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Highly Chemoselective Rauhut–Currier Reaction between Maleimides and Enones and Dual Phosphine-Mediated One-Pot Synthesis of Bicyclic and Polycyclic Skeletons

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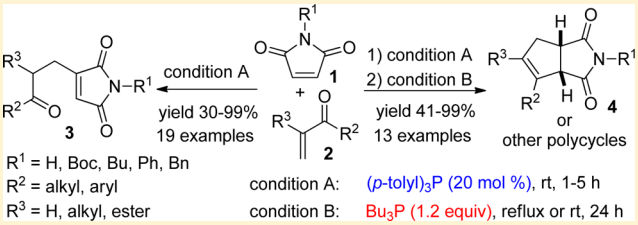
Supporting Information

ABSTRACT: A highly chemoselective phosphine-catalyzed Rauhut–Currier reaction between maleimides and enones has been realized under very mild conditions, affording the corresponding cross-coupling products in moderate to excellent yields. On the basis of this reaction, an efficient dual phosphine-mediated one-pot synthesis of bicyclic and polycyclic compounds containing a cyclopenta[*c*]pyrrole skeleton has been accordingly developed, which features a tandem sequence of intermolecular Rauhut–Currier reaction and intramolecular Wittig reaction.



INTRODUCTION

The carbon–carbon bond forming reaction is of fundamental importance in the construction of organic molecular frameworks, with continuous efforts engaged in improving the reaction efficiency, stereoselectivity, and chemoselectivity.[1] In this context, the nucleophilic Lewis base-catalyzed Rauhut–Currier (RC) reaction of electron-deficient alkenes represents a class of important carbon–carbon bond forming reactions, which have attracted much recent interest due to their enormous potential in organic synthesis.[2,3] Recently, great advances in the highly chemoselective *intramolecular* RC reaction have been witnessed.[3−5] For example, several important natural products have been successfully synthesized by Roush, Krische, and others by using the intramolecular RC reaction as a key step.[4] The asymmetric variants of the intramolecular RC reaction, first reported by Miller,[5a] were also significantly advanced in the past decade.[5] In contrast with the well-developed intramolecular RC reaction, the *intermolecular* RC reaction, particularly involving two different alkenes, lacks for a proper development since it suffers from a challenging issue of low chemoselectivity (the kinetically preferred homocoupling versus the desired heterocoupling).[3,6c] Recently, some encouraging amine-catalyzed RC reactions of two different activated alkenes have been disclosed from Miller, Shi, and other research groups.[6] Although the reported intramolecular RC reactions are predominantly catalyzed by the tertiary phosphines,[3−5] the efficient phosphine-catalyzed intermolecular RC reactions are sporadic,[7] among which only two examples of cross-coupling between two different activated alkenes were respectively reported by Morita and McClure in early time, albeit with limited substrate scope and low chemoselectivity.[7a,b] Thus, exploring chemoselective phosphine-catalyzed RC reaction between two different electron-deficient alkenes aroused our interest.

Five-membered carbocycles like cyclopentenes are ubiquitous substructures in a large number of natural products and biologically active molecules.[8] The development of highly efficient synthetic methods of such carbocycles has therefore been an attractive topic in the area of organic chemistry for a long time.[9] Recently, the rapidly emerging nucleophilic phosphine-catalyzed annulation reactions, particularly the Lu [3 + 2] annulation reaction of electron-poor allenes and activated alkenes, provide an efficient methodology to construct cyclopentenes and polycyclic structures containing a cyclopentene core.[10] Apart from the phosphine-catalyzed annulation reactions, the stoichiometric phosphine-mediated annulation reactions also provide a unique access to a variety of carbo- and heterocycles.[11] The stoichiometric phosphine-mediated annulation mode is usually accomplished through an intramolecular Wittig olefination step. Many recent reports have unveiled that an array of polysubstituted five-membered heterocycles including pyrroles and furans could be efficiently prepared by this stoichiometric mode.[12] However, the stoichiometric phosphine-mediated synthesis of five-membered carbocycles has been rarely explored.[7h,13] As part of our continuous efforts on exploring the tertiary phosphine-mediated carbon–carbon bond forming reactions,[14] herein we report a highly chemoselective phosphine-catalyzed intermolecular RC reaction of maleimides and terminal enones, and a dual phosphine-mediated one-pot synthetic strategy of bicyclic and polycyclic cyclopentenes.

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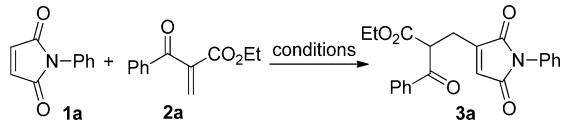
RESULTS AND DISCUSSION

We initiated our research with the substrates *N*-phenylmaleimide **1a** and 2-benzoyl acrylate **2a** (Table 1). In the presence of PPh_3 (20 mol %) and a protic additive acetic acid (10 mol %), a reaction mixture of **1a** (0.2 mmol) and **2a** (0.24 mmol) in CH_2Cl_2 (2 mL) was stirred at rt for 4 h. To our delight, an expected cross-coupling product **3a** was isolated in 70% yield after column chromatographic isolation (entry 1). This initial result revealed that a chemoselective intermolecular RC reaction between maleimide **1a** and enone **2a** could be achieved. To further improve the reaction efficiency, a condition survey was then conducted using the reaction of **1a** and **2a** as a model (Table 1). A series of tertiary phosphines were first screened (entries 2−8). Relatively electron-richer triarylphosphines exhibited better catalytic activity (entries 2−6), with $(p\text{-tolyl})_3P$ emerging as the best affording the product **3a** in 81% yield (entry 2). The alkyl-substituted phosphines such as $MePPh_2$ and PBu_3 were effective in the reaction but only afforded inferior yields (entries 7 and 8). With $(p\text{-tolyl})_3P$ chosen as the catalyst, several common solvents were examined. CH_2Cl_2 remained a preferred solvent while other solvents including $CHCl_3$, THF, toluene, CH_3CN, as well as ethanol afforded comparable or lower yields (entries 9−13). The protic additive was also surveyed (entries 14−17). Increasing the loading of acetic acid to 20 mol % (relative to **1a**) substantially improved the yield of **3a** (entry 14). Using benzoic acid in place of acetic acid even brought about a 99% yield (entry 15), although other substituted benzoic acids only afforded modest yields of **3a** (entries 16 and 17). Thus, the optimized conditions for a highly chemoselective RC reaction of maleimide **1a** and enone **2a** were established.

Table 1. Survey of Conditions for the RC Reaction of Maleimide 1a and Enone 2a[a]

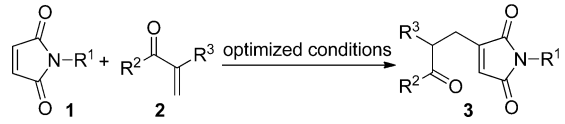


entry	phosphine	additive (mol %)	solvent	time (h)	yield (%)[b]
1	PPh_3	AcOH (10)	CH_2Cl_2	4	70
2	$(p\text{-tolyl})_3P$	AcOH (10)	CH_2Cl_2	4	81
3	$(4\text{-MeOC}_6H_4)_3P$	AcOH (10)	CH_2Cl_2	4	72
4	$(4\text{-ClC}_6H_4)_3P$	AcOH (10)	CH_2Cl_2	24	46
5	$(4\text{-FC}_6H_4)_3P$	AcOH (10)	CH_2Cl_2	24	70
6	$(4\text{-CF}_3C_6H_4)_3P$	AcOH (10)	CH_2Cl_2	24	trace
7	$MePPh_2$	AcOH (10)	CH_2Cl_2	5	60
8	PBu_3	AcOH (10)	CH_2Cl_2	12	45[c]
9	$(p\text{-tolyl})_3P$	AcOH (10)	$CHCl_3$	4	81
10	$(p\text{-tolyl})_3P$	AcOH (10)	THF	24	62
11	$(p\text{-tolyl})_3P$	AcOH (10)	toluene	6	50
12	$(p\text{-tolyl})_3P$	AcOH (10)	CH_3CN	6	69
13	$(p\text{-tolyl})_3P$	AcOH (10)	ethanol	6	51
14	$(p\text{-tolyl})_3P$	AcOH (20)	CH_2Cl_2	4	89
15	$(p\text{-tolyl})_3P$	$PhCO_2H$ (20)	CH_2Cl_2	4	99
16	$(p\text{-tolyl})_3P$	$4\text{-MeOC}_6H_4CO_2H$ (20)	CH_2Cl_2	4	54
17	$(p\text{-tolyl})_3P$	$4\text{-NO}_2C_6H_4CO_2H$ (20)	CH_2Cl_2	12	69

[a]Typical procedure: under a N_2 atmosphere, to a mixture of **1a** (35 mg, 0.2 mmol), **2a** (49 mg, 0.24 mmol), and a protic additive (0.02 or 0.04 mmol) in solvent (2.0 mL) was added phosphine (0.04 mmol), and the resulting mixture was stirred at rt for a specified time. [b]Isolated yield. [c]A trace amount of a bicyclic product **4a** (see below) was observed.

