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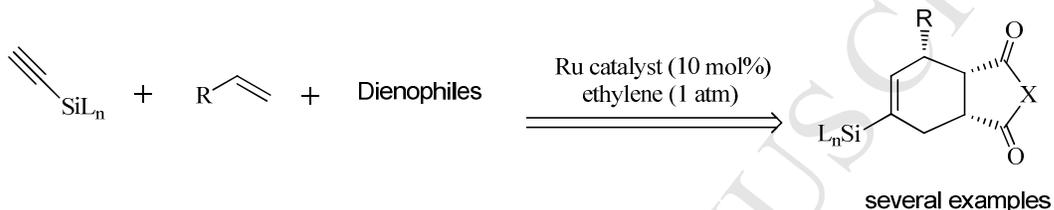
# Ruthenium Carbenes as Catalysts in Stereoselective Ene-Yne Metathesis/Diels-Alder and Ene-Yne Metathesis/Diels-Alder/Cross Coupling Multicomponent Reactions

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## Abstract

An ene-yne cross metathesis of silyl substituted alkynes and alkenes followed by a Diels-Alder reaction of the metathesis product 2-silyl-1,3-dienes has been developed. The dienes thus prepared *in situ* were shown to participate in highly diastereoselective Diels-Alder reactions. In one case the silicon substituted Diels-Alder cycloadduct was subsequently used without isolation and purification in a Hiyama cross coupling reaction. The cross coupling reactions enable these silicon dienes to be used as synthons for a variety of other dienes.

## Introduction

Reports of 2-boron and 2-silicon substituted 1,3-dienes are relatively rare in organic chemistry. In 2008, we published a review which covered boron and silicon substituted diene preparation and reaction chemistry up through 2007.[1] A review on the preparation and reaction chemistry of silyl substituted 1,3-dienes has been published in 2011[2] as well as a review of silatranes as one class of trialkyoxysilyl species where 1,3-dienes have

been reported.[3]  Krische and co-workers have also reported a ruthenium catalyzed

hydrohydroxyalkylation of silyl substituted 1,3 butadienes in 2011 as well.[4]

We reported our initial studies in 2007[5,6] and 2009[7] on the preparation and reaction

chemistry of 2-trialkoxysilyl-1,3-butadienes.  In 2010 we reported a ruthenium catalyzed

ene-yne metathesis route to silyl substituted 1,3 dienes which we subsequently used in

thermal Diels-Alder reactions.[8]  In the work that follows we report that the ene-yne

metathesis and Diels-Alder reactions can be performed as a one pot multicomponent

process which is also more stereoselective than our originally reported sequential two pot
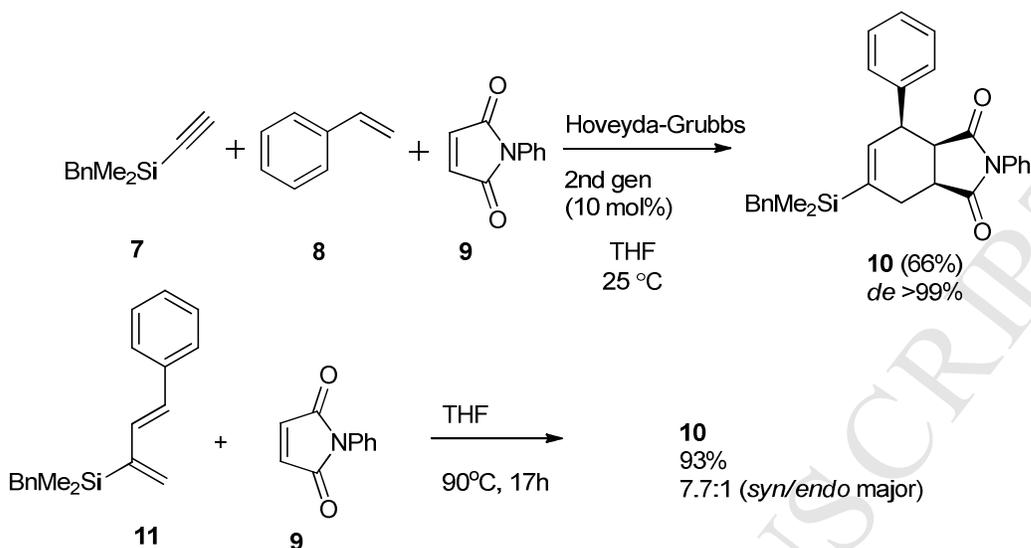
reactions.

