

## Accepted Article

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This manuscript has been accepted after peer review and appears as an Accepted Article online prior to editing, proofing, and formal publication of the final Version of Record (VoR). This work is currently citable by using the Digital Object Identifier (DOI) given below. The VoR will be published online in Early View as soon as possible and may be different to this Accepted Article as a result of editing. Readers should obtain the VoR from the journal website shown below when it is published to ensure accuracy of information. The authors are responsible for the content of this Accepted Article.

**To be cited as:** *Angew. Chem. Int. Ed.* 10.1002/anie.201900503  
*Angew. Chem.* 10.1002/ange.201900503

**Link to VoR:** <http://dx.doi.org/10.1002/anie.201900503>  
<http://dx.doi.org/10.1002/ange.201900503>

# Cycloadditions of Oxacyclic Allenes and a Catalytic Asymmetric Entryway to Enantioenriched Cyclic Allenes

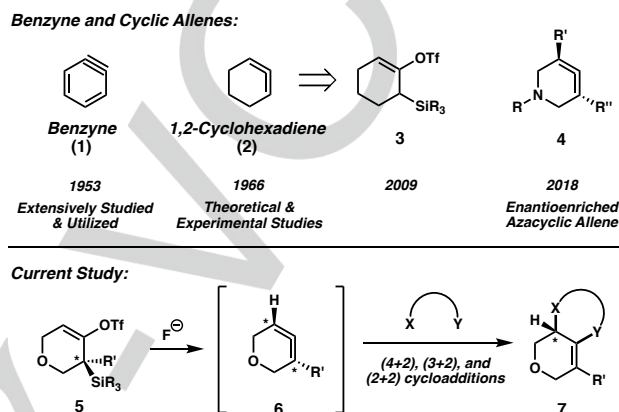
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Brian M. Stoltz,\* and Neil K. Garg\*

**Abstract:** The chemistry of strained cyclic alkynes has undergone a renaissance over the past two decades. However, a related species, strained cyclic allenes, especially heterocyclic derivatives, have only recently resurfaced and represent another class of valuable intermediates. We report a mild and facile means to generate the parent 3,4-oxacyclic allene from a readily accessible silyl triflate precursor, and trap it in (4+2), (3+2), and (2+2) reactions to provide a variety of cycloadducts. In addition, we describe a catalytic, decarboxylative asymmetric allylic alkylation performed on an  $\alpha$ -silylated substrate, to ultimately permit access to an enantioenriched allene. Generation and trapping of the enantioenriched cyclic allene occurs with complete transfer of stereochemical information in a Diels–Alder cycloaddition via a point chirality, axial chirality, point chirality transfer process.

Despite once being mere scientific curiosities, strained cyclic intermediates have become a popular arena for chemical discoveries. A notable breakthrough in the field was the discovery of benzyne (**1**), initially proposed by Wittig in 1942 and validated by Roberts in 1953 (Figure 1).<sup>1</sup> In the modern era, benzyne (**1**) and other cyclic alkynes are readily used to make natural products,<sup>2</sup> medicinal agents,<sup>3</sup> agrochemicals,<sup>4</sup> materials,<sup>5</sup> tools for chemical biology,<sup>6</sup> and ligands for catalysis.<sup>7,8</sup> The related intermediate 1,2-cyclohexadiene (**2**) has generally received less attention despite being validated not long after benzyne (**1**) in 1966.<sup>9</sup> Historically, theoretical studies of **2** and its derivatives have been popular.<sup>10</sup> However, only recently has **2** seen synthetic use in cycloadditions.<sup>11</sup> This is largely due to its ability to be accessed under mild fluoride-mediated conditions from silyl triflate **3**.<sup>12,13</sup>

One exciting opportunity in the field of strained cyclic intermediates is the ability to access heterocyclic allenes. Early efforts in this field relied on harsh reaction conditions;<sup>14,15</sup> however, we recently demonstrated that azacyclic allenes **4** (Figure 1) can be accessed using mild reaction conditions. Moreover, using chiral separation technology, enantioenriched **4**

was intercepted ( $R=Cbz$ ,  $R'=H$ ,  $R''=Me$ ), and its stereospecific trapping allowed for a unique approach to access enantioenriched cycloadducts.<sup>16</sup>



**Figure 1.** Highlights of benzyne and cyclic allene chemistry and cycloadditions of oxacyclic allenes described in this study. OTf=trifluoromethanesulfonate.