Under the optimized conditions, the substrate scope of the intermolecular RC reaction was investigated (Table 2 and Scheme 1). With *N*-phenyl maleimide **1a** used as one partner, a series of enones **2** were examined (Table 2, entries 1−9). Representative 2-benzoyl acrylates **2** bearing variable phenyl and ester groups readily afforded the corresponding cross-coupling products **3** in good to excellent yields (entries 1−7). Enones like methyl vinyl ketone **2h** and phenyl vinyl ketone **2i** were also good candidates, giving the corresponding RC

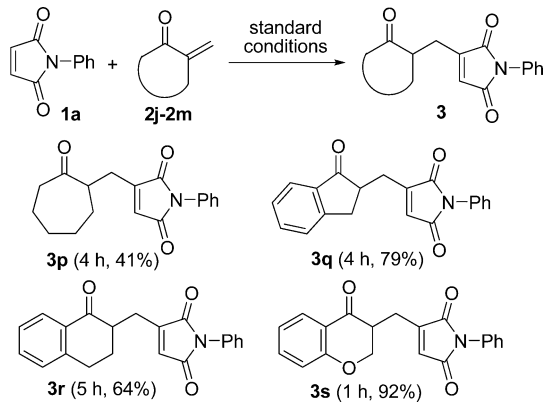
Table 2. Substrate Scope of the RC Reaction between Maleimides 1 and Enones 2[a]



entry	R^1 in **1**	R^2, R^3 in **2**	time (h)	yield of **3** (%)[b]
1	Ph (**1a**)	Ph, CO_2Et (**2a**)	4	**3a**, 99
2	Ph	4-MeC_6H_4, CO_2Et (**2b**)	5	**3b**, 96
3	Ph	4-MeOC_6H_4, CO_2Et (**2c**)	2	**3c**, 85
4	Ph	4-ClC_6H_4, CO_2Et (**2d**)	3	**3d**, 84
5	Ph	4-FC_6H_4, CO_2Me (**2e**)	5	**3e**, 80
6	Ph	Ph, CO_2Me (**2f**)	1.5	**3f**, 99
7	Ph	Ph, $CO_2Bu\text{-}t$ (**2g**)	5	**3g**, 95
8	Ph	Me, H (**2h**)	4	**3h**, 62
9	Ph	Ph, H (**2i**)	2.5	**3i**, 56
10	4-MeC_6H_4 (**1b**)	**2a**	3.5	**3j**, 98
11	$4\text{-NO}_2C_6H_4$ (**1c**)	**2d**	1.5	**3k**, 66
12	Bn (**1d**)	**2a**	5	**3l**, 90
13	Bu-*n* (**1e**)	**2a**	5	**3m**, 80
14	Boc (**1f**)	**2d**	5	**3n**, 64
15	H (**1g**)	**2d**	5	**3o**, 30

[a]Typical conditions: under a N_2 atmosphere, a mixture of maleimide **1** (0.2 mmol), enone **2** (0.24 mmol), benzoic acid (0.04 mmol), and $(p\text{-tolyl})_3P$ (0.04 mmol) in CH_2Cl_2 (2.0 mL) was stirred at rt for 1−5 h. [b]Isolated yield.

Scheme 1. RC Reaction of Maleimide 1a and Cyclic Enones



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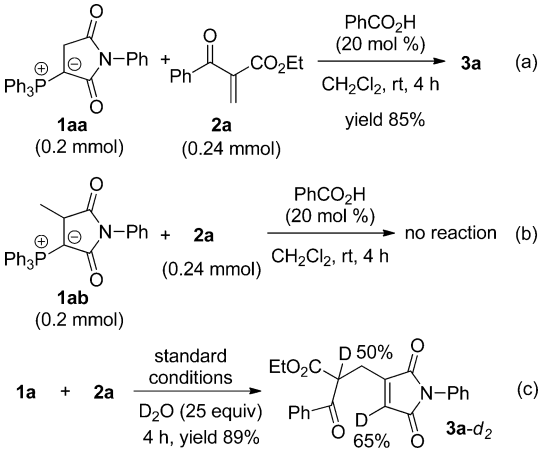
products in moderate yields (entries 8, 9). Choosing enones **2a** and **2d** as the representative substrates, several *N*-substituted maleimides **1** were further screened (entries 10−14). *N*-Aryl or *N*-alkyl maleimides **1** uneventfully gave the normal cross-coupling products **3** in good yields (entries 10−13). *N*-(*tert*-Butoxycarbonyl) maleimide **1f** readily delivered a moderate yield of its RC product with enone **2d** (entry 14). Unsubstituted maleimide **1g** was also an effective substrate to afford its RC product with enone **2d**, albeit in an inferior yield (entry 15).

Under the optimized conditions, cyclic enones **2** featuring an exocyclic alkene unit were further surveyed in the RC reaction with representative maleimide **1a** (Scheme 1). Both aliphatic and aromatic cyclic enones **2** readily afforded their normal RC products in modest to high yields. It is noteworthy that in all the cases examined in Table 2 and Scheme 1, the preferred heterocoupling products were exclusively obtained. Thus, a highly chemoselective phosphine-catalyzed intermolecular RC reaction between two different activated alkenes, the maleimides **1** and the terminal enones **2**, was successfully developed under very mild conditions.

To glean some mechanistic insights into the RC reaction of maleimides **1** and enones **2**, the following experiments were deliberately conducted (Scheme 2). In the presence of benzoic

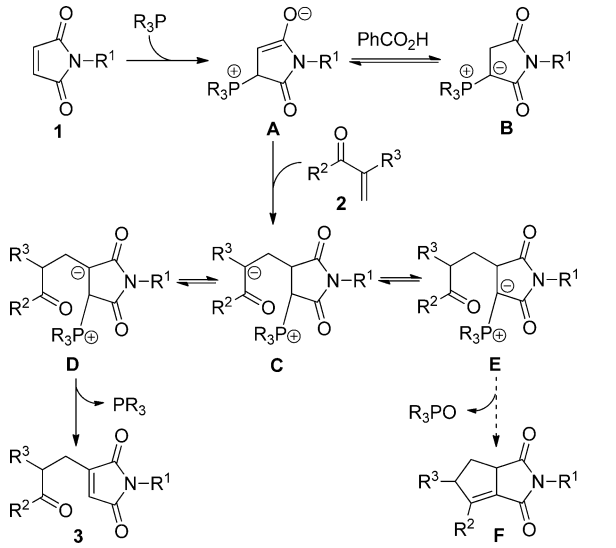
Scheme 2. Mechanistic Investigations



acid (20 mol %), a stable phosphorus ylide **1aa** (0.2 mmol), prepared from Ph_3P and *N*-phenyl maleimide **1a** by a reported procedure,[15] was treated with enone **2a** (0.24 mmol) in CH_2Cl_2 and at rt for 4 h, affording the cross-coupling product **3a** in 85% isolated yield (Scheme 2, eq. a). In contrast, an analogous phosphorus ylide **1ab**, prepared from *N*-phenyl-2-methylmaleimide, failed to bring about a similar product under the same conditions (eq. b). Furthermore, a deuterium-labeling experiment was conducted.[16] Under the standard conditions as listed in Table 2, addition of a small amount of D_2O (5.0 mmol, 0.1 mL) into the RC reaction of *N*-phenyl maleimide **1a** and enone **2a** resulted in a partially deuterated product **3a**-d_2 in 89% yield (eq. c). By interpreting the above experimental results, the following clues about the mechanism of the phosphine-catalyzed RC reaction of maleimides **1** and enones **2** may be reached: an in situ formed phosphorus ylide intermediate from the maleimide **1** is presumably involved in the RC reaction, and a substituent at the 2-position of the maleimide **1** severely retards the cross-coupling between maleimide **1** and enone **2**; the possible intermediates carrying a carbanion center at the deuterium-labeled carbons of the deuterated product **3a**-d_2 are involved in the RC reaction.

As to the nucleophilic Lewis base-catalyzed RC reaction, there is a generally accepted mechanism which encompasses the following key steps: generation of an active enolate from one activated alkene upon the nucleophilic addition of the catalyst, followed by Michael addition of the enolate to the second activated alkene and subsequent elimination of the nucleophilic catalyst.[3] According to this generally accepted mechanism and our experimental results in this study, a rationale about the phosphine-catalyzed RC reaction between maleimides **1** and enones **2** is depicted in Scheme 3.

