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Synthesis of Oxaspiranic Compounds through [3 + 2] Annulation of Cyclopropenones and Donor−Acceptor Cyclopropanes

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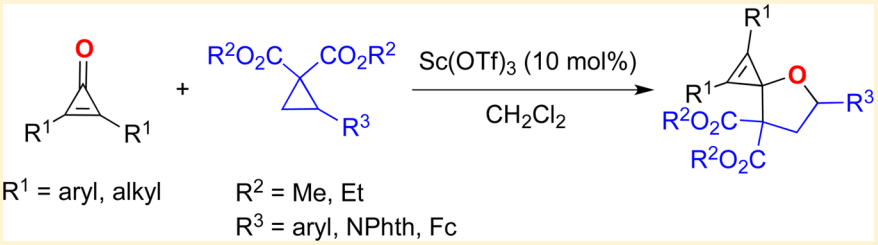
Supporting Information



ABSTRACT: The $Sc(OTf)_3$-catalyzed [3 + 2]-annulation reaction between cyclopropenones and donor−acceptor cyclopropanes is described. The process leads directly to the formation of 4-oxaspiro[2.4]hept-1-ene derivatives in good to excellent reaction yields. Density functional theory calculations suggest that the [3 + 2]-annulation pathway is strongly preferred over the possible [3 + 3]-process.

Spirocyclic compounds, species where two rings are fused by just one carbon atom, have become a synthetic target of renewed interest recently due to their enormous potential in drug discovery[1] and materials chemistry.[2] Indeed, the rigidity and conformational restriction imposed by the spiranic moiety, which is present in a great number of natural products,[3] provide a stiff framework for the attachment of pharmacophoric groups or a rigid framework for metal coordination. However, the synthesis of these species is especially challenging for organic chemists as many of the synthetic procedures toward spirocycles are based on multistep strategies and employ expensive reagents.[4,5] Although transition-metal-catalyzed processes have become an attractive alternative to synthesize spirocycles,[6] new direct routes leading to this important family of compounds are still to be developed.

At this point, we turned our attention to the chemistry of donor−acceptor cyclopropanes (DAC),[7] compounds which have proven to be very useful for the direct synthesis of five-membered carbo- and heterocycles via [3 + 2]-annulation reactions.[8] Within the context of our ongoing work in the reaction mechanisms and synthetic applications of high-order cycloaddition and annulation reactions,[9] we have recently described a novel Lewis acid catalyzed [8 + 3]-annulation reaction between tropone derivatives and donor−acceptor aminocyclopropanes (Scheme 1a).[10] This transformation leads to the formation of amino-substituted tetrahydrocyclohepta[*b*]-pyrans in good reaction yields and with complete regio- and diastereoselectivities. This synthetic strategy was first developed with a nitrogen-based donor[10] but is also compatible with a variety of different donors such as aryl, heteroaryl, and vinyl substituents.[11] Taking into account this reaction, we envisaged a new route to 4-oxaspiro[2.4]hept-1-ene derivatives by the reaction of cyclopropenones and DACs (Scheme 1b). Two possible reaction products may be formed in this transformation, i.e., the spirocycle **A** via the well-known [3 + 2]-annulation between the DAC and the ketone moiety[8] and/or the alternative [4.1.0]-oxabicyclic species **B**, through a [3 + 3]-process analogous to the [8 + 3]-annulation described previously by us.[10] We can anticipate that the formation of compounds **B** is thermodynamically very unlikely in view of the high strain imposed by the [4.1.0]-oxabicycle. If successful, this process will constitute a simple and direct methodology to the preparation of 4-oxaspiro[2.4]hept-1-ene derivatives, which contain a spirocyclopropene in its structure.[12]

Our study started with the reaction between diphenylcyclopropenone **1a** and DAC **2a** to optimize the reaction conditions (Table 1). The use of $SnCl_4$, the Lewis acid employed for the previous [8 + 3]-annulation involving tropones,[10] did not promote the reaction (entries 1−4). Similarly, other typical Lewis acids such as $FeCl_3$, $ZnCl_2$, $TiCl_4$, $NiCl_2$, $Fe(acac)_3$, or $Ni(ClO_4)_2{\cdot}6H_2O$ (the latter used in the [8 + 3]-process involving DAC **2a**),[11] were not efficient either in promoting the transformation even when the reaction was carried out at 60 °C (entries 5−11). To our delight, $Sc(OTf)_3$ (5 mol %) did catalyze the process at 40 °C leading to a reaction conversion of 30% (entry 12). Increasing the catalyst loading to 10 mol % resulted in a higher conversion of 45%. Different temperatures were also screened finding $Sc(OTf)_3$ (10 mol %) and equimolar amounts of **1a** and **2a** in DCM as solvent at 80 °C for 4 h (entry 16) as the optimal reaction conditions.[13]