Given the potential for heterocyclic allenes to provide a facile means to rapidly assemble stereochemically-rich scaffolds,<sup>16</sup> we questioned if oxacyclic allenes **6** could be employed efficiently in cycloadditions to access oxygen-containing heterocycles.<sup>17</sup> Oxygenated heterocycles are often seen in natural products and drugs<sup>18,19,20,21</sup> and are known bioisosteres for their nitrogen and sulfur-containing counterparts.<sup>22</sup> A single report by Christl demonstrated that **6** ( $R'=H$ ) could be generated using the Doering–Moore–Skattebøl rearrangement, however, this required harsh organolithium-based conditions.<sup>14</sup> If **6** could be generated under mild conditions from silyl triflates **5**, the untapped synthetic utility of this species could be unlocked. Additionally, we sought to establish a catalytic, asymmetric method to access **6** in enantioenriched form, ideally by preparing an enantioenriched precursor to the desired allene **6**. By accessing enantioenriched **5**, we could explore the possibility of transferring stereochemical information from allene precursor **5** to cycloadduct **7**, via a point chirality, axial chirality, point chirality transfer process. The results presented herein not only demonstrate the scope and utility of oxacyclic allene cycloadditions, but also showcase an exciting strategy that merges asymmetric catalysis with cyclic allene chemistry as a means to access enantioenriched scaffolds.

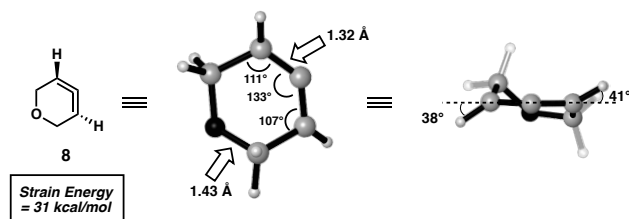
Density functional theory (DFT) calculations on the structure of heterocyclic allene **8** were performed using  $\omega$ B97XD/6-31G(d) (Figure 3).<sup>10a,10c,10d,23</sup> The C=C bond length of the allene is 1.32 Å, which is only slightly longer than the C=C bond length in a linear allene.<sup>16</sup> Furthermore, the internal angle at the central allene carbon is 133°, which is a significant deviation from the typical internal angle of 180° seen in linear allenes. The allene  $\pi$  orbitals in **8** are not perfectly orthogonal,

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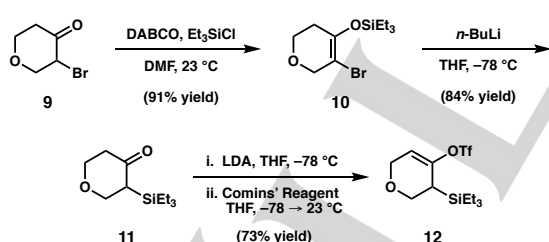
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resulting in the C–H bonds being twisted out-of-plane (i.e., 38° and 41°). Thus, **8** is inherently chiral, analogous to linear allenes. The ground state geometry deviates from C<sub>2</sub> symmetry because the molecule adopts an envelope shape; inversion of the envelope requires only 0.8 kcal/mol. Interestingly, oxacyclic allene **8** is calculated to possess 31.0 kcal/mol of strain energy, which is nearly 4 kcal/mol more than the azacyclic variant we previously reported.<sup>16</sup> This difference can be attributed to the smaller atomic radius of oxygen and the shorter C–O bond length relative to the C–N bond length in the azacyclic variant. The significant strain associated with oxacyclic allene **8** was expected to promote rapid cycloadditions.