Scheme 3. Rationale for the RC Reaction and Possible Route to Cyclization via Intramolecular Wittig Reaction



Nucleophilic conjugated addition of the phosphine to maleimide **1** generates a zwitterionic enolate **A**, which may reversibly convert into a phosphorus ylide **B** under the aid of the protic additive benzoic acid. The enolate intermediate **A** undertakes a sterically favored Michael addition to enone **2**, leading to another zwitterionic intermediate **C**. Through a necessary proton transfer,[17] intermediate **C** could reversibly convert into enolate **D** and phosphorus ylide **E**. Finally, enolate **D** undergoes an elimination of the phosphine to accomplish formation of the cross-coupling product **3** and release of the catalyst (Scheme 3). By this plausible mechanism, the highly chemoselective cross-coupling between maleimide **1** and enone **2** could be attributed to the ease of formation of the stable phosphorus ylide **B** and the bias for the Michael addition of the enolate **A** to enone **2**. Considering the interconvertibility of the intermediates **C**, **D**, and **E** by a proton transfer process, we suspected that chemoselective transformations between maleimides **1** and enones **2** could be achieved by utilizing different phosphines. Compared with trialkylphosphines, triarylphosphines have weaker nucleophilicity and better leaving-group ability.[18] Using triarylphosphines as the catalyst should favor the transformation of intermediate **D** into the cross-coupling product **3**, and therefore should be good for the RC reaction. Results from the catalyst phosphine survey (Table 1, entries 1−8) are generally in favor of this hypothesis. On the other hand, strongly nucleophilic trialkylphosphines may to some extent inhibit the conversion of intermediate **D** into the cross-coupling product **3** and meanwhile enhance the Wittig olefination

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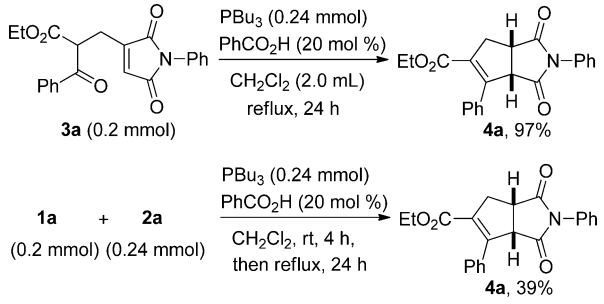
reactivity of the phosphorus ylide intermediate **E**.[19] Accordingly, a trialkylphosphine-mediated tandem cyclization could be realized via an intramolecular Wittig reaction of intermediate **E**, leading to formation of a bicyclic cyclopentene **F** (Scheme 3).

With this cyclization hypothesis in mind, we first explored the cyclization of the RC product **3a** under the mediation of stoichiometric PBu_3. Under the listed conditions, **3a** was smoothly converted into a bicyclic product **4a** as a single diastereomer in 97% isolated yield (Scheme 4). Structural

Scheme 4. PBu_3-Mediated Cyclization via Intramolecular Wittig Reaction

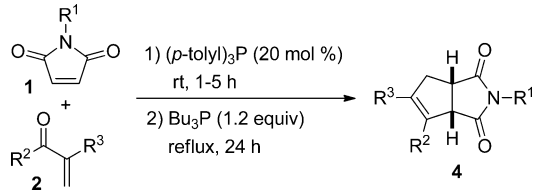


determination of **4a** (for a crystal structure of its analogue **4d**, see Supporting Information) indicated that **4a** is a double-bond migration product from the expected cyclization product **F** illustrated in Scheme 3, although such an expected product was not observed in this reaction. A one-pot tandem cyclization reaction of maleimide **1a** and enone **2a** was then tested by using single phosphine component like $(p\text{-tolyl})_3P$ or PBu_3. Under the indicated conditions, maleimide **1a** and enone **2a** indeed furnished the bicyclic product **4a** under the mediation of PBu_3, but in a substantially lowered yield (Scheme 4). Under the same conditions, using $(p\text{-tolyl})_3P$ instead of PBu_3, however, only brought about the RC product **3a** in a quantitative yield. $(p\text{-Tolyl})_3P$ was totally ineffective for the cyclization.

After analyzing the above results, we devised a one-pot dual phosphine relay strategy: under the standard conditions of the RC reaction (Table 2), the cross-coupling of the maleimide **1** and enone **2** was first accomplished under the catalysis of $(p\text{-tolyl})_3P$; subsequently the second phosphine PBu_3 (1.2 equiv) was added into the reaction mixture to fulfill the cyclization step. To validate this one-pot strategy, a group of maleimides **1** and enones **2** were examined (Table 3 and Scheme 5). As shown in Table 3, the reactions of maleimide **1a** with 2-benzoyl acrylates **2** readily afforded the bicyclic products **4** in high yields (entries 1–5) except that the bulky *tert*-butyl 2-benzoylacrylate **2g** only delivered a modest yield (entry 6). Also, the combinations of other maleimides (**1b**, **1c**, and **1e**) with chosen enones (**2c** and **2e**) smoothly afforded the corresponding bicyclic products **4** in good yields (entries 7–9). As shown in Table 3, for 2-benzoyl acrylates **2** as doubly activated alkenes, the PBu_3-mediated cyclization step was better carried out under reflux.

Several selected enones **2** including methyl vinyl ketone **2h** and cyclic ketones **2k–2m** as monoactivated alkenes were further tested (Scheme 5). Acyclic enone **2h** smoothly gave a bicyclic product **5a** in a moderate yield while cyclic enones **2k–2m** furnished their corresponding polycyclic products **5** in acceptable yields. For these monoactivated alkenes, the PBu_3-mediated cyclization step was best run at rt (Scheme 5). In

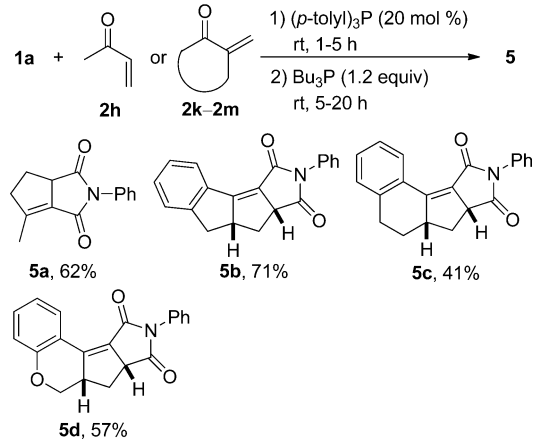
Table 3. One-Pot Dual Phosphine-Mediated Synthesis of Bicyclic Compounds 4[a]



entry	R^1 in **1**	R^2, R^3 in **2**	yield of **4** (%)[b]
1	Ph (**1a**)	Ph, CO_2Et (**2a**)	**4a**, 93
2	Ph	4-MeC_6H_4, CO_2Et (**2b**)	**4b**, 85
3	Ph	4-$MeOC_6H_4$, CO_2Et (**2c**)	**4c**, 88
4	Ph	4-ClC_6H_4, CO_2Et (**2d**)	**4d**, 99
5	Ph	4-FC_6H_4, CO_2Me (**2e**)	**4e**, 92
6	Ph	Ph, CO_2Bu-*t* (**2g**)	**4f**, 45
7	4-MeC_6H_4 (**1b**)	4-FC_6H_4, CO_2Me (**2e**)	**4g**, 79
8	4-$NO_2C_6H_4$ (**1c**)	4-$MeOC_6H_4$, CO_2Et (**2c**)	**4h**, 92
9	Bu-*n* (**1e**)	4-FC_6H_4, CO_2Me (**2e**)	**4i**, 97

[a]Typical conditions: under a N_2 atmosphere, a mixture of maleimide **1** (0.2 mmol), enone **2** (0.24 mmol), benzoic acid (0.04 mmol), and $(p\text{-tolyl})_3P$ (0.04 mmol) in CH_2Cl_2 (2.0 mL) was stirred at rt for 1–5 h as listed in Table 2. Then PBu_3 (60 μL, 0.24 mmol) was added, and the resulting mixture was stirred under reflux for 24 h. [b]Isolated yield.

Scheme 5. Synthesis of Polycyclic Compounds 5



contrast with the doubly activated alkenes such as 2-acylacrylates **2** listed in Table 3, acyclic enone **2h** and cyclic enones **2k–2m** all exclusively delivered the expected cyclization products **5**, which were supposed to be generated from a tandem sequence of RC reaction/intramolecular Wittig olefination. The structure assignment of **5** was further confirmed by the single crystal X-ray analysis for **5c** (for its crystal structure, see Supporting Information). Also, control experiments[20] indicated that the selective formation of products **4** and **5** was substrate-dependent, not condition-controlled. Thus, this one-pot dual phosphine-mediated strategy provides a convenient and efficient synthesis of bicyclic and polycyclic compounds containing a cyclopenta[*c*]pyrrole skeleton[21] from simple maleimides and terminal enones. One-pot domino/tandem reactions provide a convenient and highly efficient means to build molecular complexity.[22] Recently, organic Lewis base-catalyzed RC coupling-initiated domino/tandem reactions have attracted considerable research interest. As a result, several pioneering RC coupling-involving domino/tandem annulation reactions have emerged.[18,23] To the best of our knowledge, this

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one-pot dual phosphine-mediated synthesis of cyclopentene core represents the first tandem sequence of the Rauhut–Currier coupling/Wittig olefination.