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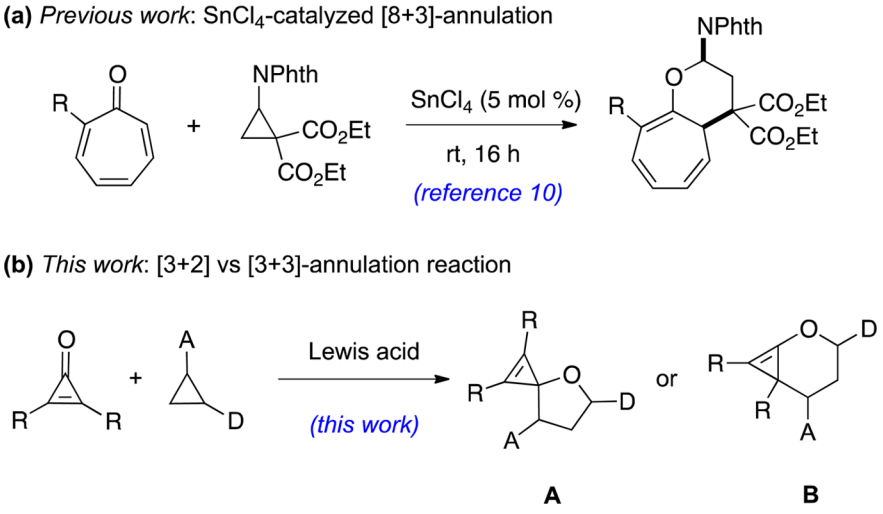
Scheme 1



Standard 1D- and 2D-NMR techniques were used to characterize the nature of the product formed (**3a**) in the reaction between **1a** and **2a**. The spectroscopic data are compatible with the formation of the spirocyclic compound **A** (Scheme 1b) as initially envisaged. For instance, the corresponding ^{13}C NMR spectrum clearly confirms the presence of the oxaspiranic carbon atom (δ = 71.2 ppm) together with the double bond of the cyclopropene moiety ($\delta \approx 128$ ppm). These chemical shifts concur quite well with those found for related 4-oxaspiro[2.4]hept-1-en-5-one derivatives.[12c] In addition, single crystals of compound **3b**, where the ethyl groups of the ester moieties were replaced by methyl groups (see also Table 2) suitable for X-ray diffraction analysis, fully confirm, by analogy, the spiranic nature of the reaction product **3a** (Figure 1).

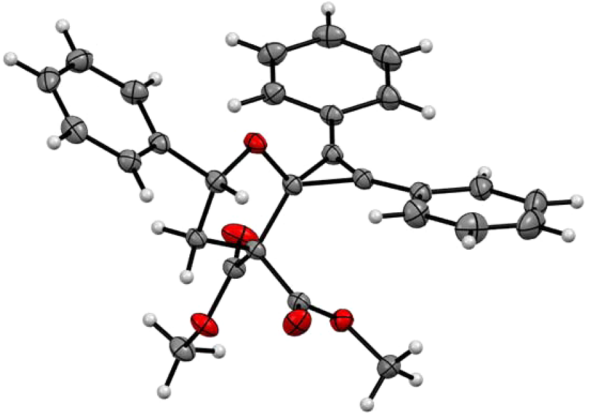
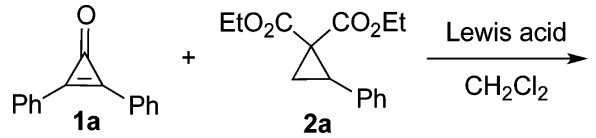


Figure 1. ORTEP diagram of compound **3b**. Ellipsoids are drawn at the 50% probability level.

With these optimized reaction conditions in hand, we next explored the scope of the process with regard to substitution at the 1,1-cyclopropanediester **2**. As readily seen in Table 2, the electronic nature of the donor moiety (R^3) of the DAC has an enormous influence on the outcome of the process. Thus, electron-withdrawing groups (F, Br, or CN groups) placed at the *para* position of the phenyl group in **2** lead to lower reaction yields (from 51% to 40% for **3d** and **3f**, respectively) than the unsubstituted phenyl group (55% for **3b**). Indeed, the reaction does not proceed at all in the presence of the strong π-acceptor

Table 1. Optimization of Reaction Conditions for the Process between 1a and 2a



entry	Lewis acid (mol %)	temp (°C)	time (h)	conv[a] (%)
1	$SnCl_4$ (20)	−78	2	0
2	$SnCl_4$ (20)	−78	8	0
3	$SnCl_4$ (20)	−20	8	0
4	$SnCl_4$ (20)	25	8	0
5	$FeCl_3$ (5)	40	8	0
6	$ZnCl_2$ (5)	40	8	0
7	$TiCl_4$ (5)	40	8	0
8	$NiCl_2$ (5)	40	8	0
9	$Fe(acac)_3$ (5)	40	8	0
10	$Ni(ClO_4)_2{\cdot}6H_2O$ (5)	40	8	0
11	$Ni(ClO_4)_2{\cdot}6H_2O$ (5)	60	8	10
12	$Sc(OTf)_3$ (5)	40	8	30
13	$Sc(OTf)_3$ (10)	40	8	45
14	$Sc(OTf)_3$ (10)	60	8	47
15	$Sc(OTf)_3$ (10)	80	8	50
16	$Sc(OTf)_3$ (10)	80	4	65
17	$Sc(OTf)_3$ (10)	100	4	50
18	$Sc(OTf)_3$ (10)	130	4	25

[a]Referred to unreacted 1,1-cyclopropane diester **2a** and measured by integration of the signals corresponding to H2 of the cyclopropane ring in the ^1H NMR spectra of reaction mixtures.