**Figure 2.** Ground state structure of oxacyclic allene **8**. The structure was computed using  $\omega$ B97XD/6-31G(d).

With the aim of accessing oxacyclic allene **8**, we first targeted silyl triflate **12** (Scheme 1), given the wide synthetic utility of silyl triflates as precursors to strained alkyne and allene intermediates.<sup>12, 24</sup> Bromoketone **9** (commercially available or readily synthesized from tetrahydro-4-pyranone) was converted to triethylsilyl enol ether **10** upon treatment with DABCO and TESC1.<sup>25</sup> Subsequent retro-Brook rearrangement furnished the desired  $\alpha$ -silyl ketone **11**. Lastly, triflation afforded silyl triflate **12**.<sup>16</sup> Our three step, scalable<sup>26</sup> synthesis of **12** provides a new strategy to synthesize  $\alpha$ -silyl ketones en route to cyclic allene precursors. Currently,  $\alpha$ -silyl ketones are most commonly prepared by 1,4-reduction of the corresponding  $\alpha,\beta$ -unsaturated ketones.<sup>11a,12,16,27</sup>

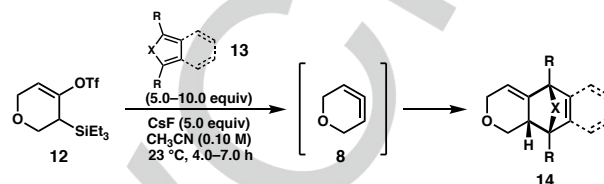


**Scheme 1.** Synthesis of silyl triflate **12**. DABCO=1,4-diazabicyclo[2.2.2]octane, DMF=*N,N*-dimethylformamide, THF=tetrahydrofuran, LDA=lithium diisopropylamide, Comins' Reagent=*N*-(5-Chloro-2-pyridyl)bis(trifluoromethanesulfonimide).

With silyl triflate **12** in hand, we generated and trapped **8** in Diels–Alder, (3+2), and (2+2) cycloadditions. By simply employing a variety of dienes, a number of cycloadducts were prepared in good to excellent yields (Table 1, entries 1–5).<sup>28</sup> In almost all cases, the reactions were performed at 23 °C, thus highlighting the mildness of the reaction conditions. Although the range of diastereoselectivities is variable, in all examples, the major diastereomer observed is the endo product. Furthermore,

the observed selectivities are supported by computations as the endo transition states were found to be more energetically favorable compared to the exo transition states.<sup>26</sup> It should be noted that in each case, the products formed are considerably complex from a structural perspective, each bearing three stereocenters, a bridged [2.2.1]-bicyclic framework, and 1 or 2 heteroatoms.

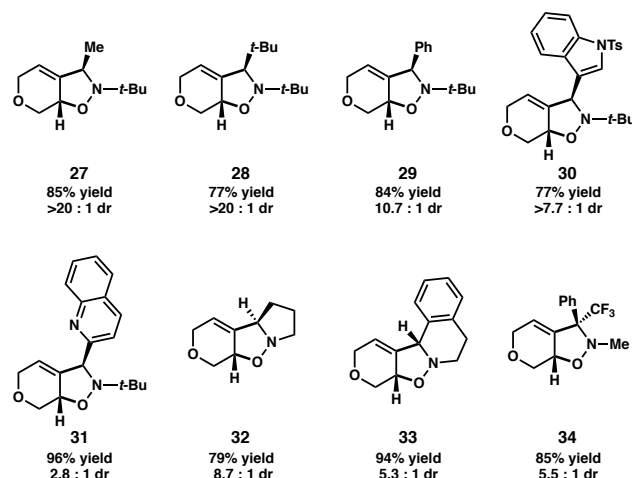
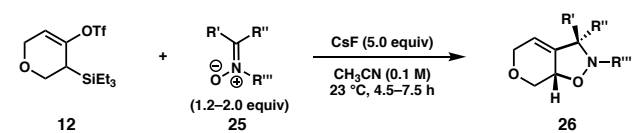
**Table 1.** Mild generation of oxacyclic allene **8** and its trapping in Diels–Alder cycloadditions.