CONCLUSION

In summary, a highly chemoselective phosphine-catalyzed intermolecular Rauhut–Currier reaction between maleimides **1** and enones **2** has been realized under very mild conditions, providing a convenient and efficient access to densely functionalized molecules. The intermolecular RC reaction presumably proceeds through generation of an active enolate upon nucleophilic addition of the catalyst phosphine to maleimide **1**, followed by a Michael addition of the enolate to enone **2** and subsequent elimination of the phosphine, thereby accomplishing the chemoselective cross-coupling of two different activated alkenes. On the basis of this reaction, an efficient dual phosphine-mediated one-pot synthesis of bicyclic and polycyclic compounds containing a cyclopenta[*c*]pyrrole skeleton has been accordingly developed, which features a new tandem sequence of intermolecular Rauhut–Currier reaction and intramolecular Wittig reaction. Future efforts in our laboratory will be directed toward developing the asymmetric variants of these transformations and exploring their applications in the organic synthesis.

EXPERIMENTAL SECTION

Unless otherwise noted, all reactions were carried out in a nitrogen atmosphere. Solvents were purified prior to use according to conventional procedures. ^{1}H and ^{13}C NMR spectra were recorded in $CDCl_3$ with tetramethylsilane (TMS) as the internal standard. HRMS spectra were acquired in the ESI mode (positive ion) with the mass analyzer of TOF used. Column chromatography was performed on silica gel (200–300 mesh) using a mixture of petroleum ether/ethyl acetate as eluant. Maleimides were prepared through the reported method from maleic anhydride and the corresponding amines.[24] 2-Benzoyl acrylates were prepared from their precursors Morita–Baylis–Hillman adducts by the conventional Dess–Martin oxidation.[25]

General Procedure for (*p*-Tolyl)$_3$P-Catalyzed Rauhut–Currier Reaction of Maleimides 1 and Enones 2 (Table 2 and Scheme 1). Under a N_2 atmosphere, to a solution of maleimide **1** (0.2 mmol), enone **2** (0.24 mmol), and benzoic acid (5.0 mg, 0.04 mmol) in CH_2Cl_2 (2.0 mL) was added (*p*-tolyl)$_3$P (12 mg, 0.04 mmol). The resulting mixture was stirred at rt until maleimide **1** was completely consumed, as monitored by TLC. Then the solvent was removed on a rotary evaporator under reduced pressure, and the residue was subjected to column chromatographic isolation on silica gel (gradient elution, petroleum ether (bp 60–90 °C)/ethyl acetate 10:1–5:1) to give products **3**.

*Ethyl 2-((2,5-dioxo-1-phenyl-2,5-dihydro-1H-pyrrol-3-yl)methyl)-3-oxo-3-phenylpropanoate (**3a**).* Following the general procedure, *N*-phenylmaleimide **1a** (35 mg, 0.2 mmol) and enone **2a** (49 mg, 0.24 mmol) were employed to give product **3a** (75 mg, 99%) as a white solid: mp 127–128 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.13–8.02 (m, 2H), 7.63 (t, J = 7.4 Hz, 1H), 7.57–7.42 (m, 4H), 7.40–7.30 (m, 3H), 6.53 (br s, 1H), 4.85 (t, J = 7.3 Hz, 1H), 4.18 (q, J = 7.1 Hz, 1H), 4.17 (q, J = 7.1 Hz, 1H), 3.31–3.17 (m, 2H), 1.18 (t, J = 7.1 Hz, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 193.4, 170.1, 169.0, 168.5, 145.9, 135.4, 134.1, 131.3, 129.1, 129.0, 128.9, 128.8, 127.9, 125.9, 62.1, 51.6, 25.1, 13.9; HRMS-ESI calcd for $C_{22}H_{20}NO_5$ $[M + H]^+$ 378.1336, found 378.1335.

*Ethyl 2-((2,5-dioxo-1-phenyl-2,5-dihydro-1H-pyrrol-3-yl)methyl)-3-oxo-3-p-tolylpropanoate (**3b**).* Following the general procedure, *N*-phenylmaleimide **1a** (35 mg, 0.2 mmol) and enone **2b** (53 mg, 0.24 mmol) were employed to give product **3b** (75 mg, 96%) as a white solid: mp 102–103 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.95 (d, J = 8.3 Hz, 2H), 7.45 (t, J = 7.7 Hz, 2H), 7.39–7.27 (m, 5H), 6.50 (br s, 1H), 4.81 (t, J = 7.3 Hz, 1H), 4.17 (q, J = 7.1 Hz, 1H), 4.16 (q, J = 7.1 Hz, 1H), 3.29–3.15 (m, 2H), 2.43 (s, 3H), 1.18 (t, J = 7.1 Hz, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 192.9, 170.1, 169.0, 168.6, 146.0, 145.2, 132.9, 131.4, 129.6, 129.1, 129.0, 128.7, 127.8, 125.9, 61.9, 51.5, 25.1, 21.7, 13.9; HRMS-ESI calcd for $C_{23}H_{22}NO_5$ $[M + H]^+$ 392.1492, found 392.1494.

*Ethyl 2-((2,5-dioxo-1-phenyl-2,5-dihydro-1H-pyrrol-3-yl)methyl)-3-(4-methoxyphenyl)-3-oxopropanoate (**3c**).* Following the general procedure, *N*-phenylmaleimide **1a** (35 mg, 0.2 mmol) and enone **2c** (69 mg, 0.24 mmol) were employed to give product **3c** (69 mg, 85%) as a white solid: mp 96–97 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.05 (d, J = 8.9 Hz, 2H), 7.45 (t, J = 7.7 Hz, 2H), 7.39–7.28 (m, 3H), 6.97 (d, J = 9.0 Hz, 2H), 6.50 (s, 1H), 4.79 (t, J = 7.3 Hz, 1H), 4.18 (q, J = 7.1 Hz, 1H), 4.17 (q, J = 7.1 Hz, 1H), 3.87 (s, 3H), 3.28–3.15 (m, 2H), 1.19 (t, J = 7.1 Hz, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 191.8, 170.1, 169.1, 168.7, 164.3, 146.1, 131.4, 129.1, 128.7, 128.4, 127.9, 125.9, 114.1, 61.9, 55.6, 51.3, 25.2, 14.0; HRMS-ESI calcd for $C_{23}H_{22}NO_6$ $[M + H]^+$ 408.1442, found 408.1445.

*Ethyl 3-(4-chlorophenyl)-2-((2,5-dioxo-1-phenyl-2,5-dihydro-1H-pyrrol-3-yl)methyl)-3-oxopropanoate (**3d**).* Following the general procedure, *N*-phenylmaleimide **1a** (35 mg, 0.2 mmol) and enone **2d** (58 mg, 0.24 mmol) were employed to give product **3d** (69 mg, 84%) as a white solid: mp 95–96 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.00 (d, J = 8.6 Hz, 2H), 7.52–7.41 (m, 4H), 7.40–7.27 (m, 3H), 6.53 (s, 1H), 4.84–4.74 (m, 1H), 4.17 (q, J = 7.1 Hz, 1H), 4.16 (q, J = 7.1 Hz, 1H), 3.30–3.15 (m, 2H), 1.18 (t, J = 7.1 Hz, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 192.3, 170.1, 168.9, 168.2, 145.6, 140.7, 133.7, 131.3, 130.3, 129.3, 129.1, 128.9, 127.9, 125.9, 62.2, 51.6, 25.0, 13.9; HRMS-ESI calcd for $C_{22}H_{19}ClNO_5$ $[M + H]^+$ 412.0946, found 412.0945.