NO_2 group (0% for **3g**). Despite that, the incorporation of a bromide substituent in **3e** would allow further synthetic transformations by transition-metal-catalyzed coupling reactions. By contrast, the good π-donor methoxy substituent not only leads to a higher reaction yield of the corresponding spirocyclic compound **3c** (85%) but also allows the reaction to proceed at much lower temperature (0 °C). This finding very likely finds its origin in the initial ring opening of the DAC promoted by the Lewis acid, since it is well-known that the formation of the corresponding intimate ion pair is facilitated by electron-rich donor groups.[14]

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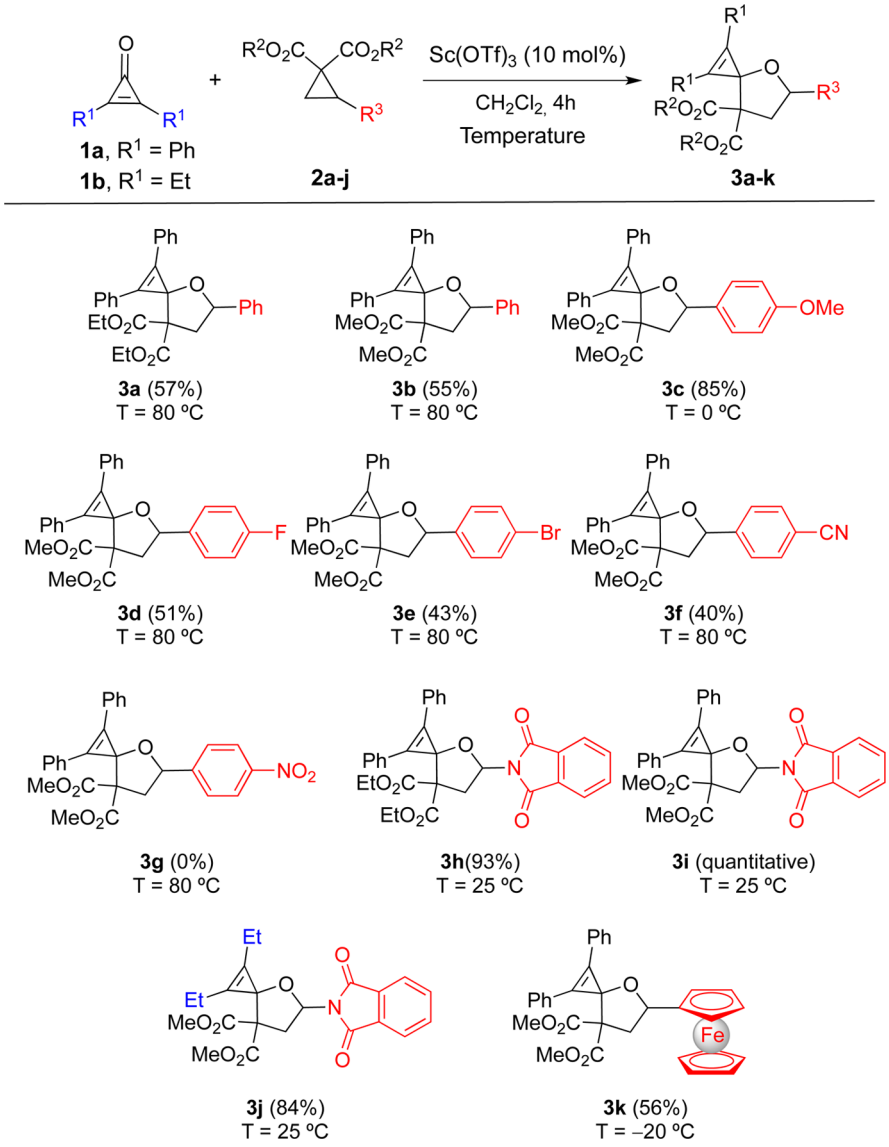
Table 2. Scope of the Sc(OTf)$_3$-Catalyzed [3 + 2]-Annulation Reaction between Cyclopropenones 1a,b and 1,1-Cyclopropanediesters 2a−j[a]



[a]Isolated reaction yields are given in parentheses.