## 2. Results and discussion

### Silyl Substituted 1,3-Diene *In situ* Preparation and Trapping via Diels-Alder Reactions.

Two examples of ruthenium carbene complex catalyzed tandem or domino reactions were

reported in 2010 which gave us cause to attempt the reaction chemistry which we now report

here.  Fuwa and coworkers reported the Hoveyda-Grubbs 2nd generation catalyst catalyzed cross

metathesis of a hydroxyl tethered olefin **1** and methyl vinyl ketone **2**.  The cross metathesis

product **3** then underwent a stereoselective intramolecular conjugate addition to produce

tetrahydropyran **4**.[9]  Also in 2010, Nandurdikar and coworkers reported a tandem ene-yne

metathesis/ intramolecular Diels-Alder reaction of **5** to produce **6** which utilized the Grubbs 2nd

generation ruthenium carbene as the catalyst.[10]

2
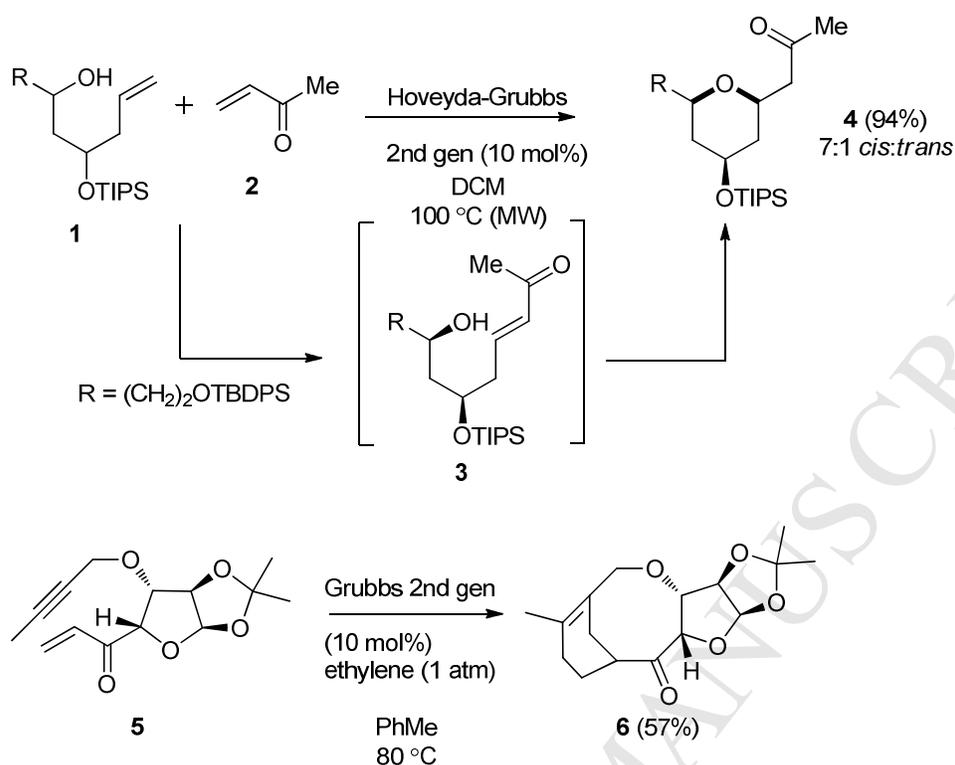
Gratifyingly, when we combined the benzyldimethyl silyl alkyne **7**, styrene **8**, and N-phenylmaleimide (NPM) **9** with Hoveyda-Grubbs 2$^{nd}$ generation catalyst (10%) in THF at 25 $^{o}$C we isolated the anticipated cycloadduct **10** in 66% yield. This reaction when originally run at 0.8M in THF required 67 hours to go to completion and we subsequently found that if run at 2.0M in THF we could isolate the desired product **10** in 62% yield after 24 h. We also noted that if the reaction was performed at 90$^{o}$C then the desired product **10** could be isolated in 57% yield after only 2 hours. Changing solvents from THF to toluene, benzene, or dichloromethane had virtually no impact on the yield whereas reducing the amount of ruthenium carbene complex present to 5% rather than 10% reduced the isolated yield of product **10** to 23%.