*Methyl 2-((2,5-dioxo-1-phenyl-2,5-dihydro-1H-pyrrol-3-yl)-methyl)-3-(4-fluorophenyl)-3-oxopropanoate (**3e**).* Following the general procedure, *N*-phenylmaleimide **1a** (35 mg, 0.2 mmol) and enone **2e** (50 mg, 0.24 mmol) were employed to obtain product **3e** (63 mg, 80%) as a white solid: mp 105–106 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.15–8.06 (m, 2H), 7.50–7.41 (m, 2H), 7.40–7.28 (m, 3H), 7.18 (t, J = 8.6 Hz, 2H), 6.53 (br s, 1H), 4.83 (dd, J = 7.9, 6.6 Hz, 1H), 3.72 (s, 3H), 3.31–3.14 (m, 2H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 191.9, 170.1, 168.9, 168.8, 166.4 (d, J = 257.1 Hz), 145.6, 131.8, 131.7, 131.3, 129.1, 129.0, 127.9, 125.9, 116.3 (d, J = 22.0 Hz), 53.1, 51.3, 25.1; HRMS-ESI calcd for $C_{21}H_{17}FNO_5$ $[M + H]^+$ 382.1085, found 382.1080.

*Methyl 2-((2,5-dioxo-1-phenyl-2,5-dihydro-1H-pyrrol-3-yl)-methyl)-3-oxo-3-phenylpropanoate (**3f**).* Following the general procedure, *N*-phenylmaleimide **1a** (35 mg, 0.2 mmol) and enone **2f** (46 mg, 0.24 mmol) were employed to obtain product **3f** (72 mg, 99%) as a white solid: mp 69–70 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.10–8.02 (m, 2H), 7.66–7.59 (m, 1H), 7.55–7.40 (m, 4H), 7.39–7.27 (m, 3H), 6.52 (br s, 1H), 4.88 (t, J = 7.2 Hz, 1H), 3.71 (s, 3H), 3.31–3.15 (m, 2H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 193.4, 170.1, 169.0, 168.9, 145.7, 135.3, 134.2, 131.3, 129.1, 129.0, 128.9, 128.8, 127.9, 125.9, 53.0, 51.3, 25.2; HRMS-ESI calcd for $C_{21}H_{18}NO_5$ $[M + H]^+$ 364.1179, found 364.1183.

*tert-Butyl 2-((2,5-dioxo-1-phenyl-2,5-dihydro-1H-pyrrol-3-yl)-methyl)-3-oxo-3-phenylpropanoate (**3g**).* Following the general procedure, *N*-phenylmaleimide **1a** (35 mg, 0.2 mmol) and enone **2g** (56 mg, 0.24 mmol) were employed to yield product **3g** (77 mg, 95%) as a white solid: mp 118–119 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.09–7.98 (m, 2H), 7.62 (t, J = 7.4 Hz, 1H), 7.55–7.41 (m, 4H), 7.40–7.28 (m, 3H), 6.51 (br s, 1H), 4.72 (t, J = 7.3 Hz, 1H), 3.20 (dd, J = 7.3, 1.4 Hz, 2H), 1.34 (s, 9H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 193.7, 170.1, 169.1, 167.5, 146.3, 135.8, 133.9, 131.4, 129.1, 128.9, 128.8, 128.6, 127.8, 125.9, 83.0, 52.7, 27.8, 24.9; HRMS-ESI calcd for $C_{24}H_{24}NO_5$ $[M + H]^+$ 406.1649, found 406.1649.

*3-(3-Oxobutyl)-1-phenyl-1H-pyrrole-2,5-dione (**3h**).* Following the general procedure, *N*-phenylmaleimide **1a** (35 mg, 0.2 mmol) and enone **2h** (25 μL, 0.3 mmol) were employed to obtain product **3h** (30 mg, 62%) as a white solid: mp 106–107 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.46 (t, J = 7.7 Hz, 2H), 7.41–7.29 (m, 3H), 6.44 (br s, 1H), 2.95–2.71 (m, 4H), 2.22 (s, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 205.9, 170.1, 169.3, 148.4, 131.4, 129.0, 127.7, 127.2, 125.9, 40.3,

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29.8, 19.7; HRMS-ESI calcd for $C_{14}H_{14}NO_3$ $[M + H]^+$ 244.0968, found 244.0968.

*3-(3-Oxo-3-phenylpropyl)-1-phenyl-1H-pyrrole-2,5-dione (**3i**).* Following the general procedure, *N*-phenylmaleimide **1a** (35 mg, 0.2 mmol) and enone **2i** (32 mg, 0.24 mmol) were employed to obtain product **3i** (34 mg, 56%) as a white solid: mp 133−134 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.03−7.95 (m, 2H), 7.64−7.56 (m, 1H), 7.54−7.41 (m, 4H), 7.39−7.30 (m, 3H), 6.49 (br s, 1H), 3.40 (t, J = 6.9 Hz, 2H), 3.00 (td, J = 6.9, 1.7 Hz, 2H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 197.5, 170.2, 169.4, 148.7, 136.3, 133.6, 131.5, 129.1, 128.8, 128.2, 127.8, 127.4, 125.9, 35.7, 20.2; HRMS-ESI calcd for $C_{19}H_{16}NO_3$ $[M + H]^+$ 306.1125, found 306.1127.

*Ethyl 2-((2,5-dioxo-1-p-tolyl-2,5-dihydro-1H-pyrrol-3-yl)methyl)-3-oxo-3-phenylpropanoate (**3j**).* Following the general procedure, maleimide **1b** (23 mg, 0.123 mmol) and enone **2a** (49 mg, 0.24 mmol) were employed to yield product **3j** (47 mg, 98%) as a white solid: mp 103−104 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.05 (d, J = 7.8 Hz, 2H), 7.62 (t, J = 7.3 Hz, 1H), 7.51 (t, J = 7.7 Hz, 2H), 7.25 (d, J = 7.6 Hz, 2H), 7.18 (d, J = 8.3 Hz, 2H), 6.50 (s, 1H), 4.83 (t, J = 7.2 Hz, 1H), 4.17 (q, J = 7.1 Hz, 2H), 3.32−3.14 (m, 2H), 2.37 (s, 3H), 1.17 (t, J = 7.1 Hz, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 193.5, 170.2, 169.2, 168.5, 145.8, 137.9, 135.4, 134.1, 129.8, 129.0, 128.9, 128.8, 128.6, 125.9, 62.0, 51.6, 25.1, 21.2, 13.9; HRMS-ESI calcd for $C_{23}H_{22}NO_5$ $[M + H]^+$ 392.1492, found 392.1491.

*Ethyl 3-(4-chlorophenyl)-2-((1-(4-nitrophenyl)-2,5-dioxo-2,5-dihydro-1H-pyrrol-3-yl)methyl)-3-oxopropanoate (**3k**).* Following the general procedure, maleimide **1c** (44 mg, 0.2 mmol) and enone **2d** (58 mg, 0.24 mmol) were employed to give product **3k** (60 mg, 66%) as a white solid: mp 144−145 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.32 (d, J = 9.2 Hz, 2H), 8.00 (d, J = 8.7 Hz, 2H), 7.67 (d, J = 9.2 Hz, 2H), 7.50 (d, J = 8.7 Hz, 2H), 6.61 (br s, 1H), 4.77 (t, J = 7.2 Hz, 1H), 4.18 (q, J = 7.1 Hz, 1H), 4.17 (q, J = 7.1 Hz, 1H), 3.32−3.18 (m, 2H), 1.18 (t, J = 7.1 Hz, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 191.9, 169.2, 168.1, 167.9, 146.4, 140.9, 137.2, 133.7, 130.3, 129.4, 129.3, 127.1, 125.2, 124.5, 62.3, 51.6, 24.9, 13.9; HRMS-ESI calcd for $C_{22}H_{17}ClN_2O_7Na$ $[M + Na]^+$ 479.0616, found 479.0619.

*Ethyl 2-((1-benzyl-2,5-dioxo-2,5-dihydro-1H-pyrrol-3-yl)methyl)-3-oxo-3-phenylpropanoate (**3l**).* Following the general procedure, maleimide **1d** (38 mg, 0.2 mmol) and enone **2a** (49 mg, 0.24 mmol) were employed to obtain product **3l** (70 mg, 90%) as a pale yellow oil: ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.05−7.97 (m, 2H), 7.60 (d, J = 7.4 Hz, 1H), 7.48 (t, J = 7.7 Hz, 2H), 7.35−7.25 (m, 5H), 6.37 (br s, 1H), 4.77 (t, J = 7.3 Hz, 1H), 4.64 (s, 2H), 4.13 (q, J = 7.1 Hz, 1H), 4.12 (q, J = 7.1 Hz, 1H), 3.21−3.07 (m, 2H), 1.12 (t, J = 7.1 Hz, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 193.5, 170.9, 169.9, 168.4, 145.9, 136.2, 135.4, 134.0, 128.9, 128.8, 128.7, 128.6, 128.3, 127.8, 61.9, 51.6, 41.6, 25.0, 13.9; HRMS-ESI calcd for $C_{23}H_{22}NO_5$ $[M + H]^+$ 392.1492, found 392.1497.