To further confirm this hypothesis, we attached the stronger π-donor NPhth group (Phth = phthaloyl) as the donor moiety of the DAC (**2h** and **2i**). This particular type of amino-DAC was also chosen due to its proven ability to produce *N*-containing hetero- and carbocycles as recently demonstrated by Waser and co-workers.[15] From the data in Table 2, it becomes clear that in the presence of this group the reaction proceeds smoothly at lower temperatures (25 °C) as compared to the parent phenyl-substituted DAC **2b** (80 °C) and, more importantly, leads to excellent reaction yields for the corresponding spirocyclic compounds (93% and quantitative yield for **3h** and **3i**, respectively). The reaction is also compatible with alkyl instead of phenyl groups in the cyclopropenone. Thus, diethylcyclopropenone **1b** also affords the corresponding oxaspirocycle **3j** in a remarkable 84% reaction yield (at 25 °C).

Finally, we were also curious to study the process involving an organometallic fragment. The ferrocenyl substituent was chosen because of its π-donor ability.[16] Again, excellent reactivity of the corresponding ferrocenyl-substituted DAC **2j** was found as it leads to the formation of the ferrocenyl-oxaspirocyclic compound **3k** at low temperature (−20 °C) in an acceptable 56% reaction yield (see Table 2). The latter result, which to the best of our knowledge constitutes one of the scarce examples of spirocyclic compounds having an organometallic fragment,[17] clearly confirms that the process is general and compatible with a wide variety of cyclopropenones and DACs.

Density functional theory (DFT) calculations have been carried out at the PCM(CH_2Cl_2)-M06/def2-TZVP//B3LYP/def2-SVP level[18] to gain more insight into the exclusive formation of spirocyclic compounds **A** over bicyclic species **B**. Thus, the corresponding computed reaction profile of the process involving the model cyclopropenone **1M** (where the ethyl groups in **1b** were replaced by methyl groups) and DAC **2b** in the presence of Sc(OTf)$_3$ is shown in Figure 2, which gathers the respective free energies, ΔG_{298}, in dichloromethane solution.

As previously reported,[10,14] the reaction begins with the nucleophilic attack of the cyclopropenone (through the lone-pair of the carbonyl group) to the electrophilic center of the intimate

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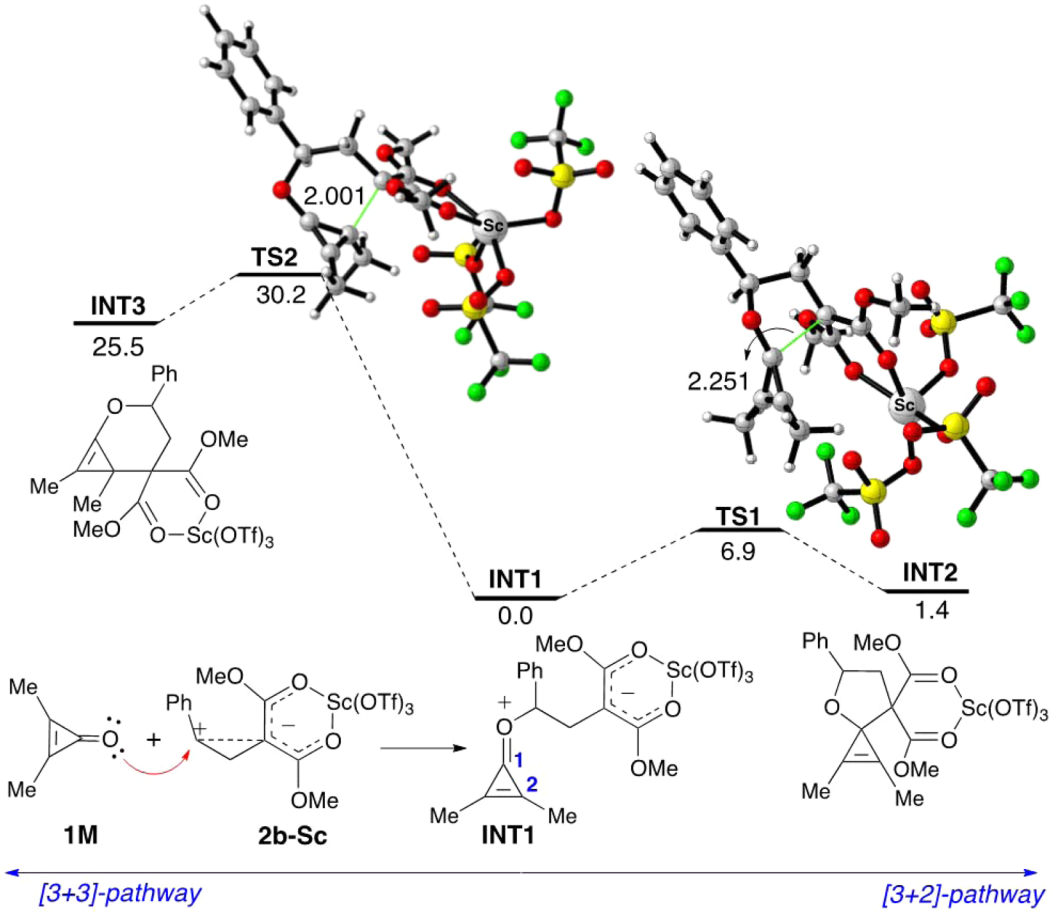