We noted that having a ruthenium complex present was not necessary to effect the Diels-Alder reaction since diene **11** reacted completely with NPM at 90 °C in THF overnight, however, the multicomponent one pot reaction produced the *syn* (*endo*) product **10** as the only detectable stereoisomer whereas the thermal reaction of the silicon diene **11** with NPM produced **10** as only a 7.7:1 mixture of diastereomers. Grubbs and coworkers have noted that ruthenium hydrides are present in solution in these metathesis reactions and that those ruthenium hydrides can be decomposed by the addition of 1,4 benzoquinone.[10] When we performed this multicomponent reaction in the presence of 10 mol% Hoveyda-Grubbs 2nd generation ruthenium carbene complex and 20 mol% 1,4 benzoquinone we still isolated the Diels-Alder cycloadduct **10** in 59% yield as the only detectable diastereomer so we conclude that a ruthenium complex other than the hydride may be responsible for the improved stereochemical outcome noted here. Overall for this tandem reaction we propose a ruthenium carbene complex catalyzed ene-yne metathesis followed by a Diels-Alder reaction. The *syn:anti* diastereomeric ratio of the isolated cycloadduct (**10**) of the reaction with N-phenylmaleimide is much higher when the reaction sequence is performed in the presence of ruthenium.

4

### Scope and Limitations of the Tandem Ene-Yne Metathesis/Diels-Alder Reaction

With an optimized protocol, we then conducted a scope and limitations study with various aryl and alkyl olefins as well as dienophiles of varied double bond substitution (**Table 1**). As seen with the original ene-yne metathesis reaction we reported in 2010,[8] the *para*-substituted styrene derivatives 4-vinyl anisole and 4-chlorostyrene performed well in this reaction (entries a,b). Alkyl olefin 4,4-dimethyl-1-pentene also produced product in moderate yield (entry d). In varying the dienophile used, mono-, di-, and trisubstituted dienophiles resulted in the corresponding cycloadducts in moderate to good yields (entries e–g). In reference to the regioselectivity of entries e and g, a significant preference for the *para* regioisomer was seen in both reactions. With cycloadduct **13e** this regiochemistry was determined by HMBC NMR spectroscopy (see supplementary material). Limitations to this reaction were seen in two cases. When attempting to use 2-trifluoromethylstyrene no product was recovered (entry c). Monitoring this reaction by GC/MS revealed that neither silyl acetylene **7** nor olefin (R = *o*-CF$_3$Ph) were consumed; indicating that ene-yne metathesis did not occur. In entry h, the use of 3,4-dimethylmaleic anhydride as the dienophile also resulted in no cycloadduct formation. In this case GC/MS analysis revealed the formation of the intermediate silyl diene **11** as expected so we suspect that the steric bulk of the tetrasubstituted dienophile **12h** inhibited the Diels–Alder reaction.
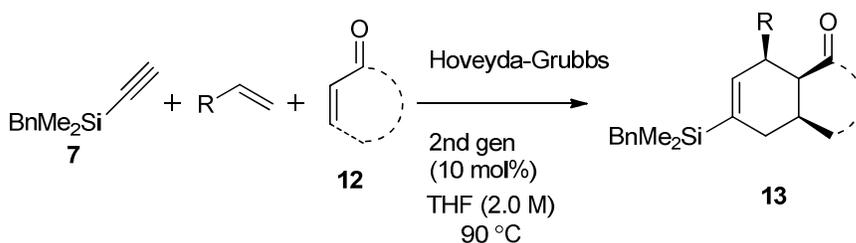
**Table I. Scope and Limitations of Multicomponent Reaction**

| Entry | R | Dienophile | Cycloadduct | % Yield |
|-------|---|------------|-------------|---------|
| a | *p*-MeOPh | NPM | **13a** | 69 |
| b | *p*-ClPh | NPM | **13b** | 53 |
| c | *o*-CF$_3$Ph | NPM | | No **13c** observed |
| d | (CH$_3$)$_3$CCH$_2$ | NPM | **13d** | 51 |
| e | Ph | ethyl acrylate | **13e** | 46 (13:1 *para*:*meta*) |
| f | Ph | diethyl maleate | **13f** | 62 (5:1 *cis:trans*) |
| g | Ph | citraconic anhydride | **13g** | 52 (8:1 *para*:*meta*) |
| h | Ph | 3,4-dimethylmaleic anhydride | | No **13h** observed |