Entry	Diene	Cycloadduct <sup>[a]</sup>	Yield <sup>[b]</sup> Diastereoselectivity <sup>[c]</sup>
1	PhN <b>15</b>	<b>16</b>	91% 3.8 : 1 dr
2	BocN <b>17</b>	<b>18</b>	74% 6.2 : 1 dr
3	Me <b>19</b>	<b>20</b>	86% 9.2 : 1 dr
4	Ph <b>21</b>	<b>22</b>	97% <sup>[d]</sup> 2.0 : 1 dr
5	<b>23</b>	<b>24</b>	83% 1.6 : 1 dr

[a] The major diastereomer is shown. [b] Yields reflect an average of two isolation experiments. [c] Diastereomeric ratios were determined by <sup>1</sup>H NMR analysis of the crude reaction mixture. [d] The reaction was performed at 60 °C for 2.5 h using 2.0 equiv of diene **21**. OTf=trifluoromethanesulfonate, Boc=*tert*-butyloxycarbonyl.

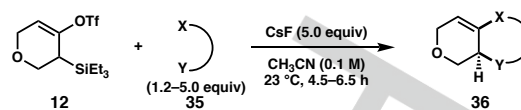
The results of the (3+2) and (2+2) cycloadditions are shown in Figure 3 and Table 2. The use of simple nitrones gave high yields of isoxazolidine products **27–29**, whereas nitrones bearing either an indole or quinoline unit delivered cycloadducts **30** and **31**. We also evaluated two cyclic nitrones where R' and R'' of **25** were tethered, which furnished tri- and tetracyclic products **32** and **33**. Additionally, a ketone-derived nitronone was utilized, ultimately giving rise to the heteroatom-rich trifluoromethylated product **34**. Azomethine imines **37** and **39** were tested, giving rise to the corresponding pyrazolidines, **38** and **40**, in good to excellent diastereoselectivities (Table 2, entries 1 and 2). The use of nitrile oxide **41** led to the formation of isoxazoline **42** in 91% yield (entry 3). With regard to (2+2) cycloaddition, the use of indene gave cyclobutane **44** in excellent yield and with high regioselectivity (entry 4).



**Figure 3.** (3+2) cycloadditions with nitrones. The major diastereomeric product is shown. Yields reflect an average of two isolation experiments. Diastereomeric ratios were determined by  $^1\text{H}$  NMR analysis of the crude reaction mixture. OTf=trifluoromethanesulfonate, Ts = *para*-toluenesulfonyl.

Overall, silyl triflate **12** was elaborated to 17 different  $\text{sp}^3$ -rich heterocyclic cycloadducts. Several of these bear a multitude of rings, stereocenters, and heteroatoms, thus showcasing the value of oxacyclic allenes for the rapid generation of complex scaffolds. Accordingly, this methodology should be especially valuable to those pursuing modern drug discovery efforts.<sup>17</sup>

