opening reactions of allylic phosphonium salts.[a]



Entry	R	t [h]	**18** [%][b]	3*E*,5*E*/3*E*,5*Z* (other)[c]
1	4-ClC_6H_4	6	96 (**18a**)	92:8 (8)
2	4-BrC_6H_4	6	92 (**18b**)	91:9 (9)
3	4-$NO_2C_6H_4$	6	96 (**18c**)	95:5 (8)
4	C_6H_5	21	97 (**18d**)	92:8 (5)
5	4-$CH_3C_6H_4$	21	95 (**18e**)	91:9 (7)
6	2-furyl	24	86 (**18f**)	86:14 (8)
7	(*E*)-PhCH=CH	24	97 (**18g**)	97:3 (11)
8	*n*-octyl	36	94 (**18h**)	86:14 (10)

[a] Reaction conditions: Phosphonium salt **1cb** (300.6 mg, 0.60 mmol), *t*BuOK (80.6 mg, 0.72 mmol), [Fe(TCP)Cl] (1.7 mg, 0.002 mmol), BDA (152 μL, 1.2 mmol), aldehyde (0.4 mmol), $PhCH_3$ (4.0 mL), 20 °C. For detailed procedures, see the Supporting Information. [b] Yield of isolated product. [c] Determined by ^1H NMR spectroscopy.

that their electronic nature is the main cause of their inactivity. Our calculations showed that the ring-opening step of the intermediate cyclopropylmethyl ylide was rapid and reversible and that the subsequent proton-transfer step was the rate-limiting step in the cyclopropane-ring-opening process; these results were further experimentally supported by cross-experiments. On the basis of these mechanistic insights, by judicious choice of the carbanion-stabilizing groups, the esters, and the base, this reaction could be steered towards either the ring-opening reaction or along the cyclopropanation reaction pathway. As has already been demonstrated in the activation of crotonate-derived model substrates, this Umpolung strategy represents a new approach to tune the reactivity of electron-deficient alkenes with metal carbenes. Further extension of this strategy to other types of substrates and reactions is currently underway in our laboratory.

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