## Cross-coupling Incorporation into the Multicomponent Reaction

To further elaborate on the transformations available in this process we attempted to effect cross-coupling in the same pot. Once the tandem ene-yne metathesis/Diels-Alder process was complete (monitored by GC/MS), palladium(0), iodobenzene, copper(I) iodide, and TBAF were added to the reaction. Unfortunately this resulted in decomposition of the silicon-substituted cycloadduct **10**; presumably due to the basic reaction conditions. We believe that this outcome was the result of catalyst "poisoning" by whatever ruthenium species is remaining in solution.[11,12] An attempt was made to prevent this poisoning by reduction of the ruthenium species present at the end of the tandem reaction with sodium borohydride but this proved ineffective. Another attempt at removal of ruthenium was conducted using aqueous hydrogen peroxide. It is reported that, under these conditions, ruthenium species are oxidized to ruthenium oxides which

6

are insoluble in organic solvent and precipitate from the reaction solution.[13] Again, the harsh reaction conditions resulted in cycloadduct **10** decomposition. Cross-coupled product **14** was attained in moderate yield (40% overall, 74% avg yield per step for 3 sequential reactions) when an intermediate step using oven-dried alumina to bind the ruthenium species before addition of palladium(0) was included. Interestingly, removal of the spent alumina by filtration was required before the third step to achieve cross-coupling.
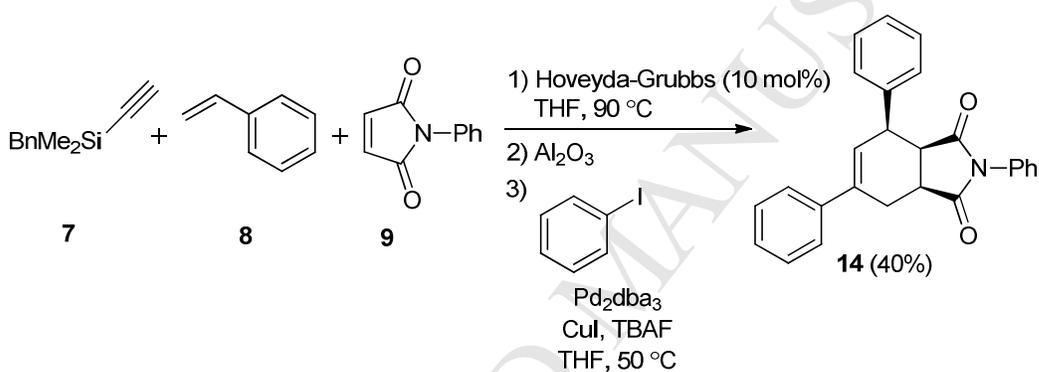


## 3. Conclusions

4-Alkyl- and 4-aryl-2-silyl-1,3 dienes can be prepared stereoselectively by ene-yne cross metathesis and these dienes can be trapped *in situ* in a highly stereoselective Diels-Alder reaction with a variety of dienophiles. The Diels-Alder cycloadduct (**10**) also participated in a cross coupling reaction. The cross coupling reaction enables the original silyl diene (**11**) to serve as a synthon for a host of organic dienes.

## 4. Experimental Section

### 4.1. General experimental

The ^{1}H NMR spectra were recorded using a Bruker Avance 300MHz spectrometer and a Bruker Avance 500MHz spectrometer operating at 300.13 MHz and 500.13 MHz

respectively. $^{13}$C NMR spectra were also recorded on the previously mentioned spectrometers operating at 75.48 MHz and 125.77 MHz respectively. Chemical shifts were reported in parts per million ($\delta$) relative to tetramethylsilane (TMS) or to residual resonances of the deuterated solvents: benzene ($C_6D_6$) or chloroform ($CDCl_3$). Coupling constants (*J* values) were reported in hertz (Hz) and spin multiplicities were indicated by the following symbols: s (singlet), d (doublet), t (triplet), q (quartet), and m (multiplet).