Figure 2. Computed reaction profile of the reaction of cyclopropenone **1M** and $Sc(OTf)_3$–DAC complex **2b-Sc**. Relative free energies (ΔG, 298 K) and bond distances are given in kcal/mol and angstroms, respectively. All data have been computed at the PCM(CH_2Cl_2)-M06/def2-TZVP//B3LYP/def2-SVP level.

ion-pair **2b-Sc**, which is formed upon coordination of the ester groups to the transition metal. This addition reaction leads to the formation of **INT1**, a zwitterionic intermediate similar to that proposed for the related [8 + 3]-annulation involving tropones,[10] which can be considered as an aromatic compound according to the computed negative nucleus independent chemical shift (NICS)[19] values (NICS(0) = −27.2 ppm and $NICS(1)_{zz}$ = −19.2 ppm). In this sense, the three-membered ring of **INT1** resembles the cyclopropenyl cation.[20]

Two possible ring closures in **INT1** can be envisioned, namely the annulation at C1 which would produce the [3 + 2]-adduct **INT2** and, alternatively, the annulation at C2, leading to the formation of the bicyclic species **INT3**. From the data in Figure 2, it becomes clear that the nucleophilic attack at C1 is strongly favored under both kinetic and thermodynamic control in view of the considerably higher activation energy required for the formation of bicyclic **INT3** ($\Delta\Delta G^{\ddagger}$ = 23.3 kcal/mol), as well as the higher reaction energy calculated for this latter intermediate ($\Delta\Delta G_R$ = 24.1 kcal/mol). As a consequence, no traces of the corresponding [3 + 3]-reaction product should be observed in the reaction crudes, as experimentally found. In addition, the respective noncoordinated reaction products derived from **INT2** and **INT3** also exhibit a similar free energy difference ($\Delta\Delta G_R$ = 19.5 kcal/mol), thus confirming that the highly strained nature of the bicyclic species **B** switches off the [3 + 3]-annulation reaction pathway.

Finally, the ring closure at C1 leading to spirocyclic compounds is preferred over the cyclization at C2 for an additional reason. As seen from the computed natural bond orbital (NBO) charges (Figure 3), the carbon atom C1 in the initial zwitterionic intermediate **INT1** clearly bears a more positive charge than C2 (or C3) (Δq = +0.364 au), thus indicating a higher electrophilic character. This difference in electrophilicity also directs the nucleophilic addition from the carbanionic center C4 (q = −0.364) toward C1 instead of C2.

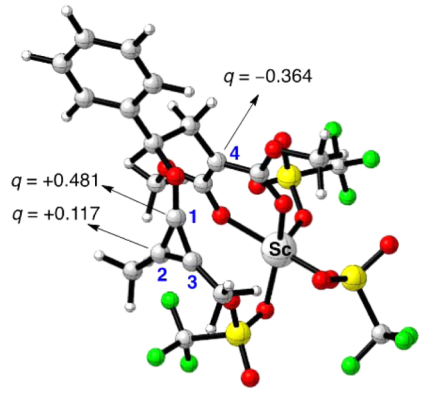

Figure 3. Computed (B3LYP/def2-SVP level) NBO charges of zwitterionic intermediate **INT1**.

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In summary, the $Sc(OTf)_3$-catalyzed reaction between cyclopropenones and different donor−acceptor cyclopropanes has been studied. This process allows the direct access to 4-oxaspiro[2.4]hept-1-ene derivatives in good to excellent reaction yields through a stepwise [3 + 2]-annulation reaction. The process is compatible with different substituents in both reactants including organometallic moieties, which might find future applications in bioorganometallic chemistry. With the help of DFT calculations it was found that the exclusive formation of the [3 + 2]-products over the [3 + 3]-bicyclic compounds takes place under both kinetic and thermodynamic control. This preference finds its origin in the higher electrophilicity of the C1 carbon atom of the aromatic zwitterionic intermediate and in the highly strained nature of the [4.1.0]-bicyclic species.

EXPERIMENTAL SECTION

General Procedures. All reactions were carried out under argon atmosphere. Dichloromethane (DCM) was distilled from calcium hydride before use. Flame-dried glassware was used for moisture-sensitive reactions. Identification of products was made by thin-layer chromatography (TLC) (Kieselgel 60F-254). UV light (λ= 254 nm) and oleum was used to develop the plates. NMR spectra were recorded at 25 °C in $CDCl_3$ on a 300 MHz (300 MHz for ^1H, 75 MHz for ^{13}C) spectrometer. Chemical shifts are given in ppm relative to TMS (^1H, 0.0 ppm) or $CDCl_3$ (^{13}C, 77.0 ppm). IR spectra were taken as solid films by slow evaporation of the solvent using the ATR (attenuated total reflectance) technique. HRMS spectra were obtained on a mass spectrometer using electronic impact (EI) or on a Q-TOF system for the electron spray ionization (ESI) experiments. Commercially available products were used without further purification. 1,1-Cyclopropanediesters were synthesized according to literature procedures: (**2a**−**d**,**f**,**i**,**j**),[21] **2e**,[22] and **2h**.[15c]