*Ethyl 2-((1-butyl-2,5-dioxo-2,5-dihydro-1H-pyrrol-3-yl)methyl)-3-oxo-3-phenylpropanoate (**3m**).* Following the general procedure, maleimide **1e** (31 mg, 0.2 mmol) and enone **2a** (49 mg, 0.24 mmol) were employed to yield product **3m** (57 mg, 80%) as a pale yellow oil: ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.03 (d, J = 7.6 Hz, 2H), 7.62 (t, J = 7.3 Hz, 1H), 7.50 (t, J = 7.4 Hz, 2H), 6.33 (s,1H), 4.78 (t, J = 7.2 Hz, 1H), 4.15 (q, J = 7.1 Hz, 1H), 4.14 (q, J = 7.1 Hz, 1H), 3.47 (t, J = 7.1 Hz, 2H), 3.14 (d, J = 7.1 Hz, 2H), 1.60−1.46 (m, 2H), 1.36−1.21 (m, 2H), 1.16 (t, J = 7.1 Hz, 3H), 0.91 (t, J = 7.2 Hz, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 193.4, 171.3, 170.3, 168.4, 145.6, 135.5, 133.9, 128.9, 128.8, 128.5, 61.9, 51.7, 37.8, 30.5, 24.9, 19.9, 13.9, 13.5; HRMS-ESI calcd for $C_{20}H_{24}NO_5$ $[M + H]^+$ 358.1649, found 358.1648.

*tert-Butyl 3-(2-(4-chlorobenzoyl)-3-ethoxy-3-oxopropyl)-2,5-dioxo-2,5-dihydro-1H-pyrrole-1-carboxylate (**3n**).* Following the general procedure, maleimide **1f** (40 mg, 0.2 mmol) and enone **2d** (57 mg, 0.24 mmol) were employed to yield product **3n** (56 mg, 64%) as a pale yellow oil: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.99 (d, J = 8.7 Hz, 2H), 7.49 (d, J = 8.7 Hz, 2H), 6.50 (br s, 1H), 4.71 (dd, J = 8.0, 6.4 Hz, 1H), 4.15 (q, J = 7.1 Hz, 1H), 4.14 (q, J = 7.1 Hz, 1H), 3.22−3.06 (m, 2H), 1.58 (s, 9H), 1.17 (t, J = 7.1 Hz, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 192.0, 167.9, 167.2, 165.4, 146.4, 145.8, 140.8, 133.6, 130.2, 130.3, 129.3, 85.4, 62.2, 51.5, 27.9, 24.9, 13.9; HRMS-ESI calcd for $C_{21}H_{26}ClN_2O_7$ $[M + NH_4]^+$ 453.1423, found 453.1424.

*Ethyl 3-(4-chlorophenyl)-2-((2,5-dioxo-2,5-dihydro-1H-pyrrol-3-yl)methyl)-3-oxopropanoate (**3o**).* Following the general procedure, maleimide **1g** (20 mg, 0.2 mmol) and enone **2d** (58 mg, 0.24 mmol) were employed to give product **3o** (20 mg, 30%) as a pale yellow oil: ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.98 (d, J = 8.6 Hz, 2H), 7.48 (d, J = 8.6 Hz, 2H), 7.41 (s, 1H), 6.38 (s, 1H), 4.72 (t, J = 7.2 Hz, 1H), 4.15 (q, J = 7.1 Hz, 2H), 3.13 (d, J = 7.1 Hz, 2H), 1.17 (t, J = 7.1 Hz, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 192.1, 170.9, 168.1, 146.6, 140.7, 133.7, 130.3, 129.9, 129.3, 62.2, 51.7, 24.7, 13.9; HRMS-ESI calcd for $C_{16}H_{14}ClNO_5Na$ $[M + Na]^+$ 358.0453, found 358.0454.

*3-((2-Oxocycloheptyl)methyl)-1-phenyl-1H-pyrrole-2,5-dione (**3p**).* Following the general procedure, *N*-phenylmaleimide **1a** (35 mg, 0.2 mmol) and enone **2j** (30 mg, 0.24 mmol) were employed to give product **3p** (24 mg, 41%) as a pale yellow oil: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.50−7.41 (m, 2H), 7.39−7.30 (m, 3H), 6.41 (br s, 1H), 3.18−2.87 (m, 2H), 2.68−2.39 (m, 3H), 1.98−1.80 (m, 4H), 1.75−1.65 (m, 1H), 1.58−1.26 (m, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 213.5, 170.4, 169.4, 147.9, 131.5, 129.0, 127.9, 127.7, 125.9, 49.6, 43.2, 31.6, 29.0, 28.9, 27.8, 23.7; HRMS-ESI calcd for $C_{18}H_{20}NO_3$ $[M + H]^+$ 298.1438, found 298.1438.

*3-((1-Oxo-2,3-dihydro-1H-inden-2-yl)methyl)-1-phenyl-1H-pyrrole-2,5-dione (**3q**).* Following the general procedure, *N*-phenylmaleimide **1a** (35 mg, 0.2 mmol) and enone **2k** (35 mg, 0.24 mmol) were employed to yield product **3q** (51 mg, 79%) as a white solid: mp 164−165 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.79 (d, J = 7.7 Hz, 1H), 7.63 (t, J = 7.5 Hz, 1H), 7.52−7.31 (m, 7H), 6.51 (br s, 1H), 3.45 (dd, J = 17.0, 7.8 Hz, 1H), 3.21−3.06 (m, 2H), 2.91 (dd, J = 17.0, 3.9 Hz, 1H), 2.84−2.70 (m, 1H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 206.1, 170.2, 169.3, 152.9, 147.4, 136.1, 135.3, 131.5, 129.1, 127.9 (2C), 127.8, 126.6, 125.9, 124.2, 45.2, 32.7, 26.9; HRMS-ESI calcd for $C_{20}H_{16}NO_3$ $[M + H]^+$ 318.1125, found 318.1129.

*3-((1-Oxo-1,2,3,4-tetrahydronaphthalen-2-yl)methyl)-1-phenyl-1H-pyrrole-2,5-dione (**3r**).* Following the general procedure, *N*-phenylmaleimide **1a** (35 mg, 0.2 mmol) and enone **2l** (38 mg, 0.24 mmol) were employed to obtain product **3r** (42 mg, 64%) as a white solid: mp 143−144 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.03 (d, J = 7.8 Hz, 1H), 7.52−7.40 (m, 3H), 7.38−7.28 (m, 4H), 7.28−7.22 (m, 1H), 6.54 (s, 1H), 3.22 (ddd, J = 15.6, 6.2, 1.5 Hz, 1H), 3.16−2.94 (m, 3H), 2.72 (ddd, J = 15.6, 6.4, 1.3 Hz, 1H), 2.28 (m, 1H), 1.97 (m, 1H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 198.1, 170.5, 169.5, 148.0, 143.8, 133.7, 132.1, 131.6, 129.1, 128.8, 128.1, 127.7, 127.6, 126.9, 125.9, 46.5, 29.2, 29.0, 26.2; HRMS-ESI calcd for $C_{21}H_{18}NO_3$ $[M + H]^+$ 332.1281, found 332.1285.

*3-((4-Oxochroman-3-yl)methyl)-1-phenyl-1H-pyrrole-2,5-dione (**3s**).* Following the general procedure, *N*-phenylmaleimide **1a** (35 mg, 0.2 mmol) and enone **2m** (32 mg, 0.24 mmol) were employed to obtain product **3s** (61 mg, 92%) as a white solid: mp 121−122 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.90 (dd, J = 7.9, 1.5 Hz, 1H), 7.56−7.41 (m, 3H), 7.35 (t, J = 7.4 Hz, 3H), 7.05 (t, J = 7.5 Hz, 1H), 6.98 (d, J = 8.4 Hz, 1H), 6.56 (s, 1H), 4.59 (dd, J = 11.5, 4.7 Hz, 1H), 4.30 (t, J = 10.3 Hz, 1H), 3.28−3.17 (m, 1H), 3.12 (ddd, J = 15.7, 6.8, 1.3 Hz, 1H), 2.71 (ddd, J = 15.7, 6.5, 1.2 Hz, 1H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 192.3, 170.1, 169.1, 161.2, 146.3, 136.3, 131.5, 129.1, 128.5, 127.8, 127.5, 125.9, 121.8, 120.3, 117.9, 70.2, 44.3, 22.5; HRMS-ESI calcd for $C_{20}H_{16}NO_4$ $[M + H]^+$ 334.1074, found 334.1070.