Analytical chromatographic techniques were performed using an Agilent Technologies 7890A gas chromatograph coupled to an Agilent Technologies 5975C mass selection detector run in electron impact mode. The gas chromatograph was run under a 50-split method and used a 5-MS capillary column (30 m, 0.25 micron film, 0.25 mm OD). The temperature sequence of the chromatograph oven was as follows: initial temperature of 50 °C held for 1 min. followed by a ramp of 12 °C/min. up to 320 °C.

High resolution mass spectrometric (HRMS) analyses were performed at the University of North Carolina at Chapel Hill Mass Spectroscopy Facility, Chapel Hill, NC. Flash chromatography was performed using thick-walled glass chromatography columns and "Ultra Pure" silica gel (Silicycle, Ind., Quebec, Canada, 40-63 μM).

All reactions were carried out under an inert atmosphere unless otherwise noted. HPLC-grade methylene chloride (DCM), toluene (PhMe), and benzene were purchased from G.J. Chemical Co. and purified using the centrally located solvent dispensing system developed by J.C. Meyer. Anhydrous THF was purchased from Acros and dried/deoxygenated using a benzophenone/sodium still. Hexanes for flash chromatography were dried over 4Å molecular sieves and purified by fractional

distillation. All reagents were purchased from Acros Organics, Sigma-Aldrich, Gelest, or Strem and used as received. Deuterated chloroform was purchased from Cambridge Isotopes and used as received.

## 4.2. General Procedure for Optimized Tandem Reactions

To an oven-dried 6-mL sealable tube equipped with a stir bar, Hoveyda–Grubbs 2nd generation catalyst (10 mol%) was added, dissolved in THF (2.0 M), and degassed with bubbling argon. After 20 minutes, benzyldimethylsilylacetylene **7** (1.0 equiv), olefin (5.0 equiv), and dienophile (0.9 equiv) were added successively to the reaction. The tube was then sealed with a crimp cap, placed in a 90 °C oil bath, and left to stir for the specified amount of time. The reaction was then allowed to cool to room temperature, the reaction mixture was condensed by rotary evaporation, and dried under reduced pressure. The crude product was then separated on silica gel with specified eluent to yield the isolated cycloadduct.

*4.2.1. Rac-cis-6-(benzyldimethylsilyl)-2,4-diphenyl-3a,4,7,7a-tetrahydro-1H-isoindole-1,3(2H)-dione* **10.** Benzyldimethylsilylacetylene **7** (0.099 g, 0.57 mmol), styrene **8** (328 μL, 2.87 mmol), *N*-phenylmaleimide **9** (0.086 g, 0.50 mmol), Hoveyda–Grubbs 2nd generation catalyst (0.035 g, 0.06 mmol), and THF (2.0 mL) were used according to the general procedure with a reaction time of 2 h. Chromatography using 8:1 benzene/ethyl acetate as eluent yielded an off-white solid **10** (0.127 g, 0.28 mmol, 57 %): R*f* 0.3 (benzene/ethyl acetate, 8:1) identical by NMR comparison to previously reported material.[8]

*4.2.2.Rac-cis*-6-(benzyldimethylsilyl)-4-(4-methoxyphenyl)-2-phenyl-3a,4,7,7a-

tetrahydro-1*H*-isoindole-1,3(2*H*)-dione **13a** (*Table 1*)**.** Benzyldimethylsilylacetylene **7**

(0.102 g, 0.59 mmol), 4-vinylanisole (381 μL, 2.87 mmol), *N*-phenylmaleimide **9** (0.092

g, 0.53 mmol), Hoveyda–Grubbs 2nd generation catalyst (0.041 g, 0.07 mmol), and THF

(2.0 mL) were used according to the general procedure with a reaction time of 1.75 h.

Chromatography using 8:1 benzene/ethyl acetate as eluent yielded an off-white solid **13a**

(0.177 g, 0.37 mmol, 69 %): $R_f$ 0.2 (benzene/ethyl acetate, 8:1) identical by NMR

comparison to previously reported material.[8]

*4.2.3. Rac-cis*-6-(benzyldimethylsilyl)-4-(4-chlorophenyl)-2-phenyl-3a,4,7,7a-tetrahydro-

1*H*-isoindole-1,3(2*H*)-dione **13b** (*Table 1*). Benzyldimethylsilylacetylene **7** (0.102 g,

0.59 mmol), 4-chlorostyrene (343 μL, 2.87 mmol), *N*-phenylmaleimide **9** (0.091 g, 0.53

mmol), Hoveyda–Grubbs 2nd generation catalyst (0.043 g, 0.07 mmol), and THF (2.0

mL) were used according to the general procedure with a reaction time of 2.5 h.