**Table 2.** Additional (3+2) and (2+2) cycloadditions.



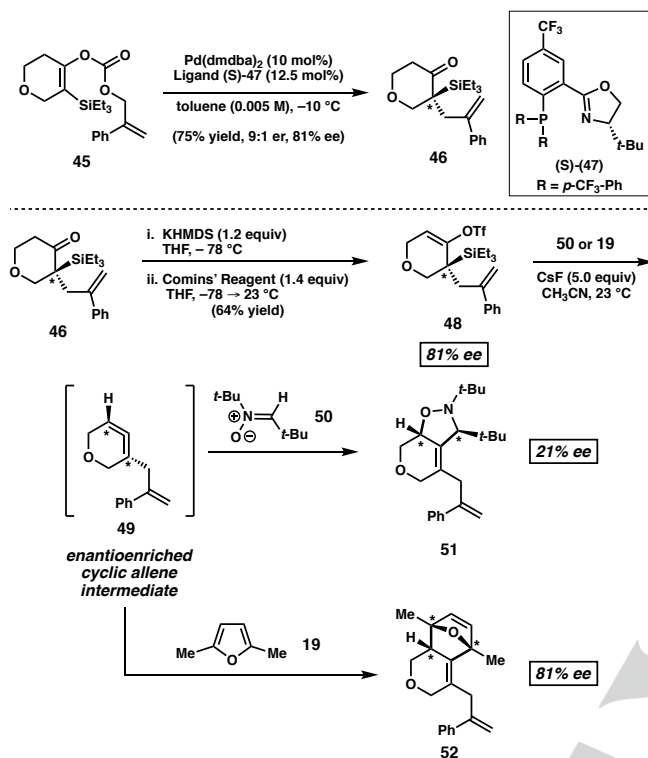
Entry	Trapping Agent	Cycloadduct <sup>[a]</sup>	Yield <sup>[b]</sup> Diastereoselectivity <sup>[c]</sup>
1			76% 7.6 : 1 dr
2			83% >20 : 1 dr
3			91% N/A
4			96% 5.2 : 1 dr

[a] The major diastereomer is shown. [b] Yields reflect an average of two isolation experiments. [c] Diastereomeric ratios were determined by  $^1\text{H}$  NMR analysis of the crude reaction mixture. OTf=trifluoromethanesulfonate.

As noted earlier, one of the most exciting opportunities regarding cyclic allene chemistry is the possibility of intercepting enantioenriched allenes for the synthesis of enantioenriched cycloadducts. In a seminal study, Christl and Engels generated 1-phenyl-1,2-cyclohexadiene in enantioenriched form, as judged by the formation of an enantioenriched cycloadduct, albeit in low yield, likely owing to the necessary use of organolithium reagents.<sup>29</sup> Our laboratory recently disclosed a mild, alternative strategy whereby silyl triflate precursors to the desired cyclic allenes could be employed in enantioenriched form.<sup>16</sup> However, in both cases, the key substrates were only accessible via chiral separation technologies. A catalytic asymmetric strategy to access enantioenriched cyclic allene precursors has not been disclosed.

Our efforts in this area are highlighted in Scheme 2. Enol carbonate **45** was formed by intercepting the enolate intermediate generated during the retro-Brook rearrangement of **10** (see Scheme 1). This set the stage for a Pd-catalyzed decarboxylative asymmetric allylic alkylation. Alkylation was attractive, given that allyl groups serve as versatile handles for further manipulation.<sup>30</sup> After extensive experimentation,<sup>26</sup> it was found that treatment of **45** with  $\text{Pd}(\text{dmdba})_2$  and (S)- $(\text{CF}_3)_3\text{-tBu-PHOX}$  ligand **7** in toluene at  $-10^\circ\text{C}$  gave the desired ketone **46** in 9:1 er (81% ee) and 75% yield. This is the first example of a decarboxylative asymmetric allylic alkylation reaction being performed on an  $\alpha$ -silyl-substituted enol carbonate. In fact, decarboxylative asymmetric allylic alkylations on substrates

bearing  $\alpha$ -heteroatoms are significantly underdeveloped.<sup>30,31</sup> **46** was converted to silyl triflate **48** in one-step, thus establishing the first catalytic asymmetric strategy for the synthesis of enantioenriched cyclic allene precursors.



**Scheme 2.** Catalytic asymmetric approach and cycloaddition results. dmdba=3,5,3',5'-dimethoxydibenzylideneacetone, KHMDS=potassium bis(trimethylsilyl)amide, Comins' Reagent=*N*-(5-Chloro-2-pyridyl)bis(trifluoromethanesulfonimide), THF=tetrahydrofuran.