General Procedure for Synthesis of Bicyclic and Polycyclic Cyclopentenes 4 and 5 from Maleimides 1 and Enones 2 (Table 3 and Scheme 5). Under a N_2 atmosphere, to a solution of maleimide **1** (0.2 mmol), enone **2** (0.24 mmol), and benzoic acid (5.0 mg, 0.04 mmol) in CH_2Cl_2 (2.0 mL) was added (*p*-tolyl)$_3$P (12 mg, 0.04 mmol). The resulting mixture was stirred at rt until maleimide **1** was completely consumed, as monitored by TLC. Then PBu_3 (60 μL, 0.24 mmol) was added, and the reaction mixture was stirred under reflux for 24 h (Table 3) or at rt for 5−20 h (Scheme 5). The solvent was removed on a rotary evaporator under reduced pressure, and the residue was subjected to column chromatographic isolation on silica gel (gradient elution, petroleum ether (bp 60−90 °C)/ethyl acetate 10:1−3:1) to give products **4** or **5**.

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*Ethyl 1,3-dioxo-2,6-diphenyl-1,2,3,3a,4,6a-hexahydrocyclopenta[c]pyrrole-5-carboxylate (**4a**).* Following the general procedure, *N*-phenylmaleimide **1a** (35 mg, 0.2 mmol) and enone **2a** (49 mg, 0.24 mmol) were employed to obtain product **4a** (67 mg, 93%) as a pale yellow oil: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.50−7.43 (m, 2H), 7.43−7.32 (m, 6H), 7.31−7.24 (m, 2H), 4.46 (dt, J = 8.1, 2.8 Hz, 1H), 4.11 (q, J = 6.9 Hz, 2H), 3.67 (ddd, J = 9.3, 8.1, 3.9 Hz, 1H), 3.46−3.31 (m, 2H), 1.13 (t, J = 7.1 Hz, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 177.1, 172.7, 163.4, 146.3, 132.6, 130.7, 130.6, 128.2, 127.8, 127.6, 127.2, 126.9, 125.3, 59.7, 56.7, 40.4, 36.0, 12.8; HRMS-ESI calcd for $C_{22}H_{20}NO_4$ $[M + H]^+$ 362.1387, found 362.1389.

*Ethyl 1,3-dioxo-2-phenyl-6-p-tolyl-1,2,3,3a,4,6a-hexahydrocyclopenta[c]pyrrole-5-carboxylate (**4b**).* Following the general procedure, *N*-phenylmaleimide **1a** (35 mg, 0.2 mmol) and enone **2b** (53 mg, 0.24 mmol) were employed to yield product **4b** (64 mg, 85%) as a white solid: mp 113−114 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.44−7.37 (m, 2H), 7.37−7.30 (m, 1H), 7.27−7.20 (m, 4H), 7.17 (d, J = 8.1 Hz, 2H), 4.42 (dt, J = 8.1, 2.7 Hz, 1H), 4.10 (q, J = 7.1 Hz, 2H), 3.62 (ddd, J = 9.4, 8.1, 3.7 Hz, 1H), 3.42−3.25 (m, 2H), 2.34 (s, 3H), 1.14 (t, J = 7.1 Hz, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 178.2, 173.8, 164.5, 147.5, 138.8, 131.7, 130.9, 130.5, 129.0, 128.7, 128.5, 128.3, 126.3, 60.7, 57.5, 41.4, 37.1, 21.4, 13.9; HRMS-ESI calcd for $C_{23}H_{22}NO_4$ $[M + H]^+$ 376.1543, found 376.1539.

*Ethyl 6-(4-methoxyphenyl)-1,3-dioxo-2-phenyl-1,2,3,3a,4,6a-hexahydrocyclopenta[c]pyrrole-5-carboxylate (**4c**).* Following the general procedure, *N*-phenylmaleimide **1a** (35 mg, 0.2 mmol) and enone **2c** (69 mg, 0.24 mmol) were employed to give product **4c** (69 mg, 88%) as a white solid: mp 161−162 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.46−7.38 (m, 2H), 7.38−7.30 (m, 3H), 7.27−7.19 (m, 2H), 6.94−6.85 (m, 2H), 4.45 (dt, J = 8.2, 2.7 Hz, 1H), 4.13 (q, J = 7.1 Hz, 2H), 3.81 (s, 3H), 3.64 (ddd, J = 9.1, 8.2, 4.0 Hz, 1H), 3.42−3.27 (m, 2H), 1.17 (t, J = 7.1 Hz, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 178.2, 173.9, 164.7, 160.1, 147.0, 131.7, 130.1, 129.1, 128.6, 126.3, 125.5, 113.3, 60.7, 57.3, 55.2, 41.3, 37.1, 13.9; HRMS-ESI calcd for $C_{23}H_{22}NO_5$ $[M + H]^+$ 392.1492, found 392.1496.

*Ethyl 6-(4-chlorophenyl)-1,3-dioxo-2-phenyl-1,2,3,3a,4,6a-hexahydrocyclopenta[c]pyrrole-5-carboxylate (**4d**).* Following the general procedure, *N*-phenylmaleimide **1a** (35 mg, 0.2 mmol) and enone **2d** (58 mg, 0.24 mmol) were employed to give product **4d** (79 mg, 99%) as a white solid: mp 129−130 °C; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.43 (t, J = 7.4 Hz, 2H), 7.39−7.31 (m, 3H), 7.31−7.19 (m, 4H), 4.40 (dt, J = 8.0, 2.6 Hz, 1H), 4.10 (q, J = 7.1 Hz, 2H), 3.72−3.59 (m, 1H), 3.44−3.25 (m, 2H), 1.14 (t, J = 7.1 Hz, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 177.9, 173.6, 164.1, 146.1, 134.9, 132.3, 131.9, 131.6, 129.8, 129.1, 128.7, 128.2, 126.3, 60.9, 57.5, 41.3, 37.1, 13.9; HRMS-ESI calcd for $C_{22}H_{19}ClNO_4$ $[M + H]^+$ 396.0997, found 396.1001.

*Methyl 6-(4-fluorophenyl)-1,3-dioxo-2-phenyl-1,2,3,3a,4,6a-hexahydrocyclopenta[c]pyrrole-5-carboxylate (**4e**).* Following the general procedure, *N*-phenylmaleimide **1a** (35 mg, 0.2 mmol) and enone **2e** (50 mg, 0.24 mmol) were employed to give product **4e** (67 mg, 92%) as a white solid: mp 45−46 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.49−7.40 (m, 2H), 7.40−7.30 (m, 3H), 7.28−7.19 (m, 2H), 7.07 (t, J = 8.7 Hz, 2H), 4.44 (dt, J = 8.2, 2.8 Hz, 1H), 3.71−3.67 (m, 1H), 3.66 (s, 3H), 3.43−3.28 (m, 2H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 177.9, 173.6, 164.6, 162.9 (d, J = 249.2 Hz), 146.8, 131.6, 131.3, 130.4, 130.3, 129.1, 128.7, 126.3, 115.1 (d, J = 21.8 Hz), 57.5, 51.8, 41.3, 37.0; HRMS-ESI calcd for $C_{21}H_{17}FNO_4$ $[M + H]^+$ 366.1136, found 366.1133.

*tert-Butyl 1,3-dioxo-2,6-diphenyl-1,2,3,3a,4,6a-hexahydrocyclopenta[c]pyrrole-5-carboxylate (**4f**).* Following the general procedure, *N*-phenylmaleimide **1a** (35 mg, 0.2 mmol) and enone **2g** (56 mg, 0.24 mmol) were employed to give product **4f** (35 mg, 45%) as a colorless oil: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.47−7.40 (m, 2H), 7.42−7.32 (m, 4H), 7.30−7.23 (m, 4H), 4.40 (dt, J = 8.1, 2.8 Hz, 1H), 3.70−3.59 (m, 1H), 3.40−3.25 (m, 2H), 1.27 (s, 9H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 178.2, 173.8, 163.8, 145.8, 134.2, 133.6, 131.7, 129.1, 128.6, 128.5, 128.2, 127.9, 126.3, 81.6, 57.8, 41.4, 37.1, 27.7; HRMS-ESI calcd for $C_{24}H_{24}NO_4$ $[M + H]^+$ 390.1700, found 390.1700.

*Methyl 6-(4-fluorophenyl)-1,3-dioxo-2-p-tolyl-1,2,3,3a,4,6a-hexahydrocyclopenta[c]pyrrole-5-carboxylate (**4g**).* Following the general procedure, maleimide **1b** (37 mg, 0.2 mmol) and enone **2e** (50 mg, 0.24 mmol) were employed to obtain product **4g** (60 mg, 79%) as a pale yellow oil: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.38−7.30 (m, 2H), 7.26−7.21 (m, 2H), 7.15−7.02 (m, 4H), 4.40 (dt, J = 8.2, 2.8 Hz, 1H), 3.70−3.61 (m, 4H), 3.40−3.26 (m, 2H), 2.35 (s, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 178.0, 173.7, 164.6, 162.9 (d, J = 248.7 Hz), 146.9, 138.8, 131.2, 130.4 (d, J = 8.3 Hz), 129.8, 129.3 (d, J = 3.2 Hz), 128.9, 126.0, 115.1 (d, J = 21.8 Hz), 57.5, 51.8, 41.3, 37.0, 21.2; HRMS-ESI calcd for $C_{22}H_{19}FNO_4$ $[M + H]^+$ 380.1293, found 380.1296.