Chromatography using 8:1 benzene/ethyl acetate as eluent yielded an off-white solid **13b**

(0.136 g, 0.28 mmol, 53 %): $R_f$ 0.3 (benzene/ethyl acetate, 8:1) identical by NMR

comparison to previously reported material.[8]

*4.2.4. Rac-cis*-6-(benzyldimethylsilyl)-4-neopentyl-2-phenyl-3a, 4, 7, 7a-tetrahydro-1*H*-

isoindole-1,3(2*H*)-dione **13d** (*Table 1*). Benzyldimethylsilylacetylene **7** (0.103 g, 0.59

mmol), 4,4-dimethyl-1-pentene (412 μL, 2.87 mmol), *N*-phenylmaleimide **9** (0.070 g,

0.40 mmol), Hoveyda–Grubbs 2nd generation catalyst (0.037 g, 0.06 mmol), and THF

(2.0 mL) were used according to the general procedure with a reaction time of 2 h.

Chromatography using 8:1 benzene/ethyl acetate as eluent yielded an off-white solid **13d**

(0.091 g, 0.20 mmol, 51 %): $R_f$ 0.4 (benzene/ethyl acetate, 8:1) identical by NMR comparison to previously reported material.[8]

*4.2.5.Rac-cis*-ethyl-5-(benzyldimethylsilyl)-1,2,3,4-tetrahydro-[1,1'-biphenyl]-2-carboxylate **13e** (*Table 1*). Benzyldimethylsilylacetylene **7** (0.105 g, 0.60 mmol), styrene **8** (328 μL, 2.87 mmol), ethyl acrylate **12e** (74.5 μL, 0.687 mmol), Hoveyda–Grubbs 2nd generation catalyst (0.037 g, 0.06 mmol), and THF (2.0 mL) were used according to the general procedure with a reaction time of 18 h. Chromatography using 10:1 hexanes/ethyl acetate as eluent yielded an amber oil **13e** (0.105 g, 0.28 mmol, 46 %): $R_f$ 0.2 (hexanes/ethyl acetate, 10:1). **Major isomer** (*para*): ^{1}H NMR (500 MHz, CDCl$_3$) δ 7.27-7.17 (m, 5H), 7.08-7.00 (m, 5H), 5.95 (ddd, $J$ = 4.4, 2.5, 1.8 Hz, 1H, H-6), 3.89 (dq, $J$ = 10.5, 7.2 Hz, 2H, H-14), 3.83 (m, 1H, H-1), 2.85 (ddd, $J$ = 11.7, 6.2, 4.0 Hz, 1H, H-2), 2.29 (m, 1H, H-4b), 2.21 (d, $J$ = 13.6 Hz, 1H, H-8), 2.16 (d, $J$ = 13.6 Hz, 1H, H-8), 2.07 (m, 1H, H-4a), 1.75 (m, 2H, H-3), 1.07 (t, $J$ = 7.2 Hz, 3H, H-15), 0.08 (s, 6H, H-7). ^{13}C NMR (125.5 MHz, CDCl$_3$) δ 173.8 (C, C-13), 140.1 (C, C-1'/C-9), 137.5 (C, C-5), 137.2 (CH, C-6), 129.6 (CH, C-2'), 128.7 (CH), 128.2 (CH), 128.1 (CH), 127.9 (CH), 126.9 (CH, C-10), 124.0 (CH), 59.9 (CH$_2$, C-14), 44.9 (CH, C-2), 43.9 (CH, C-1), 26.6 (CH$_2$, C-4), 25.1 (CH$_2$, C-8), 19.3 (CH$_2$, C-3), 14.0 (CH$_3$, C-15), -4.0 (CH$_3$, C-7), -4.2 (CH$_3$, C-7). **Minor isomer (*meta*), diagnostic peaks:** ^{1}H NMR (500 MHz, CDCl$_3$) δ 5.85 (dd, $J$ = 4.2, 2.0 Hz, 1H), 4.00 (dq, $J$ = 7.2, 3.6 Hz, 2H), 3.69 (m, 1H), 2.49 (m, 1H). ^{13}C NMR (125.5 MHz, CDCl$_3$) δ 175.3 (C), 144.0 (C), 138.9 (CH), 136.6 (C), 48.5 (CH), 45.7 (CH), 26.4 (CH$_2$), 26.0 (CH$_2$), 14.1 (CH$_3$), -4.1 (CH$_3$), -4.3 (CH$_3$). HRMS [M+Na]+

calcd for $C_{24}H_{30}NaO_2Si$, 401.1913; found, 401.1958. Regio isomer ratio 13.0:1 (*Para:meta*, determined by ^{1}H NMR integrations).