General Procedure for the Annulation Reactions. In an oven-dried pressure tube, cyclopropenone **1** (0.12 mmol), cyclopropane **2** (0.12 mmol), and scandium triflate (10 mol %) were dissolved in anhydrous dichloromethane (2.5 mL) at 25 °C. The reaction mixture was stirred under argon atmosphere at the specified temperature. After completion of the reaction (checked by TLC), the solvent was removed under reduced pressure to give the crude reaction mixture, which was submitted to column chromatography (SiO_2, hexanes to 1:10 EtOAc/hexanes) to yield pure oxaspiranic compounds **3**.

*Compound **3a**.* The reaction was performed at 80 °C following the general procedure described above from cyclopropenone **1a** (25 mg) and cyclopropane **2a** (31 mg). Compound **3a** was isolated as a colorless solid (32 mg, 57%); ^1H NMR (300 MHz, $CDCl_3$) δ 7.86−7.78 (m, 4H), 7.51−7.28 (m, 11H), 5.31 (dd, J = 10.2, 5.7 Hz, 1H), 4.18−4.03 (m, 1H), 4.00−3.82 (m, 3H), 3.29 (dd, J = 12.9, 5.7 Hz, 1H), 2.86 (dd, J = 12.9, 10.2 Hz, 1H), 0.99 (q, J = 7.3 Hz, 6H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 170.9, 169.8, 142.2, 130.4, 130.2, 129.60, 129.55, 129.0, 129.0, 128.96, 128.8, 128.03, 126.1, 120.8, 120.7, 77.2, 71.2, 62.1, 61.8, 61.0, 45.3, 14.1, 14.0; IR (ATR) $\tilde{\nu}$ = 2982, 1730, 1389, 1211, 1093, 759, 690 cm^{-1}; HRMS (ESI) calcd for $C_{30}H_{29}O_5$ $[M + H]^+$ 469.2010, found 469.2022.

*Compound **3b**.* The reaction was performed at 80 °C following the general procedure described above from cyclopropenone **1a** (25 mg) and cyclopropane **2b** (28 mg). Compound **3b** was isolated as a colorless solid (27 mg, 51%): ^1H NMR (300 MHz, $CDCl_3$) δ 7.81 (t, J = 7.0 Hz, 4H), 7.54−7.25 (m, 11H), 5.33 (dd, J = 10.3, 5.5 Hz, 1H), 3.54 (s, 3H), 3.48 (s, 3H), 3.32 (dd, J = 12.9, 5.5 Hz, 1H), 2.88 (dd, J = 12.9, 10.3 Hz, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 171.2, 170.3, 142.0, 130.4, 130.2, 129.7, 129.1, 129.0, 128.8, 128.0, 127.8, 127.7, 126.1, 120.7, 120.5, 77.4, 71.4, 60.8, 53.0, 52.9, 45.3; IR (ATR) $\tilde{\nu}$ = 2952, 1733, 1439, 1270, 1090, 977, 760, 693 cm^{-1}; HRMS (ESI) calcd for $C_{28}H_{25}O_5$ $[M + H]^+$ 441.1697, found 441.1701.

*Compound **3c**.* In an oven-dried Schlenk tube, cyclopropenone **1a** (0.12 mmol, 25 mg) and scandium triflate (10 mol %) were dissolved in anhydrous dichloromethane (2 mL). The mixture was stirred under argon at 0 °C for 5 min before the addition of cyclopropane **2c** (0.12 mmol, 32 mg) in anhydrous dichloromethane (0.5 mL). The reaction mixture was stirred under argon atmosphere at 0 °C until the completion of the reaction (checked by TLC). Evaporation of the solvent under reduced pressure gave the crude reaction mixture, which was submitted to column chromatography (SiO_2, hexanes to 1:10 EtOAc/hexanes) to yield pure compound **3c** as a yellow oil (48 mg, 85%): ^1H NMR (300 MHz, $CDCl_3$) δ 7.89−7.76 (m, 4H), 7.54−7.36 (m, 8H), 6.91 (d, J = 8.7 Hz, 2H), 5.26 (dd, J = 10.3, 5.4 Hz, 1H), 3.82 (s, 3H), 3.52 (s, 3H), 3.48 (s, 3H), 3.25 (dd, J = 13.0, 5.4 Hz, 1H), 2.86 (dd, J = 13.0, 10.3 Hz, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 171.3, 170.5, 159.6, 133.9, 130.4, 130.2, 129.6, 129.1, 129.0, 128.2, 127.9, 127.7, 127.5, 120.9, 120.4, 114.2, 77.2, 71.2, 60.9, 55.7, 53.0, 52.9, 45.3; IR (ATR) $\tilde{\nu}$ = 2953, 1733, 1313, 1439, 1247, 1174, 1084, 762, 691 cm^{-1}; HRMS (ESI) calcd for $C_{29}H_{27}O_6$ $[M + H]^+$ 471.1802, found 471.1808.