**48** was treated with trapping agent **50** or **19** in the presence of CsF in acetonitrile at 23 °C. Interestingly, the nitron cycloadduct, isoxazolidine **51**, was obtained in 21% ee. On the other hand, the Diels–Alder cycloadduct, oxabicyclo **52**, was obtained in 81% ee (>20:1 dr), reflective of complete transfer of stereochemical information. Given this latter result, we surmise that enantioenriched **49** is formed under the mild reaction conditions with complete transfer of stereochemical information. In the case of the nitron trapping, previous computational studies have demonstrated that trapping may occur through either a stepwise or concerted pathway,<sup>11a</sup> which accounts for the partial loss of stereochemical information.<sup>32</sup> However, in the case of the Diels–Alder reaction, it is likely that a concerted pathway is operative, based on our recent computational investigation of azacyclic allenes,<sup>16</sup> thus leading to complete transfer of stereochemical information.

The overall conversion of **48** to **49** to **52** deserves special attention. This is a scenario wherein the silyl-bearing stereocenter in **48** was ultimately accessed by asymmetric catalysis. The point chirality in **48** is then transferred to the axially chiral transient intermediate **49**, which is then relayed to product **52**, which possesses point chirality. Enantioenriched cycloadduct **52** contains three stereocenters, none of which

were present in the starting material that bears only one stereocenter. The transformation occurs preferentially with the olefin more distal to the 2-phenyl allyl group undergoing cycloaddition. This is presumably because of favorable electronic interactions in the transition state based on our prior studies,<sup>16</sup> however, we cannot rule out the steric impact of the 2-Ph allyl chain as a contributor to the observed regioselectivity.

We have discovered an efficient synthetic route to prepare a silyl triflate precursor to 3,4-oxacyclohexadiene, the first generation of an oxacyclic allene under mild conditions, and the in situ trapping of the oxacyclic allene in diastereo- and regioselective cycloadditions. These efforts collectively establish the synthetic utility of oxacyclic allenes for the rapid generation of complex heterocyclic scaffolds. In addition, we have uncovered the first catalytic, asymmetric approach to access an enantioenriched cyclic allene precursor. This relies on a Pd-catalyzed allylic alkylation, performed for the first time on an  $\alpha$ -silyl substituted substrate, ultimately permitting access to the necessary enantioenriched silyl triflate precursor. We show that trapping of the enantioenriched oxacyclic allene in a Diels–Alder reaction occurs with complete transfer of stereochemical information via a point chirality, axial chirality, point chirality transfer process. These results showcase an exciting strategy that merges asymmetric catalysis with cyclic allene chemistry as a means to access densely functionalized, enantioenriched scaffolds.

## Acknowledgements

The authors are grateful to NIH-NIGMS (R01 GM123299-01A1 and R01 GM117016 to N. K. G. and R01GM080269 to B.M.S), Caltech, and UCLA for support. M. M. Y. acknowledges the National Science Foundation GRFP (DGE-1144087). A. N. thanks the Royal Thai Government Scholarship Program. Dr. Scott Virgil (Caltech) is thanked for instrumentation and SFC assistance. These studies were supported by shared instrumentation grants from the NSF (CHE-1048804) and the National Center for Research Resources (S10RR025631). This study used computational and storage services associated with the Hoffman2 Shared Cluster provided by UCLA Institute for Digital Research and Education's Research Technology Group.

**Keywords:** cyclic allenes • cycloadditions • enantioselective • heterocycles • catalysis

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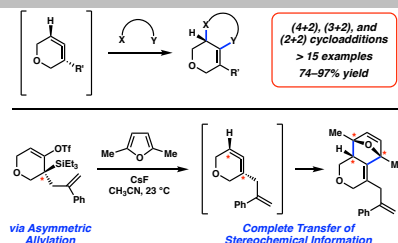
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## Entry for the Table of Contents

## COMMUNICATION

We report a mild and facile means to generate 3,4-oxacyclohexadiene and trap it in situ in (4+2), (3+2), and (2+2) reactions. In addition, we describe a catalytic, asymmetric approach for arriving at enantioenriched cyclic allene precursors.



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Cycloadditions of Oxacyclic Allenes and a Catalytic Asymmetric Entryway to Enantioenriched Cyclic Allenes