*4.2.6.    Rac-cis*-diethyl    5-(benzyldimethylsilyl)-1,2,3,4-tetrahydro-[1,1'-biphenyl]-2,3-dicarboxylate **13f** (*Table 1*).    Benzyldimethylsilylacetylene **7** (0.105 g, 0.59 mmol), styrene **8** (328 μL, 2.87 mmol), diethyl maleate **12f** (69.0 μL, 0.595 mmol), Hoveyda–Grubbs 2nd generation catalyst (0.042 g, 0.07 mmol), and THF (2.0 mL) were used according to the general procedure with a reaction time of 6 h.    Chromatography using 8:1 benzene/ethyl acetate as eluent yielded a brown oil **13f** (0.118 g, 0.26 mmol, 62 %): $R_f$ 0.5 (benzene/ethyl acetate, 8:1).    **Major diastereomer** (*cis*): ^{1}H NMR (500 MHz, CDCl$_3$) δ 7.26-7.20 (m, 5H), 7.05-6.89 (m, 5H), 5.96 (m, 1H, H-6), 4.11 (q, $J$ = 7.0 Hz, 2H, H-15), 3.92 (m, 1H, H-1), 3.84 (q, $J$ = 7.1 Hz, 2H, H-16), 3.16 (dd, $J$ = 12.1, 6.5 Hz, 1H, H-2), 2.83 (dt, $J$ = 11.8, 5.4 Hz, 1H, H-3), 2.56 (dd, $J$ = 12.3, 5.0 Hz, 1H, H-4b), 2.22 (d, $J$ = 13.8 Hz, 1H, H-8), 2.18 (d, $J$ = 14.0 Hz, 1H, H-8), 2.13 (m, 1H, H-4a), 1.23 (t, $J$ = 7.3 Hz, 3H, H-17), 1.02 (t, $J$ = 7.3 Hz, 3H, H-18), 0.11 (s, 3H, H-7), 0.09 (s, 3H, H-7). ^{13}C NMR (125.5 MHz, CDCl$_3$) δ 175.6 (C, C-13), 172.4 (C, C-14), 139.2 (C, C-1'), 136.8 (CH, C-6), 135.7 (C, C-5), 129.5 (CH, C-2'), 128.3 (CH), 128.1 (CH), 128.0 (CH, C-10), 127.2 (CH), 124.2 (CH), 60.6 (CH$_2$, C-15), 60.2 (CH$_2$, C-16), 46.9 (CH, C-2), 44.0 (CH, C-1), 37.1 (CH, C-3), 31.0 (CH$_2$, C-4), 24.9 (CH$_2$, C-8), 14.3 (CH$_3$, C-17), 13.9 (CH$_3$, C-18), -4.1 (CH$_3$, C-7), -4.2 (CH$_3$, C-7).    **Minor diastereomer** (*trans*), **diagnostic peaks:** ^{1}H NMR (500 MHz, CDCl$_3$) δ 5.83 (m, 1H, H-6), 3.57 (m, 1H), 2.97 (dt, $J$ = 6.5, 5.3 Hz, 1H), 2.70 (t, $J$ = 11.4 Hz, 1H), 2.48 (m, 1H), 0.93 (t, $J$ = 7.3 Hz, 3H), 0.08 (s, 3H, H-7), 0.06 (s, 3H, H-7).    ^{13}C NMR (125.5 MHz, CDCl$_3$) δ 174.4 (C), 142.5

(C), 139.6 (C), 138.8 (CH), 135.2 (C), 60.7 ($CH_2$), 50.2 (CH), 47.6 (CH), 42.9 (CH), 30.1 ($CH_2$), 29.7 ($CH_2$), 25.0 ($CH_2$), 14.1 ($CH_3$), 13.8 ($CH_3$), -4.4 ($CH_3$, C-7). HRMS $[M+Cs]^+$ calcd for $C_{27}H_{34}CsO_4Si$, 583.1281; found, 583.1317. Diastereomer ratio 5.0:1 (*cis:trans*, determined by $^1$H NMR integrations).