*Compound **3d**.* The reaction was performed at 80 °C following the general procedure described above from cyclopropenone **1a** (25 mg) and cyclopropane **3d** (30 mg). Compound **3d** was isolated as a white solid (28 mg, 51%): ^1H NMR (300 MHz, $CDCl_3$) δ 7.83−7.75 (m, 4H), 7.52−7.39 (m, 8H), 7.04 (t, J = 8.7 Hz, 2H), 5.27 (dd, J = 10.2, 5.6 Hz, 1H), 3.52 (s, 3H), 3.47 (s, 3H), 3.27 (dd, J = 13.0, 5.6 Hz, 1H), 2.82 (dd, J = 13.0, 10.2 Hz, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 171.2, 170.3, 162.7 (d, J = 246 Hz), 137.7 (d, J = 3 Hz), 130.3, 130.2, 129.7, 129.1, 129.06, 127.8 (d, J = 8 Hz), 127.6, 120.7, 120.3, 115.7 (d, J = 21 Hz), 76.8, 71.4, 60.7, 53.0, 52.9, 45.4; IR (ATR) $\tilde{\nu}$ = 2951, 1734, 1487, 1434, 1270, 1009, 760, 690 cm^{-1}; HRMS (EI) calcd for $C_{28}H_{23}FO_5$ $[M]^{\cdot+}$ 458.1524, found 458.1527

*Compound **3e**.* The reaction was performed at 80 °C following the general procedure described above from cyclopropenone **1a** (25 mg) and cyclopropane **2e** (38 mg). Compound **3e** was isolated as a white solid (27 mg, 43%): ^1H NMR (300 MHz, $CDCl_3$) δ 7.87−7.69 (m, 4H), 7.56−7.28 (m, 10H), 5.24 (dd, J = 10.2, 5.7 Hz, 1H), 3.51 (s, 3H), 3.46 (s, 3H), 3.27 (dd, J = 12.9, 5.7 Hz, 1H), 2.78 (dd, J = 12.9, 10.2 Hz, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 171.1, 170.2, 141.2, 131.9, 130.3, 130.2, 129.8, 129.7, 129.1, 129.07, 127.8, 127.7, 127.6, 121.7, 120.5, 120.4, 76.6, 71.5, 60.7, 53.04, 52.96, 45.2; IR (ATR) $\tilde{\nu}$ = 2951, 1730, 1438, 1403, 1265, 1041, 1078, 972, 759, 690 cm^{-1}; HRMS (EI) calcd for $C_{28}H_{23}BrO_5$ $[M]^{\cdot+}$ 518.0723, found 518.0729.

*Compound **3f**.* The reaction was performed at 80 °C following the general procedure described above from cyclopropenone **1a** (25 mg) and cyclopropane **2f** (31 mg). Compound **3f** was isolated as a yellow oil (22 mg, 40%): ^1H NMR (300 MHz, $CDCl_3$) δ 7.89−7.72 (m, 4H), 7.65 (d, J = 8.3 Hz, 2H), 7.56 (d, J = 8.3 Hz, 2H), 7.55−7.35 (m, 6H), 5.34 (dd, J = 10.1, 5.9 Hz, 1H), 3.54 (s, 3H), 3.47 (s, 3H), 3.34 (dd, J = 13.0, 5.9 Hz, 1H), 2.78 (dd, J = 13.0, 10.1 Hz, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 170.9, 169.9, 147.8, 132.7, 130.3, 130.2, 129.92, 129.87, 129.2, 129.1, 127.5, 127.4, 126.6, 120.3, 120.2, 119.3, 111.7, 76.3, 71.7, 60.4, 53.1, 53.0, 44.9; IR (ATR) $\tilde{\nu}$ = 2953, 2228, 1735, 1440, 1271, 1085, 974, 761, 692 cm^{-1}; HRMS (ESI) calcd for $C_{29}H_{24}NO_5$ $[M + H]^+$ 466.1649, found 466.1659.

*Compound **3h**.* The reaction was performed at 25 °C following the general procedure described above from cyclopropenone **1a** (25 mg) and cyclopropane **2h** (40 mg). Compound **3h** was isolated as a colorless oil (63 mg, 93%): ^1H NMR (300 MHz, $CDCl_3$) δ 7.96−7.90 (m, 2H), 7.84−7.76 (m, 2H), 7.70−7.62 (m, 4H), 7.45−7.27 (m, 6H), 6.36 (dd, J = 8.7, 6.7 Hz, 1H), 4.07−3.95 (m, 3H), 3.95−3.87 (m, 1H), 3.83−3.71 (m, 1H), 3.18 (dd, J = 13.2, 6.7 Hz, 1H), 0.95 (t, J = 7.1 Hz, 3H), 0.87 (t, J = 7.1 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 170.7, 168.8, 168.0, 134.6, 132.3, 130.9, 130.0, 129.7, 129.0, 128.9, 127.7, 127.68, 123.9, 121.5, 118.7, 110.0, 77.0, 70.9, 62.4, 61.9, 60.1, 36.8, 14.2, 13.9; IR (ATR) $\tilde{\nu}$ = 2979, 1721, 1369, 1267, 1086, 720 cm^{-1}; HRMS (ESI) calcd for $C_{32}H_{28}NO_7$ $[M + H]^+$ 538.1860, found 538.1862.