*Ethyl 6-(4-methoxyphenyl)-2-(4-nitrophenyl)-1,3-dioxo-1,2,3,3a,4,6a-hexahydrocyclopenta[c]pyrrole-5-carboxylate (**4h**).* Following the general procedure, maleimide **1c** (44 mg, 0.2 mmol) and enone **2c** (69 mg, 0.24 mmol) were employed to obtain product **4h** (80 mg, 92%) as a semisolid: ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.26 (d, J = 9.1 Hz, 2H), 7.52 (d, J = 9.1 Hz, 2H), 7.35 (d, J = 8.8 Hz, 2H), 6.91 (d, J = 8.8 Hz, 2H), 4.52 (dt, J = 8.2, 2.6 Hz, 1H), 4.13 (q, J = 7.1 Hz, 2H), 3.82 (s, 3H), 3.74−3.65 (m, 1H), 3.42−3.30 (m, 2H), 1.17 (t, J = 7.1 Hz, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 177.4, 173.2, 164.5, 160.2, 146.7, 146.3, 137.2, 130.3, 130.1, 126.7, 125.1, 124.3, 113.4, 60.9, 57.1, 55.2, 41.4, 37.2, 13.9; HRMS-ESI calcd for $C_{23}H_{24}N_3O_7$ $[M + NH_4]^+$ 454.1609, found 454.1609.

*Methyl 2-butyl-6-(4-fluorophenyl)-1,3-dioxo-1,2,3,3a,4,6a-hexahydrocyclopenta[c]pyrrole-5-carboxylate (**4i**).* Following the general procedure, maleimide **1e** (31 mg, 0.2 mmol) and enone **2e** (50 mg, 0.24 mmol) were employed to give product **4i** (67 mg, 97%) as a pale yellow oil: ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.36−7.25 (m, 2H), 7.12−7.02 (m, 2H), 4.27 (dt, J = 8.0, 2.8 Hz, 1H), 3.64 (s, 3H), 3.54−3.40 (m, 3H), 3.32−3.19 (m, 2H), 1.55−1.44 (m, 2H), 1.31−1.18 (m, 2H), 0.89 (t, J = 7.3 Hz, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 177.8, 173.8, 163.6, 161.9 (d, J = 248.9 Hz), 145.9, 129.7, 129.3 (d, J = 8.4 Hz), 128.4 (d, J = 3.4 Hz), 114.1 (d, J = 21.7 Hz), 56.5, 50.7, 40.1, 37.8, 35.7, 28.6, 18.9, 12.5; HRMS-ESI calcd for $C_{19}H_{21}FNO_4$ $[M + H]^+$ 346.1449, found 346.1445.

*6-Methyl-2-phenyl-4,5-dihydrocyclopenta[c]pyrrole-1,3(2H,3aH)-dione (**5a**).* Following the general procedure, *N*-phenylmaleimide **1a** (35 mg, 0.2 mmol) and enone **2h** (20 μL, 0.24 mmol) were employed to give product **5a** (28 mg, 62%) as a white solid: mp 129−130 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.46 (t, J = 7.7 Hz, 2H), 7.37 (t, J = 7.4 Hz, 1H), 7.30 (d, J = 7.6 Hz, 2H), 3.97 (m, 1H), 3.10−2.92 (m, 1H), 2.60 (dd, J = 17.2, 8.6 Hz, 1H), 2.51−2.38 (m, 1H), 2.18 (s, 3H), 2.15−2.07 (m, 1H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 175.4, 164.3, 153.2, 132.1, 129.1, 128.9, 128.2, 126.6, 51.4, 42.7, 28.1, 15.7; HRMS-ESI calcd for $C_{14}H_{14}NO_2$ $[M + H]^+$ 228.1019, found 228.1019.

*Polycyclic Compound **5b**.* Following the general procedure, *N*-phenylmaleimide **1a** (35 mg, 0.2 mmol) and enone **2k** (35 mg, 0.24 mmol) were employed to obtain product **5b** (43 mg, 71%) as a white solid: mp 191−192 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.10−8.00 (m, 1H), 7.48−7.29 (m, 8H), 4.39 (m, 1H), 4.09−3.94 (m, 1H), 3.28 (dd, J = 16.4, 8.6 Hz, 1H), 2.95−2.84 (m, 1H), 2.78 (dd, J = 16.4, 6.0 Hz, 1H), 2.03 (m, 1H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 175.5, 163.7, 163.2, 151.8, 133.4, 132.2, 131.7, 128.9, 128.1, 127.6, 126.5, 125.7, 121.8, 56.0, 55.8, 38.5, 36.4; HRMS-ESI calcd for $C_{20}H_{16}NO_2$ $[M + H]^+$ 302.1176, found 302.1174.

*Polycyclic Compound **5c**.* Following the general procedure, *N*-phenylmaleimide **1a** (35 mg, 0.2 mmol) and enone **2l** (38 mg, 0.24 mmol) were employed to give product **5c** (26 mg, 41%) as a white solid: mp 167−168 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.91 (dd, J = 7.8, 1.0 Hz, 1H), 7.50−7.42 (m, 2H), 7.41−7.24 (m, 5H), 7.19 (d, J = 7.3 Hz, 1H), 4.12 (m, 1H), 3.53−3.41 (m, 1H), 3.07−2.85 (m, 2H), 2.73−2.61 (m, 1H), 2.30−2.19 (m, 1H), 1.89−1.67 (m, 2H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 175.1, 164.1, 151.7, 139.9, 132.3, 131.5, 131.1, 129.1, 128.9, 128.8, 128.3, 126.7 (2C), 124.9, 51.4, 51.0, 34.3, 30.8, 30.2; HRMS-ESI calcd for $C_{21}H_{18}NO_2$ $[M + H]^+$ 316.1332, found 316.1333.

*Polycyclic Compound **5d**.* Following the general procedure, *N*-phenylmaleimide **1a** (67 mg, 0.39 mmol) and enone **2m** (52 mg, 0.325 mmol) were employed to give product **5d** (59 mg, 57%) as a white solid: mp 221−222 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.62 (dd, J =

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7.9, 1.2 Hz, 1H), 7.48 (t, J = 7.6 Hz, 2H), 7.43−7.29 (m, 4H), 7.07−6.98 (m, 1H), 6.94 (d, J = 8.3 Hz, 1H), 4.60 (dd, J = 10.7, 5.8 Hz, 1H), 4.23−4.12 (m, 1H), 3.95−3.83 (m, 1H), 3.81−3.66 (m, 1H), 2.73−2.60 (m, 1H), 1.81 (m, 1H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 174.7, 163.8, 156.4, 145.2, 133.4, 132.2, 131.6, 129.1, 128.4, 126.7, 124.5, 121.7, 117.2, 117.1, 71.0, 51.3, 47.0, 30.9; HRMS-ESI calcd for $C_{20}H_{16}NO_3$ $[M + H]^+$ 318.1125, found 318.1119.

■ ASSOCIATED CONTENT

Supporting Information

Copies of NMR (^{1}H, ^{13}C) spectra of new compounds (**3**, **4**, and **5**); X-ray crystallographic data (CIF files) for compounds **4d** and **5c**. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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(20) The following control experiments were run: (1) under the PBu_3-mediated cyclization conditions (Table 3), polycyclic product **5d** was treated under reflux for 24 h, and no double-bond migration product was observed; (2) in the presence of benzoic acid (20 mol %), the RC product **3c** (0.2 mmol) was treated with PBu_3 (1.2 equiv) in CH_2Cl_2 at rt for 24 h, only delivering bicyclic product **4c** in 38% yield.

(21) 1,3-Dioxocyclopenta[*c*]pyrrole skeleton can be readily reduced into octohydrocyclopenta[*c*]pyrrole structure, which is the core unit in the antivirus drug candidate telaprevir. For relevant reports, see: (a) Zhao, Q.; Han, X.; Wei, Y.; Shi, M.; Lu, Y. *Chem. Commun.* **2012**, *48*, 970. (b) Znabet, A.; Polak, M. M.; Janssen, E.; de Kanter, F. J. J.; Turner, N. J.; Orru, R. V. A.; Ruijter, E. *Chem. Commun.* **2010**, *46*, 7918. (c) Kohler, V.; Bailey, K. R.; Znabet, A.; Raftery, J.; Helliwell, M.; Turner, N. J. *Angew. Chem., Int. Ed.* **2010**, *49*, 2182.

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