*4.2.7.Rac-cis*-6-(benzyldimethylsilyl)-3a-methyl-4-phenyl-3a,4,7,7a-tetrahydroisobenzofuran-1,3-dione **13g** (*Table 1*). Benzyldimethylsilylacetylene **7** (0.105g, 0.57 mmol), styrene **8** (328 μL, 2.87 mmol), citraconic anhydride **12g** (46.4 μL, 0.516 mmol), Hoveyda–Grubbs 2$^{nd}$ generation catalyst (0.037 g, 0.06 mmol), and THF (2.0 mL) were used according to the general procedure with a reaction time of 18 h. Chromatography using 8:1 benzene/ethyl acetate as eluent yielded a yellow amorphous solid **13g** (0.105 g, 0.27 mmol, 52 %): R$_f$ 0.4 (benzene/ethyl acetate, 8:1) identical by NMR comparison to previously reported material.[8] Regioisomer ratio 8.0:1 (*para:meta*, determined by $^1$H NMR integrations).

## 4.3 Procedure for Cross-coupling Incorporation to Yield Compound 14

To an oven-dried 6-mL sealable tube equipped with a stir bar, Hoveyda-Grubbs catalyst (0.012 g, 0.02 mmol) was added and dissolved in THF (0.6 mL). To this flask benzyldimethylsilylacetylene **7** (0.029 g, 0.17 mmol), styrene **8** (91 µL, 0.80 mmol), and *N*-phenylmaleimide **9** (0.025 g, 0.14 mmol) were added successively. The reaction was purged using argon, sealed, and placed in a 90 °C oil bath. After 2 h the reaction was cooled to room temperature, unsealed, and oven-dried alumina (0.900 g) was added. After stirring under argon at room temperature for 1 h, the alumina was pelleted by centrifugation and the liquid was pipetted off into a dried 10-mL round bottom flask.

This process was repeated twice by addition of THF (2 x 0.8 mL), 1 minute agitation, centrifugation, and decantation. To the reaction solution iodobenzene (24 µL, 0.22 mmol), $Pd_2dba_3$ (0.016 g, 0.02 mmol), and copper(I) iodide (0.062 g, 0.33 mmol) were added. After 5 minutes, TBAF (1.0M in aq THF, 0.43 mL, 0.43 mmol) was added dropwise to the reaction. The flask was purged with argon and placed in a 50 °C oil bath. After 2 h the reaction was cooled to room temperature, quenched with DI $H_2O$ (5 mL), and extracted with $Et_2O$ (3 x 5 mL). The organic layers were combined, washed with DI $H_2O$ (10 mL), washed with brine (10 mL), and dried over $MgSO_4$. The solution was then condensed by rotary evaporation and dried under reduced pressure to yield a brown residue (0.067 g). This crude product was separated on silica gel with eluting 1:1 hexanes/ethyl acetate to yield a pale yellow residue **14** (0.022 g, 0.06 mmol, 40 %): $R_f$ 0.4 (hexanes/ethyl acetate, 1:1) identical by NMR comparison to previously reported material.[8]

**4.4 Diels-Alder Reaction of Diene 11 with NPM 9 to produce *Rac-cis*-6-(benzyldimethylsilyl)-2,4-diphenyl-3a,4,7,7a-tetrahydro-1H-isoindole-1,3(2H)-dione 10**

Diene **11** (0.170 g, 0.591 mmol), *N*-phenylmaleimide **9** (0.083 g, 0.473 mmol), and THF (2 mL) were heated in a sealed tube. After 17 h at 90 °C the reaction solution was condensed by rotary evaporation and dried under vacuum overnight. The resulting yellow residue was purified by flash chromatography using silica gel and 2:1 hexanes/ethyl acetate as eluent to yield a white powder (0.203 g, 0.449 mmol, 94%) identical by spectroscopic comparison to material reported previously.[8] Diastereomeric ratio 7.7:1 (determined by ^{1}H NMR integrations).

**Supporting Information Available**: $^{1}$H and $^{13}$C NMR spectra of all novel compounds produced.

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