*Compound **3i**.* The reaction was performed at 25 °C following the general procedure described above from cyclopropenone **1a** (25 mg) and cyclopropane **2i** (36 mg). Compound **3i** was isolated as a colorless oil (62 mg, quantitative): ^1H NMR (300 MHz, $CDCl_3$) δ 8.06−7.95 (m, 2H), 7.92−7.85 (m, 2H), 7.79−7.70 (m, 4H), 7.53−7.36 (m, 6H), 6.35 (dd, J = 8.4, 6.8 Hz, 1H), 3.99 (dd, J = 13.3, 8.4 Hz, 1H), 3.59 (s, 3H), 3.50 (s, 3H), 3.23 (dd, J = 13.3, 6.8 Hz, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 171.0, 169.4, 168.0, 134.7, 132.3, 130.8, 130.0, 129.8, 129.7, 129.1, 129.0, 127.5, 127.3, 124.0, 121.1, 118.8, 76.9, 71.1, 60.0, 53.2,

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53.0, 37.0; IR (ATR) $\tilde{\nu}$ = 2953, 1719, 1371, 1273, 1137, 1086, 720 cm^{-1}; HRMS (ESI) calcd for $C_{30}H_{24}NO_7$ $[M + H]^+$ 510.1547, found 510.1540.

Compound ***3j***. The reaction was performed at 25 °C following the general procedure described above from cyclopropenone **1b** (13 mg) and cyclopropane **2i** (36 mg). Compound **3j** was isolated as a colorless oil (41 mg, 84%): ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.89−7.83 (m, 2H), 7.75−7.68 (m, 2H), 6.00 (t, J = 7.5 Hz, 1H), 3.82 (s, 3H), 3.76 (s, 3H), 3.65 (dd, J = 13.2, 7.5 Hz, 1H), 3.05 (dd, J = 13.2, 7.5 Hz, 1H), 2.64−2.42 (m, 4H), 1.20 (t, J = 7.4 Hz, 3H), 1.19 (t, J = 7.5 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 171.3, 169.5, 167.9, 134.6, 132.3, 126.3, 123.8, 120.8, 75.9, 73.6, 60.5, 53.3, 53.0, 36.9, 17.8, 17.0, 14.16, 13.96; IR (ATR) $\tilde{\nu}$ = 2970, 1717, 1434, 1272, 1137, 1088, 720 cm^{-1}; HRMS (ESI) calcd for $C_{22}H_{24}NO_7$ $[M + H]^+$ 414.1547, found 414.1563.

Compound ***3k***. In an oven-dried Schlenk tube, cyclopropenone **1a** (0.12 mmol, 25 mg) and scandium triflate (0.012 mmol) were dissolved in anhydrous dichloromethane (2 mL). The mixture was stirred under argon at −20 °C for 5 min before the addition of the cyclopropane **2j** (0.12 mmol, 41 mg) in anhydrous dichloromethane (0.5 mL). The reaction mixture was stirred under argon atmosphere at −20 °C until completion of the reaction (checked by TLC). Evaporation of the solvent under reduced pressure gave the crude reaction mixture, which was submitted to column chromatography (SiO_2, hexanes to 1:6 EtOAc/hexanes) to yield pure compound **3c** as a yellow oil (37 mg, 56%): ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.87−7.73 (m, 4H), 7.58−7.33 (m, 6H), 5.08 (dd, J = 10.2, 5.6 Hz, 1H), 4.41−4.16 (m, 9H), 3.51 (s, 6H), 3.25 (dd, J = 12.9, 5.6 Hz, 1H), 2.98 (dd, J = 12.9, 10.2 Hz, 1H); ^{13}C NMR (75 MHz, $CDCl_3$): δ 171.4, 170.7, 130.3, 130.1, 129.6, 129.5, 129.1, 128.9, 128.0, 127.8, 121.5, 120.5, 87.4, 74.4, 71.1, 69.1, 68.8, 68.7, 68.6, 66.6, 60.9, 52.95, 52.90, 43.1; IR (ATR) $\tilde{\nu}$ = 2951, 1732, 1434, 1268, 1105, 1047, 759, 736 cm^{-1}; HRMS (ESI) calcd for $C_{32}H_{29}FeO_5$ $[M + H]^+$ 549.1359, found 549.1370.

■ ASSOCIATED CONTENT

Supporting Information

X-ray crystal structure data (CIF file) for compound **3b**, ^{1}H and ^{13}C NMR spectra for compounds **3a**−**k**, computational details, Cartesian coordinates, and energies of all the stationary points discussed in the text. 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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